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Heat Transfer Analysis of Metal Bellows in Thermal Environments

Sunil D. Wankhede[1,2*], Shravan H. Gawande[2]

[1] Mechanical Engineering Department, Trinity College of Engineering and Research, S. P. Pune University, Pune 411048, India
[2] Mechanical Engineering Department, M.E.S. Wadia College of Engineering, S. P. Pune University, Pune 411001, India

Corresponding Author Email: shgawande@gmail.com

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ABSTRACT

This paper presents a comprehensive study on the heat transfer analysis of metal bellows. Metal bellows are structural components characterized by a corrugated or wave-like pattern along the surface of a cylindrical tube, specifically designed to provide flexibility and elasticity. Wavy channels are preferred over straight channels due to their increased surface area, which enhances mass and momentum transfer during heat exchange processes. The heat transfer phenomena in metal bellows are inherently complex, making it challenging to derive an exact theoretical heat transfer coefficient. Consequently, experimental methods are employed to establish empirical correlations for the heat transfer coefficient. This study utilizes experimental techniques to review the heat transfer characteristics of metal bellows in both radial and longitudinal directions. The analysis is carried out by systematically varying critical geometric parameters of the bellows—namely, the outer diameter, convolution height, and the number of convolutions—in order to evaluate their influence on heat transfer performance. The resulting data are benchmarked against established correlations from the existing literature, as well as compared with newly formulated empirical relationships. In addition, this study presents an experimental investigation into the thermal performance of bellows under controlled thermal conditions. The experimental phase examines the effect of geometric configurations, including variations in outer diameter, convolution height, and convolution count, on heat transfer behavior across a range of flow velocities and thermal loads. Key thermal performance indicators—such as the heat transfer coefficient, Nusselt number, and Reynolds number—are analyzed under varying operational inputs, encompassing flow velocities of 1 m/s, 2 m/s, and 3 m/s, and heat inputs of 50 W, 100 W, 150 W, and 200 W.

1. INTRODUCTION

Metal bellows are flexible components characterized by a wavy surface on a cylindrical tube, designed to enhance elasticity and adaptability. In heat exchangers and pressure vessels, expansion joints incorporating metal bellows are used to accommodate thermal expansion and serve as pressure-containing elements. These bellows are generally used in shell and tube heat exchangers, handling vibrations and accommodating angular, radial, and axial displacements. Their applications extend to industrial plants, aerospace equipment, hose pipes, air conditioning, and vacuum systems. A metal expansion joint allows for axial, longitudinal, and angular movement in pipelines, vessels, and ducts. Adding fixtures enhances its functionality and complexity. Common accessories consist of weld ends, liners, collars, flanges, reinforcing and equalizing rings, tie rods, limit and control rods. Expansion joints come in various types, including rectangular and round designs, expansion compensators, single expansion joints, laminated and formed bellows, externally pressurized and universal joints, as well as bellows pump connectors.

Ahmed et al. [1] employed the finite volume method to conduct a numerical analysis of laminar forced convection heat transfer involving a copper-water nanofluid in a trapezoidal-corrugated channel. The use of copper-water nanofluid, rather than conventional fluids, improves heat transfer efficiency in such channels. Wankhede and Gawande [2] heat transfer analysis of bellows was studied by analytical and statistical methods. Taguchi DOE is used for statistical analysis, and a mathematical model is proposed and implemented for analytical analysis. The three process parameters, such as height, pitch, and thickness of the convolution, are studied and found that the height of convolution is the dominating parameter in heat transfer; henceforth, bellows with different heights of convolution are used for experimentation in the subsequent paper. Wankhede and Gawande [3] a comprehensive review was carried out on the diverse applications related to the design, analysis, and manufacturing of bellows. Also, study the performance of bellows, affected by the geometric parameters such as height, thickness, and number of convolutions in a thermal environment. Makke et al. [4] formulated a regression model to enhance the design parameters of bellows, such as thickness, pressure, and convolution depth. The Taguchi method was utilized to determine the optimal conditions.

Sun and Zeng [5] conducted both experimental and numerical investigations on the heat transfer characteristics of turbulent flow within a corrugated tube. The evaluation of performance was conducted using the friction factor (f), Reynolds number (Re), and Nusselt number (Nu). The wavy tube demonstrated superior heat transfer compared to a simple tube, though it resulted in higher friction. Siginer and Akyildiz [6] examined how the waviness of a corrugated tube influences the friction factor and Nusselt number. Performance was influenced by velocity, temperature, and changes in the corrugation angle. Rush et al. [7] analysed local heat transfer and flow behavior in a sinusoidal wavy passage under laminar and transitional flow conditions, revealing that microscopic mixing improves local heat transfer. Shokouhmand and Bigham [8] developed a numerical method for analyzing fluid flow and heat transfer through wavy microchannels and investigated the thermal behavior of gaseous flow within them.

Tong et al. [9] investigated heat transfer and fluid flow around sinusoidal corrugated tubes with different sine chamber configurations and developed a correlation equation, Nu = f (Re), for heat transfer analysis. With an increase in the size of the sine chamber, the flow resistance coefficient decreases, whereas the convective heat transfer coefficient increases. Heidary and Kermani [10] examined the effects of dimensionless amplitude, Reynolds number, and nanoparticles on the shear stress and Nusselt number of corrugated surfaces. Adding nanoparticles and incorporating horizontal wavy walls improved heat transfer in the channel by 50%. Yan et al. [11] examined the influence of pipe diameter and structural parameters of bellows in heat transfer enhancement. In steady flow conditions, the average heat transfer coefficients both inside and outside the bellows were 3 to 5 times greater, with the heat transfer improvement being 5 to 7 times higher compared to a smooth pipe. Kareem et al. [12] assessed passive heat transfer enhancement in corrugated tubes for both laminar and turbulent flow regions through numerical and experimental approaches. The helically coiled corrugated tube demonstrated improved heat transfer owing to the combined effects of corrugation and curvature.

Gunake and Kadam [13] simulated heat transfer and fluid flow in the laminar and turbulent regions of tubes with internal ribs, comparing the outcomes to the Dittus-Boelter correlation. The pipe with a 30° orientation exhibited the lowest pressure drop and highest heat transfer coefficient, while other orientations resulted in higher pressure drops and lower heat transfer coefficients. Qi et al. [14] investigated the improvement in heat transfer and flow resistance characteristics of TiO2-water nanofluids in stainless steel circular and corrugated tubes through numerical and experimental methods. The use of nanofluids combined with the corrugated tube led to a maximum heat transfer enhancement of approximately 54%.

Dong et al. [15] carried out an experimental study to examine the heat transfer characteristics and friction in corrugated tubes with different geometric parameters. The experiments were conducted at various Reynolds numbers, and the heat transfer performance of the corrugated tube was compared to that of a smooth tube. Pethkool et al. [16] examined heat transfer enhancement and friction factor characteristics in a helically corrugated tube. It was observed that increasing the pitch and rib height ratio led to higher Nusselt number, friction factor, and thermal performance factor. Sudula [17] performed a thermo-structural analysis of liner and non-liner bellows using the Expansion Joint Manufacturers Association (EJMA). At elevated temperatures and pressures, the liner bellows demonstrated better thermal strength and stability, whereas the non-liner bellows exhibited lower heat flux compared to the liner counterparts.

Babin and Peterson [18] created a computer-based model to enhance the optimization and formulation of the conceptual design for a flexible bellows heat pipe. The design process involved experimental testing of various flexible bellows heat pipes with different lengths and diameters. Wang et al. [19] analyzed the differences in heat transfer performance and thermal strain between a conventional tube and an outward convex corrugated tube receiver. Their findings indicated that the outward convex corrugated tube receiver improved heat transfer efficiency while also minimizing thermal strain. Kumaresan et al. [20] utilized nanoparticles to enhance the heat transfer capability in a receiver tube. To improve heat transfer efficiency and reduce heat loss, nanofluids were employed within the receiver tube of a parabolic trough collector. Jaipurkar et al. [21] conducted a study on the thermo-mechanical design and characterization of flexible metal bellows. Rozzi et al. [22] examined how wall corrugation influences heat transfer and pressure drop enhancement in both Newtonian and non-Newtonian fluids. Mokkapati and Lin [23] investigated the thermal performance of concentric tube heat exchangers incorporating twisted tape inserts, with a focus on their impact on engine efficiency. Their findings indicated that the integration of twisted tapes within corrugated tubes enhances heat transfer, leading to fuel savings and a reduction in harmful emissions. Zimparov [24] conducted an experimental analysis on the thermal and hydraulic characteristics of a two- and three-start spiral corrugated tube embedded with twisted tape inserts. The combined configuration was found to significantly improve heat transfer rates while potentially reducing the required heat transfer surface area. Vicente et al. [25] experimentally evaluated the thermal performance and frictional behavior of corrugated tubes under isothermal conditions. Compared to smooth tubes operating at steady-state flow, corrugated tubes demonstrated an increased pressure drop alongside improved heat transfer efficiency. Notably, both the friction factor and Nusselt number exhibited a positive correlation with increasing Prandtl number. Mahmud et al. [26] examined the influence of geometric parameters—specifically amplitude and wavelength—on fluid flow within wave-walled tubes under laminar flow conditions. The results highlighted that a higher amplitude-to-wavelength ratio significantly enhances thermal performance, as evidenced by increased Nusselt number, heat transfer coefficient, and pressure drop. Zachar [27] proposed enhancement strategies for helically coiled tube heat exchangers and demonstrated that the use of helically corrugated walls could yield a heat transfer improvement of approximately 80–100% compared to traditional smooth helical coils. Xie et al. [28], through numerical simulations, analyzed the thermal and flow characteristics within wavy channels across a Reynolds number range of 100–1100 at a fixed Prandtl number of 0.7. It was observed that increasing wave height and reducing wave pitch led to a rise in both friction factor and average Nusselt number. Sui et al. [29] studied periodically wavy channels with rectangular cross-sections and observed substantial variation in Dean vortex structures along the flow direction. Despite the associated pressure increase, the improvement in heat transfer was found to be proportionally greater, thereby validating the effectiveness of such designs. Zhang and Zhang [30] employed computational simulations to investigate turbulent flow in heat exchangers utilizing wave-walled tubes. Their results showed that, while pressure drop increased gradually with Reynolds number, wave-walled configurations consistently exhibited lower average pressure drops than straight-walled counterparts under equivalent flow conditions. Arman and Hassanzadeh [31] numerically explored the heat transfer and flow dynamics in wavy circular tubes using the finite volume method. They concluded that increasing wave amplitude or reducing wavelength enhances both heat transfer and pressure drop due to intensified secondary flow structures. Zhang et al. [32] assessed the overall thermal performance of different wave-walled tube geometries using the performance evaluation criterion (PEC). Arc-shaped wave tubes outperformed sine-shaped designs, particularly under higher Reynolds numbers, and the introduction of pulsating flow further augmented the heat transfer coefficient. Gao et al. [33] performed a numerical analysis on nanofluid ice slurry flow within spiral bellows, showing that increasing the ice crystal concentration from 10% to 30% at the inlet led to a substantial enhancement in heat transfer performance. In helical corrugated tube configurations, the heat transfer coefficient and average Nusselt number were found to be approximately 1.4 and 1.44 times greater, respectively, than those observed in straight tubes. Furthermore, Zhang et al. [34] studied the influence of pulsation parameters—including flow rate, frequency, and amplitude—on thermal performance in wavy-walled heat exchangers. Their findings reported an approximate 8.2% improvement in overall heat transfer efficiency compared to straight-walled designs. In a related study, Zhang et al. [35] investigated the effects of Reynolds number, nanoparticle concentration, and particle size on the thermal performance of wavy-walled heat exchangers. Results demonstrated that the corrugated design substantially outperforms straight tubes in terms of convective heat transfer, with a 9.67% enhancement in heat transfer coefficient and a 5.25% reduction in pressure drop observed at comparable Reynolds numbers.

A thorough examination of existing literature underscores the critical importance of thermal analysis in the effective design and application of bellows across a wide range of engineering domains. Bellows are frequently employed in systems subjected to thermal loads; however, the thermal behavior of these components remains insufficiently understood. A key challenge faced by researchers is the complex interplay between geometric parameters—such as the number of convolutions, convolution height, pitch, and wall thickness—and their collective influence on heat transfer performance. These geometrical factors significantly affect the distribution of thermal stresses, surface area for heat exchange, and the fluid flow regime within the bellows structure. Despite their extensive utility in sectors including aerospace, automotive, cryogenics, and energy systems, the thermal performance of bellows has not been a focal point in most experimental or computational investigations. The available body of research often emphasizes mechanical or fatigue characteristics, with comparatively limited attention directed toward thermal-fluid interaction under varying operating conditions. This gap in the literature represents a notable limitation, especially given the growing demand for high-efficiency, thermally stable components in compact and dynamic systems. The present study addresses this research void by focusing specifically on the thermal analysis of bellows under controlled thermal environments. By systematically investigating the influence of key geometric variables on heat transfer behavior, the study aims to contribute to the development of more thermally optimized bellows designs. Moreover, it seeks to provide a methodological foundation for future investigations, facilitating more accurate and application-specific heat transfer analyses of bellows in thermally active systems.

2. MATERIAL AND METHOD

2.1 Experimental setup and components

The experimental setup, as shown in Figure 1, was developed to perform the thermal analysis and pilot testing of bellows. Metal bellows are flexible element that compress under external pressure or expand under vacuum. Once the pressure or vacuum is removed, the bellows return to their original shape, as long as the material has not exceeded its yield strength. The air from a blower passes through a pipe on a heater, then the heated air passes through the bellows, and the temperature at various points is recorded. The recorded temperatures are used for heat analysis calculations. In the setup, use a blower of 0.5 HP and place it at 1m from the flow control valve. Ball type one way flow control valve is used and placed at a distance of 2 m from the orifice plate (Taper-45°, ID-40 mm and OD-50 mm). Also, the distance between the orifice plate and the metal bellows is 2 m.

Figure 1. Experimental setup

2.2 Component and function

The components used in the setup and their function are as underneath.

Blower: A blower is a device designed to accelerate the flow of air or gas by directing it through rotating impellers. It is primarily used for applications such as exhaust, aspiration, cooling, and ventilation. In certain setups, it is used to boost the air velocity when passing through bellows.

Flow Control Valve: A flow control valve regulates the volume of air flow in a pneumatic system. Controlling flow is essential in pneumatic systems, as the movement speed of fluid-powered machines or actuators is dependent on the flow rate of the pressurized fluid. It is used to adjust and control the volume and velocity of flow within a setup.

Orifice Plate: An orifice plate is a device used for flow measurement, which determines fluid flow by assessing the pressure drop as the fluid passes through the plate. When fluid flows through a restriction in a pipe, a pressure difference develops between the upstream and downstream sections. It is used in the setup to find the mass flow rate passing through the bellows.

Manometer: A manometer is an instrument that measures the pressure difference between two points in a pipe, utilizing the relationship between pressure and head. In this setup, it measures the pressure difference across the orifice plate in the pipe.

Heaters: A heating element transforms electrical energy into heat via Joule heating, where the electric current encounters resistance, causing the element to heat up. In the setup, the heaters are used to heat the air before it passes through the bellows.

Metal Bellows: It is the main component of the experimental setup, which is used (Table 1) to study the heat transfer and heat transfer analysis.

Control Panel: This device is useful to turn the heat exchanger ON/OFF automatically by controlling the temperature when the temperature inside the panel is above or below a fixed temperature. In the setup, it regulates the temperature of the flowing air by adjusting the electrical supply.

2.3 Experiment procedure

The experiments were conducted in the open-loop system. The loop consists of a blower, orifice plate, heaters, flow control valves, thermocouples, a manometer, and a metal expansion joint. The pressure drop in the orifice meter and bellows is measured with the help of a manometer. The volumetric air flow rates are varied with a flow control valve situated at the inlet of the pipe and after the blower. An electric heater was used to heat the bulk of the air during the experiment. Thermocouples placed on the expansion joint measure the inlet and outlet air temperatures. The flow characteristics, Nusselt number, and Reynolds number are determined based on the average temperature of the bellows wall and the outlet air temperature. The average Nusselt number is calculated, with all properties assessed at the bulk mean temperature. Now, by varying temperatures and flow rates, various sets of readings were taken to calculate the various parameters as discussed below.

2.4 Heat transfer analysis

The heat transfer analysis of bellows, which is modelled as a corrugated pipe, examines the heat transfer characteristics of the corrugated structure. This same analytical approach is extended to the metal expansion joint, given its analogous construction. Air serves as the working medium, circulating through the bellows. It is assumed that steady-state heat transfer is equivalent to heat loss from the bellows, allowing for a comprehensive evaluation of thermal performance. It was found that heat transfer (ht) increases as the convolution height (w) increases. Both analytical and regression (statistical) analyses show a close match for the below specifications, with the height of convolution being the highest contributing parameter for heat transfer. Therefore, the varying convolution heights bellows are chosen for experimentation, as detailed in Table 1.

2.5 Heat transfer performance estimation

A different set of steady state experiments is performed for different input conditions, and data has been recorded. For each experiment, the pressure drop across the orifice and test bellows is noted. The temperature was measured by thermocouples mounted at different locations in the bellows. The bulk temperature is calculated, and all air properties required for calculation are taken at the bulk temperature. The control panel was used to control the heater input and display the temperature of the test bellows. This data was used to estimate the Nusselt number as well as heat transfer coefficient. The velocity of flow is determined through the pressure difference obtained in the orifice meter, and it is verified by an anemometer. Some of the equations used for data analysis are as follows.

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

where, V is the velocity of flow, and D is the mean diameter of the bellows.

It was assumed that the heat absorbed through the air (Q_{air}) from constant heat supplied to the bellows is considered equal to internal forced circulation convection (Q_{conv}). The heat equation becomes as,

$$Q_{air} = Q_{conv} \tag{2}$$

where, the Q_{air} is the amount of heat received to the bellows from air, which was estimated by Eq. (3),

$$Q_{air} = \dot{m}C_p\,(T_{exit} - T_{entrance}) \tag{3}$$

The Nusselt number is the non-dimensional parameter for heat transfer enhancement. A higher Nusselt number corresponds to greater heat transfer enhancement in bellows. The Eq. (4) represent Nusselt number (Nu).

$$Nu = \frac{hD}{k} \tag{4}$$

The average heat transfer coefficient is determined using Eq. (5),

$$Q_{conv} = hA_s\,(T_w - T_b) \tag{5}$$

where, T_w is the average temperature measured by thermocouples placed on different locations of bellows, T_b is the bulk temperature (average of the inlet temperature of bellows and atmospheric temperature of air), and A_s is the surface area of bellows. For the Nusselt number, the Dittus-Boelter equation is given by,

$$Nu = 0.023 \times \mathrm{Re}^{0.8} \times \mathrm{Pr}^{0.4} \tag{6}$$

Table 1. Bellows specifications (All dimensions are in 'mm')

Bellows	ID	OD	Height of Convolution (w)	Pitch of Convolution (q)	Thickness of Convolution (t)	No. of Convolution	Bellows Length (L)
B1	88.9	108.9	10	16	0.5	7	152
B2	88.9	108.9	10	16	0.5	8	168
B3	88.9	112.9	12	16	0.5	7	152
B4	88.9	112.9	12	16	0.5	8	168
B5	88.9	116.9	14	16	0.5	7	152
B6	88.9	116.9	14	16	0.5	8	168

The Nusselt number obtained using the Dittus-Boelter equation (Eq. (6)) has been compared with the values calculated using Eq. (4). The comparison reveals that the Nusselt number computed by both equations exhibits close agreement, particularly at a flow velocity of 1 m/s. This consistency between the results validates the experimental findings by demonstrating their alignment with established theoretical correlations. Thus, the experimental methodology employed in this study is effectively corroborated through comparison with the widely accepted standard equation, reinforcing the reliability and accuracy of the obtained data.

3. RESULTS AND DISCUSSION

3.1 Estimation of Nusselt number (Nu) and Reynolds number (Re) at constant velocity

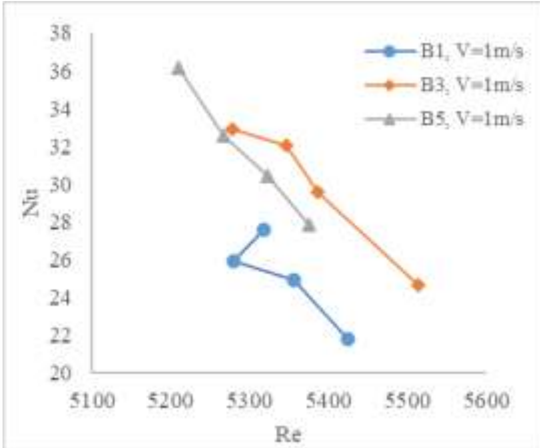
Figure 2 presents the variation of the Nusselt number (Nu) and Reynolds number (Re) for metal bellows with seven convolutions at flow velocities of (a) 1 m/s, (b) 2 m/s, and (c) 3 m/s, respectively. The subfigures 2(a), 2(b), and 2(c) depict the influence of various geometric parameters of the bellows, including convolution heights of 10 mm, 12 mm, and 14 mm; a fixed bellows length of 152 mm; and outer diameters of 108.9 mm, 112.9 mm, and 116.9 mm.

The graphs illustrate the relationship between Nu and Re for bellows with seven convolutions, where the convolution height is varied while maintaining constant flow velocities of 1 m/s, 2 m/s, and 3 m/s, respectively. These analyses are conducted for different heater input values of 50 W, 100 W, 150 W, and 200 W, as shown in Figures 2(a), 2(b), and 2(c). The presented data provides insights into the effect of convolution height and flow velocity on heat transfer performance, contributing to a better understanding of the thermal behavior of metal bellows under varying operational conditions.

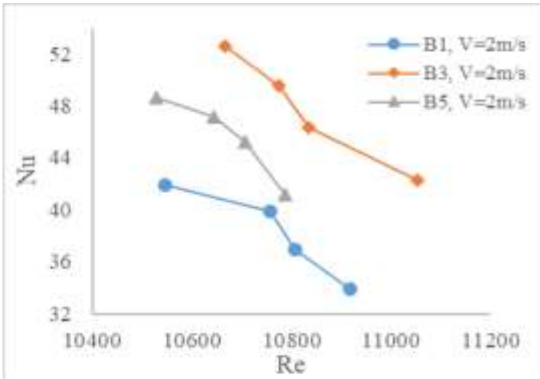
The increase in the Nusselt number is attributed to the rise in heat input, which enhances convective heat transfer. Conversely, the Reynolds number decreases despite the increase in heat supply, as the flow velocity remains constant. The observed trend of increasing Nusselt number and decreasing Reynolds number can be explained by the presence of convolutions in the bellows, which disrupt the flow and induce turbulence. This disruption enhances fluid mixing and improves heat transfer efficiency. The unique corrugated geometry of the bellows promotes turbulence even at relatively low Reynolds numbers, leading to an increased convective heat transfer coefficient. As a result, the higher turbulence levels contribute to a significant rise in the Nusselt number, demonstrating the effectiveness of the bellows design in augmenting heat transfer performance.

Figure 3 illustrates the variation of Nusselt number (Nu) and Reynolds number (Re) for eight-convolution bellows at flow velocities of (a) 1 m/s, (b) 2 m/s, and (c) 3 m/s. The analysis considers different geometric specifications of bellows, including convolution heights of 10 mm, 12 mm, and 14 mm; a fixed bellows length of 168 mm; and outer diameters of 108.9 mm, 112.9 mm, and 116.9 mm. The plots for Figure 3 (a), (b), and (c) depict these variations at constant velocities of 1 m/s, 2 m/s, and 3 m/s, respectively, with heater inputs of 50 W, 100 W, 150 W, and 200 W.

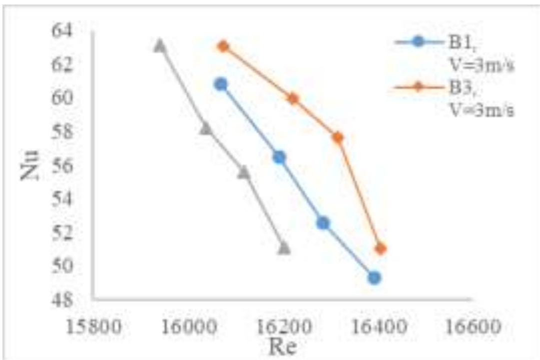
The results from Figure 3 indicate that as air flows through the bellows, the Nusselt number (Nu) increases and the Reynolds number (Re) decreases with increasing heat supply across the flow velocities of 1, 2, and 3 m/s. The increase in Nusselt number and the decrease in Reynolds number can be attributed to the convolution geometry of the bellows, which disrupts the flow and induces turbulence. This turbulence improves the heat transfer coefficient, thereby resulting in higher Nusselt numbers. This turbulence improves the heat transfer coefficient, thereby resulting in higher Nusselt numbers. The increase in Nusselt number and the decrease in Reynolds number was attributed to the convolution geometry of the bellows, which disrupts the flow and induces turbulence. This turbulence improves the heat transfer, thereby resulting in higher Nusselt numbers.



(a)

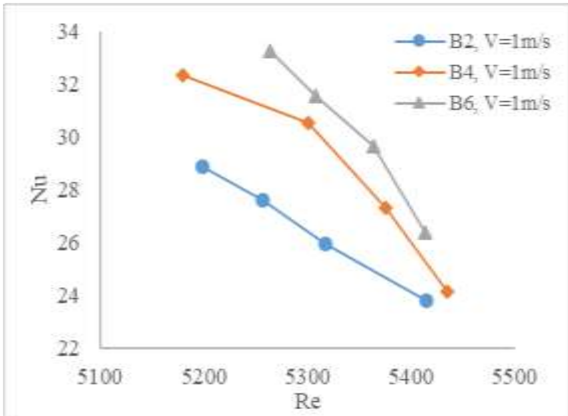


(b)

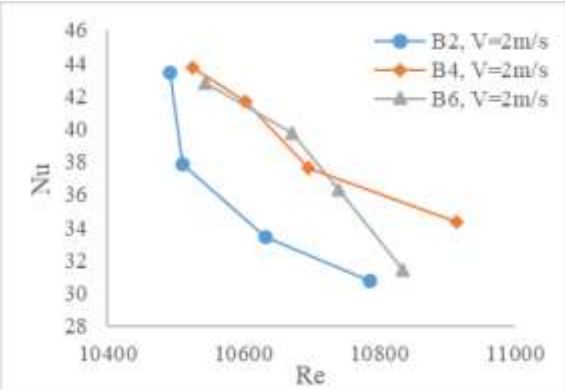


(c)

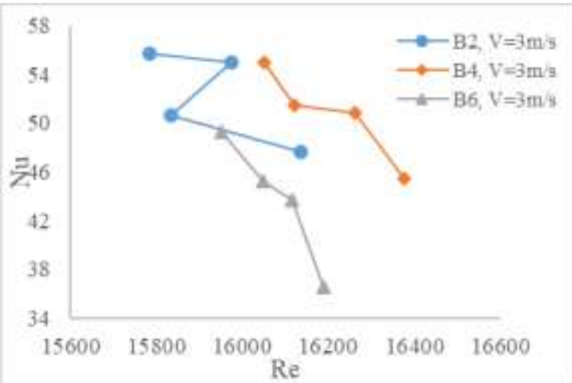
Figure 2. Variation of Nusselt number (Nu) and Reynolds number (Re) for 7 convolution bellows at velocity's of (a) 1 m/s, (b) 2 m/s, and (c) 3 m/s



(a)



(b)

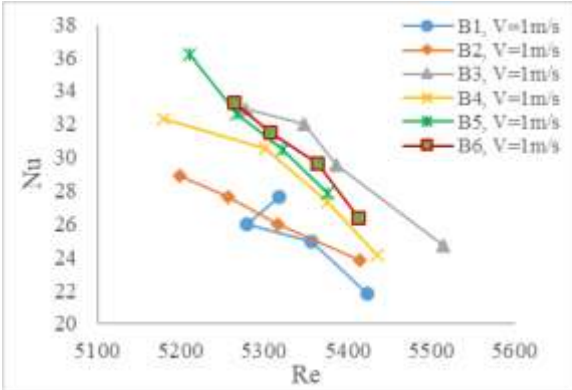


(c)

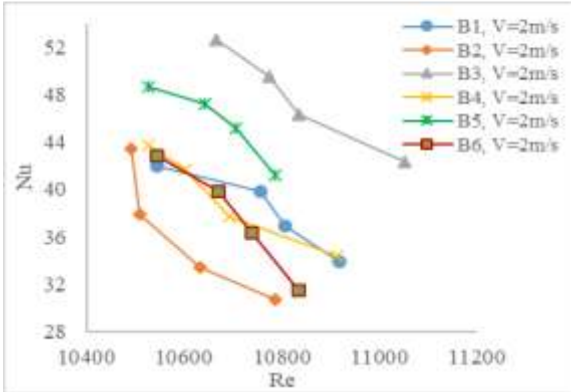
Figure 3. Variation of Nusselt number (Nu) and Reynolds number (Re) for 8 convolution bellows at (a) 1 m/s, (b) 2 m/s, and (c) 3 m/s, of velocity's

Figure 4 illustrates the correlation between the Nusselt number (Nu) and Reynolds number (Re) for bellows configurations with seven and eight convolutions, evaluated at flow velocities of (a) 1 m/s, (b) 2 m/s, and (c) 3 m/s. The analysis incorporates variations in geometric parameters, including convolution heights of 10 mm, 12 mm, and 14 mm; overall bellows lengths of 152 mm and 168 mm; and outer diameters of 108.9 mm, 112.9 mm, and 116.9 mm. Each subfigure reflects these configurations under heat inputs of 50 W, 100 W, 150 W, and 200 W.

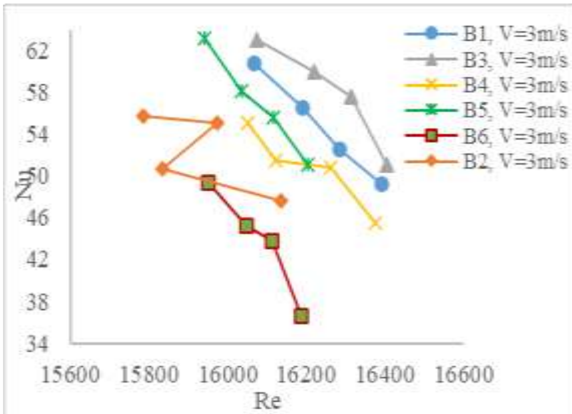
The data presented in Figure 4 reveal a consistent trend: with increasing heat input, the Nusselt number rises, while the Reynolds number shows a marginal decline across all considered flow velocities and bellows geometries. The rise in Nu indicates enhanced convective heat transfer, primarily driven by the increased thermal energy introduced into the system. The observed decrease in Re, despite constant flow velocities, was attributed to changes in fluid properties—particularly the decrease in dynamic viscosity due to temperature elevation. The convolution geometry of the bellows plays a significant role in this phenomenon by inducing turbulence, which enhances heat transfer and leads to a higher Nusselt number even at lower Reynolds numbers.



(a)



(b)



(c)

Figure 4. Variation of Nusselt number (Nu) and Reynolds number (Re) for 7 and 8 convolution bellows at velocity's of a) 1 m/s, (b) 2 m/s, and (c) 3 m/s

Figures 2 through 4 collectively demonstrate that the unique corrugated structure of the bellows significantly influences thermal performance. The presence of convolutions disrupts the flow, inducing localized turbulence, which in turn enhances fluid mixing and promotes more effective heat exchange. This flow disturbance is particularly impactful at lower Reynolds numbers, where such induced turbulence leads to a considerable increase in the convective heat transfer.

Consequently, the Nusselt number exhibits a notable upward trend as a function of heat input.

Moreover, when the flow velocity is held constant, and only the heat supply is varied across different bellows geometries, the changes observed in the Nusselt number are primarily governed by the geometric design of the bellows rather than by flow regime variation. The convoluted or wave-like profiles enhance surface area and disrupt boundary layers, thereby intensifying local heat transfer. This effect becomes increasingly dominant with higher heat inputs, resulting in elevated Nu values even when Re remains relatively unchanged. These findings underscore the critical role of bellows geometry in optimizing thermal performance and validate the effectiveness of corrugated designs in facilitating enhanced convective heat transfer across varying operational conditions.

3.2 Estimation of Nusselt number (Nu) and Reynolds number (Re) at constant heat supply

Figure 5 presents the relationship between the Nusselt number (Nu) and Reynolds number (Re) for a seven-convolution bellows configuration under varying thermal inputs: (a) 50 W, (b) 100 W, (c) 150 W, and (d) 200 W. The analysis considers a fixed bellows length of 152 mm, with geometric variations in convolution height—10 mm, 12 mm, and 14 mm—and outer diameters of 108.9 mm, 112.9 mm, and 116.9 mm. Each subfigure 5(a)–5(d) illustrates the behavior of Nu and Re across three flow velocities (1 m/s, 2 m/s, and 3 m/s), while maintaining a constant heat supply in each case. The results demonstrate a clear and consistent trend: as flow velocity increases, the Reynolds number exhibits a near-linear rise, leading to a corresponding increase in the Nusselt number. This behavior is indicative of enhanced convective heat transfer performance at higher velocities. The observed improvement is primarily attributed to the increase in the convective heat transfer, which arises due to intensified fluid motion. Greater flow velocity reduces the thermal boundary layer thickness, thereby improving heat exchange between the fluid and the bellows surface. These findings highlight the significant influence of fluid dynamics on thermal performance, especially under varying geometric and thermal conditions.

Figure 6 presents the variation in Nusselt number (Nu) and Reynolds number (Re) for an eight-convolution bellows subjected to varying thermal input conditions: (a) 50 W, (b) 100 W, (c) 150 W, and (d) 200 W. The investigation considers diverse geometric configurations, specifically convolution heights of 10 mm, 12 mm, and 14 mm; a total bellows length of 168 mm; and outer diameters of 108.9 mm, 112.9 mm, and 116.9 mm.

Figure 6(a) through (d) illustrates the thermal-fluidic behavior at fixed heat inputs of 50 W, 100 W, 150 W, and 200 W, respectively, across flow velocities of 1 m/s, 2 m/s, and 3 m/s. The analysis indicates a consistent increase in both Nusselt number and Reynolds number with rising flow velocity. This trend is attributed to the direct proportionality of Reynolds number to velocity, signifying a transition in flow dynamics and enhanced convective heat transfer with increasing fluid momentum. Also, at constant heat supply, increasing the flow velocity results in higher Nusselt and Reynolds numbers, thereby significantly enhancing convective heat transfer within the bellows. These findings underscore the importance of flow velocity in optimizing the thermal performance of bellows systems.

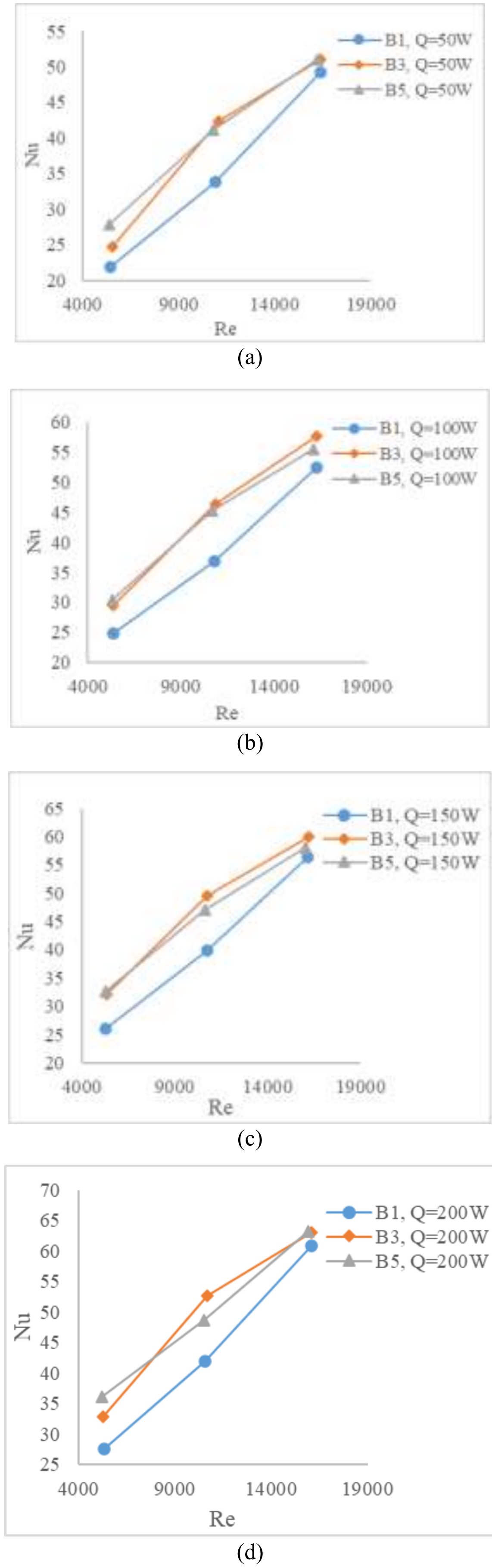


Figure 5. Variation of Nusselt number (Nu) and Reynolds number (Re) for 7 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W

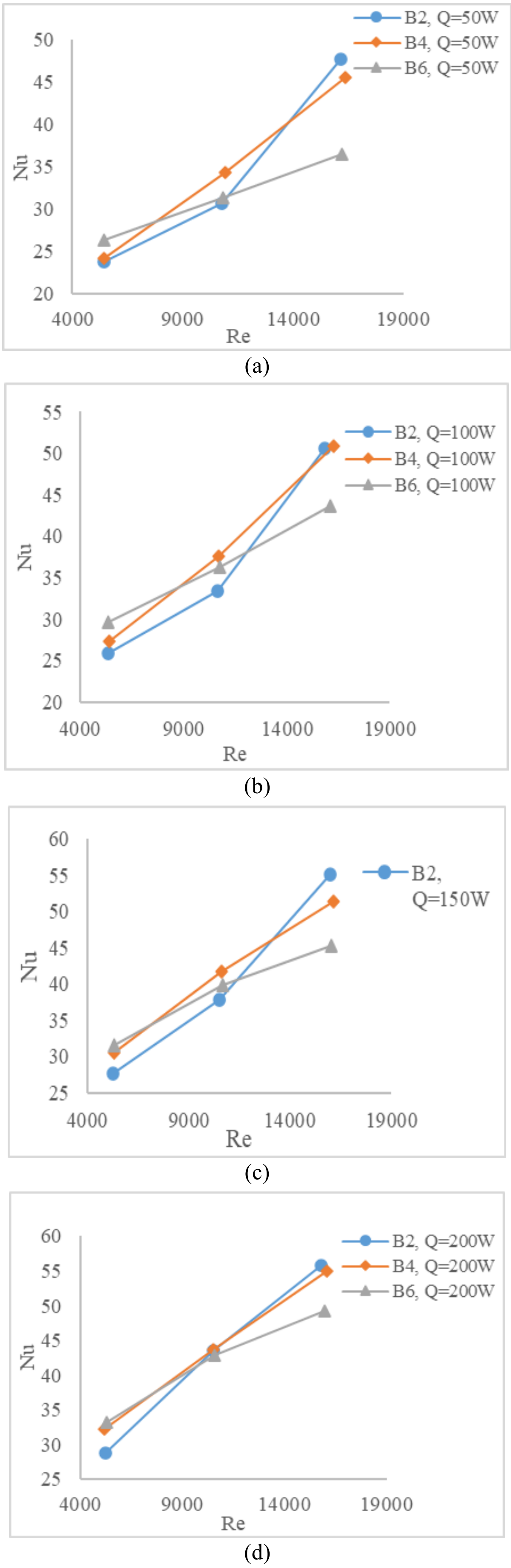


Figure 6. Variation of Nusselt number (Nu) and Reynolds number (Re) for 8 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W

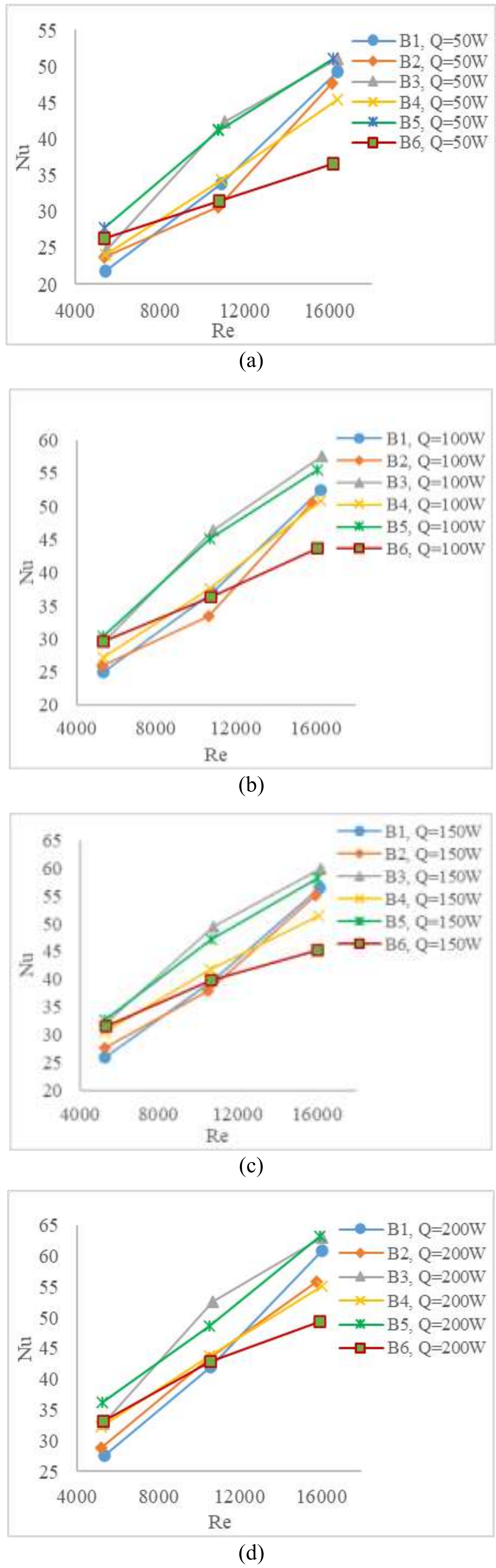


Figure 7. Variation of Nusselt and Reynolds number for 7 and 8 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W

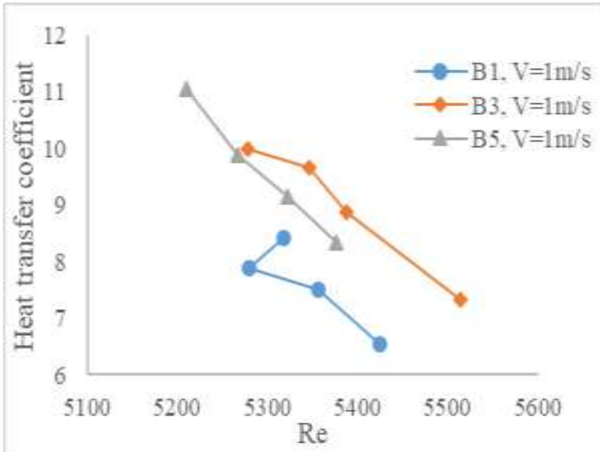
Figure 7 illustrates the comparative variation of the Nusselt number (Nu) and Reynolds number (Re) for bellows with seven and eight convolutions under distinct thermal input conditions: (a) 50 W, (b) 100 W, (c) 150 W, and (d) 200 W. The analysis incorporates a range of geometric parameters, including convolution heights of 10 mm, 12 mm, and 14 mm; bellows lengths of 152 mm and 168 mm; and outer diameters of 108.9 mm, 112.9 mm, and 116.9 mm. Figures 7(a) through 7(d) represent these variations at constant heat inputs of 50 W, 100 W, 150 W, and 200 W, respectively, for inlet flow velocities of 1 m/s, 2 m/s, and 3 m/s. The results indicate a linear increase in Reynolds number with flow velocity, consistent with its direct dependence on velocity. Correspondingly, the Nusselt number exhibits a progressive rise as a function of the Reynolds number, influenced by the prevailing flow regime. This enhancement in Nu signifies increased turbulence intensity and more effective convective heat transfer across the bellows structure.

Figures 5 through 7 collectively demonstrate a pronounced positive correlation between the Nusselt number (Nu) and the Reynolds number (Re) under conditions of constant heat input and varying flow velocities. As fluid velocity increases, both Re and Nu exhibit substantial growth, indicative of a shift toward more turbulent flow regimes. This transition enhances fluid mixing and disrupts the thermal boundary layer, thereby augmenting convective heat transfer efficiency. The consistent rise in Nu underscores the increasing dominance of convection over conduction at elevated velocities. These findings underscore the pivotal role of flow velocity in enhancing the thermal performance of bellows-based systems under steady thermal loading. Also, understanding and controlling fluid dynamics can lead to more efficient thermal management, highlighting the critical interdependence between Nusselt and Reynolds numbers in evaluating and enhancing heat transfer performance.

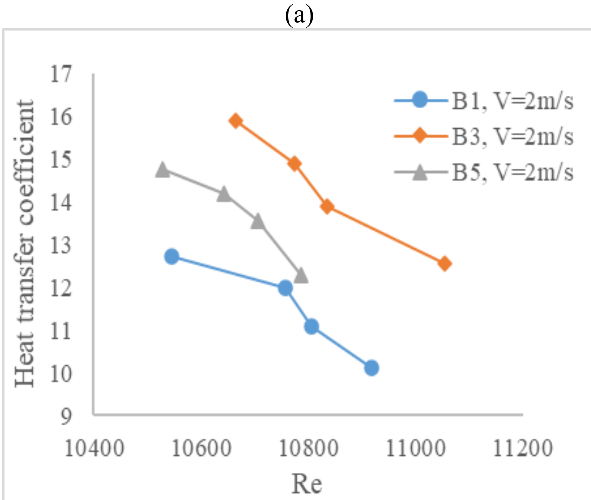
3.3 Estimation of h, heat transfer coefficient, and Re, Reynolds number at constant velocity

Figure 8 illustrates the changes in ‘h’ and ‘Re’ for a seven-convolution bellows at three different velocities: (a) 1, (b) 2, and (c) 3 m/s, respectively. Figure 8(a), (b), (c) shows the difference of heat transfer coefficient and Reynolds number for various geometric specification of bellows such as 10, 12, 14 mm of convolution height; 152 mm bellows length; and 108.9, 112.9, 116.9 mm are the outer diameters; at constant velocities as 1, 2 and 3 m/s respectively, for heater input of 50, 100, 150 and 200 W. The graph concerning the heat transfer coefficient (h) and Reynolds number (Re) for bellows, of a constant flow velocity and varying heat supplies, shows the increase in heat transfer coefficient as heat supply increases, while ‘Re’ remains constant or slightly decreases, as indicated in Figure 8. The Reynolds number is found by the flow velocity, fluid properties, and characteristic length; it does not change with variations in heat supply when the flow velocity is kept constant. However, the ‘h’ increases due to higher heater input, indicating that the temperature gradient between the bellows surface and the fluid becomes steeper, thereby enhancing the heat transfer process.

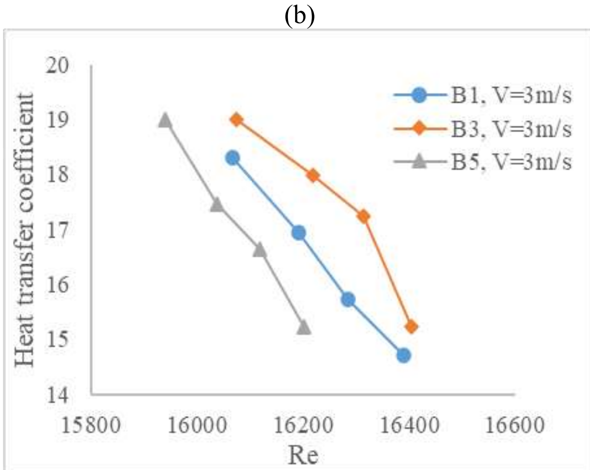
Figure 9 shows the variation of (h) and (Re) for 8 convolution bellows at three different velocities (m/s): (a) 1, (b) 2, and (c) 3. Also Figure 9(a), (b), (c) shows the variation in heat transfer coefficient and Reynolds number for different geometric specification of bellows such as 10, 12, 14 mm of convolution height; 168 mm bellows length; and 108.9, 112.9, 116.9 mm are the outer diameters; at constant velocity of 1 m/s, 2 m/s, and 3 m/s respectively, for heater input of 50, 100, 150 and 200W. The graph between (h) and (Re) for the bellows, at a constant flow velocity and varying heat supplies, shows the increase in ‘h’ as heat supply increases, while the Reynolds number remains unchanged or small decrease as presented in Figure 9. The actual effectiveness of heat transfer is significantly influenced by the amount of heat supplied to the bellows.



(a)

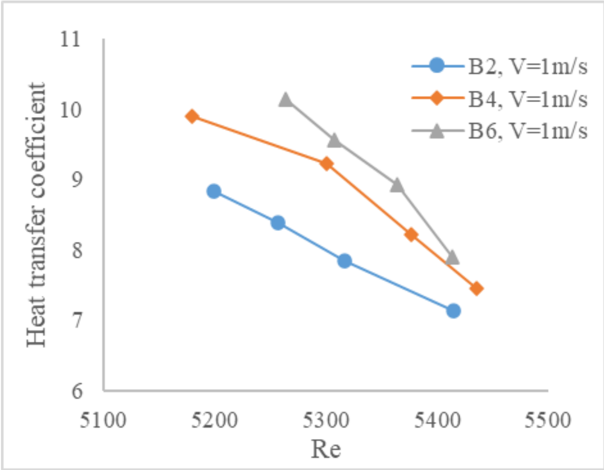


(b)

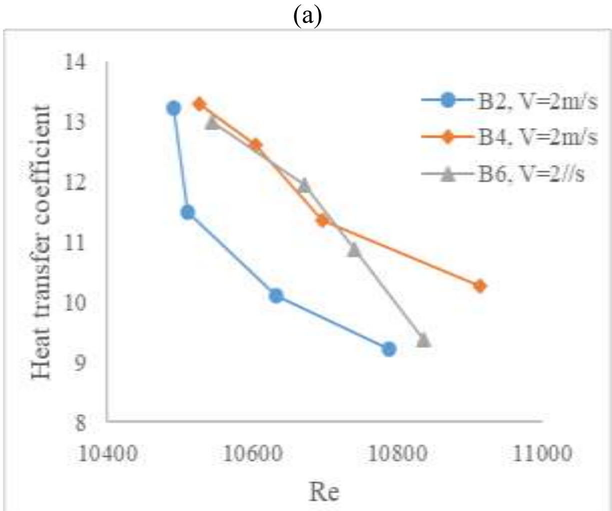


(c)

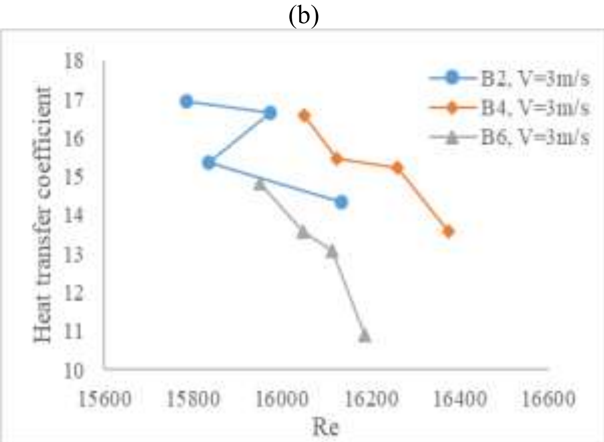
Figure 8. Variation of ‘h’ and Reynolds number for 8 convolution bellows at three different velocities in m/s: (a) 1, (b) 2, and (c) 3



(a)



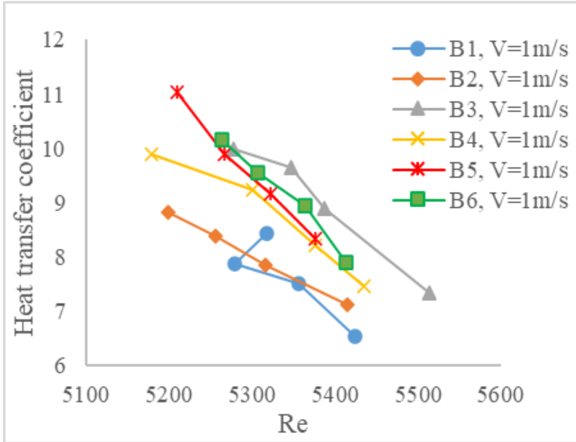
(b)



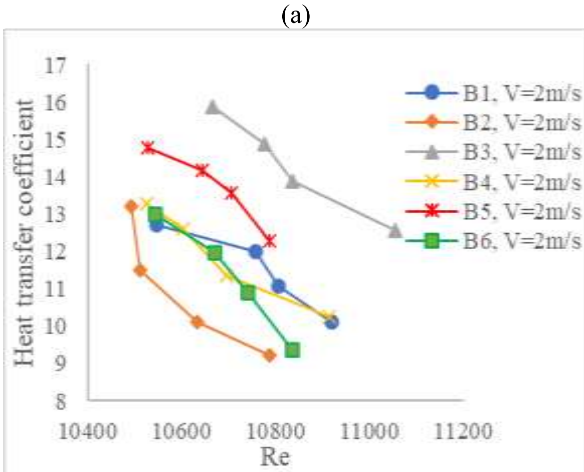
(c)

Figure 9. Variation of 'h' and Reynolds number for 8 convolution bellows at three different velocities: (a) 1 m/s, (b) 2 m/s, and (c) 3 m/s

Figure 10 shows a variation in heat transfer coefficient (h) and Reynolds number (Re) for a 7 and 8 convolution bellows at three different velocities: (a) 1 m/s, (b) 2 m/s, and (c) 3 m/s. Figure 10 displays the deviation of heat transfer coefficient and Reynolds number for varied geometric bellows specification such as 10, 12, 14 mm of convolution height; 152, 168 mm bellows length; and 108.9, 112.9, 116.9 mm are the outer diameters; at constant velocity as 1 m/s, 2 m/s, and 3 m/s respectively, for heating input of 50, 100, 150 and 200 W. The graph of heat transfer coefficient and Reynolds number, for bellows, with a constant flow velocity and varying heat supply shows that the heat transfer coefficient increases as increased in heat supply increases, and 'Re' slightly decreases, as shown in Figure 10. The observed trend highlights the role of thermal input in optimizing the performance of heat transfer, even if a fluid flow regime is stable. The relation between Reynolds number and heat transfer coefficient under varying heat supply conditions, emphasizing the impact of heat input on the bellows thermal performance despite a constant flow regime.



(a)



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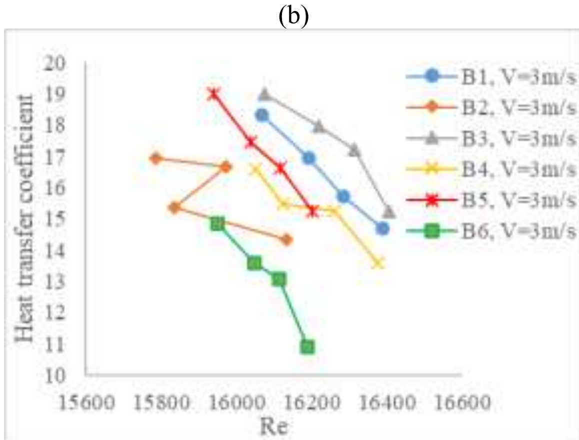


(c)

Figure 10. Variation of heat transfer coefficient and Reynolds number for 7 and 8 convolution bellows at three different velocities: (a) 1 m/s, (b) 2 m/s, and (c) 3 m/s

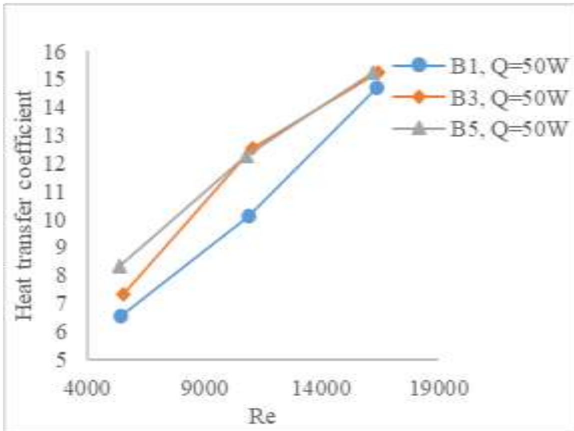
Figures 8, 9, and 10 reveal that, under conditions of constant flow velocity, an increase in heat input leads to a noticeable rise in the heat transfer coefficient (h), while the Reynolds number (Re) exhibits a slight decline. Since Re is primarily governed by flow velocity, fluid properties, and characteristic geometric length, it remains largely unaffected by changes in heat supply when velocity is held constant. The observed increase in ‘h’ with higher thermal input is attributed to an intensified temperature gradient between the bellows surface and the surrounding fluid, which enhances convective heat transfer. The slight reduction in Reynolds number is influenced by changes in fluid viscosity due to localized heating or by geometric factors inherent to the bellows configuration. This trend underscores the important role of thermal input in improving heat transfer performance, even when the flow regime remains hydrodynamically stable. It highlights the fact that thermal enhancements can be achieved through temperature-driven boundary layer effects, independent of significant changes in flow dynamics.

Investigating the relationship between the heat transfer coefficient and Reynolds number at constant velocity while varying heat input across different bellows geometries is both rational and technically valuable. It deepens our understanding of how thermal load interacts with structural design to influence convective performance, challenges the predictive capacity of conventional design models, and contributes to the advancement of energy-efficient, safe, and robust thermal systems.

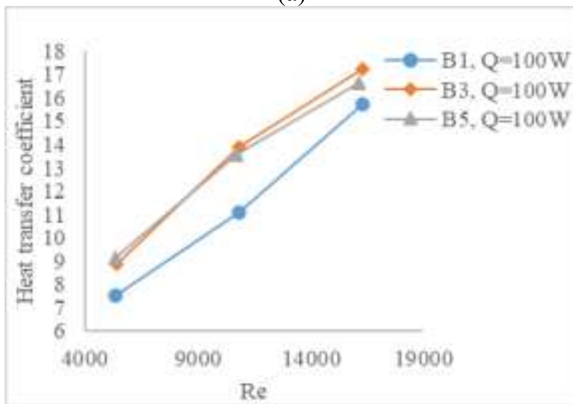
3.4 Estimation of heat transfer coefficient (h) and Reynolds number (Re) at constant heat supply

Figure 11 shows a variation in a ‘h’ and ‘Re’ for 7 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W. Figure 11 explains the distinction of heat transfer coefficient and Reynolds number for unlike geometric specification of bellows such as 10, 12, 14 mm of convolution height; 152 mm bellows length; and 108.9, 112.9, 116.9 mm are the outer diameters; at a heat supply of 50, 100, 150 and 200 W for a velocities of 1, 2 and 3 m/s respectively. The graph concerning the heat transfer coefficient and Reynolds number for the bellows, with a constant heat supply and varying flow velocities, reveals a direct relation between these parameters, as shown in Figure 11. As the flow velocity increases, the heat transfer coefficient and Reynolds number both increase for each heat input and velocity. An increase in Reynolds number with higher flow velocities reflects the transition from laminar to turbulent flow regimes. This transition enhances fluid mixing and disrupts the thermal boundary layer, leading to additional efficient heat transfer. Consequently, the heat transfer coefficient also increases, indicating improved convective heat transfer performance.

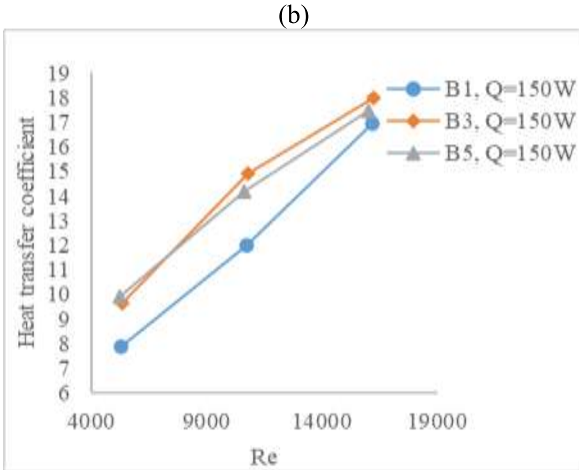
Figure 12 shows the variation of heat transfer coefficient and Reynolds number for 8 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W. Figure 12 specifies the variation of heat transfer coefficient and Reynolds number for dissimilar geometric specification of bellows such as 10, 12, 14 mm of convolution height; 168 mm bellows length; and 108.9, 112.9, 116.9 mm are the outer diameters; at a heat input of 50, 100, 150 and 200W for a velocities of 1, 2 and 3 m/s respectively. The graph of h and Re, with a constant heat supply and varying flow velocities, reveals a direct relationship between these parameters, as shown in Figure 12. As the flow velocity increases, it results in a corresponding rise in both the Reynolds number and the heat transfer coefficient. Under constant heat supply conditions, higher flow velocities significantly enhance the heat transfer coefficient by promoting turbulence, as reflected by the increase in Reynolds number.



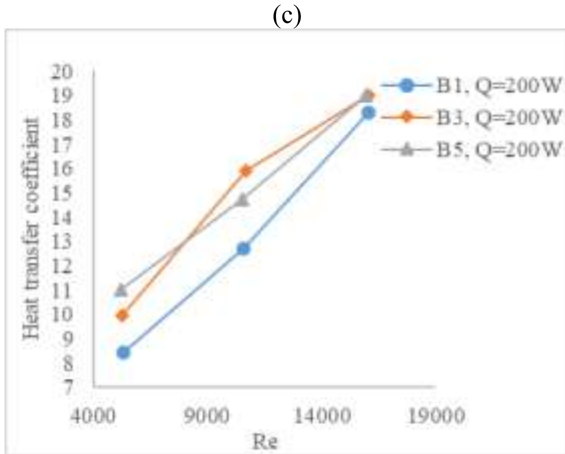
(a)



(b)

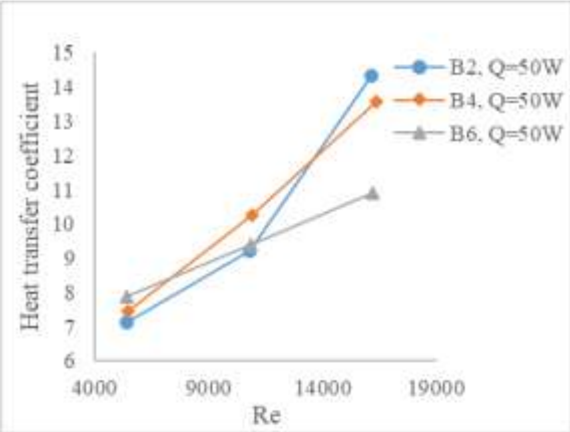


(c)

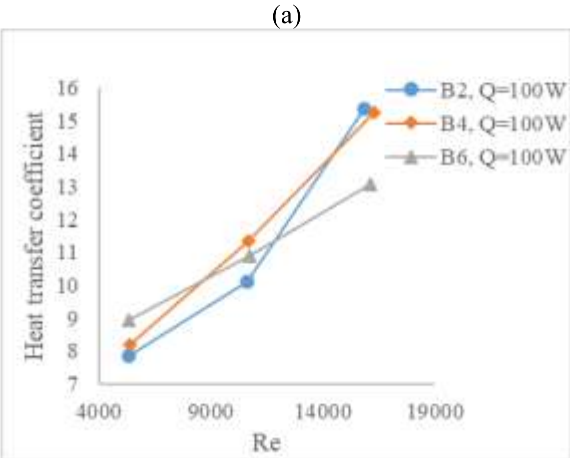


(d)

Figure 11. Variation of heat transfer coefficient (h) and Reynolds number (Re) for 7 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W



(a)



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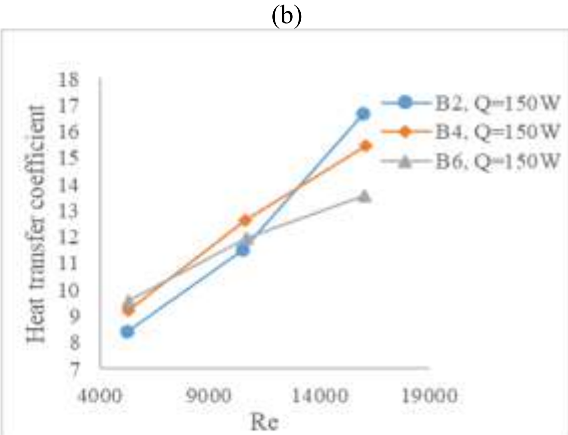

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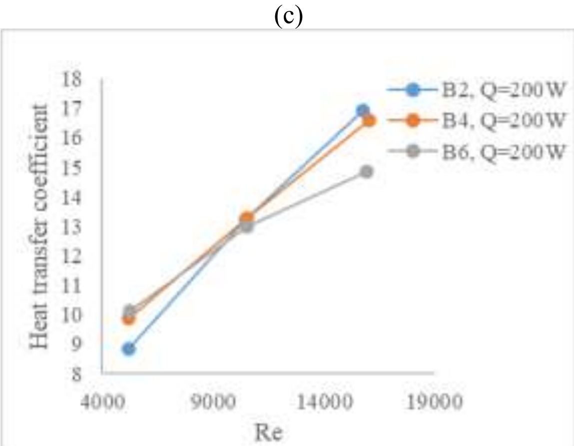
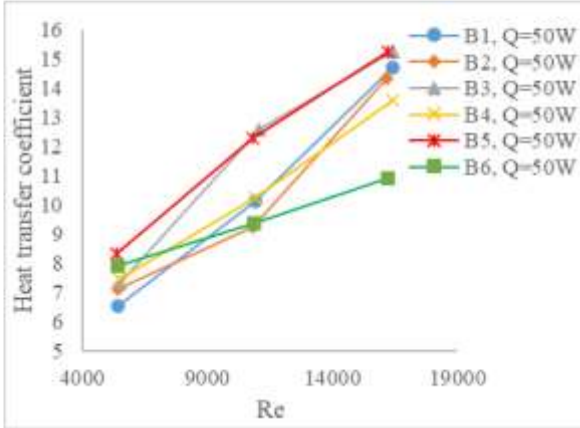
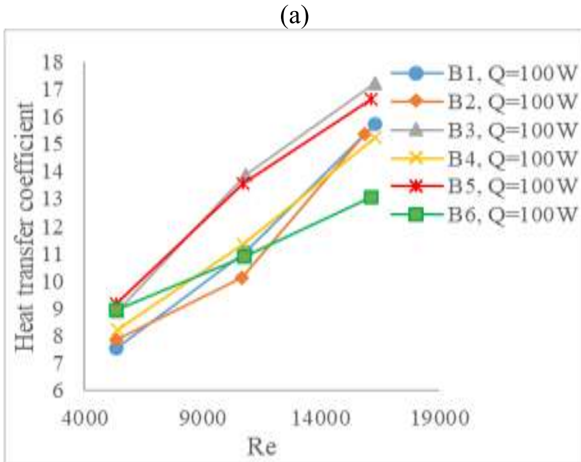


(d)

Figure 12. Variation of heat transfer coefficient (h) and Reynolds number (Re) for 8 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W



(a)



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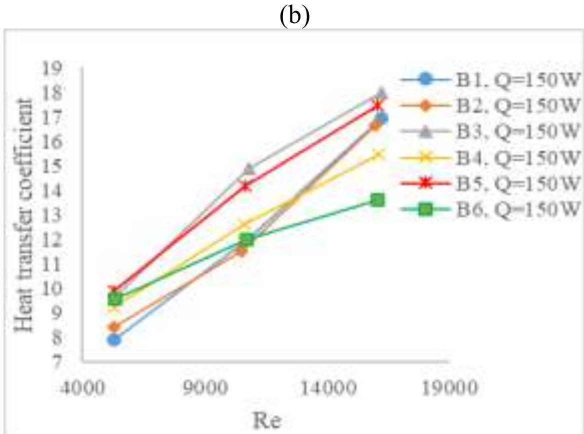

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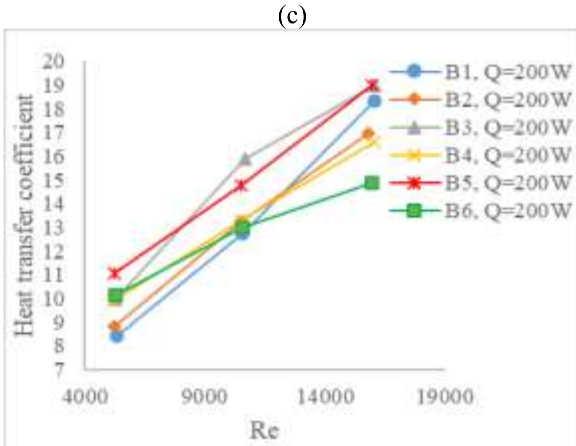

(d)

Figure 13. Variation of heat transfer coefficient (h) and Reynolds number (Re) for 7 and 8 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W

Figure 13 shows the distinction in 'heat transfer coefficient' and Reynolds number for 7 and 8 convolution bellows at (a) heat supply-50 W, (b) heat supply-100 W, (c) heat supply-150 W, (d) heat supply-200 W. Figure 13 shows a variation in heat transfer coefficient and Reynolds number for diverse specification of bellows geometry such as 10, 12, 14 mm of convolution height; 152, 168 mm bellows length; and 108.9, 112.9, 116.9 mm are the outer diameters; at a heat supply of 50, 100, 150 and 200W for a velocities of 1, 2 and 3 m/s respectively. Figure 13 also shows a relationship between the heat transfer coefficient and Reynolds numbers of bellows, with a constant heat supply and varying flow velocities. As the flow velocity increases, both the Reynolds number and heat transfer coefficient increase. A Reynolds number increase at advanced flow velocities reflects the transition of laminar to turbulent flow regimes. This transition enriches fluid mixing and disrupts the thermal boundary layer, leading to more efficient heat transfer. This relationship is crucial for optimizing heat transfer in systems involving bellows, where adjusting flow velocity proves to be an effective strategy for improving thermal performance.

Figures 11, 12, and 13 demonstrate that increasing flow velocity leads to a corresponding rise in both the heat transfer coefficient (h) and the Reynolds number (Re). Under constant thermal input conditions, elevated flow velocities substantially enhance the heat transfer coefficient due to the intensification of turbulence, as indicated by the increasing Reynolds number. This correlation underscores the critical role of flow dynamics in augmenting convective heat transfer, particularly in bellows-based systems, where velocity modulation emerges as an effective means of improving thermal efficiency.

Examining the relationship between the heat transfer coefficient and Reynolds number at fixed heat supply levels across varying flow velocities and bellows geometry is both technically justified and strategically important. Such an investigation provides a deeper understanding of how geometric design and flow conditions interact to influence heat transfer mechanisms. It also supports the development of optimized bellows configurations tailored for dynamic flow environments and contributes essential empirical data for refining thermal performance. Ultimately, these insights facilitate the design of energy-efficient, high-performance thermal systems with enhanced reliability and operational adaptability.

4. CONCLUSION

This study presents an experimental investigation into the heat transfer performance of bellows subjected to thermal environments. The research evaluates the influence of varying flow velocities and heat inputs on heat transfer characteristics for different geometric configurations of bellows, including outer diameter, convolution height, and the number of convolutions. Key thermal performance indicators such as the heat transfer coefficient, Nusselt number, and Reynolds number are analyzed across a range of operating conditions—specifically, flow velocities of 1 m/s, 2 m/s, and 3 m/s, and heat inputs of 50 W, 100 W, 150 W, and 200 W. The major conclusions derived from the experimental analysis are as follows:

Influence of Heat Input on Nusselt and Reynolds Numbers- As increasing heat input leads to a rise in the Nusselt number and a concurrent decrease in the Reynolds number. The increased Nusselt number with higher heat input confirms the effectiveness of the bellows geometry in promoting thermal exchange.

Effect of Flow Velocity on Nusselt and Reynolds Numbers- As the flow velocity increases, both Nusselt and Reynolds number exhibit substantial growth, emphasizing the role of velocity in enhancing convective heat transfer performance in bellows.

Influence of Heat Input on Heat Transfer Coefficient and Reynolds Number - It is observed that as the heat input increases, the heat transfer coefficient increases while the Reynolds number experiences a small decline due to the temperature gradient between the fluid and the bellows surface and the Reynolds number experiences a small declination due to constant velocity.

Effect of Flow Velocity on Heat Transfer Coefficient and Reynolds Number- At a fixed heat input, increasing flow velocity significantly boosts the heat transfer coefficient, as reflected by corresponding increases in the Reynolds number. This underlines the importance of velocity optimization in bellows-based heat transfer systems.

This structural and thermal analysis provides valuable insights into the key factors governing heat transfer in bellows. It also highlights the importance of geometric and operational parameter optimization to enhance thermal performance, offering a solid foundation for future research and design improvements in thermal systems incorporating bellows.

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NOMENCLATURE

Re	Reynold’s number
C_P	specific heat, $J \cdot kg^{-1} \cdot K^{-1}$
h	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
k	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
Nu	Nusselt number

Greek symbols

ρ	density, $kg \cdot m^{-3}$
μ	dynamic viscosity, $kg \cdot m^{-1} \cdot s^{-1}$