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Innovative Heat Transfer Enhancement in Tubular Heat Exchanger: An Experimental Investigation with Minijet Impingement

Shital Yashwant Waware[1,2,*], Sandeep Sadashiv Kore[1], Anant Sidhappa Kurhade[2], Suhas Prakashrao Patil[3]

[1] Department of Mechanical Engineering, BRACT’s Vishwakarma Institute of Information Technology, Pune – 411048, Maharashtra, India
[2] Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology, Sant Tukaram Nagar, Pimpri, Pune- 411018, Maharashtra, India
[3] Department of Mechanical Engineering, Arvind Gavali College of Engineering, Satara, 415015, Maharashtra, India

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ABSTRACT

This paper investigates heat transfer in a horizontally oriented tubular heat exchanger through a comprehensive examination of both numerical simulations and experimental analyses. The primary focus is on copper as the material of interest, specifically examining an inner tube with a 14 mm internal diameter and 1 mm thickness, as well as an outer tube with a 29 mm external diameter and 1 mm thickness. In addition to these components, two perforated pipes with internal diameters of 11 mm and 20 mm are incorporated; contributing to an overall length of the heat exchanger measuring 281 mm. Notably, the perforation pipe features a 5 mm diameter hole on its periphery. A comprehensive assessment was conducted to appraise heat transfer and coefficients within a straightforward tubular heat exchanger. The mass flow rate of chilled water in the annular space fluctuated between 0.01 kg/sec and 0.11 kg/sec, while the steady flow rate of hot water within the inner tube remained constant at 0.11 kg/sec. Inlet temperatures for the hot water were established at 55 °C, 75 °C, and 85 °C, with the cold water maintaining a consistent inlet temperature of 29 °C throughout the experiment.

1. Introduction

Improving the thermal efficiency of heat exchangers can be accomplished through diverse strategies aimed at enhancing heat transfer. Among these approaches, the passive heat transfer enhancement technique referred to as tape insertion stands out, playing a crucial role in various heat transfer applications such as air conditioning, refrigeration systems, and food processing. Recent research, notably conducted by Yang *et al.,* [1], Akpinar *et al.,* [2], and Ma *et al.,* [3], has made notable progress in elevating heat transfer rates. Their investigations have highlighted the potential benefits of this technique, including energy savings, heightened thermal efficiency, and prolonged equipment lifespan.

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[*] *Corresponding author.*
E-mail address: shital.221p0009@viit.ac.in

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In a subsequent investigation, Lachi *et al.,* [4] delved into the time constants of both a shell and tube heat exchanger (HE) and a tubular heat exchanger (HE). The focus of this study was to categorize the characteristics of these heat exchangers under transient conditions, specifically when abrupt changes in inlet velocities were introduced. The analysis utilized a model with two crucial parameters: time delay and time constant. It is crucial to highlight that the analytical formulation was derived through the application of the energy balance equation. Additionally, an experimental approach was employed to validate the numerical results, revealing a maximum observed deviation of under 10%.

Furthermore, Aicher *et al.,* [5] conducted a comprehensive review exploring the effects of counterflow within the nozzle segment of a tubular heat exchanger (HE) positioned along the shell-side wall. The investigation unveiled a significant influence of counterflow on both pressure drop and heat transfer, particularly pronounced in smaller dimensions of the HE and reduced ratios of free cross-sectional areas. Practical methodologies for predicting heat transfer rates under turbulent flow conditions were proposed.

In a separate exploration, Mare *et al.*, [6] conducted an experimental and numerical investigation of heat transfer in concentric double-pipe heat exchangers (DPHEs) featuring mixed heat transfer with backflow. The working fluid for this investigation was water, operating under laminar flow conditions. Particle Image Velocimetry (PIV), a widely adopted flow visualization technique, was employed for visualizing flow patterns.

Pourahmad and Pesteei [8] conducted tests on a dual-pipe heat exchanger, integrating corrugated strip turbulators into the inner pipe, revealing significant enhancements in heat transfer properties. Ibrahim [9] observed improved laminar flow and heat transfer in simple tube designs through the inclusion of helical screw tape inserts. Targui *et al.,* [10] investigated the influence of porous baffles and flow pulsations on concentric tube heat exchangers, proposing that the introduction of oscillating equipment within the inner tube amplifies heat transfer. Sheikholeslami *et al.,* [11] conducted an analysis of using both plain and perforated variable spacing helical tabulators, investigating heat transfer and fluid flow for different area and pitch ratios, with results indicating the influence of open area ratio and pitch ratio on effectiveness.

The subsequent Shital *et al.,* [12] review concentrates on tubular heat exchangers and their significance across various industries. It underscores jet impingement cooling as an efficient method for enhancing heat transfer rates, encompassing experimental and numerical investigations exploring the impact of factors like Reynolds numbers, surface shapes, and nanofluids, providing insights for potential future research in heat transfer enhancement. Anant *et al.,* [21-24] explain material selections and CFD approaches towards thermal cooling. Nima Ahmadi *et al.,* [25,26] elaborate on the thermal performance of the Double-Pipe Heat Exchanger and the heat transfer and hydraulic characteristics of the tubular heat exchanger. Valiyollah Ghazanfari *et al.,* [27] discuss the thermal performance of the shell and tube heat exchanger using twisted tubes and Al2O3 nanoparticles. Anand Kishorbhai Patel *et al.,* [28] explains advancements in heat exchanger design for waste heat recovery in industrial processes.

However, it is crucial to note the limited literature on the use of tubular heat exchangers to enhance heat transfer. Consequently, the primary objective of this current study is to explore heat transfer enhancement by varying the inlet temperature of hot water with constant temperature of cold water, utilizing perforated tubes.

2. Experimental Facility and Procedure

Figure 1 provides a schematic representation of the testing facility. The cold tap water was divided into two distinct streams: one directed straight to the heat exchanger, and the other directed to an electrical heater for heating to the required conditions for the hot side of the heat exchanger. Both water streams were equipped with fine filters to purify the water effectively and protect other equipment in the facility. The electrical heater, under precise control facilitated by an autotransformer, allowed for smooth adjustments. Volumetric flow rates were measured using rotameters with a class 1 level of accuracy. Temperature measurements at the inlets and outlets of hot and cold water were conducted using T-type thermocouples with an accuracy of approximately ± 0.1 K, individually calibrated to achieve this level of precision.

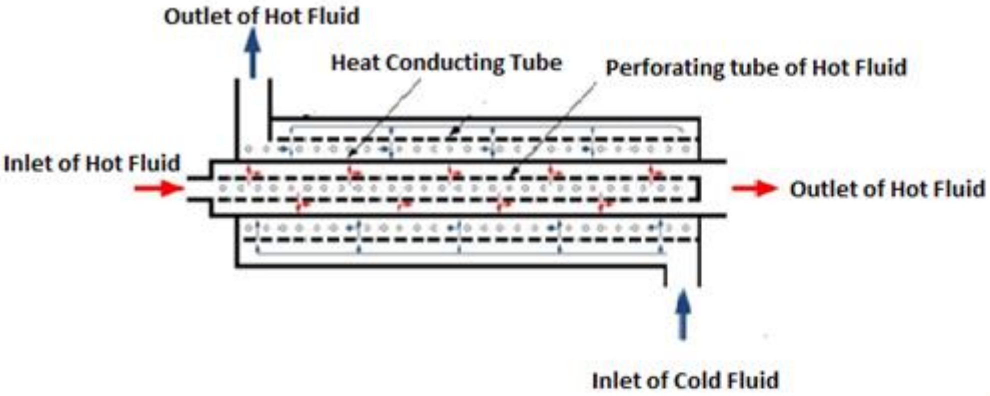

Fig. 1. Schematic diagram of tubular heat exchanger

Throughout the experiments, the volumetric flow rate of hot and cold water varied within the range of 100 to 400 litres per hour (lph). The hot water's temperature at the heat exchanger's inlet was set at three different levels: 55 °C, 75 °C, and 85 °C, while the cold-water temperature remained constant at 29 °C for each set of measurements. These temperature settings were selected based on potential waste heat source temperatures. Additionally, the pressure drop was measured using a differential pressure transducer with an accuracy of 0.25% of the full range (0-20 kPa).

The specimen section comprises a straight copper tube with both an outer tube and an inner tube, totalling 281 mm in length. The inner pipe has an 11 mm inner diameter and a 12 mm outer diameter, while the outer pipe features a 27 mm inner diameter.

To monitor temperature variations, thermocouples are attached at the inlet and outlet sections for both hot and cold water. The experimental trials involved different initial temperatures for the hot water, maintaining a constant flow rate, while the flow rate of cold water entering the test section underwent variation. Precise control over the inlet temperatures of the hot and cold water was ensured through the use of temperature controllers. Before data collection, the system underwent a stabilization period to achieve a steady-state condition.

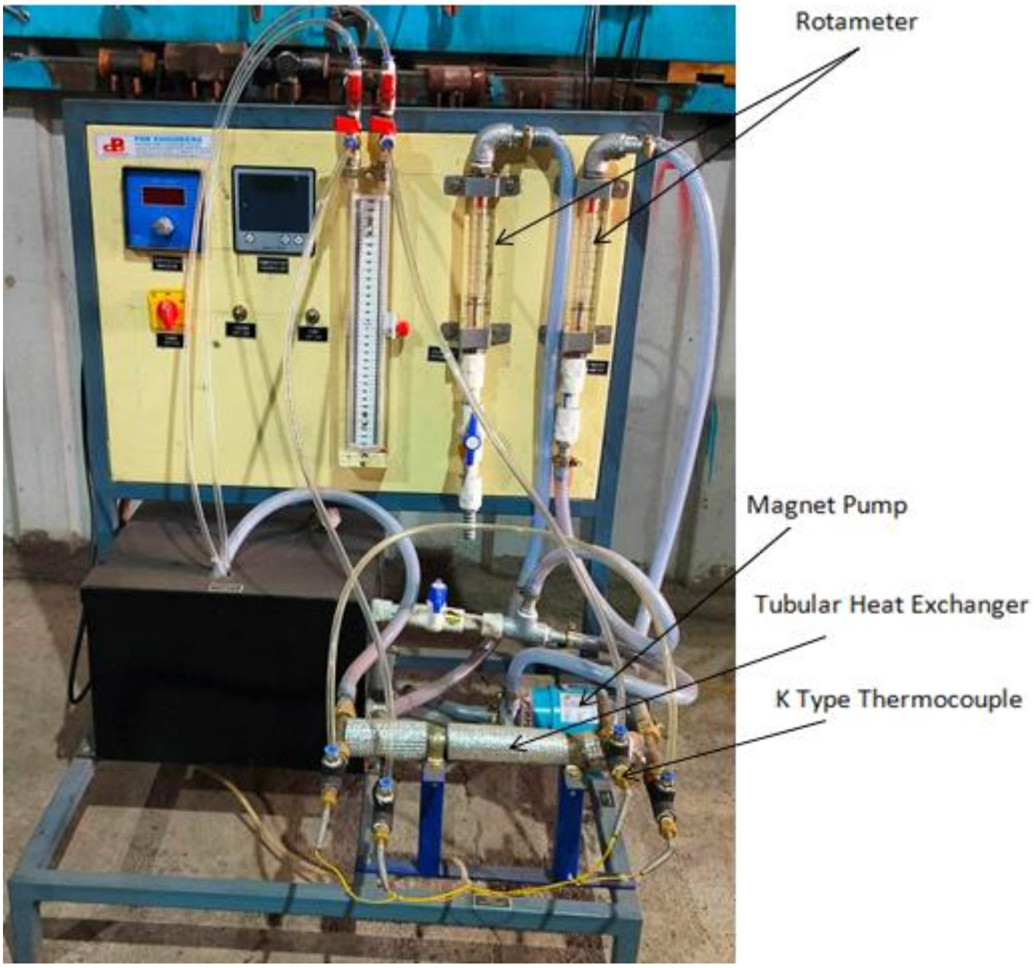

Fig. 2. Experimental setup of tubular heat exchanger after assembly

3. Data Reduction

For the temperatures deviations, a log means temperature difference (LMTD)

$$\mathrm{LMTD} = \frac{[(\mathrm{T_W.hin} - \mathrm{T_W.Cin}) - (\mathrm{T_W.hout} - \mathrm{T_W.Cout})]}{\mathrm{In}\,[\frac{\mathrm{T_W.hin} - \mathrm{T_W.Cin}}{\mathrm{T_W.hout} - \mathrm{T_W.Cout}}]} \tag{1}$$

For parallel flow and

$$\frac{[(\mathrm{T_W.hin} - \mathrm{T_W.Cout}) - (\mathrm{T_W.hout} - \mathrm{T_W.Cin})]}{\mathrm{In}\,[\frac{\mathrm{T_W.hin} - \mathrm{T_W.Cin}}{\mathrm{T_W.hout} - \mathrm{T_W.Cout}}]} \tag{2}$$

For counter flow is used.

Heat transferred to the cold water in the annulus, $Q_{W,C}$, can be determined from

$$\mathrm{Q_{W,C}} = \mathrm{m_{wc} C_p w}\,(\mathrm{T_{wcout}} - \mathrm{T_{wcin}}) = \mathrm{U_0 A_0 LMTD} \tag{3}$$

In this context, "mwc" represents the flow rate of cold water passing through the annulus, "Uo" is the heat transfer coefficient, "Ao" signifies the surface area of the outer diameter of the inner pipe, "Cpw" represents the specific heat of both cold and hot water, and "Twcin" and "Twcout" denote the initial and final temperatures of the cold water as it enters and exits the system, respectively.

Heat transferred from the hot water in the inner pipe, $Q_{w,h}$, can be determined as

$$Q_{W,h} = m_{wh} C_p w \, (T_{whout} - T_{whin}) = U_i A_i LMTD \tag{4}$$

In this context, "mw, h" represents the flow rate of hot water passing through the inner tube of the heat exchanger, "Ui" stands for the heat transfer coefficient, "Ai" denotes the surface area of the inner pipes inside diameter, "Cp, w" represents the specific heat of both cold and hot water, and "Tw, h, in" and "Tw, h, out" signify the initial and final temperatures of the hot water as it enters and exits the system, respectively.

The average heat transfer rate, Q_{avg}, is determined from the hot water side and cold-water side as

$$Q_{avg} = \frac{Q_{wc} + W_{wh}}{2} \tag{5}$$

The total heat transfer coefficient, Uo, based on the outer surface area of the inner pipe, can be calculated using the energy balance equation, taking into account minimal heat losses to the surroundings, as derived from LMTD of Parallel and Counter flow.

$$Q_{avg} = U_0 A_0 LMTD \tag{6}$$

4. Results and Conclusion

To corroborate the experimental results, a comparison was undertaken with the work of Lachi *et al.,* [4] to evaluate heat transfer and heat transfer coefficients in a basic tubular heat exchanger. The comparison indicates an error percentage of less than 5% between Lachi and the present study. The mass flow rate of cold water circulating in the annulus of the heat exchanger ranged from 0.01 kg/sec to 0.11 kg/sec, while the mass flow rate of hot water within the inner tube remained constant at 0.11 kg/sec. The inlet temperature of the hot water varied between 55 °C, 75 °C, and 85 °C, whereas the cold water's inlet temperature remained fixed at 29 °C.

Figure 3 illustrates the increase in the average heat transfer rate with variations in the mass flow rate of cold water in the annulus of the tubular tube heat exchanger at hot water inlet temperatures of 55 °C, 75 °C, and 85°C, respectively. This analysis involves different perforated tubes with an 11 mm internal diameter and a length of 281 mm. Notably, at specific hot water inlet temperatures of 55 °C, 75 °C, and 85°C, the heat transfer rate is directly proportional to the cold-water mass flow rate. This behaviour arises because heat transfer across the test section is contingent on the heat capacity of the hot water.

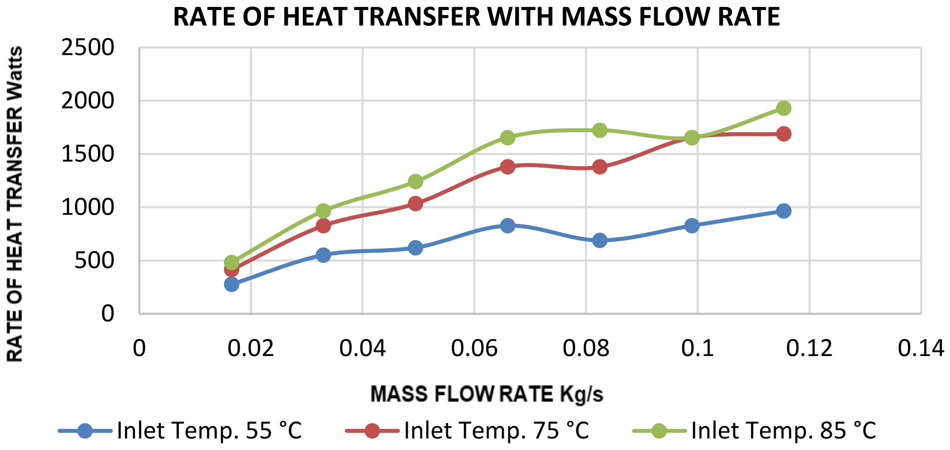

Fig. 3. Rate Heat transfer with mass flow rate at inlet temperature of hot fluid

Figure 4 illustrates the variation in the heat transfer coefficient in parallel flow conditions with the mass flow rate of cold water. The heat transfer coefficients exhibit an increase, aligning with the explanation previously provided for Figures 3, as outlined above.

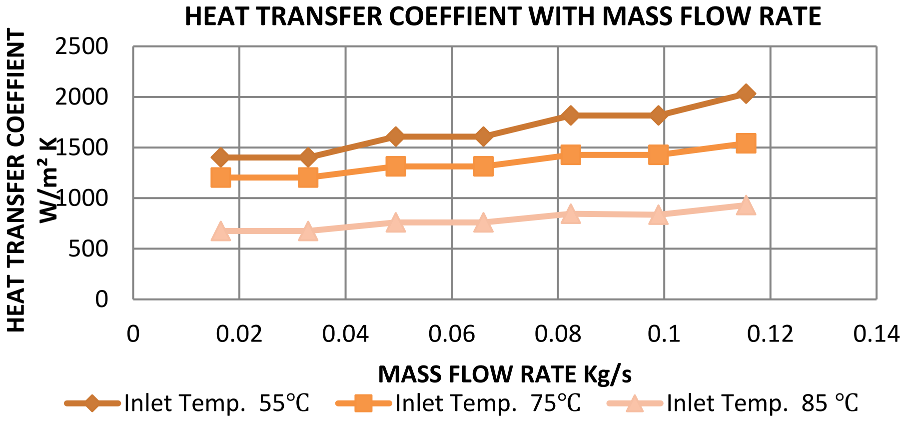

Fig. 4. Heat transfer coefficient with mass flow rate at inlet temperature

Heat transfer enhancement in tubular heat exchangers has become a focal point for optimizing thermal efficiency in various industrial applications. The incorporation of innovative techniques, such as jet impingement, has proven instrumental in augmenting heat exchange rates within the tubular design. By directing high-velocity jets onto the tube surfaces, jet impingement effectively enhances convective heat transfer, leading to improved overall performance. This approach is particularly valuable in scenarios where maximizing heat transfer efficiency is paramount. The comprehensive investigation of the heat transfer properties within the tubular heat exchanger has done with analysing the effects of different inlet temperatures and mass flow rates. Our research revealed the significant influence of the working fluid's characteristics as it enters the annulus and the presence of perforation tubes on heat transfer. Importantly, our findings demonstrated a direct correlation between the mass flow rates of the hot and cold fluids and the rate of heat transfer, as well as the heat transfer coefficient. Furthermore, our results indicated a noticeable improvement in both the heat transfer coefficient and heat transfer rate when compared to a plain tube.

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