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Experimental Investigation of the Effect of Different Parameters on Plate and Frame Heat Exchanger Effectiveness

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ABSTRACT

Plate & frame heat exchangers use a series of metal plates to conduct heat transfer between fluids. These fluids are directed through specific channels, ensuring they remain isolated while allowing efficient heat exchange. In recent years, researchers have looked at how different characteristics affect heat exchanger performance. The purpose of this study is to examine the impact of various factors on the effectiveness of the heat exchanger. The experimental analysis was conducted using pure water, considering different Re numbers ranging from 6000 to 30000 and varying hot fluid inlet temperatures between 25°C and 35°C. It was observed that under turbulent flow conditions, the heat transfer effectiveness increased of 13.6% when the Reynolds number varied between Re = 6000 – 20000 at constant $T_{h,in}$=35°C. However, the extent of this increase diminished significantly within the Re = 20000-30000 range. When the inlet temperature of hot fluid was raised Th,in=25°C to 35°C the plate & frame heat exchanger effectiveness increased of 4.3%. This study provides a basis for future studies on heat exchangers used in industrial applications with different geometries and different fluids. It is considered that the results of this study could be used in the future to design more modular and efficient plate heat exchangers for industrial applications.

Plakalı ve Çerçeveli Isı Değiştiricisi Etkinliğine Farklı Parametrelerin Etkisinin Deneysel İncelemesi

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Anahtar Kelimeler
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ÖZ

Plakalı ve çerçeveli ısı değiştiricileri, akışkanlar arasında ısı transferini sağlamak için bir dizi metal plaka kullanır. Bu akışkanlar, belirli kanallar boyunca yönlendirilip izole edilmeleri sağlanırken verimli bir ısı alışverişi gerçekleşir. Son yıllarda, araştırmacılar farklı özelliklerin ısı değiştirici performansı üzerindeki etkilerini incelemişlerdir. Bu çalışmanın amacı, çeşitli faktörlerin ısı değiştiricinin etkinliği üzerindeki etkisini araştırmaktır. Deneysel analiz, farklı 6000 ile 30000 arasında değişen Re sayıları ve 25°C ile 35°C arasında değişen sıcak akışkan giriş sıcaklıkları dikkate alınarak saf su kullanılarak gerçekleştirilmiştir. Türbülanslı akış koşulları altında, $T_{h,in}$=35°C sabitken, Reynolds sayısının 6000 ile 20000 arasında değişmesi durumunda ısı transfer etkinliğinin %13,6 arttığı gözlemlenmiştir. Ancak, bu artış, Re = 20000-30000 aralığında önemli ölçüde azalmıştır. Sıcak akışkan giriş sıcaklığı $T_{h,in}$=25°C'den 35°C'ye artırıldığında, plakalı ve çerçeveli ısı değiştiricisinin etkinliği %4,3 artmıştır. Bu çalışma, farklı geometrilere ve farklı akışkanlar için endüstriyel uygulamalarda kullanılan ısı değiştiricileri üzerine yapılacak gelecekteki çalışmalar için bir temel oluşturmaktadır. Bu çalışma sonuçlarının, gelecekte endüstriyel uygulamalar için daha modüler ve verimli plakalı çerçeveli ısı değiştiricileri tasarımında kullanılabileceği düşünülmektedir.

1. INTRODUCTION

Plate heat exchangers (PHE) have grown more necessary components in a variety of sectors, including chemical processing, energy systems, food production, and HVAC systems, thanks to their small size, excellent heat transmission efficiency and ease of maintenance. These devices are highly prized for their capacity to offer a wide surface area for heat transmission in a confined volume, making them excellent for applications with limited space but critical thermal performance [1-2]. Khan et al. [1] shown that using corrugated plates in PHEs improves turbulence and boosts convective heat transfer.

In literature, studies in this field are quite diverse. Heat transfer enhancement methods, the impact of flow patterns, hydraulic performance, fouling, performance of the material used, CFD modeling and experimental studies are some of the research interests. In the past few decades, both experimental and numerical research have significantly improved our understanding of fluid flow phenomenon and heat transfer in PHEs. The chevron pattern on the plates, for example, has a considerable influence on heat transmission and pressure drop performance, as demonstrated by Martin [3] and Gherasim et al. [2]. The chevron angle is very important in defining the degree of turbulence within the heat exchanger, which has a direct influence on thermal performance and energy consumption [4]. Dvořák and Vít [5] utilized computational fluid dynamics (CFD) to investigate heat transfer and fluid flow in PHEs, providing valuable insights for device optimization. Mocnik et al. [6] studied the effect of low Reynolds number flow, $70 \leq Re \leq 469$, on heat exchanger plates in a dimple structure. They stated that there are dead and live zones in the flow channel in such a structure. According to their findings, as the Reynolds number rises, so does the volumetric proportion of dead zones. At $Re \geq 469$, the channel experiences totally turbulent flow. Jouhara et al. [7] experimentally and theoretically studied multi-pass heat pipe-based heat exchangers. The findings demonstrated that the Reynolds number and number of flows are closely related to heat transfer rate, with effectiveness improving as the number of flows rose. The use of nanofluids has emerged as a viable option for improving heat transmission in PHEs. Javadi et al. [8] discovered that adding nanoparticles to the working fluid can significantly enhance heat transfer rate, but it could also result in a rise in pressure loss. When designing PHE systems, it is critical to evaluate the trade-off between enhanced thermal performance and higher pumping power. Similarly, Rios-Iribe et al. [9] studied non-Newtonian fluids and their influence on the thermal-hydraulic performance of PHEs, adding to our understanding of fluid characteristics in these systems.

Zheng et al. [10] examined the heat transfer properties of plate heat exchangers utilized in solar power installations using various nanofluids. The results indicated that nanofluids induce more heat transfer along with pressure loss than the primary fluid. Ahmadi et al. [11] studied the thermal conductivity of nanofluids with experimental and theoretical studies. The study found that temperature, nanoparticle form, and condensation all had an impact on thermal conductivity. The findings suggested that the thermal conductivity of nanofluids increases with rising temperature and nanoparticle concentration. Yang et al. [12] researched the heat transfer approach of pure water on strip fins at 18 various values, stressing the significance of the ratio of a single cell's front fin tip area to the square of the fin thickness. The outcomes suggest that the smaller the ratio, the better the heat transfer capability of the water. Song et al. [13] investigated the heat transfer qualities of the strip fin at different Reynolds numbers, highlighting the importance of a relationship between the fins' heat transfer and flow resistance properties as a foundation for heat exchanger improvement. Jiang et al. [14] performed experimental and theoretical studies on the thermo-hydraulic qualities of liquid helium flow via offset-strip fins. The study identified a tendency in the fluctuation of fin performance under various temperature settings. Wang et al. [15] proposed a novel heat exchanger structure that combines optimized topology and the moving asymptotic technique. They examined the improved structure's thermal and hydraulic performance, as well as its channel composition. The findings indicate that parameter adjustments have an effect on topology. Yu et al. [16] used an efficient and exact technique to improve capsule-type plate heat exchangers. They used a back propagation neural network to generate an approximation model. Following optimization, the heat transfer coefficient improved by 8.3%, while the friction coefficient increased by 14.3%, hence improving the heat transfer effect.

Ho et al. [17] examined micro-surfaces using electrochemical etching, a new method for increasing the thermo-hydraulic capacity of plate heat exchangers. The experimental findings on heat transfer and pressure drop of smaller surfaces were obtained in the Reynolds number ranges of 3000-15000. Investigations illustrate that compared to a smooth surface, the friction factor and pressure drop rise, while the NTU number improves dramatically. Wci'slik [18] investigated the link between the Nusselt number and the efficiency of a TiO_2:SiO_2/EG: DI nanofluid injected in varying percentages to a chevron-type heat exchanger. The findings indicated that the Nusselt number has a considerable impact on efficiency. Liu et al. [19] provided a physical and mathematical model for a three-layer, two-channeled plate heat exchanger. The heat transfer efficiency and pressure drop results, utilizing water as the working fluid, are analyzed by integrating both numerical simulations and experimental data. Thermal stress and life analysis are also simulated at various temperatures. The results reveal that the lifespan reduces as the working temperature rises, stress concentration spots appear, and thermal stress increases. Kilic and Efeoglu [20] used the impinging fluid jet approach to statistically examine how nanofluids may improve heat transfer from the surface which subjected to high heat flux. The study evaluated the variance in the average Nusselt number. Nazari et al. [21] utilized nanoparticles for working fluids and vortex generators to improve the functioning of fin-plate heat exchangers. They investigated the hybrid nanofluid MWCNT-Fe_3O_4/H_2O with varied fin orientations. The use of vortex generators improves heat transfer mostly by reducing the thermal boundary layer and developing turbulent flow, whereas nanofluids enhance thermal performance by increasing the fluid's thermal conductivity. Dvořák and Vít [22] compared CAE methodologies for PHE design and utilized CFD simulations to simulate a plastic recuperative counter-flow PHE. Their findings revealed the efficacy of CFD tools in estimating pressure drop and heat transfer performance, offering an efficient alternative to experimental trials. They discovered that altering the plate pitch and thickness of the material could have major effects on both pressure drop and the heat transfer coefficient, making CFD an effective tool for developing PHE systems.

Al-Turki et al. [23] studied the frictional, thermal, and exergetic properties of non-parallel plate arrangements in PHE. Their study compares eight different non-parallel layouts to the standard parallel design frequently employed in PHEs. Using verified 3D numerical simulations, the paper demonstrates that non-parallel designs dramatically improve heat transfer performance, with certain configurations obtaining Nusselt values that much exceed those of parallel arrangements. The authors conclude that non-parallel plate layouts provide a viable option for increasing the efficiency of PHEs, particularly in applications requiring improved heat transfer.

Mikhaeil et al. [24] introduced a novel plate heat exchanger for adsorption heat pumps and heat energy storage systems. Their experimental setting indicated a significant increase in water adsorption efficiency, which contributed to a 310% gain in total system performance. This work highlights the potential for adsorber heat exchangers to transform adsorption-based thermal systems. Li and Hrnjak [25] studied the improper distribution of single-phase fluid flow in heat exchangers. The work employs both experimental and mathematical techniques to highlight the impact of unequal flow distribution among parallel streams on overall heat exchanger performance. Owing to the authors, pressure drop across headers and across channels has the largest influence on uneven distribution. Their findings reveal that flow maldistribution gets more significant as the number of plates grows, resulting in a loss of thermal efficiency. Two distribution models based on equal total pressure drop were presented and validated using experimental data, revealing that, while overall flow rate has little influence, the variety of plates has a considerable impact on uneven distribution.

Kilic et al. [26] emphasized the importance of surface deformations in industrial cylinders and performed computational analyses on the cooling process of a commercial cylinder with swirling jets for a variety of parameters, including Re number and hot fluid input temperature. As a result of their findings, they observed that an increase in the Reynolds number leads to a significant reduction in the temperature difference between the inner and outer surfaces of the cylinder, decreasing by 45.4%. This reduction indicates that higher Reynolds numbers enhance the convective heat transfer, promoting better thermal equilibrium within the system. A smaller temperature differential suggests that the heat is being more effectively transferred across the surfaces, likely due to the increased turbulence and fluid mixing associated with higher Reynolds numbers. Consequently, the efficiency of heat dissipation improves, highlighting the importance of Reynolds number optimization in such thermal systems.

Chen et al. [27] studied the reliability of a new plate heat exchanger construction in a solid oxide fuel cell (SOFC) setup. To investigate natural convection heat transmission in the SOFC setup, the researchers used an inverse computational technique that combined numerical simulations and experimental temperature measurements. Their findings show how the positioning of two ducts (high-temperature and low-temperature) influences the creation of primary vortices, velocity patterns, and air temperature distribution within the hot box. The study shows that reliable heat transfer predictions in systems with lower duct spacings require proper flow models, like the realizable k-ε model with a standard wall function.

A review of the literature reveals the presence of various types of heat exchangers and experimental studies with different types of fluids. Unlike previous studies, this research experimentally investigates the impact of different parameters on the effectiveness of a heat exchanger commonly used in industrial applications. Specifically, the study examines the effects of varying Re numbers between Re = 6000 - 30000 and hot fluid inlet temperatures ranging from Th,in = 25 ℃ - 55 ℃ on the effectiveness of the plate and frame heat exchanger. This study will provide a basis for future studies with different fluids for heat exchangers of different types and geometries.

2. MATERIAL AND METHOD

The plate-type heat exchanger used in this study is made of stainless steel, a material recognized for its high corrosion resistance, durability, and thermal conductivity, making it suitable for heat exchanger applications. The unit is made up of six plates, which play an important role in allowing heat transmission between fluids. The number of plates has a direct impact on the surface area available for heat exchange, with more plates typically resulting in higher heat transfer efficacy due to greater contact area between the fluids. The use of stainless steel as a material ensures that the exchanger can withstand a wide range of circumstances, including high temperatures and harsh conditions, without sacrificing its rigidity or performance. The heat transfer area is 480 cm2. In terms of dimensional dimensions, length is 450 mm, width is 250 mm and height is 100 mm. A list of the most commonly used heat exchanger materials in practice is presented in Table 1.

Table 1. The most frequently utilized heat exchanger materials in practice

Material	Maximum operation temperature (℃)	Typical application	References
Carbon steel	427	Low-cost heat exchangers in oil and gas industry	[28], [29]
Stainless steel	816	High-temperature, corrosive environments like chemical and power plants	[30], [31]
Copper	260	Electronics cooling and heat sinks	[28], [29], [31]
Copper alloy	400	Marine and desalination applications	[29], [31]
Aluminum alloy	204	Automotive and lightweight applications	[29], [32], [33]

The Reynolds number was selected between Re = 6000 - 30000 in the study. Pure water is used as cold and hot fluid. The plates of the heat exchanger were arranged to allow counterflow of hot water between them. In the experiment, hot water was introduced into the system at different flow rates with inlet temperatures of $T_{h,in}$ = 25 ℃, 35 ℃, 45 ℃, and 55 ℃, and the cold inlet temperature was kept constant at $T_{c,in}$= 20 ℃.

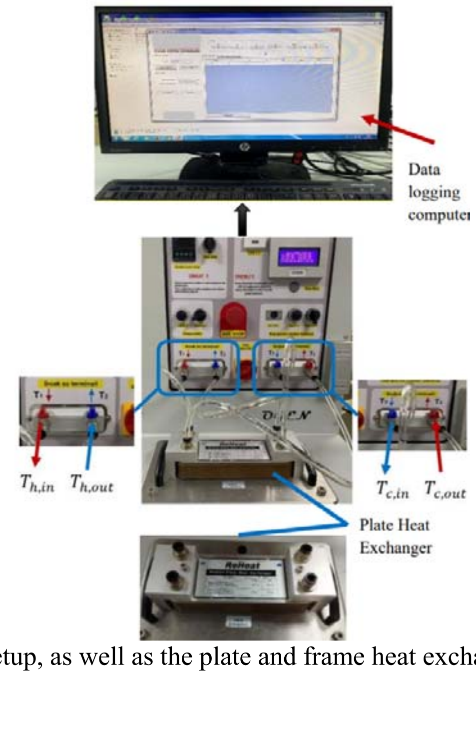

Figure 1. The experimental setup, as well as the plate and frame heat exchanger, are shown schematically

The technical requirements for the plate and frame heat exchanger, as shown in Table 2, emphasize the significance of material selection in determining the unit's performance and lifetime. The choice of materials, such as stainless steel or carbon steel, is crucial for guaranteeing longevity, corrosion resistance, and good heat conductivity. Choosing the proper material may have a considerable impact on the heat exchanger's heat transfer efficiency, capacity to endure operating conditions, and maintenance needs, all of which have a direct impact on both operational costs and system dependability over time.

Table 2. Technical details of the plate & frame heat exchanger and experiment parameters

Plate & frame heat exchanger	
Plate material	Stainless steel
Plate number	6
Heat transfer area	480 cm^2
Length*width*height	450*250*100 mm

The heat exchanger plate is made of stainless steel, which is known for its exceptional corrosion resistance, high temperature tolerance, and mechanical strength. These characteristics guarantee consistent performance under a variety of temperature and chemical environments while retaining structural integrity. The six plates offer a balanced heat transfer surface area of 480 cm², maximizing heat exchange while reducing space needs. The tiny dimensions (450*250*100mm) reflect a design that is optimized for efficiency in areas where space and energy savings are critical, without sacrificing performance.

To get reliable and useful findings from studies using the plate and frame heat exchanger, flow parameters must be precisely set. The choice of Reynolds numbers and inlet temperatures for both hot ($T_{h,in}$) and cold ($T_{c,in}$) streams is critical, since they have a direct impact on heat transfer efficacy and system performance. The Reynolds number, which regulates the flow regime (laminar or turbulent), is changed to mimic various operational circumstances. Inlet temperatures are calibrated to create a constant thermal gradient between the hot and cold streams, resulting in detectable heat transfer behavior throughout a wide variety of flow rates and thermal loads. The working ranges of the parameters in the experimental study are expressed in the table.

Table 3. The parameters performed in the study

Experiment parameters		
Re number	**$T_{h,in}$ (°C)**	**$T_{c,in}$ (°C)**
6000	25	20
15000	35	20
20000	45	20
30000	55	20

The flow parameters used in this study are especially intended for systems that run at low temperatures, such as waste heat recovery systems, where efficiency in moderate thermal settings is critical. These systems often deal with small temperature differentials; thus, it is critical to optimize flow conditions for optimal heat transmission. The Reynolds values used (6000 to 30000) range from lower to higher turbulent flow regimes, ensuring that a wide range of operating scenarios are covered. This range is appropriate for applications that demand improved convective heat transfer while minimizing pressure losses. The cold input temperature is kept constant at 20°C to imitate circumstances often observed in industrial cooling operations, while altering the hot inlet temperature enables for the evaluation of heat exchanger performance under various thermal loads. This technique gives full knowledge of the system's behavior in real-world applications requiring waste heat recovery at low to moderate temperatures.

3. DATA REDUCTION

In this experimental study, inlet temperature and Reynolds number are used as parameters to calculate heat transfer performance and effectiveness. The Reynolds number (Re), a dimensionless quantity, is calculated using the following equation: (1-4) [34]

$$Re = \frac{\rho V D_h}{\mu} \tag{1}$$

where ρ is the fluid density (kg/m³), V is the fluid velocity (m/s), Dh is the hydraulic diameter of the fluid inlet (m), and μ is the fluid's dynamic viscosity (Pa·s). This formula links essential flow properties, assisting in determining whether the flow regime is laminar, transitional, or turbulent. The Reynolds number is critical in the analysis of fluid flow and heat transfer in heat exchangers, since it has a direct influence on convective heat transfer efficiency. For hot and cold fluid flows:

$$\dot{Q}_{cold} = \dot{m}_c c_{pc}(T_{c,out} - T_{c,in}) \tag{2}$$

$$\dot{Q}_{hot} = \dot{m}_h c_{ph}(T_{h,in} - T_{h,out}) \tag{3}$$

The expression $\dot{m}_c c_p$ is the product of the specific heat and the mass flow rate of the fluid and is calculated separately for each of the hot fluid and cold fluid.
Maximum heat transfer rate in the heat exchanger is determined as;

$$\dot{Q}_{max} = C_{min}\Delta T_{max} \tag{4}$$

Heat transfer effectiveness is expressed by the dimensionless parameter ε and is defined as

$$\varepsilon = \frac{Q_{act}}{Q_{max}} = \frac{Actual\ heat\ transfer\ rate}{Maximum\ heat\ transfer\ rate} \tag{5}$$

The actual heat transfer rate is the quantity of heat exchanged between fluids during the operation of a heat exchanger [34]. It is an important aspect in calculating the heat exchanger's efficacy, which is the ratio of actual heat transfer to maximal heat transfer under ideal conditions. The maximum heat transfer implies ideal efficiency, but the actual heat transfer considers real-world variables such as fluid flow rates, temperature variations, and the heat exchanger's physical design. This ratio assesses the heat exchanger's efficiency in comparison to its theoretical maximum.

4. RESULTS AND DISCUSSION

4.1. Effect of Different Re Number on Heat Exchanger Effectiveness

At a constant water temperature of 35°C, the flow rate was gradually adjusted, resulting in an increase in the Reynolds number from Re = 6000 to Re = 30000. The experimental results revealed that when the hot inlet temperature $T_{h,in}$ was maintained at 35°C, the effectiveness of the heat exchanger increased significantly as the Reynolds number rose from Re = 6000 to Re = 20000. Beyond Re = 20000, however, the increase in effectiveness was minimal. (Figure 2)

At 35 °C, while the effectiveness increased by 11.6% as the Reynolds number raise from Re = 6000 to Re = 20000, only a 2.0% increase was observed when the Reynolds number further increased from Re = 20000 to Re = 30000.

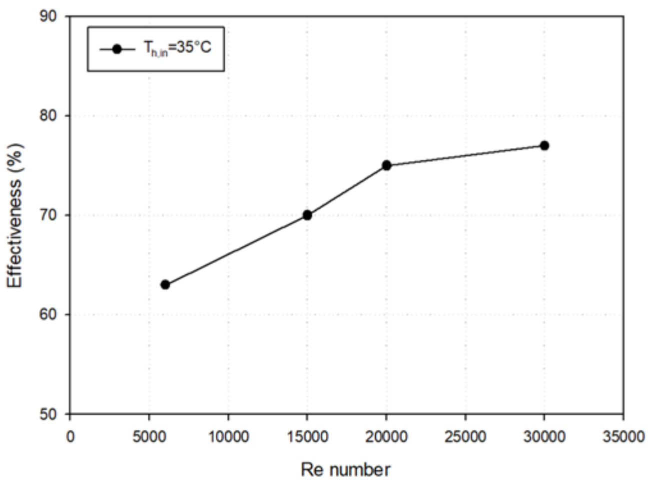

Figure 2. Variation of heat exchanger effectiveness at different Reynolds numbers at constant hot inlet temperature

The results clearly demonstrate that raising the Reynolds number from 6000 to 20000 at a constant input temperature of 35°C improves heat exchanger efficacy by 11.6%, owing to improved turbulence and convective heat transfer. However, above Re = 20000, the gain in effectiveness is negligible, at just 2%, showing that the system is approaching an ideal turbulence level where additional increases in flow rate provide diminishing benefits. This demonstrates the practical limitations of the Reynolds number's influence on heat transfer within this setup.

4.2. Effect of Different Hot Inlet Temperatures on Heat Exchanger Effectiveness

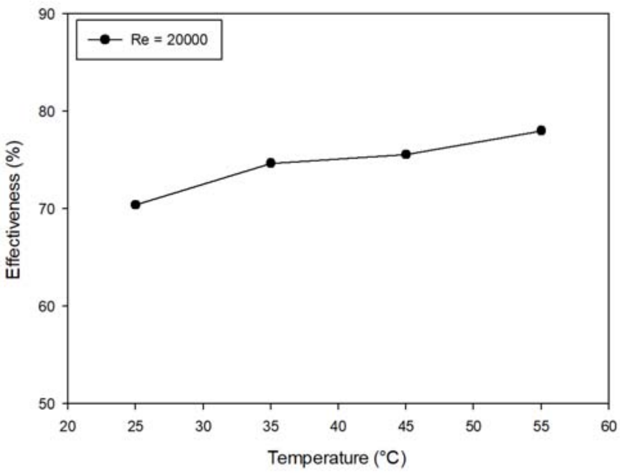

Figure 3. The effect of different $T_{h,in}$ temperature on the constant Re = 20000 on the effectiveness

When examining the effect of hot inlet temperature on effectiveness at a constant Reynolds number of 20000, a total increase of 7.6% in effectiveness was observed as the temperature increased from 25°C to 55°C. The most significant increase, 4.3%, occurred between 25°C and 35°C. Subsequently, a more moderate increase of 2.4% was noted between 45°C and 55°C. This pattern suggests that the initial rise in inlet temperature significantly enhances effectiveness, but the rate of increase slows as the temperature approaches higher levels (Figure 3).

5. CONCLUSIONS

In this study, the effect of different parameters on the effectiveness of plate and frame heat exchanger was investigated experimentally. The investigated parameters are Re number ranging from 6000 to 30000 and hot fluid inlet temperature ranging from 25 °C to 55 °C. In conclusion;

a. When the Reynolds number was rose in the range of 6000-30000, it was determined that the heat exchanger effectiveness increased of 13.6% at a constant $T_{h,in}$ = 35 °C. It was examined that the heat exchanger effectiveness increases at all Re numbers since the velocity of the fluid increases the value of the overall heat transfer coefficient.

b. When the inlet temperature of hot fluid was increased in the range o $T_{h,in}$ = 25 °C - 55 °C, it was determined that the heat exchanger effectiveness increase of 4.3%. The comparatively minor improvement in effectiveness at higher inlet temperatures can be ascribed to the fact that heat exchanger performance is not primarily determined by inlet temperature. While the intake temperature affects the thermal gradient between the hot and cold fluids, the total performance of the heat exchanger is determined by a number of parameters, including heat exchanger design, flow characteristics, and available surface area for heat transfer. As the temperature rises, the system may reach a point where further increases in inlet temperature have diminishing impacts on efficacy due to constraints in these other elements, such as the previously set flow regime or the exchanger's maximum heat transfer capacity.

c. Based on the findings of this study, future research can explore the performance of various heat exchanger types and alternative working fluids, such as nanofluids, across differently structured heat transfer surface areas. These investigations could provide valuable insights into optimizing heat exchanger designs. Additionally, the results of this study offer a foundation for developing new heat exchanger models with modular construction, aiming to achieve superior heat transfer effectiveness and adaptability for diverse industrial applications.

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ABBREVIATIONS

PHE	Plate Heat Exchangers
NTU	Number of transfer unit
Re	Reynolds number
$T_{h,in}$	Inlet temperature of hot fluid
CAE	Computer-Aided Engineering
SOFC	Solid Oxide Fuel Cell
$T_{c,in}$	Inlet temperature of cold fluid
HVAC	Heating, Ventilation, and Air Conditioning
$T_{c,out}$	Outlet temperature of cold fluid
EG	Ethylene Glycol
$T_{h,out}$	Outlet temperature of hot fluid
DI	Deionized Water
MWCNT	Multi-Walled Carbon Nanotubes