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COMPARATIVE THERMODYNAMIC ANALYSIS OF DIFFERENT TYPES OF HEAT EXCHANGERS

Heat exchangers are among the most important components used in many industrial thermal systems such as power plants, chemical processes, refrigeration systems, and HVAC applications. Their efficient utilization plays a significant role in improving energy efficiency and reducing operational costs. In particular, the selection of an appropriate heat exchanger type is a crucial factor affecting the thermal performance and reliability of energy systems. In this study, a comparative thermodynamic analysis of three different heat exchanger types—double pipe, shell-and-tube, and plate heat exchangers—was performed experimentally. The performance of these heat exchangers was evaluated under different operating conditions. The cold water flow rate in the experimental setup was kept constant at 1.5 L/min, while the hot water flow rate was varied as 0.8, 1.6, and 2.4 L/min. In addition, the hot water inlet temperature was selected as 50°C, 60°C, and 70°C. Experiments were carried out for both parallel-flow and counter-flow configurations. The thermodynamic performance of each heat exchanger was evaluated using heat transfer rate and power density parameters calculated from the experimental data. The results showed that increasing the inlet temperature and flow rate significantly enhanced the heat transfer rate. Furthermore, the counter-flow configuration provided better thermal performance compared to the parallel-flow configuration. Among the tested heat exchanger types, the shell-and-tube heat exchanger exhibited the highest power density, while the double pipe heat exchanger showed the lowest performance. The obtained results indicate that the appropriate selection of heat exchanger type can significantly improve the efficiency of thermal systems. The findings of this study provide useful experimental data for selecting suitable heat exchanger types in thermal systems and may contribute to improving the efficiency of industrial heat transfer applications. In addition, the presented analysis may serve as a useful reference for future experimental and numerical studies on heat exchanger performance. Furthermore, the obtained results highlight the importance of selecting appropriate operating conditions and heat exchanger configurations in practical applications. The experimental comparison presented in this study contributes to a better understanding of the performance differences among commonly used heat exchanger types and may support engineers and researchers in designing more efficient thermal systems.

Keywords: *Heat exchanger, thermodynamic analysis, heat transfer, double pipe heat exchanger, shell-and-tube heat exchanger, plate heat exchanger, thermal performance.*

Introduction. Thermal applications play a significant role in meeting the increasing global demand for energy. In such systems, cost, efficiency, and environmental considerations are among the most important factors that must be addressed. Efficient utilization of energy while minimizing environmental impact has therefore become a major objective in modern thermal engineering systems. In this context, heat exchangers are considered one of the most essential components of thermal applications [3]. Heat exchangers are devices that enable heat transfer between two or more fluids at different temperatures without direct mixing. Such heat transfer processes are widely encountered in many engineering applications including heating, ventilation and air-conditioning (HVAC) systems, refrigeration technologies, and industrial heat recovery systems [4, 5]. Due to their importance in energy systems, improving the thermal performance of heat exchangers has become a major research focus in recent years [6].

Various techniques have been proposed to enhance heat transfer performance in heat exchangers, including the use of extended surfaces, surface modifications, and turbulence generation within the flow field [7]. In addition, selecting the most appropriate heat exchanger configuration is a crucial step in solving heat transfer problems. The selection process generally depends on operating parameters such as temperature levels, flow rates, pressure drops, construction materials, and economic considerations [8-12]. Among different heat

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exchanger types, tubular heat exchangers are widely used in industrial applications due to their relatively simple structure and effective heat transfer performance. In these systems, one fluid flows through the tubes while the second fluid flows outside the tubes, allowing heat transfer through the tube wall. Tubular heat exchangers can be designed in different configurations such as shell-and-tube, double-pipe, and spiral heat exchangers. Among these types, shell-and-tube heat exchangers are the most widely used because they can operate under a wide range of temperatures and pressures. Shell-and-tube heat exchangers consist of a shell containing a bundle of tubes through which one fluid flows while the second fluid circulates on the shell side. Their flexible design allows them to be manufactured in various sizes and flow arrangements, making them suitable for many industrial processes [12]. The heat transfer performance of these heat exchangers depends on several geometric and operational parameters such as tube diameter, shell diameter, tube arrangement, and baffle configuration [13]. Numerous studies have been conducted to improve the performance of shell-and-tube heat exchangers. For example, Shah and Sekulic (2003) and Abd and Naji (2017) investigated the influence of geometric parameters on heat transfer characteristics. Similarly, Shinde and Chavan (2017) reported that tube spacing and baffle configuration significantly affect heat transfer performance. Other studies have also shown that parameters such as baffle spacing, tube arrangement, and shell diameter play an important role in improving heat transfer efficiency and reducing pressure losses [14-18]. Double-pipe heat exchangers represent one of the simplest heat exchanger configurations. In this design, a smaller pipe is placed concentrically inside a larger pipe, allowing one fluid to flow through the inner pipe while the other flows through the annular space. Due to their simple construction, flexibility, and relatively low installation and maintenance costs, double-pipe heat exchangers are widely used in industrial applications. However, their main limitation is the relatively large surface area required for high heat transfer rates [18]. Various studies have proposed methods for improving their thermal performance through the use of turbulence promoters and enhanced surfaces. Plate heat exchangers are another widely used heat exchanger type consisting of thin metal plates that form flow channels between them. These heat exchangers are known for their compact structure and high heat transfer efficiency due to the turbulence generated by the plate geometry. Plate heat exchangers are commonly used in heating, cooling, heat recovery, condensation, and evaporation processes [19]. In applications involving high operating pressures, heat exchangers designed for low-pressure conditions are generally unsuitable. For operating temperatures below approximately 200 °C, gasketed plate heat exchangers are often preferred due to their compact design and high efficiency. However, for systems operating at higher temperatures and pressures, double-pipe, shell-and-tube, or welded plate heat exchangers are typically more suitable. In particular, double-pipe heat exchangers are appropriate for small-capacity systems operating under relatively high-pressure conditions [20].

Researchers have also applied different optimization techniques to improve the thermal performance of heat exchanger systems. Several studies have used advanced optimization algorithms to enhance the performance of shell-and-tube, plate-fin, and regenerative heat exchangers [21,22]. In this study, the thermal performance of different heat exchanger types is comparatively analyzed, and the effects of varying flow rate and temperature on heat exchanger performance are investigated. Despite the extensive research conducted on heat exchanger design and performance optimization, comparative experimental studies evaluating different heat exchanger types under similar operating conditions remain limited in the literature. In particular, the influence of varying flow rates and inlet temperatures on the thermal performance of different heat exchanger configurations requires further investigation. Therefore, the present study aims to provide a comparative thermodynamic analysis of different heat exchanger types under controlled experimental conditions in order to better understand their performance characteristics.

Materials and methods

The schematic diagram of the experimental setup used in this study is presented in Figure 1.

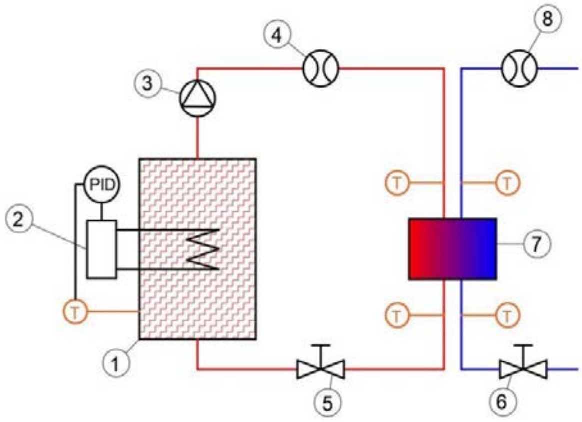

Fig. 1. Schematic diagram of the experimental heat exchanger test system
1 – Tank; 2 – Electric heater; 3 – Pump; 4 – Flow meter (hot water); 5 – Control valve (hot water); 6 – Control valve (cold water); 7 – Heat exchanger; 8 – Flow meter (cold water)

The experimental system mainly consists of two main sections: a heating tank used for heating the hot water and a test section where different types of heat exchangers are installed. The water in the tank is heated by an electrical resistance heater. A Pt100 temperature sensor located in the middle of the tank is connected to a PID temperature controller, which allows the water temperature to be adjusted to the desired level. A circulation pump located at the outlet of the tank is used to control the flow rate of the working fluid. The heated fluid passes through a vane-type flow meter and the heat exchanger before returning to the tank, completing the circulation loop. The heat exchanger section of the experimental setup is modular, allowing different heat exchanger types to be easily installed or removed using connection fittings. In the test section, four connection hoses are used for the inlet and outlet of the heat exchangers: two for the hot fluid line and two for the cold fluid line. Temperature measurements at both the inlet and outlet of the hot and cold streams are obtained using K-type thermocouples.

All experimental data are monitored and recorded through an automation system. The heat exchanger types used in the performance tests and their corresponding flow configurations are illustrated in Figure 2.

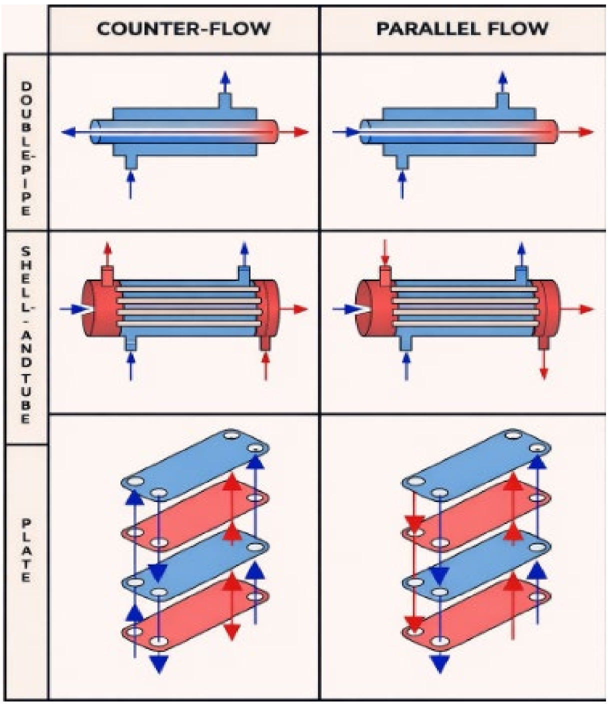

Fig. 2. Schematic representation of counter-flow and parallel-flow configurations for different heat exchanger types: double-pipe, shell-and-tube, and plate heat exchangers.

Data Processing

In the experimental system, it was assumed that the entire heat transferred by the hot fluid in the test section was conveyed to the cold fluid through the convection mechanism. Therefore, heat losses to the surroundings were neglected, and the amount of heat absorbed by the cold fluid was calculated using Equation (1). The ratio of Equation (2) to Equation (1) was used to verify whether the heat losses in the system were negligible. Since the three different heat exchanger types installed in the test section have different heat transfer surface areas, the heat transfer areas vary for each configuration. Equation (3) represents the power density values obtained by dividing the heat transfer rate of each heat exchanger by its corresponding heat transfer surface area.

The heat exchanger types used in the experiments and their corresponding heat transfer surface areas are presented in Table 1.

Table 1

Heat exchanger types used in the experiments and their heat transfer surface areas

Heat Exchanger Type	Heat Transfer Surface Area (m²)
Double-Pipe Heat Exchanger	0.025
Plate Heat Exchanger	0.048
Shell-and-Tube Heat Exchanger	0.020

$$Q_{gain}=\dot{m}C_p(T_{out,c}-T_{in,c}) \tag{1}$$

$$Q_{loss}=\dot{m}C_p(T_{in,h}-T_{out,h}) \tag{2}$$

$$q''=Q/A \tag{3}$$

Uncertainty Analysis

The uncertainty of the experimental parameters was evaluated using the method proposed by Kline and McClintock [23]. In this method, R represents the result function of the system, while $x_1, x_2, x_3, \ldots, x_n$ denote the independent variables affecting R:

$$R = R(x_1, x_2, \ldots, x_n)$$

If $w_1, w_2, \ldots, w_n$ represent the uncertainties of the independent variables, the overall uncertainty of the result can be calculated as follows (Kline and McClintock, 1953):

$$W = \left[(\partial R/\partial x_1 \cdot w_1)^2 + (\partial R/\partial x_2 \cdot w_2)^2 + \ldots + (\partial R/\partial x_n \cdot w_n)^2 \right]^{1/2} \tag{4}$$

In this study, the uncertainties of the main experimental parameters, temperature and flow rate, were calculated using the values presented in Table 2. The uncertainty of temperature measurement was determined as ±1.224 °C, while the uncertainty of the flow rate measurement was ±0.0141.

Device	Technical Specification	Accuracy	Total Uncertainty
Data logger	K-type thermocouple; measurement range (-200 °C – 1200 °C)	±0.5 °C	±1.224 °C
Flow meter	Measurement range (0 – 30 L/min)	±0.01 L/min	±0.0141

Results and Discussion

In this section, the power outputs of three different heat exchanger types used in the experiments are presented and compared under different temperature and flow rate conditions. In addition, the power density values of the heat exchangers are evaluated. Both temperature and flow rate significantly affect the performance of the heat exchangers. For all three heat exchanger types, the counter-flow configuration showed better performance than the parallel-flow configuration under the same operating conditions.

For the double-pipe heat exchanger under counter-flow conditions at a flow rate of 2.4 L/min, the power values were 1440.7 W, 1527.6 W, and 1609.1 W at 50 °C, 60 °C, and 70 °C, respectively.

For the shell-and-tube heat exchanger, the corresponding power values were 1538 W, 1628.4 W, and 1696.3 W.

For the plate heat exchanger, the power values were significantly higher, reaching 3955.2 W, 3996.4 W, and 4098.9 W at the same temperature conditions.

These values correspond to the results obtained at a flow rate of 2.4 L/min under counter-flow conditions. The power values for other flow rates are presented graphically in Figures 3, 4, and 5. Although the plate heat exchanger produced the highest power output, the highest power density (power per unit heat transfer area) was not obtained from the plate heat exchanger. The power density results are presented in Figures 6, 7, and 8.

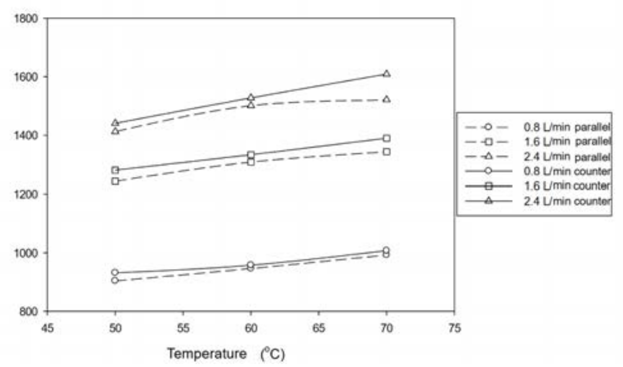

Fig. 3. Temperature–power graph for the double-pipe heat exchanger

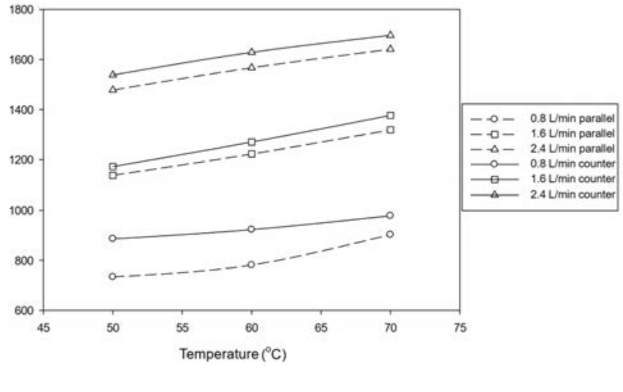

Fig. 4. Temperature–power graph for the shell-and-tube heat exchanger

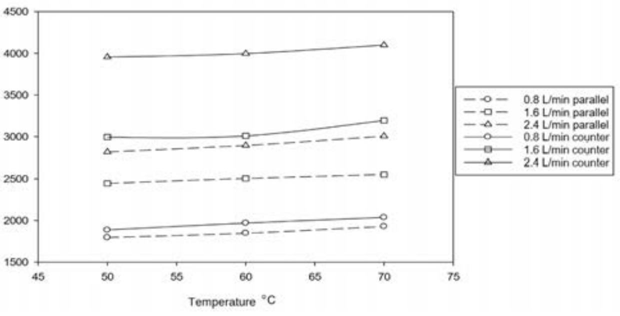

Fig. 5. Temperature–power graph for the plate heat exchanger

As can be seen from the obtained values, variations in temperature and flow rate resulted in different responses for each heat exchanger type. It is considered that this variation is closely related to the heat exchanger type and its design characteristics. Based on the experimental data, selecting the optimum operating parameters and the appropriate heat exchanger type significantly affects the thermal performance.

When Figures 6, 7, and 8 are examined, it is observed that the highest power density was obtained in the shell-and-tube heat exchanger, while the lowest power density was obtained in the double-pipe heat exchanger. For each heat exchanger type, better performance was achieved under counter-flow conditions.

For the shell-and-tube heat exchanger, which showed the best performance, the power density values at hot water flow rate of 0.8 L/min were 44.28 kW/m², 46.13 kW/m², and 48.88 kW/m² at temperatures of 50, 60, and 70 °C, respectively. At a hot water flow rate of 1.6 L/min, the power density values at 50, 60, and 70 °C were 59.60 kW/m², 63.51 kW/m², and 68.82 kW/m², respectively. When the hot water flow rate was 2.4 L/min, the power density values at 50, 60, and 70 °C were 92.61 kW/m², 96.94 kW/m², and 99.60 kW/m², respectively.

Based on these results, the highest power obtained per unit heat transfer area (m²) was 99.60 kW/m² using the shell-and-tube heat exchanger under counter-flow conditions at a flow rate of 2.4 L/min. On the other hand, the lowest power value was obtained with the double-pipe heat exchanger under parallel-flow conditions at a flow rate of 0.8 L/min, with a value of 36.15 kW/m².

Figures 6, 7, and 8 present the power density values at different flow rates for the heat exchanger types used in the experiments.

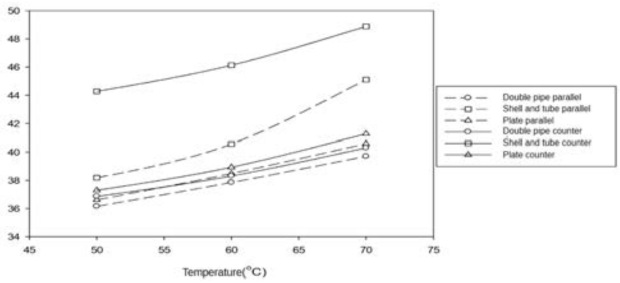

Fig. 6. Power density comparison of different heat exchanger types at a flow rate of 0.8 L/min

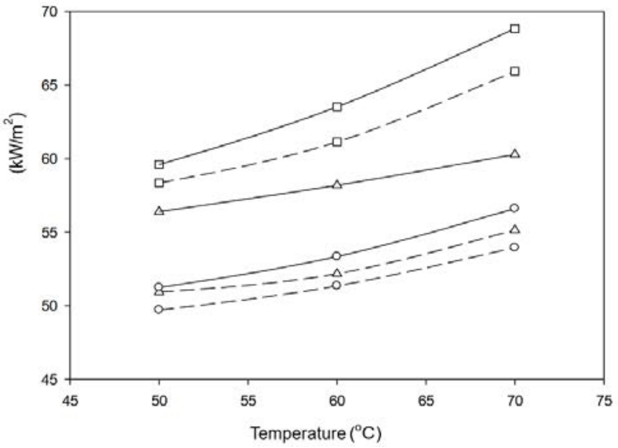

Fig. 7. Power density comparison of different heat exchanger types at a flow rate of 1.6 L/min

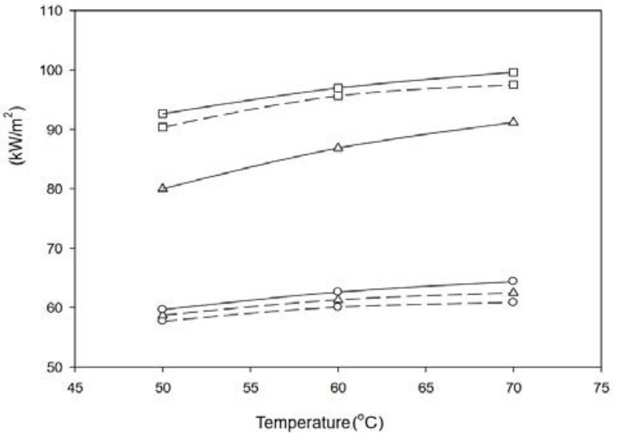

Fig. 8. Power density comparison of different heat exchanger types at a flow rate of 2.4 L/min

Conclusion. Heat exchangers are widely used in industrial thermal systems, and their efficient utilization plays a critical role in improving heat transfer performance. In this study, the performances of three commonly used heat exchanger types—double-pipe, shell-and-tube, and plate heat exchangers—were experimentally compared. The experiments were conducted at three inlet water temperatures (50 °C, 60 °C, and 70 °C) and three flow rates (0.8 L/min, 1.6 L/min, and 2.4 L/min). The experimental results indicated that increasing both the inlet water temperature and flow rate significantly enhanced the heat transfer rate. In addition, for all heat exchanger types, the counter-flow configuration provided better thermal performance compared to the parallel-flow configuration. Among the investigated heat exchanger types, the shell-and-tube heat exchanger demonstrated the highest sensitivity to temperature changes. The counter-flow configuration improved the power density by approximately 3.87% for the shell-and-tube heat exchanger, 3.89% for the double-pipe heat exchanger, and 11.53% for the plate heat exchanger compared to the parallel-flow configuration. The influence of flow direction was found to be most significant in the plate heat exchanger, while the double-pipe and shell-and-tube heat exchangers exhibited similar sensitivity to flow direction.

Furthermore, under counter-flow conditions, the shell-and-tube heat exchanger provided approximately 19.06% higher power density compared to the double-pipe heat exchanger, while the plate heat exchanger provided approximately 9.09% higher power density. Under parallel-flow conditions, the shell-and-tube heat exchanger achieved about 18.08% higher power density than the double-pipe heat exchanger, whereas the plate heat exchanger provided approximately 1.61% higher power density. Overall, considering the power density per unit heat transfer area, the performance ranking of the investigated heat exchangers from highest to lowest was determined as: shell-and-tube heat exchanger, plate heat exchanger, and double-pipe heat exchanger. In addition, the results of this study demonstrate that the appropriate selection of heat exchanger type and operating conditions can significantly influence the overall efficiency of thermal systems. The experimental findings obtained in this work may provide useful guidance for engineers and researchers in selecting suitable heat exchanger configurations for various industrial applications.

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Еюбова К. ПОРІВНЯЛЬНИЙ ТЕРМОДИНАМІЧНИЙ АНАЛІЗ РІЗНИХ ТИПІВ ТЕПЛООБМІННИКІВ

Теплообмінники є одними з найважливіших компонентів, що використовуються у багатьох промислових теплових системах, таких як електростанції, хімічні процеси, холодильні системи та системи опалення, вентиляції і кондиціонування повітря (HVAC). Ефективне використання теплообмінників відіграє важливу роль у підвищенні енергоефективності та зниженні експлуатаційних витрат. Тому аналіз і порівняння різних типів теплообмінників привертають значну увагу в останні роки [1–3].

Зокрема, вибір відповідного типу теплообмінника є ключовим фактором, що впливає на теплову ефективність і надійність енергетичних систем. У цьому дослідженні експериментально проведено порівняльний термодинамічний аналіз трьох різних типів теплообмінників: двотрубного, кожухотрубного та пластинчастого теплообмінників. Ефективність цих теплообмінників оцінювалася *за різних умов експлуатації. Витрата холодної води в експериментальній установці підтримувалася сталою на рівні 1,5 л/хв, тоді як витрата гарячої води змінювалася і становила 0,8; 1,6 та 2,4 л/хв. Крім того, температура на вході гарячої води була обрана на рівні 50°C, 60°C і 70°C. Експерименти проводилися як для паралельної, так і для протитечійної схем руху теплоносіїв. Термодинамічні характеристики кожного теплообмінника оцінювалися за допомогою параметрів теплового потоку та густини потужності, розрахованих на основі експериментальних даних. Результати показали, що підвищення температури на вході та витрати рідини суттєво збільшує інтенсивність теплопередачі. Крім того, протитечійна схема забезпечує кращу теплову ефективність порівняно з паралельною. Серед досліджених типів теплообмінників кожухотрубний теплообмінник продемонстрував найвищу густину потужності, тоді як двотрубний теплообмінник показав найнижчу ефективність. Отримані результати свідчать про те, що правильний вибір типу теплообмінника може суттєво підвищити ефективність теплових систем. Результати цього дослідження надають корисні експериментальні дані для вибору відповідних типів теплообмінників у теплових системах і можуть сприяти підвищенню ефективності промислових процесів теплопередачі. Крім того, представлений аналіз може слугувати корисним джерелом для подальших експериментальних і чисельних досліджень ефективності теплообмінників. Отримані результати також підкреслюють важливість правильного вибору умов експлуатації та конфігурацій теплообмінників у практичних застосуваннях. Представлене експериментальне порівняння сприяє кращому розумінню відмінностей у продуктивності між поширеними типами теплообмінників і може допомогти інженерам та дослідникам у проєктуванні більш ефективних теплових систем.*

Ключові слова: *теплообмінник, термодинамічний аналіз, теплообмін, двотрубний теплообмінник, кожухотрубний теплообмінник, пластинчастий теплообмінник, теплові характеристики.*

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