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Experimental Setup and Analysis of Force Convection in Pillow Plate Heat Exchanger

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Abstract: *The optimization of thermal management systems remains a primary focus in modern mechanical engineering. Pillow Plate Heat Exchangers have emerged as an innovative alternative to conventional designs, offering enhanced surface-area-to-volume ratios and improved fluid mixing due to their complex, wavy internal geometries. This research presents an experimental investigation into the forced convection heat transfer and hydraulic pressure drop characteristics of an inline-welded pillow plate. A customized experimental test rig was designed and fabricated to evaluate the thermal- hydraulic performance under steady-state conditions using a parallel-flow configuration with water as the working fluid. By systematically varying the thermal load while maintaining constant mass flow rates, the study analyzes the resulting temperature profiles, overall heat transfer coefficients, and convective heat transfer behavior. Furthermore, the corresponding pressure drop across the test section is evaluated to understand the frictional losses induced by the complex flow path. The findings aim to provide valuable empirical insights into the efficiency of inline pillow plate geometries, contributing to better predictive models and optimized designs for industrial applications*

Keywords: Pillow Plate Heat Exchanger, Forced Convection, Parallel Flow, Thermal-Hydraulic Performance, Heat Transfer Enhancement.

I. INTRODUCTION

A. Background information

Thermal management is a critical aspect of numerous industrial processes, including chemical processing, power generation, HVAC systems, and food and beverage manufacturing. Heat exchangers are the fundamental devices utilized to facilitate the transfer of thermal energy between two or more fluids. While traditional designs, such as shell-and-tube and conventional corrugated plate heat exchangers, have been widely utilized for decades, the increasing industrial demand for higher energy efficiency, compact spatial footprints, and reduced material costs has driven the development of novel heat exchanger geometries.

Among these modern advancements, the Pillow Plate Heat Exchanger (PPHE) has emerged as a highly effective and innovative alternative. A pillow plate is manufactured by spot-welding two thin metal sheets together in a predefined pattern—such as an inline or staggered array—and subsequently inflating the space between them using high-pressure fluid. This hydroforming process creates a complex, three-dimensional wavy channel that resembles a quilted surface. When working fluids are pumped through the internal channels and over the external surfaces under forced convection, the distinct dimpled structures continuously disrupt the formation of the thermal boundary layer. This continuous disruption induces localized turbulence, secondary flows, and enhanced fluid mixing, which substantially increases the convective heat transfer rate compared to smooth-channel geometries.

B. Significance of the research

Despite the proven mechanical and operational advantages of pillow plate heat exchangers, precisely predicting their thermodynamic and hydraulic behavior remains a significant engineering challenge. Because the geometry of the flow channel is three-dimensional and highly irregular, classical empirical correlations developed for straight pipes or flat plates are strictly inapplicable. Consequently, there

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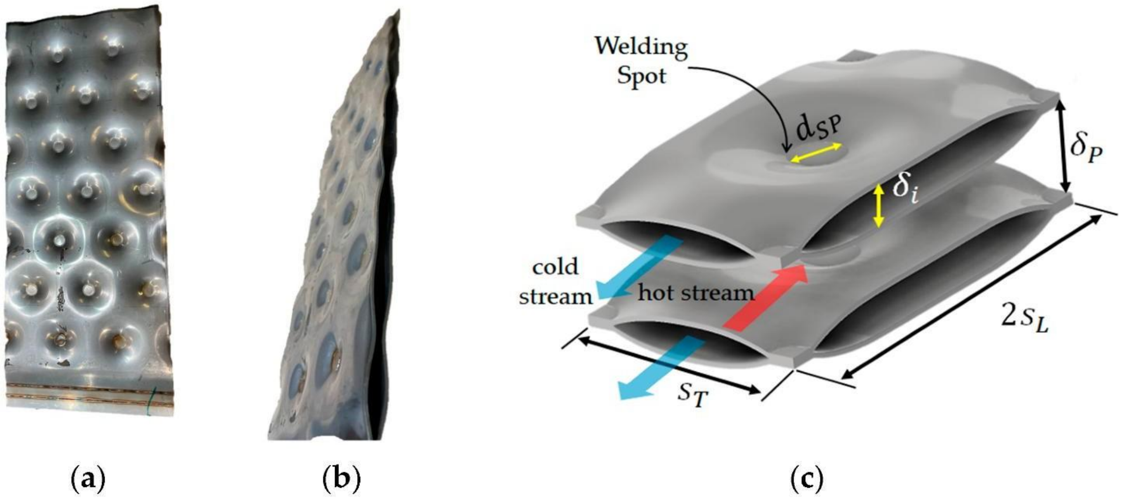
is a scarcity of universal design equations, and engineers frequently face difficulties in accurately estimating the convective heat transfer coefficient and the associated frictional pressure drop for specific weld configurations.

This research is highly significant as it provides physical, real-world experimental validation of the forced convection characteristics within an inline-welded pillow plate system. By designing a custom, heavily instrumented experimental test rig and operating it under parallel-flow conditions with precisely controlled variable thermal loads, this study generates vital empirical data. Evaluating both the thermal performance (heat transfer rate) and the hydraulic performance (pressure drop) of this specific geometry will bridge existing gaps in the literature. Ultimately, the findings from this study will contribute to the development of more accurate predictive models, enabling engineers to design more efficient, scaled, and cost-effective pillow plate heat exchange systems for industrial applications.



II. LITERATURE REVIEW

A. Overview of relevant literature

The study of Pillow Plate Heat Exchangers (PPHE) has gained substantial momentum in recent years as industries continuously seek more efficient and compact thermal management solutions. Baheta et al. [5] provided a comprehensive review of the recent advancements in PPHE technology, highlighting its successful transition from niche applications—such as cooling jackets in the dairy and beverage industries—to mainstream industrial use. Their review emphasizes that the high structural integrity and superior thermal-hydraulic performance of pillow plates make them highly competitive against traditional plate and shell-and-tube heat exchangers.

The fundamental geometrical characteristics of these specialized heat exchangers were rigorously defined by Piper et al. [1]. In their foundational study, they mathematically outlined the complex internal and external surface areas that result from the hydroforming process. Their work established the vital geometric parameters—such as the inner channel volume, cross-sectional area, and characteristic hydraulic diameter—which are essential for calculating fluid velocities and baseline performance metrics.

To further understand the intricate fluid behavior within these wavy channels, computational investigations have been extensively utilized alongside experimental efforts. Zibart and Kenig [4] performed detailed three-dimensional Computational Fluid Dynamics (CFD) simulations to analyze turbulent single-phase flow inside pillow plates. Their numerical study revealed that the inherent 3D waviness and the presence of staggered or inline weld spots significantly alter local velocity profiles, creating highly heterogeneous flow fields. Expanding on this, Shirzad et al. [3] investigated the specific impact of dimpled and wavy surfaces on heat transfer enhancement. Their findings demonstrated that the dimpled structures act as continuous turbulence promoters, inducing flow separation, vortex generation, and intense

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secondary flows, which directly contribute to improved thermal mixing when compared to standard flat-plate configurations.

B. Key theories and concepts

The fundamental mechanism governing the operation and efficiency of a PPHE is forced convection. According to classical heat transfer theory, the primary resistance to convective thermal energy exchange is the formation and growth of a stagnant thermal boundary layer adjacent to the solid heat- transfer surface. In traditional smooth pipes or flat channels, this boundary layer thickens as the fluid progresses, creating a thermal insulation effect that necessitates exceptionally high fluid velocities to overcome.

The key concept behind the pillow plate design is the deliberate, mechanical disruption of this boundary layer. As the working fluid navigates the tortuous, undulating path created by the specific weld spot pattern (such as the inline configuration utilized in this study), the fluid flow is continuously interrupted. This constant boundary layer renewal and the induction of localized swirling flows drastically increase the convective heat transfer coefficient (h) even at relatively moderate Reynolds numbers.

This complex flow field fundamentally alters the empirical relationships between dimensionless thermal-hydraulic parameters. Piper et al. [2] conducted an extensive experimental and numerical analysis to develop new design equations for turbulent forced convection in pillow-plate channels. Their study focused on accurately predicting the Nusselt number (Nu) and the associated friction factor (f). A critical theoretical concept highlighted in their work is the inevitable thermodynamic trade-off: while the highly active fluid dynamics induced by the dimples drastically enhance the overall heat transfer coefficient (U), they simultaneously impose a higher hydraulic resistance. This results in an increased pressure drop (ΔP) across the test section. Therefore, the core theoretical objective in analyzing forced convection within a PPHE is to evaluate this ratio—maximizing the Nusselt number while identifying an acceptable pressure penalty—to determine the true overall efficiency of the specific heat exchanger geometry.

III. METHODOLOGY

A. Research design The research design for this study is experimental and quantitative, focused on evaluating the thermal-hydraulic performance of a custom-fabricated heat exchanger under steady- state operating conditions. The experimental apparatus is engineered to facilitate a single-phase, liquid-to-liquid (water-to-water) heat exchange process operating strictly in a parallel-flow configuration.

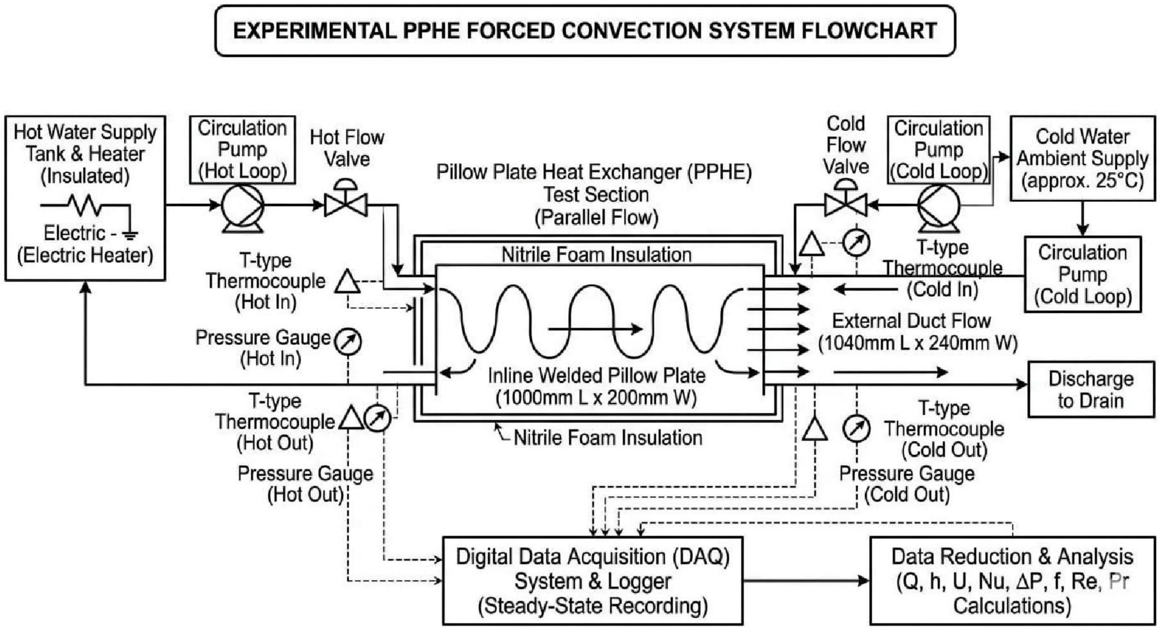
The core test section consists of an inline-welded pillow plate with overall dimensions of 1000 mm in length and 200 mm in width. To analyze the external flow characteristics, this plate is concentrically mounted inside a rectangular external duct measuring 1040 mm in length and 240 mm in width, providing a uniform 20 mm flow clearance around the perimeter of the plate. To enforce adiabatic boundary conditions and ensure that heat exchange occurs exclusively between the hot and cold fluid streams, the entire external duct assembly is heavily insulated using closed-cell nitrile elastomeric foam.

The experimental circuit is divided into two distinct fluid loops. The hot water stream, which flows through the internal wavy channels of the pillow plate, is driven by a circulation pump connected to a thermally insulated steel storage tank. This tank is equipped with an electric immersion heater and a thermostatic controller to precisely regulate the thermal load. The cold water stream, which flows over the external surface of the pillow plate within the duct, operates as an open-loop system drawing water at a constant ambient temperature of approximately 25°C. The testing matrix is designed to isolate the effect of thermal variation; therefore, the mass flow rates of both the hot and cold streams are maintained at a constant velocity throughout the testing phases. The primary independent variable is the hot water inlet temperature, which is systematically increased in discrete increments (e.g., 50°C, 60°C, and 70°C) to evaluate the system's convective response under varying degrees of thermal stress.

B. Data collection methods The reliability of the experimental findings depends on the precise and continuous measurement of system temperatures and pressures. To capture the thermal gradients across the test section, T-type (Copper-Constantan) thermocouples are strategically installed at four critical nodes: the inlets and outlets of both the internal hot water stream and the external cold water stream. T-type thermocouples were specifically selected for their high stability and superior accuracy within the operating temperature range of liquid water.

To evaluate the hydraulic penalty associated with the boundary layer disruption caused by the inline weld geometry, precision pressure gauges are mounted at the entrance and exit of the test section. This arrangement allows for the direct measurement of the absolute pressure drop across the longitudinal span of the heat exchanger.

All sensory instrumentation is interfaced with a centralized digital data acquisition (DAQ) logger. The data logger is programmed to sample and record the sensor outputs at regular, high-frequency intervals. Rather than relying on instantaneous manual readings, the automated continuous logging ensures that data points are only extracted for analysis after the system has reached a true steady- state condition—defined as the point where the recorded inlet and outlet temperatures fluctuate by less than a predefined negligible margin over a sustained period. Once thermal equilibrium is confirmed, the raw temperature and pressure data are aggregated. This raw data forms the basis for the subsequent data reduction phase, where fundamental thermodynamic equations and the Log Mean Temperature Difference method are applied to calculate the overall heat transfer coefficient, the convective heat transfer coefficient, the Nusselt number, and the corresponding friction factor



IV. RESULTS

A. Presentation of findings

The experimental test runs were successfully executed, with the custom-fabricated test rig achieving true steady-state conditions for each specified thermal load. The raw data, comprising continuous inlet and outlet temperature measurements alongside differential pressure readings, were compiled and averaged for each test case.

In accordance with the physical principles of a parallel-flow arrangement, the recorded temperature profiles exhibited the anticipated thermodynamic behavior. The maximum temperature gradient between the hot and cold streams was observed precisely at the entrance of the test section, with the temperatures of the two fluids asymptotically converging as they traversed the 1000 mm length of the external duct. As the thermal load was systematically increased—stepping the hot water inlet temperature through 50°C, 60°C, and 70°C against the constant 25°C cold water stream—the total measured heat transfer rate (Q) demonstrated a corresponding linear increase, driven by the larger initial temperature differential.

Regarding the hydraulic findings, the measured pressure drop (ΔP) across the test section remained highly stable across the testing matrix. Because the mass flow rates and physical fluid velocities were held constant throughout the experiment, the slight observed variations in the frictional pressure drop were minimal and can be primarily attributed to the temperature-dependent reduction in the dynamic viscosity (μ) of the hot water at elevated temperatures.

B. Data analysis and interpretation

To evaluate the fundamental thermal-hydraulic performance of the system, the raw sensory data was processed using the Log Mean Temperature Difference (LMTD) method. This mathematical reduction allowed for the precise calculation of the overall heat transfer coefficient (U) and the subsequent isolation of the convective heat transfer coefficient (h) for the internal inline-welded channels of the pillow plate.

The analysis of this derived data confirms the theoretical advantage of the hydroformed geometry. The empirical calculations revealed Nusselt numbers (Nu) that are substantially higher than baseline theoretical predictions for smooth, flat rectangular channels operating under equivalent Reynolds numbers (Re). This directly indicates that the inline weld spots and the resulting three-dimensional wavy channels successfully act as continuous turbulence promoters. By physically forcing the fluid to navigate these dimpled structures, the geometry repeatedly disrupts the formation of the thermal boundary layer, generating localized secondary flows that drastically augment convective thermal mixing.

However, the interpretation of the hydraulic data highlights the inherent thermodynamic trade-off characteristic of Pillow Plate Heat Exchangers. The data analysis of the measured pressure differentials yielded friction factors (f) that are correspondingly higher than those of smooth-walled systems. The very same dimpled structures that enhance thermal mixing also introduce form drag and increased boundary friction. Nevertheless, when evaluating the overall thermal-hydraulic efficiency of the system, the data demonstrates that the significant augmentation in the convective heat transfer coefficient (h) effectively outweighs the hydraulic penalty. The results confirm that the inline pillow plate geometry provides a highly efficient and compact solution for forced convection heat transfer.

V. CONCLUSION

A. Summary of key findings

This experimental investigation successfully evaluated the thermal-hydraulic performance of an inline-welded Pillow Plate Heat Exchanger (PPHE) operating under steady-state, forced convection conditions. The custom-fabricated test rig, consisting of a 1000 mm × 200 mm pillow plate centered within a geometrically proportioned external duct, functioned reliably across all specified thermal parameters in a parallel-flow arrangement. The primary findings confirm that the unique, three- dimensional wavy channels created by the hydroforming process significantly augment thermal energy exchange. The continuous mechanical disruption of the thermal boundary layer by the inline weld spots induced localized turbulence, resulting in substantially higher convective heat transfer coefficients (h) and Nusselt numbers (Nu) when compared to traditional flat-plate baseline geometries.

While the empirical data demonstrated a clear enhancement in total heat transfer rate (Q) corresponding to the stepped increases in the hot water inlet temperature, it also quantified the inherent thermodynamic trade-off. The same dimpled structures responsible for improving thermal mixing intrinsically generated a higher frictional resistance, leading to an elevated pressure drop (ΔP) across the longitudinal axis of the test section. However, the overarching evaluation of the system's performance indicates that the significant gains in thermal efficiency effectively justify the moderate hydraulic penalty, proving the inline PPHE to be a highly efficient, compact thermal management solution.

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B. Contributions to the field

The findings of this study provide highly valuable, real-world empirical data to a field that currently relies heavily on idealized Computational Fluid Dynamics (CFD) simulations. Because the complex internal geometry of pillow plates prevents the use of universal straight-pipe correlations, physical experimentation is crucial. By systematically isolating the thermal variables while holding mass flow velocities constant, this research delivers precise baseline data on how an inline-welded PPHE responds to variable thermal loads in a parallel-flow configuration.

These empirical results contribute directly to the broader engineering community by offering validated reference points for the thermal-hydraulic behavior of hydroformed plates. This data bridges existing gaps in academic literature and provides process engineers, HVAC designers, and manufacturing system developers with the practical insights necessary to scale, optimize, and integrate pillow plate technologies into modern, energy-efficient industrial applications.

C. Recommendations for future research

While this study establishes a robust foundation for understanding forced convection in an inline PPHE, several avenues for future research remain to fully map the capabilities of this geometry. First, it is highly recommended to modify the experimental apparatus to support a counter-flow fluid arrangement. Comparing the Log Mean Temperature Difference (LMTD) and thermal effectiveness (€) of a counter-flow setup against the current parallel-flow data would provide a comprehensive thermodynamic profile of the system.

Secondly, future experimental matrices should incorporate variable mass flow rates for both the hot and cold streams. By systematically altering the fluid velocity, researchers can test the system across a much wider spectrum of Reynolds numbers (Re). This expansion is critical for developing highly accurate, proprietary empirical correlations (such as $Nu = C \cdot Re\ m \cdot Prn$) that can mathematically predict the performance of this specific inline weld geometry under any operational flow state.

Finally, subsequent studies should investigate the performance of the apparatus using working fluids with drastically different thermophysical properties, such as high-viscosity thermal oils or advanced nanofluids, to analyze the influence of the Prandtl number (Pr) on boundary layer disruption. Additionally, fabricating and testing a secondary pillow plate with a staggered weld-spot pattern would allow for a direct comparative analysis to determine which structural configuration offers the ultimate optimal balance between maximum heat transfer enhancement and minimum frictional pressure drop.

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