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Review IJICEGT

Heat Transfer Performance in an Internally Dimpled Tube Heat Exchanger Composed of Various Materials Examined Using CFD: A Review

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Abstract

A review of the most important findings for thermal enhancement on circular pipe is presented, the focus is on the heat transfer and thermal gradient in these heat exchangers. The use of circular dimpled pipes, surfaces, and other techniques to promote heat transmission has been the subject of several studies in the past. Reviews are conducted on a sizable number of research papers pertaining to computational and experimental investigations. Various characteristics, including Reynolds number (Re), geometric parameter, and nanofluids, have been discovered to impact flow and improve energy transfer in various configurations. The heat transfer of a flow impinging on a pipe has been the subject of just a few studies because of the pipe's intricate design, the use of many materials for its construction, and the difficulties in conducting a thorough experimental research. Profiles of the working nanofluid's mean velocity, turbulence rates, and heat transfer coefficients are often shown in investigations. It was found that, in comparison to a simple tube heat exchanger, the dimples enhanced the heat transfer coefficient of the pipe heat exchanger. Although the heat performance was greater than that of a plain pipe, a larger pressure loss was observed in comparison to plain pipe heat exchangers. For example, the dimples' size and location greatly affect the flow and thermal characteristics of the pipe. In this work, the thermal-hydraulic performance of dimpled tubes with different geometric pitches, two different types of helical pattern configurations (15^0 and 30^0) for the dimple structure, and six different dimple populations will be numerically investigated for a constant velocity under a constant external heat flux. The dimple pipe utilised in the simulation is built using three different sorts of materials. Due to their high heat conductivity, copper, aluminium, and cast iron are the materials for pipe used in the simulation.

Keywords: Dimpled pipe tubes section, computational fluid dynamic, heat transfer coefficient. thermal energy, fluid flow

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INTRODUCTION

When it's necessary to move heat between two systems, exchangers are usually used. Different configurations of heat transfer systems may be achieved based on their intended use. In real-world applications, calculating heat balances and pressure drops plays a major role in device sizing. Understanding the thermal and hydrodynamic properties that provide good transfer coefficients without appreciable losses, resulting in high thermal efficiency and high heat exchange, is the aim of optimising the thermal performance of these systems and increasing heat transfer. Establishing arrangements that minimise energy losses while maximising energy transfers is advised.

Figure 1. Model views of the dimpled pipe.

From an industrial perspective, it is critical to enhance the existing heat transfer equipment's efficiency in order to prevent the harmful consequences of burning and overheating. It is also crucial to eliminate any surplus heat created. The surface area per unit volume is the only variable that may be changed; the temperature levels depend on the application (Figure 1).

Enhancing heat transfer may be achieved via a variety of techniques, such as increasing turbulence or changing the geometry of the current structure. To stop the thermal boundary layer from expanding or to make it thinner, turbulence is necessary. An ideal design is usually beneficial since it is often noted that using these strategies may frequently result in pressure decreases. In the case of systems employing low-grade fuel, the design should also be sufficient to address issues such as surface fouling and scaling, which often tend to reduce the rate of heat transfer. Pin fins, louvred fins, twisted tape inserts, slit fins, ribs, protrusions, and dimple tubes are a few methods for enhancing heat transmission. When compared to the other methods in the chart, the dimple tube approach maximises heat transfer rates while minimising pressure drops. The primary purpose of geometric variations is to provide longer surfaces. However, numerous studies have been done due to the need for lightweight, compact, and cost-effective solutions. This technology would also be very beneficial in many petrochemical heat transfer processes because it has the potential to lower the fouling rate and provide minimal pressure drop penalty [4-10].

Adding surface dimples may significantly enhance heat transmission. Dimples are used to improve heat transfer in vehicle radiators, HE in textile and chemical processes, and turbine blade cooling. Another way to reduce thermal resistance and so enhance heat transmission is to make the dimples deeper. Because they encourage turbulent mixing in the flow, surface dimples (vortex generators) improve heat transmission. Surface dimples reduce the hydrodynamic barrier to fluid flow over the surface, resulting in a reduced pressure drop and increasing the surface area accessible for heat exchange. By tripping the fluid flow, the pipe's dimples reduce the expansion of the thermal border and promote fluid mixing [11]. Therefore, the performance of a heat exchanger, or the ratio of enhanced heat transfer to increased pressure drop across the pipe, has to be investigated.

LITERATURE REVIEW

Harsh V. Malapur, Sanjay N. Havaldar et al. (2022) [1], Circular dimpled pipes, surfaces, and other techniques have been the subject of several research studies in the past to enhance heat transmission. Examples of dimples that significantly affect a pipe's flow and thermal characteristics include their size and location. The computer study examined five different designs of internally dimpled pipes. With water serving as the working fluid and steel pipes with internal dimples, the flow was simulated using ANSYS Fluent 16. Under comparable circumstances, the thermal performance of a plain tube heat exchanger was compared with the impact of dimple number and diameter on flow and thermal parameters using five distinct internal dimple designs. The flow channel from entrance to exit saw a greater pressure drop as a consequence of internal dimples, or inner protrusions in tube heat exchangers

[12]. When compared to a simple tube heat exchanger, it was found that the pipe heat exchanger's dimples enhanced its heat transfer coefficient. Despite the fact that the heat performance was greater than that of conventional pipe heat exchangers (HE), a larger pressure loss was discovered. Because of the pressure reduction, the flows' Reynolds numbers altered. There was more heat exchange in the experiment when the Reynolds number was lower because the friction factor was found to be greater. Based on the numerical analysis, it can be concluded that the presence of dimples in the tube HE enhances heat transfer between the hot and cold fluids through the tube HE wall by promoting flow mixing and the formation of a thermal boundary layer.

Mothana Bdaiwi, Abdulrazzak Akroot et al. (2023) [16] This paper offers a comprehensive examination of the data about how boils affect the degree of flow separation as well as the rate of heat transfer. Passages are little dangers printed on a smooth surface that serve as a guide to assess how rough the surface is. The quantity of dynamic masses that manipulating entities have to deal with. Recent research has shown that boils inside the tubes might lessen the problematic friction that the painting encounters. This is achieved by reducing the tension caused by the skin, which in turn replaces clouds for the pressure caused by boils, finally yielding an international benefit [13]. Whether or if the bumps help reduce the amount of friction and vapours created has not yet been established in a way that can be considered conclusive. Furthermore, by drawing attention to crucial systematic techniques needed to meaningfully compare a smooth surface with one that has boiled in relation to the removal of clouds, this article offers some recommendations for future research as well as an explanation of a number of factors that help to make sense of contradictory information found in the research.

Liang Zhang, Wei Xiong et al. (2021) [17] Using the k-ε model, the cross combined dimple tube's heat transfer and flow properties have been numerically examined, and for the first time, an enhanced model based on composite form surface technologies has been constructed. The findings show that, as compared to a single ellipsoidal dimple tube under the examined operating circumstances, the heat transfer index, friction factor, and performance evaluation criteria increase significantly. Specifically, in comparison to the conventional single ellipsoidal tube, the heat transfer improvement increases by 18.8–48.3%, with an average of 24.8%. In order to clarify how dimples, affect thermal performance, a 3D simulation is used. The simulation's conclusion is that dimples may improve heat transfer even more by altering the temperature distribution and raising the core region's gradient at the dimple section. The concave surface profile may improve the combination of hot and cold fluid by interfering with boundary layer growth and stable flow. A higher overall thermohydraulic performance is obtained with a bigger number and volume of dimples, as shown by the discussion of the impacts of geometric factors on thermal and hydraulic performances [14].

Mohammad Hassan Cheraghi et al. (2020) [18] Enhancing heat transfer is significant from an industrial perspective. A novel improved tube structure has been quantitatively examined in this work. Deep dimples were applied to the traditional plain tube to produce the geometry for this new kind of tube. Deep dimpled tubes' flow-field and heat-transfer properties have been examined, as well as the impacts of multiple dimple configurations—three distinct pitches, diameters, and depths of dimples—resulting in twenty-seven combinations. Performance Evaluation Criteria (PEC) has been researched for all geometries and is often employed in heat transfer improvement themes. To investigate thermo-fluid properties, the local temperature, velocity, streamline, and Nusselt number of the deep dimpled tube have been shown in relation to the plain tube. Three distinct Reynolds numbers have been investigated for each configuration: Re = 500, 1000, and 2000. Numerical investigations have been conducted using the k-e turbulent model. Deeply dimpled tubes have been shown to transport heat more quickly at larger depths, diameters, and pitches up to 600%. This has resulted in a significant increase in the friction factor. PEC of the deep dimpled tubes has been shown to vary between PEC = 1.15 and 3.3 in most situations. Moreover, PEC of deep dimpled tubes increases with increasing diameter, pitch, and Reynolds number and decreases with depth. PEC of these tubes reaches PEC = 3.3 at Re = 2000 when diameter = 18 mm, depth = 2 mm, and pitch = 4D [15].

The enormous demand these days has almost drained the energy supplies. Therefore, attempts were made all over the globe to develop novel heat transfer techniques in order to get desirable results at a lower cost. The past several decades have seen a widespread usage of surface modification to improve heat transmission since it lowers the size and expense of heat transport systems. The forced convective heat transfer within a circular tube with an inline configuration and a dimpled surface was investigated numerically. The dimple size was expressed in terms of d/D and fell within the range of (1/6). The study used ZnO water nanofluids with volume fractions of (0.2, 0.6, 0.8, and 1)% to examine internal turbulent flow conditions. There was research done on the size and placement of dimples. The obtained results demonstrated a direct relationship between the heat transfer coefficient and the volume percentage of nanofluids and the size of the dimples. The greatest enhancement attained, it was determined, was 2297 at a volume fraction of 1 and a Reynold number of 12000. On the other hand, 1013 performed worse with a volume fraction of 0.2 and a Reynold number of 6000.

Mousa Aqeel Ali et al. (2023) [19] This research uses numerical analysis to examine the heat convection through a double-pipe heat exchanger with a dimpled tube at various Reynolds numbers. This study's primary goal is to look into how the hydrothermal properties of water flow are affected by the geometrical features of the inner dimpled tube. Pitch ratio, dimple distribution angle, and inline and staggered dimple layouts are examples of geometrical parameters. We examine and contrast the inner dimpled tube's heat transmission performance with that of the traditional smooth tube. Furthermore provided is the thermal performance factor, or TPF. The temperature and pressure contours are shown in order to explain the processes that are responsible for enhanced heat transfer. According to the numerical simulation, the inner dimpled tube with staggered arrangement outperforms the dimpled tube with inline configurations by around 50% as Nusselt number. It can be inferred that the maximum heat transfer efficiency is achieved at a distribution angle of 60º. TPF values ranged from 1.67 to 5.22 for inline-arranged dimpled tubes and from 4.91 to 8.633 for staggered-arranged dimpled tubes. Furthermore, the findings demonstrate that the highest significant TPF value, 9.07, was reached when the geometrical parameters of dimple diameter (D = 6 mm), pitch (P = 8 mm), and Reynolds number (Re = 10,000) were examined in a staggered configuration.

Rizwan Sabir et al. (2022) [20] The objective of this work is to statistically analyse, across a broad range of Reynolds numbers (Re), the thermal-hydraulic performance of dimpled tubes with different geometric pitches under a constant external heat flux of 10 kW/m2. Using steady-state Reynolds-Averaged Navier-Stokes simulations, the performance of improved tubes with ellipsoidal 0◦, teardrop, and ellipsoidal 45◦ dimples of equal volumes is studied. It is found that there are large variations in dimple pitch (P) and Re variation in the performance of dimpled tubes. Therefore, by altering 3.2 mm ≤ P ≤ 13.2 mm and 9000 ≤ Re ≤ 40000, optimal pitches and working ranges of Re are discovered for all dimpled tube topologies. It has been determined that the teardrop dimpled and ellipsoidal 45◦ tubes have adequate operating ranges of 14000 ≤ Re ≤ 40000 and 9000 ≤ Re ≤ 30000, with an ideal pitch of 3.2 mm. The thermal-hydraulic performance was improved by the ellipsoidal 45◦ and teardrop dimpled tubes with optimal pitch by 45.7% and 31.2%, respectively. Nonetheless, the thermal-hydraulic performance gain of ellipsoidal 0◦ tubes is restricted, and their operating ranges are quite small.

GEOMETRY SETUP AND MODELLING

Geometry of Membrane

The effect of incorporating dimple protrusions on the inner pipe of a heat exchanger to enhance heat transfer rates is studied. The dimples have helical patterns in their pitch variations. The pipe is filled with water that is kept at a steady temperature. Three distinct types of materials are used to make a dimple pipe for the simulation. For the sake of comparative analysis, the helical pattern's design and arrangement are changed. Two different helical pattern configurations (15^0 and 30^0) of the dimple structure are employed, and there are six dimple populations. The dimpled pipe's front and orthogonal views are shown in Figures 2 and 3, respectively, and the fluid domain within the pipe is shown in Figure 4. Tables 1 and 2 is a list of the arrangement's structural features.

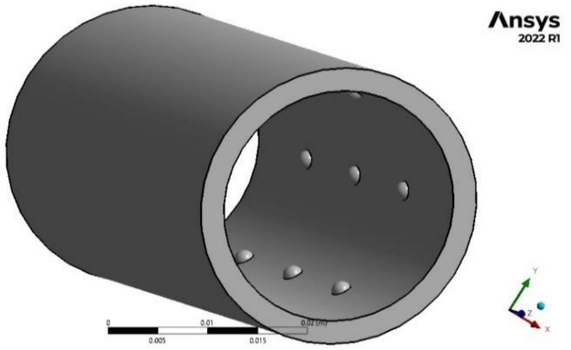

Figure 2. Orthogonal views of the dimpled pipe (30^0 helical pattern).

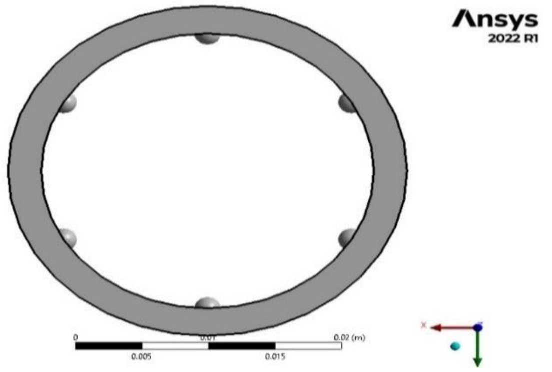

Figure 3. Front views of the dimpled pipe. (30^0 helical pattern).

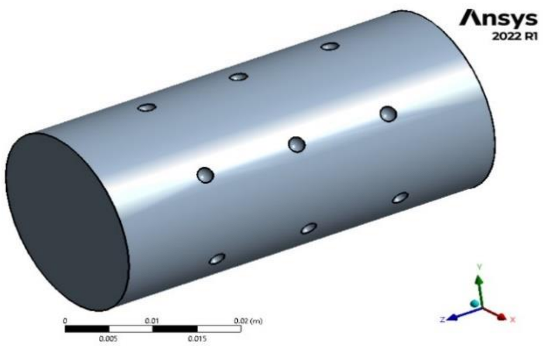

Figure 4. Modelling of the fluid domain within the pipe.

Table 1. Geometry parameters.

S.N.	Parameters	Value & units
1	HE tubes length (L)	50 mm
2	Inside diameter of tube (Di)	25 mm
3	Outside diameter of tube (Do)	30 mm
4	Number of dimples (cross section)	6 nos
5.	Diameter of dimples	2 mm

Table 2. Various configuration models.

S.N.	Design Number	Design Details
1	Design No. 1	Plain cylindrical pipe
2	Design No. 2	Dimpled Pipe with 15^0 helical patterns
3	Design No. 3	Dimpled Pipe with 30^0 helical patterns

The dimple pipe for the simulation is built using three different kinds of materials. Due of their excellent heat conductivity, aluminium, copper, and cast iron, were used for the simulation. Tables 3–5 lists the properties of each of the four materials.

Meshing

The ANSYS FLUENT 22 R1 pre-processor stage generated a simplified 3-D model. Even though grid types and simulation results are connected, when ANSYS is set up, a coarse mesh is created. This need resulted in a disorganized overall framework for the completed book. Unit-sized ICEM Tetrahedron cells with triangle boundary faces make up the mesh. The experiment uses a minor flowing curvature in addition to a mesh metric (Figure 5).

Table 3. Property of copper

S.N.	Properties	Value & units
1	Density	8978 Kg/m3
2	Specific heat	381 J/Kg*K
3	Thermal conductivity	387.6 W/m*K

Table 4. Property of aluminium.

S.N.	Properties	Value & units
1	Density	2691 Kg/m3
2	Specific heat	921 J/Kg*K
3	Thermal conductivity	210 W/m*K

Table 5. Property of cast iron.

S.N.	Properties	Value & units
1	Density	7850 Kg/m3
2	Specific heat	440 J/Kg*K
3	Thermal conductivity	48 W/m*K

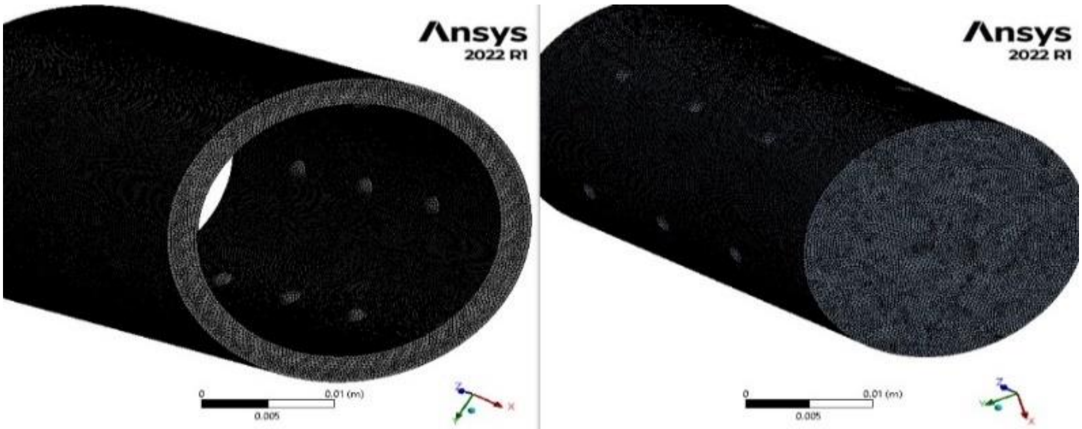

Figure 5. Meshed Model of the dimple pipe and fluid domain.

Boundary Condition

For numerical simulations in this work, two distinct dimple pipe layouts were simulated. A straight pipe and a cylindrical one with interior dimples A. To validate the model, dimpled pipes (Front View) were created with identical interior and exterior pipe diameters. It was believed that every solid wall served as an impenetrable and non-slip barrier.

The finite volume formulation of the ANSYS Fluent 22 R1 SIMPLE method was used to solve the energy equation and the equation for conservation of mass repeatedly. Equations (1) through (3) were solved using a 2ndorder upwind method. The following formula was then used to determine the flow rate:

$$\rho i * Ai * vi = \rho o * Ao * vo \ldots \quad (1)$$

where, Ai is the cross-sectional area at inlet, Ao is the cross-sectional area at outlet. The pressure drop throughout the pipe's length was calculated using Eqn. (2) and the Darcy-Weisbach equation. Equation (3) was used to get the friction factor (Moody).

$$\Delta p = \frac{\boldsymbol{\rho f l v^2}}{\boldsymbol{2D}} \ldots.. \quad (2)$$

$$f = 64/R_e \ldots.. \quad (3)$$

Where, $R_e = \frac{\rho v D}{\mu}$

With ANSYS Fluent 22 R1, the experiment's calculations were completed. Design, meshing, setup, and simulation for the input parameters were all done using the programme. After then, the solution was examined and evaluated. The apparatus is treated by the software as a route function, where each cell and node might have a unique set of properties. This configuration provides more efficient and precise setup outcomes at every stage of the equipment. The simulated conditions found in Tables 6 and 7.

RESULTS AND DISCUSSIONS

A comparison with the study work was done in order to verify the correctness of the proposed numerical technique [2].

The steel pipe used in the experiment has 30^0 helical pattern combinations with internally dimpled tube sections at certain pitches. Through the use of study work comparison, the temperature distribution result is compared with one plain type tube and another 30^0 helical pattern designs internally dimple tube sections [3].

Case 1

To determine the water's outlet temperature, we're utilising a steel plain section pipe and water flowing as a working fluid with boundary conditions.

Case 2

We are analysing the water's outlet temperature by employing internally dimpled tube sections with 30^0 helical pattern configurations made of steel and flowing water as a working fluid with boundary conditions.

Table 6. Details of boundary condition.

S.N.	Boundary condition	Value
1	Gauge Pressure	Pascal (Zero)
2	Entry	Flow velocity-inlet
3	Exit	Flow pressure-outlet
4	Fluid inlet temperature	320K
5	Pipe temperature	298K

Table 7. Property of the working fluid (Water).

S.N.	Parameters	Value
1	Water density (kg/m3)	998.2
2	Fluid velocity (m/s)	1
3	Mass flow of Hot fluid(kg/s) (M_h)	0.0386
4	Viscosity of Water (kg/m-s)	0.001003

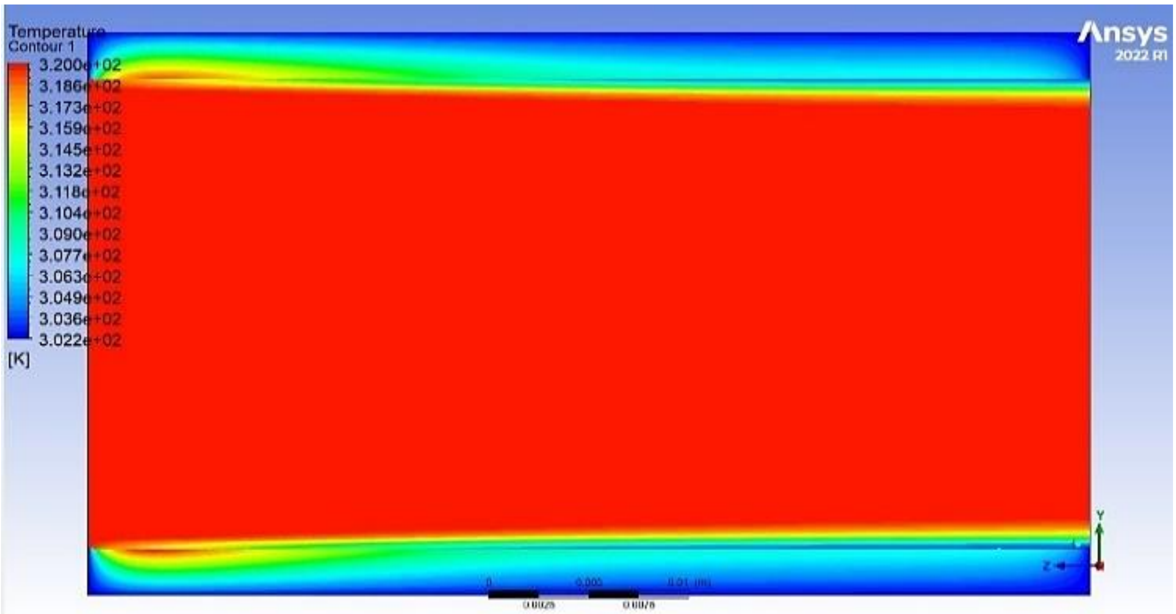

Figure 6. Temperature counter of fluid on plain pipe.

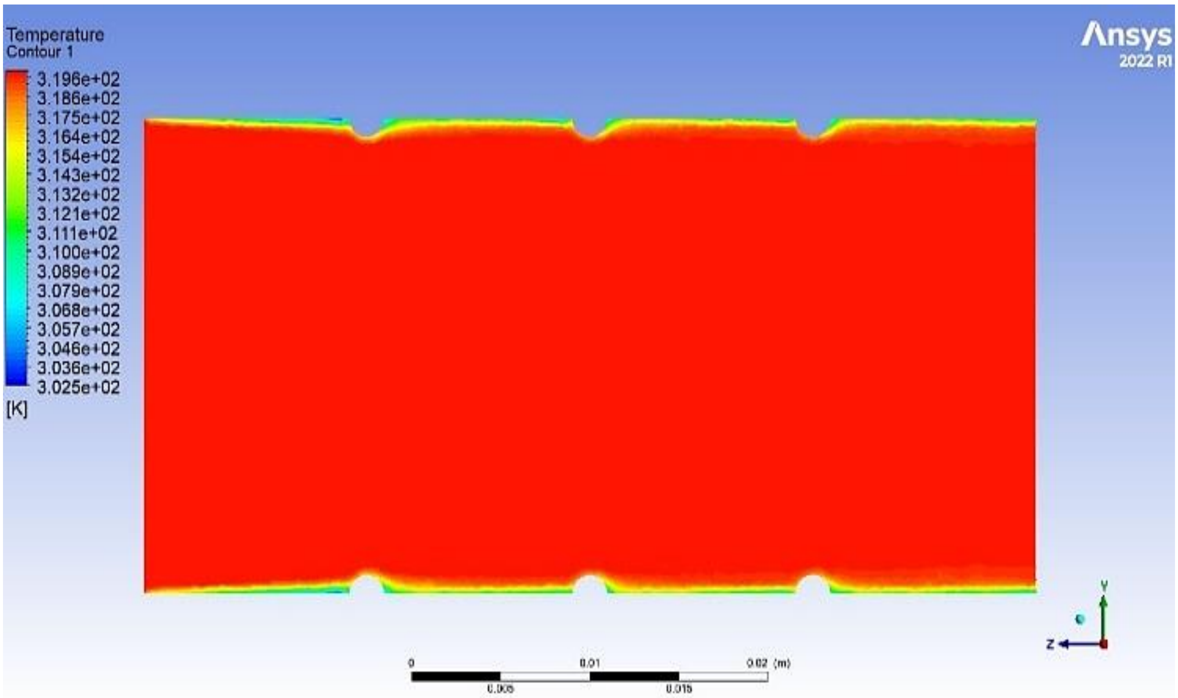

Figure 7. Temperature counter of fluid on Dimple pipe.

Figures 6 and 7 depict the fluid temperature in the plain pipe and the dimpled pipe, respectively. Ansys Fluent 22 R1 software was used for both analyses. The pipe (298 K) is located in the outside (blue) part, while the hot water (320 K) is contained in the inner (red) section. As the hot water gets closer to the outlet, the distribution shows that it is becoming colder.

As can be seen from the Figure 8, the outlet temperatures for both models computed using numerical analysis are found to be closer to those obtained using reference paper [1], suggesting that the numerical model of the plain and internally dimpled pipe utilising base fluid is correct. The difference between the numerical and experimental findings is much less.

Table 8. Temperature distribution.

S.N.	Parameters	Out let Temperature	
		Plain pipe	***Dimpled pipe***
1	Reference Paper	302.10	302.30
2	Present analysis	302.24	302.52

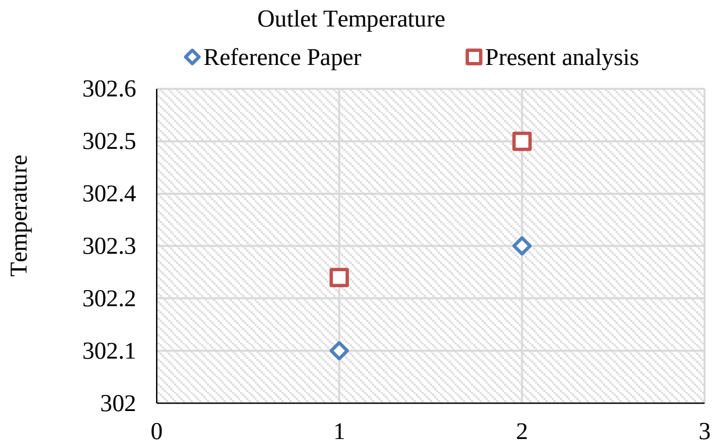

Figure 8. Comparison of outlet temperature.

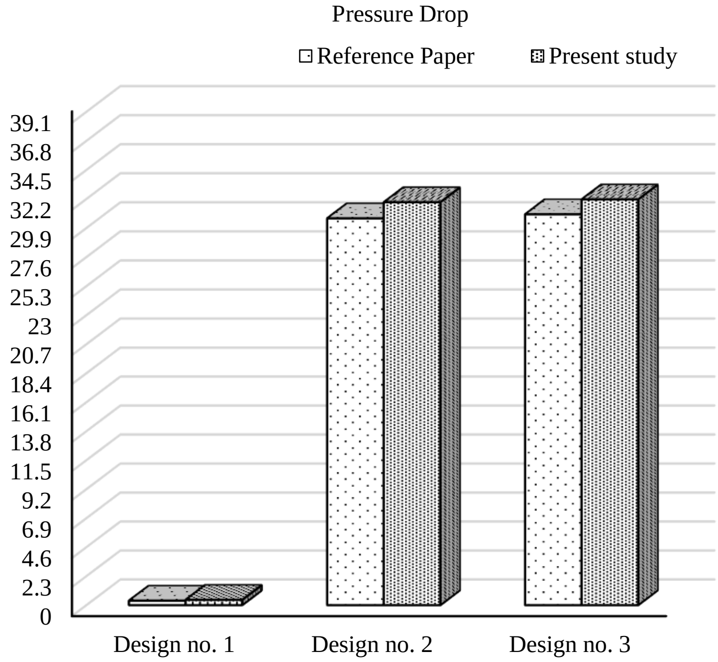

Figure 9. Comparison of pressure drop value.

Using the cited work [1], Figure 9 also shows the minuscule dimples that cause a spinning motion and pressure loss in the fluid streamline.

The analysis's two model configurations' respective fluid output temperatures are shown in Table 8. The largest heat gain for the fluid at the exit is shown in design number 3, which is a convoluted pipe with a 30^0 helical pattern. Comparing design models 2 and 3, respectively, reveals a little larger pressure drop and, as a result, frictional loss. Three examples had pressure drops of 0.416 Pa, 31.94 Pa, and 32.16 Pa, respectively, that we were able to determine.

CONCLUSIONS

The CFD simulation revealed that dimpled pipes have better heat transfer properties than plain pipes. The heat transfer properties vary depending on the flow's Reynolds number. If the Reynolds number is lower, the pipe's friction factor is higher, which aids in better heat dissipation.

If instead of steel pipe we make pipes from three different types of materials, then the thermal efficiency of the pipe will be affected because different types of materials have different thermal conductivity. Changing the pipe material will also affect the thermal gradient and heat flux. This simulation will provide insight into the impact it will have on a pipe made of a different material compared to a steel pipe, while keeping all boundary conditions the same. Changing the working fluid will also affect the heat transfer rate. The effect of different Raynold numbers and changes in velocity on the Nusselt number also increases the thermal efficiency.

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