Flow Pattern Investigation and Thermohydraulic Performance Enhancement in Three-Dimensional Circular Pipe under Varying Corrugation Configurations

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Abstract. Varying methods were tested on the improvement of heat transfer in order to upgrade the concerning equipment, mostly in thermal performance devices. These methods revealed important impacts when employed in heat exchanger pipes. One of the significant methods utilized was the passive performance technique. Corrugations characterize the passive method. Moreover, it offers efficient enhancement of heat transfer due to its joint turbulators and extended surface features. So, Computational Fluid Dynamics (CFD) method is applied for water flowing with a range of Reynolds number (Re) from 1500 to 23000 in different corrugated pipes configurations. This research target to investigate the flow pattern, pressure drop, and thermal performance for smooth and corrugated pipes. The criteria of thermal performance evaluation are analysed for corrugated pipes, and the computational outcomes of pressure drop, heat transfer coefficient (h), friction factor Nusselt number (Nu), ratios of \(\frac{f}{fo}\) and \(\frac{Nu}{Nu_0}\) are investigated with those of smooth plain. Outcomes revealed the best range of thermal performance is between 1.3 to 1.1 for the pipe, which has the corrugated ring diameter 0.5 mm for Re of 1500.

Keywords: Flow pattern, Thermohydraulic performance, Corrugation configurations

1. Introduction

Heat exchangers are essential equipment for ensuring heat transfer from the medium to another at a desired temperature and rate. The most common heat exchangers are liquid-to-air heat and liquid-to-liquid exchangers. Heat exchangers have been used for the conversion and recovery of heat in many industrial and domestic applications such as HVAC, liquid boiling, steam condensation for power plants, chemical industries, petrochemical plants, and natural gas processing. There is a great interest in heat transfer device enhancement since it can result in energy and cost savings. Recently, various studies have been done on the heat transfer enhancement of heat exchangers for the circular pipe under varying corrugation configurations\cite{1},\cite{2},\cite{3}. The circular pipe surface modification concept has gained attention since it has a combination of heat transfer enhancement and a lower pressure loss penalty \cite{4},\cite{5}. A numerical investigation has been conducted by Özceyhan et al. \cite{6} to study the effect of the spacing between the circular rings on heat transfer rate characterization and friction factor, Reynolds number range between (4475 to 43725). The enhancement was about 18% when the spacing between circular rings is 3D, and Reynolds is 15,600. They observed that the heat transfer rate and friction factor increase with decreasing ring spacing. Liu et al. \cite{7} discussed the heat transfer performance of the exhaust gas recirculation helical baffle cooler with spiral corrugate tubes. They found that the deviations errors between the numerical and experimental for Nu, pressure drop, and friction factor were about...
6.1%, 7.4%, and 7.4%, respectively. They observed that the heat transfer rate and friction factor increased with the decrease of the ring spacing, Dongwei et al. [8] numerically investigated the effects of the heights of the smooth tube and ten different corrugated tubes on the enhancement of heat transfer and friction factor characteristics of the corrugated at turbulent flow. Their preliminary results showed that as the Re increased from 6000 to 57000, the friction factor decreased, with increasing Reynolds number Nu increased, and f decreased. The performance of the ribbed tube with a pitch of 12.5 mm has good advantages as compared to 10 mm under the same conditions. Darzi et al. [9] reported that the heat transfer of Al2O3 nanofluid inside helical corrugate pipe using two phase mixture model under constant heat flux with Reynolds numbers range of 10,000 to 40,000. The results have shown an increase in the heat transfer coefficient from a factor of 3.31 with the addition of 4% Al2O3 nanoparticles to water. Their results indicated that the existence of secondary flow plays an important role in the enhancement of heat transfer, Barba et al. [10] analyzed the thermal performances, pressure drop, and heat transfer of corrugated tubes used in the chemical industries for single-phase flow in steady state at Reynolds numbers range of 100 - 800 using ethylene glycol, the highly viscous Newtonian fluid, as the working fluid. They reported that for the corrugated pipe, the friction factor increased with a factor of 2.45, and the pressure drop increased by a factor of 2.5 at Reynolds number in comparison to the smooth pipe. Vicente et al. [11] performed experiments on the mixed convection heat transfer and pressure drop in corrugated pipes with different roughness geometries under the same flow conditions. They reported that the Nusselt number and friction factor coefficient of the corrugated pipes increased by 250% and 300%, respectively with comparison to the smooth pipes. The main goal of this work is to investigate the corrugation depth influence on the thermohydraulic performance enhancement of the heat exchanger with different corrugation geometrical configurations with various range of Reynolds number numerically.

2. Physical Geometrical Model Configurations
Using corrugated pipes can provide more efficient thermal performance improvement in heat exchanger. Hence, the pipe has 1920 mm length and 11.08 mm diameter with 1 mm thickness is simulated with different corrugation configurations based on the CFD method at different ranges of Re from 1500 to 23000, as described in Figure 1. This corrugation parameter, including corrugated ring diameter, including 0.5, 1, and 1.5 mm under different operating conditions, the distance between two corrugated rings is 12.5 mm. Three various pipes are tested. Each pipe has the same pipe length and diameter characteristic parameters with different corrugation configurations.

3. Generation of Mesh and Independence Grid Testing
Mesh domain generation is an important part of numerical calculations that impacts on computational time and results accuracy. The tetrahedral mesh system is used in the computational simulation using the CFD method for numerical 3D smooth and corrugated pipes, as represented in Figure 2. To capture the temperature and velocity gradients, the near wall grid is adequately fine. Various cell numbers are
conducted the mesh independence, including 1.3 million, 2.6 million, and 3.5 million, and the 3.5 cells are chosen for analysis purpose due it provides more accurate results as compared to other cases.

Figure 2: Three dimensional flow mesh generation for corrugated pipe

4. Validation Results
Figure 3 illustrates the validation of Nusselt number (Nu) of present computational smooth pipe results, which subjected to similar experimental boundary conditions was conducted by Albanesi et al. [12] at a various range of Reynolds numbers (Re). As obviously noticed that a good agreement for both results (simulation and experimental data), the average deviation errors is ±7%. This error deviation can cause due to assuming the fluid properties and numerical solutions.

Figure 3: Comparison of numerical and experimental validation outcomes

5. Flow Behaviour Analysis
A 3D turbulent flow computational calculations of full corrugated pipes based on the CFD method are presented in this section. Figure 4 describes the altering in velocity flow magnitude for different corrugated pipe configurations are 0.5, 1, and 1.5 mm corrugated diameter (CD) with Re from 1500 to 23000. It is perceived that as the water flows passing near corrugated ring surfaces that leads to the flow speed direction closed the corrugated wall surface changes. Hence, fluid flow disturbance and boundary layer formation changes. Rising in the boundary layer disturbance lead to promote the surface layer, then that cause enhancement of heat performance.

Figure 5 depicts the temperature field contour in the corrugated pipe with varying corrugation geometrical configurations, including corrugated diameters are 0.5, 1, and 1.5 mm under different boundary conditions with Re range from 1500 to 23000.
Figure 4: Velocity flow magnitude under different corrugation configurations

It is apparent that the higher temperature reached 310 K and 313 K, with a change in temperature as the pipe length increases. Using corrugations surfaces can lead to disturbance in flow patterns due to flow mixing, secondary flow, and swirl flow.

Figure 5: Temperature variations in the corrugated pipe

6. Thermal Performance Analysis

In heat exchanger pipes, the investigation of pressure drop is the significant evaluation parameter due to it connects to the requirement of pumping power as recognized that flow restrictors, for instance, ribs, dimples, and corrugation surfaces, can help to enhance turbulence flow. Pressure drop analysis for smooth and corrugated pipe with different corrugation configurations pipes is calculated at temperature 313.15 K with various Re range. Figure 6 depicts the pressure drop across both smooth and corrugated pipes. It is evidently observed that as the corrugation configuration increase, the pressure sharply increases. Hence, the higher pressure takes place with a CD of 1.5 mm. Moreover, pressure for varying configuration parameters is higher than in smooth pipe as expected. Pressure drop improvement is augmented as Re increases. Figure 6 b represents the variations in Nu. It is seen that the Nu increases with corrugated pipe parameters rise. The value of Nu for the corrugated pipe is higher than the smooth pipe. Increasing in Nu due to the corrugations configuration can effectively improve the heat performance inside the heat exchanger pipes.

Figure 7 a, and b illustrates the variations in fraction factor (f) and the ration of (f/fo), it is noted that both f and f/fo increase with corrugation parameters rise. The higher values of f and f/fo are at a corrugated ring of 1.5 mm. This happened due to the high pressure dope due to the effect of corrugated rings on the pipe.
Figure 6: Pressure drops and Nu variations with varying of corrugation configurations

Figure 7: Friction factor and ratio of \((f/fo)\) variations with varying of corrugation parameters

Figure 8: Variations in Nu/Nuo and PEF

7. Conclusion

In this analysis, the CFD method is used to investigate the flow pattern and enhancement of heat performance using different corrugation configurations under various operating conditions. The following conclusions can be found:

1. Corrugated pipe leads to change the pipe's surface shape, then the liquid can continuously generate more flow disturbance, mixing flow and vortex, so to strengthen the disturbance on the boundary layer, then making the heat performance is highly improved.
2. Using corrugate shape has a high influence on flow behavior and thermal hydraulic performance.
3. The value of Nu for the corrugated pipe is higher than the smooth pipe. Increasing in Nu due to the corrugation’s configuration can effectively improve the heat performance inside the heat exchanger pipes.
4. Both f and f/fo increase with corrugation parameters rise. The higher values of f and f/fo are at a corrugated ring of 1.5 mm.
5. The value of PEF reduces as a rise in ring diameter, and the ring diameter of 0.5 mm provides the best thermal performance at the Re is 1500.
6. Results revealed the best range of thermal performance is between 1.3 to 1.1.

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