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DEVELOPING INNOVATIVE HEAT EXCHANGERS IN A SMALL-MEDIUM ENTERPRISE: MODELLING AND IMPLEMENTATION OF PILLOW PLATE HEAT EXCHANGERS

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Abstract

The increasing demand for energy-efficient thermal management solutions has driven innovative approaches in heat exchanger design, with Pillow Plate Heat Exchangers (PPHEs) emerging as a promising technology. After a concise but complete overview on the available scientific literature, this research explores the design, experimental validation, and application potential of Pillow Plate Heat Exchangers (PPHE) through a comprehensive investigation conducted within a Small-Medium Enterprise (SME) environment. This study first develops a robust effectiveness-NTU design methodology, adapting established heat transfer principles to the unique geometric characteristics of pillow plates across diverse applications including natural convection, sensible heat transfer, sand cooling, with an only drafted conceptualisation for condensation heat recovery. Within this research work, experimental set ups and prototypes are built for model validation, with a custom-designed Small-Scale Pillow Plate Heat Exchanger (SSPPHE) apparatus revealing critical insights into thermal and hydraulic performance. Tomographic analysis and laser scanning emerged as practical techniques for geometric characterization, identifying significant border effects that explained the consistent 15-30% underestimation of pressure drop by current correlations applied to SSPPHE. Despite these geometric complexities, thermal performance predictions demonstrated acceptable agreement with experimental measurements, with thermal power deviations typically within ±15%.

A major achievement was the establishment of a complete 3kW laser welding production facility, enabling rapid prototype development while generating critical manufacturing insights regarding material selection, welding parameters, and quality assurance protocols. This production capability facilitated successful implementation across multiple industrial applications, including natural convection systems for tank heating, a 400kW sand cooling system for foundry applications, and specialized AISI 904L heat exchangers for corrosive diesel exhaust and biomass combustion gases. This section is also a testimony of the Return on Investment of R&D investment in the dynamic and customer focused environment of a SME; the product lines created from the PPHE prototypes went on generating revenues useful for more research endeavours.

Preliminary condensation heat recovery experiments demonstrated substantial thermal intensification potential, with latent heat recovery increasing total thermal power by up to 567% compared to sensible-only conditions. When cooling hot waste fumes, or when drying with hot air, great amounts of energy are wasted in the moisture content, and condensation is often avoided due to the corrosion damage it can cause to conventional heat exchanger equipment. PPHE represent a promising alternative, due to their great cleanability, availability of tested corrosion materials and surface treatments.

Ultimately, this research establishes a bidirectional knowledge transfer mechanism between theoretical modelling and practical implementation, demonstrating that successful PPHE advancement requires integration of scientific understanding with manufacturing expertise. While identifying several critical areas requiring further investigation, including refined geometric modelling and correlation development, this work provides a foundational framework for both future research and industrial application of this promising heat exchanger technology.

Thesis Index

To my Grandfather, Augusto,

A mio Nonno, Augusto,

"One must imagine Sisyphus happy."

— Albert Camus

1. Introduction and Motivation

Pillow Plate Heat Exchangers (PPHEs) represent a promising thermal management technology combining superior heat transfer characteristics with robust structural integrity. Despite demonstrated advantages in compactness, thermal performance, and design flexibility, PPHEs face implementation barriers from limited standardized design methodologies and comprehensive experimental validation. This chapter examines the gap between theoretical research and industrial application that has delayed widespread PPHE adoption. The literature review reveals significant advancements in geometrical modelling, thermohydraulic characterization, and manufacturing techniques, while identifying critical research gaps in design standardization, validation across diverse applications and materials. A section is dedicated to the objectives of this research and how it addresses these limitations through an integrated approach that balances theoretical rigor with practical implementation within a Small and Medium Enterprise (SME) context. This chapter has a last section dedicated to the thesis synopsis, allowing the reader to understand the connection between the chapters and to better trace the content presented. The reader is encouraged to explore this chapter references as they were selected as the most practical and reliable to build a foundation in PPHE design.

Chapter Index

1.1. Need for innovative Heat Exchangers

1.1.1. Heat Exchanger Evolution and Current Challenges

The global energy landscape faces mounting challenges related to efficiency, sustainability, and resource optimization. Heat exchangers, as fundamental components in numerous industrial processes, represent a critical intervention point for addressing these challenges. For decades, shell-and-tube heat exchangers (STHEs) have dominated industrial applications due to their established design methodologies, proven reliability, and extensive operational experience. However, increasing pressure for more compact, efficient, and sustainable thermal management solutions has driven significant innovation in heat exchanger technology [1].

The emergence of plate-type heat exchangers (PHEs) has challenged the traditional dominance of STHEs in various applications, offering enhanced compactness and thermal efficiency. Among these innovations, Pillow Plate Heat Exchangers (PPHEs) have emerged as a particularly promising technology, combining superior heat transfer characteristics with robust structural integrity. Despite their potential advantages, PPHEs have not yet achieved the technological readiness level of conventional equipment, primarily due to their complex geometry and limited research foundation [2].

1.1.2. A brief comment on PPHE nomenclature

Pillow plates have been assigned different nomenclatures to identify their numerous geometrical features in many ways across literature, even in the few studies cited in this section. In this research work, the nomenclature developed by Piper et al. [3] was used, except for W, which substitutes B to indicate the width of a Pillow Plate (PP). A PP consists of two metal sheets that are superimposed and spot-welded in a specific pattern and subsequently inflated through hydroforming, creating a characteristic pillow-like structure that induces complex flow patterns and enhanced heat transfer. Then, a PPHE is composed by stacking Pillow Plates, that act as a base repeating unit that can also modelled as a base periodically repeating unit, as seen on the right side of Figure 1.1. This relatively simple manufacturing concept yields a remarkably versatile heat exchanger geometry capable of accommodating diverse fluid combinations and operating conditions. Moreover, in Figure 1.1, it is also possible to see the relevant geometrical parameters for the definition of a PPHE from a design point of view, excluded the number of plates to be stacked, and the pitch among these plates which defines the width of the Outer Channel (OC). The shown parameters, namely the longitudinal (2sl) and transversal (st) welding pitches, the spot diameter (dsp), the plate thickness (dp) and the internal inflation (hi), influence both the shape of the IC and the resulting fluid motion field and the mechanical properties of the PPHE, particularly the behaviour of the IC. The parameters for the OC will influence similarly the performance of that channel.

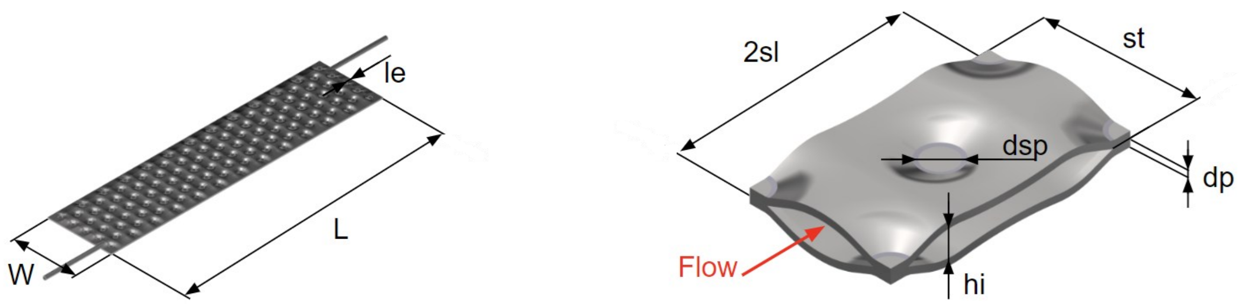

Figure 1.1: Pillow Plate (left) and Pillow Plate repeating unit (right) with geometry defining parameters

1.1.3. Driving Forces for Innovation

Industry demands for compact designs with enhanced energy efficiency have accelerated interest in PPHE technology. The driving forces behind this interest include not only the pursuit of higher thermal performance but also considerations of space utilization, material reduction, and operational flexibility. As industrial processes become increasingly constrained by spatial limitations and energy costs, the advantages offered by PPHEs become particularly relevant. The disconnect between industrial application and academic research represents a significant barrier to PPHE adoption. While manufacturers have accumulated substantial practical knowledge through iterative development, this expertise often remains proprietary and inaccessible to the broader engineering community. Concurrently, academic research has produced valuable but disjointed insights, frequently constrained by limited access to industrial-scale facilities and manufacturing capabilities. This fragmentation has impeded the development of standardized design methodologies and reliable performance prediction tools comparable to those available for conventional heat exchanger technologies [4].

1.1.4. PPHE Technology as an Emerging Solution

As anticipated, PPHEs consist of two metal sheets welded together in a specific pattern and subsequently inflated through a hydroforming process to create a characteristic "pillow-like" structure. This unique geometry induces complex flow patterns that enhance heat transfer while maintaining structural integrity for high-pressure applications. The historical development of PPHE technology can be traced back to the early 1970s, with significant advancements in manufacturing techniques occurring in the late 1990s [1]. Over the last decade, the foreseen advantages of the PPHE have been demonstrated to be numerous. This innovative heat transfer geometry combines different beneficial properties that contribute to low costs of production and operation, high quality and high performance. First, their geometry presents an enhanced compactness: the research presented in this thesis has validated a heat transfer to volume ratio of approximately 350 m^2/m^3, significantly higher than conventional STHEs. Moreover, the possibility of starting from virtually any sheet metal shape, choosing the plate number and spacing and even the welding pattern and inflation, contribute to a nearly limitless design freedom. Secondly, their construction method with a final hydroforming phase, combined with a welding pattern that is a design variable both lead to high pressure capability with the ability to withstand pressures up to hundreds of bars in the inner channel. Finally, the wavy shape obtained shows superior thermal performance, with this peculiar geometry promoting boundary layer disruption and enhanced mixing, resulting in improved heat transfer coefficients compared to smooth channels, especially at low Reynolds numbers. These three characteristics show a strong heat transfer solution that is reliable both under the mechanical, thermal, and fluid-dynamic point of view. The picture is completed by the manufacturing efficiency of PPHEs, with their production process allowing for cost-effective manufacturing with reduced material requirements compared to conventional heat exchangers [5]. As the fundamental PPHE design demonstrates clear advantages, then it is possible to explain the remarkable adaptability across applications ranging from natural convection to gas cooling and potential condensation heat recovery [6]. Recent bibliometric analysis reveals an accelerating research interest in PPHEs, with approximately 74% of published studies appearing after 2015 [2]. This surge reflects growing recognition of PPHE potential coupled with advances in computational modelling and experimental techniques. Notable contributions include the development of geometrical characterization methodologies [3], heat transfer correlations for various pillow plate configurations [7], [8] and comprehensive investigations of flow patterns within pillow plate channels [9], [10], [11].

Despite these advantages, the widespread adoption of PPHE technology faces several implementation barriers, many coming directly from their actual advantages. The complex three-dimensional wavy structure created by the hydroforming process presents challenges for accurate geometric characterization and thermohydraulic modelling, and their relative recent discover implies limited design standards: unlike STHEs, which benefit from established design codes and standards, PPHEs currently lack standardized design procedures and performance prediction methodologies. Moreover, research gaps, mainly experimental validation studies, remain, creating uncertainty in performance prediction. As for their manufacturing, the specialized production processes, while potentially cost-effective at scale, require specific expertise and equipment not universally available in the heat exchanger industry.

1.2. Literature review

Research on PPHEs has gained momentum over the past two decades, with significant contributions in several key areas that draft the foundations for a thorough comprehension of this technology.

1.2.1. Manufacturing Processes and Materials

The manufacturing of PPHEs involves several critical processes that significantly influence their thermal and hydraulic performance. The evolution from early forming techniques using resistance welding to prepare pressure vessels with single embossed Pillow Plates, to current methods employing laser welding followed by hydroforming represents a significant advancement in manufacturing capability.

Material selection for PPHEs has traditionally focused on austenitic stainless-steel grades (304, 316L, 321, 316Ti) due to their favourable combination of ductility, corrosion resistance, and weldability. Recent research has explored alternative materials, including aluminium alloys, which can provide 10-25% lower thermal resistance compared to stainless steel alternatives, though with limitations in pressure capability [12].

1.2.2. Geometrical Modelling Approaches

Accurate geometrical characterization of PPHEs represents a fundamental challenge due to the complex three-dimensional structure created by the hydroforming process. Several approaches have been developed:

1. Mathematical Functions: Early attempts utilized trigonometric functions to approximate the inflated geometry, though these failed to capture the offset of maximum inflation height from the intersection of surrounding weld spots [13].
2. Structural Formation Simulation: More advanced approaches employ finite element analysis to simulate the hydroforming process, providing more accurate representation of the actual geometry [3].
3. Experimental Characterization: Direct measurement techniques, including destructive testing and tomographic analysis, were introduced by the author during this research work and provide validation for theoretical models while highlighting local variations and border effects [14].

The work by Piper et al. [3] was of paramount importance as it established critical geometric parameters for PPHE design, introducing a more precise framework for calculating hydraulic diameters, heat transfer areas, and flow cross-sections. This geometric understanding is so important since it is the foundation to develop and then use correlations for heat transfer and pressure loss determination [7]. In fact, the development of classification systems based on the weld spot ratio has enabled more systematic characterization of flow behaviour, with longitudinal, mixed and transversal configurations identified [8].

1.2.3. Thermohydraulic Characterization

Research into the thermohydraulic behaviour of PPHEs has revealed distinct flow patterns that influence heat transfer and pressure drop characteristics, with separate analyses for Inner and Outer Channels, all well documented by the most recent reviews[1], [2].

The thermohydraulic advantages of PPHEs derive from their unique geometry, which disrupts boundary layer formation and generates complex three-dimensional flow patterns. The waviness of pillow plate surfaces induces flow mixing and secondary flows that enhance heat transfer coefficients while maintaining acceptable pressure drop characteristics. Numerical investigations have demonstrated that PPHEs can achieve heat transfer coefficients up to 25-40% higher than smooth channels at equivalent Reynolds numbers [13]), while experimental validation has confirmed superior performance compared to conventional tube bundles, particularly at lower Reynolds numbers [4], [15], [16].

Heat transfer correlations have been developed for both inner and outer channels, typically in the form of Nu = f(Re, Pr), with specific coefficients for different geometric configurations. Similarly, pressure drop correlations follow Blasius-type equations relating friction factor to Reynolds number, with coefficients dependent on geometric parameters.

1.2.4. Design Methodologies

The development of reliable design methodologies for Pillow Plate Heat Exchangers represents a critical challenge in advancing their industrial implementation. Unlike shell-and-tube heat exchangers that benefit from well-established design standards, PPHEs currently lack standardized design procedures, creating uncertainty in performance prediction and dimensioning. Early design approaches relied primarily on empirical correlations derived from limited experimental datasets, typically constrained to specific geometric configurations and narrow operational ranges. Mitrovic and Peterson [17] presented initial correlations for heat transfer and pressure drop, but their applicability was restricted to specific geometrical parameters and flow conditions. This fragmented approach, while valuable for specific applications, impeded broader PPHE adoption due to limited generalizability. A significant methodological advancement emerged with the application of the effectiveness-Number of Transfer Units (ε-NTU) method to PPHE design. Arsenyeva et al. [4] developed a comprehensive approach integrating geometric characterization with thermohydraulic correlations within the ε-NTU framework. Their methodology demonstrated efficiency for design optimization when exploiting the maximum allowable pressure drop to minimize heat transfer area. This approach provided a systematic foundation for single-phase applications, though still constrained by the available correlation database. The integration of computational fluid dynamics (CFD) with experimental validation has further enhanced design capabilities. Piper et al. [7] introduced a two-zone model that differentiated between recirculation zones and meandering core flow, providing more nuanced understanding of heat transfer mechanisms within PPHEs. This advancement enabled more accurate prediction of thermohydraulic performance across varied geometrical configurations, particularly for longitudinal pitch patterns where the distinction between flow zones is most pronounced.

1.2.5 Documented Benefits

PPHEs offer several quantifiable advantages compared to conventional heat exchangers:

1. **Thermal Performance**: Enhanced heat transfer coefficients due to boundary layer disruption and flow mixing, with longitudinal configurations demonstrating superior performance compared to transversal arrangements [8], [15].

2. **Structural Advantages**: The welded construction provides excellent pressure containment capabilities, with higher structural integrity compared to gasketed plate designs.
3. **Economic Considerations**: The increased compactness implies reduced material requirements and potentially lower manufacturing costs compared to conventional STHEs of equivalent thermal capacity.
4. **Operational Flexibility**: The ability to accommodate significant differences in flow rates between inner and outer channels without substantial performance degradation (Arsenyeva et al., 2019), the ability to distribute the same heat transfer area in different aspect ratios helps accommodate stringent hindrance requirements and for retrofitting older equipment with new, high performance heat recovery PPHEs.
5. **Cleanability**: The absence of crevices or dead zones in properly designed PPHEs enhances cleaning effectiveness, particularly important in food and pharmaceutical applications. Their wavy surface made of parallel PPs is also easier to clean and inspect than staggered tube bundles or fined tubes.
6. **Installation Simplicity**: The compact design facilitates integration into existing systems with minimal spatial requirements, especially useful for top mounted PPHEs in distillation applications [18].

1. **Maintenance Accessibility**: Depending on the specific configuration, PPHEs can offer improved access for inspection and maintenance compared to conventional designs. The parallelepipedal shape allows easy implementation of inspection doors and to even extract the plates from the frame during maintenances.
2. **Adaptability**: The fundamental design can be modified for various applications, from natural convection to high-pressure gas cooling.

1.2.6 Research Gaps

Despite significant advancements in PPHE research and development, several critical gaps delay a widespread industrial adoption. These limitations span theoretical, experimental, and practical domains, with the most significant methodological limitation lying in design standardization. Unlike conventional heat exchangers with established codes and standards, PPHEs lack unified design procedures and prediction methodologies. Current approaches typically assume uniform inflation patterns and neglect border effects, which substantially influence performance in compact configurations. The fragmentation of design approaches across research groups has impeded standardization, with different methodologies employing varied geometrical definitions and correlation formats. This absence of consensus might create barriers or confusion for engineers implementing PPHE technology without specialized expertise.

Validation requirements represent another critical gap. Limited experimental data, particularly for small-scale configurations and specialized applications, creates uncertainty in performance prediction. The available correlations often derive from specific geometric configurations with restricted operational ranges, limiting their possible generalization and scale effects understanding remains incomplete, particularly regarding the influence of border effects in compact designs.

Material optimization presents another research opportunity. While austenitic stainless steel dominates current implementations, the balance between thermal performance, mechanical requirements, and manufacturing considerations for alternative materials requires further investigation. Aluminium alloys demonstrate potential for enhanced thermal performance, but their pressure capabilities and manufacturing requirements need systematic characterization [12].

The development of integrated design software tools remains nascent, with limited validation across diverse industrial applications. Future methodological development requires systematically extending correlation databases to wider operational ranges, establishing standardized geometric characterization procedures, and validating performance predictions across varied applications and scales. Addressing these research gaps requires an integrated approach, combining theoretical modelling, experimental validation, and industrial implementation feedback. Such advancements would significantly contribute to reducing implementation barriers and accelerating industrial adoption of PPHE technology.

1.5. Research Objectives

This research addresses fundamental gaps in PPHE technology through an integrated approach that balances theoretical rigor with practical industrial implementation. This work is placed within the operational context of a small and medium enterprise (SME), where resource constraints necessitate strategic prioritization but simultaneously offer advantages in decision-making agility and experimental flexibility. The primary objective centres on developing a robust design methodology for PPHEs that is focused on delivering practical engineering tools, rather than looking for perfect theoretical rigor. This methodology adapts the effectiveness-NTU approach to accommodate the distinctive geometrical characteristics of pillow plates, incorporating implementations of geometric characterization methods to enhance predictive accuracy. Of particular importance is the accurate modelling of border effects in compact designs, where traditional assumptions of periodicity break down. The research extends existing heat transfer and pressure drop correlations to wider operational ranges through systematic experimental validation, thereby establishing greater confidence in performance prediction across diverse applications. Experimental validation constitutes a critical dimension of this research, tackling a range of industrial applications that demonstrate the versatility of PPHE technology. Beginning with natural convection applications for tank heating and passive thermal management, the work progresses through increasingly complex scenarios including sensible heat transfer in liquid-liquid and gas-liquid configurations. The investigation of high-temperature applications with corrosive exhaust gases expands the applicability envelope, while the novel implementation of PPHEs for cooling granular materials confirms their utilization beyond conventional fluid-fluid applications. Small-scale implementations receive particular attention through the characterization of compact PPHE designs, facilitating deeper understanding of scaling effects and border influence. The study concludes investigating a two-phase application focused on latent heat recovery from humid gas streams, addressing a gap in current PPHE research and possibly creating a new interesting branch to study.

The SME environment provides a unique framework for this research, imposing practical constraints while enabling rapid prototyping and implementation cycles not typically possible in larger industrial or purely academic settings. This context demands thoughtful allocation of resources while allowing immediate feedback loops between theoretical modelling and practical application. The accelerated decision-making processes, characteristic of SMEs, facilitate experimental iteration, particularly beneficial when exploring novel applications or addressing unforeseen implementation challenges. In fact, beyond technical characterization, this research deliberately engages with market implementation considerations. The evaluation of economic viability through the creation of real prototypes and marketing of products, positions PPHEs within the competitive landscape of thermal management solutions. Investigation of the stages of production, particularly laser welding and hydroforming parameter implementation, addresses some gaps between theoretical and academic studies and practical manufacturing constraints. The research demonstrates application versatility across diverse industrial scenarios, from food processing to energy recovery, establishing a foundation for broader market adoption. Through this multifaceted approach, the research aims to transform PPHE technology from a promising but underutilized concept to a reliably implementable solution for diverse thermal management challenges. By integrating theoretical advances with practical implementation within an SME context, this work contributes to both the scientific understanding of PPHEs and their industrial accessibility.

1.6 Thesis Synopsis

This thesis presents a comprehensive investigation of Pillow Plate Heat Exchangers (PPHEs), bridging the gap between theoretical understanding and practical industrial implementation. The research journey navigates from fundamental heat transfer principles to market validation, with each chapter building upon the preceding foundations to establish a cohesive narrative of PPHE technology advancement. The reader will find useful to read the carefully selected references found along the text. This research work had the benefit and privilege to implement the work of previous great research teams, and it tries to build a useful contribution to it.

Chapter 1 establishes the research context and motivation, introducing PPHEs as an emerging technology with significant potential for enhancing thermal management efficiency across diverse industrial applications. The literature review identifies critical research gaps, particularly regarding design methodologies, experimental validation, and implementation strategies that have hindered widespread PPHE adoption despite their demonstrable advantages.

Chapter 2 develops the methodological framework that supports this research, presenting a heat exchanger model using an adapted effectiveness-NTU (ε-NTU) for heat transfer calculation, and a geometrical model for the PPHE. The methodology integrates established heat transfer principles with the unique geometric considerations of pillow plates, creating a design framework that balances theoretical rigor with practical applicability. Five distinct model implementations are presented, each addressing specific application domains selected through market feedback. While acknowledging the methodological limitations inherent in industrial innovation contexts, this chapter establishes a structured foundation that enables subsequent experimental and industrial validation.

Chapter 3 details the experimental apparatus and protocols developed and built to validate the theoretical models, describing two primary experimental platforms: the Small-Scale Pillow Plate Heat Exchanger (SSPPHE) test facility and the Condensation Heat Recovery (CHR) setup. The methodological considerations, measurement techniques, and technical challenges encountered provide critical context for interpreting the experimental results presented in Chapter 6. This experimental framework represents a significant advancement in PPHE validation methodology, particularly for compact geometries where border effects substantially influence performance.

Chapter 4 examines the manufacturing processes essential for PPHE production, from material selection through laser welding to hydroforming and quality assurance. This chapter synthesizes practical knowledge gained through the implementation of a dedicated PPHE production facility, highlighting the interplay between design specifications and manufacturing constraints. The documentation of these processes contributes valuable insights for future PPHE manufacturing initiatives, addressing a significant gap in the existing literature.

Chapter 5 presents multiple industrial case studies demonstrating PPHE implementation across diverse applications, including natural convection in immersed configurations, sand cooling systems, high-temperature exhaust gas recovery, and biomass combustion heat recovery. In this Chapter the methodological basics explained in Chapter 2 combine with practical knowledge from Chapter 4 and each case study examines the design considerations, implementation challenges, and operational feedback, providing qualitative validation that is to be combined with the results that will be explained in the following chapter. While rigorous quantitative validation was not always feasible within industrial environments, these implementations offer compelling evidence of PPHE versatility and practical value.

Chapter 6 analyses the experimental results obtained from the SSPPHE and CHR test facilities, discussed in Chapter 3; The effectiveness-NTU design methodology is validated across varied operational conditions. The thermal performance measurements demonstrated acceptable agreement between model predictions and experimental data, with thermal power deviations typically within ±15%. However, hydraulic characterization revealed systematic underestimation of pressure drop by current correlations, attributable to border effects not adequately captured in existing geometric models. The sequential testing confirmed the applicability of heat transfer correlations beyond their established literature ranges, particularly extending outer channel correlation validity to Reynolds numbers as low as 1000—a significant finding for compact PPHE applications. The preliminary findings from the CHR experimental campaigns show a significant intensification of the heat transfer process with respect to sensible heat transfer operation, with effective condensation and condensate production and elimination.

Chapter 7 synthesizes the research findings, articulating both the significant contributions to PPHE understanding and the critical areas requiring further investigation. The validated design methodology, manufacturing process advancements, and demonstrated application versatility collectively establish a foundation for broader PPHE adoption. Future research directions are identified, with particular emphasis on refined geometrical modelling to account for border effects, extended correlation development for diverse fluids and flow regimes, and comprehensive condensation heat recovery characterization.

Throughout this research journey, the interplay between theoretical modelling, experimental validation, and industrial implementation creates a bidirectional knowledge transfer mechanism that enhances both scientific understanding and practical application. The positioning within a Small and Medium Enterprise (SME) context introduces resource constraints but simultaneously enables agile decision-making and rapid prototyping cycles that accelerate technology development. The systematic advancement from theoretical concept to market implementation demonstrates not only the technical viability of PPHE technology but also its economic and operational advantages across diverse thermal management applications. This thesis contributes to both the fundamental understanding of PPHE technology and its practical implementation, establishing methodological frameworks, validation approaches, and application strategies that collectively advance the technological readiness of this promising heat exchanger class. While acknowledging the limitations inherent in the research scope, particularly regarding exhaustive quantitative validation across all potential applications, the demonstrated performance and implementation success provide compelling evidence of PPHE potential for enhancing energy efficiency and thermal management effectiveness across numerous industrial sectors.

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2. Methodology

The following chapter outlines the methodological framework supporting the design and analysis of Pillow Plate Heat Exchangers (PPHEs) across various applications. The effectiveness-NTU (ε-NTU) method is adopted as the central analytical approach, selected for its computational efficiency, physical meaning and predictive accuracy. Five implementations are presented for PPHEs: natural convection, sensible heat transfer, sand cooling, sensible heat transfer (in a small scale PPHE), and condensation heat recovery models. Each adaptation incorporates models and correlations from established works from the scientific literature and tailored assumptions relevant to their intended applications. The methodological approach balances theoretical rigor with practical implementation constraints, addressing the unique validation challenges inherent to industrial innovation contexts. Experimental validation is complemented by customer feedback in a dual-verification strategy, while computational validation is positioned as a targeted future endeavour and was not performed. This comprehensive framework provides a structured foundation for both laboratory-scale experimental campaigns and industrial-scale implementations, establishing a methodological bridge between academic research and practical application of PPHE technology.

Chapter Index

2.1. Theoretical Framework of the Effectiveness and NTU method

2.1.1. Basic Principles and Mathematical framework

The effectiveness- Number of Thermal Units (ε-NTU) method is a fundamental approach for analysing heat exchanger performance that becomes particularly valuable when dealing with complex geometries like those found in Pillow Plate Heat Exchangers (PPHEs). This relatively simple method was developed in 1955 by Keys and London to solve the problem of tedious iterations required to obtain the heat transfer rate with the Logarithmic mean temperature method, when the outlet temperatures are unknown [1]. This method is still applicable after 70 years thanks to its easy implementation and its defining quantities like Effectiveness (E) and Number of Transfer Units (NTU) that have physical meaning.

Heat exchanger effectiveness (E) represents the ratio of actual heat transfer to the maximum theoretical heat transfer in an ideal counterflow heat exchanger of infinite length. This dimensionless parameter ranges from 0 to 1 and provides a direct measure of heat exchanger performance:

$$\varepsilon = \frac{q}{q_{max}} \tag{2.1}$$

Where q is the actual heat transfer rate achieved by the heat exchanger, and q_{max} is the maximum possible heat transfer rate under the same operating conditions, as seen in Eq.2.2:

$$q_{max} = \left(\dot{m}c_p\right)_{min}(T_{1i} - T_{2i}) \tag{2.2}$$

Which is the product between the minimum capacity rate (minimum between the two products of specific heat at constant pressure and mass flowrate) and the difference between the inlet temperature of the two fluids. The Number of Transfer Units (NTU) is another dimensionless parameter that characterizes a heat exchanger's thermal size or capability. It represents the ratio of the overall thermal conductance to the minimum heat capacity rate:

$$NTU = \frac{UA}{(\dot{m}c_p)_{min}} \tag{2.3}$$

Where U is the overall heat transfer coefficient, A is the heat transfer surface area.

The Number of Transfer units is a clear indication of the potentiality that a heat exchanger has, to exchange therma120.136l power, normalised with the thermal power that is carried by the fluid with the smallest capacity rate. This definition appears logical since along the heat exchanger, the lower capacity fluid tends to approach in temperature the higher capacity fluid. Since the lower capacity fluid approaches the higher one to realise the ideal maximum heat transfer, NTU will indicate how prone this phenomenon is to occur and thus the effectiveness to be close to its ideal maximum, 1.

Another important parameter for defining a heat exchanger heat transfer dynamics is the capacity rate ratio (Cr), which compares the heat capacity rates of the fluids:

$$C_r = \frac{(\dot{m}c_p)_{min}}{(\dot{m}c_p)_{max}} \tag{1}$$

A capacity rate ratio approaching zero (as for condensers or evaporators) results in higher effectiveness values at the same NTU value, as the maximum capacity rate fluid will change less in temperature and the mean temperature difference will be conserved more through the heat exchanger length.

These fundamental parameters form the basis for analysing heat exchanger performance across various applications, from small-scale laboratory prototypes to industrial-scale installations. While this method was originally developed for conventional heat exchangers, its adaptation to PPHEs requires careful consideration of their unique geometry and flow characteristics, which will be addressed in subsequent sections.

The relationship between effectiveness (ε), Number of Transfer Units (NTU), and capacity rate ratio (Cr) forms the mathematical foundation for heat exchanger analysis. For a counter-current flow arrangement, which was used in the experimental validation of small-scale PPHEs, this relationship is expressed as:

$$\varepsilon = \frac{1 - \exp\,[-NTU(1 - C_r)]}{1 - C_r \exp\,[-NTU(1 - C_r)]} \tag{25}$$

However, industrial applications often require more passages in the internal channels, and a crossflow arrangement with multiple passages in the pillow plate internal channel must be adopted. The internal channel inlet and outlet are usually positioned in opposite with the inlet and outlet of the outer channel, to have a crossflow-counterflow arrangement that asymptotically tends to the effectiveness of the counterflow arrangement. The relationship for a crossflow arrangement with unmixed fluids is:

$$\varepsilon = 1 - exp\left\{\left(\frac{1}{C_r}\right) NTU^{0.22}[exp(-C_r \cdot NTU^{0.78}) - 1]\right\} \tag{3}$$

This equation allows prediction of heat exchanger performance when inlet temperatures and flow rates are known, without requiring iteration to solve for outlet temperatures. In fact, the actual heat transfer rate can be calculated inverting Eq.2.1 and substituting q_{max} with Eq.2.2. The outlet temperatures will be calculated from this value. The assumption of unmixed flow in both channels is yet to be tested, but can be easily substituted with the suited equation for Eq. 2.6.

For PPHEs, the calculation of heat transfer coefficients requires consideration of the complex geometry created by the pillow-like structure [2]. The hydraulic diameter and flow areas vary along the channel length, necessitating the use of mean values for these parameters. This geometrical complexity will be addressed in detail in the following section on PPHE-specific correlations.

2.1.2. Rationale for adoption

The development of reliable design methodologies for Pillow Plate Heat Exchangers (PPHEs) has evolved significantly over the past decade. Arsenyeva et al. [3] illustrated the applicability of E-NTU methodology to small-scale PPHEs, validating its potentiality to design optimised PPHEs. While their work confirmed the applicability of the method to two case studies, the text is concluded highlighting the requirement for further investigation on PPHE in different geometrical configuration and applications. Recent comprehensive reviews [2], [4] have highlighted the persistent need for reliable, practical design tools in PPHE development, while other heat exchanger geometries are thoroughly studied and characterised. The E-NTU method allows to build models in minutes, and thus to study many unknown applications. It is simple, but scalable and can be implemented into a cell-method for increased accuracy [5] and ultimately represent a clear framework for experimental validation and to communicate quickly and within a certain error margin with the market needs. All these factors considered together allow to define the E-NTU method as the core of a robust design methodology that also allows optimisation to be performed and thus deserves to be studied in depth.

2.2. General Approach for model creation

2.2.1. Core components of the PPHE design model

In this Thesis, it will be possible to read about the implementation of PPHE in several novel applications, both industrial case studies and laboratory studies. Each application starts from the study of the physical situation in which the heat exchanger operates, with specified boundary conditions and assumptions. Every application has its two working fluids with inlet temperatures and pressures and flow rates, and often there is a requirement on the thermal power to be exchanged, or the outlet temperature of one of the two fluids (it is not possible to constrain both inlets, outlets and flow rates, one parameter must be left free). The possible solutions to an application are then to be explored. However, no specific optimization procedure was chosen or followed: the focus was to explore the different applications rather than solving another peculiar situation. To do so, a general logical approach for model creation was chosen. The E-NTU method is the kernel of all the models: that is because it allows to separate the internal channel and the external channel of the pillow plate and to account for the single thermal resistances into the global heat transfer coefficient, which is then used to determine the NTU and eventually the heat exchanger efficiency. Before implementing the heat transfer correlations into the design, the first component to consider is the geometrical model. Its function is to translate the macro design parameters, such as number and dimensions of plates, welding pattern and inflation etc, into working parameters such as the passage and heat transfer areas, hydraulic diameters, cross sectional eras and more. This component is fundamental as it allows to determine from the fluid inlet conditions (flow rate, pressure and temperature), the nondimensional numbers which describe the fluid and thermal flow characteristics. To complete this process, another element is needed, which is a database for fluid properties, or more properly, a library of equations to determine pure and mixture properties: Coolprop was preferred due to its open-source nature, good integration between different software (from Excel to Maplesoft, Scilab, MATLAB etc.) and good precision [6]. These components, the geometrical model and the fluid property library, allow the model, together with a user input describing geometry and boundary conditions, to determine the nondimensional numbers which describe fluid and thermal flow: Reynolds, Prandtl and Nusselt. These numbers are then used together within correlations for the heat transfer and friction factor calculation. The first are then used by the E-NTU method to determine the overall heat transfer coefficient, then the Number of Transfer Units (NTU) and together with the capacity rate, the Effectiveness (E). From here, the behaviour of the PPHE is determined, with resulting outlet temperatures and pressure drop on both channels, which are calculated from the Reynolds number with the aid of Blasius relations for PPHE available in literature [4].

The characterization of pillow-plate heat exchanger (PPHE) geometry has evolved substantially through various methodological approaches. Initial attempts to quantify PPHE geometric parameters employed simplified mathematical approximations using trigonometric functions to represent the complex pillow-like channel structures [7], [8].These approaches, while computationally efficient, exhibited substantial limitations in capturing the intricate geometric details essential for accurate thermohydraulic performance prediction. Piper et al. [9] introduced a significant advancement through finite element method (FEM) simulations of the hydroforming process. This approach enabled more comprehensive geometric characterization, yielding predictions for critical parameters including cross-sectional areas, hydraulic diameters, and heat transfer surface areas. Their methodology defined the mean hydraulic diameter (MHD) according to the standard definition for compact heat exchangers, where P_w indicates the wetted perimeter and A_c the cross-sectional area:

$$d_h = \frac{4A_c}{P_w} \tag{2.7}$$

Piper's approach established correlations between geometric parameters (inflation height, diagonal welding spot pitch, transversal and longitudinal welding pitches) and thermohydraulic characteristics. Their methodology distinguished between reference periodic elements and generic elements within the pillow plate structure, enabling systematic characterization of fluid domains for simulation purposes. Finally, Sabourishirazi et al. [10] developed a refined approach that addresses the limitations of previous methodologies. Their contributions start with the implementation of more sophisticated hydroforming simulation incorporating non-linear material behaviour models (multilinear isotropic hardening), large deformation geometric non-linearity, and shell theory implementation for computational efficiency. This approach yielded significantly more accurate channel geometry representations. Their analysis resulted in the development of a comprehensive correlation incorporating multiple geometric parameters and showed also the implementation of artificial neural networks (ANNs). Sabourishirazi's methodology demonstrated a significant error reduction across multiple metrics, with RMSE values decreasing from 0.7233 (Piper's method) to 0.1376 (Sabourishirazi's correlation) and 0.0475 (Sabourishirazi's ANN) [10].

The methodological evolution from simplified trigonometric approximations to sophisticated FEM simulations incorporating material non-linearity and geometric complexity represents a significant advancement in PPHE characterization. However, the models presented in this work were developed much earlier than the publication of these new findings (2020), and while Sabourishirazi's approach is extremely interesting, both methods show R2 values higher than 0.9, and the observed accuracy of PPHE performance predictions was satisfactory for industrial purposes.

2.2.2. Heat transfer correlations for PPHES

The selection and implementation of heat transfer and pressure loss correlations for PPHEs followed a pragmatic approach balancing theoretical rigor with industrial applicability. This methodology was driven by the need to develop functional prototypes while maintaining sufficient accuracy for industrial applications. Heat transfer correlations were chosen based on their compatibility with operational Reynolds and Prandtl number ranges and their applicability to specific PPHE geometry types (longitudinal, transversal, or mixed patterns) and ultimately, their ease of implementation in design calculations: that is the reason why the most recent correlation developed for the internal channel with the 2-zone approach [11], was not considered, and simpler approaches such as Dittus and Boelter correlations were preferred.

2.2.3. Pressure Loss Calculations

Pressure losses in both channels were evaluated using correlations of the Blasius type, shown in Eq.2.8. In these experimental correlations, the Darcy friction factor, defined in Eq.2.9, depends only on the Reynolds (Re) number:

$$\boldsymbol{\xi_{Darcy}} = \boldsymbol{n1} \cdot \boldsymbol{Re^{n2}} \tag{2.8}$$

$$\xi_{Darcy} = \frac{2 \cdot \Delta P \cdot dh}{\rho \cdot v^2 \cdot L} \tag{2.9}$$

The calculation includes pressure drop (ΔP), mean fluid velocity (*v*), density at mean temperature (ρ), the MHD (dh) and the channel path length (L). Both in the Darcy friction factor, and Reynolds number calculation, there is a dependency from the hydraulic diameter and the velocity. Thus, pressure drop calculation accuracy strongly depends on the geometrical modelling for the design phase, and on the geometrical measurements in the experimental results analysis.

2.2.4. Adaptation Strategy

After describing the components of the model and pointing out fundamental literature references, Figure 2.1 can help visualise the logical process in common to all methods. Adaptation of the base E-NTU design methodology across diverse PPHE applications required a systematic approach to accommodate varying geometries, working fluids, and operating conditions. The model's input-output structure remained consistent across applications, with input parameters describing the PPHE geometry and the working conditions, common dimensionless groups (Reynolds, Prandtl, Nusselt) forming the computational backbone, and output parameters allowing to validate the design, as it will be better explained in the following sections. The models developed for each application all present a common framework that maintains the core E-NTU calculations while adapting its components to specific requirements. For each application domain—ranging from natural convection to condensation heat recovery—the modelling process begins with geometric parameter translation. The fundamental parameters and methodology defined by Piper et al. [9] were maintained, but their implementation was adjusted to accommodate different channel configurations. Since the E-NTU method, in particular in the calculation of the NTU, depends on the global heat transfer coefficient (U), which is given by a series of thermal resistance, is very easy to tailor to a specific application, since only the method for the heat transfer coefficient calculation has to be adjusted. In natural convection applications, for instance, the determination of the Outer Channel (OC) convective thermal resistance requires to incorporate free convection coefficients rather than forced convection correlations typically used in conventional PPHE implementations. Correlation selection for heat transfer coefficient calculation (related to thermal resistance calculation) was based on Reynolds and Prandtl number ranges: thanks to the efforts of previous researchers, it is also possible to easily find and test different correlations, as the ones thoroughly categorised and documented by Joybari et al. [4]. When adapting the model for the sand cooling application, this approach allowed integration of solid-to-surface heat transfer mechanisms within the existing E-NTU structure while preserving the fundamental calculation methodology. This structured adaptation strategy ensures methodological consistency while accommodating diverse applications.

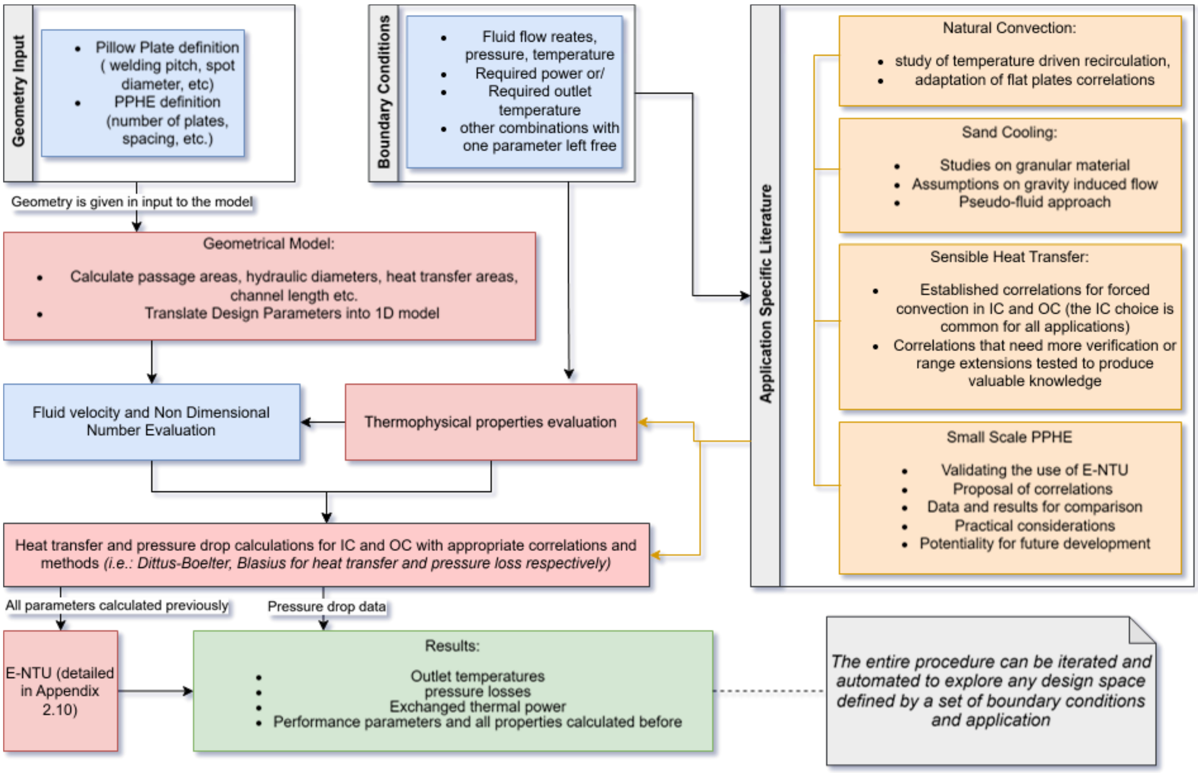

Figure 2.1: Simplified diagram visualizing the different components of a generic design model. Red colored components are to be changed across the different application to represent different geometrical configurations, different physical phenomena, or correlations.

2.3. Natural Convection Model

At the beginning of this research work and right after a first literature review, a model for PPHE in natural convection was developed. This elementary model addresses applications where PPHEs operate in open environments such as tanks, basins, or water bodies, rather than conventional shell configurations. This methodology integrates standard PPHE geometric characterization with established natural convection principles.

2.3.1. Theoretical Framework

Natural convection phenomena are simply described as fluid motion fields where the driving force is the density gradient that results from the fluid temperature gradient. The density gradient is in fact responsible of a gradient in the buoyancy forces that thus cause the fluid motion against the inertial forces. This situation is complex to model closely, since temperature influences motion, and motion influences the heat transfer coefficient, thus creating an interdependency between the two variables that are no more independent. The Grashof number, as shown in Eq. 2.10, is the correspondent to the Reynolds number in forced convection, while the Rayleigh number combines the Grashof number with the Prandtl number (Pr) to characterize the natural convection heat transfer regime. These numbers are used in empirical or semiempirical correlations to determine the Nusselt number.

$$\boldsymbol{Gr} = \frac{\boldsymbol{g} \cdot \boldsymbol{\beta} \cdot (\boldsymbol{T}_{\boldsymbol{w}} - \boldsymbol{T}_{\infty}) \cdot \boldsymbol{L}}{\boldsymbol{\nu}^{2}} \tag{2.10}$$

$$Ra = Gr \cdot Pr \tag{2.11}$$

Where g represents gravitational acceleration, β the thermal expansion coefficient of the fluid, $\boldsymbol{T}_{\boldsymbol{w}}$ and $\boldsymbol{T}_{\infty}$ the wall and fluid temperatures, L the characteristic length, and $\boldsymbol{\nu}$ the kinematic viscosity.

Its physical meaning is to show the ratio between buoyancy and viscous forces in a fluid in natural convection. Natural convection happens primarily vertically, in the direction of the gravitational field, and becomes turbulent after the developing inlet length, typically for Grashoff number values over 10^9. Natural convection occurs at the boundary layer where the difference with the bulk temperature is significant: oversimplifying, when two heating or cooling surfaces are close enough, there is the possibility of an overlap of the thermal boundary layers of the single surfaces, with the creation of a chimney effect that further enhances fluid motion and heat transfer. Since no established methods or experimental procedure is known on PPs in natural convection, a simplified approach was chosen: the model neglects any contribution of the chimney effect and regards the external plate surface as flat. It allows to design a PPHE that works with a fixed flow rate and inlet temperature, exchanges a predetermined power with the bulk fluid at a specified temperature (any fluid implemented in Coolprop could be chosen).

2.3.2. Model Implementation

The model, as anticipated, is based on the E-NTU method, and it illustrates to the reader a first example of implementation of the equations by Piper et al. [9] into a geometrical model of the PPHE. The model receives in input the set of dimensional parameters that define the PPHE structure, including the total length (L) and width (W) of the heat exchanger, number of plates (Num) and more. Physical dimensions are normalized to establish dimensionless ratios which are used in the analytical expressions from [9] to calculate the essential geometrical characteristics. The model incorporates interpolation factors for volume (avn,ref) and wetted area (awn,ref) that account for the geometric effects of varying pitch ratios. These factors are expressed as polynomial functions of the pitch ratio. These polynomials, elaborated from the analysis of simulated PP geometries, are used to determine the internal and external volume, the wetted areas and cross-sectional areas for both inner (Acs,i) and outer (Acs,o) channels, together with the hydraulic diameters. Thermophysical properties of the fluids are determined with Coolprop at the mean temperature (outlet temperature must be guessed from the PPHE expected rating) for the internal channel, and bulk fluid temperature for the external channel. The internal channel is modelled in forced convection and its Darcy friction factor and heat transfer coefficient are calculated with correlations proposed in [11] for the pressure drop and global heat transfer coefficient. For the external channel under natural convection conditions, the model employs dimensionless numbers to characterize the flow and heat transfer phenomena through the Grashof and Raileigh numbers. The Nusselt number for natural convection is calculated using the correlation by Churchill and Chu [12], expressed in Eq. 2.12, which accommodates a wide range of Rayleigh numbers and accounts for the transition between laminar and turbulent natural convection:

$$Nu = \{0.825 + \frac{0.387 \cdot Ra^{\frac{1}{6}}}{\left[1 + \left(^{0.492}/_{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\}^{2} \tag{2.12}$$

With this relation developed for vertical isothermal plates, the external heat transfer coefficient is determined according to the definition of the Nusselt number (Nu).

The global heat transfer coefficient (UA) integrates the thermal resistances of both channels and the plate material in a series configuration. This is expressed in Eq.2.13.

$$UA = \frac{1}{\frac{1}{h_{IC} \cdot A_{HT,IC}} + \frac{0.5 \cdot \delta_P}{k_P \cdot (A_{HT,IC} + A_{HT,OC})} + \frac{1}{h_{OC} \cdot A_{HT,OC}}} \tag{2.13}$$

Where h_{ic} represents the inner channel heat transfer coefficient, k_P the thermal conductivity of the plate material, and $A_{HT,IC}$ and $A_{HT,OC}$ the total heat transfer areas of the inner and outer channels respectively.

Effectiveness is calculated from NTU referred to the internal channel, with the formulation expressed in Eq.2.14 for a near zero capacity ratio:

$$\varepsilon = 1 - \exp\left(-NTU\right) \tag{4}$$

The outlet temperature for the internal channel can be calculated from the Effectiveness definition, as seen before, and thus the exchanged power and pressure loss. These parameters are to be checked with the initial temperature guess that allowed fluid properties determination, and with the total thermal dispersions from the tank. In short, the designer can verify a design configuration with this simplified model that allows for a first estimation of the lower performance limit of a PPHE immersed in an infinite fluid basin.

2.3.3. Key Assumptions

1. Average heat transfer coefficient over the external plate surface.
2. Quasi-steady state conditions with constant ambient temperature.
3. Negligible thermal stratification in the surrounding medium.
4. Standard PPHE correlations applicable for internal flow.
5. External surface treated as a vertical heated/cooled plate.
6. Undetermined capacity ratio for the E-NTU method.

2.4. Sensible Heat Transfer Model (liquid-liquid, gas-liquid)

The sensible heat transfer model addresses both liquid-liquid and gas-liquid heat transfer applications in PPHEs, incorporating a wide range of industrial scenarios. This methodology was developed to model PPHE in exhaust gas heat recovery applications, in which heat from combustion gases was transferred to heat water or oil. This methodology leverages established PPHE correlations while accounting for fluid-specific considerations and is applicable to all sensible heat transfer situation, with the correct choice of correlations for heat transfer coefficient and friction factor determination. This is a simple yet very useful tool that works for countless situations found in industry: from heat recovery from boiler combustion smoke (economisers), to cooling or heating of process fluids.

2.4.1. Theoretical Framework

The model is built to allow the designer to predict the behaviour of a PPHE when working fluids in forced turbulent convection exchange sensible heat, respectively decreasing and increasing temperature. The PPHE is defined by user input macroscopic geometrical parameters, and its behaviour is determined from the starting boundary conditions given by the fluid flow rates, inlet temperature and required rating. PPHE correlations are chosen for both channels, with attention to the ranges and fluids they were developed for. The fluid properties are calculated with the Coolprop library. While the following section will explain in more detail the implementation of this logic, it is important to stress that with a gas in the external channel, special attention is to be given to the integration of appropriate pressure drop calculations for compressible flow; Re must be calculated from the mass flow rate since the density of the gas is not determined at the beginning and at the end of the algorithm, the mean density and thus pressure drop can be calculated when the outlet temperature is determined by the E-NTU method, according to Eq. 2.14:

$$p_{inlet} - p_{outlet} = \frac{G^2}{2 \cdot \rho_{inlet}} \cdot (2\left(\frac{\rho_{inlet}}{\rho_{outlet}} - 1\right) + \frac{\rho_{inlet}}{\rho_{mean}} \cdot \frac{\xi_{Darcy}}{dh}) \quad (5)$$

Which is to be solved for p_{outlet}, which allows to determine the pressure differential accounting for the density (rho) variation and the frictional losses.

2.4.2. Model Implementation

The model begins with the specification of geometrical parameters essential for PPHE characterization, which are elaborated with the equations from the work of Piper et al. [9], as in section 2.3.2. Following geometric characterisation and calculation, the model uses the Coolprop library, the inlet temperatures and a guess for the outlet temperatures to determine the thermophysical properties of the fluids at their mean temperature. This step could insert a critical imprecision if the fluid properties vary a lot with temperature, or in case of important temperature variation across the length of the heat exchanger: in such cases the E-NTU method works well as a cell method. Calculations are then performed to determine the thermo-fluid dynamic behaviour in the internal and external channel. This is performed by determining Reynolds number from the flow rates and the geometrical parameters (passage area, hydraulic diameter etc.), Prandtl number (Coolprop and mean Temperature) and specifically chosen correlation from the literature. The flow configuration is counter-crossflow, with multiple passages in the internal channel and one in the external channel (crossflow). The fluid is considered mixed in the external channel and unmixed in the internal channel (since the pillow plates are independent channels in hydraulic parallel) and the relation for effectiveness is indicated by Equations. 2.5-2.6 depending on the flow configuration. Then the E-NTU method is applicable, and the output of the heat exchanger can be determined. Heat transfer and pressure drop correlation are to be chosen from literature [4] according to the indicated ranges. In Section 2.6 an example of chosen correlations is indicated.

2.4.3. Key Assumptions

1. Negligible thermal resistance of fouling, which can be accounted for in the overall heat transfer coefficient, while its mechanics need validation.
2. Fully developed flow conditions, steady state operation.
3. Constant fluid properties within temperature ranges.
4. Applicability of correlations beyond strict validation ranges when supported by experimental evidence.

5. Crossflow arrangement can use the E-NTU relationship for mixed or unmixed fluids, it is still not clear which assumptions holds true for most situations, and the right equation must be chosen each time.

2.5. Sand cooling model

The sand cooling model addresses the unique challenges of designing PPHEs as particle-to-fluid heat exchangers, specifically for applications involving granular material cooling. This methodology integrates established heat transfer principles for packed beds with PPHE-specific correlations.

2.5.1. Theoretical Framework

Particle heat exchangers with packed and moving beds demonstrate utility across several industrial sectors where conventional heat transfer technologies prove inadequate. These systems may be used for waste heat recovery from slag handling operations, in metallurgical industries, for catalytic reaction temperature regulation and solid reactant thermal conditioning. The power generation sector integrates particle heat exchangers within concentrated solar power systems, Moving packed bed heat exchangers have demonstrated to be promising in solar concentration plants where they can be used as a thermal storage with inexpensive materials such as silica-based solid particles. Mining and mineral processing operations utilize these systems for controlled cooling of calcined products and preheating of raw feedstocks. The robust design characteristics accommodate the abrasive nature of mineral processing environments while maintaining thermal performance [13].

While these applications demonstrate the existence of a specialised niche that particle heat exchangers occupy within industrial thermal management systems, their modelling is complicated by the fact that one working fluid is, in fact, not a fluid.

While other solutions exist for solid particles heat exchangers, such as fluidised bed, this model works with particles with a random packing factor that slowly move due to a combination of gravity and mechanically induced vibrations. Obuskovic proposed an “hydrodynamic” approach to model solid particles, that were treated as a continuous, which confirms the idea to design these exchangers with the E-NTU method but also requires further explanation [14]. Heat must transfer from particle to particle and through the particle itself through conduction, with the adverse contribution of the contact resistance both in the inter-particle and the particle to wall heat transfer. Heat can also be transported through advection if the particles physically move close to the walls due to mixing. Other heat transfer mechanisms are radiation and through gas movement across the porosity volume fraction. In packed particle beds, thermal resistance of the particles is responsible for the 87% of the overall resistance [15] which allows to proceed with the elaboration of a model for PPHE sizing that must combine the known behaviour of the internal channel with the external heat transfer between the granular material and PPHE surface in the E-NTU method, while the geometrical modelling remains unchanged.

Key references [16], [17] on particle to supercritical carbon dioxide show that the local Nusselt coefficient for packed powder beds within flat plate heat exchangers, is related to the Graetz and Peclet numbers as seen in Equations 2.15-2.17.

$$\boldsymbol{Nu} = \frac{\boldsymbol{h(y)\cdot D}}{\overline{\boldsymbol{k_S}}} \tag{2.15}$$

$$Gz = \frac{D \cdot Pe_L}{y} \tag{2.16}$$

$$Pe_L = Re \cdot Pr = \frac{v \cdot L}{\alpha} \tag{2.17}$$

The resulting behaviour on the external channel is that the heat transfer coefficient weakly depends on the mass "flow rate" of the sand, mostly because the heat transfer is limited by the capacity rate of the sand, especially at low flow rates. However, at values of flow rate with technical relevance, the heat transfer coefficient tends to an asymptote due to conduction, and can be enhanced only increasing particle mixing, especially by using different plate banks with staggered plate position: in this way the conductive heat transfer front is physically broken at the outlet of a bank by the plate of the following banks that divides equally the particle flow in two underlying channels. Reducing channel thickness is another way to increase heat transfer, and it is interesting to note that to achieve this, PPHE are a superior alternative to flat plates and tubes; they offer increased mechanical strength and improved heat transfer at low Re values in the internal channel, and their slight curvature allows mixing without detachment of the plate flow that horizontal tube bundles show in the lower part of each tube, due to the non-continuity of this pseudo-fluid.

In conclusion, to correctly model the outer channel, the solid properties must be considered. Baumann et al. [18] offer direct measurements of quartz and bauxite sands, which are taken and interpolated directly in the model, creating polynomials that allows for calculation of conductivity of different sand types, while Pankratz et al offer a solution for oxides specific heat calculation [19], as shown in Equations 2.18-2.20:

$$\boldsymbol{k_{Sand} = 0.0854122 + 0.000578 \cdot T - 3.696 \cdot 10^{-7} \cdot T^2 + 2.873 \cdot 10\hat{}(-10) \cdot T^2} \tag{2.18}$$

$$c_{P,mol} = \begin{cases} 9.679 + 10.66 \cdot 10^{-3} \cdot T - 1.989 \cdot 10^5 \cdot T^{-2}; T \leq 847K \\ 16.155 + 0.616 \cdot 10^{-3} \cdot T - 0.326 \cdot 10^5 \cdot T^{-2}; T > 847K \end{cases} \tag{2.19}$$

$$c_P = \frac{4184 \cdot c_{P,mol}}{m_{mol,quartz}} \tag{2.20}$$

2.5.2. Model implementation

The model, as explained in previous sections, first defines the fundamental geometric parameters of the PPHE, from the design input by the user. The code adopts the geometric modelling approach established by Piper et al. [9], which serves as the reference framework for all models. The internal channel working with water is modelled exactly as in section 2.4, while the external channel implements the sand properties, accounting with a piecewise function the transition point of the specific heat of the sand at around 847K. The specific heat and conductivity are calculating with an integral mean in the temperature interval of the sand for increased precision. The model calculates the potential thermal power recovered from the sand and uses it to determine the required mass flow rate for water to maintain the specified temperature differential. Peclet and Graetz number are defined, and so is the local Nusselt number, which is integrated over the chosen length of the heat exchanger. Leveraging the approach proposed by Fang [17], the heat transfer coefficient is then calculated and the E-NTU method can be applied normally. In order to have a greater precision, in this case the E-NTU method was implemented as a 3-cell method, which shows with better resolution the temperature profile.

2.5.3. Key Assumptions

1. 1D plug model used by Albrecht et al. [16] is deemed not precise enough, it does not solve the temperature profile close to the walls and thus necessitates to preset a value for the heat transfer coefficient
2. Continuous solid model by Fang et al. is chosen [17], thus material contact with PPHE surface must be guaranteed, this is deemed true due to the low curvature of their surface and flow control below the exchanger
3. Negligible thermal resistance at solid-plate interface
4. Uniform solid material properties
5. Quasi-steady state operation
6. Negligible radiation effects

2.6. Sensible Heat Transfer in a Small scale PPHE

The Small-Scale Pillow Plate Heat Exchanger (SSPPHE) model represents an adaptation of the methodological framework established for conventional PPHEs in sensible heat transfer applications, with specific considerations for compact geometries and their distinctive thermo-hydraulic characteristics. This model extends the ε-NTU approach to address the unique challenges presented by miniaturized pillow plate configurations, where border effects become increasingly significant relative to the periodic elements.

2.6.1. Theoretical Framework

The SSPPHE model builds upon the sensible heat transfer approach described in section 2.4, incorporating in the experimental methodology targeted refinements to account for the disproportionate influence of border regions in small-scale geometries. Unlike conventional PPHEs, where periodic elements dominate the overall performance, SSPPHEs exhibit notable deviations from idealized geometric models due to the relatively high proportion of border elements with suboptimal inflation patterns.

The fundamental theoretical principles remain anchored in the effectiveness-NTU method, performing a separate analysis of the thermal resistances in the inner channel (IC) and outer channel (OC).

For the inner channel, the model implements the Nusselt number correlations from [11] (IC) and [20] (OC), which are expressed in Equations 2.21-2.24 and Eq. 2.25 respectively:

$$\boldsymbol{Nu = n3Re^{n4}Pr^{n5}} \tag{2.21}$$

$$\mathrm{n3} = -0.163\mathrm{b} + 0.711\mathrm{c} + 0.022 \tag{2.22}$$

$$\mathrm{n4} = 0.29\mathrm{b} - \mathrm{c} + 0.8 \tag{2.23}$$

$$\mathrm{n5} = 0.4 \tag{2.24}$$

$$Nu = 0.06Re^{0.745}Pr^{0.35} \tag{2.25}$$

With b representing the ratio of welding spot diameter to transversal pitch (b = dsp/st) and c representing the ratio of plate internal inflation to transversal pitch (c = hi/st).

These correlations, originally validated for Reynolds numbers in the ranges 1000 < Re < 8000 (IC) and 9500 < Re < 30000 (OC), were applied to lower Reynolds regimes (down to Re = 500) in the SSPPHE model, with the intention to investigate their validity to evaluate the transferability of results [4].

The methodology behind the investigation of the border effect will be discussed in the following chapters of the thesis.

2.6.2. Model Implementation

The calculation methodology follows the same structure as the one explained in section 2.4.2, and illustrated in Figure 2.1, which is summarised below:

1. Input PPHE design parameters
2. Calculation of geometrical parameters (area increase, influence of spots, interpolation parameters for wet area and volume, passage areas, hydraulic diameters, etc)
3. Input fluid operating parameters
4. Fluid properties are calculated from inlet temperatures and pressure and a guess of the outlet values.
5. Determination of velocity, Reynolds number, Nusselt (correlations from literature) and Darcy (IC)
6. Determination of pressure loss and heat transfer coefficient (IC)
7. Determination of velocity, Reynolds number, Nusselt (correlations from literature) and Darcy (OC)
8. Determination of pressure loss and heat transfer coefficient (OC)
9. Determination of the overall heat transfer coefficient and Number of Transfer Units
10. Determination of Effectiveness
11. Determination of outlet temperatures

The model was then used to predict the behaviour of different PPHE geometries and then to select laboratory equipment. One prototype was selected with the smallest achievable and yet relevant geometry and consequently tested.

2.6.3. Key Assumptions

1. Applicability of standard correlations for heat transfer and pressure drop
2. Uniform flow distribution
3. Negligible thermal edge effects (thermal insulation in lab conditions)
4. Steady-state operation

2.7. Condensation Heat Recovery

The Condensation Heat Recovery (CHR) model should address the complex phenomena of vapor condensation in PPHEs, specifically targeting applications involving humid gas streams. A promising application of PPHE is to extend dramatically the heat recovery possibilities with humid waste gas or air flows. Moreover, waste heat represents the highest energy loss in boiler rooms and is one of the highest losses in many other processes involving combustion [21]. In this work, a heat recovery from a food drying process was studied. This methodology is currently under development, with ongoing experimental validation to refine the theoretical framework. Unfortunately, the construction of the dedicated equipment employed more time than anticipated, shifting the development of a design model to future work. However, a preliminary characterisation is described in Chapter 3, 5 and 6, from the experimental setup, to construction and finally results.

2.7.1. Theoretical Framework Development

The model should integrate multiple heat transfer mechanisms:

1. Sensible Heat Transfer: Cooling of humid air
2. Latent Heat Transfer: Film condensation on surfaces below the dew point temperature
3. Two-Phase Flow Considerations: Liquid film formation and drainage, Vapor-liquid interaction, Local heat transfer coefficient variation due to film thermal resistance.

2.7.2. Proposed Implementation Methodology

The calculation procedure is structured to address:

1. Division of the domain into smaller interconnected cells- discrete element modelling.
2. Psychrometric Analysis: Humidity ratio determination, Dew point evaluation, Condensation potential assessment
3. Heat Transfer Characterization: Sensible component evaluation, Latent heat contribution
4. Performance Prediction
5. Mass transfer rate estimation
6. Condensate collection consideration
7. Total recovered power, temperature and outlet humidity.

2.7.2. Key Research Questions

The ongoing methodology development focuses on characterising the phenomenon experimentally across different working points.

2.8. The validation problem

The validation methodology for PPHE design models presents unique challenges in an industrial innovation context, requiring a balanced approach between academic rigor and practical implementation constraints. This section examines the complementary roles of experimental validation and customer feedback in establishing model reliability.

2.8.1. Experimental Validation Framework

Laboratory-scale experimental validation, while providing precise quantitative data, presents several limitations in a Small-Medium Enterprise (SME) context such as resource constraints and high equipment and instrumentation costs, time-intensive setup and testing procedures, and limited personnel availability. The uncertainty of marketable results, due to geometric scale considerations, difficulty in replicating full-scale industrial conditions with border effects more pronounced in laboratory prototypes and flow distribution variations between scales pose an additional complexity layer. Finally, there is only so many conditions that can be tested in advance, while the potential for innovation often comes from customers that are willing to implement PPHEs in new conditions, which would be tested in laboratory only on a restricted range of testable conditions, simplified fluid combinations and idealized environmental parameters. On the other hand, information from the industrial world is not easy to obtain, for several reasons. The first, often overlooked in academic publications, is that heat exchangers are not machines, thus they are integrated within other machines or processes. This creates several layers of separations between the producer of the heat exchanger and the process in which it is employed, putting several walls of confidentiality between the designer and the PPHE. Another practical observation is that industrial processes involve great amounts of energy, manpower and resources and cannot be slowed down, let alone be stopped or modified to test a single component such as a heat exchanger. However, the limitations of experimental validation, both in laboratory and on the field, pose also the elements for an approach that can advance the knowledge and adoption of PPHE.

This research work was in fact oriented to gathering from the market heat transfer problems that could be solved effectively by PPHEs (need for increased process efficiency, use of fouling fuels or media, more compactness, mechanical resistance, etc.), partially validating the design models on a laboratory scale and then select customers willing to experiment with this new technology, which led to several case studies that work as a qualitative validation, but also allow to quickly understand the applications worth exploring, problematics that could arise in real world and aspects that need more deepening.

2.8.2. Customer Validation Approach

As stated above, customer validation was inserted as a functional part of this industrial research. Industrial implementation is believed by the author to be a complementary validation through real world performance assessment of actual operating conditions and possible variations, long-term reliability evaluation and system integration effects. Yet, it is very complex to obtain data from final customers, but with a scientific approach, qualitative feedback gives precious information on operational practicality, maintenance requirements and installation considerations, but most importantly it validates the model, with the chosen safety margin, for a working point.

Several customer validations can be analysed and studied as market validation, which is a real-world verification of the cost-effectiveness of PPHEs applications, indicating which are worth studying more, and which should be abandoned because the drawbacks hamper the final application under study.

2.8.3. Computational Validation Considerations

While Computational Fluid Dynamics (CFD) offers detailed flow field visualization and parametric study capabilities, its implementation for PPHE validation presents specific challenges in an SME context. The current state of the art of numerical analyses on PPHEs pose difficulty for producing meaningful new information. First, the complex geometry of PPHE needs at least a validated finite element model to be represented faithfully without approximated methods. However, the most recent proposed method in literature, is to use Artificial Neural Networks (ANNs) [10] trained on numerous deformation simulations, which increases further the complexity. Similarly, CFD analyses must be prepared thoroughly to be meaningful, with mesh sensitivity considerations, turbulence model selection and validation and finally significant computational resource demands. This complexity results in implementation barriers, with specialized expertise requirements and a substantial initial investment in software and training. Extended development timeframes are another problem for a SME exploring PPHEs applications, all while still needing validation against experimental data.

Consequently, while the latest publications focusing on geometrical modelling and the state of the art of PPHE research, show that numerical modelling of PPHEs is necessary at a certain point of their development: it is in fact useful to have a precise digital representation of a given PPHE geometry, to predict in advance inflation and burst pressure, and to have the geometric domain available to perform analyses between validated experimental points, or to explore possible trends. Within this context it is consequential that computational analyses were scheduled as future work, to first focus on establishing a simpler and quicker strategy to study PPHEs.

2.8.4. Validation Strategy Implementation

The adopted methodology prioritizes strategic experimental campaigns, with the aim of validating the design model on a specific yet relevant phenomenon such as sensible heat transfer in forced convection, with the additional complication of using a small-scale geometry to study in addition border effects by comparison with studies on larger geometries, which will be explained in depth in the following chapter. In sequence, a second campaign was scheduled for a thorough investigation of a novel applications which has, to the best of the author knowledge, no studies published yet: heat recovery from the condensation of moisture in humid air. In parallel, the development of PPHE prototypes started right at the beginning of this research, with a conservative design approach through implementation of safety margins and consideration of worst-case scenarios. Starting this process early allowed an iterative improvement process which brought a progressive safety margin reduction via the integration of customer feedback, but also the production of knowledge on best practises for design and production and a sensibility on the relative importance of the different aspects of the PPHE design and production process.

The research strategy therefore prioritizes experimental validation supplemented by customer feedback, reserving computational approaches for specific future investigations where detailed flow visualization or parametric studies provide essential insights not readily obtainable through other methods.

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2.10. Appendix

This Appendix presents a complete implementation of the ε-NTU methodology for a sensible heat recovery application using pillow plate heat exchangers using Maple software, by Maplesoft, a mathematical engine with dedicated mathematical programming language and engineering libraries, but due to its simplicity, it can be easily implemented in other software such as Microsoft Excel, Scilab or MATLAB or Wolfram Mathematica. This script serves as a practical demonstration of the theoretical framework described in sections 2.2-2.7. The implementation follows the general approach outlined in section 2.2, beginning with the definition of geometric parameters that characterize the PPHE structure. These parameters are then processed through the geometrical model to calculate essential characteristics such as hydraulic diameters, cross-sectional areas, and heat transfer surfaces - directly implementing the methodology from Piper et al. described in section 2.2.1.

The script continues by calculating fluid properties using the CoolProp library (sections 1.2.1-1.3.1), as discussed in section 2.2.1, and then implements the heat transfer and pressure drop correlations for both channels. For the inner channel, the script uses the correlations presented in section 2.2.2, while for the outer channel, it employs correlations appropriate for the specific fluid and flow regime. The core ε-NTU calculations are then implemented in section 1.6.1 of the script, integrating the thermal resistances from both channels and the plate material to determine the overall heat transfer coefficient, NTU, and effectiveness. The implementation includes the adaptation for crossflow with unmixed fluids as discussed in section 2.1.1.

This script exemplifies the sensible heat transfer model detailed in section 2.4 and follows exactly the sequence outlined in section 2.4.2: geometry definition, fluid property determination, Reynolds and Prandtl number calculation, correlation selection, and thermal performance prediction. To the reader is offered a tangible example of how the methodological framework can be operationalized, serving both as validation of the approach and as a reference for those seeking to implement similar models for their specific PPHE applications.

Sensible Heat Recovery

Geometry Input

```
> restart :
  with(Statistics) :
  with(ThermophysicalData) :
  with(CoolProp) :
  with(Units) :
  UsingSystem( );
  with(plottools) :
  with(plots) :
```

Automatically loading the Units[Simple] subpackage

$$SI \tag{1.1.1}$$

> $L := evalf(1500 \cdot 10^{-3})\,\mathrm{m} : W := evalf(750 \cdot 10^{-3})\,\mathrm{m} : le := (15 \cdot 10^{-3}\mathrm{m}) :$ # *L &W are defined according* **to** *the direction of the external flow. L is lenght, W is width., le is unwelded edge*

$two\_s_L := evalf(72 \cdot 10^{-3})\,\mathrm{m} : s_T := evalf(42 \cdot 10^{-3})\,\mathrm{m} : \delta_i := evalf(5 \cdot 10^{-3})\,\mathrm{m} : d_{SP} := evalf(10 \cdot 10^{-3})\,\mathrm{m} :$ *#sl* **and** *st are referred* **to** *L* **and** *W respectively,* **and** *the notation follows* "Determination of the geometric design parameters of pillow−plate heat exchangers" *Piper et al 2015*

$\delta_P := 1 \cdot 10^{-3}\,\mathrm{m} : h_P := 21 \cdot 10^{-3}\mathrm{m} : k_{plate} := 16\,\frac{\mathrm{W}}{\mathrm{m\,K}} :$ *#input of plate thickness, PP spacing* **and** *conductivty of the material*

Num := 30 : *#Plate number*

n_pass := 8 :*#IC is divided* **in** *n_pass channels*

n_pass2 := 1 : *#legacy,* **not** *used*

$s_L := \frac{two\_s_L}{2} :$

$B := evalf((h_P + 2 \cdot \delta_P) \cdot Num);$

$a := \frac{2 \cdot s_L}{s_T}; b := \frac{d_{SP}}{s_T}; c := \frac{\delta_i}{s_T}; check\_me := \frac{1}{a};$

 # a must be between 1 *e* 1.72 , **or** $\frac{1}{a}$ *should be between* 0.58 **and** 1.

$$B := 0.6900000000\ \mathrm{m}$$
$$a := 1.714285714$$
$$b := 0.2380952381$$

$c := 0.1190476190$
$check\_me := 0.5833333334$ **(1.1.2)**

Calcolo Parametri Geometrici

> *#The fitting used to determine the MHD work when* $\frac{s_T}{2\, s_L}$ *is between* 0.58 **and** 1, *so we first, check the condition* **and** *swap* **if** *necessary·(MHD is invariant* **to** *a* 90 *deg rotation, see reference)*

$swapped := false;$
if $s_T / (2 * s_L) > 1$ **then**
$temp := s_T;$
$s_T := 2 * s_L;$
$s_L := temp / 2;$
$swapped := true;$
end if;

$\Phi_A := evalf\left(1 - \frac{\mathrm{Pi} \cdot d_{SP}^{\ 2}}{4 \cdot s_T \cdot s_L}\right) : f_{SP} := 1.37 \cdot \Phi_A^{\ 2.58} : s_{\mathrm{D}} := \mathrm{sqrt}\left(\left(0.5 \cdot s_T\right)^2 + s_L^{\ 2}\right) :$
#calculate influence of spot diameter dsp on the internal volume (fsp) and area (Φ_A)

$a_{vn,ref} := 0.1 \cdot \left(\frac{s_T}{2 \cdot s_L}\right)^2 - 0.18 \cdot \left(\frac{s_T}{2 \cdot s_L}\right) + 0.19 :$
 # interpolation for the volume relation of a generic element to the reference element.

$a_{wn,ref} := 3.12 \cdot \left(\frac{s_T}{2 \cdot s_L}\right)^2 - 5.74 \cdot \left(\frac{s_T}{2 \cdot s_L}\right) + 3.08 :$
 # interpolation parameter accounting for a generic area increase with respect to a reference element

$A_0 := 0.5 \cdot s_T \cdot s_L - \frac{\mathrm{Pi} \cdot d_{SP}^{\ 2}}{8}$: *#calculate area before inflation*

$Area\_increase := evalf[3]\left(\frac{a_{wn,ref} \cdot \delta_i^{\ 2}}{s_{\mathrm{D}}^{\ 2}} \cdot 100\right)$:*# % area increase with inflation*

$A_{w,i} := \left(\frac{a_{wn,ref} \cdot \delta_i^{\ 2}}{s_{\mathrm{D}}^{\ 2}} + 1\right) \cdot A_0 : A_{w,i,mm} := convert\left(A_{w,i}, \text{'units'}, \text{'mm}^2\text{'}\right) : \ V_i := a_{vn,ref} \cdot \delta_i \cdot s_{\mathrm{D}}^{\ 2} \cdot f_{SP} : Vi\_mm := convert\left(V_i, \text{'units'}, \text{'mm}^3\text{'}\right) :$

 # Swap back if values were previously swapped
if *swapped* **then**
$temp := s_T;$
$s_T := 2 * s_L;$
$s_L := temp / 2;$
end if;

$$d_h := \frac{4 \cdot V_i}{A_{w,i}} : \ d_{h,\ interno} := convert(d_h, 'units', 'mm');$$ #obtain MHD and wet area, IC

#calculate geometrical parameters from MHD and wet area

$A_{cs,i} := \frac{V_i}{s_T}$; #cross sectional inner area, m^2, area must be perpendicular to water passage, which is in crossflow respect to air, so it must be perpendicular to the transversal pitch.

$A_{cs,i,tot} := \frac{A_{cs,i} \cdot 4}{n\_pass} \cdot \left(\frac{L - 2 \cdot le}{s\_\_L} \right) \cdot Num$; #the total passage area is obtained multiplying **by** the number of elements **in** the channel

$A_{w,i,tot} := A_{w,i} \cdot 4 \cdot \left(\frac{W - 2 \cdot le}{s_T} \right) \cdot \left(\frac{L - 2 \cdot le}{s_L} \right) \cdot Num$: #total wet area m^2

$$A_{HT,i} := A_{w,i} : \ A_{HT,i,tot} := A_{w,i,tot};$$

$$Volume := V_i \cdot 4 \cdot \left(\frac{W - 2 \cdot le}{s_T} \right) \cdot \left(\frac{L - 2 \cdot le}{s_L} \right) \cdot Num;$$

#dati del canale esterno

$$A_{w,o} := A_{w,i} + 0.125\ \mathrm{Pi} \cdot d_{SP}^{\ 2} : \ V_o := \frac{1}{2} \cdot s_L \cdot s_T \cdot \left(\frac{1}{2} h_P + \delta_P \right) - V_i - A_{w,o} \cdot \delta_P : \ A_{HT,o,} := A_{w,o,} : d_{h2} := \frac{4\ V_o}{A_{w,o}} :$$

$d_{h,\ esterno} := convert(d_{h2}, 'units', 'mm'); \ A_{cs,o} := \frac{V_o}{s_L}$: #cross sectional outer area, m^2

$A_{cs,o,tot} := \frac{A_{cs,o} \cdot 4 \cdot \left(\frac{W - 2 \cdot le}{s_T} \right) \cdot Num}{n\_pass2}$; #total cross sectional area

$A_{w,o,tot} := A_{w,o} \cdot 4 \cdot \left(\frac{W - 2 \cdot le}{s_T} \right) \cdot \left(\frac{L - 2 \cdot le}{s_L} \right) \cdot Num$: #totale wet area

$A_{HT,o,tot} := A_{w,o,tot}$; #heat transfer area

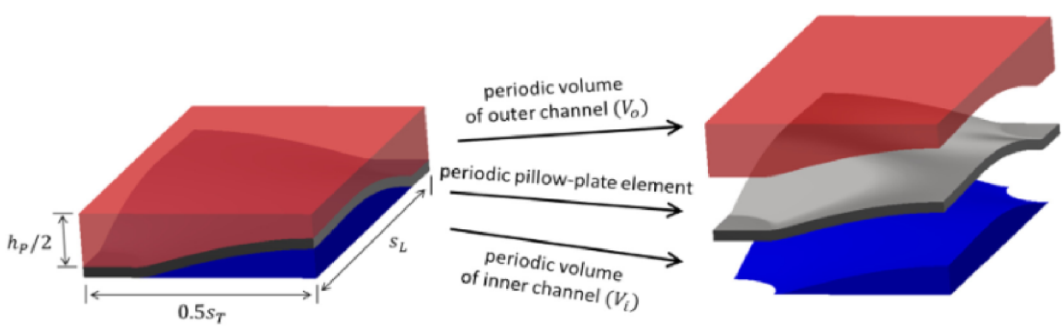


Fig. 2. Characteristic periodic element of a PPHE for the evaluation of V_i and A_w.

$$swapped := false$$

$$d_{h,interno} := 6.809945540 \text{ mm}$$
$$A_{cs,i} := 0.00002938466476 \text{ m}^2$$
$$A_{cs,i,tot} := 0.01799810717 \text{ m}^2$$
$$A_{HT,i,tot} := 60.89276142 \text{ m}^2$$
$$Volume := 0.1036690973 \text{ m}^3$$
$$d_{h,esterno} := 35.04738476 \text{ mm}$$
$$A_{cs,o,tot} := 0.3826091625 \text{ m}^2$$
$$A_{HT,o,tot} := 64.19143371 \text{ m}^2 \quad (1.2.1)$$

Fluid Properties: (1) water, internal channel; (2) humid air, outer channel

> $T1i := 80 \text{ degC} : T1o := 90 \text{ degC} : T1mean := evalf\left(\frac{(T1i + T1o)}{2}\right);$

#input operating parameters

$\rho 1 := Property(density, Water, temperature = (T1mean + 273.15 \text{ degC}), pressure = 100000 \text{ Pa}, 'useunits' = true)\ ;\ \#\frac{kg}{m3}$ *density is calculated* **to** *operate with volumetric* **and** *mass flow rate*

$mdot1 := 4.44 \frac{\text{kg}}{\text{s}};$

$Q1 := \frac{mdot1}{\rho 1};$

$cp1 := Property(massspecificconstantpressurespecificheat, Water, temperature = (T1mean + 273.15 \text{ degC}), pressure = 100000 \text{ Pa}, 'useunits' = true);$

$k1 := Property(thermalconductivity, Water, temperature = (T1mean + 273.15 \text{ degC}), pressure = 100000 \text{ Pa}, 'useunits' = true);$

$\mu 1 := Property(viscosity, Water, temperature = (T1mean + 273.15 \text{ degc}), pressure = 100000 \text{ Pa}, 'useunits' = true);$

$Pr1 := Property(prandtl, Water, temperature = (T1mean + 273.15 \text{ degC}), pressure = 100000 \text{ Pa}, 'useunits' = true)\ ;$ *#prandtl*

$potenza1 := mdot1 \cdot cp1 \cdot (T1o - T1i);$

$T2i := 160 \text{ degC} : T2o := 110 \text{ degC} : T2mean := evalf\left(\frac{(T2i + T2o)}{2}\right);\quad \#\frac{kg}{h},$ *total mass flow rate*

$\rho 2i := Property(density, Air, temperature = (T2i + 273.15 \text{ degC}), pressure = 100000 \text{ Pa}, 'useunits' = true);$

$Q2 := 17000 \frac{\text{m}^3}{\text{h}};$

$g := 9.81 \frac{\text{m}}{\text{s}^2} :$

$T2m := convert(T2mean, temperature, kelvin);$

$mdot2_{tot} := Q2 \cdot \rho 2i$;

$mdot2h := convert\left(mdot2_{tot}, 'units', \frac{'kg'}{'h'}\right)$; #mass flow rate

$cp2 := HAPropsSI\left(cp, T, T2m, P, 101325\,\mathrm{Pa}, \mathrm{Omega}, 0.097\,\frac{\mathrm{kg}}{\mathrm{kg}}\right)$;

$k2 := HAPropsSI\left(k, T, T2m, P, 101325\,\mathrm{Pa}, Omega, 0.097\,\frac{\mathrm{kg}}{\mathrm{kg}}\right)$;

$\mu 2 := HAPropsSI\left(\mathrm{mu}, T, T2m, P, 101325\,\mathrm{Pa}, \mathrm{Omega}, 0.097\,\frac{\mathrm{kg}}{\mathrm{kg}}\right)$;
#viscosità dinamica $Pa \cdot s$

$Pr2 := \frac{\mu 2 \cdot cp2}{k2}$;

$v2 := \frac{\mu 2}{\rho 2}$; # $\frac{m^2}{s}$

$mdot2 := mdot2_{tot}$;

$potenza2 := mdot2 \cdot cp2 \cdot (-T2o + T2i)$;

$$T1mean := 85.\ {}^\circ\mathrm{C}$$

$$\rho 1 := 968.6108400\ \frac{\mathrm{kg}}{\mathrm{m}^3}$$

$$mdot1 := 4.44\ \frac{\mathrm{kg}}{\mathrm{s}}$$

$$Q1 := 0.004583884278\ \frac{\mathrm{m}^3}{\mathrm{s}}$$

$$cp1 := 4200.746773\ \frac{\mathrm{J}}{\mathrm{kg\,K}}$$

$$k1 := 0.6700664259\ \frac{\mathrm{W}}{\mathrm{m\,K}}$$

$$\mu 1 := 0.0003333469350\ \mathrm{Pa\,s}$$

$$Pr1 := 2.088097668$$

$$potenza1 := 186513.1567\ \mathrm{W}$$

$$T2mean := 135.\ {}^\circ\mathrm{C}$$

$$\rho 2i := 0.8040749512\ \frac{\mathrm{kg}}{\mathrm{m}^3}$$

$$Q2 := 17000\ \frac{\mathrm{m}^3}{\mathrm{h}}$$

$$T2m := 408.1500000\ \mathrm{K}$$

$$mdot2_{tot} := 3.797020603\ \frac{\mathrm{kg}}{\mathrm{s}}$$

$$mdot2h := 13669.27417\ \frac{\mathrm{kg}}{\mathrm{h}}$$

$$cp2 := 1095.098499\ \frac{\mathrm{J}}{\mathrm{kg\,K}}$$

$$k2 := 0.03265460196\ \frac{\mathrm{W}}{\mathrm{m\,K}}$$
$$\mu 2 := 0.00002179145930\ \mathrm{Pa\,s}$$
$$Pr2 := 0.7307942201$$
$$v2 := \frac{0.00002179145930}{\rho 2}\ \mathrm{Pa\,s}$$
$$mdot2 := 3.797020603\ \frac{\mathrm{kg}}{\mathrm{s}}$$
$$potenza2 := 207905.5782\ \mathrm{W} \qquad (1.3.1)$$

Internal Channel

> $_{m1} := \frac{Q1}{A_{cs,i,tot}};$

$Rey1 := \frac{u_{m1} \cdot \rho 1 \cdot d_h}{\mu 1};$

#correlation from Tab3 in Piper et al 2017

$n1 := 1.35 \cdot b + (2.8 \cdot c + 0.92) :$

$n2 := 0.3 \cdot b + (0.53 \cdot c - 0.29) :$

$n3 := -0.163 \cdot b + (0.711 \cdot c + 0.022) :$

$n4 := 0.29 \cdot b + (-c + 0.8) :$

$n5 := 0.4 :$

$Nus1 := n3 \cdot Rey1^{n4} \cdot Pr1^{n5};$

$Dar1 := n1 \cdot Rey1^{n2};$

$\Delta p1 := \frac{Dar1 \cdot \rho 1 \cdot u_{m1}^{2} \cdot s_T}{2\, d_h};$ #Pa

$channel\_length := (W - 2\, le) \cdot n\_pass;$

$\Delta p1_{tot} := convert\left(\frac{\Delta p1 \cdot (W - 2 \cdot le)}{s_T} \cdot n\_pass, 'units', 'bar'\right);$ #bar

$h_{m1} := convert\left(\frac{Nus1 \cdot k1}{d_h}, 'units', \frac{'W'}{'m'^2 \cdot 'K'}\right);$

$$u_{m1} := 0.2546870199\ \frac{\mathrm{m}}{\mathrm{s}}$$
$$Rey1 := 5039.684040$$
$$Nus1 := 54.46856879$$
$$Dar1 := 0.4183881135$$
$$\Delta p1 := 81.06211713\ \mathrm{Pa}$$
$$channel\_length := 5.760000000\ \mathrm{m}$$
$$\Delta p1_{tot} := 0.1111709035\ \mathrm{bar}$$

(1.4.1)

$$h_{m1} := 5359.449497\ \frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{K}} \tag{1.4.1}$$

Outer Channel

> $G2 := \frac{mdot2}{A_{cs,o,tot}}$;
$Rey2 := \frac{G2 \cdot d_{h2}}{mu2}$;
#dati per la correlazione proposta in Piper et al 2016
$Nus2 := 0.091 \cdot Rey2^{0.74} \cdot Pr2^{\frac{1}{3}}$;
$Dar2 := 3.46 \cdot Rey2^{-0.39}$;
$h_{m2} := convert\left(\frac{Nus2 \cdot k2}{d_{h2}}, 'units', \frac{'W'}{'m'^2 \cdot 'K'}\right)$;

$$G2 := 9.924019014\ \frac{\mathrm{kg}}{\mathrm{m}^2\ \mathrm{s}}$$
$$Rey2 := 15960.88210$$
$$Nus2 := 105.6578718$$
$$Dar2 := 0.07941159370$$
$$h_{m2} := 98.44431393\ \frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{K}} \tag{1.5.1}$$

E-NTU

> $UA :=$
$convert\left(1 \Big/ \left(\frac{1}{h_{m1} \cdot A_{HT,\ i,\ tot}} + \frac{\delta_P}{k_{plate} \cdot (A_{HT,i,tot} + A_{HT,o,tot})} + \frac{1}{h_{m2} \cdot A_{HT,o,tot}} + \frac{(2.5 \cdot 10^{-3})\ \frac{\mathrm{m}^2 \cdot \mathrm{K}}{\mathrm{W}}}{A_{HT,\ o,\ tot}}\right), 'units', \frac{'W'}{'K'}\right)$;
$Umean := convert\left(\frac{UA}{0.5 \cdot (A_{HT,i,tot} + A_{HT,o,tot})}, 'units', \frac{'W'}{'m'^2 \cdot 'K'}\right)$;

$UA_{singola} := \frac{UA}{Num}$:

$c1 := convert\left(mdot1 \cdot cp1, 'units', \frac{'W'}{'K'}\right)$;

$$c2 := convert\left(mdot2\cdot cp2,'units', \frac{'W'}{'K'}\right);$$

$$cmin := \min(c1, c2) : cmax := \max(c1, c2) : \#\frac{W}{K}, \textit{heat capacity ratios}$$

$$cr := \frac{cmin}{cmax};$$

$$NTU := \frac{UA}{cmin};$$

$$\#\varepsilon_{hx} := \frac{(1 - \exp(-NTU\cdot(1 + cr)))}{1 + cr}; \#equicorrente$$

$$\varepsilon_{hx} := 1 - \exp\left(\frac{1}{cr}\cdot NTU^{0.22}\cdot(\exp(-cr\cdot NTU^{0.78}) - 1)\right) \#\textit{crossflow, non mixed fluids}$$

$$UA := 4981.179016\ \frac{\mathrm{W}}{\mathrm{K}}$$

$$Umean := 79.64521835\ \frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{K}}$$

$$c1 := 18651.31567\ \frac{\mathrm{W}}{\mathrm{K}}$$

$$c2 := 4158.111563\ \frac{\mathrm{W}}{\mathrm{K}}$$

$$cr := 0.2229393163$$

$$NTU := 1.197942609$$

$$\varepsilon_{hx} := 0.6523496251 \quad \textbf{(1.6.1)}$$

> $\Phi := convert(\text{varepsilon}_{hx}\cdot cmin\cdot(T2i - T1i),'units', 'kW');$
> #Watts, rating of the heat exchanger

$$\phi_{piastra} := \frac{\Phi}{Num}; \#\textit{rating of the single plate (average)}$$

$$\Phi := 217.0034015\ \mathrm{kW}$$

$$\phi_{piastra} := 7.233446717\ \mathrm{kW} \quad \textbf{(1.6.2)}$$

> #outlet temperature calculations

$$T1o := T1i + \frac{\text{varepsilon}_{hx}\cdot cmin}{c1}\cdot(T2i - T1i);$$

$$T1o := 91.63475035\ °\mathrm{C} \quad \textbf{(1.6.3)}$$

> $T2o := T2i - \frac{\text{varepsilon}_{hx}\cdot cmin}{c2}\cdot(T2i - T1i);$

$$T2o := 107.8120300\ °\mathrm{C} \quad \textbf{(1.6.4)}$$

> #outer channel pressure drop calculation

$$Ra := 287\ \frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}} : p2i := 101330\ \mathrm{Pa} :$$

1

$\rho 2i := Property(density, Air, temperature = (convert(T2i, temperature, kelvin)), pressure = p2i, 'useunits' = true);$

$$\rho 2o := \frac{p2o}{Ra \cdot convert(T2o, temperature, kelvin)}:$$

$$\rho_{2m} := \left(\frac{1}{2}\cdot\left(\frac{1}{\rho 2i}+\frac{1}{\rho 2o}\right)\right)^{-1}:$$

$$\Delta p := \frac{G2^2}{2\cdot\rho 2i}\cdot\left(2\left(\frac{\rho 2i}{\rho 2o}-1\right)+\frac{Dar2\cdot L}{d_{h2}}\cdot\frac{\rho 2i}{\rho_{2m}}\right):$$

#attenzione modificare L W a seconda della lunghezza percorsa dall'aria

$p2o := solve(p2i - p2o - \Delta p, p2o)[2]:$

$$\rho 2i := 0.8147664180\ \frac{\mathrm{kg}}{\mathrm{m}^3} \quad \textbf{(1.6.5)}$$

> $$\rho 2o := \frac{p2o}{Ra \cdot convert(T2o, temperature, kelvin)};$$

$\Delta p2 := p2i - p2o;$

$$u2o := \frac{G2}{\rho 2o};$$

$$u2 := \frac{G2}{0.5\cdot(\rho 2o + \rho 2i)};$$

$$\rho 2o := 0.9251405309\ \frac{\mathrm{kg}}{\mathrm{m}^3}$$

$$\Delta p2 := 178.7400\ \mathrm{Pa}$$

$$u2o := 10.72703949\ \frac{\mathrm{m}}{\mathrm{s}}$$

$$u2 := 11.40752845\ \frac{\mathrm{m}}{\mathrm{s}} \quad \textbf{(1.6.6)}$$

Exporting Results

> $geometria := evalf[5]\left(\left\langle Num, n\_pass, convert(L, unit\_free, \mathrm{m}), convert(W, unit\_free, \mathrm{m}), convert(B, unit\_free, \mathrm{m}), convert\left(u2, unit\_free, \frac{\mathrm{m}}{\mathrm{s}}\right), convert\left(u_{m1}, unit\_free, \frac{\mathrm{m}}{\mathrm{s}}\right), Rey1, Rey2\right\rangle\right):$

$dett\_termici := \left\langle convert(\mathrm{Phi}, unit\_free, \mathrm{kW}), convert(A_{HT,o,tot}, unit\_free, \mathrm{m}), convert\left(Umean, unit\_free, \frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}\right), NTU, \mathrm{varepsilon}_{hx}, convert(LMTD, unit\_free,\right.$

```
    degC ), 0, Pr1, Pr2⟩ :
aria := evalf[5]( ⟨ convert(d_{h, esterno}, unit_free, mm ), convert( mdot2, unit_free, kg/s ),
    convert( ρ2i, unit_free, kg/m^3 ) , convert( ρ2o, unit_free, kg/m^3 ), convert( Δp2,
    unit_free, Pa ), convert( h_{m2}, unit_free, W/(m^2K) ) , convert( T2i, unit_free, degC ),
    convert( T2o, unit_free, degC ), convert( mu2, unit_free, Pa·s )⟩ ) :
acqua := ⟨convert( d_{h, interno}, unit_free, mm ), convert( Q1, unit_free, m^3/s ),
    convert( mdot1, unit_free, kg/s ), convert( Δp1_{tot}, unit_free, Pa ), convert( h_{m1},
    unit_free, W/(m^2K) ), convert( T1i, unit_free, degC ), convert( T1o, unit_free, degC ),
    convert( mu1, unit_free, Pa·s ), 0⟩ :
dettagli := evalf[5]( ⟨convert( Volume, unit_free, m^3 ), convert( δ_f, unit_free, m ),
    convert( δ_P, unit_free, m ), convert( h_P, unit_free, m ) , convert( d_{SP}, unit_free, m ),
    convert( 2 s_L, unit_free, m ), convert( s_T, unit_free, m ), convert( A_{cs, i, tot}, unit_free,
    m^2 ), convert( A_{cs, o, tot}, unit_free, m^2 )⟩ ) :
> F := Matrix(9, 5) :
  F( .., 1 ) := geometria :
  F( .., 2 ) := dett_termici :
  F( .., 3 ) := aria :
  F( .., 4 ) := acqua :
  F( .., 5 ) := dettagli :

> path := FileTools[AbsolutePath]("data.xlsx") :
  flag := 1 ;
                                   flag := 1                                   (1.7.1)
> if flag = 1 then
  Export( path, F, format = "Excel", target = file ) :
  end if:
```

3. Laboratory Setup and Experimental Methods

This chapter presents a comprehensive overview of the experimental equipment and methodologies employed in this research to characterize and validate Pillow Plate Heat Exchanger (PPHE) performance. The experimental framework encompasses multiple iterations of Small-Scale Pillow Plate Heat Exchanger (SSPPHE) test platforms and a Condensation Heat Recovery (CHR) setup, each designed to address specific research objectives and technical challenges.

Chapter Index

3.1. Small Scale Pillow Plate (SSPPHE) Investigation

Recent interest in exploring novel applications for PPHE has brought researchers to reduce the size of Pillow Plates to investigate their performance and the validity of the studies made on bigger plates [1]. Moreover, keeping the scale down allows to perform more tests since the energy and material requirements for prototypes are lower. Studying a geometry with the same aspect ratio but with smaller (half, one third) main dimensions, is also beneficial to understand border effects: this knowledge would also be beneficial for large scale Pillow Plates, since they are rarely designed as single passage in the inside channel. The laser welding production technology allows in fact to create serpentines and to divide the internal channel in smaller channels which could be affected by the same border effects on the fluid and thermal flow. Ultimately, recent trends of using pillow plates for high speed flows and turbomachinery [2] could open the aviation and aerospace sectors, which would require geometries far smaller than the ones currently employed in other industries. Being this the first experimental campaign, a setup with water as working fluid was chosen, for easiness of implementation, safety and availability.

3.1.1. SSPPHE version 1 (location: University of Trento)

3.1.1.1. Purpose and General Specifications

The initial experimental setup was designed to validate the effectiveness-NTU (ε-NTU) design model for Small-Scale Pillow Plate Heat Exchangers through thermal and hydraulic characterization. This platform aimed to evaluate SSPPHE performance in the smallest achievable geometric configuration, exploring both laminar and transitional flow regimes within Reynolds number ranges of 500-3000. The experimental apparatus featured a compact PPHE prototype with a heat transfer to volume ratio of approximately 350 m^2/m^3, capable of withstanding pressures up to 80 bar in the inner channel.

3.1.1.2. Technical Details

The SSPPHE prototype comprised two parallel pillow plates, each measuring 450 mm in length and 80 mm in width, with a plate thickness of 1 mm. This configuration, shown in Figure 3.1, created two inner channels (ICs) and three outer channels (OCs). The plates featured an internal inflation height of 3 mm, resulting in an inflated plate thickness of 5 mm (including the plate material). The median surface distance between adjacent plates was maintained at 8 mm. In order to minimise border effects in the outer channel, the internal walls of the shell were made with single embossed pillow plate not connected to any hydraulic circuit: this is to recreate the three-dimensional motion field typical of PPHE even in the two external outer channels. The pillow plate geometry was defined by a longitudinal pitch (sl) of 18 mm, transversal pitch (st) of 21 mm, non-inflated welded edges of 3 mm length, and welding spot diameter of 5 mm. This configuration represented the smallest feasible pillow plate geometry achievable through current laser welding technology constraints, mainly curvature radius realisable by electric motors and encoders, making it particularly valuable for investigating the performance characteristics of compact PPHE designs. The experimental system operated with water as the working fluid in both the hot inner channel circuit and the cold outer channel circuit, allowing for controlled heat transfer experiments across various flow rates and temperature differentials. The apparatus was designed for counter-current flow configuration to maximize thermal performance.

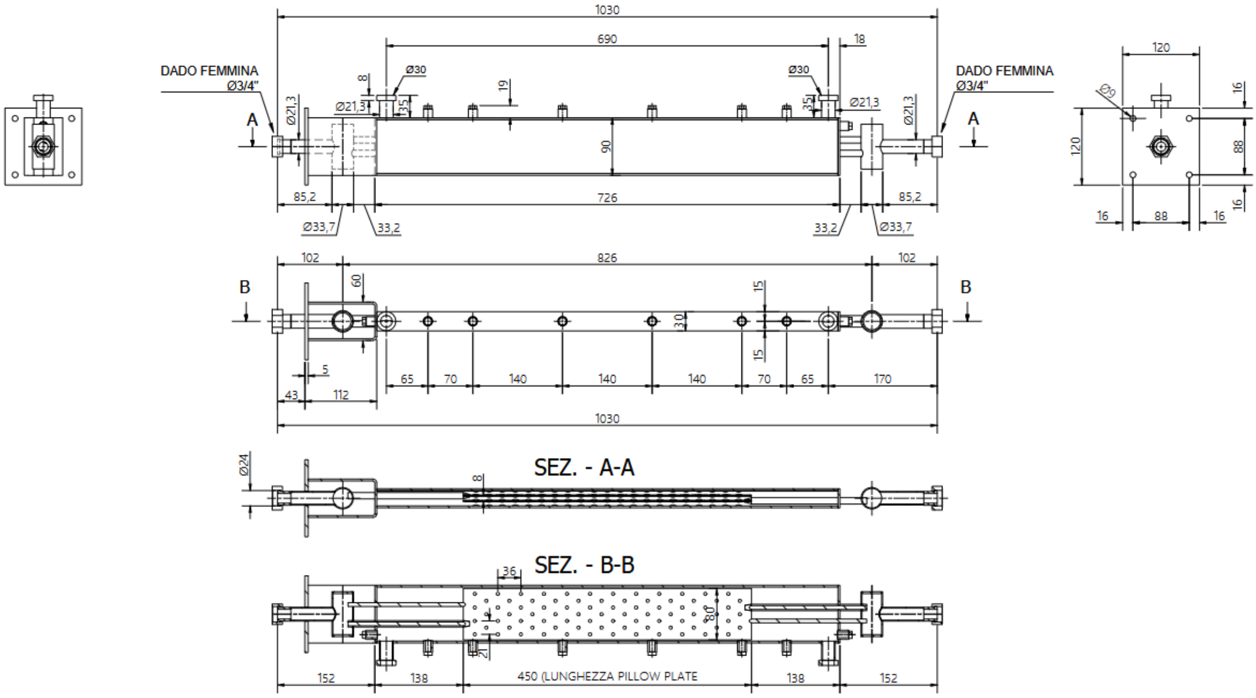
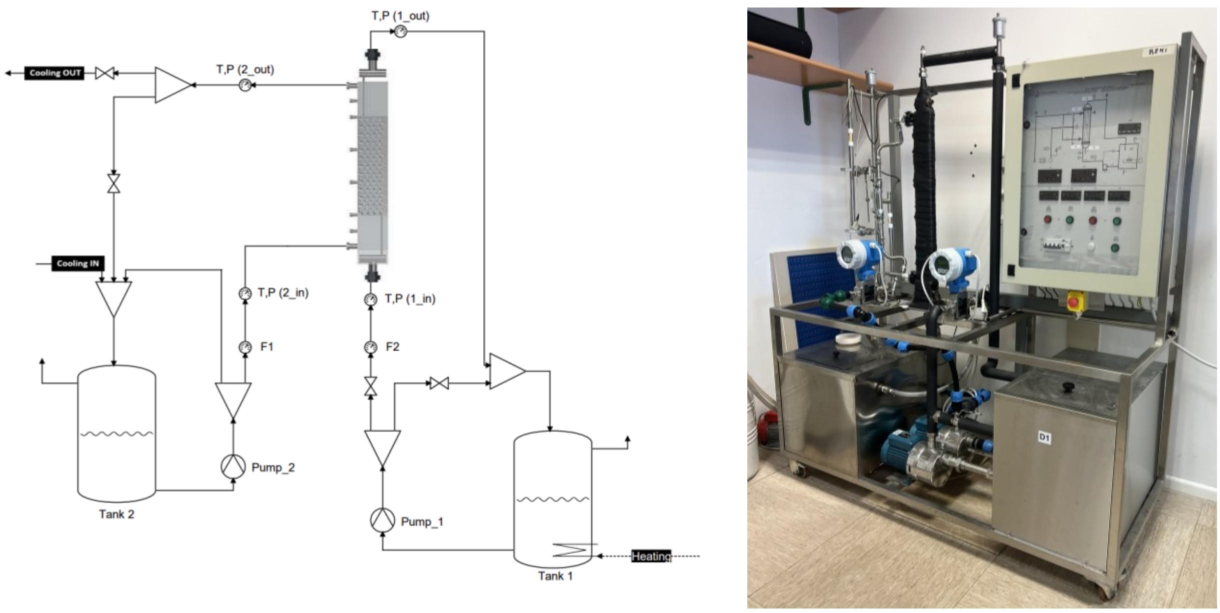


Figure 3.1: Technical drawing to manufacture the Small Scale PPHE prototype – version 1.

3.1.2.3. Instruments

The experimental apparatus, shown in Figures 3.2 a and b, was equipped with instrumentation to measure key performance parameters. Table 3.1 summarises the relevant technical aspects behind the measurements. Calibrated Pt100 sensors (3 mm diameter) were initially installed to monitor fluid temperatures at the inlet and outlet of both inner and outer channels. The IC sensors were installed on the headers, while the OC sensors were installed in the shell, where the water mixes at the inlet and outlet of the OC. Additional sensor housings were positioned along the shell length, however, it was



a) b)

Figure 3.2: a) the schematic of the experimental set-up, with hot (1) (Inner SSPPHE Channel) and cold (2) (Outer Channel) sides and sensors. (b) A picture of the compact experimental set-up

discovered that these sensors affected fluid motion between plates and had to be eliminated to avoid flow disturbance. Flow measurement was performed by two volumetric flow meters (designated F1 and F2) in the cold and hot fluid circuits, respectively. These measurements enabled the calculation of Reynolds numbers and, indirectly with the calculated density, the mass flux rates. Pressure measurement was performed through differential pressure installed at the inlet and outlet of both channels, though the pressure drops in the outer channel proved to be below the sensor's accuracy threshold (5 mbar). The temperature of the hot source was controlled by an on-off 5kW electric resistance heater in Tank 1 provided temperature control for the hot fluid circuit, while the temperature of the cold source was maintained by rejecting the heated water in the municipal sewage system and integrating with fresh cold water from the municipal supply. The entire SSPPHE assembly was thermally insulated to minimize heat losses to the environment, and data acquisition systems recorded temperature, pressure, and flow measurements every second, to provide continuous data to be averaged and then analysed. However, the control of the apparatus was largely manual through mechanical bypass valves and a single setpoint for the hot water. Moreover, the thermal sources were not thermally insulated, and the cold source was limited by the fixed outlet temperature of the municipal water supply, preventing comprehensive characterisation.

Table 3.1: Instrumentation and measurement parameters for the Small-Scale Pillow Plate Heat Exchanger (SSPPHE) version 1 at the University of Trento. This initial experimental setup established baseline measurement capabilities for PPHE thermal and hydraulic characterization under laboratory conditions.

Parameter	Location	Instrument	Specifications	Acquisition Method
Temperature	IC inlet/outlet (headers)	2 Pt100 sensors, class A IEC60751	3mm diameter	Electronic logging, 1 reading/sec
Temperature	OC inlet/outlet (shell)	2 Pt100 sensors, class A IEC60751	3mm diameter	Electronic logging, 1 reading/sec
Flow Rate	Cold circuit	Volumetric flow meter (F1)	Not specified	Electronic logging, 1 reading/sec
Flow Rate	Hot circuit	Volumetric flow meter (F2)	Not specified	Electronic logging, 1 reading/sec
Pressure Drop	IC inlet/outlet	Differential pressure sensor	>5 mbar sensitivity	Electronic logging, 1 reading/sec
Pressure Drop	OC inlet/outlet	Differential pressure sensor	>5 mbar sensitivity (insufficient)	Electronic logging, 1 reading/sec
Thermal Control	Hot source	On-off 5kW electric resistance heater	Tank 1	Indirect reading from IC inlet temperature
Thermal Control	Cold source	Municipal water supply	Variable temperature – Manual control	NA
System Insulation	PPHE frame and headers	Thermal insulation material	Rockwool and neoprene tape	NA

3.1.2. SSPPHE version 2 (location: industrial laboratory)

3.1.2.1. Purpose and General Specifications

Following the initial SSPPHE campaign, a second experimental platform was developed to address the limitations identified in the first setup and expand the scope of research. Both the prototype and the apparatus were redesigned to provide enhanced measurement precision, improved thermal stability, and greater automation of experimental procedures. The primary objectives included more detailed characterization of border effects, extension of the Reynolds and Prandl number range for correlation validation, and more precise measurement of the outer channel pressure drop. In Figure 3.3, the set-up is schematised, with two controlled heat sources (cold in blue, hot in red), inverter-controlled pumps and a redesigned prototype with more strategically positioned sensors and 3-way manual valves that allow to invert the hot and cold channel and the flow arrangement from counter-flow to parallel-flow.

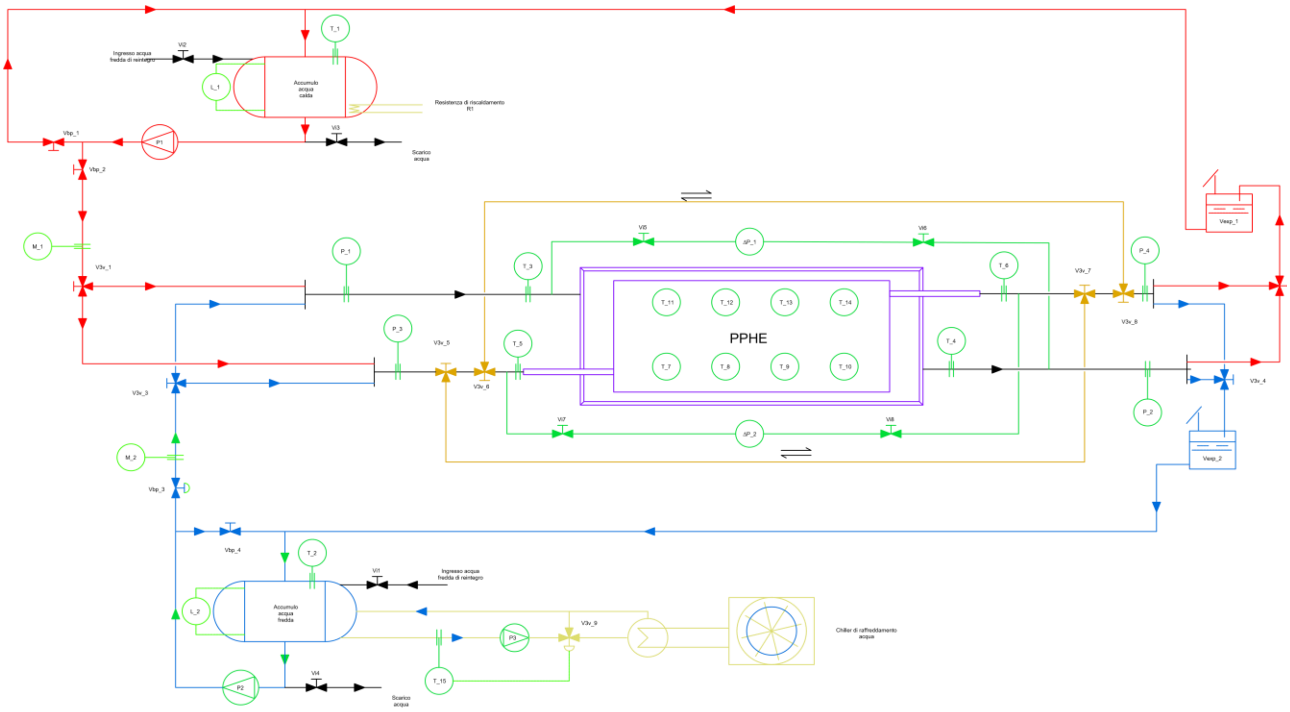


Figure 1.3: Schematic of the experimental set-up and prototype – version 2. It is possible to notice that this version uses a chiller for control of the cold source, and that there are 3-way valves that allow to invert the hot and cold channels and switch from counterflow to parallel flow.

3.1.2.2. Technical Details

The SSPPHE version 2 changed many aspects from version 1. As noticeable from Figure 3.4, there are still two plates, entirely immersed in the shell, headers excluded. This is the only similarity with the precedent version. The Pillow Plates are now wider; to look for a reduction of the predominant border effect found in the previous campaign and appreciate the differences. The plate dimensions are 188mm in width and 506 in length, with 10mm welded edges, 0.8mm sheet metal thickness with an inflated plate thickness of 6mm and a pitch between median surfaces of 9mm. The configuration is one OC and two IC, since in the previous campaign there were suspects of fluid maldistribution in the shell, which is to be expected when simple shapes are used with small configurations. Four pt100 sensors were chosen to monitor temperatures at the inlets and outlets, while two arrays of type T thermocouples were installed for temperature profile acquisition. An innovative solution was attempted to obtain such profile in this small configuration: by welding capillaries to the domes of the wavy pillow plate surface, and the thermocouple was introduced in the IC trough a previously carved hole. Other capillaries were welded to the spots, which were also carved to introduce the thermocouples in the OC. Leaks were prevented using a sealant for the capillary length.

The experimental setup was improved too, with enhanced temperature control with a 40kW chiller unit, serving the cold source through a dedicated circuit with a PHE and capable of cooling water up to 5°C (safety limit to avoid ice formation and consequent burst failure in the service PHE). An automated control system was implemented on pumps, heating and cooling together with datalogging, to allow comprehensive testing. Different probes were predisposed for pressure measurements with the idea of characterising the new prototype with the old sensors and buy more accurate sensors later. This choice was made since sensor accuracy of pressure transducers is often inversely proportional to their resistance: it was thus decided to characterise the maximum operating pressure at the maximum flow rate first. The hot source was equipped with twin 9kW electrical resistances. Thermal insulation was enhanced in both reservoir tanks to increase system stability and reduce losses and bypass piping returning to the tanks and controlled with manual valves were built to reduce stratification.

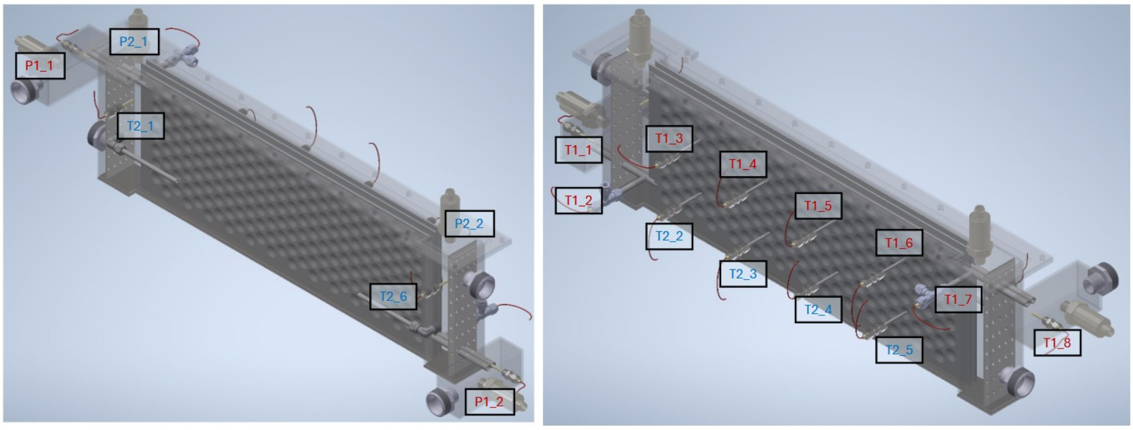


Figure 3.4: CAD views of the Small Scale PPHE – version 2, with indications of the positioning of the sensors with the identification rule being: LetterNumber1_Number2, with the letter T indicates temperature, P pressure, the first number indicates 1 for the internal channel, 2 the external, while the last number is for progressive numeration.

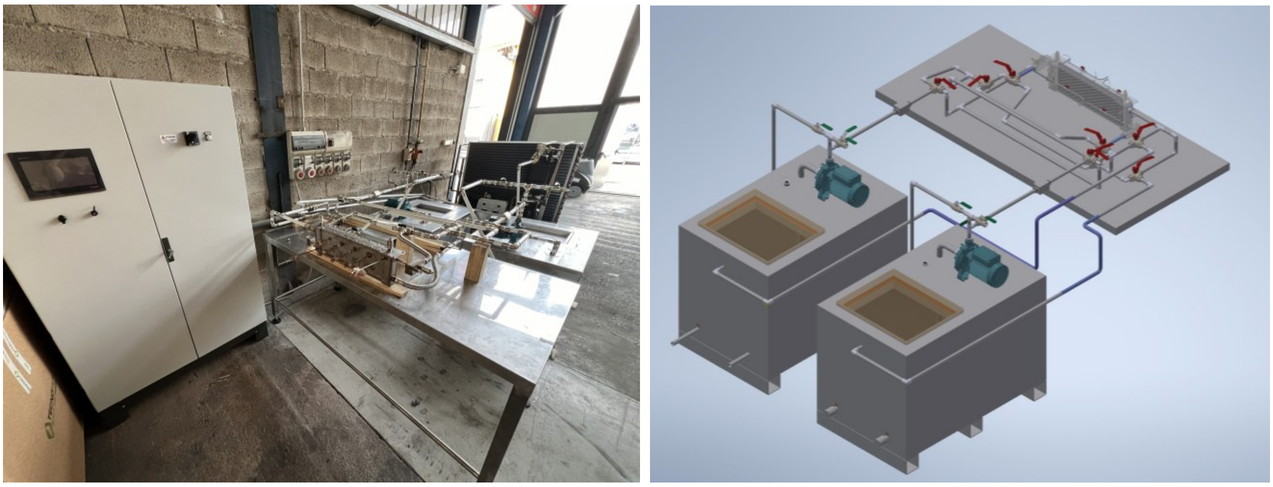
3.1.2.3. Instruments

The instrumentation suite for SSPPHE v2, as showcased in Table 3.2, included 4 Pt100, class A, 3mm diameter, 50mm length and 10 type T thermocouples., 2 Electromagnetic Flow Meters Picomag, DMA20, DN20 ¾" by Endress Hauser, Schneider inverter and electronics and inverter controlled pumps, Schneider PLC and HMI "Magelis" system for signal reading and sending, control and data visualisation: industrial grade components were chosen to ensure long lasting equipment, and the possibility of

Table 3.2: Advanced instrumentation and control systems implemented in SSPPHE version 2 at the industrial laboratory. This enhanced setup incorporated industrial-grade measurement equipment and automated control systems for more comprehensive data acquisition and experimental flexibility.

Parameter	Location	Instrument	Specifications	Acquisition Method
Temperature	Inlets/outlets	Pt100, Class A IEC60751	3mm diameter, 50mm length	Schneider PLC and HMI system
Temperature	Profiles in IC	Type T thermocouples IEC60751	Arrays via welded capillaries	Schneider PLC and HMI system
Temperature	Profiles in OC	Type T thermocouples IEC60751	Mounted at weld spots	Schneider PLC and HMI system
Flow Rate	Both circuits	Electromagnetic Flow Meters	Picomag, DMA20, DN20 ¾" by Endress Hauser	Schneider PLC and HMI system
Pressure Drop	Both channels	Pressure transducers	Multiple sensors for characterization	Schneider PLC and HMI system
Thermal Control	Cold source	40kW chiller unit	Cooling to 5°C minimum	Automated control system
Thermal Control	Hot source	Twin 9kW electrical resistances	Up to 80°C	Automated control system
Flow Control	Both circuits	Inverter-controlled pumps	Flow range: 1-50 l/min	Schneider inverter and electronics
System Control	All systems	Schneider PLC	Industrial grade components	Automated with manual override
Geometric Analysis	Pillow plates	Laser scan	0.2mm resolution	Image processing software
Flow Configuration	System valves	3-way manual valves	Allowed flow inversion and arrangement changes	Manual operation

expansion and modification of hardware and software, while maintaining safety and reliability standards for industrial research. The resulting equipment is shown in picture in Figure 3.5a, and in CAD representation in Figure 3.5b. The instrumentation was carefully calibrated and validated to ensure



a) b)

Figure 3.5: a) Picture of the constructed experimental setup, during preliminary testing. It is possible to see first on the left, the electrical cabinet with the control panel and datalogger, the SSPPHE prototype, the piping and in distance the chiller. b) Rear CAD view of the setup, where it is possible to see the two fluid reservoirs, one has piping for the chiller circuit, the other has two embedded electrical heating resistances.

measurement accuracy and reliability throughout the experimental campaigns.

3.1.2.4. Preliminary Findings and Problems

The SSPPHE v2 experimental campaign yielded valuable insights while also revealing certain operational challenges that caused its temporary suspension. The previous prototype had a pillow plate reinforced shell, which was no longer a flat surface and thus showed no resistance problem. In the new prototype, since there was only one OC in between the Pillow Plates, it was not deemed necessary to have that extra feature on the 4mm shell wall containing the outer channel, and a simple insulating foam together with small baffles was deemed enough to avoid flooding the crevice between the shell wall and the unused external PP surface, as seen in Figure 3.6. Unfortunately, this was a serious design oversight: probably due to an accidental valve throttling during maximum flow rate operation caused an unexpected pressure spike that plastically deformed the shell, with a maximum deviation of 5mm that was however enough to let water flood the crevice soaking the insulating foam, causing irreparable damage to the prototype. However, these findings provide valuable guidance setting the foundation for the future development of SSPPHE version 3, which will be tested with the described laboratory setup.

3.1.3. SSPPHE v3

3.1.3.1. Concept

Building upon the knowledge gained from previous experimental campaigns, SSPPHE version 3 will try and solve the same research questions as its unlucky predecessor. This proposed setup aims to address the specific challenges identified in earlier iterations while expanding the experimental capabilities to explore wider parameter ranges and more diverse operating conditions. The experimental setup is already capable of fluid flow ranges of 1 to 50l/min on both channels, with the hot source temperature that can be set between ambient temperature and 80°C, and the cold source temperature between 5 and 50°C (maximum temperature tested). Channels can also be swapped, so it would be possible to characterise a wide range of Pr and Re numbers in both channels. The new construction will abandon

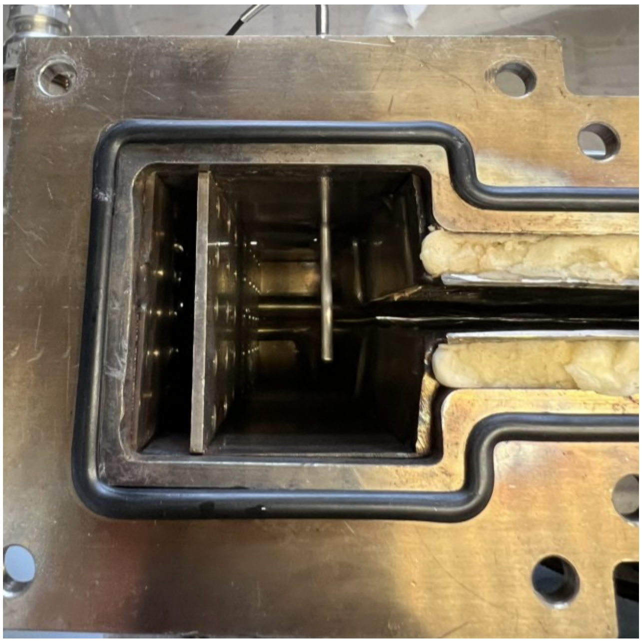


Figure 3.6: Top view, closeup of the inlet/outlet chamber for the Small Scale PPHE – version 2. From the left it is possible to see the flow equalization grid, the immersed pt100, baffles for flow direction in the only central channel between two PPs and the insulating foam, prior to equipment failure. On the top of the chamber, the reader can see a gasketed flange for the bolted cover, on the bottom the two capillaries that direct the internal flow in the IC of the PPs.

the shell and pillow plate configuration, using the pillow plates directly as the heat exchanger walls, with a single OC in the middle. Integrated headers, possibly 3D printed, will be used to avoid having the IC connections immersed in the shell, and on the long, narrow edges, flanges with adequately dimensioned inspection panels will be installed for flow visualisation.

3.1.3.2. Objectives

The SSPPHE v3 concept is designed to achieve several key objectives:

1. Expanded Operating Range: Enable testing across wider Re and Pr number ranges, from deep laminar to fully turbulent flow regimes, to validate correlation applicability and identify transition phenomena.
2. Enhanced Visualization Capabilities: Incorporate advanced flow visualization techniques to directly observe flow patterns, recirculation zones, and mixing phenomena within both inner and outer channels.
3. Border Effect Quantification: Develop specific measurement protocols to isolate and quantify border effects, providing data for improved geometrical modelling of compact PPHE designs.

3.1.3.3. Future Work

The development and implementation include several planned initiatives, from advanced geometrical modelling, with an integration of computational methods with experimental geometric data to develop more accurate representations of pillow plate structures, particularly for compact designs with significant border effects, correlation validation and refinement and the collection of comprehensive experimental data. A comparison with the former successful campaign will allow to compare border effects at different scales of SSPPHE. This will be achieved through a simple set of tasks that will be performed after the Condensation heat Recovery campaign is completed:

1. Conceptual design: completed.
2. Technical drawing and bill of material preparation.
3. Material procurement.

4. Pillow plate production, extra samples are produced for geometric characterisation.
5. Geometric characterisation.
6. Production.
7. Initial tests and calibration.
8. Experimental campaigns.

3.1.3.4. Technical Advice and Considerations

Based on the cumulative experience from previous experimental campaigns, several technical recommendations have been identified for the successful implementation of SSPPHE v3:

1. Sensor Selection and Positioning: Pillow Plates present a plate like structure that makes the channels narrow and hardly fitting any sensor. Moreover, smaller sensors such as thermocouple wires are hard to position and to keep in position. From the preliminary findings of the SSPPHE-v2 campaign, thermal profiles appeared unrealistic, probably to unintended contact of the sensors with the plate walls. It might be prudent to avoid such measurements altogether, and switch to thermal imaging, with a reminder that stainless steel reflectivity must be accounted for or eliminated through painting.
2. Pressure Measurement Approach: using robust pressure transducers to first SSPPHEs and then choosing dedicated sensors is advisable.
3. Data Management Strategy: The implementation of structured data collection and analysis protocols, ensures consistency and traceability throughout the experimental program.

3.2. Condensation Heat Recovery (CHR)

3.2.1. CHR version 1

3.2.1.1. Purpose and General Specifications

The Condensation Heat Recovery (CHR) experimental setup represents a significant expansion of the research scope, addressing the complex phenomena of condensation of moisture contained in an airflow with PPHEs. This specialized apparatus is designed to investigate heat and mass with particular focus on a food processing application developed in synergy with a selected customer. This strategic campaign allows PPHE utilisation to recover heat from waste airflow from food drying processes, which is a paramount treatment to obtain a vast range of food products. This is also a first step into the application of PPHE in heat recovery from humid gas streams such as combustion exhaust gases or industrial process exhausts, which currently show wide margins of improvement [3]. The CHR v1 setup aims to characterize PPHE performance in environments where both sensible and latent heat transfer occur simultaneously. This represents a critical advancement in PPHE research, as condensation heat recovery offers substantial energy efficiency improvements in various industrial applications and there is no established method or even characterisation available [4]. As depicted by the technical drawing in Figure 3.7, the setup is comprised of an insulated channel made by an aluminium frame and 60mm rockwool thermal insulation. The main channel is larger and in sequence shows electrical heating resistances, an adiabatic humidifying carboard mesh that is continuously wet by an electrical submerged pump, a droplet separator, the PPHE, another droplet separator, and a pulling ventilator to avoid maldistributions typical of a pushing ventilator. The air is then recirculated by a smaller return channel. The recirculation can be interrupted by manually activated flaps that open on the external. This configuration was chosen to keep the electrical power to manageable orders of magnitude, since humidifying air is an energy intensive process it would be senseless to waste it right after the heat exchanger and make the experimentations too expensive for a preliminary laboratory work.

Recirculation allows to reduce the power requirement from 220kW to 20kW for a nominal flow rate of 1500m^3/h with 130g of water for kg of air. The drawback is obviously an increased operational complexity that was solved with the development of PID (proportional, integral, derivative) controls for heating and humidifying and a dedicated test procedure. The cooling channel works with water and is the exact circuit that is described in section 3.1.2.

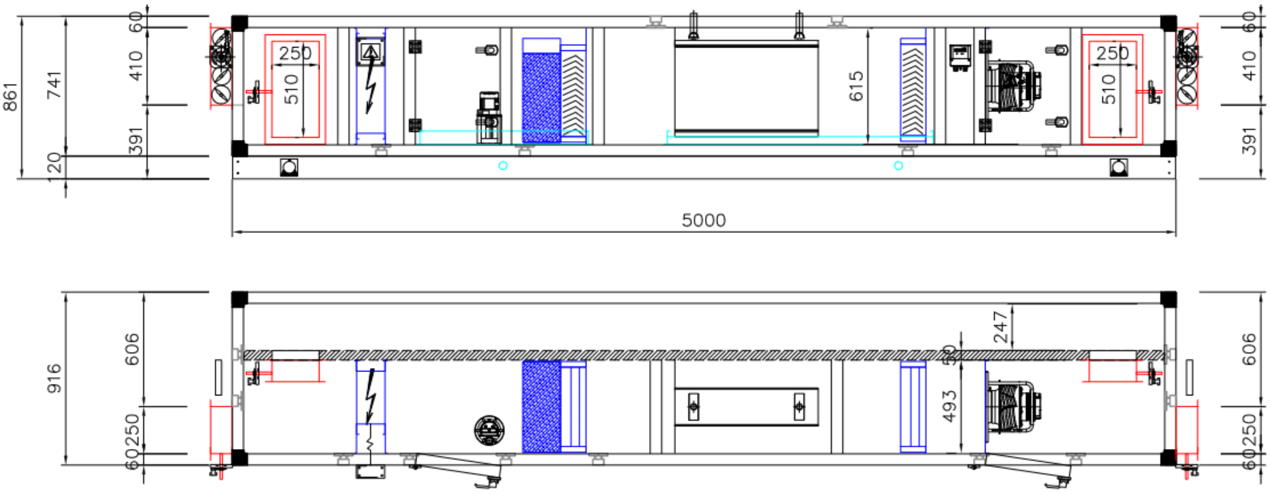


Figure 3.7: Schematic of the experimental set-up for the characterization of the Condensation Heat Recovery prototype. The air is recirculated by the fan on the right, is heated by electrical resistances on the left, then humidified by evaporating (evaporative adiabatic cooling) water from a cardboard mesh pack moistened by an electrical pump. Droplet separators are present before and after the centrally positioned PPHE. Condensate discharge is performed by dedicated piping under the PPHE.

3.2.2.1. Technical Details

The CHR v1 experimental apparatus is configured to simulate condensation conditions in a controlled environment. The Heating and Humidification System has a double zinc coated steel electrical resistance, with a total power of 17.4kW, a 0.2kW immersed pump and a cardboard mesh pack. Its performance is only characterised at steady state conditions (inlet air 65°C, 11% RH exits at 37°C, 70% RH, with a 11g/kg of humidifying capacity) which is only indicative since the humidifying occurs progressively through recirculation. The heating elements works with a software PID control (proportional – integrative – derivative) that modulates its work, while the pump works with a PID that regulates activation time following the target relative humidity at the inlet of the PPHE. The PPHE testing section incorporates droplet separators and a dedicated collection tank and piping, which allows to quantify condensate production rates through weighting. It should be noted that all panels are removable, so different PPHEs could be tested in future endeavours. The cooling circuit is the same as for the SSPPHE-version 2 apparatus and uses the same chiller, to reduce startup costs. The fan has a 0.5kW motor with integrated speed controller and different working points, with a composite turning blade for increased corrosion resistance and works in suction. The prototype is the scaled version of a bigger prototype that is being developed for a pilot production. As shown in Figure 3.8, the PPHE is made of 5 pillow plates, 750mm long and 400mm high, and its nominal operating conditions are 40°C inlet water temperature, 50l/min flowrate, and 65°C with 65% relative humidity, or 120-130 g/kg of absolute humidity, at 1500-2000m^3/h, with an expected condensate production of 10 to 20kg per hour, and an expected rating of 13kW, obtained with a commercial software that was independently developed without experimental validation or experience.

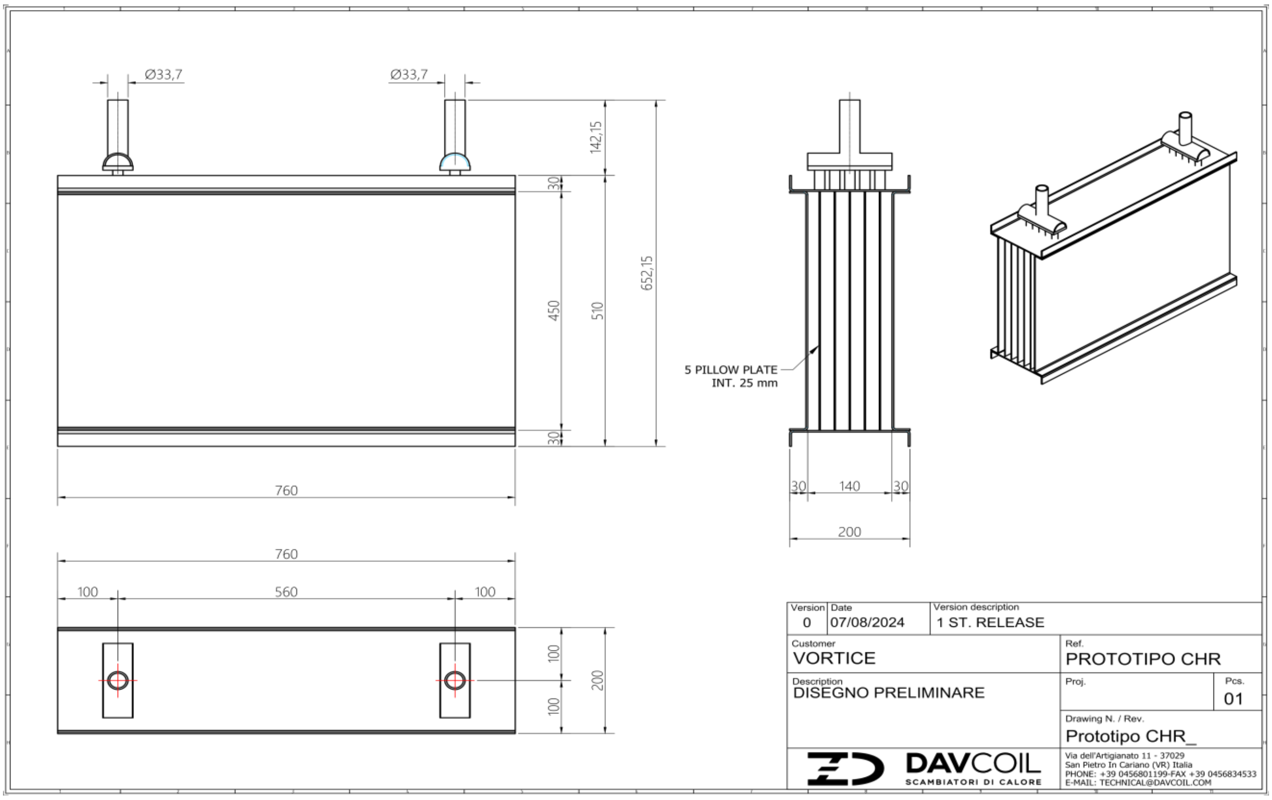


Figure 3.8: Technical drawing of the Condensation Heat Recovery PPHE

3.2.1.3. Instruments

The CHR v1 platform, represented in Figure 3.9, is equipped with instrumentation thought to characterise the heat recovery through condensation phenomena. Two temperature-humidity sensors, Galltec+Mela BKK3.00.F148.A13, are put after the first and the second droplet separator, to

a) b)

Figure 3.9: Pictures of the Condensation Heat Recovery experimental set-up, with a particular of the PPHE during sensor installation (a), and the entire system after the initial positioning (b).

characterise air entering and exiting the PPHE section through capacitive sensors embedded in a porous metal encasing. The PPHE, in another attempt to obtain thermal profiles during operation, was embedded with 10 Pt100 sensors, class A for the inlets and outlets, class 1/10 DIN for the intermediate points. The disposition is made to divide the PPHE in four cells that can be modelled separately in accordance with experimental data. A final measurement on the air flow rate is provided by a differential pressure transducer calibrated in accordance with Eq. 3.1 and a k value of 67, provided by the manufacturer:

$$Q\ [\frac{m^3}{h}] = k \cdot \sqrt{\Delta p} \tag{6}$$

Table 3.3 summarises this information, leaving a blueprint for future improved iterations and improvement, starting from a better solution for air flow rate determination and differential pressure transducers for the air side.

Table 3.3: Specialized measurement and control systems for the Condensation Heat Recovery (CHR) experimental apparatus. This setup was designed to investigate the combined sensible and latent heat transfer mechanisms in humid air streams, with dedicated instrumentation for temperature, humidity, and condensate collection.

Parameter	Location	Instrument	Specifications	Acquisition Method
Temperature	IC inlet/outlet	Pt100, Class A IEC60751	Not specified	Schneider PLC and HMI system
Temperature	IC intermediate	Pt100, Class 1/10 DIN IEC60751	Higher precision (readings unsuccessful)	Schneider PLC and HMI system
Temperature & Humidity	Air inlet/outlet	Galltec+Mela BKK3.00.F148.A13	Capacitive sensors in porous metal encasing	Schneider PLC and HMI system
Flow Rate	Water circuit, after reservoir	Electromagnetic Flow Meter	Same as SSPPHE v2	Schneider PLC and HMI system
Air Flow Rate	Before and after Fan	Differential pressure transducer	Calibrated with k value of 67	Schneider PLC and HMI system
Condensate Production	Sink under PPHE	Weighing system	Not specified	Manual measurement
Thermal Control	First module, before PPHE	Double zinc coated steel electrical resistance	17kW total power	PID control system
Humidification	After heating, before PPHE	0.2kW immersed pump with cardboard mesh	11g/kg humidification capacity	PID control system
Air Movement	After PPHE	Fan with composite turning blade	0.5kW motor with integrated speed controller, suction configuration	NA
Condensate Collection	After PPHE	Dedicated collection tank and piping	quantification through weighing	Manual measurement
System Control	Electrical Cabinet	PLC with PID controllers	Separate controls for heating and humidifying	Automated with manual override
Channel Structure	External frame and ducting	NA	60mm rockwool (90kg/m3) and 0.6mm zinced steel panels with aluminium frame	NA

3.2.1.4. Technical Advice and Considerations on Experimental Procedure

As it will be possible to evaluate in the Results section, the first experimental tests showed a successful condensation process that exceeded the first estimations. However, it is significant to share some observations. To avoid interdependencies between the heating and humidifying PID controls, the testing procedure undergoes the following operations:

1. Heating of the cold reservoir from ambient temperature to 40°C through the dedicated chiller that can work as a heat pump. No water circulation in the PPHE.
2. Simultaneous to 1, the air is heated in the setup until the setpoint is reached (admissible range: ambient to 85°C) and maintained. The air volume is small, so there will always be slight oscillation around the setpoint.
3. The humidifying system is turned on, while the heating elements maintain the temperature (which tends to drop due to adiabatic evaporative cooling). If the temperature is maintained in this way, there is no risk of excessive oscillation that cause problems with the relative humidity measurement and setpoint.
4. Once the humidity and temperature of air are reached and kept for a satisfying time, the water circuit can be turned on and the experimental run can begin. Data can be recorded for the whole procedure or only from this step once the behaviour of the machine is understood better.
5. The controls, especially the proportional parts of the PID require experience and trials to work properly, but if humidity is not being kept constant within a reasonably wide band, chance is that the heat exchanger is condensing and cooling more than the machine can handle!

Another useful remark is once again to be made on thermal profiles and the difficulties in measuring with precision certain locations in PPHEs. After the first trials and sensor calibration in ice and boiling water, it was in fact discovered during the first experimental runs that all the intermediate pt100 sensor readings, both inner and outer channels, would have invalidated the principles of thermodynamics. Upon close inspection, and trials, these sensor positioning had to be discarded for the following reasons:

- Intermediate sensors immersed in the IC had to be installed once again in a capillary, however this capillary passes through the frame, the first OC and then goes into the first plate which is the measured one: this means that air heats up the capillary length exposed in the OC. This is further demonstrated by the fact that when water is circulated without air, sensor values tend to align, and when air is turned on the readings have no longer physical meaning. More insulation would not be possible as its hindrance would change the flow in one of the OCs.
- Intermediate sensors for air pass through holes in the pillow plate and are probably cooled by it: further tests are needed with extra insulation.
- The inlet and outlet sensors are easier to place, for the OC directly in front of the inlets and outlets, and for the IC they are immersed in the header, making the measure more stable and trustable.

In conclusion, the humidity sensors had to be moved from the ceiling to the side, since stratification was not absent, probably due to abrupt changes in the channel size after the droplet separators, so special consideration is advised for well tapered geometrical irregularities.

3.3. Chapter references

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4. Implementation of the Pillow Plate Production Process

The manufacturing of Pillow Plate Heat Exchangers (PPHEs) involves several critical processes that influence their thermal and hydraulic performance. This chapter examines the key production stages, from material selection to final testing, with particular emphasis on technical considerations and quality assurance measures essential for reliable industrial applications. A significant step of this industrial innovation research, was to understand the process and implement it in the partner company, with a project management approach adopted by the author, which covered the study of the welding technologies, industrial visits to pillow plate producers and laser manufacturer, the analysis of different suppliers, a preparatory step of the dedicated premises with an analysis of the requirements for the production environment and finally the installation of the welding machine, with the implementation of all the complementary production operations. This joint effort between research and the board of the hosting company allowed a fast implementation of a production process with an annexed laboratory, with mutual benefits between the research team and the other SME business units. As direct implementation of the most updated scientific information allowed better implementation results of a previously unknown process, adding hands on production experience to the research team allowed faster production of more and better prototypes and a broader understanding of Pillow Plates and the difference between the ideal models and the real products.

Chapter Index

4.1. Materials

The selection of appropriate materials for PPHE manufacturing is fundamental to their performance, durability, and application suitability. While a variety of materials can theoretically be employed, several considerations constrain practical material choices.

4.1.1. Stainless Steel

Austenitic stainless-steel grades constitute the predominant material choice for commercial PPHE production, owing to their favourable combination of properties:

- **Mechanical Properties:** The ductility of austenitic stainless steel facilitates the hydroforming process without compromising structural integrity.
- **Corrosion Resistance:** Excellent resistance to diverse process fluids and environmental conditions.
- **Weldability:** Compatible with various welding techniques, particularly laser welding.
- **Thermal Conductivity:** While not optimal compared to alternatives like copper or aluminium, stainless steel provides an acceptable compromise between thermal performance and manufacturability.

Common austenitic stainless-steel grades employed in PPHE manufacturing include:

- AISI 304L (1.4307): General-purpose grade with good corrosion resistance
- AISI 316L (1.4404): Enhanced corrosion resistance, particularly in chloride environments
- AISI 321 (1.4541): Titanium-stabilized grade resistant to intergranular corrosion
- AISI 316Ti (1.4571): Titanium-stabilized version of 316 with improved high-temperature properties

For specialized applications requiring enhanced corrosion resistance, such as diesel exhaust heat recovery systems, higher-grade alloys like AISI 904L are employed, as illustrated in the following section, and showcased in a prototype in the following chapter.

4.1.2. Alternative Materials

While stainless steel dominates commercial applications, alternative materials offer potential advantages for specific scenarios:

- Aluminium Alloys: Characterized by higher thermal conductivity, lower density, and reduced carbon footprint when produced using renewable energy. Zibart and Kenig [1] demonstrated that aluminium can provide 10-25% lower thermal resistance compared to stainless steel alternatives, though pressure capabilities are limited. EN AW-5083 aluminium alloy has been identified as suitable for low-pressure applications.
- Specialized Alloys: For extreme operating conditions, materials such as:
    - Inconel 625: Utilized in thermal solar systems and concentrated solar power receivers.
    - Hastelloy Alloys: Applied in highly corrosive environments

- o Duplex Stainless Steel: Employed where combined mechanical strength and corrosion resistance are required
- o AISI 904L (1.4539) for increased corrosion resistance.

Material for pillow plate sheets follow the norm EN 10028-7:2016 (sheets for Pressure Equipment Directive PED2014/68/UE) with the inspection certificate 3.1 that provides the chemical and mechanical tests for the exact production batch of the sheets. The material selection ultimately represents a compromise between thermal performance, mechanical requirements, corrosion resistance, manufacturability, and economic considerations. The development of new manufacturing techniques, such as the electrohydraulic incremental forming method described by Dutka et al. [2] and shown as promising future possibility by the most recent review [3], may expand the range of viable materials for future PPHE applications. For now, it is a process that shows promise for small geometries but works on a limited area and would require complex technical adaptations to work with the typical 2 to 4 m2 PP that are often seen in industrial applications.

4.2. Laser Welding

The laser welding process constitutes a critical manufacturing stage that directly influences PPHE geometry, structural integrity, and production economics. Through the systematic implementation of a laser welding facility within the industrial partner's production capabilities, this research has generated significant insights into optimal welding practices.

4.2.1. Welding Methods

While multiple welding techniques are potentially applicable to PPHE manufacturing, three primary methods have been established in industrial practice:

- **Laser Welding:** Delivers high precision, speed, and automation capability with minimal heat-affected zones.
- **Resistance Welding:** Provides efficient spot welding for specific applications
- **Tungsten Inert Gas (TIG) Welding:** Utilized with metal filling for specialized configurations

The establishment of the dedicated 3kW laser welding facility at Dav Coil on May 2023, represents a significant advancement in manufacturing capability, enabling precise control over weld spot patterns and geometrical parameters. Historically, the production of Pillow Plates had been carried out with resistance welding, a technique that requires far more energy and manpower to be operated, traditionally.

4.2.2. Laser Welding Process and Features

Laser welding represents the principal manufacturing method for pillow plates, offering enhanced precision, processing speed, and joint quality compared to conventional joining techniques. The laser welding process for pillow plates incorporates numerous critical features and parameters that directly influence both the geometric characteristics and thermomechanical performance of the resultant product.
The fabrication sequence begins with precise alignment of two metal sheets, followed by implementation of specific welding patterns, as depicted in Figure 4.1. Primary welding features include spot welds, edge seams, serpentines, and specialized joining elements. Spot welds, configured in triangular (staggered) or rectangular (inline) arrays, constitute the fundamental structural elements that define the post-inflation geometry. The triangular pattern, characterized by the ratio of longitudinal to transversal pitch (s_2/s_1), exhibits superior thermohydraulic performance, particularly when this ratio exceeds 1.56, as illustrated by Piper et al. with their consolidated work[4]. These spot welds must maintain structural integrity during subsequent hydroforming while acting as fixed constraints against

the hydroformation pressure, thus creating characteristic flow patterns within the channels that enhance heat transfer through boundary layer disruption and flow mixing mechanisms. Edge welding, executed as continuous seams along the plate perimeter, creates a hermetically sealed envelope with apertures maintained only at designated inlet and outlet locations. This continuous weld requires precise parameter regulation to ensure complete fusion while preserving sufficient material ductility for the subsequent hydroforming operation. In applications where the plate may experience exposure to corrosive media or condensation conditions, lap-joint welding configurations are implemented at these edges to minimize crevice formation, thereby significantly reducing susceptibility to localized corrosion in operational environments.
Serpentine welds represent another critical feature in pillow plate design, facilitating the creation of complex flow paths within a single plate. These continuous weld lines partition the internal channel into multiple passages, effectively increasing flow length while maintaining compact dimensions. The geometric configuration of these serpentines must be designed for flow distribution, pressure drop considerations and is a design parameter during thermal design. For plates with complex geometries or varying thickness combinations, stitch welding may be employed as a preparatory step before the primary welding process. This technique, comprising small, discrete welds at strategic locations, secures the top plate position relative to the bottom plate, minimizing the risk of misalignment or gap formation during the subsequent welding sequence. The laser welding parameters require precise calibration for each specific combination of materials and thicknesses. Power settings typically range from 2kW for standard stainless-steel plates (0.8-1.5mm thickness) to 6kW for specialized applications involving thicker materials. Welding speed, another critical parameter, varies from 4-12 m/min depending on material composition and thickness, with higher velocities generally employed for thinner materials to prevent excessive heat input and potential distortion. Focus height adjustment constitutes a particularly significant parameter in pillow plate manufacturing. The precise positioning of the focal point relative to the material surface directly influences penetration depth and weld profile. For spot welds, the focus is typically positioned slightly below the interface between the two sheets to ensure

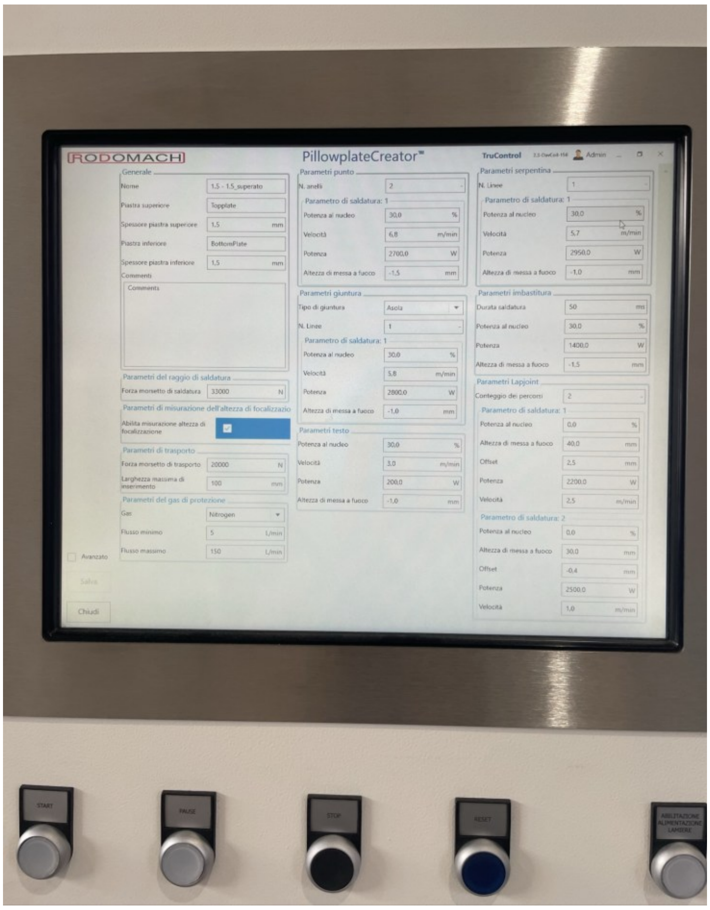


Figure 4.1: Showcase of machine parameters specific to a thickness and material combination

adequate fusion while minimizing the heat-affected zone. For edge welds and serpentines, where complete penetration is essential, the focal position may be adjusted to produce a narrower weld profile with consistent penetration throughout the seam length. More passes can also be performed for special welds that require preheating. As shown in Figure 4.2, all these features allow to produce a custom, highly repeatable base unit (the Pillow Plate) to build a PPHE. Shielding gas composition and flow rate represent additional critical parameters in the laser welding process. Nitrogen or Argon are commonly employed for standard stainless-steel applications, with flow rates calibrated to provide adequate protection of the molten pool without disturbing weld formation. For specialized alloys such as AISI 904L used in highly corrosive environments, particular attention must be paid to shielding gas parameters to ensure adequate fusion and corrosion resistance of the welded joints. This is especially important when dealing with high-alloy materials that can present different laser beam absorption characteristics than standard stainless-steel grades. Quality assurance in pillow plate manufacturing extends beyond parameter control to involve comprehensive inspection protocols. Visual examination, performed during and after welding, can identify surface defects including incomplete fusion, excessive spatter, or burn-through. More rigorous methodologies include pressure testing of the sealed envelope prior to hydroforming, ensuring the integrity of all welded joints before subsequent processing. For critical applications, metallographic examination of sample welds may be conducted to verify proper fusion, penetration depth, and microstructural characteristics that influence both mechanical properties and corrosion resistance. The implementation of process monitoring systems, including power measurement, focus position verification, and shielding gas flow monitoring, provides real-time quality control throughout the manufacturing process. These systems, integrated within modern laser welding equipment, enable automatic parameter adjustment and fault detection, significantly enhancing production consistency and reducing defect rates in industrial-scale pillow plate manufacturing operations. Figure 4.3 shows the level of automation of the equipment, and the controllable environment in which the welding occurs.

a) b)

Figure 4.2: Pillow Plate after welding stage, uninflated (a). Upon close inspection the reader may see the lap-joint welding on the edge (bottom plate is slightly larger and longer), with a closely welded double seam, serpentines and welding spots in a longitudinal triangular pattern. On the right (b), from the left: welding spots, seam weld, lap-joint, slightly burnt due to ongoing welding parameter optimization

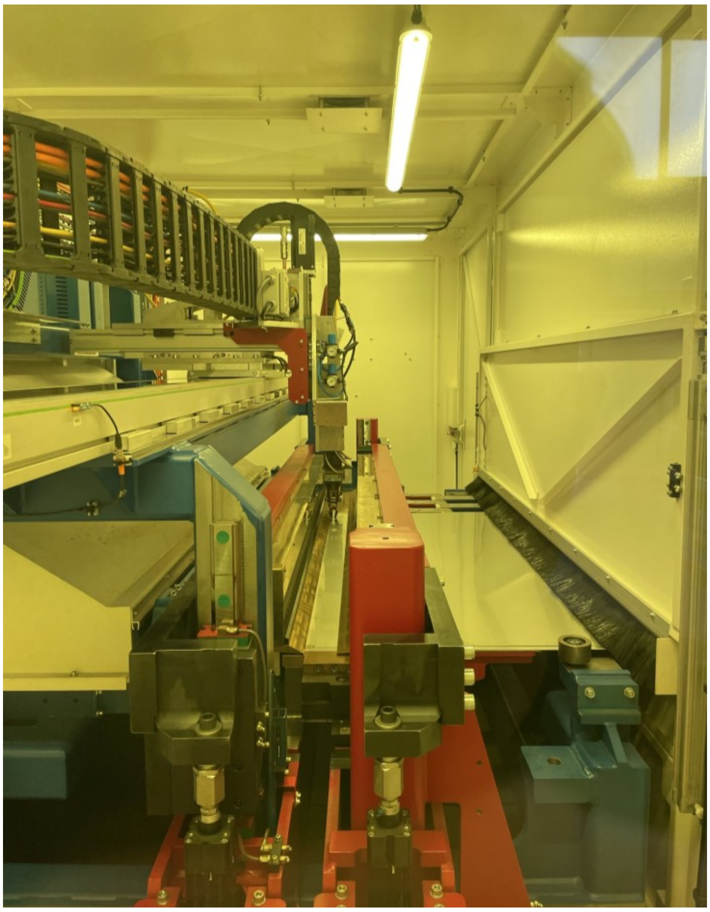


Figure 4.3: Inside view of the Welding Machine (Rodomach), on the left the electrical actuators, in red the clamping beams to avoid space and slippage between the metal sheets, and transport them after the welding area is completed; in far view, there is the welding head, with the coaxial fiber 3kW laser employed for industrial production

Quality control is also paired with protocols derived from the norms regarding PED, which is a fundamental requisite for marketing of PPHEs. The documentation regarding the Welding procedure specification (WPS) for automated processes records all the relevant parameters for the laser welding, like it would do for a TIG welding procedure. This procedure is elaborated internally and derived from the Welding procedure qualification record (WPQR) which is emitted by a certifying body according to UNI EN ISO 15614-11-2003 (specification and qualification of welding procedures for metallic materials), which is a welding procedure test specific to electron and laser beam welding. This document is elaborated from welding tests performed on the actual production equipment with a Notified Body – Certified institution, that analyses the results and certifies the process. This procedure also defines the ranges (material thickness) in which a process (with a set of welding parameters) must be used. Moreover, the different welds that can be performed on a PP are seen differently by the norms. Thus, different procedures must be certified for the spots, the serpentines, and the lap-joints. Finally, the welding operator that has set the parameters and operated the machine, receives a test certificate UNI EN ISO 14732:2013. All this composes a welding book which is specific to the machine, its operator, the tested material and a range of thickness and weld types. This is to ensure that welding, that has a critical impact on the properties of the materials that is joining, is thoroughly verified, from the starting conditions of the materials to the final joined product.

4.3. Connection Installation

The integration of inlet and outlet connections represents a critical interface between the PPHE and the broader system and presents both technical challenges and opportunities for design optimization. The single Pillow Plates are in fact connected to the inlet and outlet headers by means of piping of varying type and construction. Before the final assembly, there is also the need to connect the uninflated internal channel to the pressurising equipment to perform the pressure assisted inflation after the welding of the metal sheets[5]. The joining technique for the connection to the pillow plates is once again welding, specifically TIG welding since it is indicated for small diameters and thicknesses. TIG also allows to control the welding pool with precision to penetrate the base material, with shielding and backing gas to avoid contamination and oxidation, without excessive penetration that would obstruct the carefully inflated welding channels. This is a manual operation which is not easy to automate, even if in the last 5 years robotic arms with several degree of freedom and integrated welding heads have become more common and affordable. Filler material for the TIG welding of the connection to the PPs must be chosen carefully and accordingly to the norm relative to the chosen material. While simple materials such as AISI 304L and 316L require to use the same material, which could be 316L for both, other special materials could require special prescriptions. For example, Inconel (2.8431) could be used to enrich in molybdenum the welded joints in AISI 904L for a better corrosion resistance and resistance to stress and hot cracking. This is a result of direct experimentation with different production techniques and is an interesting topic for further future development.
Theoretically the final connections and headers are rated for the same pressure as the pillow plates, which usually means that they could be used also for the inflation step. However, on a practical note, it is much safer to weld capillary tubes for the inflation step, which easily withstand several hundreds of bars, and then to cut them and proceed with a second welding of the final connections. This also allows to have a simpler inflation station, without the need of different fittings, since every Pillow Plate could potentially have a different connection solution.

4.3.1. Connection Types

Multiple approaches to connection installation have been identified through industrial investigation:

- Welded Nozzles: Direct welding of pipe connections to the PPHE envelope, providing robust, leak-tight interfaces suitable for high-pressure applications
- Threaded Connections: Utilized for smaller-scale applications or where frequent disassembly may be required
- Integrated Headers: Custom-designed manifolds that distribute flow across multiple plates, optimizing flow distribution and minimizing pressure drop
- Combinations of the above: Pillow plates have design flexibility as their strongest point, and this applies also to the rest of the Heat Exchanger that they form.

The selection of connection type must consider not only the operating conditions (pressure, temperature, fluid characteristics) but also installation constraints, maintenance requirements, and thermal expansion effects. Connections might act as the weakest link of the PPHE chain, if not properly designed. They also introduce variability from the ideal geometry of numerical or analytical studies: even if the passage area is equalised, the standard welded connections represent an abrupt change in the aspect ratio of the passage area, from pipe to pillow plate, and a cause for unforeseen recirculation zones with fluid maldistribution at the inlet and outlet of the plate. A properly welded connection, as shown in Figure 4.4, must be thoroughly TIG welded with backing gas, and the welds must be treated after, together with the rest of the plate.

4.3.2. Location Optimization

The positioning of connections significantly influences flow distribution within the PPHE. Through experimental work with the SSPPHE prototype, several considerations for connection placement have been identified:

- Flow Distribution: Strategic placement to minimize maldistribution and ensure uniform utilization of the heat transfer surface
- Thermal Stress Mitigation: Positioning to accommodate differential thermal expansion between the PPHE and connecting pipework. This is especially relevant when there is a high temperature gradient. However, this problem can be moved by uncoupling the headers from the frame and using dilation joints on the connections between the whole PPHE and the process it is connected to.
- Practical Installation: Consideration of space constraints and accessibility for system integration. As specified above, it is almost mandatory to weld the connections to the Pillow Plates. It is also common to weld the connection to the headers. This implies that the spacing between adjacent Pillow Plates will be constrained by the minimum distance required by the manual TIG welding, which can vary due to expertise of the welder and available tools. This limit can be overcome by offsetting the connections in adjacent pillow plates, with a resulting small difference in the fluid flow.
- Drainage Capability: Particularly important for condensation applications, ensuring effective condensate removal. This aspect is also influenced by the orientation of the PPHE, vertical or horizontal.

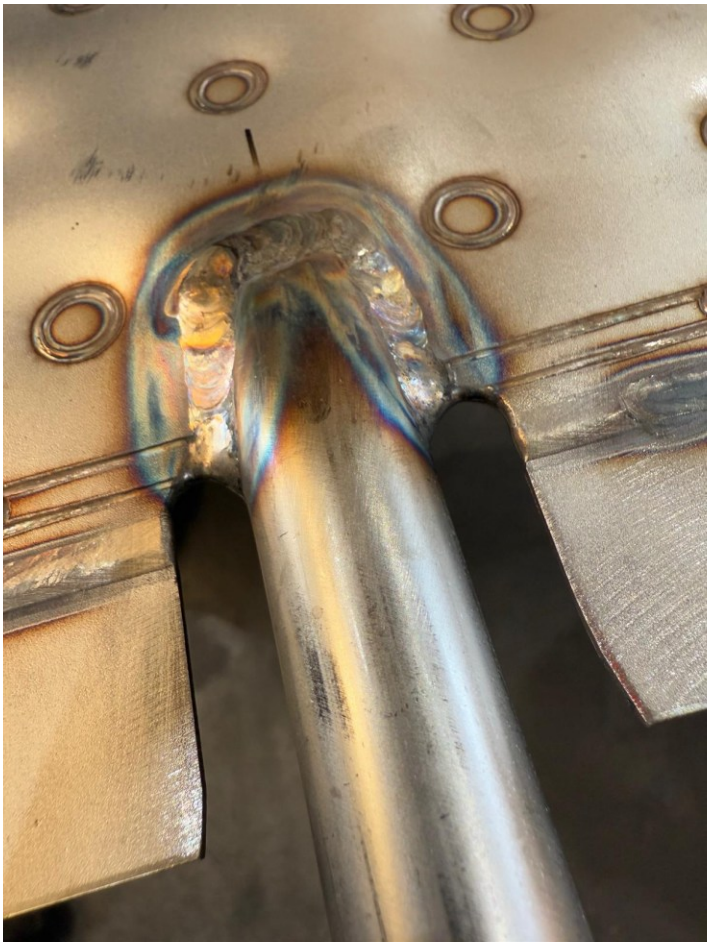


Figure 4.4: Instance of a proprietary connection design owned by Dav Coil S.r.l.

The integration of specialized connections for the condensation heat recovery application presents additional challenges related to simultaneous gas flow and condensate drainage, requiring careful consideration of orientation and internal flow paths.

4.3.3. Manufacturing Challenges

Several technical challenges associated with connection installation have been identified through the manufacturing of various prototypes:

- Material Compatibility: Ensuring metallurgical compatibility between the connection and plate materials. While this aspect seems obvious in theory, it is not in practise, especially when exploring new materials. While PPs are made from sheet metal, which is a format that allows a vast freedom of choice in material, connections are mostly derived from piping, which is economically viable when its laser welded, but then the choice is limited, or very expensive when bought in the seamless format (extruded). This limit can be overcome if connections are custom made from laser cut sheet metal, which however means a more costly production process.
- Heat Input Management: Controlling welding parameters to prevent thermal damage to the PPHE structure or pre-existing welds.
- Sealing Integrity: Achieving and maintaining hermetic seals under varying thermal and mechanical loads
- Quality Assurance: Development of appropriate inspection and testing protocols to verify connection integrity. For example, while it is straightforward to test PPs for leakage after inflation, with the temporary inflation connections still welded and using the inflation pressure to cut time and costs, this could lead to insufficient quality metrics as the welding of the final connection could introduce new unforeseen leaks. It must also be noted that once PPs are welded together into a PPHE, checking and repairing leaks becomes a task that is extremely expensive if not impossible.

The optimization of connection design represents a significant opportunity for enhancing PPHE performance and reliability, particularly for specialized applications such as the condensation heat recovery system under development.

4.4. Hydroforming or Nitrogen Forming

The inflation process represents the defining manufacturing stage that creates the characteristic pillow-like structure essential to PPHE performance.

4.4.1. Hydroforming Process

The conventional hydroforming process involves several key stages:

1. Media Introduction: Injection of an incompressible medium, typically water, between the welded plates through designated inlet points
2. Gradual Pressurization: Controlled increase in pressure to induce plastic deformation of the metal sheets in the unwelded areas
3. Pressure Staging: Implementation of multiple pressure stages to ensure uniform deformation and maintain consistent sheet thickness
4. Pressure Release and Drainage: Controlled depressurization and removal of the forming medium

The hydroforming process typically requires pressures ranging from tens to hundreds of bars for stainless steel plates, with the specific pressure profile dependent on material properties, plate thickness, and desired inflation height. Water is chosen, even if this complicates the choice of the high-pressure pump, since it is simpler to dry than other media such as oils. It is also safer and readily available in many industrial premises. However, some

4.4.2. Nitrogen Forming Alternative

While water remains the predominant forming medium, nitrogen gas presents an alternative approach with distinct advantages:

- Reduced Post-Processing: Elimination of water drainage and drying requirements. This is especially convenient when the PPHE is destined to operate with fluids that can have adverse if not dangerous reactions with water, such as refrigerants (NH3, CO2) or thermal oils.
- Simplified Quality Control: Easier leak detection through pressure monitoring or immersion in water.

Nitrogen represents also an uncomplicated technical choice since it is possible to obtain it in tanks, since it is a common protection gas for welding. It is typically used up to 30-50bars and since it is a compressible medium, special attention must be placed since a failure in the equipment could be much more catastrophic than a failure when operating with pressurised water. Another aspect left to investigate, is that in long pillow plate channels, the compressibility of the gas might lead to a gradient in density and thus to an uneven inflation, which is usually controlled by an external flat die, which has a construction similar to an hydraulic or electric press.

4.4.3. Inflation Characteristics and Challenges

The hydroforming process presents several technical challenges that influence the resultant PPHE geometry:

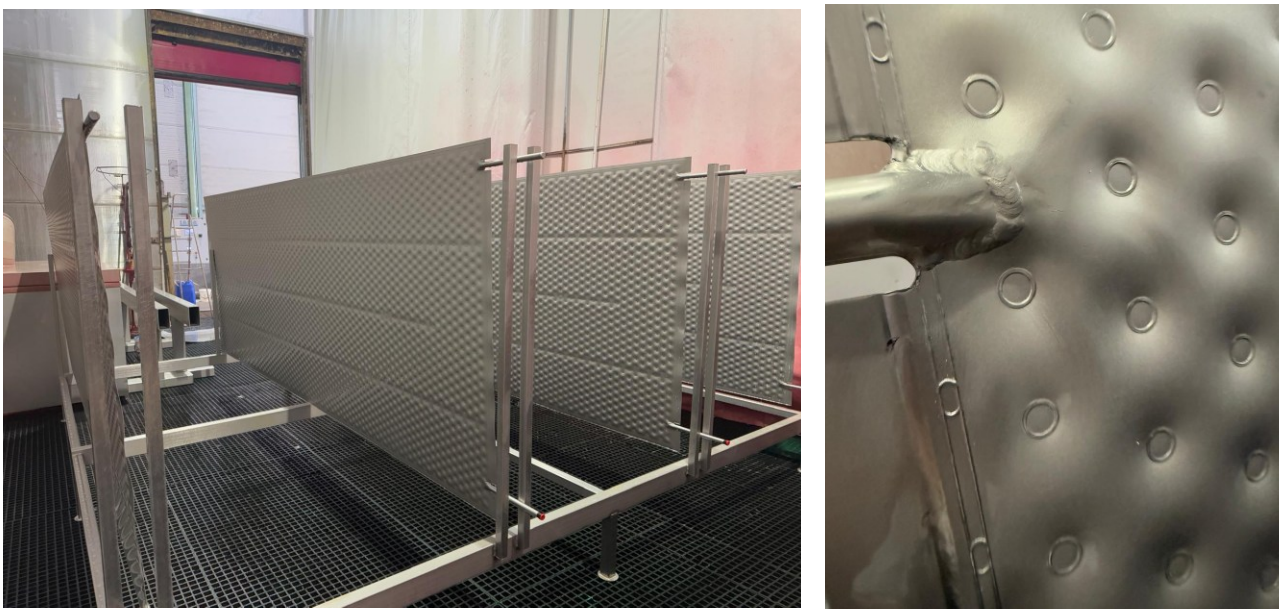
- Border Effects: As identified through tomographic analysis of the SSPPHE prototype, areas near the plate edges exhibit different inflation characteristics compared to central regions, with significant implications for flow distribution and pressure drop. This effect interests also areas around serpentines and other seams.
- Weld Spot Influence: The pattern, spacing, and size of weld spots determine the inflation behaviour, with the experimental work revealing that the central portion of Small-Scale Pillow Plates inflates in a manner consistent with theoretical models, while border areas show a distinct behaviour. Moreover, the SSPPHE shows that when the aspect ratios and scaling parameters are kept equal or similar, the inflation away from the borders is equivalent even at small scale.
- Material Uniformity: Maintaining consistent material thickness throughout the inflation process requires careful control of forming parameters
- Geometry Prediction: The complexity of predicting the exact three-dimensional shape after inflation, particularly for small-scale designs with significant border effects, is still an unsolved challenge.

The experience collected with the construction of the prototypes mentioned in this work and many more showed that Pillow Plates might often vary from the ideal designed shape, but the variations are small and their weight on the performance of normal to large scale PPHEs is marginal. For example, high inflation ratios and residual heat inputs on PP with elongated aspect ratios (base>heigh or vice versa) lead to an extra waviness of the uninflated borders, which can be eliminated with an extra cutting step, or kept in selected applications as it seems beneficial to fluid mixing and turbulence.

4.5. Cleaning, Pickling and Passivation

The post-manufacturing treatment of PP, particularly those constructed from high-performance alloys such as 904L (EN 1.4539, seen in Figure 4.5), Duplex, and Superduplex stainless steels, requires restoring and enhancing corrosion resistance properties. This is critical since welding and thermal processing remove the protective passive film and contaminate surfaces with impurities that inhibit natural repassivation. The treatment consists of three sequential stages. The initial stage involves mechanical and chemical to remove coarse impurities while chemical degreasing eliminates oils, greases, and manufacturing residues. The cleaner is applied via spray pump and allowed to act for 30 minutes at ambient temperature. The component is then thoroughly rinsed with pressurized hot water. Degreasing is essential before subsequent chemical treatments, as contaminants can inhibit pickling effectiveness or create zones with varying degrees of protection. Pickling constitutes the fundamental treatment for removing oxides and discoloration from the metal surface: a pickling agent is applied either by spray pump or brush application of pickling gel, with processing time varying by material type: 1 hour for 904L, minimum 2 hours for Duplex, and minimum 3 hours for Superduplex at ambient temperature. This treatment removes welding oxides, the chromium-depleted layer, and other defects that could generate localized corrosion. Following the specified dwelling time, the component is cleaned with pressurized hot water. Finally, a passivation agent can be used to accelerate the formation of the passive layer, left to dry naturally, while the microscopic passive protective oxide film forms on the finished PP.

The entire process follows strict safety protocols, with operators required to wear impermeable clothing, boots, gloves, goggles, and respirators. The work area must be segregated with forced ventilation activated before operations begin, and only qualified personnel with appropriate training may perform or access the treatment area. Documentation and quality control measures include following a treatment checklist and, when required by clients, issuing official pickling and passivation certificates validating the process. This multi-stage treatment enhances the corrosion resistance and service life of Pillow Plate Heat Exchangers in demanding industrial applications by restoring the protective layer compromised during manufacturing.



a) b)

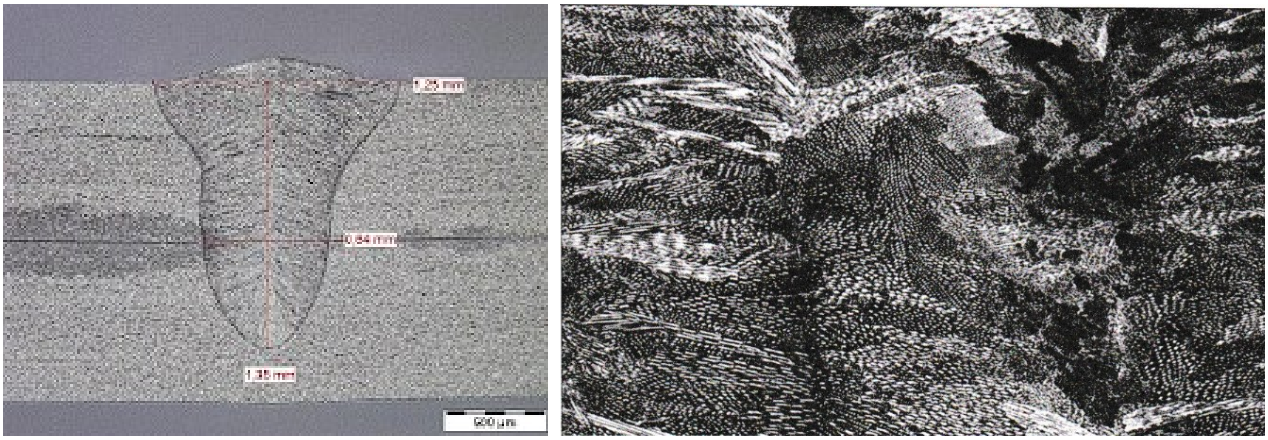
Figure 4.5: a) Plates in the cleaning area, after passivation and b) the connection area depicted in Figure 4.4 after cleaning and passivation, material AISI 904L

4.6. Quality Assurance and Testing

The reliable implementation of PPHEs in industrial applications necessitates comprehensive quality assurance protocols throughout the manufacturing process and rigorous performance testing of the completed units.

4.6.1. In-Process Quality Control

Several critical quality control measures have been implemented during the manufacturing process. Welding quality inspection is performed to ensure proper fusion and absence of defects, with PED as guide for quality standard creation and improvement, as seen in Figure 4.6. This endeavour is also fundamental for laser parameters settings. Measurement of critical geometrical parameters including plate dimensions, weld spot patterns, and edge configurations and the traceability and the verification of material composition and properties through standardized testing and documentation complete the set. Continuous monitoring and recording of key process parameters including welding power, speed, focus ensures a complete control of the process and trust in the results, for highly complex and specialised applications and advanced prototyping of new solutions.



a) b)

Figure 4.6: a) Micrographic cut and analysys of weld width and penetration and b) microscopic examination after attack with Adler's etchant UNI EN ISO 17639:2022 of the fused bath.

4.6.2. Structural Integrity Testing

Before thermal performance evaluation, completed PPHEs undergo structural testing to verify their mechanical integrity:

- Pressure Testing: Hydrostatic or pneumatic testing at pressures exceeding design requirements to verify structural integrity and identify potential leakage points
- Leak Detection: Implementation of specialized techniques including leak detection under water (Figure 4.7).
- Non-destructive testing: visual testing and penetrating liquid testing
- Dimensional Verification: Confirmation of final dimensions, including inflation height and overall geometry

4.6.3. Performance Validation

The final evaluation stage could involve a thermal performance testing to verify that manufactured units meet design specifications:

- Heat Transfer Rating: Measurement of thermal power under specified operating conditions on a reduced scale.

- Pressure Drop Characteristics: Quantification of hydraulic resistance in both inner and outer channels for new welding patterns. Samples of one plate (internal channel) or scaled PPHEs (external channel working with air) are commonly used.
- Temperature Distribution: In specialized applications, verification of temperature uniformity across the heat transfer surface.

The comprehensive experimental methodology developed for the SSPPHE validation, as described in Chapter 3, provides a framework for standardized thermal performance testing applicable to industrial production, and wants to be an useful advice for building a comprehensive PPHE units able to produce and market while innovating itself.

4.6.4. Specialized Testing for Applications

Depending on the intended application, additional specialized testing may be required:

- Cyclic Testing: Evaluation of thermal fatigue resistance for applications involving frequent temperature fluctuations
- Corrosion Testing: Verification of material compatibility with specific process fluids
- Vibration Testing: Assessment of structural integrity under vibration conditions relevant to the installation environment

The integration of these quality assurance and testing protocols throughout the manufacturing process is essential for establishing the reliability and performance consistency necessary for industrial acceptance of PPHE technology.

4.7. Conclusive remarks on PPHE production and research synergy

The implementation of a complete PPHE production capability within the industrial partner's facilities has yielded substantial benefits for both research advancement and manufacturing innovation, creating beneficial feedback and mutual problem-solving. The laser welding facility established in May 2023 marked a significant upgrade from conventional resistance welding, providing the precision necessary for experimental validation while reducing energy consumption and labour requirements. This technological advancement enabled the systematic investigation of welding parameters—spot patterns, edge seams, serpentines—and their direct influence on thermal performance. The documentation requirements for PED certification further structured our understanding of critical process variables and their acceptable ranges. Material selection emerged as a fundamental consideration throughout the research, with experimental work confirming the practical viability of

Figure 4.7: Pillow Plate after inflation and prior to cleaning undergo a first leak test

austenitic stainless-steel grades while identifying specialized alloys for corrosive environments. The hydroforming process, including the alternative nitrogen forming approach, revealed critical insights into the relationship between inflation parameters and resultant geometry. Tomographic analysis of prototypes identified significant border effects in small-scale designs, informing both theoretical models and manufacturing techniques. This interplay between detailed characterization and production optimization exemplifies the research-manufacturing synergy. Connection installation, often overlooked in theoretical models, proved crucial for system integration and performance and will require further investigation and development. Practical manufacturing experience with TIG welding techniques are required; they are documented and described, together with post-manufacturing treatments—cleaning, pickling, and passivation— as the practical requirements for transitioning from theoretical performance to industrial reliability. The developed quality assurance methodology integrated research insights with industrial requirements, creating systematic approaches applicable beyond the specific prototypes.

Through producing multiple prototypes for diverse applications (natural convection, sand cooling, exhaust gas recovery, condensation), we gained practical understanding of how theoretical models translate to manufactured products. Discrepancies between ideal models and actual performance led to refinements in both design approaches and manufacturing techniques: this relationship between research and production accelerated the implementation timeline while enhancing innovation potential. The research team's scientific insights informed manufacturing decisions, while production experience provided critical feedback for theoretical refinements.

As PPHE technology continues to develop, this integrated approach to research, and manufacturing provides a foundation for further efficiency improvements and application expansions. The systematic knowledge generated through this process enhances current capabilities while informing future design innovations for advanced heat transfer solutions.

4.8. Chapter References

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5. Industrial Case Studies

This foundational chapter begins illustrating key aspects of the author's personal experience in working daily within a Small Medium Enterprise (SME), with the intent to formalise and set up R&D processes that line up industrial development and innovation with the state of the art of literature and create a positive interchange relationship. These pages then present a comprehensive examination of Pillow Plate Heat Exchanger (PPHE) industrial applications through multiple case studies solved during this research. The integration of theoretical research with practical implementation represents a critical aspect of advancing PPHE technology beyond laboratory settings. Names and economic data are redacted as for privacy law compliance and to maintain research independence. All case studies shown were preliminary analysed with the models developed with this research, overdesign and caution were merged with a 50-year expertise in manufacturing prototypes that eventually became marketed products. This qualitative feedback confirms the potentiality for the Pillow Plate wavy surfaces, with a reliable yet simple construction logic, to in the heat recovery and management. Appendix 5.6 can be used with Appendix 2.10 to see both sides of thermal design and performance prediction of the PPHE developed in this work. The former, is a datasheet that provides easy information between departments and with customers.

Chapter Index

5.1. Internship and Industry-Academic Integration

5.1.1. Role and Responsibilities

The research project was predominantly conducted at Dav Coil Srl, establishing a framework for direct knowledge transfer between academic research and industrial application. This integration within an industrial environment created unique opportunities for interaction across engineering, production, and sales departments, fostering a multidimensional understanding of PPHE implementation challenges. The responsibilities encompassed a spectrum of activities ranging from technical customer engagement to prototype development and production facility implementation. Technical interviews with potential customers provided valuable insights into specific thermal management challenges across diverse industrial sectors, enabling the identification of applications where PPHE technology could offer significant advantages over conventional heat transfer solutions. These interactions informed subsequent analysis of industrial processes, where potential PPHE integration points were evaluated based on technical requirements, spatial constraints, and economic considerations. One significant aspect of the research involved translating theoretical PPHE models into practical design specifications, requiring careful consideration of manufacturing capabilities, material availability, and quality assurance requirements. This translation process necessitated continual refinement of design methodologies to accommodate real-world constraints while preserving the fundamental thermal and hydraulic advantages of PPHE technology.

The development of multiple prototypes, supported by the production and design teams, provided critical validation of theoretical models while generating practical insights into manufacturing considerations not apparent from purely academic analysis. Each prototype iteration incorporated lessons from previous implementations, establishing an evolutionary approach to PPHE development that balanced innovation with practicality.

Perhaps most significantly, the research involved managing the implementation of a dedicated PPHE production facility, including the selection, procurement, and commissioning of a 3kW laser welding system. This facility, operational since May 2023, not only facilitated prototype development but also demonstrated the commercial viability of PPHE technology through industrial-scale manufacturing capability.

This multifaceted role enabled direct addressing of industry-specific challenges while maintaining scientific rigor, creating a bidirectional knowledge flow that enriched both academic understanding and industrial implementation of PPHE technology.

5.1.2. Academic Research in an SME Environment

A significant challenge emerges from the divergent detail requirements between industrial applications and scientific research. The level of detail required to implement a Pillow Plate Heat Exchanger (PPHE) for industrial applications is often less extensive than that demanded by scientific research, creating potential conflicts between budgetary constraints and research necessities. Within the characteristically dynamic or volatile SME environment, maintaining optimal equilibrium becomes particularly challenging; excessive depth in research studies leads to extended time-to-market, potentially causing project failure, while insufficient investigative depth fails to generate knowledge that effectively advances the discovery activities driving the projects [1].

The allocation of human resources presents additional complexity within SMEs. Unlike larger enterprises where individual roles often become the responsibility of specialized teams, SMEs that design, produce, and commercialize their own products must manage inward and outward flows of raw materials, transformed materials, data, information, and stakeholder interactions with significantly fewer personnel [2]. Consequently, individuals assume multiple roles or responsibilities. When this operational paradigm extends to research teams, research efficiency may be diminished. The transformation of raw data and theoretical concepts into applicable information and usable knowledge demands cognitive processes fundamentally different from other responsibilities assigned to R&D teams and other business units. The former requires sustained concentration and analytical focus, whereas conventional operational work typically exhibits lower predictability and frequently originates from external inputs [3]. Scientific and critical thinking processes interrupted by routine organizational communications and operations—such as customer emails, quality issues, or procurement activities—result in diminished research output both qualitatively and quantitatively [4].

The resolution of this apparent stalemate between business imperatives and research requirements may be addressed through implementation of a dynamic three-level pyramidal project portfolio. This approach necessitates advance project selection with allocated budgets, categorized according to three risk-reward tiers. The foundational level comprises low-investment, high-return research initiatives, typically encompassing industrial and enterprise optimization tasks. These often involve components, machinery, procedures, or optimization problems requiring quantifiable investment while generating consistent returns over extended periods. For instance, a specific investigation of welding parameters resulting in a 5% reduction in production time generates cost reduction or productivity enhancement persisting throughout the process lifecycle. Such projects provide budgetary justification for maintaining dedicated research teams within SMEs. This foundational research may be facilitated through public funding, though potential conflicts with confidentiality requirements and market competitive advantage must be carefully managed.

The intermediate tier of the R&D pyramid accommodates moderate-risk projects: initiatives transitioning from open innovation to implementation phases, solutions to complex optimization problems with uncertain returns, and similar endeavours requiring substantial but measured investment. The apex of the pyramid is reserved for high-risk projects characterized by substantial investment and uncertain returns, including open innovation initiatives without immediate market applications. These projects represent the cornerstone of SME research and development, leveraging the inherent flexibility and dynamism of smaller organizations capable of rapidly modifying procedures or processes without the complex bureaucratic structures typical of larger corporations. Without radical innovation, growth-oriented companies become constrained to market bidding wars and internal cost reduction measures. Through engagement with cutting-edge research and technology, SMEs create opportunities for serendipitous discovery, introducing non-zero probability that investigated innovations may be integrated into company operations, developed into viable products, or potentially revolutionize the market.

This strategic approach has demonstrated efficacy in practice. Prior to the initiation of the joint research collaboration between industry and university, PPHEs were understood by the company and its customers only to a limited degree. Initial investigation of "the PPHE problem" would have been conceptualized in this framework, as a moderate to high-risk project, and that turned into a success while new productions and concurrent process improvements were supporting the initial investment. Following this investment period, while numerous open innovation projects yielded minimal results, several studied PPHE applications were successfully implemented, generating revenue sufficient for laboratory development and production unit establishment. Production challenges are now optimized with minimal research team intervention, enabling the R&D team to concentrate on moderate to high-risk projects while maintaining efficient resource utilization, a finding consistent with effectiveness of strategic task management documented by Franssila et al. [2].

5.1.3. Project Management of PPHE Production Line

The implementation of a dedicated Pillow Plate Heat Exchanger production facility constituted a significant strategic initiative, born from a case study prepared for Project Management course, to assisting and practising in such real-world scenario. A project charter, of which a draft is shown in the appendix 5.5, established the foundational framework for this initiative, defining critical parameters including strategic justification based on quantified market demand, comprehensive scope encompassing complete production capabilities, financial parameters with an initial investment and five-year return expectations, with a fixed annual production capacity target, and compliance with PED requirements and ISO 9001 standards. The implementation timeline established procurement (March 2022), commissioning (November 2022), and operational capability (December 2022) as critical milestones against which progress was measured. The resource acquisition phase involved systematic assessment of laser welding technologies through comparative analysis of multiple suppliers and site visits to manufacturers in Poland, Germany and the Netherlands, culminating in the selection of a 3kW laser welding system with advanced control capabilities. Concurrent facility preparation addressed technical requirements including structural modifications, utility installations for power and compressed air, environmental controls for welding operations, and establishment of dedicated quality control infrastructure. The project incorporated informal risk management addressing technical challenges regarding software functionality and manufacturing capability, supply dependencies for specialized materials, market uncertainties in securing orders prior to production capability, and operational concerns regarding knowledge transfer and equipment maintenance. Figure 5.1 illustrates the projected financial model for the production facility, demonstrating the relationship between annual expenditures, revenue generation, and cumulative cash flow across the five-year investment horizon. The model projected initial negative cash flow during the investment phase (year 0), transitioning to positive annual contribution in year 1, with complete investment recovery projected by year 3. A fundamental aspect of the implementation strategy involved systematic knowledge integration between academic research and practical manufacturing, with research findings regarding geometrical characterization informing manufacturing parameter selection, experimental correlation data enhancing production quality standards, and production experience refining theoretical models. This bidirectional approach accelerated both the implementation timeline and theoretical understanding, creating a cooperative relationship between research and production capabilities. Due to unforeseen supply chain delays for critical machine parts, the machine was finally accepted at its destination by May 2023, with a record startup of production (by the company's standards) by July 2023, a 4 month operation that started with an acceptance test on April 2023 at the supplier's premises involving a multifaceted team composed by the author as R&D and project manager, production, quality and direction members.

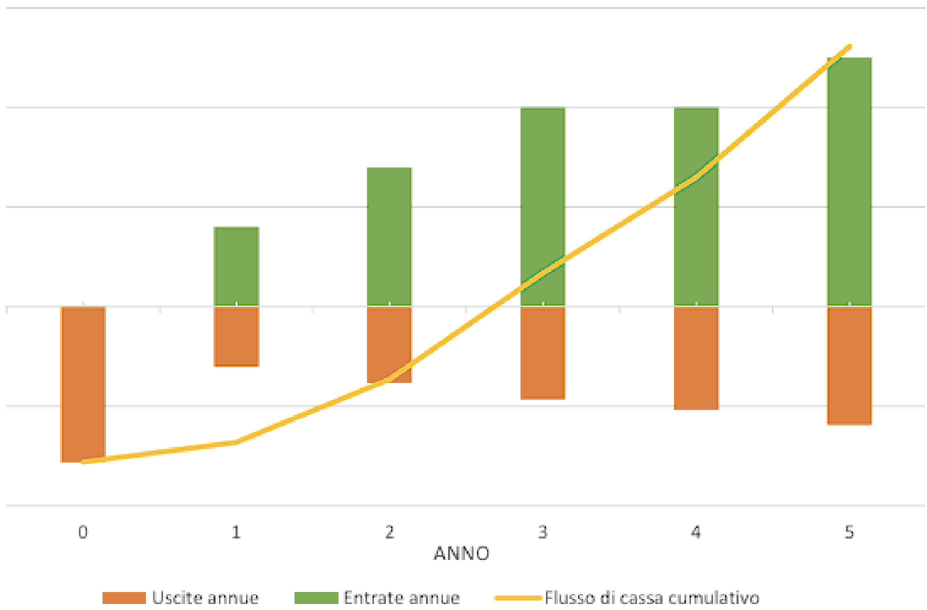

Figure 5.1: a partially redacted reproduction of the cashflow (yellow segmented trendline) for the PPHE Business Unit

In Figure 5.2, the first picture of the installed machine after factory commissioning. The successful establishment of this production capability not only facilitated prototype development but also demonstrated the commercial viability of PPHE technology, creating a foundation for future industrial adoption.

5.1.4. Scientific Relevance of Industrial Integration

The systematic integration of academic research within a Small and Medium Enterprise (SME) environment represents a critical methodology for advancing novel thermal technology development, exemplified through the comprehensive investigation of Pillow Plate Heat Exchangers (PPHEs). This research demonstrates how targeted industrial innovation can accelerate technological readiness through a structured approach of facility implementation and prototype production.
The establishment of a dedicated 3kW laser welding facility in May 2023 marked a pivotal technological transition, enabling precise manufacturing capabilities and experimental validation. By developing

Figure 5.2: Laser Welding Machine, seen from the outlet

multiple prototypes across diverse thermal management applications—including natural convection, sand cooling, and exhaust gas recovery—the research systematically explored the practical constraints and performance characteristics of PPHEs. Meanwhile, the implementation process gave the chance of recording insights into manufacturing complexities, including material selection, welding parameter optimization, and quality assurance protocols. The bidirectional knowledge transfer between academic research and industrial production facilitated rapid technological advancement, addressing fundamental limitations in existing heat exchanger design methodologies.

This approach not only validated theoretical models but also provided a robust framework for translating innovative heat transfer concepts into industrially viable technologies, demonstrating the significant potential of integrated research-industrial collaboration in technological innovation.

5.2. Design Methodology Implementation into the Industrial Case Studies

The industrial case studies presented in this chapter were developed following a systematic design methodology illustrated in Figure 5.3. This approach integrates multiple knowledge domains while ensuring technical feasibility and market validation. In the building and operating of such workflow, the author was able to research and study the production aspects illustrated in the previous chapter, and to experience the entire process of solving a heat transfer problem with a PPHE solution. This approach is at least peculiar to be seen in a scientific manuscript, however it has hidden advantages and potential to finally break the adoption barriers once and for all allowing market needs to suggest significant applications. Attending and eventually managing customer interviews and relationships while searching the scientific literature allows to clearly see the application potential and then quickly prepare a design for prototypes ready for industrial implementation, made possible by reliable industrial processes; the same processes can be easily adapted thanks to the knowledge exchange between research and industry. The creation of a prototype allows to further shape the design model and methodology conceptualisation, since the researcher is forced to meet reality and constraints given by real joining techniques, limits on machine parameters or material properties. The involvement within the buying, quality and administrative processes allows to better understand the pros and cons of different solutions for materials and accessories due to their availability, import fees, export laws, etc., which ultimately helps creating a solid understanding of the Pillow Plate Heat Exchanger.

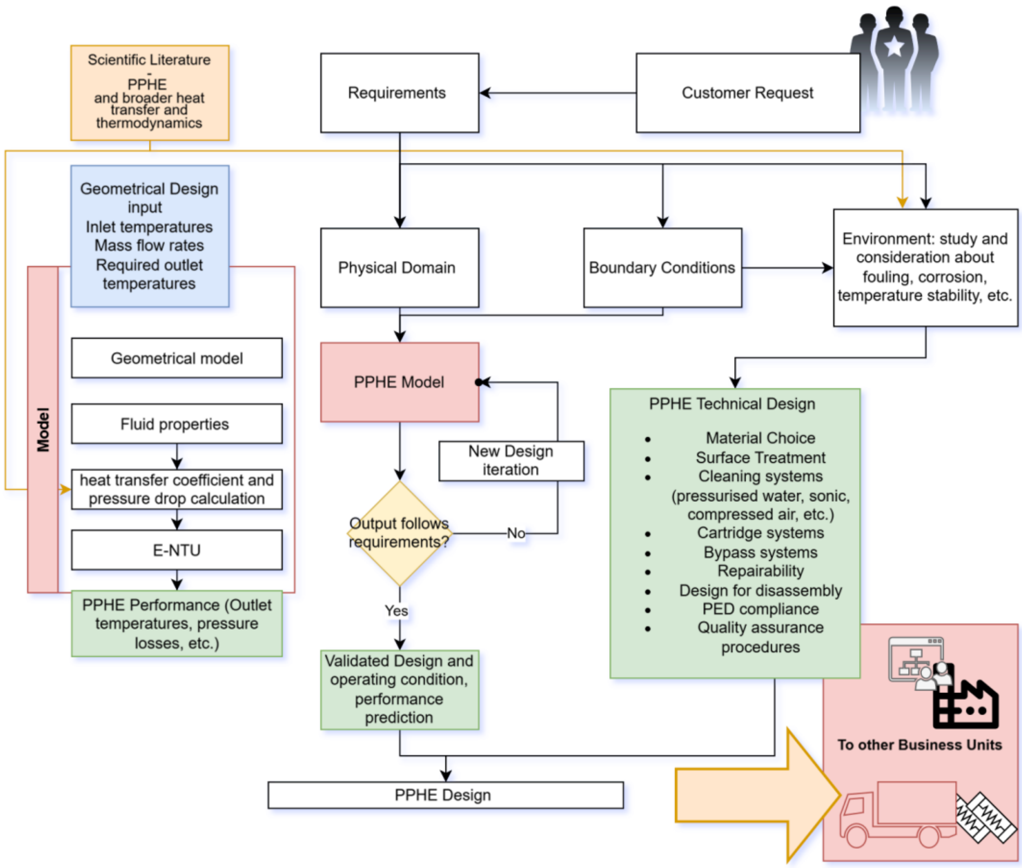

Figure 5.3: Visual representation of the integrated research and development methodology: Demonstrating how scientific literature, empirical research, and industrial engineering knowledge converge to transform complex thermal management challenges into optimized Pillow Plate Heat Exchanger (PPHE) solutions through a systematic, iterative process of requirement analysis, theoretical modeling, environmental characterization, and performance validation

The methodology begins with two primary input sources: customer requirements and scientific literature on heat transfer phenomena and PPHE technology. Customer problems were studied looking for answers into the scientific literature domain as first endeavour. These information sources inform the analysis of physical domain constraints and boundary conditions, while environmental considerations (fouling potential, corrosion resistance, temperature stability) are systematically evaluated. The “simple” E-NTU core is now incorporated into a complex yet efficient company mechanism; the problem becomes a physical model with assumptions to verify and requirements that must be translated into technical constraints and solved with a PPHE solution that works with a series of accessories that ensure its correct operation -bypass mechanism and ducting, cartridge modular construction, cleaning systems, anti-freezing electrical heaters-. The central PPHE model incorporates geometric characterization, fluid property analysis, heat transfer coefficient calculation, and ε-NTU method implementation to predict thermal performance. Design iterations continue until performance requirements are satisfied, at which point the validated design parameters are integrated with technical considerations including material selection, surface treatments, cleaning systems, and regulatory compliance. This methodical approach ensures that each case study benefited from comprehensive thermal analysis while addressing practical implementation challenges.

During the consultation of the following sections, the reader might find beneficial to return to this diagram as it illustrates how the context systematically translates into practical requirements across the diverse applications presented in this chapter. The reader will also understand how the corresponding methodology from Chapter 2 is derived into the PPHE model for each application. For instance, in the natural convection application

5.2.1 Natural Convection in Immersed Pillow Plates

5.2.1.1. Context & Motivation

Natural convection heat transfer represents a critical thermal management challenge in storage and process applications, particularly in scenarios requiring gentle, uniform heating of temperature-sensitive materials. Traditional heating approaches, such as internal coil systems, often demonstrate limitations in heat distribution, space utilization, and thermal efficiency.
Pillow Plate Heat Exchangers (PPHEs) offer a novel approach to addressing these constraints, leveraging their unique geometric characteristics to enhance natural convection heat transfer performance. The research explored multiple prototype configurations to investigate the potential of immersed pillow plates in thermal management applications.

5.2.1.2. Technical and Design Choices

The developed prototypes encompassed diverse design strategies:

1. Double-Embossed Vertical Immersion Configuration:
    - Pillow plates arranged vertically within storage tanks (Figure 5.4).
    - Steam, refrigerant or water circulation through internal channels
    - External surface facilitating natural convection heat transfer
    - Constructed from stainless steel to ensure compatibility with various stored products
2. Single-Embossed Surface Configurations:
    - Plates integrated directly onto tank external surfaces (Figure 5.5)
    - Mounted using thermal interface materials
    - Designed to enhance heat transfer from existing thermal infrastructure

This apparently simple application was the first case study developed and helped test and incrementally develop the design model that was used in all other projects.

5.2.1.3. Key Observations and Findings

The implementation revealed several important findings. The only objective information here is that the designed PPHEs were installed tested and then accepted and ordered in series by the customer(s).

Figure 5.4: A steam powered PPHE for natural convection heating of a tank. Modular prototype which originated two recorded productions.

Nonetheless, with consideration to the context explained and boundary conditions that were presented, it is useful to enhance potential areas of research for product optimization:

1. Enhanced natural convection: The wavy external surface of pillow plates seems to promote boundary layer disruption, enhancing natural convection compared to smooth surfaces or older thermoplates which were stamped and formed by a continuous serpentine.
2. Compact design advantage: The PPHE is often chosen due to easiness of cleaning, high resistance, manufacturability and high performance to cost ratio.
3. Temperature uniformity: The distributed heat transfer surface with customisable IC patterns solves more easily temperature distribution problems within tanks The relatively flat plate surface is also able to create a chimney effect for the vertical length of the plate.

Figure 5.5: Stack of single embossed pillow plates before shipment. The designed application is for heating preexisting tanks, through application on lateral surfaces with heat transfer mastic.

4. The compact design and the almost absolute design freedom given by the PPHE geometry facilitated retrofit installation in existing tanks with minimal modifications.

5.2.1.4. Feedback and Industrial Validation

As stated before, the prototype underwent testing in an industrial setting, with feedback focusing on the thermal performance compared to existing heating systems. Customer feedback confirmed the theoretical advantages of the PPHE design while highlighting practical considerations for industrial implementation.

5.2.1.5. Lessons Learned

This case study provided valuable insights for both PPHE design and application:

1. Natural convection modelling: The need for refined correlations specific to wavy pillow plate external surfaces for natural convection applications to reduce safety margin. The effect of varying the pitch between adjacent PPs on the chimney effect should be studied to maximise performance.
2. Connection design: Critical importance of connection design and placement for proper steam distribution and condensate removal.
3. Installation considerations: Practical constraints related to tank access and internal structures must be incorporated early in the design process. It should be noted that in almost all the projects described, the spatial constraints were often the most important and the most rigid.
4. Performance validation methods: Challenges in accurately measuring heat transfer performance in industrial installations necessitate robust indirect validation methods.
5. Study on pressure drop optimisation here lies the most room of improvement, since advancements in this fields result in lowered operating cost for the owner and higher process efficiency.

This application demonstrated the viability of PPHEs for natural convection applications, expanding their potential application range beyond forced convection scenarios that dominate existing literature.

5.2.2. Sand Cooling System

5.2.2.1. Context & Motivation

In foundry applications, sand is used together with binder to build dies. Once a die is used, it must be restored with heat treatment, to burn the spent components. A great amount of energy is used, and then retained by the sand, which needs to be cooled. A specific heat exchanger is thus required to speed up the process and to eventually recover the wasted heat.

Foundry sand cooling represents a challenging thermal management problem characterized by:

1. High-temperature particulate material requiring rapid cooling
2. Abrasive conditions leading to accelerated wear of heat exchange surfaces
3. Continuous operation requirements with minimal maintenance
4. Space constraints in foundry environments
5. Energy recovery potential from high-temperature waste heat

Conventional cooling approaches typically employ water spraying or ambient air cooling, both of which present limitations in terms of energy efficiency, cooling rate control, and water consumption. This case study explored the application of PPHEs as an innovative solution for foundry sand cooling.

5.2.2.2. Technical and Design Choices

The sand cooling heat exchanger prototype represents a novel thermal management solution for foundry processes, addressing the critical challenge of efficiently cooling sand after die-making operations. As illustrated in Figure 5.6, the system employs a modular configuration comprising three identical heat exchanger modules, with an additional redundant module designed to ensure operational continuity and enhanced thermal performance. The prototype's design leverages the unique geometric characteristics of pillow plate heat exchangers to optimize heat transfer between the hot foundry sand (750°C) and an high water flowrate at 30-4+50°C. Constructed from high-grade stainless steel, the heat exchanger features double-embossed pillow plate cartridges arranged in a vertical stack configuration. This arrangement capitalizes on the pillow plates' enhanced heat transfer capabilities, particularly their ability to create complex flow patterns that maximize thermal exchange efficiency. The modular design strategy is implementable thanks to the simple Pillow Plate geometry. The implementation of three redundant modules, supplemented by a heavy-duty unit, provides a robust thermal management solution that ensures continuous operation even during maintenance or potential component failure. Economically, the prototype demonstrates exceptional performance, with the thermal energy recovery generating sufficient cost savings to justify the addition of supplementary modules. This approach exemplifies a strategic design philosophy that balances operational reliability with economic optimization.

Testing by the customer validated the design's efficacy, confirming the heat transfer principles underlying the pillow plate geometry.

Figure 5.6: First iteration of the packed bed sand cooling PPHE, made of three identical and redundant cartridges, plus a double cartridge for heavy duty operation in the back.

5.2.2.3. Key Observations and Findings

While the energy recovery potential was validated, long stress testing showed unexpected wear on the plate edges, which are not cooled down by water and thus undergo thermal stress and high temperature oxidation.

5.2.2.4. Feedback and Industrial Validation

The 400kW prototype underwent extensive testing in an industrial foundry environment, with feedback focusing on:

1. Cooling performance compared to specifications, which was deemed more than satisfying.
2. Operational reliability: which was not met due to unforeseen high temperature wear in the non-cooled edges.

Customer feedback validated the theoretical advantages while providing critical insights into practical implementation challenges.

5.2.2.5. Lessons Learned and Second Iteration

Based on the initial prototype performance and feedback, a second-generation design, displayed in Figure 5.7, was developed with several refinements:

- Laser welded construction, expected to reduce edges footprint thanks to more precision, and better-quality welds,
- Improved the construction material from AISI 304 to AISI316L, better suited for high temperatures
- Improved plate spacing and reduced overdesign.

However, even after this redesign aimed at increased wear resistance, thermal cracking is still a problem which will require the use of materials that are more heat resistant, or the reduction of the uninflated area with special technical solutions.

Figure 5.7: Second iteration San Cooling prototypes, 4 identical modules

5.2.3. Diesel Smoke Heat Recovery with AISI 904L

5.2.3.1. Context & Motivation

Heat recovery from diesel engine exhaust represents a critical intervention point for efficiency improvement in remote power generation facilities. The prototype described in this section was implemented on a hot water generating plant in a geographically isolated location where diesel generators remain the primary power source. In such contexts, maximizing fuel efficiency through effective heat recovery is fundamental to reducing operational costs and environmental impact. This application domain holds particular significance as diesel generators continue to be widely utilized in developing regions due to their reliability and independence from centralized infrastructure. While the ultimate objective remains transitioning to cleaner energy sources, intermediate technological solutions that improve efficiency can deliver immediate environmental benefits while infrastructure development progresses; However, knowledge gained from this diesel exhaust application provides valuable transferable insights applicable to biomass combustion systems, as will be demonstrated in the subsequent case study. Heat recovery from diesel engine exhaust in these contexts presents unique challenges:

- Corrosive exhaust gases containing sulphur compounds and particulates
- High-temperature operation with thermal cycling
- Remote installation with minimal maintenance requirements
- Compact design requirements for integration with existing equipment
- Need for high efficiency to maximize energy recovery

Traditional heat recovery systems often employ shell-and-tube designs, which present limitations in terms of compactness, thermal efficiency, and fouling resistance. This case study explored the application of PPHEs manufactured from high-alloy stainless steel (AISI 904L) to address these challenges.

5.2.3.2. Technical and Design Choices

The 500kW prototype developed for this application featured:

- Double-embossed pillow plates manufactured from AISI 904L for corrosion resistance
- Diesel exhaust flow through the outer channel between plates
- Water circulation within the pillow plate internal channels
- Specialized connection design to maximise PPHE compactness and fit into the existing equipment, as seen in Figure 5.8 and Figure 5.9.
- Removable baffles to increase permanence of Diesel smoke and thus heat recovery
- External production while building the laser welding production facility.

a) b)

Figure 5.8: AISI 904L PPHE prototype, a) front view in operating conditions, b) PPHE on the side, with removable baffles mounted.

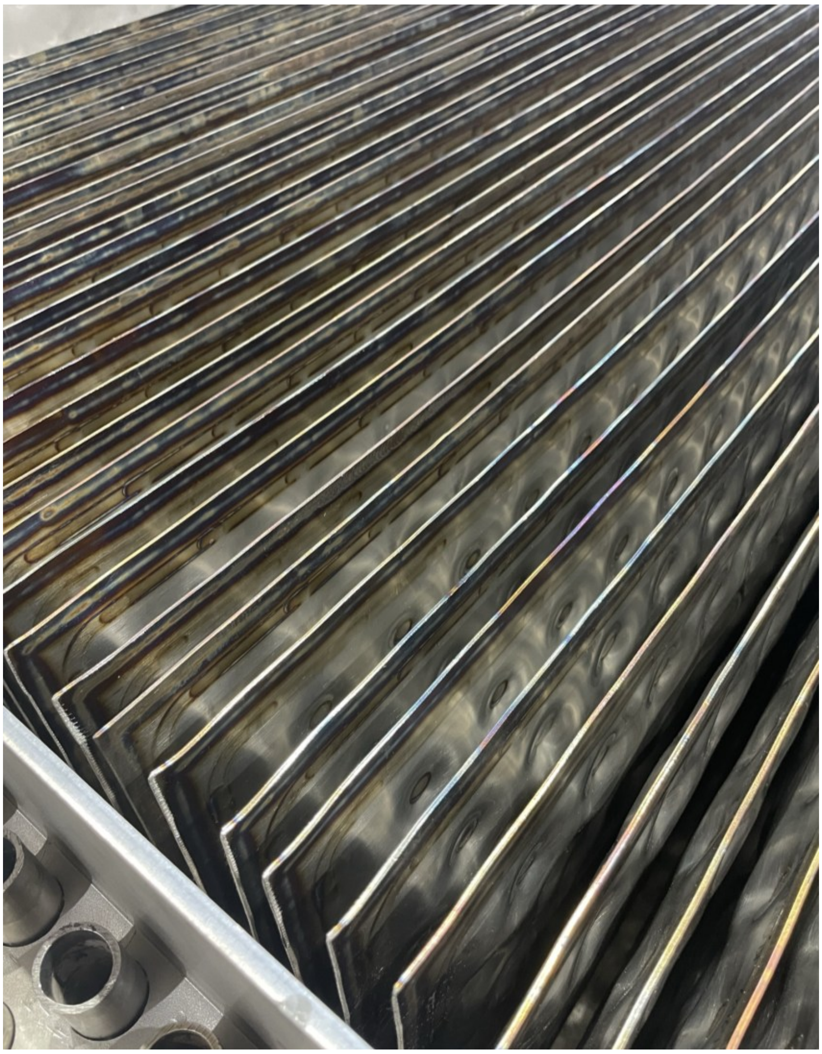

Figure 5.9: A close up to the densely stacked 904L plates, before cleaning and passivation.

Key design parameters included:

- Material selection (AISI 904L) for resistance to sulphur-containing compounds
- Weld spot pattern optimized for high-temperature structural integrity
- Flow path configuration designed to minimize recirculation zones in the internal channel
- Connection design for reliable sealing under thermal cycling

The design process used existing heat transfer correlations to account for the unique characteristics of diesel exhaust and the wavy channel geometry of PPHEs.

5.2.3.3. Key Observations and Findings

The prototype's development process integrated advanced manufacturing techniques, including precision laser welding and hydroforming processes, to achieve the required geometric and thermal performance characteristics. Preliminary implementation revealed the potential for significant energy recovery while demonstrating the validity of the design model developed for this application. However, the initial deployment encountered challenges with the integrity of the connection piping, specifically leakages in weld zones resulting from errors made by an external supplier: a fault in the quality control system allowed the use of the wrong filler material for the manual TIG welding. These technical complications underscore the critical importance of comprehensive quality control protocols in advanced heat exchanger manufacturing, and after analysis were one of the drivers for the verticalization of the PPHE production process.

Such findings contribute to a broader understanding of specialized heat exchanger design methodologies, particularly for applications requiring extreme compactness and resistance to corrosive operational conditions.

5.2.3.4. Feedback and Industrial Validation

The prototype underwent field testing in a remote power generation facility, with feedback focusing on:

1. Corrosion resistance
2. Required thermal rating

While initially the customer feedback confirmed the theoretical advantages, leakages were discovered in the zones around the welds for the connections between the PPs and the headers of the PPHE.

5.2.3.5. Lessons Learned

This case study provided valuable insights for both PPHE design and application:

This application was a complex project with demonstrated the viability of PPHEs for high-temperature, corrosive environments, expanding their potential application range to challenging heat recovery scenarios. The failure of the prototype, where other types of HEs already failed, brought a series of invaluable lessons on quality control and the employment of nonstandard materials, firstly the clear advantage of having an internal production. Moreover, it is advised that leak detection must be done at every productive step (visual after weld, for leaks after inflation, for leaks after connection installation and one with parameters fixed by Pressure Equipment Directive (PED) after PPHE production. Pressure should be held for long times, especially in the late testing stages, to see if there are microleaks: compact designs translate unfeasible repairing if leaks are found after PPHE welding-

These lessons were implemented in future prototypes, and the creation of dedicated documentation and procedures for AISI 904L Pillow Plate production.

5.2.4. Heat Recovery from Biomass Combustion

5.2.4.1. Context & Motivation

Heat recovery from biomass combustion systems presents distinct challenges that come with handling particulate-laden exhaust gases requiring reliable filtration systems and cleanable heat exchanger solutions. Moreover, these systems often work with variable flow rates, while monitoring the condensation potential of acidic components in the design phase. The equipment must have cleaning access and maintenance, with a requirement for compact design for integration with existing systems.

Conventional heat recovery systems often struggle with fouling and corrosion issues in biomass applications, while flat tube bundles have high hindrance and weight: this case study explored the application of PPHEs with integrated bypass and cleaning features to address these challenges.

5.2.4.2. Technical and Design Choices

The prototype developed for this application is shown in Figure 5.10, and was parent to a series of PPHEs dedicated to biomass smoke:

- 120-180°C smoke temperature, 80-120g/kg of moisture

- 100-150kW heat recovery

- Double-embossed pillow plates cartridge extractable from the frame, which has integrated bypass channels and optional cleaning systems (sonic horn, spraying nozzles, etc.)

- Flow inversion after the PPHE cartridge to collect soot.

- Access ports for mechanical cleaning and optional sonic horn for cleaning

- Biomass combustion products flowing through the outer channel

- Water circulation within the pillow plate internal channels

- Corrosion-resistant construction with attention to avoid acid dew point (given by gas composition and empirical correlations).

- Access port configuration for effective mechanical cleaning

The design process required integrating practical maintenance considerations with heat transfer optimization, representing a balance between theoretical performance and operational practicality, which was a necessary condition for the customer and a decision point in favour of the PPHE geometry.

5.2.4.3. Key Observations and Findings

The implementation revealed several important findings:

Figure 5.10: PPHE for heat recovery from biomass smoke, featuring an extractable PPHE cartridge, motorized bypass, soot collection at the bottom and bolt on frame for easy transport and final positioning

1. Cleaning access importance: The integrated access ports demonstrated superior cleaning capability compared to conventional designs, while Pillow plates, due to their flat aspect, are cleanable while staggered smooth tubes bundles are not. Same goes for finned packs or finned tubes, which would have higher or comparable performance, but would irremediably foul and break due to thermal stress.

2. Bypass functionality: The bypass system allows for continuous operation during maintenance, and variable load operation, enhancing system availability. The parallelepipedal geometry of PPHE cartridges allows for an easy design integration of the PPHE and the bypass within the same frame.

3. Particulate deposition: The wavy channel geometry demonstrated a good cleanability and less fouling than conventional geometries. deposition patterns requiring targeted cleaning approaches.

4. Heat transfer performance: Despite the provision for cleaning access, the system maintained higher heat transfer coefficients than conventional designs at low design Re numbers in the internal channel, guaranteeing low pressure drop in both channels, favouring an economical operation of the PPHE.

5.2.4.4. Feedback and Industrial Validation

The prototype underwent field testing at the service of a series of biomass boilers, with feedback focusing on:

- Heat recovery efficiency under varying conditions
- Cleaning effectiveness and maintenance interval requirements
- Bypass system performance
- Integration with existing biomass combustion systems

Customer feedback validated the practical advantages of the design while providing insights into operational considerations.

5.2.4.5. Lessons Learned and work in progress

This case study provided valuable insights for both PPHE design and application: the validated prototype was then turned into a modular design for different sizes of boilers, with bigger examples as shown by Figures 5.11 and 5.12.

a) b)

Figure 5.11: Large scale PPHE for heat recovery from dirty combustion media, a) after inspection, b) after painting with corrosion protective coating.

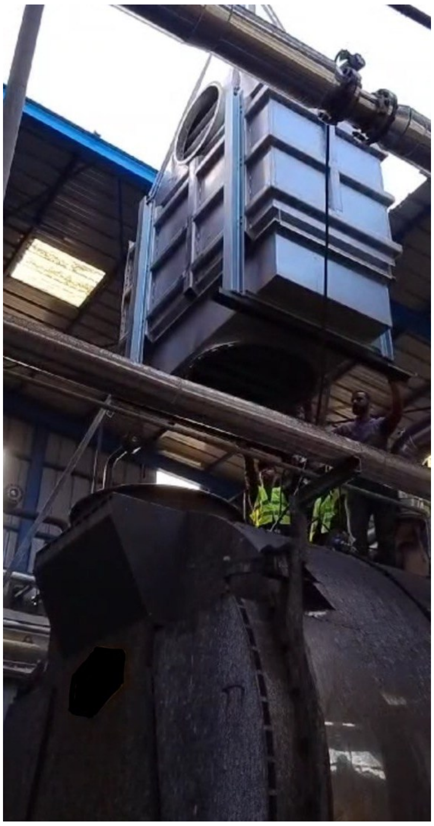

Figure 5.12: The PPHE shown in Figure 5.9, inside its frame, during mounting on 20.000t/h steam boiler.

This application demonstrated the adaptability of PPHE technology from challenging biomass combustion environments to any dirty waste gaseous flow. By stacking these findings with knowledge from diesel smoke heat recovery and corrosion resistant painting, the PPHE solution for dirty media shows a great potential for future studies and developments, as for cement production plants, paper plantes, glass production plants, etc.; some of which, have been or are being produced right now.

5.2.5. Condensation Heat Recovery

5.2.5.1. Context & Motivation

Recovery of latent heat from humid air streams represents a significant energy conservation opportunity across various industries. The energy consumption associated with phase change processes is substantial, particularly in:

- Drying processes in the food, paper, and textile industries, where considerable energy is expended to evaporate water, resulting in high-moisture-content exhaust streams
- Combustion processes generating water vapor, with typical moisture content ranging from 8-15% by volume in natural gas combustion to over 20% in biomass combustion
- Food processing operations with significant steam releases from cooking, sterilization, and blanching processes

According to Vasilyev et al. [5], moisture condensation from humid air flows can recover substantial thermal energy that would otherwise be wasted, with potential recovery rates of 2.5-3.5 kW per kg/h of condensate in typical industrial applications. However, conventional condensing heat exchangers face several technical challenges in these environments:

- Condensate management: Difficulty in effectively draining condensate without impeding gas flow
- Fouling propensity: Accelerated deposit formation at the gas-liquid interface
- Efficiency limitations: Poor thermal performance due to condensate film thermal resistance
- Corrosion susceptibility: Formation of acidic compounds when cooling below acid dew points in combustion applications

This case study explores the application of Pillow Plate Heat Exchangers (PPHEs) for condensation heat recovery, capitalizing on their unique geometric characteristics to address these limitations. The work represents a novel application with significant energy efficiency implications, with a high-performance primary surface that works where other geometries fail, like the finned tubes in Figure 5.13. Going back at Figure 5.3, it is possible to understand the meaning of integrated design approach and notice that thermal design had to go along a study of moisture condensation, corrosion protection and the correct material selection according to the expected lifespan of the PPHE prototype.

Figure 5.13: Condensation damage after months of operation on a finned tube heat exchanger that worked in unintended condensing operation.

5.2.5.2. Technical and Design Choices

The prototype development for this condensation heat recovery application incorporated several critical design considerations, better explained in Chapter 3, but most importantly was carried out along the construction of a dedicated experimental setup for a prompt characterisation of an unknown phenomenon. The experimental apparatus, described in detail in Chapter 3, was configured to simulate industrial conditions with controlled temperature, humidity, and flow rates. Along the process, literature was fundamental to make a first design iteration and individuating the driving forces for the process, like cooling flowrate and temperature. [6]

5.2.5.3. Work in Progress

The condensation heat recovery application represents an ongoing research focus with significant potential for expanding PPHE utilization. A first thorough characterisation of the phenomenon, with a specified PPHE geometry is being performed, which will be the basis for analytical and numerical modelling. The objective of present and future work is to integrate the design methodology with an approach to determine latent heat transfer once conditions for condensation are met.
This ongoing work addresses a significant gap in the current PPHE research literature and expands the potential application range of these heat exchangers: this addresses a significant market need, particularly in energy-intensive industries with high moisture content exhaust streams, or, daringly, any boiler room that uses combustion to generate heat. Preliminary market validation has identified food drying processes as a particularly promising application domain, where:

- Current heat recovery technologies achieve limited efficiency, typically recovering only sensible heat
- The compact nature and cleanability of PPHEs align with food industry requirements, with possibility of advanced materials and surface treatment
- Process integration challenges favour the adaptable geometry of PPHE solutions

The current prototype, scaled to match a specific industrial application, demonstrates the feasibility of integrating PPHE technology into existing drying processes while validating the technical performance necessary for energy recovery. While commercial implementation requires further development, particularly regarding long-term performance and maintenance requirements, the initial results confirm the potential for significant energy efficiency improvements in these applications.

5.3. Summary and Cross-Case Analysis

The diverse industrial implementations detailed throughout this chapter demonstrate the adaptability and performance potential of Pillow Plate Heat Exchanger. The systematic integration of theoretical research illustrated in Chapter 2, with the showcased practical implementations, has yielded significant insights into both technical capabilities and implementation constraints. While the fundamental PPHE design principles have proven transferable across applications ranging from passive natural convection to high-temperature industrial waste heat recovery, the above-mentioned adaptability manifests through configuration flexibility, material compatibility, and process integration capabilities. The observed performance characteristics demonstrated advantages compared to conventional technologies, particularly regarding heat transfer efficiency, surface to volume ratio, fouling resistance, and operational flexibility. Each implementation revealed application-specific constraints that influenced design decisions. Material selection emerged as critical in high-temperature applications, with the sand cooling highlighting thermal stress limitations at plate edges. Connection design and manufacturing precision demonstrated particular significance in corrosive environments, as evidenced by the diesel exhaust implementation. The biomass recovery prototype validated the importance of integrating maintenance considerations into initial design parameters to encourage market adoption. On the other hand, PPHEs have proven easily integrable with added value solutions like bypasses, frame and cartridge systems, cleaning systems etc. The progressive technological advancement pathway—from natural convection validation through solid-fluid interfaces to high-temperature corrosive environments and finally two-phase applications—provides a structured development framework with each implementation built upon previous lessons while addressing increasing complexity.

Although this bidirectional knowledge transfer between theoretical research and practical implementation has accelerated both scientific understanding and industrial adoption, it is also leaving many questions unanswered, with the hope that this qualitative feedback would direct and incite future research efforts.

5.4. Chapter References

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5.5. Chapter Appendix: Project Charter

In this Appendix, a draft of the Project Charter underlying the implementation work of PPHE production that shows a simplified version of the reasoning behind this choice and the involvement of the author to create a synergic action between R&D and other departments.

Creating a Pillow Plate Heat Exchanger Business Unit

Background

Dav Coil Srl is a Small Medium Enterprise specialized in providing engineered and configured to order, innovative solutions to heat exchange industrial problems. Pillow Plate Heat Exchanger (PPHEX) geometries have emerged in the market as a conceptually simple and performing alternative to more classic geometries. PPHEX show great mechanical resistance, easy maintenance and cleaning, reliability in harsh environment, with improved performance. Their wavy shape grants an enhanced three-dimensional heat exchange which is also complex to model and design. During the years it has become for Dav Coil more and more interesting to study this heat exchanger geometry, with efforts in Research and Development that grew into financing a Doctorate scholarship in Industrial Innovation, with a research project on innovative heat exchange modelling and design, to deeply comprehend PPHEX. Meanwhile the PPHEX market quote has grown, as their application is showing advantages in a growing number of areas, in particular heat recovery. This is a paramount application due to the great impact of the investment, given that the heat exchangers work recovering waste heat, making processes more ecological, reducing their environmental cost, saving fossil fuel and thus CO2, which results in a great return on investment. PPHEX can be used to recover sensible or latent heat efficiently, from aggressive and dirty smoke, thanks to their fluid passage channels that are easily cleaned, and the fact that they are made from sheet metal: countless corrosion resistant materials are available in this format, and they are cheaper with respect to other semifinished products such as pipes. Dav Coil has been offering PPHEX solutions for 15 years, with outsourced production, but recently the need of developing the process internally has become unavoidable and advantageous due to several factors: an increase of PPHEX demand on quantity, but most importantly for high quality and added value PPHEX solutions. Moreover, designated suppliers are struggling to meet the demand in quality and quantity requested by the Company. It is thus interesting to proceed and have a dedicated business unit that can design and produce in house this flourishing Heat Exchanger category.

Goals

1. Profit generation within the first year of production, with a five-year investment payback.
2. Totally internal process, from customer acquisition to shipment of the product, with elective use of already existing company resources.
3. Target production on a single eight-hour shift, five workday weeks of Xm^2 of heat exchange area, with typical sheet metal dimensions of 1250x1250mm, 1mm thickness.
4. Capability of producing special formats and shapes (i.e., arc of a circular crown), and special alloys such as titanium or duplex stainless steel.
5. Products must follow constructive and design standards already followed by Dav Coil (i.e., PED, UNI EN ISO 9001, UNI EN 3834).
6. Capability of solving heat recovery problems with possible condensation phenomena.

Scope

The new Business Unit (BU) will belong to Dav Coil and receive from it logistic, technical, and economical support, but will be able to act and work separately from it to facilitate the management of a process and a product particularly different from Dav Coil usual production. Dav Coil resources from other divisions are used every time it is beneficial for both the parties and the cashflow is managed by Dav Coil itself. The chosen location is in the former Dav Coil buildings, now used as storage, and former offices, still functional and suited to host a design department.

A PPHEX is made of a structural frame, fittings, and other accessories, and by a repeating fundamental unit: the Pillow Plate. Pillow plates are built from the welding of two sheets of metal, in a diamond-like pattern of circular welds and perimetral sealing welds. They are then hydroformed into their final pillow-like shape. The external channel is made by two adjacent plates. Sometimes minor finishing operations are needed, such as TIG welds during the assembly of the heat exchanger. Therefore, the process must start from the customer's needs, from which the thermal and mechanical design is developed. In the design phase, recently developed correlations from scientific literature are used, together with the results from Dav Coil R&D efforts. Drawings are developed with CAD software and then CAM software develops the control code for an automatic laser welding machine. A sales engineer is needed to work with a mechanical designer, plus a welder and a workman to use the machine and for the assembly, other than rupture and watertightness tests. It must be provided an area for assembly, and another for pickling or painting and other finishing operations, plus a load and unload space. The described process has the capability of producing Xm^2 of heat exchange surface, according to cautious estimates. Customers will be acquired before the start of the actual production, with an edge against the risk of delays will be given by the present pillow plates suppliers.

Stakeholders

Role	Name and details	Authority and/or position
Customer	Dav Coil S.R.L. ownership	Board of Directors
Sponsor	redacted	Redacted
Project Manager	Ing. Alessandro Dai Pré	Engineer, University of Trento PhD student, R&D Dav Coil
Project Management Team	Not Defined	Economics and Management figure

Milestones

- Start of the marketing campaign for customer acquisition: January 2022.
- Choice and procurement of Pillow Plate laser welding machine: February 2022.
- Production line inauguration: October 2022.
- Closing of the building phase and full capacity operation of the plant: December 2022.

Project Budget

An investment of Y€ must be destined to the welding machine procurement. The Project Management team will be composed by the sponsor and CEO of Dav Coil, the Project Manager already involved in R&D activities and an elective technical-economic supporting figure to solve specific problems. It is expected to work on demand with commercial partners, suppliers of the welding machines, other suppliers, building contractors and consultants for financial management, or access to tax allowances for 4.0 industry projects. Resources to produce up to Xm^2 of heat exchange surface are allocated, according to simulations from the welding machine producers and prices from material suppliers. A budget must be assigned to have liquidity to pay the salaries for 4 workers with an annual cost ranging from Z,000€ to 2Z,000€, while X,000€ are needed for the materials and W,000€ is the cost of energy. Given that salaries and materials will be sustained by the production, only a fraction of the expected costs for the yearly operation is to be kept in liquidity. This budget is estimated to be R,000€ which could ensure three months of autonomous functioning without cashflow. Again, it is important to note that this budget is an edge against unforeseen risk, but the Business Unit can produce turnover since the start of production. While the Project lasts until the completion of all the objectives in the second year, it will start to yield results starting from its first year.

Project control parameters

Constraints	☐ Commercial agreements of Dav Coil. ☐ Welding machine delivery in 8 months. ☐ The designated construction building is at work and must be cleared
Assumptions	• Automatic laser welding is the best production technology for Pillow Plate. • redacted software by redacted GmbH is chosen as best thermal design alternative, as it is developed by the most expert team in the field, according to scientific literature evaluation.
Risks and dependencies	• As redacted does not guarantee its results in the license agreement, overdesign must be used in the first phases of start-up. • Orders will be taken before the start of production, with a risk of having to use outsourcing again, on process start-up. • Process malfunctioning risk.
Success criteria	Goal number 1,3,5,6 must be met in the designated time, goals 2 and 4 can be met outside the scope of the project, even if they are to be pursued from the start.
Authority in determining success and project exit	Client and sponsor, unanimity.
Exit criteria	• Success • Goal 1 cannot be met

Signatures

redacted (Sponsor) Ing. Alessandro Dai Pré (Project Manager)

5.6. Chapter Appendix: Datasheet from model

In this Appendix, a technical datasheet implemented exporting relevant data from Maple to an Excel file with a mask; a fundamental deliverable to communicate effectively research results with the drawing, engineering, sales department or even the final customer. The same result could be achieved with many other options within the software cited in appendix 2.10, regardless it is important to use reports like these to illustrate clearly and quicky key information about a design configuration.

DAVCOIL SCAMBIATORI DI CALORE

Dav Pillow Heat Recoverer - Thermal Design

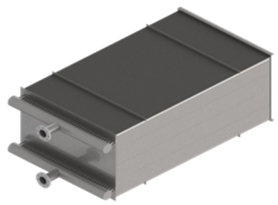
R&D Dav Coil - University of Trento Via dell'Artigianato 11, 37029 San Pietro in Cariano (VR), Italia	*Dav EcoPillow - Economizzatore per recupero di calore da fumi di biomasse.*	19/04/2025

Geometry

Plates (np)	30	-	pillowlenght (L)	1.5	m
Number of passes (water)	8	-	pillow width (W)	0.75	m
inflation (hi)	5	mm	depth (np*hp)	0.69	m
Material	Inox				

Thermal data

Recovered Heat	217.00	kW
Required Capacity	200.00	kW
Heat Exchange surface	64.19	m^2
Global Heat Transfer Coefficient	80	W/m2K
NTU	1.20	
Epsilon	0.65	
LMDT	45.1	°C



Flue gas side (2)

Cross sectional area	0.3826	m^2			
Mass flow	3.797	kg/s			
Inlet density (rho2i)	0.81	kg/m^3			
Outlet density (tho2o)	0.93	kg/m^3			
pressure loss (DeltaP)/error	178.74	Pa	10%		
partial heat transfer coefficient	98.44	W/(m^2 K)			
fluid velocity	11.41	m/s			
Inlet Temperature	160.0	°C	Reynolds (2)	15961	
Outlet temperature	107.8	°C	Prandtl (2)	0.73	

Water Side (1)

Cross sectional area	0.017998	m^2			
Mass flow	4.440	kg/s			
pressure loss (DeltaP)/error	0.19	bar	10%		
partial heat transfer coefficient	5359	W/(m^2 K)			
fluid velocity	0.25	m/s			
Inlet Temperature	80	°C	Reynolds (1)	5039.7	*1000÷8000*
Outlet temperature	91.6	°C	Prandtl (1)	2.09	*1÷150*

Details

$2S_L$	72	mm
S_T	s	mm
pillow plate pitch (hp)	21.00	mm
welding diameter	10.00	mm
plate thickness	1	mm
volume	0.10367	m^3
hydraulic diameter (1)	6.8	mm
hydraulic diameter (2)	35.0	mm

6. Results and Discussion

This chapter presents a systematic experimental investigation of Small-Scale Pillow Plate Heat Exchanger (SSPPHE) performance, validating the effectiveness-NTU design methodology across varied operational conditions. The experimental campaign employed custom-designed apparatus to characterize both sensible heat transfer and condensation heat recovery processes, complemented by advanced geometric analysis techniques including destructive testing and tomographic examination. Thermal performance measurements demonstrated acceptable agreement between model predictions and experimental data, with thermal power deviations typically within ±15%. Hydraulic characterization revealed systematic underestimation (15-30%) of pressure drop by current correlations, attributable to border effects not adequately captured in existing geometric models. Sequential testing confirmed the applicability of heat transfer correlations beyond their established literature ranges, particularly extending outer channel correlation validity to Reynolds numbers as low as 1000. Condensation experiments demonstrated substantial thermal intensification potential, with latent heat recovery increasing total thermal power by up to 567% compared to sensible-only conditions. Comparative analysis across experimental configurations identified critical limitations in current measurement techniques and geometric modelling approaches while establishing a validated foundation for PPHE design methodology. These findings provide essential insights for both future research directions and practical design considerations for industrial implementation.

Chapter Index

6.1. Laboratory Experimental Results

This chapter presents the experimental findings from laboratory investigations, providing quantitative validation to complement the qualitative insights gained through industrial case studies. While the industrial implementations demonstrated practical application versatility, laboratory experiments are indispensable for performance characterization and theoretical model validation. These controlled investigations specifically address fundamental thermal and hydraulic behaviors of Small-Scale Pillow Plate Heat Exchangers (SSPPHE) and Condensation Heat Recovery (CHR) systems through physical testing, without numerical simulations. The experimental results presented are useful benchmarks for design methodology validation, offering measurable data on heat transfer effectiveness, pressure drop characteristics, and geometric influences that cannot be reliably obtained from field implementations. By isolating specific parameters and maintaining controlled conditions, these experiments enable empirical correlation validation and extension, while highlighting performance-limiting factors. This quantitative approach not only validates existing design models but also identifies promising directions for future technological development, creating a foundation for subsequent research initiatives and more refined industrial applications.

6.1.1. Small-Scale Pillow Plate Heat Exchanger (SSPPHE) Validation

The experimental validation of the effectiveness-NTU (ε-NTU) design methodology for Small-Scale Pillow Plate Heat Exchangers (SSPPHEs), exchanging heat between two water flows, revealed insights into both the thermal performance and hydraulic characteristics of these compact heat transfer devices. Through systematic experimental campaigns conducted at the University of Trento, comprehensive data was collected to validate the theoretical models and assess their predictive accuracy.

6.1.1.1. Geometric Characterization Findings and Pressure drop characterisation

Accurate geometrical characterization emerged as a critical factor for reliable performance prediction of Pillow Plate Heat Exchangers (PPHEs). The SSPPHE prototype featured dimensions of 450 mm length

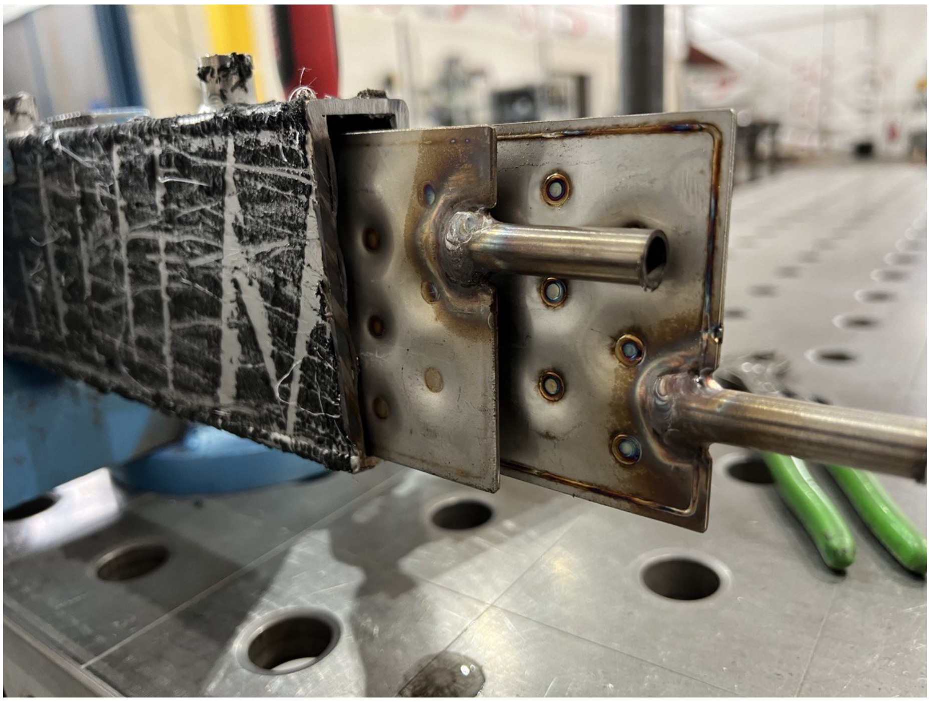


Figure 6.1: Detail of the prototype subjected to destructive testing. It is possible to see the compact construction and the particularity of the shell with Pillow Plates (not working with the fluid) embedded on the internal walls.

and 80 mm width with plate thickness of 1 mm. To determine precise geometric parameters, multiple characterization techniques were employed including destructive testing, optical microscopy, and tomographic analysis. The first step, shown in Figure 6.1, was to perform clean cuts on the prototype to extract plates and cut samples from them. Cross-sectional cuts of the SSPPHE provided direct measurements of internal geometry and the variation in channel geometry along the width, as shown in Figure 6.2.

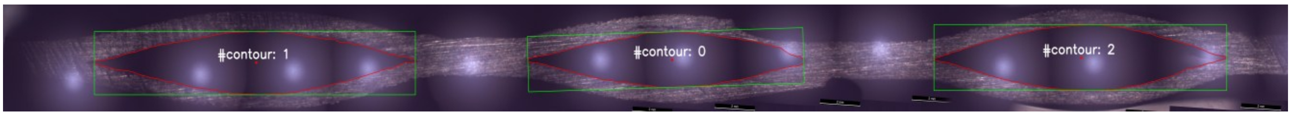
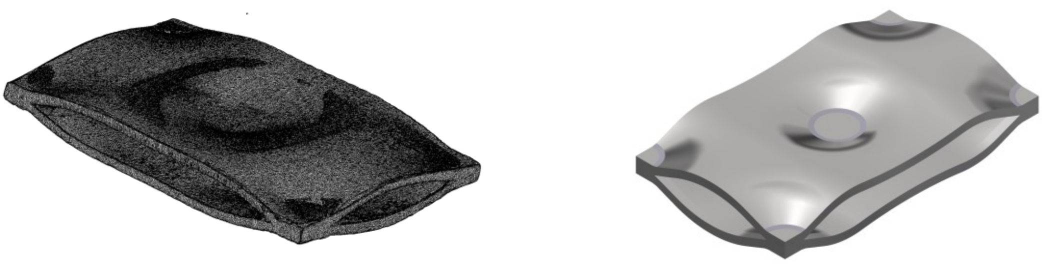


Figure 6.2: Optical microscope images of cut sections, with slight light aberration due to a damaged optical element.

The measurements revealed local variations in inflation height, with values ranging between 2.52 mm and 2.99 mm. While these measurements generally aligned with the nominal design value of 3 mm, the local variations were thought to significantly affect flow behaviour and hydraulic performance and required further investigation. The cross-sectional area measurements through destructive testing yielded a mean value of 118.36 mm^2, with minimum and maximum values of 77.60 mm^2 and 148.60 mm^2 respectively, demonstrating significant variation across the geometry. Tomographic analysis provided three-dimensional visualization of the internal structure, confirming these findings while revealing additional insights. Figure 6.3 illustrates a comparison between the actual tomographic reconstruction of a periodic element and the simulated element based on theoretical models. The tomography confirmed that the hydraulic diameter calculated using the approach by Piper et al. [1] (4.07 mm) aligned with theoretical prediction.

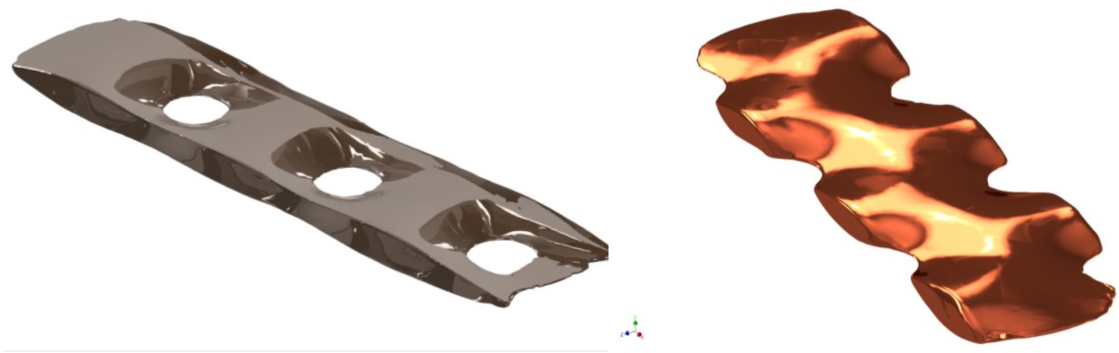


a) b)

Figure 6.3: Comparison of a) tomography and b) hydroforming simulation

However, the same analysis identified pronounced border effects and non-uniform inflation patterns not accounted for in current geometrical models: the transversal slice tomography, shown in Figure 6.4, revealed a critical feature: alternating recirculation zones along the transverse direction. These zones generate parasitic pressure losses not accounted for in current models and explain the significant deviation between theoretical predictions and experimental measurements of pressure drop. Pressure drops measurements focused primarily on the inner channel due to unexpectedly low pressure drops in the outer channel (below the sensor's 5 mbar accuracy threshold). The analysis of pressure drop data, revealed significant discrepancies between theoretical predictions and experimental measurements, with the experimental Darcy factor values showing deviations of up to 30% from theoretical predictions. Three different approaches were employed to calculate the hydraulic diameter and cross-sectional area:

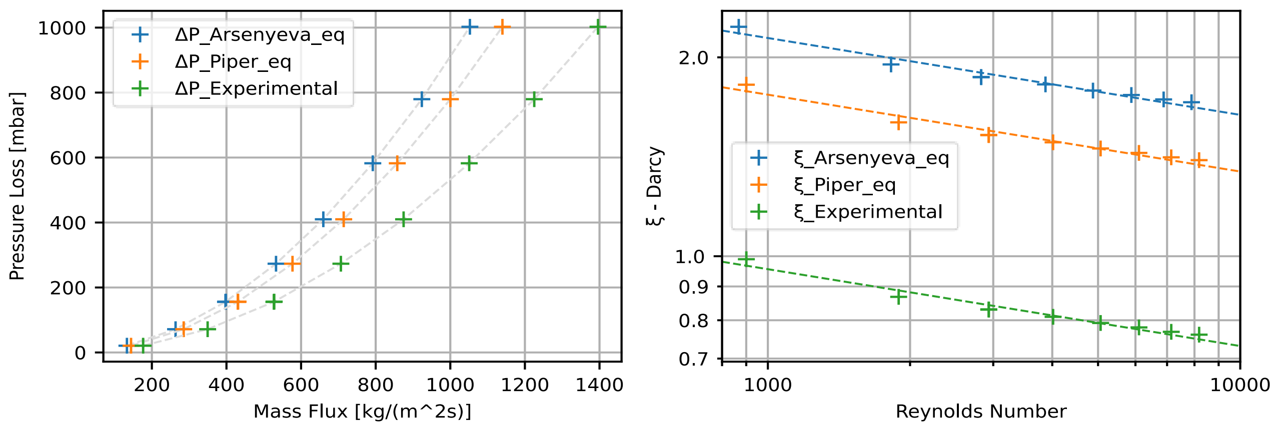
1. Method by Arsenyeva et al. [2], yielding Dh = 4.24 mm
2. Method by Piper et al., yielding Dh = 4.06 mm
3. Experimental parameters derived from destructive testing, yielding Dh = 3.32 mm



a) b)

Figure 6.4: fluid volume around three adjacent welding spots (a) and between two rows of spots (b), both in the transversal direction. These volumes were obtained from tomographic meshes and show the alternating recirculation and dead zones due to border effects

The pressure drop data, when processed using these different geometrical parameters, resulted in substantially different interpretations of the flow behaviour, as illustrated in Figure 6.5. The experimentally derived hydraulic diameter of 3.32 mm provided the most consistent results when compared to available correlations for similar PPHE geometries. Analysis of the Darcy friction factor against Reynolds number revealed a relationship best described by the values of n1=2.135 and n2=-0.116 for the Blasius correlation, when using the experimental geometric parameters. Figure 6.6 presents a direct comparison between these experimental values and those predicted by established correlations, highlighting the significant deviation from theoretical predictions. This underscores the impact of border effects and non-uniform inflation, which are particularly pronounced in compact PPHE designs. These findings demonstrate that while the central portion of Small-Scale Pillow Plates inflated normally—reaching a conformation close to the ideal geometry used in theoretical approaches—the border areas exhibited distinctly different geometric characteristics. The presence of many underinflated alternating areas results in a reduced effective cross-sectional area compared to theoretical models, explaining the consistent underestimation of the Darcy friction factor in current prediction methodologies. The integration of destructive testing with advanced tomographic analysis provides a comprehensive characterization of SSPPHE geometry, establishing a foundation for



a) b)

Figure 6.5: Representation of a) pressure drop data against mass flux; b) Darcy friction factor (ξ) against Reynolds number. Both diagrams present different curves obtained from the same data. Sets of points and curves, from top to bottom, blue to green, are respectively calculated with different values for hydraulic diameter and passage area of the PPHE from corresponding references and experimental values from this work.

improved modelling approaches that explicitly account for border effects and non-uniform inflation patterns in compact designs. These geometric insights proved essential for accurate interpretation of thermal performance data, as discussed in the following section.

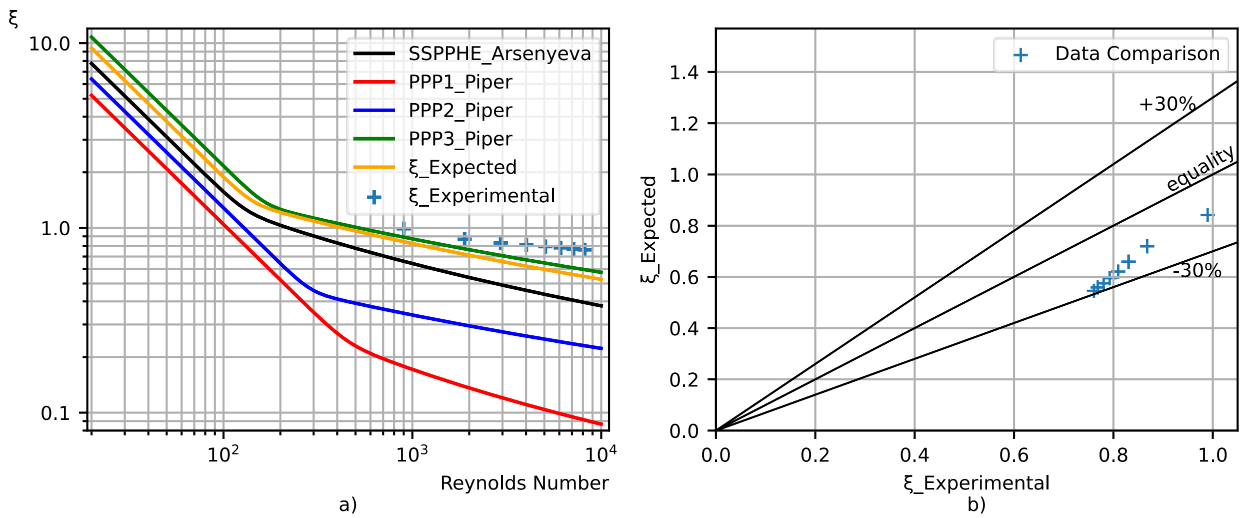


Figure 6.6: Analysis of Darcy friction factor (ξ) vs Reynolds number; Fig. 2a): Experimental data points are plotted against curves (Eq.7) presented by Arsenyeva et al. in [2] and the same correlation implemented with the geometrical parameters of this study (*ξ_Experimental*). Fig. 2b) directly compares the experimental values for the Darcy friction factor and the ones determined by us with the approach proposed in [1]

6.1.1.2. Thermal Performance Analysis

The experimental validation campaign generated comprehensive data on SSPPHE thermal and hydraulic performance across multiple operating conditions. Table 6.1 presents a systematic summary of key performance parameters, enabling direct comparison between experimental measurements and theoretical predictions. The effectiveness values (ε) demonstrate reasonable agreement between

Table 6.1: Summary of key parameters of influence for performance evaluation: effectiveness (ε), global heat exchange coefficient (U), Non-adiabaticity (NA), Reynolds (Re) and Prandtl (Pr) numbers calculated by the presented ε-NTU model, heat exchange coefficients (h) calculated by the model, Power (P). The subscript "exp" is for values calculated from experimental data, "comp" is for parameters computed by the model, while 1 and 2 indicate the inner (hot) and outer (cold) channel.

ID	ε_{exp} (%)	ε_{comp} (%)	U_{exp} (W/m2K)	NA (%)	Re1	Re2	Pr1	Pr2	h1 (W/m2 K)	h2 (W/m 2K)	U_{comp} (W/m 2K)	P_{comp} (W)
1&1	36.78	33.81	919	4.25	2649	524	3.73	6.51	814	936	814	2727
1&2	28.13	25.41	1410	3.97	2657	1000	3.87	6.88	1218	1537	1218	4160
1&3	23.93	27.12	1132	5.31	2737	1121	3.82	7.42	1321	1703	1321	4736
1&4	26.86	30.09	1270	1.78	2705	1351	3.86	7.62	1471	1970	1471	5316
1&5	31.09	34.7	1492	2.57	2663	1807	3.93	7.8	1718	2460	1718	6180
2&1	50.83	56.04	1039	1.92	914	1269	4.26	8.09	4056	1909	1204	3759
2&2	35.34	37.61	1292	2.63	1904	1327	4.02	7.91	6794	1962	1399	4982
2&3	27.19	28.13	1440	3.82	2947	1354	3.91	7.8	9249	1984	1495	5605
2&4	27.19	28.02	1437	1.59	2945	1346	3.92	7.82	9252	1977	1491	5564
2&5	21.91	22.42	1515	3.8	4026	1368	3.83	7.73	11528	1995	1552	5991
2&6	23.24	23.31	1578	1.93	5071	1368	3.76	7.62	13552	1989	1581	6219
2&7	23.76	23.93	1602	6.04	6112	1368	3.74	7.64	15502	1990	1606	6395
2&8	25	24.49	1668	0.9	7150	1370	3.73	7.6	17354	1990	1624	6472
2&9	25.46	24.84	1701	3.8	8190	1380	3.71	7.57	19118	1999	1645	6614

experimental measurements and model predictions, with differences typically within acceptable engineering margins. Tests 1&1 and 1&2, corresponding to the lowest outer channel Reynolds numbers (Re2 = 524 and 1000), show experimental effectiveness exceeding model predictions by approximately 8.8% and 10.7% respectively. These deviations occur at Reynolds numbers approaching the lower boundary of the correlation's validated range. Conversely, in test 2&1 with the lowest inner channel Reynolds number (Re1 = 914), the model overestimates effectiveness by approximately 10.3%, supporting the observation that correlation accuracy diminishes when operating below its validated range (Re < 1000). The overall heat transfer coefficient values exhibit consistent patterns that align with theoretical expectations. As anticipated, the overall heat transfer values increase with Reynolds number in both channels, confirming the fundamental relationship between flow velocity and heat transfer performance. The non-adiabaticity parameter (NA), ranging from 1.59% to 5.31%, quantifies thermal interaction with the environment despite insulation efforts and explains the discrepancy between inner and outer channel power measurements visible in Figure 6.7.

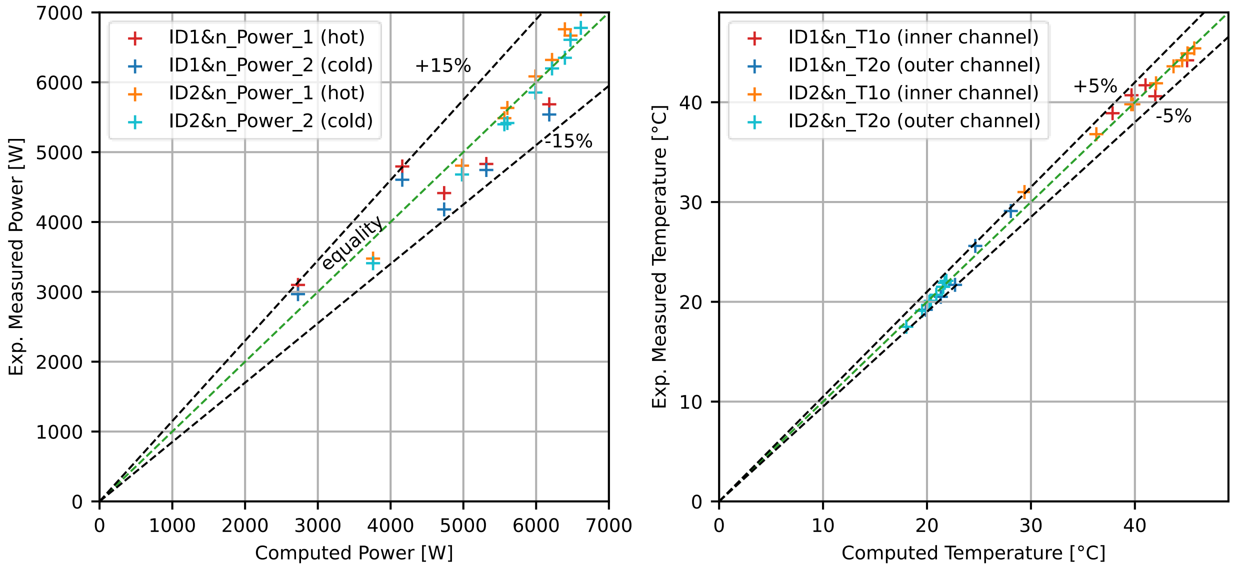


Figure 6.7: Comparison between a) the power and b) the temperature computed by the design model, against the respective experimentally measured value. Positive deviation from equality corresponds to underestimation of the quantity by the model.

Figure 6.7a illustrates the relationship between computed and measured power values, with most data points falling within a ±15% deviation band—an acceptable margin for heat exchanger design purposes considering the geometric complexity of the system. The systematic pattern of deviations demonstrates a transition from underestimation to overestimation in the first campaign (ID1&n with varying outer channel flow rates), while the second campaign (ID2&n with varying inner channel flow rates) shows more consistent behaviour across the tested range. The temperature predictions, illustrated in Figure 6.7b, exhibit superior agreement with measured values, with deviations typically below ±5%. This enhanced accuracy in temperature prediction compared to power prediction stems from the direct measurement of temperature values, whereas power calculations incorporate additional parameters and their associated measurement uncertainties. The model-calculated heat transfer coefficients (h1, h2) provide critical insights into the system's thermal resistance distribution. For the inner channel, h1 increases substantially with Reynolds number in the second campaign, rising from 4056 W/m^2K at Re1 = 914 to approximately 19118 W/m^2K at Re1 = 8190. This progression demonstrates the transition toward increasingly turbulent flow conditions and highlights the performance enhancement potential at higher flow rates. The outer channel coefficients (h2) exhibit more moderate variation across the tested conditions, suggesting their dominant contribution to overall thermal resistance in most operating scenarios. The experimental campaign successfully validates the applicability of the selected heat transfer correlations beyond their strictly established literature ranges. The results support extension of the outer channel correlation to Reynolds numbers as low as 1000, substantially below the previously validated minimum of 9500. This extension significantly broadens the potential application range of SSPPHEs to lower flow rate conditions often encountered in compact heat exchanger applications. The findings indicate that the ε-NTU model can reliably predict SSPPHE thermal performance within the validated Reynolds number range, with the potential to extend the applicability of outer channel correlations down to Reynolds numbers as low as Re = 1000, significantly below the previously established limit of Re = 9500.

6.1.1.3. Model Prediction Accuracy Assessment

The comprehensive evaluation of the ε-NTU design methodology revealed both strengths and limitations in its application to SSPPHEs:

1. Thermal Predictions: The model demonstrated good accuracy for thermal power predictions, generally within ±15% of experimental values, confirming its utility for preliminary design purposes.
2. Pressure Drop Predictions: Significant discrepancies were observed in pressure drop predictions, with the model underestimating the Darcy friction factor by 15-30%. This underestimation is primarily attributed to border effects and non-uniform inflation patterns not captured by current geometrical models.
3. Heat Transfer Coefficient Correlations: The existing correlations for heat transfer coefficients proved applicable to SSPPHEs, though with reduced accuracy at the extremes of their validated ranges. The findings suggest potential for extending their applicability to lower Reynolds numbers, particularly for the outer channel.
4. Non-Adiabaticity: The experimental setup exhibited varying degrees of non-adiabaticity (NA), ranging from 0.9% to 6.04%, which did not demonstrate clear correlation with flow conditions or thermophysical properties. This variability introduces an additional source of uncertainty in the experimental validation.

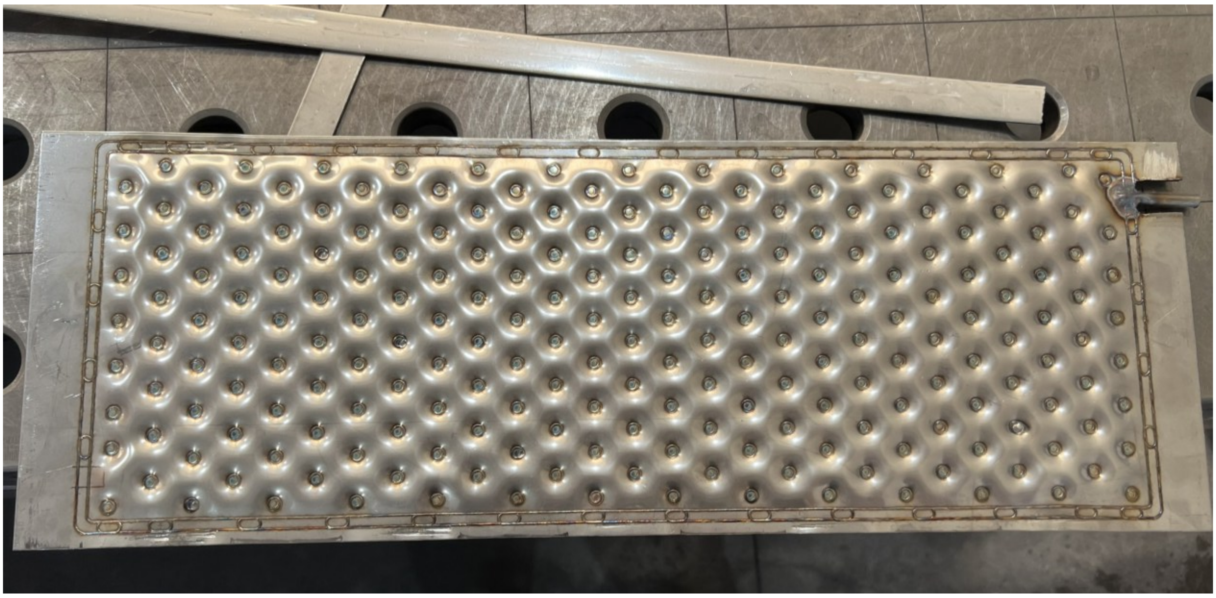
The model validation confirms the fundamental applicability of the ε-NTU approach for SSPPHE design but highlights the critical need for refined geometrical modelling that accounts for border effects and non-uniform inflation, particularly for compact designs where these effects become proportionally more significant.

6.1.1.4. Border Effects Analysis and Implications

The experimental and analytical findings collectively emphasize the significance of border effects in SSPPHEs. In compact designs, the proportion of the heat exchanger affected by edge conditions becomes substantially larger relative to the idealized periodic elements that form the basis of current geometrical models. Another campaign is pending to evaluate a similar configuration with larger plates, of which a laser scan was performed, with Figure 6.8 showcasing this production ready and fast technique against an image of the real geometry.

6.1.2. Condensation Heat Recovery (CHR) Preliminary Findings

The Condensation Heat Recovery (CHR) experimental campaign represents a significant advancement in the application of Pillow Plate Heat Exchangers (PPHEs) to latent heat recovery processes. The preliminary experimental setup, designed to investigate the combined sensible and latent heat transfer mechanisms in humid air streams, provides initial insights into the performance characteristics of PPHEs under condensing conditions. The results showcased in the present section are purely



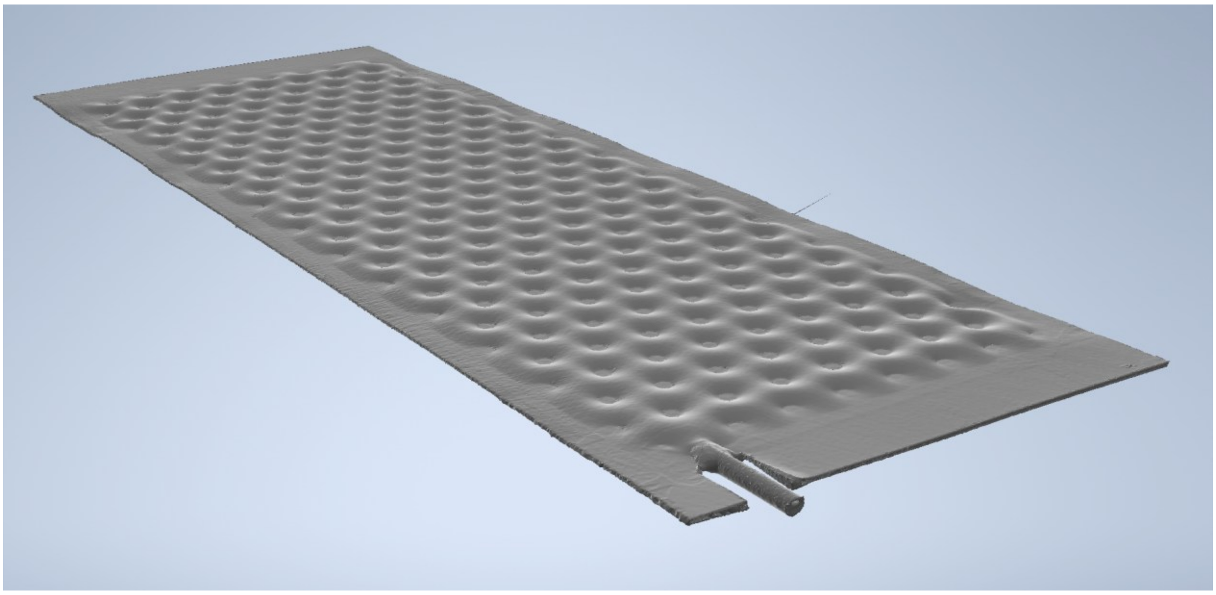


Figure 6.8: Comparison of Pillow plate produced for the SSPPHE version 2 prototype (top) and laser scan with 0.2mm resolution (bottom)

experimental and preliminary, since the construction of the setup was finished at the end of year 2024, during the writing of this elaborate. The experimental runs where four and the data presented is

6.1.2.1. First results without condensation

The initial experimental run data presented in Table 6.2 establishes baseline thermal performance characteristics prior to condensation occurrence. The system operates with an inner channel (IC) inlet temperature of 40.84°C and outlet temperature of 42.63°C, while the outer channel (OC) demonstrates higher temperatures (inlet: 65.11°C, outlet: 58.73°C). This temperature gradient yields a thermal power of 5.06 kW with a volumetric flow rate of 40.4 L/min for the IC working fluid. Figure 6.9 provides critical insight into the system's thermal stability during operation. The x axis is correspondent to a measurement operation (1 every 5 seconds). The temporal temperature profiles exhibit minimal fluctuations, with the OC inlet temperature (T2_1) maintaining approximately 65°C and outlet temperature (T2_5) stabilizing at approximately 59°C. Concurrently, the IC temperatures (T1_1, T1_5) demonstrate greater stability at approximately 40-43°C. The step change observed in the volumetric

Table 6.2: Summary of averaged data of the first experimental run, starting from inlet and outlet temperatures of IC (1) and OC (2) respectively, flow rates, specific heat and thermal power calculated from water temperature increase. Temperatures are named after the channel and the inlet/outlet position, e.g.: T_{1_5} refers to the outlet temperature of the IC.

T_{1_1} (°C)	T_{1_5} (°C)	T_{2_1} (°C)	T_{2_5} (°C)	Q_1 (l/min)	Q_2 (m3/h)	C_P (kJ/kgK)	$Power_1$ (kW)
40.84	42.63	65.11	58.73	40.4	1967.0	4.2	5.06

flow rate (Q1) represents an operational adjustment to achieve steady-state conditions. The absence of significant temperature oscillations confirms thermal equilibrium attainment, validating data reliability for subsequent heat transfer calculations. This sensible heat transfer baseline establishes a reference point for quantifying additional thermal power recovery during condensation operations. The temperature differential between incoming air (65.11°C) and the cooling medium (40.84°C) ensures adequate driving potential for both sensible and latent heat transfer when condensation conditions are established in subsequent experimental runs.

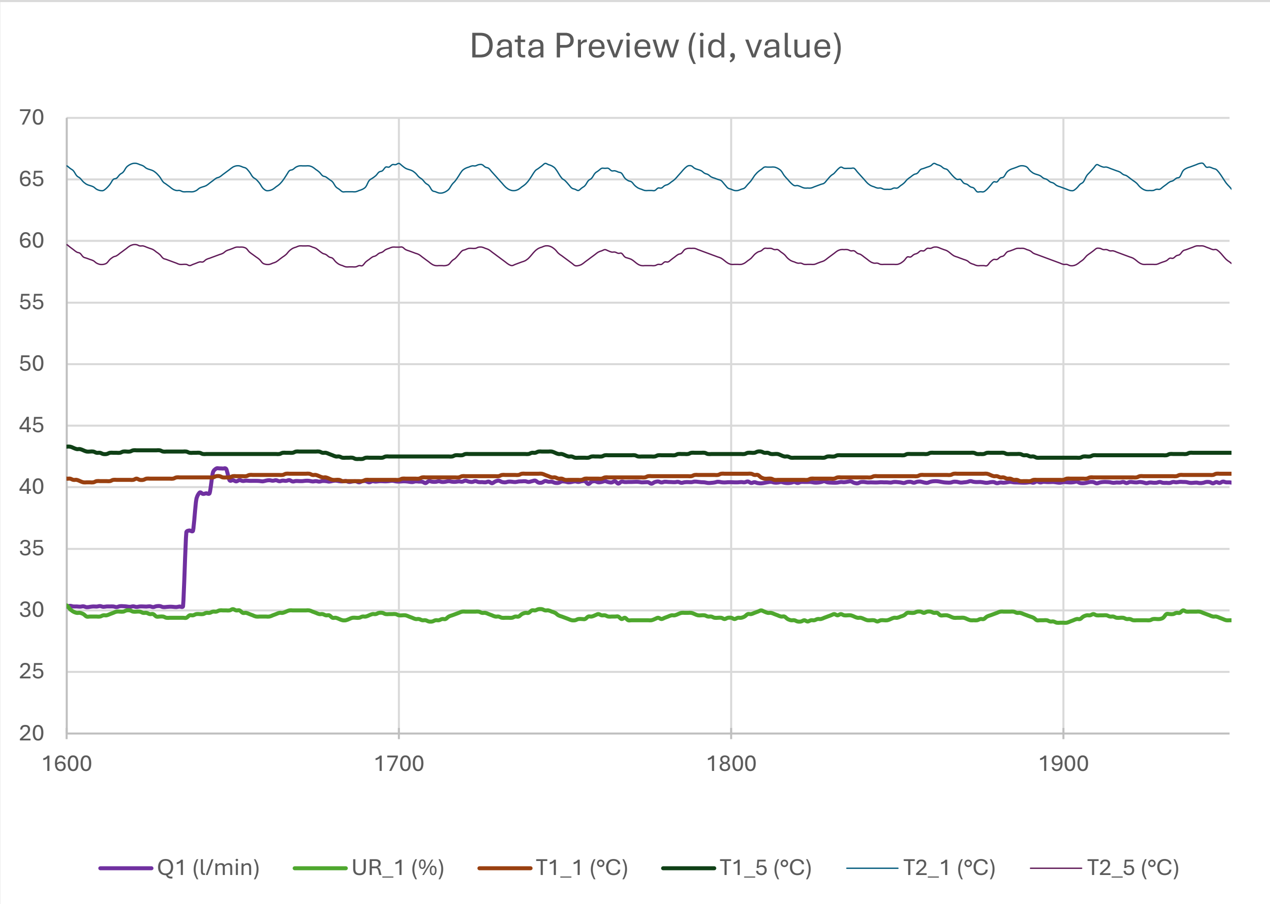


Figure 6.9: Schematic of the experimental set-up, with hot (1) (Inner SSPPHE Channel) and cold (2) (Outer Channel) sides and sensors.

6.1.2.2. Thermal Performance Under Condensing Conditions

The experimental data presented in Tables 6.3-6.6 provide a comprehensive characterization of the PPHE performance across three distinct operating conditions, progressively demonstrating the transition from sensible-only to combined sensible-latent heat transfer regimes. Run 1 (ID 1) established again baseline performance without condensation, evidenced by the minimal humidity reduction (ΔAH = 0.3 g/kg) between inlet and outlet flows. The thermal power recovered in this case (1816.90 W from water-side measurements, 1468 W from air-side calculations) demonstrates good

Table 6.3: Summary of key measured values, in order: temperature at inlet and outlet of IC (T_{1_1},T_{1_5}), inlet and outlet of OC (T_{2_1},T_{2_5}), derived absolute humidity, measured relative humidity. Each row is an experimental run, identified by an ID unique across the following tables.

id	T_{1_1}	T_{1_5} (°C)	T_{2_1} (°C)	T_{2_5} (°C)	AH_{IN} (g/kg)	AH_{OUT} (g/kg)	RH_{IN} (%)	RH_{OUT}(%)
1	40.83	41.30	50.60	48.12	45.0	45.3	48.5	59.2
2	40.57	42.45	49.93	47.93	72.9	67.9	81.2	74.3
3	48.11	51.27	64.55	60.92	122.8	113.9	63.8	76.7

Table 6.4: Summary of key parameters for the calculation of thermal power (P_1) recovered by the water in the IC: mean temperature, outlet-inlet temperature difference, specific isobaric heat, flow rate.

id	T_{1mean} (°C)	ΔT_1 (K)	C_{P1} (J/kgK)	Q_1 (l/min)	$Power_1$ (W)
1	41.07	0.48	4179.53	54.89	1816.90
2	41.51	1.88	4179.58	55.15	7214.59
3	49.69	3.16	4181.26	55.09	12133.32

agreement between measurement methodologies and confirms operation in the sensible-only regime. The absence of condensate collection (Table 6.6) further verifies this operating condition. Runs 2 and 3 demonstrated substantial condensation effects with progressively increasing thermal performance. Run 2 exhibited moderate condensation with 9.19 kg/h of condensate production, corresponding to humidity reduction of 5.2 g/kg. This condensation activity significantly enhanced thermal recovery to 7214.59 W (water-side measurement), representing a 297% increase over the non-condensing baseline despite similar approach temperatures. The latent heat contribution (6611 W) constituted approximately 85% of the total heat transfer, demonstrating the substantial thermal recovery potential of condensation processes. Run 3 achieved the highest thermal performance with 15.13 kg/h condensate production and 8.9 g/kg humidity reduction. The total thermal power recovered increased to 12133.32 W, approximately 6.7 times the non-condensing baseline. This dramatic enhancement occurred with only modest increases in the temperature differential (3.16 K vs. 0.48 K), underscoring the thermal intensification potential of latent heat recovery. The progressive performance enhancement across the experimental runs demonstrates the PPHE's capacity for effective moisture extraction from humid air streams. The wavy surface geometry appears particularly advantageous for condensation applications, facilitating efficient condensate drainage while maintaining thermal performance. The

Table 6.5: Summary of key parameters for the calculation of thermal power (P_2) recovered from the humid air flow, calculated from the enthalpy difference, obtained from relative humidity, pressure and temperature and the usage of Coolprop libraries.

id	T_{2mean}	h_{2IN} (J/kg)	h_{2OUT} (J/kg)	Δh_2 (J/kg)	ρ_2 (kg/m3)	$Power_2$ (W)
1	49.36	167678	165714	1964	1.07	1154
2	48.93	239211	223823	15387	1.05	8884
3	62.73	386365	358761	27603	0.99	14756

Table 6.6: Summary of key parameters for the calculation of latent heat recovery from the collected condensate mass flow rate (m_{cond}), and sensible heat recovery calculated from the temperature differential of the air. Data differs slightly from other tables, due to imprecisions in calculation and measurements of condensate production.

id	Q_2 (m3/h)	ΔT_2 (K)	C_{P2} (J kg/K)	h_{VAP} (kJ/kg)	m_{cond} (kg/h)	Q_{Latent} (W)	$Q_{Sensible}$ (W)	Q_{TOTAL} (W)
1	1982.29	2.48	1007.40	2590.16	Nd	0	1468	1468
2	1971.03	2.00	1007.37	2589.40	9.19	6611	1163	7773
3	1947.24	3.64	1008.20	2613.58	15.13	10987	1959	12946

data reveal excellent correspondence between condensate collection rates and enthalpy reduction calculations, validating the measurement methodology and confirming the substantial contribution of latent heat transfer to overall thermal performance. This experimental validation establishes the PPHE as a promising technology for condensation heat recovery applications, with potential for significant energy efficiency improvements in industrial processes involving humid air streams.

6.2 Integrated Discussion

6.2.1 Correlation Between Academic Findings and Industrial Implementation

The systematic integration of experimental validation with industrial implementation provides a framework for evaluating the effectiveness of PPHE technology across multiple application domains and scales. This section synthesizes the cross-cutting themes emerging from both laboratory and industrial contexts, examines methodological implications, and identifies critical research trajectories warranting further investigation.

6.2.1. Bidirectional Knowledge Transfer

The research program established a productive bidirectional knowledge transfer mechanism between theoretical modelling, laboratory experimentation, and industrial application. The effectiveness-NTU methodology, initially validated through controlled laboratory testing, was successfully deployed across diverse industrial contexts including natural convection, granular material cooling, and exhaust gas heat recovery. This translation was facilitated by several methodological factors:

- Iterative Model Refinement: Laboratory findings informed industrial design parameters, particularly regarding weld spot patterns, material selection, and connection design. Conversely, implementation challenges encountered in industrial settings—including spatial constraints, cleanability requirements, and thermal cycling—guided subsequent experimental focus areas.
- Geometric Characterization Advancement: The tomographic analysis of SSPPHE prototypes revealed significant border effects that informed both design methodology refinements and manufacturing parameter selection for industrial-scale production.
- Performance Correlation Extensions: The experimental validation extended the applicability range of heat transfer correlations, particularly for the outer channel to Reynolds numbers as low as 1000, substantially expanding the operational envelope for Small Scale industrial applications.

This knowledge integration accelerated both theoretical understanding and practical implementation, demonstrating the efficacy of concurrent research-industrial development compared to traditional sequential approaches.

6.2.2. Critical Analysis of Methodological Limitations

Despite the demonstrated correlation between laboratory predictions and industrial performance, several methodological limitations warrant critical examination:

- Measurement Constraints: The experimental campaigns encountered significant instrumentation challenges, including insufficient pressure sensor sensitivity for outer channel characterization and flow disturbance from temperature probes. These constraints limited the comprehensive characterization of spatial temperature distributions and local heat transfer phenomena, necessitating validation through indirect performance indicators.

- Geometric Modelling Inadequacies: Current geometric modelling approaches demonstrated substantial limitations in accurately predicting border effects and inflation patterns, particularly significant in compact designs where edge regions constitute a higher proportion of total heat transfer area. The systematic underestimation of pressure drops (15-30% in SSPPHE validation) indicates a fundamental limitation requiring more sophisticated modelling approaches.
- Validation Dataset Limitations: While the experimental campaigns provided validation across multiple flow conditions, the range of geometric configurations tested remains limited compared to the vast parameter space available in PPHE design. This constraint potentially limits the transferability of findings to significantly different geometric configurations.

6.2.3. Implications for PPHE Design and Implementation

6.2.3.1. Practical Implications

This research offers several practical insights for heat exchanger design:

1. Size considerations: Smaller PPHE designs showed that edge effects significantly influence performance. Our measurements revealed that these border regions behave differently than predicted, affecting pressure drop by 15-30%. Designers need to account for these effects, especially when working with compact units.

2. Application-Specific Approaches: Different applications require different design choices. For example, natural convection units needed specific plate arrangements to promote movement, while high-temperature applications prioritized thermal stress resistance at connections. These requirements prevented us from developing universal design guidelines.

3. Manufacturing Constraints: Production capabilities directly limited what could be achieved in practice. Sheet metal thickness, welding pattern precision, and inflation control all affected final performance. Our testing revealed that even minor production variations could significantly impact thermal and hydraulic behaviour in Small Scale PPHEs, while normal or large scale PPHEs are much less sensible. While establishing a dedicated production facility improved manufacturing control, the connection between production parameters and performance remains to further analyse and to be modelled in future.

6.2.3.2. Future Work Needed

Several areas require further investigation:

1. Geometrical Modelling: While the used models make errors in predicting the behaviour of border regions and non-uniform inflation in SSPPHEs, quick and simple characterisation techniques showed useful for geometrical characterisation. More accurate geometric representation would improve design reliability, particularly for compact units. Finite Element Modelling will for sure need to be a future endeavour for further advancing this research work.

2. Condensation Understanding: Our preliminary condensation tests showed promising results, but we lack fundamental understanding of how condensate forms and drains across the complex surface geometry. This knowledge gap limits our ability to optimize designs for these high-potential applications.

3. Long-Term Performance: While initial performance matched predictions reasonably well, we have limited data on how these units perform over extended periods, especially in fouling environments or under thermal cycling. This information is essential for realistic lifecycle assessment.

4. Material Selection: Our work with specialized materials like AISI 904L showed both benefits and manufacturing challenges. More research on material-specific production techniques could address corrosion resistance limitations while maintaining thermal performance.

This work has demonstrated PPHE technology's potential across several applications, while also revealing significant knowledge gaps that must be addressed before widespread industrial adoption becomes feasible.

6.3. Chapter references

[1] M. Piper, A. Olenberg, J. M. Tran, and E. Y. Kenig, ‘Determination of the geometric design parameters of pillow-plate heat exchangers’, *Applied Thermal Engineering*, vol. 91, pp. 1168–1175, Dec. 2015, doi: 10.1016/j.applthermaleng.2015.08.097.

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7. Conclusions and Future Work

This research has investigated the state of the art of Pillow Plate Heat Exchangers in literature, elaborated a methodology for model creation and thus design, moving then into their production aspects, industrial implementation and experimental validation, contributing to both theoretical understanding and practical application of this promising heat transfer technology. By systematically integrating methodological development with experimental validation and industrial case studies, this work addresses critical gaps in PPHE knowledge while establishing a framework for wider industrial adoption.

Chapter Index

7.1 Research Summary and Key Contributions

The comprehensive investigation of PPHEs conducted in this thesis has yielded several significant contributions to the field of thermal management. The effectiveness-NTU design methodology developed and validated through experimental campaigns provides a reliable framework for predicting thermal performance across diverse operating conditions, with expected accuracy of the thermal power predictions typically within ±15% of experimental measurements. This methodological advancement addresses the need for robust design tools to facilitate broader PPHE adoption [1].

The experimental characterization of Small-Scale Pillow Plate Heat Exchangers (SSPPHEs) revealed crucial insights into the thermo-hydraulic behaviour of compact heat exchangers, particularly regarding the influence of border effects and non-uniform inflation patterns. Through destructive testing, optical microscopy, and tomographic analysis, this research identified significant geometric variations not adequately captured in existing models, explaining the consistent underestimation of pressure drop (15-30%) using current prediction methodologies. The investigation of condensation heat recovery applications demonstrated substantial thermal intensification potential, with latent heat recovery increasing total thermal power by up to 567% compared to sensible-only conditions. This finding establishes PPHEs as promising candidates for energy efficiency improvements in industrial processes involving humid air streams, representing a novel application domain not previously explored in the literature.

Perhaps most significantly, this research tried to merge theoretical development and industrial implementation through multiple case studies spanning natural convection, sand cooling, high-temperature heat recovery, and condensation applications. The successful deployment of working prototypes validated the versatility of PPHE technology while generating practical insights into manufacturing considerations, material selection, and application-specific design requirements through the assistance in the development of a production and business unit dedicated to PPHE.

7.1.2. Methodological Advancements

The development of a robust design methodology represents a fundamental contribution of this research. The effectiveness-NTU approach, while established for conventional heat exchangers, required adaptation for application to PPHEs due to their unique geometric characteristics and flow patterns. The methodology integrates geometric characterization with thermohydraulic correlations, incorporating refined models for both inner and outer channels. The geometric modelling approach initially adopted from Piper et al. [2] was systematically, revealing both its capabilities and limitations. While this approach provided acceptable accuracy for thermal performance prediction, it demonstrated significant limitations in accounting for border effects and non-uniform inflation, particularly in compact designs. A significant methodological advancement emerged from the extension of heat transfer correlation applicability beyond their established literature ranges. The experimental validation confirmed the applicability of outer channel correlations to Reynolds numbers as low as 1000, substantially below the previously validated minimum of 9500. This extension shows that PPHE performance is not only higher than conventional solutions but also tends to be stable over a wide range of properties.

The integration of tomographic analysis with traditional destructive testing provided unprecedented insights into the three-dimensional structure of inflated pillow plates, enabling more accurate interpretation of experimental data and identifying critical geometric features not captured in theoretical models. This multi-method characterization approach establishes a foundation for more refined geometric modelling methodologies that explicitly account for border effects and non-uniform inflation patterns.

7.1.3. Experimental Validation and Findings

The experimental campaigns conducted in this research yielded several critical findings regarding PPHE performance characteristics and design methodology validation. The thermal performance measurements demonstrated acceptable agreement between model predictions and experimental data, with thermal power deviations typically within ±15%. This validation provides confidence in the methodology's applicability for preliminary design purposes, particularly when operating within the validated parameter ranges for the implemented correlations. However, hydraulic characterization revealed systematic underestimation of pressure drop by current correlations, attributable to border effects not adequately captured in existing geometric models. The tomographic analysis confirmed that while the central portion of Small-Scale Pillow Plates inflated normally—reaching a conformation close to the ideal geometry used in theoretical approaches—the border areas exhibited distinctly different geometric characteristics. The presence of many underinflated alternating areas resulted in a reduced effective cross-sectional area compared to theoretical models, explaining the consistent underestimation of the Darcy friction factor. This information is fundamental for designs with a lot of internal passages or plate complications such as curved edges or holes and other fixtures.

The condensation heat recovery experiments provided preliminary validation of PPHE performance under combined sensible and latent heat transfer conditions. The progressive performance enhancement across the experimental runs demonstrated the PPHE's capacity for effective moisture extraction from humid air streams, with effective condensate production rates. The wavy surface geometry looks particularly advantageous for condensation applications, facilitating efficient condensate drainage while maintaining thermal performance.

7.1.4. Industrial Implementation Insights

The implementation of PPHEs across different industrial applications generated valuable insights beyond laboratory experimentation, addressing practical considerations essential for commercial viability. While research has been traditionally focused on more theoretical or laboratory scale experimentation, these examples of industrial operations are deemed useful to the state of the art of PPHE, to generate more confidence in the technology and branches of research progressing heat transfer technologies.

The natural convection implementation demonstrated the adaptability of PPHE technology to passive thermal management applications, exploiting the enhanced surface area and boundary layer disruption provided by the wavy external surface. The successful integration with existing tank structures validated the retrofit potential while revealing critical considerations regarding connection design and placement for proper fluid distribution.

The sand cooling application extended PPHE technology to solid-to-fluid heat transfer, with the 400kW implementation highlighting both potential advantages and limitations. The modular extractable cartridge design provided both enhanced cooling performance and practical maintenance advantages, while the identified thermal stress issues at plate edges informed subsequent material selection and design refinements for the second-generation implementation.

The high-temperature heat recovery application, utilizing AISI 904L for diesel exhaust heat recovery, demonstrated the adaptability of PPHEs to corrosive, high-temperature environments. Despite implementation challenges related to connection integrity and quality issues with external suppliers, this application validated the potential for PPHEs in demanding waste heat recovery scenarios while establishing critical quality control requirements for specialized alloy manufacturing.

The establishment of a dedicated 3kW laser welding facility represented a significant advancement in manufacturing capability, enabling precise control over weld spot patterns and geometrical parameters. The insights gained regarding welding parameters, material compatibility, and pattern optimization contribute significantly to the manufacturing knowledge base for PPHEs, addressing practical implementation barriers identified in previous literature. Ultimately, the industrial implementations validated the bidirectional knowledge transfer mechanism established in this research, where laboratory findings informed industrial design parameters while implementation challenges guided subsequent experimental focus areas. This integrated approach accelerated both theoretical understanding and practical implementation, demonstrating the efficacy of concurrent research-industrial development compared to traditional sequential approaches.

7.1.5. Limitations and Critical Reflections

Despite the significant advancements achieved, several limitations warrant critical examination to contextualize the findings and guide future research efforts. First, the experimental campaigns encountered significant instrumentation challenges, including sensitivity issues, unwanted parasitic effects, and flow disturbance from temperature probes. These constraints limited the comprehensive characterization of spatial temperature distributions and local heat transfer phenomena, necessitating validation through indirect performance indicators. Future experimental work would benefit from non-intrusive measurement techniques specifically adapted to the complex geometries of PPHEs. Moreover, the adopted geometric modelling demonstrated substantial limitations in accurately predicting border effects and inflation patterns in compact designs where edge regions constitute a higher proportion of total heat transfer area. While the tomographic analysis provided valuable insights into these effects, this work would have benefited from a combination of manufacturing simulation and geometrical validation. While the experimental campaigns provided validation across multiple flow conditions, the range of geometric configurations tested remains limited compared to the vast parameter space available in PPHE design. This constraint potentially limits the transferability of findings to significantly different geometric configurations, particularly those with alternative weld spot patterns or aspect ratios. However, the good qualitative results in operating conditions (industrial feedback) suggest that PPHEs performances are robust against variating conditions and does not show completely unintended behaviours even at low Reynolds values or with new fluids. If possible, this information promotes the potential of further research on the treated applications.

The condensation heat recovery investigation, while demonstrating promising results, remains in a preliminary stage with limited characterization of film formation, distribution, and drainage patterns. More detailed investigation of these phenomena is required to fully optimize PPHE designs for condensation applications.

7.2 Future Research Directions

Based on the findings and limitations identified in this research, several promising directions for future investigation emerge.

7.2.1. Refined Geometrical Modeling

The development of more sophisticated geometrical models that explicitly account for border effects and non-uniform inflation represents a critical need for accurate performance prediction, particularly for compact designs. Future research should focus on:

- Integration of manufacturing simulation with direct laser scanning or tomography to create a database for machine learning and simulation validation
- Thorough quantification of border effects with respect to geometry aspect ratio
- Investigation of modified manufacturing approaches to improve inflation uniformity
- Application of machine learning techniques to predict geometric characteristics from manufacturing parameters

The recent work of Sabourishirazi et al. [3] provides a promising foundation for such advancements, particularly their approach using artificial neural networks to predict geometric parameters based on manufacturing inputs. Under an industrial point of view, it would be interesting to study non-destructive imaging techniques more. The creation of a database of Pillow Plate geometries would help creating reliable digital models of PPHE across the whole design space.

7.2.2. Sensible Heat Applications

While this research has successfully validated and extended existing correlations, several opportunities for further development exist:

- Extension of correlation validity to wider Reynolds and Prandtl ranges for expanded application range: a comprehensive characterisation in the likes of the drafted Small Scale PPHE version 3 would provide this.
- Experimental characterization of natural convection with single plates or with multiple plates, including study of the chimney effect
- Development of correlations for solid-to-surface heat transfer with granular materials

These advancements would significantly expand the application range of PPHEs while enhancing design methodology accuracy across diverse operating conditions.

7.2.3. Condensation Heat Recovery Characterization

The condensation heat recovery application represents a particularly promising frontier for future research:

- Detailed characterization of film formation, distribution, and drainage patterns
- Investigation of surface wettability effects and potential surface treatments to obtain droplet condensation
- Development of specific design methodologies for optimized condensation heat recovery
- Long-term performance assessment under various operating conditions and with different condensable components

Given the substantial thermal intensification potential demonstrated in the preliminary experiments, this application domain warrants comprehensive investigation to fully realize its energy efficiency implications.

7.3 Final Remarks

This research has significantly advanced the understanding and implementation of Pillow Plate Heat Exchanger technology, bridging the gap between theoretical models and practical industrial applications. The development of a validated design methodology, characterization of performance across diverse applications, and establishment of manufacturing capabilities collectively represent substantial progress toward wider industrial adoption of this promising technology. The comprehensive approach integrating theoretical modelling, experimental validation, and industrial implementation has demonstrated the potential of PPHEs to enhance energy efficiency across various thermal management applications. By providing a robust foundation for both further academic research and industrial implementation, this work contributes to advancing sustainable thermal management solutions for increasingly demanding industrial applications.

The challenges identified throughout this research, particularly regarding geometrical modelling limitations and manufacturing constraints, should not be viewed as impediments but rather as opportunities for further innovation. As noted by Sabourishirazi et al. [4], the field of PPHE research remains in a developmental phase with significant opportunities for advancement. The demonstrated versatility and performance advantages of PPHE technology, combined with the established manufacturing capabilities, position this technology for continued development and expanding industrial adoption.

7.6 Chapter References

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