

Heat transfer and pressure characteristics of Tri Ethylene Glycol/water and Ethylene Glycol/water mixtures in copper pipe heated flow systems

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Abstract

Enhancing heat transfer efficiency and pressure regulation in copper pipe flow systems is crucial for advancing modern cooling and heating technologies, particularly given the widespread use of copper piping in these applications. This study investigates the thermal and hydraulic performance of ethylene glycol/water (EG/water) and tri ethylene glycol/water (TEG/water) mixtures as working fluids in copper pipe systems. A series of controlled experiments was carried out on a dedicated copper pipe test section to evaluate the effects of varying flow rates on the heat transfer coefficient and pressure drop for each fluid mixture. The results indicate that the TEG/water mixture yielded a ~2.0% increase in heat transfer coefficient and a ~1.0% reduction in pressure drop compared to the EG/water mixture, with a corresponding increase in Reynolds number of approximately 37.0%. The reduction in pressure drop is primarily attributed to the lower viscosity of the TEG/water fluid. These findings provide valuable comparative insights into the thermophysical behaviour of both glycol-based mixtures and offer practical guidance for optimizing the selection of thermal fluids in large-scale cooling and heating systems that utilize copper piping.

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INTRODUCTION

Improving the heat transfer efficiency and managing the pressure characteristics of copper pipe flow systems are essential for advancing thermal management in modern heating and cooling technologies. Copper pipes have been widely adopted in various systems because of their high durability, thermal conductivity, and flexibility. However, although water is traditionally used as a working fluid, it exhibits rapid evaporation due to its relatively low boiling point, making it unsuitable for high-temperature applications.

The structural design of thermal systems, as well as the nature of the working fluid, significantly influence the system's efficiency. Utilizing high-boiling-point fluids in thermal systems enhances performance and supports efforts to achieve the Sustainable Development Goals (SDGs), particularly in the areas of clean water access and sanitation. Fluids such as ethylene glycol (EG) and tri ethylene glycol (TEG) are increasingly utilized because of their high boiling points and stability under thermal loads [1, 2, 3]. Although EG is more commonly integrated into HVAC and industrial thermal

applications, despite being chemically similar, TEG has more limited use owing to its higher viscosity and cost.

The heat transfer coefficient is a crucial quantitative measure for evaluating the rate at which heat is conducted from a fluid to a surface [4][5]. It reflects the fluid's capacity to conduct heat and is influenced by the physical properties of the fluid, flow velocity, surface properties, and thermophysical conditions [6, 7, 8, 9, 10]. The key parameters affecting the HTC include fluid density [11][12], velocity [13, 14, 15], thermal conductivity [16][17], viscosity [18], and the addition of nanoparticles to the base fluid [19]. Accurate HTC characterization is essential for designing and optimizing thermal systems, such as heat exchangers [19][20] and advanced cooling systems, which directly affect their heat transfer performance and energy efficiency [21][22].

Heat transfer units are vital components in industrial and residential settings, including power generation units, automotive systems, and climate control infrastructure [23, 24, 25]. Optimizing these systems requires balancing the thermal performance with the hydraulic efficiency to achieve high heat transfer rates while minimizing pressure loss [26, 27, 28]. Although pressure drop and heat transfer are interdependent, they are frequently analyzed in isolation. This disconnection may hinder the holistic optimization of systems. EG- and TEG-based fluids are widely used in industrial thermal management, vehicle cooling systems, and HVAC units [29], and their effectiveness is significantly influenced by their mixing ratios with water [30]. The selection of EG/water or TEG/water compositions is typically dictated by operational requirements such as freezing point depression and target working temperature ranges.

Numerous studies have examined the performance of glycol-based water mixtures [31].

Manik et al. [32] investigated a 40:60 EG/water mixture functioning as the cold-side fluid, while hot water was the heat source. They evaluated the thermal performance using a radiator with varying hot-fluid discharge rates ranging from 6.7 to 27 LPM. In a separate investigation, Abolarin et al. [33] analyzed the pressure drop and heat transfer using twisted tape inserts across test sections under varying flow regimes. Their setup, as shown in Figure 1, operated with a constant heat flux between 1.35 and 4 kW/m², covering Reynolds numbers ranging from 300 to 11,404, including laminar, transitional, and turbulent flows.

Ghozatloo et al. [34] examined EG-based nanofluids with graphene (Grn) at concentrations of 0.1–1.5% using a shell-and-tube heat exchanger (STHE), where the EG/Grn nanofluid circulated on the cold side and pure EG on the hot side of the STHE. The heat convection efficacy was compared with that of the EG systems. Azari et al. [35] investigated the local and overall heat transfer coefficients using a 40:60 EG/water mixture, offering insights into heat exchanger applications.

This study investigated the thermal performance of EG/water and TEG/water mixtures in a heated copper pipe system. This study examined the interdependence between HTC, fluid flow rate, and pressure drop, providing a foundational understanding of these glycol-based fluids under varying conditions. Although studies have explored similar working fluids, comprehensive analyses of the HTC and friction factor (Fr) correlation within single-pipe configurations, particularly for EG/water and TEG/water at 60 °C and a 40:60 volume ratio, remain limited. This study addresses this gap through systematic experiments conducted across various flow rates to determine the volumetric relationships that affect thermal and hydraulic responses.

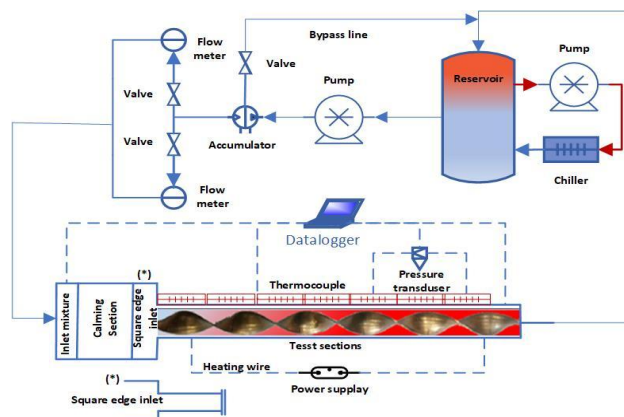


Figure 1. Experimental test section and configuration (adapted from [33])

The results aim to provide insights for optimizing thermal systems using glycol-water mixtures, while establishing a baseline for future studies involving additive integration, to enhance heat transfer efficiency in systems transitioning from moderate to high-performance regimes.

METHOD

Properties of Ethylene Glycol and Tri Ethylene Glycol

The thermophysical properties of fluid mixtures are fundamental to heat transfer applications in industrial and engineering systems [36]. EG has a melting point of -13°C and a boiling point of 197.3°C , respectively. At 20°C , EG exhibits favorable heat transfer behavior with a specific heat capacity of approximately $2430\text{ J/kg}\cdot\text{K}$, thermal conductivity of $0.25\text{ W/m}\cdot\text{K}$, and density of 1113.4 kg/m^3 [30]. Water exhibits excellent thermal storage characteristics at this temperature, with a specific heat capacity of $4180\text{ J/kg}\cdot\text{K}$ and a density of 998.2 kg/m^3 . Its thermal conductivity of $0.606\text{ W/m}\cdot\text{K}$ enhances its functionality as a heat-transfer medium. A comprehensive understanding of these thermophysical parameters is essential for designing or optimizing systems involving TEG/water and EG/water mixtures for cooling, heating, and industrial fluid circulation applications. Table 1 lists the representative thermophysical properties of the TEG used in this study.

Experimental Configuration

The experimental setup consisted of a copper test section with an inner diameter of 18

mm and a wall thickness of 1.5 mm. Ten K-type thermocouples (T_1 – T_{10}) were mounted along the pipe wall, with additional sensors at the inlet (T_i) and outlet (T_o) to monitor the fluid temperatures. Pressure sensors were placed at both ends (P_i and P_o), and a centrifugal pump circulated the working fluid from a 20 L reservoir. All the sensors were calibrated before testing to ensure measurement accuracy.

Heating was supplied by two 1500 W tubular heaters, regulated by a variable voltage controller (220 VAC, 50/60 Hz, up to 250 VAC). The temperature, pressure, and flow rate were recorded at one-second intervals using a calibrated data logger with accuracies of $\pm 0.1^{\circ}\text{C}$, $\pm 0.1\text{ psi}$, and $\pm 0.01\text{ L/min}$, respectively. The tests commenced when the inlet temperature reached 60°C and were stabilized using a chiller acting as a heat exchanger. All experiments were conducted under controlled environmental conditions to ensure the repeatability of the results. A schematic of the test loop is presented in Figure 2.

Heat transfer coefficient (HTC), h

The HTC characterizes the thermal energy transfer between the surface and the surrounding fluid. Its magnitude depends on the fluid velocity, geometric configuration, temperature gradient, and thermal properties of the materials involved. HTC is crucial in evaluating heat exchange mechanisms, particularly in convection processes and phase transitions involving liquid–solid interactions.

Table 1. Thermophysical properties of the TEG/water mixture with a volume ratio of 40:60 [37][38]

Temperature (K)	Density (kg/m^3)	Viscosity (Pa.s)	Heat Specific ($\text{J/kg}\cdot\text{K}$)	Thermal conductivity ($\text{W/m}\cdot\text{K}$)
273	273	0.0110	3457	0.416
278	278	0.0084	3487	0.417
283	283	0.0070	3517	0.417
288	288	0.0059	3546	0.418
293	293	0.0051	3575	0.418
298	298	0.0043	3603	0.418
303	303	0.0037	3631	0.419
313	308	0.0032	3657	0.420
323	313	0.0028	3683	0.420
333	318	0.0024	3708	0.420
343	323	0.0021	3733	0.421
353	328	0.0019	3757	0.422
363	333	0.0016	3781	0.422
373	338	0.0015	3803	0.422
393	343	0.0013	3825	0.423
413	348	0.0012	3847	0.424
433	353	0.0010	3869	0.424
453	358	0.0009	3888	0.424
473	363	0.0008	3907	0.425

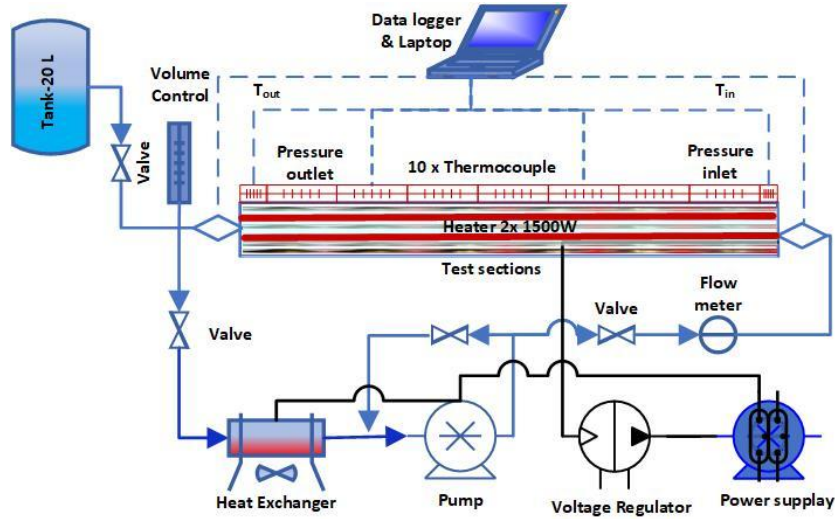


Figure 2. Experimental setup

The convective heat transfer coefficient, h , was obtained from (1) [39]:

$$h = \frac{Q}{T_s - T_m} \quad (1)$$

where T_s denotes the average surface temperature (K) at the suction test location, calculated using (2) [25].

$$T_s = \frac{(\sum_{i=1}^8 T)}{10} \quad (2)$$

where T_m is the bulk fluid temperature, which is calculated using (3):

$$T_m = \frac{T_{in} - T_{out}}{2} \quad (3)$$

In this study, the heat transfer rate, Q (W), was evaluated as the average of the power input and the fluid-based heat transfer, as expressed in (4) [32]:

$$Q = \frac{Q_1 + Q_2}{2} \quad (4)$$

where Q_1 denotes the heat transfer rate (W) from the power input, calculated using Eq. (5), and Q_2 reflects the fluid-based heat transfer rate from (6) [40].

$$Q_1 = VI \quad (5)$$

$$Q_2 = \dot{m}C_p(T_o - T_i) \quad (6)$$

where V , I , C_p , and $\dot{m}$ represent the voltage (V), current (A), specific heat capacity (J/kg·K), and mass flow rate (kg/s), respectively. The heat flux, in W/m², quantifies the thermal energy transferred per unit area.

The heat flux (q'') was computed using Eq. (7), with heat input (Q) derived from voltage, current, mass flow rate, and fluid specific heat [32]. Here, D and L denote the pipe's inner diameter (m) and length (m).

$$q'' = \frac{Q}{\pi DL} \quad (7)$$

Hydrodynamic and Thermal Characterization

The Reynolds number (Re) is a dimensionless parameter that represents the ratio of inertial to viscous forces within a fluid flow, serving as a fundamental criterion for distinguishing between laminar, transitional, and turbulent flow regimes. It is defined by (8) [41, 42, 43].

$$Re = \frac{\rho v D}{\mu} \quad (8)$$

where ρ is fluid density (kg/m³), v is velocity (m/s), D is hydraulic diameter (m), and μ is dynamic viscosity (mPa·s)

The Nusselt number (Nu) is a dimensionless parameter that characterizes the enhancement of heat transfer owing to convection relative to pure conduction across a thermal boundary layer. It is defined in (9) [44][45].

$$Nu = \frac{hD}{k} \quad (9)$$

This study estimated the Nusselt number (Nu) using two well-established empirical correlations: the Dittus–Boelter equation and the Notter–Rouse correlation, as expressed in (10) and (11) [46].

$$Nu = 0.023Re^{0.8}Pr^{0.4} \quad (10)$$

$$Nu = 5 + 0.015Re^{0.856}Pr^{0.347} \quad (11)$$

Pressure Drops and Friction Factor

The pressure drops (ΔP), expressed in pascals (Pa), reflect the energy losses owing to friction, flow separation, and geometrical variations along the flow path. This parameter is key to assessing flow efficiency and system performance. The friction factor (f), a dimensionless quantity, characterizes the wall shear-induced resistance and depends on the flow

regime, surface roughness, and channel geometry. In this study, ΔP was measured between the inlet and outlet of the test section, and the friction factor was used to evaluate the hydraulic performance. The pressure drop was calculated using (12) [39]:

$$\Delta P = P_{in} - P_{out} \quad (12)$$

The Darcy friction factor (f) is a dimensionless parameter essential for quantifying frictional losses in internal flows and is critical for predicting pressure drops in piping systems. This dimensionless parameter was calculated experimentally using (13), which relates the pressure drop (ΔP), pipe length (L), hydraulic diameter (D), fluid density (ρ), and mean velocity (v) [47].

$$f = \frac{\Delta P}{\left(\frac{L}{D}\right)\left(\rho f \frac{v^2}{2}\right)} \quad (13)$$

In addition to experimental measurements, f can be estimated using empirical correlations. For turbulent flow in smooth tubes, the Petukhov correlation is expressed in (14) [35]:

$$f = (0.79 \ln Re - 1.64)^{-2} \quad (14)$$

For lower Reynolds numbers or transitional regimes, the Blasius correlation provides an empirical estimate of the Darcy friction factor, as expressed in (15) [35]:

$$f = \frac{0.3164}{Re^{0.25}} \quad (15)$$

These formulations are used in thermal-fluid system design to evaluate energy losses from the wall shear stress and flow resistance.

RESULTS AND DISCUSSION

Analysis of Heat Transfer Coefficient (HTC), h

HTC was determined using (1). Experimental observations were used to assess the effect of varying flow rates on EG/water and

TEG/water mixtures. The results showed a direct relationship between the Reynolds number (Re) and HTC, confirming that a higher flow velocity promotes convective heat transfer. A marked enhancement in HTC occurred as the flow rate increased from 4 LPM to above 12 LPM, indicating improved thermal performance under higher turbulence. This behavior aligns with classical heat transfer principles, wherein higher flow rates lead to thinner thermal boundary layers and more efficient heat transfer. Based on these findings, new empirical correlations for estimating the HTC in TEG/water and EG/water mixtures were formulated in (16) and (17).

$$h_{TEG/Water} = 160.1 + 84.24 \text{flowrate} \quad (16)$$

$$h_{EG/Water} = 163.1 + 82.32 \text{flowrate} \quad (17)$$

The findings of this study reaffirm the theoretical understanding that the heat transfer rate increases proportionally with the HTC, which is consistent with previous reports [32]. Furthermore, a strong positive correlation between heat transfer and fluid flow rates, as extensively documented in the literature [29], was substantiated. The experimental data also revealed a direct relationship between the mass and volumetric flow rates of the working fluid, corroborating the results of previous studies [34][48]. As shown in Figure 3, higher fluid flow rates led to enhanced HTC values, which were attributed to more vigorous convective transport phenomena. The fluid flow rate directly influences the Reynolds number (Re), with higher flow rates resulting in higher Re . To further clarify this relationship, an analysis was conducted to examine the impact of Re on the HTC. The results indicate that the HTC reached its maximum at Re values exceeding 5500 for the TEG/water mixture and 9000 for the EG/water mixture.

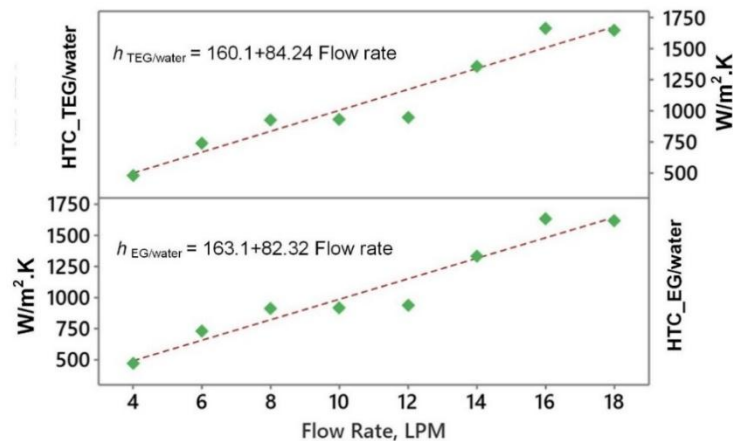


Figure 3. Impact of EG/water flow rate on the heat transfer coefficient

Conversely, the lowest HTC values were observed at Re values of approximately 2000, as shown in (18) and (19).

$$HTC_{TEG/Water} = 81.9 + 0.2893Re \quad (18)$$

$$HTC_{EG/Water} = 81.3 + 0.2793Re \quad (19)$$

These findings demonstrate a significant increase in HTC as a function of Re, with both base fluids exhibiting a linear trend, as shown in Figure 4 (a). A similar linear behavior was observed concerning the pressure drop (ΔP), where an increase in ΔP corresponded to higher HTC values (Figure 4b). This correlation is expressed by (20) and (21):

$$HTC_{TEG/Water} = 416.7 + 0.4228 \Delta P \quad (20)$$

$$HTC_{EG/Water} = 414.3 + 0.4092 \Delta P \quad (21)$$

These linear correlations suggest that the enhancement in convective heat transfer is strongly associated with increased flow velocity and the pressure drop. Fluid dynamics principles support the underlying physical mechanisms and can be further understood by interpreting the fundamental formulations in (1), (8), (9), (10), and (11) [39, 41, 43, 45, 46]. The overall influence of the Re variation on the HTC is illustrated in Figure 4.

Pressure drops, friction factor, and Reynolds number analysis

The pressure drop (ΔP) and Darcy friction factor (f) were calculated using (12). The average pressure drop values were subsequently analyzed to assess the effect of the Reynolds number (Re) on the flow behavior of the EG/water mixture. Figure 5 shows a consistent increase in ΔP with increasing Re, indicating a direct relationship between the flow velocity and hydraulic resistance. The lowest Re values corresponded to a pressure drop of approximately 500 Pa. In contrast, the highest Re values were associated with a ΔP of approximately 5500 Pa for the TEG/water mixture and 9000 Pa for the MEG/water mixture. Based on Bernoulli's principle (8), Re is strongly influenced by the flow velocity,

which is directly proportional to the pressure difference, as indicated in (22) [49].

$$\Delta P = P_1 - P_2 = \left(\frac{\rho v_2^2}{2} + \rho g h_2 \right) - \left(\frac{\rho v_1^2}{2} + \rho g h_1 \right) \quad (22)$$

Given $h_1 = h_2$, (22) can be rewritten as follows:

$$\Delta P = P_1 - P_2 = \left(\frac{\rho v_2^2}{2} \right) - \left(\frac{\rho v_1^2}{2} \right) \quad (23)$$

The Darcy friction factor was determined experimentally using (13) and compared with the theoretical values calculated from Petukhov and Blasius correlations (14) and (15), respectively [33]. As illustrated in Figure 6, the friction factor decreased with increasing Reynolds number for both the TEG/water and EG/water mixtures at all temperatures. This inverse relationship closely followed the trends predicted by the Petukhov and Blasius models, confirming the consistency between the experimental and theoretical results. The highest friction factor values occurred near $Re \approx 2000$, indicating the onset of the laminar-to-turbulent flow transition at this Reynolds number.

Conversely, the lowest friction factors were observed in the fully turbulent regime, specifically at $Re > 5500$ for TEG/water and $Re > 9000$ for EG/water, respectively. This trend reflects the decreasing flow resistance as inertial forces increasingly dominate viscous forces, which aligns with the expected behavior during the laminar-to-turbulent transition in thermal-fluid systems. These findings are consistent with previous reports [34][35], which highlight the inverse relationship between the friction factor and Reynolds number (Re) and the associated impact on the pressure drop. In this study, the fluid velocity and flow rate increased proportionally with Re, reinforcing the established understanding that Re is primarily governed by the flow rate and fluid properties [30][29]. Consequently, the friction factor decreased as Re increased, accompanied by reduced pressure drops at higher flow rates, an outcome that aligns with Bernoulli's principle and well-established hydrodynamic models.

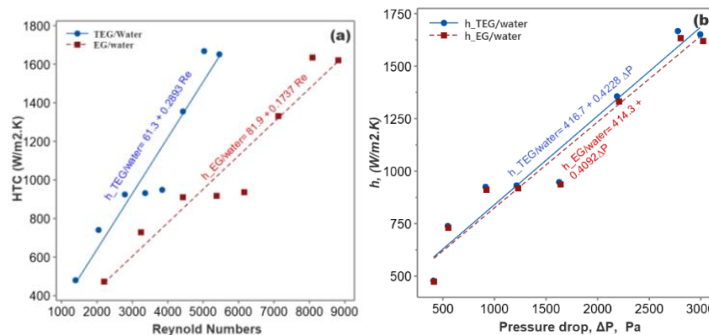


Figure 4. The effect of the EG/Water fluid flow rate on the Nusselt number

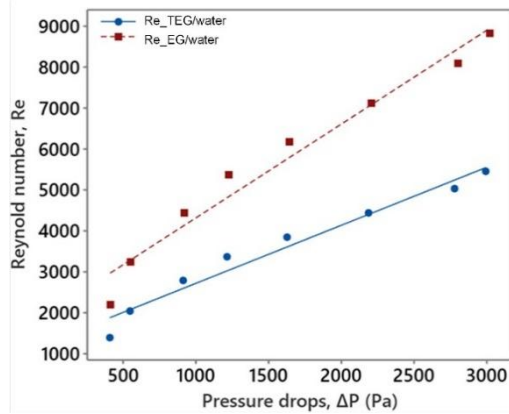


Figure 5. Effect of Reynolds number on pressure drop

Analysis of Reynolds number (Re) and Flow rate correlations

The Nusselt number (Nu) was evaluated against the predictions from the Dittus–Boelter (10) and Notter–Rouse (11) correlations, considering the variations in the flow rate. As shown in Figure 7, Nu increased consistently with the flow rate, ranging from a minimum of 4 LPM to a maximum of 18 LPM. The experimental data showed strong agreement with the Dittus–Boelter predictions at moderate and high flow rates, whereas the Notter–Rouse model tended to

underestimate Nu under similar conditions.

This behavior supports the theoretical correlation between Nu , Re , and HTC , as outlined in (9) and discussed in [25, 32, 33]. Because the flow rate and fluid properties directly influence Re , the observed increase in Nu at higher flow rates confirms their interdependency. These results are consistent with previous findings [29], which identified the flow rate as the dominant factor influencing the convective heat transfer performance. In this study, Nu exhibited a clear positive correlation with the fluid flow rate [50]. An increase in the flow rate consistently resulted in higher Nu values, indicating the fluid medium's enhanced convective heat transfer performance. This behavior is consistent with the theoretical expectation that a higher velocity promotes thinner thermal boundary layers, thereby improving heat transfer efficiency.

Figure 7(b) illustrates the relationship between flow rate and pressure drop. The data indicate that the pressure drop increased proportionally with the flow rate. This trend is well explained by Bernoulli's principle and energy conservation across the flow domain, as described by (16) and (17) [49], which underscores the trade-off between the thermal enhancement and hydrodynamic penalties in forced convection systems.

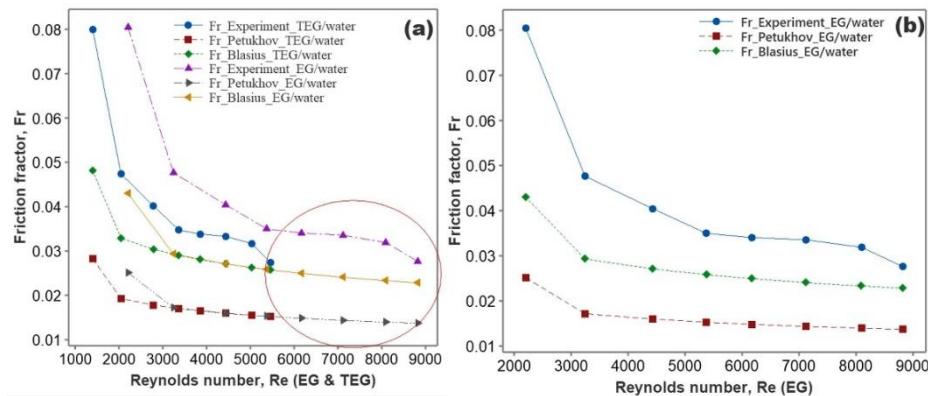


Figure 6. Effect of Reynolds number on friction factor: (a) TEG/water and EG/water, (b) EG/water.

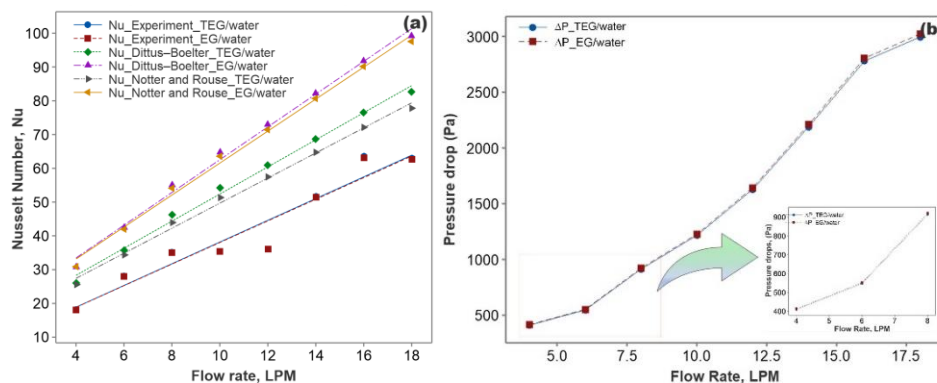


Figure 7. Effect of flow rate on (a) Nusselt number and (b) pressure drop

CONCLUSION

This study investigated the heat transfer coefficient (HTC) and pressure drop (ΔP) in copper pipe flow systems using TEG/water and EG/water binary fluids at a 40:60 volumetric ratio and an operating temperature of 60 °C. The results demonstrate that variations in the flow rate significantly influence both the HTC and ΔP , highlighting the interplay between the thermal performance and hydrodynamic resistance in such binary coolant systems.

- a. The rising heat transfer coefficient (HTC) observed in both the TEG/water and EG/water fluids passing through the copper pipe, in conjunction with increased flow rates, can be attributed to the corresponding increase in the Reynolds number, directly proportional to the higher flow rates. Consequently, the TEG/water fluid had a higher HTC than the EG/water fluid.
- b. The ΔP within the fluid in the copper pipe directly increased with the flow rate, whereas the friction factor in the TEG/water and EG/water fluids decreased as the flow rate increased.
- c. The Reynolds number of the fluid within the copper pipe maintained a directly proportional relationship with the fluid flow rate throughout the study.

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