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Evaluating the Thermal Performance of Shell-and-Tube Heat Exchangers: The Role of Flow Rate in Water-Based Systems

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ABSTRACT

This research investigates the performance of water as a working fluid in the shell side of shell-and-tube heat exchangers (STHEs), explicitly analyzing how variations in flow rate influence the heat transfer rate, pressure drop, and friction factor characteristics. Experiments were conducted using an STHE with a SUS 201 stainless steel shell and a pure copper tube featuring an inner diameter of 10 mm and an outer diameter of 13 mm. The flow rates of the cold fluid varied at 9, 10, and 12 liters per minute (LPM), while the hot fluid flow was maintained at a constant rate of 6.67 LPM. A PID system was used and controlled by a 600 W heater to evaluate thermal performance, with water serving as the hot fluid on the shell side and the cold fluid on the tube side. Results demonstrate a significant increase in the heat transfer rate with higher flow rates of the cold fluid, with the maximum heat transfer rate recorded at 12 LPM and the minimum at 9 LPM. The STHE exhibited high efficiency, with heat transfer rate differences between the shell and tube sides remaining below 5%. Although pressure fluctuations were observed with increasing flow rates, they did not substantially affect the friction factor, indicating a predominantly turbulent flow regime. These findings provide critical insights for optimizing heat transfer performance in STHEs, contributing to advancements in thermal management technologies and enhancing the design of efficient heat exchangers.

Keywords: *Friction factor, Reynolds number, Heat transfer rate, Pressure drops, Shell and tube heat exchanger*

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1. INTRODUCTIONS

Studying heat transfer technology is crucial for improving operational efficiency and optimizing production processes across various industries [1-4]. It is essential in sectors that depend heavily on heat energy transfer, such as the oil and gas industry, where optimizing heat transfer processes is necessary [5-7]. Heat exchanger technology, which relies on temperature and pressure differences between two fluids separated by a thin boundary within distinct devices, is central to these processes [8]. This work examines the role and findings of a study on heat exchanger technology, focusing on three primary types of heat exchangers. Recent evaluations underscore the importance of efficiency, fluid flow velocity, and variations in flow rate in understanding the performance and practical applications of heat exchangers. Specifically, the article explores the impact of fluid flow rate in shell and tube heat exchangers (STHEs) using water as the working fluid in the shell and water in the tube, with the co-current flow direction. It offers a detailed analysis of both theoretical and practical aspects to provide a comprehensive understanding of efficiency and heat transfer within this heat exchanger technology [9]. The figure depicting STHE type-E has been adapted from the TEMA standard [10].

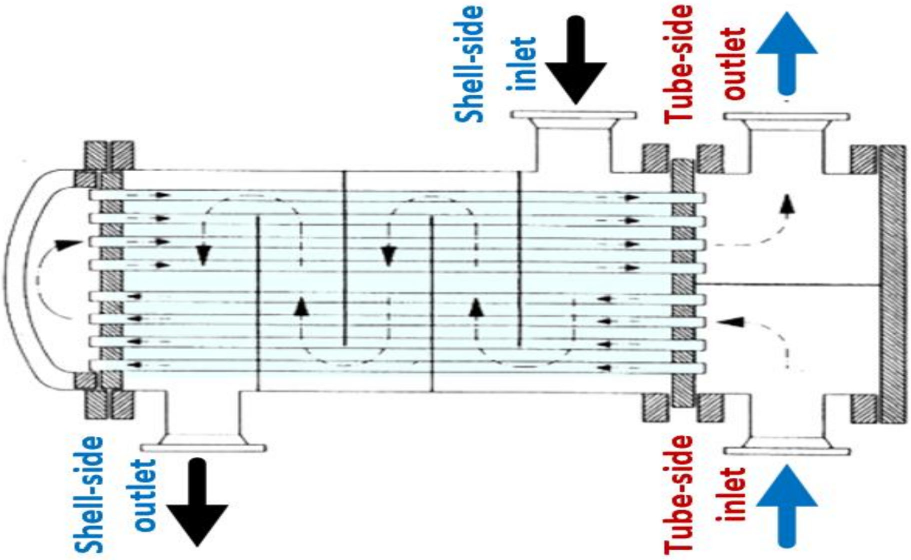

Figure 1. 1-2 Phase STHE-Type E- Standard TEMA [10].

Previous studies have evaluated various parameters affecting the efficiency of heat exchanger technology, including the impact of fluid flow velocity on performance [11]. Some research has specifically examined different fluid flow rates in shell and tube heat exchangers (STHEs), particularly with co-current flow on both the shell and tube sides using water as the fluid [12]. Despite these efforts, a comprehensive analysis of how variations in fluid flow rate affect pressure drop and heat transfer coefficient in STHEs still needs to be completed to aims to provide a deeper understanding of the effects of fluid flow rate variations on co-current flow STHEs, focusing on using water as a cooling fluid [10, 13]. The research is expected to significantly enhance the knowledge and practical applications of heat exchanger technology across various industries. Ghozatloo et al. [14] examined nanofluids with ethylene glycol/graphene (EG/Grn) ratios, varying volume concentrations from 0.1% to 1.5%. They tested heat transfer coefficients using a shell and tube heat exchanger (STHE) and compared the performance of EG/Grn with EG as cold and hot fluids, contrasting their findings with those for EG-based nanofluids. Azari et al. [15] focused on heat transfer coefficients and overall heat transfer performance using a 40:60 EG/water ratio. They employed a compact heat exchanger and compared their experimental data with the performance of water-based fluids. Salem et al. [16] investigated the impact of γ-Al_2O_3/water nanofluids on heat transfer and pressure drop in shell and coil heat exchangers with various coil curvatures, assessing performance improvements with different coil designs. Zainith et al. [17] analyzed the application of graphene nanofluids in shell and tube heat exchangers, evaluating their effectiveness in enhancing heat transfer rates compared to conventional fluids. Bahiraei et al. [18] explored nanofluids in shell and tube heat exchangers with helical baffles, demonstrating that combining nanofluids and baffle designs can significantly enhance energy efficiency and thermal performance.

This study investigates the performance of primary water as a heat transfer fluid in shell-and-tube heat exchanger (STHE) systems, focusing on heat transfer rate, pressure drop, and friction factors. While water-based fluids are prevalent in thermal management systems, existing literature lacks detailed analyses heat transfer rate and friction factors specifically for STHE configurations. To address this gap, we conducted experiments at an operational temperature of 42°C, systematically varying fluid flow rates to assess their

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impact on heat transfer rate and friction factors. Our results provide novel insights into the thermal performance of primary water, revealing critical relationships that can inform the design and optimization of STHE systems. This research contributes significantly to the field of thermal management by offering practical recommendations for enhancing system efficiency, particularly in applications where improved heat transfer rates are essential.

2. METHOD

2.1. Properties of water

Water's thermal and physical properties are crucial for various industrial and scientific applications, particularly heat transfer and fluid dynamics [2]. Water is an effective heat storage medium at room temperature due to its high specific heat capacity of approximately 4180 J/kg·K and relatively high density of 998.2 kg/m³. It enables water to retain significant thermal energy and exhibit a thermal conductivity of 0.606 W/m·K [19]. A thorough understanding of these properties is essential when designing systems that utilize water as a hot or cold fluid, heat transfer medium, or for other industrial purposes. Table 1 provides data on the thermophysical properties of water.

Table 1. The thermophysical properties of water [31].

Temperature (K)	Density (kg/m^3)	Viscosity (Pa.s)	Heat Specific (J/kg. K)	Thermal conductivity (W/m. K)
303	1041.3	0.00219	3674	0.441
308	1039.1	0.00188	3688	0.445
313	1036.8	0.00163	3702	0.450
318	1034.4	0.00143	3716	0.453
323	1031.8	0.00126	3730	0.457
328	1029.2	0.00113	3745	0.460
333	1026.4	0.00101	3759	0.463
338	1023.5	0.00092	3773	0.466
343	1020.4	0.00083	3787	0.469

2.2. Experimental set up

The test section is fabricated from SUS 304 stainless steel for the shell and pure copper for the tube, which features a thickness of 1.5 mm and an inner diameter of 18 mm, forming the shell and tube heat exchanger (STHE) system. K-type thermocouples are installed at the inlet (T_i) and outlet (T_o) of the shell and tube to measure temperature. At the same time, pressure sensors monitor the pressure difference between the inlet (P_i) and outlet (P_o). A centrifugal pump circulates water through the shell of the STHE. A data logger records pressure and temperature data with accuracies of 0.1 psi and 0.25°C, respectively. The heater, regulated by a voltage controller with input specifications of 220 VAC, 50/60 Hz, and an output voltage range of 0-250 VAC, is in a 1-litre feeder tank. A 600 W tubular heater heats the fluid within this tank. Before initiating the testing process, all measuring instruments are calibrated to ensure the accuracy of data collection. Water is introduced into the tank and heated to approximately 42°C using a heater. A centrifugal pump then circulates the heated water through the shell side of the experimental setup until all pipes and hoses are filled. On the tube side, water flows through the STHE, maintaining a temperature of 38°C with a 350 W cooler.

The cold fluid's flow rates vary at 9, 10, and 12 LPM, while the hot fluid flow is held constant at 6.67 LPM. Data collection occurs at 1-second intervals. Once the inlet temperature on the shell side (hot fluid) reaches 31°C, the heater cycles on and off to maintain a temperature of 43°C. That triggers data recording for temperature, pressure, and fluid flow rate. The cooler in the heat exchanger ensures that the inlet

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temperature on the tube side remains stable at 38°C. The accuracy of the recorded data is approximately 0.01°C for temperature, 0.01 PSI for pressure, and 0.01 LPM for flow rate, ensuring reliable and precise measurements throughout the experiment. The experimental design is intended to establish relationships among the input parameters—flow rate, temperature, and pressure—under fully developed conditions. Effective management of the experimental setup is critical, and including a control group is essential for ensuring reliable control of variables. Figure 2 provides a schematic of the test section in this study.

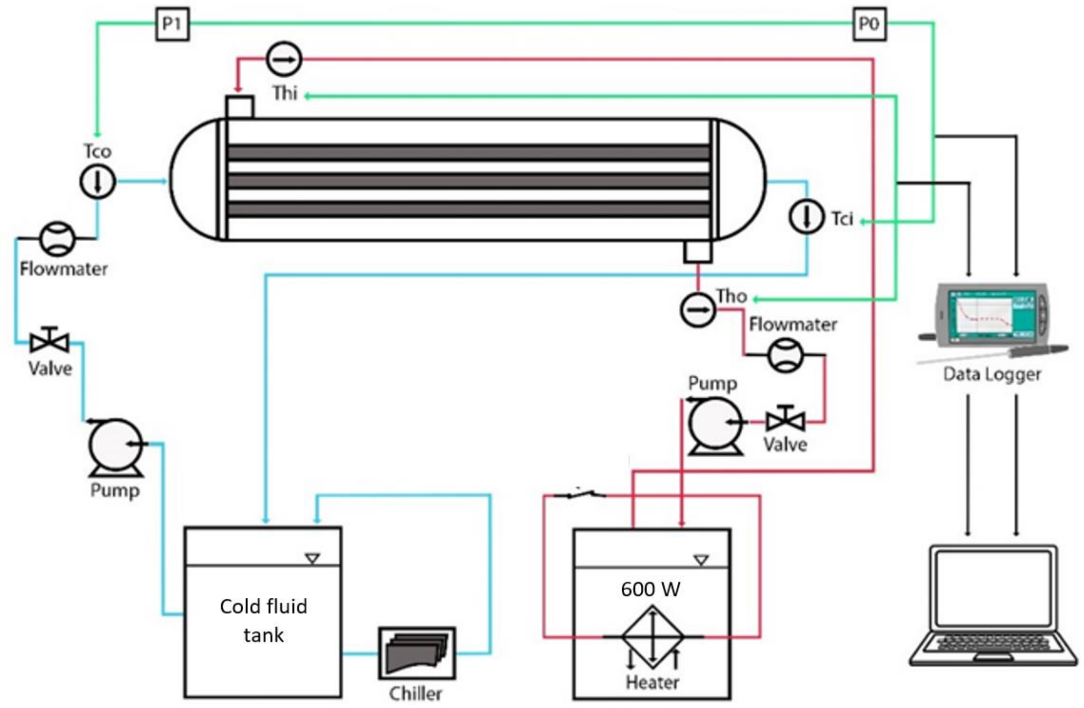

Figure 2. Experimental set up

2.3. *Data processing*

The experimental data were used to determine the overall heat transfer coefficient, heat transfer rate, and Nusselt number for nanofluids at various cold fluid flow rates and Reynolds numbers. The thermophysical properties were assessed using the average bulk temperature of EG/water ratio of 40:60. The heat transfer rate, q on the shell and tube sides of the heat exchanger can be expressed by Equations (1) and (2).

$$q_h = \dot{m}_h \, Cp_h \, (T_{hi} - T_{ho}) \quad (1)$$

$$q_c = \dot{m}_c \, Cp_c \, (T_{ci} - T_{co}) \quad (2)$$

where $\dot{m}$ represents the mass flow rate (kg/s), Cp denotes the specific heat capacity (J/kg-C), and T donated for the temperature (°C). The subscripts c, h, i, and o refer to cold fluid, hot fluid, inlet side, and outlet side, respectively.

Considering the heat losses and gains in hot and cold fluids, the experimental heat transfer rate was determined by averaging the thermal powers, as specified in Equation (3) [20].

$$Q_{ave} = \frac{q_h + q_c}{2} \quad (3)$$

Overall heat transfer coeficient, U (OHTC)at which heat transfers across a surface, measured in watts per square meter (W/m².K). This indicates the amount of heat flowing through each square meter of the surface as specified in Equation (4) [21] .

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$$U = \frac{Q_{ave}}{A\Delta T_{LMTD}} \quad (4)$$

Where, U denotes the overall heat transfer coefficient (OHTC) (W. m^{-2}°C^{-1}), A denotes the heat transfer area (m^2) and ΔT_{LMTD} denotes the logarithmic mean temperature difference (°C). For unidirectional flow in a heat exchanger, ΔT_{LMTD} LMTD can be calculated using Equation (5) [22].

$$\Delta T_{LMTD} = \frac{[(T_{hi}-T_{ci})-(T_{ho}-T_{co})]}{In[(T_{hi}-T_{ci})/(T_{ho}-T_{co})]} \quad (5)$$

T_{hi} and T_{ho} represent the inlet and outlet temperatures of the hot fluid, respectively, while T_{ci} and T_{co} represent the inlet and outlet temperatures of the cold fluid. The effectiveness of the heat exchanger design is evaluated by calculating the heat transfer different (*HD*) between the hot fluid on the shell side and the cold fluid on the tube side using Equation (6) [23].

$$HD = \frac{|q_h - q_c|}{Q_{ave}} \, x \, 100\% \ \leq 5\% \quad (6)$$

2.4. Determination of Reynolds Number (Re) and Nusselt number (Nu)

The Reynolds number is a dimensionless parameter that represents the ratio between inertial forces and viscous forces in a flow. It is calculated using Equation (7). The Reynolds number is crucial for classifying flow types—laminar, turbulent, or transitional. By determining the Reynolds number, engineers and scientists can identify the prevailing flow regime, which is essential for understanding fluid behavior and optimizing designs across various applications [24] .

$$Re = \frac{\rho v D}{\mu} \quad (7)$$

Where *Re* represents the dimensionless Reynolds number, v represents fluid velocity (m/s),), μ represents the absolute viscosity of the fluid (mPs), and ρ denotes fluid density (kg/m³) [25].

The Nusselt number (Nu) is a dimensionless parameter that characterizes convective heat transfer at a surface by quantifying the temperature gradient. In this experiment, Nu was determined using Equation (8). Understanding this parameter is essential for evaluating the efficiency of heat transfer at the surface, which is crucial in heat transfer and fluid dynamics studies [26]. The Nusselt numbers obtained in this study were compared using Bottler's Disstut formula and Notter & Rouse's formula, as detailed in Equations (9) and (10), respectively. These comparisons help evaluate the system's efficiency and heat transfer coefficient, providing valuable insights into the overall heat transfer performance [16, 17].

$$Nu = \frac{hD}{k} \quad (8)$$

$$Nu = 0.023Re^{0.8}Pr^{0.4} \quad (9)$$

$$Nu = 5 + 0.015Re^{0.856}Pr^{0.347} \quad (10)$$

2.5. Pressure drops and friction factor

Pressure drop, ΔP (PSI), refers to the reduction in energy that occurs when a fluid encounters resistance as it flows through the STHE. This resistance can arise from factors such as friction between the fluid and the pipe walls, changes in flow velocity, or variations in pipe geometry. The friction factor *f*, quantifies the effect of this friction on fluid flow and is crucial for calculating the pressure drop. It varies depending on the flow regime (laminar or turbulent) and the geometry of the piping. The pressure drop in the STHE is typically calculated as the difference between the pressures at the system's inlet and outlet, using Equation 1 [18, 19].

$$\Delta P = P_{in} - P_{out} \quad (11)$$

The Darcy friction factor is a dimensionless parameter used to evaluate frictional losses in the STHE. The factor is critical for understanding and quantifying fluid flow resistance, especially in engineering and fluid

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dynamics applications where it is used to determine pressure drops and losses in STHE systems [27]. Equations (12) and (13) show how to calculate the friction factor at shell side and and tube side respetively [28]. These alternative formulas provide ways of calculating the friction factor in specific flow conditions, providing useful tools for analyzing and predicting the behaviour of fluids in different situations [29, 30].

$$f_s = \frac{\Delta P}{\left(\frac{L}{D}\right)\left(\rho_f \frac{v^2}{2}\right)} \quad (12)$$

$$f_t = \frac{0.3164}{Re^{0.25}} \quad (13)$$

3. RESULT AND DISCUSSIONS

3.1. *Analysis of heat transfer rate*

The heat transfer rate was determined from experimental data using Equation (1). The results were averaged and analyzed to assess the impact of fluid flow rate on heat transfer in a shell and tube system. The analysis revealed that the heat transfer rate increases with higher fluid flow rates. The lowest heat transfer rate was observed at a flow rate of 8 LPM, while the highest was recorded at flow rates exceeding 12 LPM. Figure 3 illustrates the effect of varying flow rates on the heat transfer rate in both the shell and tube sides. These findings align with established theory, which suggests a direct proportionality between fluid flow rate and heat transfer rate, as supported by reference [31]. This research confirms that fluid flow rate significantly influences heat transfer rate, consistent with previous studies [32, 33]. Additionally, a positive correlation between fluid mass flow rate and heat transfer efficiency was observed, indicating that higher flow rates enhance heat transfer efficiency.

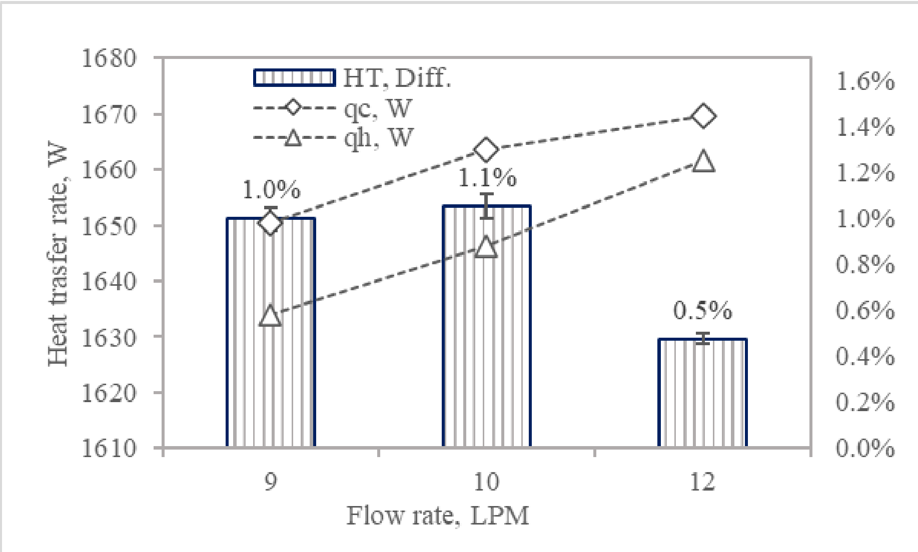

Figure 3. The effect of fluid flow rate on the heat transfer rate in shell and tube side.

The effectiveness of heat transfer between the hot fluid on the shell side and the cold fluid on the tube side is evaluated by calculating the heat transfer difference (HD) using Equation (6) [23]. The results confirm that the heat transfer rate between the hot fluid in the shell side and the cold fluid in the tube side is less than 5%, as determined by Equation (6). Figure 3 shows that the heat transfer rate of the cold fluid in the tube side is higher than that of the hot fluid in the shell side, with a deviation of less than 2%.

3.2. *Reynolds number, pressure drops and friction factor analysis*

Pressure drop (*ΔP*) and friction factor (*f*) calculations were performed using Equation (11)-(13). The calculated *ΔP* results were averaged and analyzed to understand the impact of fluid flow rate variations in the shell and tube side of the STHE system. Figure 4 illustrates that *ΔP* decreases as the fluid flow rate

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increases. The lowest ΔP was observed at a flow rate of approximately 9 LPM, while the highest ΔP occurred when the flow rate surpassed 12 LPM. This observation indicates that pressure drop increases with the Reynolds number, as shown in Figure *4*. The flow rate is directly proportional to fluid velocity, which contributes to this phenomenon. Consistent with the results documented by reference [16], which indicate that pressure drop increases with flow rate and Reynolds number, these findings also demonstrate an increase in pressure drop. These results align with established theory, suggesting a direct proportionality between fluid flow rate, pressure drop, and friction factor, as supported by reference [31]. This research confirms that pressure drop and friction factor significantly influence flow rate, consistent with previous studies [32, 33].

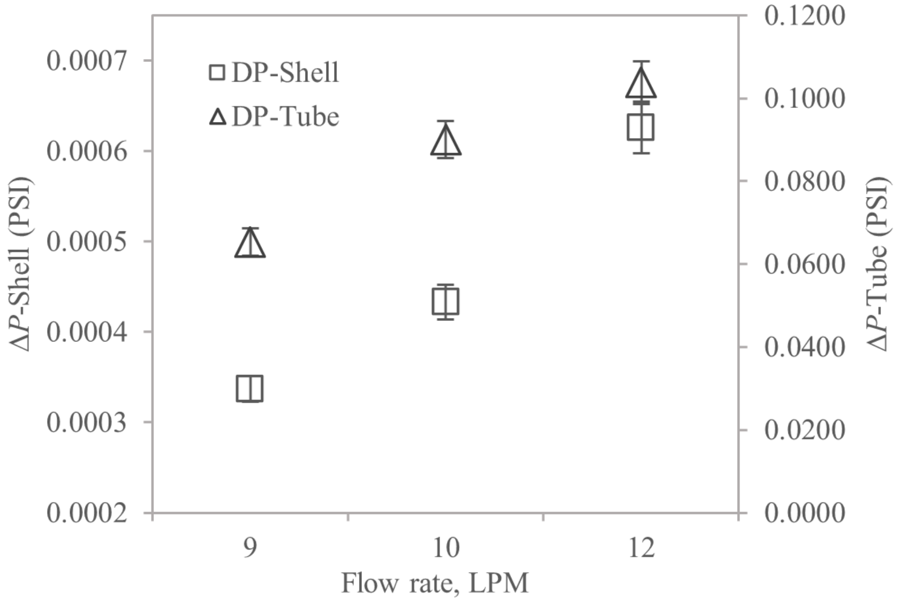

Figure 4. The effect of the EG/Water fluid flow rate on pressure drop.

Equations (12) and (13) were used to calculate the friction factor for the fluid in the shell and tube sides, respectively [16]. Figure 5 illustrates the effect of the Reynolds number on the friction factor, showing that it decreases with increasing Reynolds number on both sides. Specifically, the highest friction factor on the shell side occurs at approximately Reynolds number 4586, while the lowest is recorded at Reynolds number exceeding 4707. It indicates that the friction factor decreases as the shell-side fluid flow increases, reflecting the system's flow characteristics, as shown in Figure 5(a). On the tube side, the highest friction factor is around Reynolds number 5634, with the lowest above Re 7455. It suggests a similar trend where the friction factor decreases as the Reynolds number rises, as illustrated in Figure 5(b).

The friction factor is a critical parameter in assessing resistance to fluid flow due to frictional forces and calculating pressure drop across each side of the heat exchanger. On the shell side, it is influenced by the flow regime (laminar or turbulent), shell geometry (including baffle design), fluid properties (such as viscosity), and tube bundle arrangement. Accurate determination of the friction factor—often through experimental data or empirical correlations—is essential for optimizing heat exchanger performance, ensuring efficient flow distribution, and minimizing pressure losses. On the tube side, the friction factor reflects resistance within the tubes and is affected by factors like tube diameter, wall roughness, and fluid properties. While laminar flow typically has a lower friction factor calculated with more straightforward formulas, turbulent flow requires empirical correlations or Moody charts for accurate determination.

The results of this research consistently support established theories, corroborated by references [27] and [28], which show a direct proportionality between the friction factor and the Reynolds number. It is widely acknowledged that the Reynolds number is influenced by fluid velocity, as noted in reference [30], and fluid flow rate, as reported by [34]. This study observed that fluid velocity and flow rate directly correlate with the Reynolds number, concluding that the friction factor decreases as the Reynolds number increases.

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Thus, higher fluid flow velocity and flow rate reduce pressure losses.

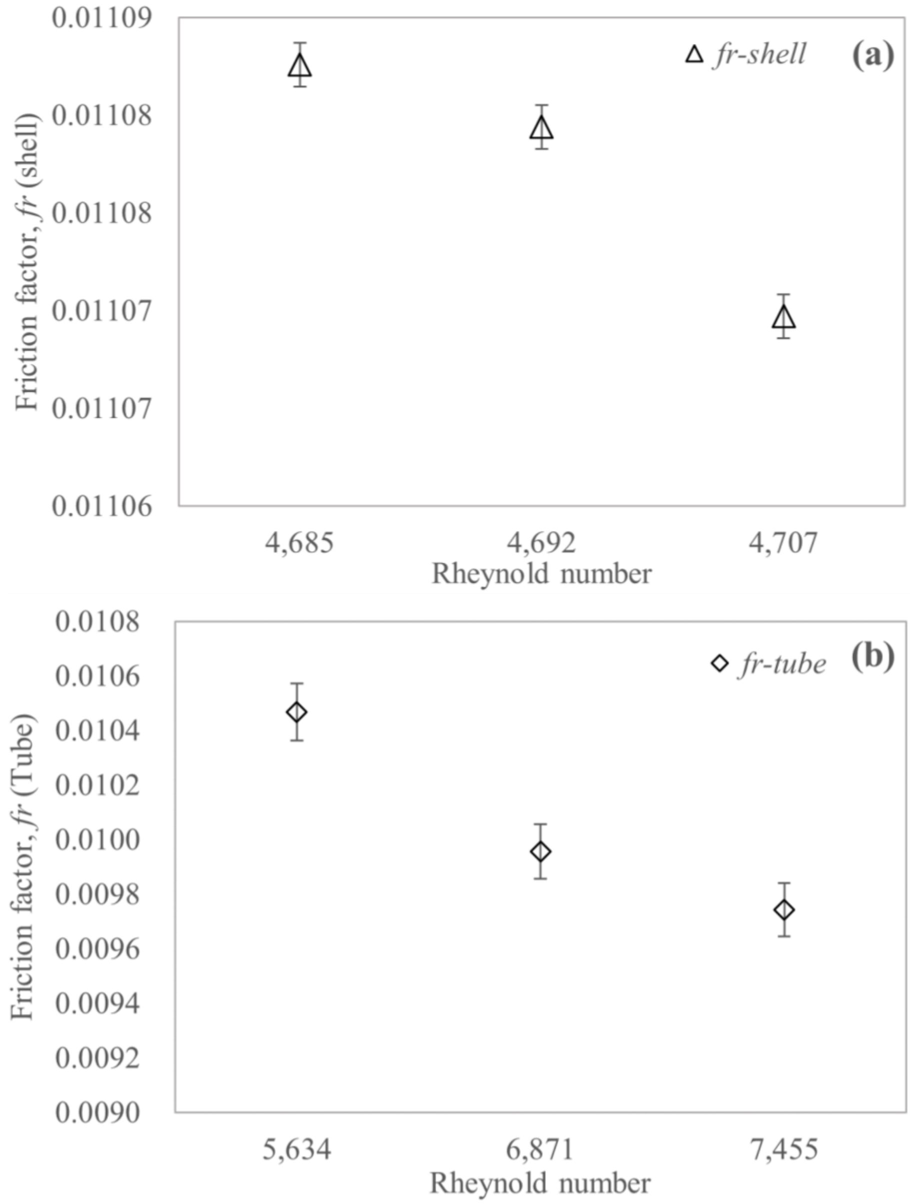

Figure 5. Effect of Reynolds number on Friction factor.

3.3. Nusselt number (Nu) and heat trasnfer rate analysis

The *Nu* number, as defined by Equation (9) in reference [26], shows a direct proportionality with the heat transfer rate, consistent with the findings in reference [25]. Additionally, the Nu number is closely related to the Reynolds number (Re), as indicated by references [16, 31]. It is well-established that the Nu number is influenced by the fluid flow rate, as acknowledged in reference [34]. Our research confirms that the Nu number exhibits a direct proportionality with the fluid's flow rate, meaning that an increase in flow rate results in a corresponding increase in the Nu number. It indicates an enhanced heat transfer rate through the fluid. Figure 6 illustrates the correlation between Nu numbers and the heat transfer rate on both the shell and tube sides.

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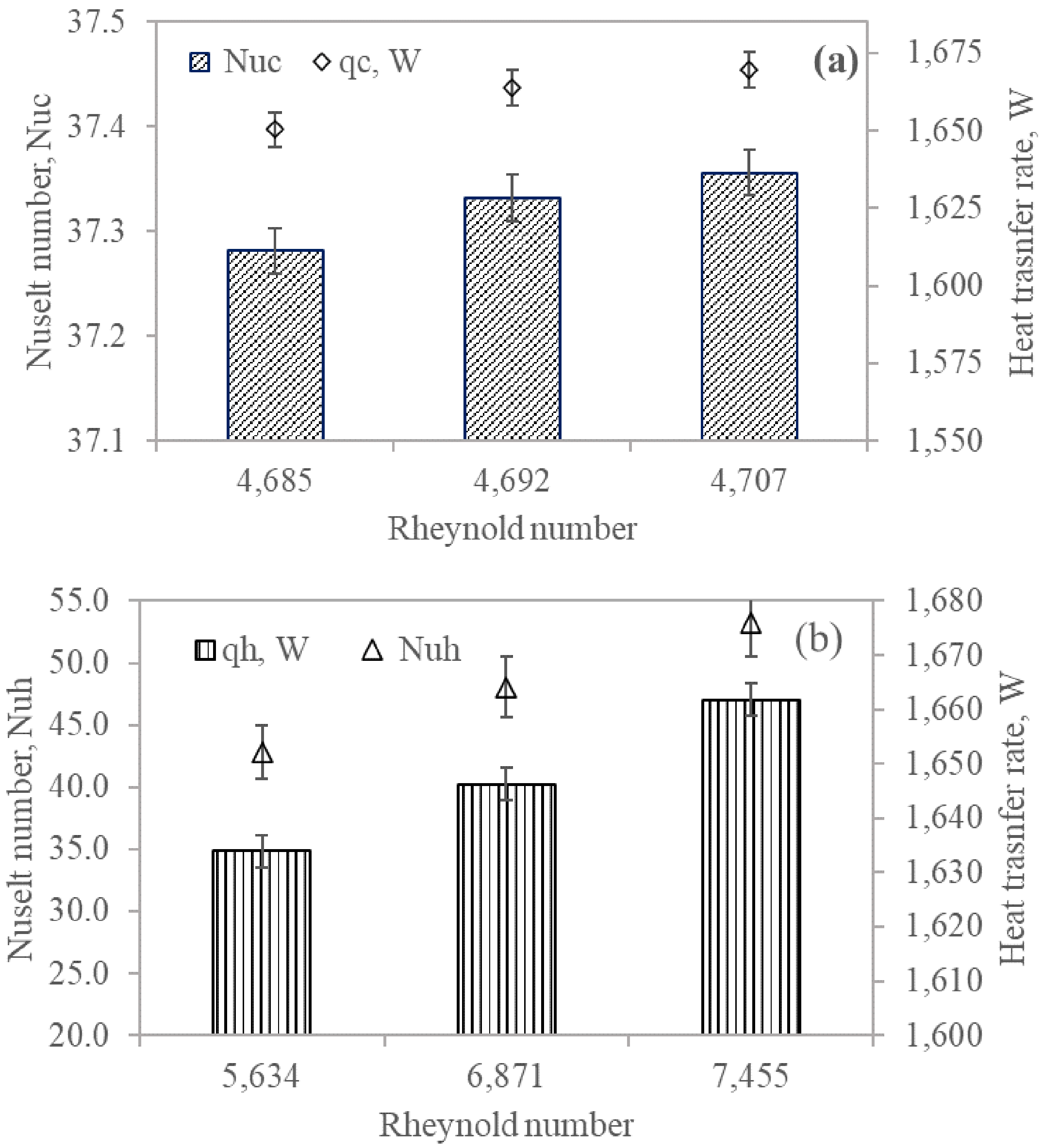

Figure 6. Effect of EG/Water fluid flow rate on *Re* and *Pr*.

Figure 6a shows the correlation between the Reynolds number, Nusselt number, and heat transfer rate on the tube side of the heat exchanger, revealing a positive relationship for both parameters. The Nusselt number ranges from 37.3 to 37.5, with the lowest value occurring at a Reynolds number of approximately 4685 and the highest at 4707. Although the Nusselt number increases, the change is relatively modest. In contrast, heat transfer rate demonstrates a more pronounced rise at the same Reynolds number, aligning with the fluid flow rate data presented in Figure 3.

Figure 6b illustrates the correlation between the Reynolds number, Nusselt number, and heat transfer rate on the shell side of the heat exchanger, where both parameters exhibit a positive relationship as well. The Nusselt number on the shell side varies from 40.0 to 55.5, with the lowest value occurring at a Reynolds number of approximately 5643 and the highest at 7245. The increase in the Nusselt number on the shell side is more substantial than on the tube side. This significant change in the Nusselt number is accompanied by a notable increase in heat transfer rate at corresponding Reynolds numbers, which is consistent with the fluid flow rate data shown in Figure 3.

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4. CONCLUTIONS

The results of this study indicate that the heat transfer rate in a shell-and-tube heat exchanger (STHE) increases with the fluid flow rate, with the heat transfer rate on the tube side at 12 LPM and its minimum at 9 LPM. The difference in heat transfer rate between the shell and tube sides remains below 5%, demonstrating adequate STHE performance. Analysis reveals that the pressure drop (ΔP) decreases as the flow rate increases, reaching its lowest value at 9 LPM. It aligns with a corresponding increase in the Reynolds number (Re), indicating turbulent flow. Both sides of the exchanger show decreasing friction factors with increasing Re, supporting the theoretical relationship. While the Nusselt number on the tube side increases moderately, a significant rise on the shell side suggests that design and operational factors have a more pronounced impact on heat transfer efficiency. Overall, this study underscores the importance of optimizing flow rate and friction factor to minimize pressure loss and enhance the performance of thermal management systems.

AUTHOR'S DECLARATION

Authors' contributions and responsibilities

The authors played significant roles in conceiving and designing the study. The authors also took on the responsibility for data analysis, interpretation, and the discussion of results. All authors reviewed and gave their approval for the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

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