

The Effects of Dimples on Heat Transfer and Fluid Flow on a Circular Tube: A Computational Investigation

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Abstract

The use of similar sort of dimples with different arrangements i.e., by changing the linear and angular distance between the dimples have different effects of their own. This present work is analyzed numerically for a three-dimensional circular tube with different types of dimples with different arrangements on its inner surface. In this paper, it was found that using spherical dimples leads to a great amount of increase in the heat transfer rate as compared to that of a normal tube without dimples. It was also found that the change of shape from spherical to rectangular box type of dimples of similar size didn't create much considerable difference in the improvement of heat transfer characteristics. Eventually, the spherical dimples were found to be more efficient than the rectangular box type dimples. However, the change of dimple arrangement from inline to staggered arrangement enhances the heat transfer characteristics to a noticeable amount, which was not of very high in magnitude compared to others but may further be studied for higher scale implementation with some corresponding moderations.

Keywords

Dimples, Nusselt number, Heat transfer coefficient, CFD, Reynolds number

1. Introduction

The technological know-how of heat transfer is involved with the analysis of the rate of warmth switch taking vicinity in a system. The energy transfer via heat flow cannot be measured at once. However, the idea has physical explanations, which are far associated with the measurable quantity called temperature. While there exists a temperature difference in a system, heat flows from location of excessive temperature to low temperature. As heat transfer takes vicinity whenever there exists a temperature gradient in a system, sound knowledge approximating the distribution of temperature in a system is a have to in studying heat transfer. Issues related to the dedication of temperature distribution and heat flow characteristics are of super interest in many branches of science and engineering for this reason. In designing heat exchangers which include boilers, condensers, radiators and so on, as an instance, heat transfer evaluation is critical for sizing such device. In the layout of nuclear reactor cores, an intensive heat transfer evaluation of gasoline factors is important for proper sizing of gas elements to prevent burnout. In aerospace technology, temperature distribution and heat transfer analysis are crucial because of weight boundaries and safety concerns. In heating and air conditioning problems for buildings, a proper heat transfer evaluation is important to estimate the quantity of insulation needed to save one's immoderate heat losses or profits.

One of the most important factors for designing and optimizing the fluid flow systems is to understand the fluid flow through pipes and ducts and their corresponding characteristics. Basically, the change of flow rate and the pressure variation due to the change of flow rate plays an important role in designing and optimizing the fluid flow systems. In the recent past, a number of great works have been done either to design the most effective fluid flow system or to optimize the existing fluid flow systems to the maximum possible level. Dimples are small depressions formed on body surfaces to increase the heat transfer rate and to change the fluid flow characteristics through or within the body. These dimples act as an obstacle to the flow and create turbulence. This in turn increases the heat transfer rate through the body and also does affect the flow of fluid through or around the body.

Using dimples on the pipe surface is a passive technique of enhancing the heat transfer characteristics of a pipe. Dimples may be provided on the outer or inner side of the tube. Their effects can be varied by changing their shapes, orientation, depths, etc. It is found that dimples have increased the convective heat transfer by a great margin in comparison with a simple tube having no dimples. In the consideration of heat transfer, it is vital to bear in mind three great modes of heat transfer. They're conduction, convection and radiation. In truth temperature distribution in a medium is controlled via the mixed consequences of those three modes of heat transfer.

1.1 Objectives

- To investigate the effect of different types of dimples on fluid flow and heat transfer characteristics of a circular tube with dimples.
- To investigate the effect of Reynolds number on surface heat transfer coefficient and the surface Nusselt number for fluid flow through a circular tube.
- To investigate the effect of different dimple arrangements on fluid flow and heat transfer characteristics of a circular tube with dimples.

2. Literature Review

In the recent past, various types of works have been done to investigate the effect of dimpled surfaces on the fluid flow and heat transfer characteristics through different types of objects. In 2005, Kim and Choi have worked on how the shape of a dimpled channel can be optimized to enhance turbulent heat transfer. From their analysis, the objective function is most likely dependent on the ratio of dimple depth to the dimple print diameter [1]. In 1998 Chen et al. have investigated how to improve heat transfer in a coaxial pipe using dimples as the heat transfer modification on the inner surface of the tube. They found that at constant Reynolds number, the heat transfer improvement ranges from 25% to 117% and at constant pumping power the improvement ranges from 15% to 84% [2]. In 2007 Marotta and Fletcher investigated flow structure and enhanced heat transfer in channel flow with dimpled surface. They have found that heat transfer in small heat sinks tends to improve by as much as 2.5 times due to the use of dimples on the sink surface. They have also found that relative dimple depth of 0.2-0.25 gives the best performance. Higher dimple depth gives rise to increased turbulence causing high frictional loss without much improvement in the heat transfer [3]. Carlos et al. in 2009 have investigated that how to optimize the fin performance in laminar channel flow through dimpled surfaces. They have found that circular dimples on the surface work more efficiently than the normal flat tube. They also found that double and oval dimples offer better performance than circular dimples when the long axis is aligned perpendicular to the flow direction. Oval dimples show poorer performance when the long axis is aligned parallel to the flow direction [4]. In 2010, Wang et al. investigated the enhanced heat transfer tube with the ellipsoidal dimple on the surface. They have found that from laminar to transition region, the friction factor drops very quickly. Then from transition to maximum, the friction factor rises rapidly. Above that region, the friction factor curve decreases with the increased Re values [5]. In 2015-16, Li et al. have worked on single-phase heat transfer and pressure drop analysis of a dimpled enhanced tube. They conducted a steady-state single-phase experiment with water as the working fluid and found more than 200% of enhancement in heat transfer rate using the dimpled enhanced tube while comparing the results with the same obtained results from a smooth tube [6]. In 2017-18, Xie et al. performed an investigation on the heat transfer and fluid flow traits in more suitable tubes with dimples and protrusions. They wanted to analyze the effect of dimple and protrusions and the importance of dimple and protrusions intensity and top inside the heat switch and fluid flow behavior [7]. Recently in 2018-19, Piper et al. have worked on heat transfer enhancement of the pillow type plate heat exchanger with dimples on the surface. They have used a stack of pillow plates with waviness of dimples at the surface of the plate for their analysis [8]. Later in 2018, Xie et al. made an overall investigation on flow and heat transfer characteristics through a pipe with teardrop dimples. They compared the results with the earlier investigations that were made in this field with spherical and elliptical dimples. They also investigated the effect of dimple depth and pitch on fluid flow, and heat transfer characteristics and found that heat transfer coefficient and Nusselt number increases with the use of dimples while the pressure loss due to friction decreases with the use of dimples [9]. In 2019, Elamsa et al. made an investigation on using nanofluid through a dimpled tube for heat transfer enhancement. They investigated the effect of different dimple angles on flow and heat transfer characteristics. They also have inserted tapes with different twisted ratios and analyzed their effects on the flow characteristics as well. They have found the best dimple angle was about 45degrees [10]. In the same year, Zheng et al. experimented with a noble tube to improve the heat transfer characteristics using slotted dimples on the tube surface. The heat transfer and the flow characteristics of the enhanced tube with dimpled surface were then compared against that of an enhanced tube with spherical or elliptical dimpled tube as experimented numerically by them earlier in 2018. They have found that the average temperature rise in using slotted dimples is higher than that of using either spherical or elliptical dimples. Consequently, the heat transfer characteristics also get improved further by using slotted dimples [11]. Moreover, Farzad et al. analyzed the characteristics of turbulent flow in a three-dimensional channel. They mainly focused on identifying the effect of dimpled fin surface and CuO nanoparticles in the augmentation of heat transfer characteristics and improvement of cooling performance of a channel under the action of constant heat flux [12]. Milad et al. investigated the effect of dimple fins on a vertical channel wall to improve the natural convective heat transfer characteristics of different nanofluids. They mainly used Aluminum Oxide, Titanium Oxide, Cu and CNT in their analysis [13]. Eiamsa et al. in the same year had investigated the heat transfer improvement of Titanium Oxide nanofluid inside a dimpled tube with a twisted tape insert. They found a strong impact of dimple angle, twist

ratio, and Titanium Oxide concentration on thermohydraulic performance [14]. The effect of trapezoidal dimples in an enhanced tube to improve the heat transfer characteristics and flow behavior had been studied numerically by Toygun and Orhan. They applied trapezoidal dimples on the surface of a horizontal tube and had conducted their study by applying constant heat flux at the outer surface of the tube [15]. Cheraghi et al. numerically analyzed the enhancement of heat transfer and corresponding pressure drop in an inside deeply dimpled enhanced tube. They investigated the effect of various dimple diameters, pitch and dimple depths on the heat transfer and flow characteristics inside the deeply dimpled tube. They have found that velocity increases at the bottom of the dimples. They also found that vortices were formed behind the dimples and axial swirl being generated along the flow direction [16]. Shabbir et al. assessed the thermo-hydraulic performance of an inward dimpled tube with variation in angular orientation. They performed their investigation by using conical, spherical and ellipsoidal dimples on the inner surface of a tube. They have found that the ellipsoidal dimples in comparison with the other dimple types were providing the most amount of increment in the heat transfer rate [17].

In this present study, the effect of dimples on the fluid flow characteristics and heat transfer enhancement in a circular tube will be investigated. The investigation will be based on using different shapes and geometries of dimples on the inner surface of the tube and then observing the heat transfer enhancement and change in fluid flow behavior due to the use of dimples on the tube. Also, the effect of different alignments of dimples on the tube surface will be analyzed by applying those various-shaped dimples on different spacing and the obtained results will be compared with the values of a smooth tube.

3.1 Theory

3.1.1 Internal forced convection

Liquid or gas flow through pipes or ducts is commonly used in heating and cooling operations, process industries or energy conversion technologies. In external flow, the fluid has a free surface and the boundary layer over a surface is free to grow without any constraints. But in internal flow, the fluid is completely confined by the inner surfaces of the tube and there is a limit on the boundary layer development. Although, in external flow, the only information required is whether the flow is laminar or turbulent. But in internal flow, other than this, internal flow characteristics are also required.

3.1.2 Flow condition

Consider a laminar flow of fluid flowing inside a circular tube. Fluid enters into the tube with a uniform velocity. As the fluid comes in contact with the surface, the effect of viscosity becomes significant and the development of a boundary surface takes place with the increase in the tube length. This improvement of this boundary layer is on the price of shrinking inviscid drift area and concludes with the boundary layer merger at the centerline. Following this merger, the impact of viscosity extends over the whole pass segment and the rate profile now does not change with the increasing period.

3.1.3 Hydrodynamic Entry Length

When dealing with the internal fluids, it is crucial to be cognizant of the extent of the access vicinity, which relies upon whether the flow is laminar or turbulent. The Reynolds number for flow in a circular tube is defined as,

$$Re = \frac{\rho v D}{\mu}$$

Where, v = Mean fluid velocity over the cross section

D = Tube diameter

ρ = Density of fluid

μ = Viscosity of fluid

In a fully developed flow with the flow, the essential Reynolds quantity corresponds to the onset of turbulence is

$$Re = 2300$$

Even though a good deal large Reynolds number ($Re = 10000$) is a must to achieve fully turbulent conditions. The transition to the turbulence is likely to begin within the developing boundary layer of the entrance location.

For laminar flow, the hydrodynamic entry length can be acquired from the expression, $x_{fd} = 0.05 * Re_D * D$

For turbulent flow, $10 * D \leq x_{fd} \leq 60 * D$

3.1.4 Thermal consideration

If the tube flow situation is consistent thru implementing both a uniform flow temperature or uniform heat flux, a thermally simply developed scenario may be completed. The form of completely advanced temperature profile differs whether or not a uniform ground temperature or warm temperature flux is maintained. For each surface condition, the

quantity with the beneficial useful resource of which fluid temperatures exceed the entrance temperature will increase with the increasing period.

For laminar go with the flow, thermal access period may be expressed as, $x_{fd,t} = 0.05 * R_e * D * P_r$

If $P_r \geq 1$, that means, $x_{fd,h} < x_{fd,t}$

that means the hydrodynamic boundary layer develops greater hastily than the thermal boundary layer.

If $P_r < 1$, that means, $x_{fd,h} > x_{fd,t}$

The thermal boundary layer develops extra rapidly than the hydrodynamic boundary layer.

However P_r dependency in turbulent flows is notably minimum and it could be assumed as, $x_{fd,t} = 10D$

3.2 Governing equations

These equations are mainly the mathematical expressions of the three most fundamental physical statements based on which fluid dynamics mainly operate.

The continuity equation is based on the principle that when a fluid is in motion, it moves in such a way that the mass is conserved. According to the equation,

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

The differential form of continuity equation can be expressed as,

$$\frac{\partial(\rho U_x)}{\partial x} + \frac{\partial(\rho U_y)}{\partial y} + \frac{\partial(\rho U_z)}{\partial z} + \frac{\partial \rho}{\partial t} = 0$$

The momentum equation is based on the 2nd law of Newton. It is a vector relation and thus can be divided into three components.

The x component of the momentum equation is given by,

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \rho g_x - \frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

The y component of the momentum equation is given by,

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = \rho g_y - \frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)$$

The z component of the momentum equation is given by,

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = \rho g_z - \frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)$$

It is based on the principle that the net energy of a fluid element remains constant. The energy equation in non-conservation form is given as,

$$U_x \frac{\partial T}{\partial x} + U_y \frac{\partial T}{\partial y} + U_z \frac{\partial T}{\partial z} = \frac{k}{\rho c_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

4.1 Methodology

The software used on this numerical evaluation is the Ansys Fluent, version 16.2. With the state-of-the-art of Fluent, amateur or expert customers will run fluids simulations, in a good deal much less time and with whole lot much less training than ever earlier. This also gives better and easy quick solutions in a single corridor. Besides it provides a faster and accurate meshing for different complex geometries. This also maintains an easily understandable interface and also keeps updating to cope up with customer satisfaction at a regular interval.

4.2 Geometry and Meshing

The pipe required for this numerical study was generated using Ansys Fluent software version 16.2. Fig: 1 and Fig: 2 show geometry and mesh generation of the circular tube.

At first two concentric circles with radius 50 and 60 mm respectively were drawn on the XY plane from the sketching command. Then the circles were extruded along the positive Z-axis for a depth of 100mm. Then a sphere was created from the primitive's command. The location of the center of the sphere was:

X-axis coordinate = 25mm, Y axis coordinate = 0 mm, Z axis coordinate = 50 mm

Then using the circular pattern option, three more replicas of this sphere were created. After that, by using the Boolean command, the spheres and the earlier extruded pipe were united into a single body. This was followed by the application of linear pattern command and seven more replicas of this single part were created. Then all these eight parts were united into a single body by using the Boolean command once again. This final single body is the desired circular tube with inside dimples. The overall dimensions of the tube are as follows:

Length = 800mm

Inner radius = 50mm

Outer radius = 60mm

Dimple radius = 2.5mm
 Number of dimples in each row = 4
 Number of rows of dimples = 8
 Distance between two consecutive rows of dimples = 100mm

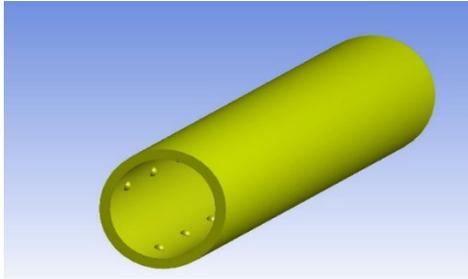


Fig. 1: Circular tube with dimples

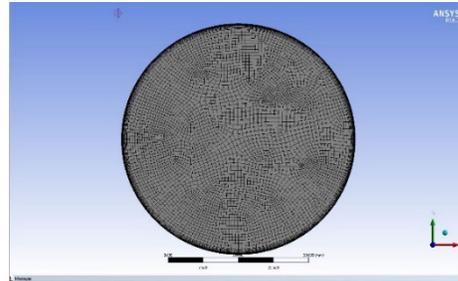


Fig. 2: Mesh generation

4.3 Boundary Conditions

Steel is used for the materials of dimples, and circular pipe and water as a fluid domain.

- at inlet (velocity inlet), velocity= 0.0200961731m/s, temperature = 300K
- at outlet (pressure outlet), backflow temperature = 300K
- at wall, temperature = 400K and no slip boundary condition
- at dimples, temperature = 400K and no slip boundary condition

5. Result and discussion

Fig: 3 shows the velocity contour of the fluid at different lengths of the tube for various Reynolds number.

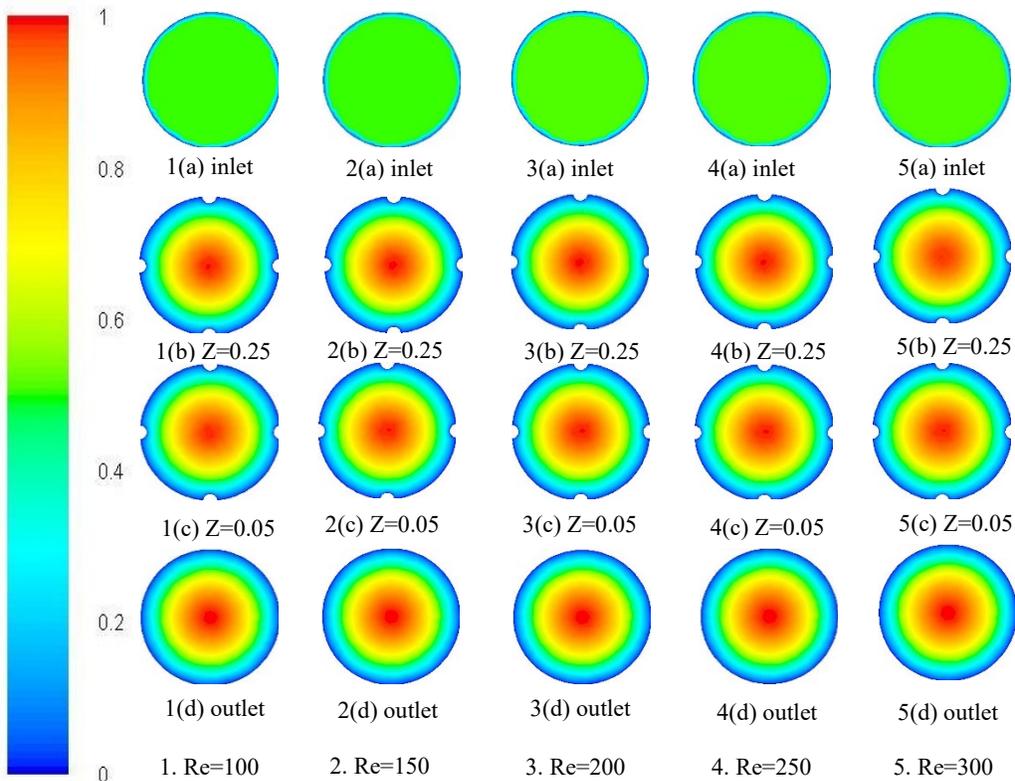


Fig: 3

From Fig: 3, it is seen that the inlet velocity is kept constant for different values of Reynolds number during the experiment and the velocity keeps increasing radially towards the center of the tube with different Reynolds number.

Effect of Reynolds number (Re) on Nusselt number (Nu) and heat transfer coefficient (h) for both simple tube and spherical dimpled tube (Inline arrangement) is shown in Fig: 4 and Fig: 5.

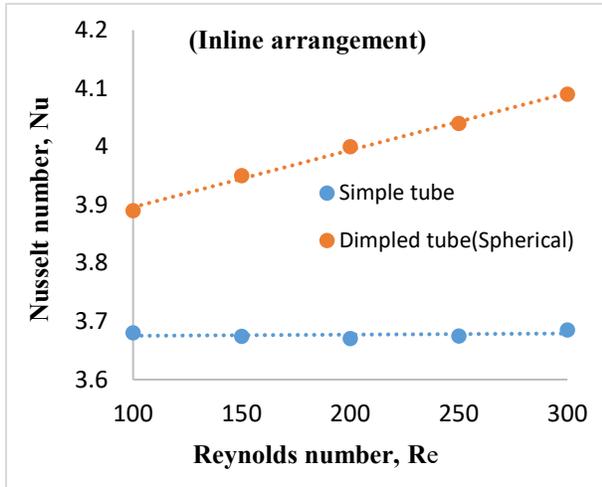


Fig: 4

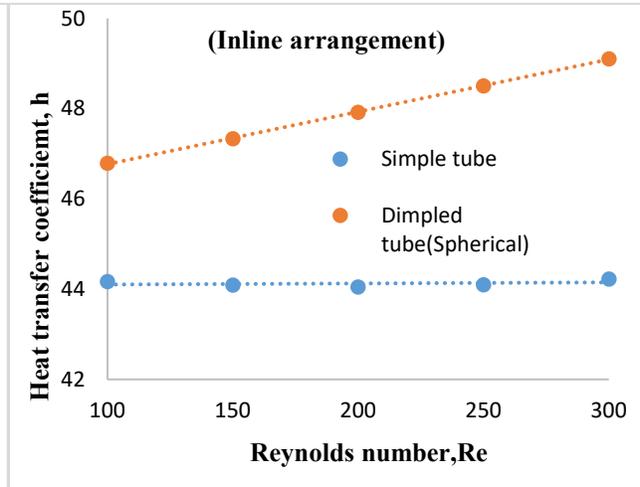


Fig: 5

From fig: 4 and fig: 5 it is seen that using spherical dimples on the inside of the tube, makes a great improvement in the Nusselt number and heat transfer coefficient as compared to that of the simple tube without the dimples. The values of the Nusselt number and the heat transfer coefficient keep increasing along with the increase in Reynolds number. This implement that the use of dimples is more efficient in case of flows with higher Reynolds number as the effect of dimples in creating turbulence becomes more severe.

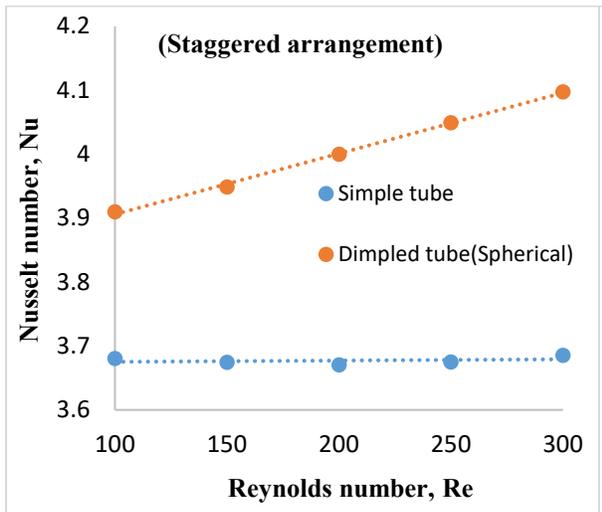


Fig: 6

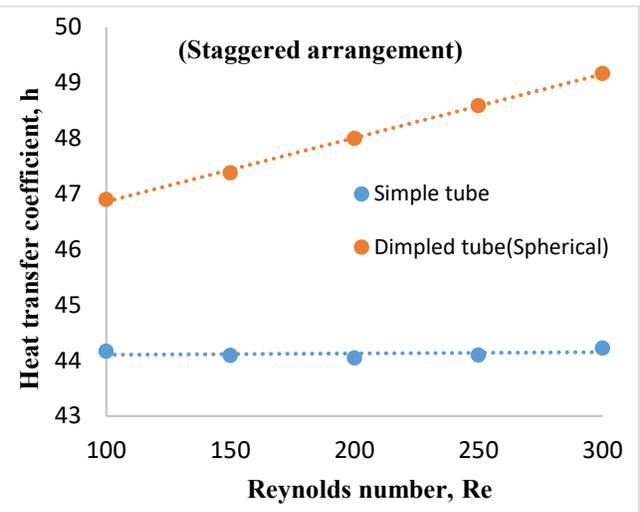


Fig: 7

It is also seen from fig: 6 and fig: 7 that using spherical dimples with the staggered arrangement, makes a great improvement in the Nusselt number and heat transfer coefficient as compared to that of the simple tube without the dimples. The values of the Nusselt number and the heat transfer coefficient keep increasing along with the increase in Reynolds number.

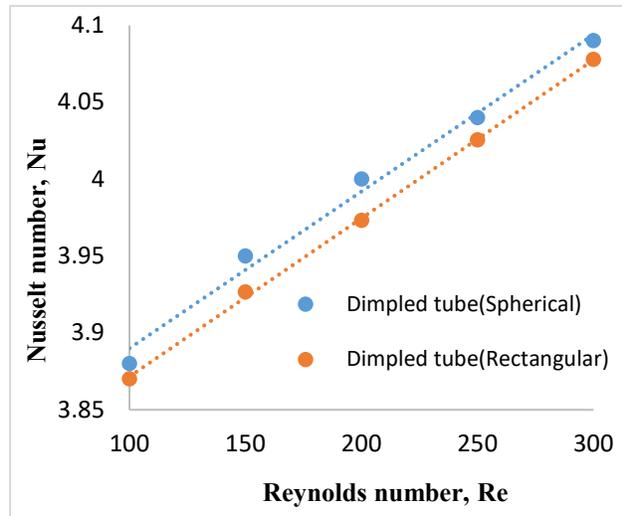


Fig: 8

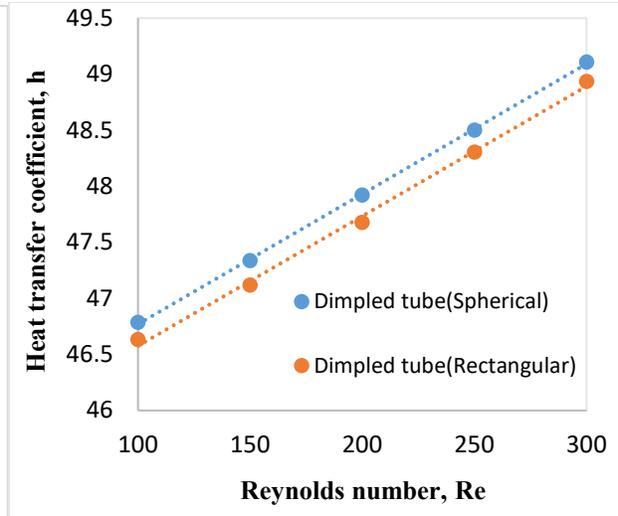


Fig: 9

From fig: 8 and fig: 9, it is seen that using spherical dimples provides a greater enhancement in Nusselt number and heat transfer coefficient than the rectangular box type dimples of the same size. This implements that spherical dimples are more efficient than rectangular box type dimples of the same size.

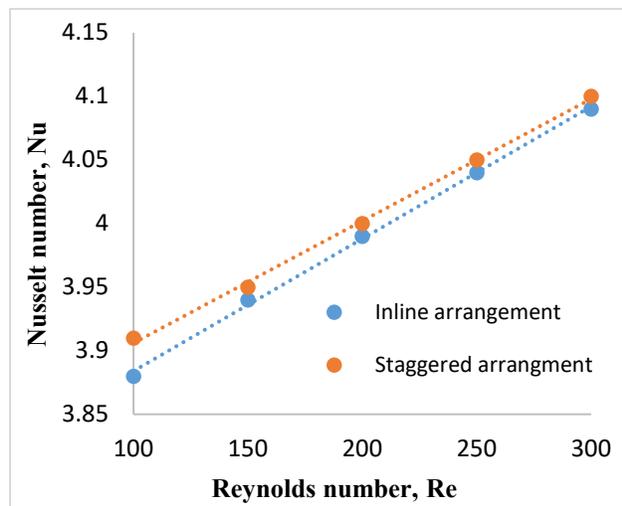


Fig: 10

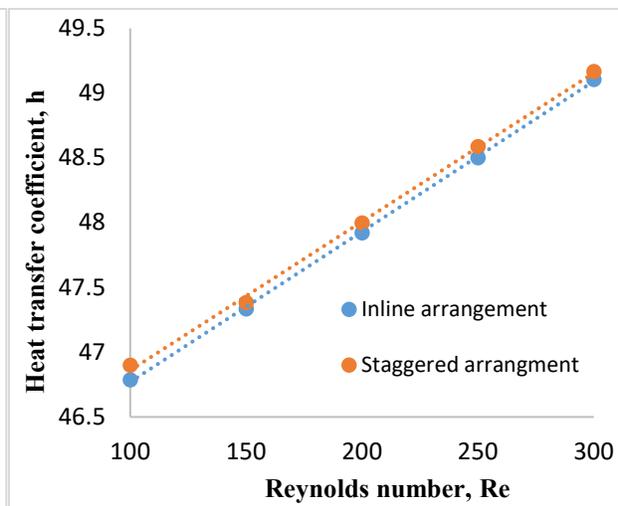


Fig: 11

Changing the arrangement from inline to staggered makes a slightly noticeable change in the Nusselt number and heat transfer coefficient which can be seen from fig: 10 and fig: 11. This difference can be noticed as a way of improving the heat transfer characteristics of the tube. However, the difference seems to be little along with the increase in Reynolds number.

6. Conclusion

From this numerical analysis, it has been seen that the use of dimples on the inner surface of the tube, increases the heat transfer characteristics to a great extent as compared to using a simple tube without any dimples. Thus, it is quite evident that using dimples on the inner surface leads to better heat transfer characteristics and can be considered as an important factor in the designing of heat exchangers. However, changing the dimple shape from spherical to rectangular box type does not have much effect to be considered. It shows only a little increase in heat transfer characteristics. More importantly, it shows that spherical dimples are more efficient than rectangular box type dimples of the same size. The use of the staggered arrangement of dimples instead of inline arrangement however increases the heat transfer characteristics slightly more than that was obtained by changing the shapes. This change is not

significant but is noticeable and may be used for performing analysis on a large scale. It is also evident from the study that, the effect of dimples is more severe at higher Reynolds number as compared to that of lower Reynolds number. The Nusselt number and the heat transfer coefficient keep increasing along with the increase in Reynolds number.

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