International Journal of Research in Engineering Sciences and Management
Vol.2, No.2, July-December' 2025
E-ISSN: 3107-4383

A Comprehensive Evaluation of Effect of Reynolds Number on Thermal–Hydraulic Performance of Dimpled Tube Heat Exchangers

Munish Baboria[1*], Priya Devi[2]

[1*]Assistant Professor, Mechanical Engineering Department, GCET Jammu, Jammu and Kashmir (UT), India

[2]PG Research Scholar, Jammu University, Jammu and Kashmir(UT), India

*** munishb.me.2021@gmail.com,pdevi8493@gmail.com**

Abstract

The heat transfer enhancement technology has attracted much attention taking environmental and economic concerns into account. Heat transfer can be enhanced using active and passive techniques. It has been seen that passive methods have been used to improve the efficiency of heat exchangers on account of their lower cost. This research work underscores the significance of dimpled tubes in increasing heat transfer rates, with studies showing practical applications over smooth tubes. The geometry of this new type of tube was made by exerting deep dimples on the conventional plain tube. Flow-field and heat transfer characteristics of deep dimpled tubes have been studied. Methodology includes experimental setup with a heat source and dimpled tubes, monitoring low rates, placing temperature sensors, and calculating heat transfer coefficients. From tabular values and plots it was found that using spherical dimples leads to a significant increase in the heat transfer rate as compared to that of a normal tube without dimples. Also, it was seen that the change of dimple arrangement from inline to staggered arrangement enhances the heat transfer characteristics to a noticeable amount as compared to others but may further be studied for higher scale implementation with some corresponding moderations.

Keywords – Dimples, heat exchanger, Heat transfer coefficient (h), inline arrangement, Nusselt number (Nu), Reynolds number (Re)

1. Introduction

In the domain of thermal engineering, the efficient exchange of heat plays a pivotal role in various industrial processes, ranging from power generation to advanced cooling systems. 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. Heat transfer enhancement techniques are continually sought after to optimize the performance of heat exchangers and improve energy efficiency. One such method that has gained substantial attention in recent years is the utilization of dimpled tubes. 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. **Figure 1** represents plain copper tube taken for testing along with dimpled tube having equidistant dimples /dents at 0°,15°,30°,and 45°.

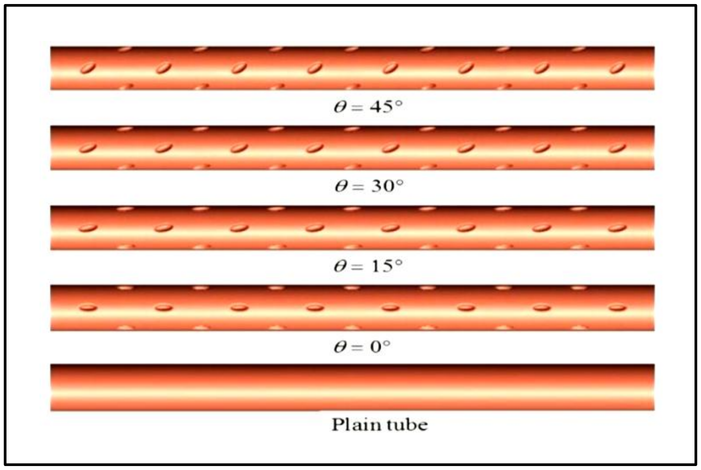

Figure 1: Dimpled tube and Plain (Smooth tube)

Dimpled tubes, characterized by their surface modifications in the form of small, concave, and convex depressions, have emerged as a promising solution for augmenting heat transfer in various heat exchange applications. These deep dimpled tubes increase the heat transfer through the tube by increasing the fluid turbulence, disrupting the thermal boundary layer, and expanding the heat transfer surface area. They cause various mechanisms of fluid flow i.e. increment of local flow velocity, the formation of vortexes behind the dimples, and axial swirling of the flow through the tube. Geometry of dimpled tube is shown in **Figure 2**.

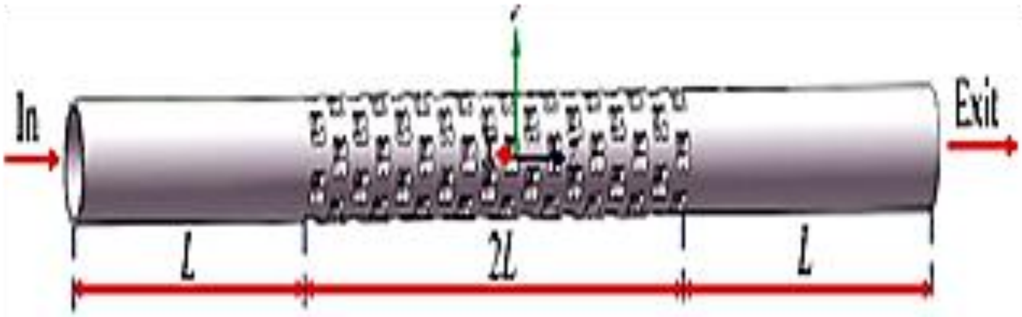

Figure 2: Geometry of dimpled tube

It has been observed that tubes with dimples transfer heat much more effectively than smooth tubes without any surface features. The dimples in tubes produce turbulences in the fluid flow. It leads to better mixing and closer contact between the fluid and the tube wall, which improves convective heat transfer. It has been observed that heat transfer takes place through three basic mechanisms: conduction, convection, and radiation. Conduction is responsible for the movement of heat within solids, convection occurs when heat is carried by a moving fluid, and radiation allows heat to be transferred in the form of energy waves. Under normal ambient conditions, these mechanisms work together rather than separately. The way temperature spreads through a material or system is the result of the combined action of conduction, convection, and radiation.

2. Formulation of the Problem

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

$$\mathrm{Re} = \frac{\rho v D}{\mu} \qquad (1)$$

where, v = Mean fluid velocity over the cross section, D= Tube diameter

ρ = Density of fluid

μ = Viscosity of fluid

In a fully evolved go with the flow, the essential Reynolds quantity corresponds to the onset of turbulence is approximately come out to be 2300.It has been seen that a 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.

3. Literature Review

The growing demand for high-performance thermal systems has led to significant interest in techniques for improving heat transfer. This field of study is commonly referred to as heat transfer augmentation, enhancement, or intensification. Extensive research has been conducted on a variety of augmentation methods, with particular emphasis on surface modification techniques such as roughened surfaces, transverse and spiral ribs, transverse grooves, knurling, corrugated and spirally corrugated tubes, straight fins, and spiral or annular ribs. In the present investigation, heat transfer enhancement is achieved through the use of dimpled surfaces, where dimples are arranged in a predefined pattern along the tube of a double-pipe heat exchanger to increase the effective heat transfer area on the tube side. In general, heat transfer enhancement techniques are classified into two broad categories: active and passive methods. The active techniques require external input such as mechanical actuation or electrical power, but the passive ones are popular because of consuming no external energy [1,2]. The passive techniques aim at promoting the turbulence near the tube wall to reduce the thermal boundary layer thickness and strengthening the mixture of cold fluid and hot fluid, among which corrugated spiral tubes [3,4], twisted inserts [5–7] and surface dimple tubes [8–12] have been put into operation. Significant contribution in the study of dimpled tubes has been done by Kalinin et al. [13] and Giovannini et al. [14] and work on corrugated tubes has been reported by Marto et al. [15]. Augmented surfaces can create one or more combinations of the following conditions that are favorable for increasing the heat transfer coefficient. The relationship between the thermal and hydraulic performance must also be considered. Major process operational variables include the rate of heat transfer, pumping power, pressure drop, heat flow rate and fluid velocity. Webb [16] proposed a broad range of performance evaluation criteria for single-phase flow in tubes to obtain the optimum" surface geometry. Three performance objectives considered were increased heat duty, reduced surface area, and reduced pump power. A comparison of the performance of dimple tube with other heat transfer augmentation designs in terms of heat transfer and friction factor performance. The curves for other designs have been taken from a paper by Bergles and Jensen [17]. The dimples installed over the tube surface can separate flow and induce the second flow on the upper half part of dimples, because of which the velocity and thermal boundary layers are destroyed and heat transfer is strengthened [18,19]. It was shown that the dimple tubes provide not only a better heat transfer but also a higher pressure drop through experiments [20]. Furthermore, the computation results from numerical simulation on dimple tubes captured the local flow details near the dimple and offered an explanation for how heat transfer is enhanced by the dimples [21]. Investigation of an enhanced tube using Glycol/water in a double pipe heat exchanger was presented to depict heat transfer and pressure drop characteristics, and it was found pressure drop. Enhancement was lower than heat transfer enhancement at any given operating condition, therefore resulting in higher PEC [22]. Moreover, the fully-developed flow field in different sinusoidal and spirally corrugated tubes has been investigated to discuss how the height and length of corrugation affect thermo-hydraulic behaviors [18]. An experimental study by Aroonrat et al. [23] investigated the heat transfer and pressure drop of R-134a inside a dimple tube, and showed the tube has an increase of 30–40 % for Nu and 180–310 % for friction factor f.A very peculiar type of tube, ETTD (enhanced tubes with teardrop dimples), which has a better heat transfer and a lower pressure drop through the comparison with the spherical and elliptical dimple tube was studied by Xie et al. [24]. Additionally, Li et al. [25] analyzed the effect of shape, depth and diameter on heat transfer and flow by the numerical method and then optimized the design. The field synergy theory was proposed to reveal the inherent relationship between the heat transfer enhancement and the synergy between velocity and temperature gradient. The theory pointed out that the decrease of thermal boundary layer, the increase of flow interruption and the increase of velocity gradient all lead to the reduction of intersection angle.[26] A comprehensive exploration of [27] is about the development and status of the dimple surface technology, including sphere, ellipsoid, rib and teardrop. Therefore, a new type of enhanced dimple tube is designed by adoption of composite-shape surface technologies, which is called double cross-combined ellipsoidal dimple tube. Numerical simulation on the tube is carried out to provide a prediction of its heat transfer and flow in the range of Reynolds number (Re) from 6880 < Re < 37500. The study of [28] employs numerical simulations to explore fluid flow and heat transfer in heat exchanger tubes with different dimple patterns. The key parameters of local and overall Nusselt numbers, friction factor, are thoroughly examined. The research suggests practical applications where smooth tubes can be replaced by selected dimpled tubes to achieve enhanced heat transfer without altering key parameters such as the number of tubes, tube diameter, flow rate, pressure drop, heat transfer amount, and maximum wall temperature. This study of [29] revealed the investigation of the flow structures and heat transfer performance in circular and annular microchannels with dimples. For annular microchannels, an increase in Reynolds number resulted in improved heat transfer enhancement in circular micro-channels, the study revealed that dimple cases generally exhibited poor heat transfer capacity. However, the staggered arrangement exhibited lower effectiveness, particularly in the protrusion cases. The key findings of [30] indicate that using deep dimples induces significant changes in fluid flow patterns, promoting increased velocity at dimple bottoms. The study highlights the enhancement of the Nusselt number with larger dimple diameters and depths and lower pitches. The study recommends future research directions, including an exploration of the cooling process and an investigation into two-phase flow passing through deep-dimpled tubes.

4. Experimental Set up and Methodology adopted

An experimental arrangement was designed to quantify the heat transfer enhancement achieved with dimpled tubes relative to smooth tubes. The setup comprised dimpled tubes as test specimens and smooth tubes as control specimens. Heat was supplied externally, and surface temperatures were monitored using thermocouples mounted at predetermined axial locations on the tubes. The flow rate of the working fluid was regulated and measured using a rotameter, while the corresponding pressure drop was determined with the aid of a manometer with thermosyphon. To minimise heat losses, the test section and associated piping were fully insulated using suitable cladding materials. Provision was made for the continuous circulation of water or an appropriate heat transfer fluid through the system to prevent overheating and to maintain steady-state operating conditions. A schematic diagram of the experimental setup is presented in **Figure 3.**

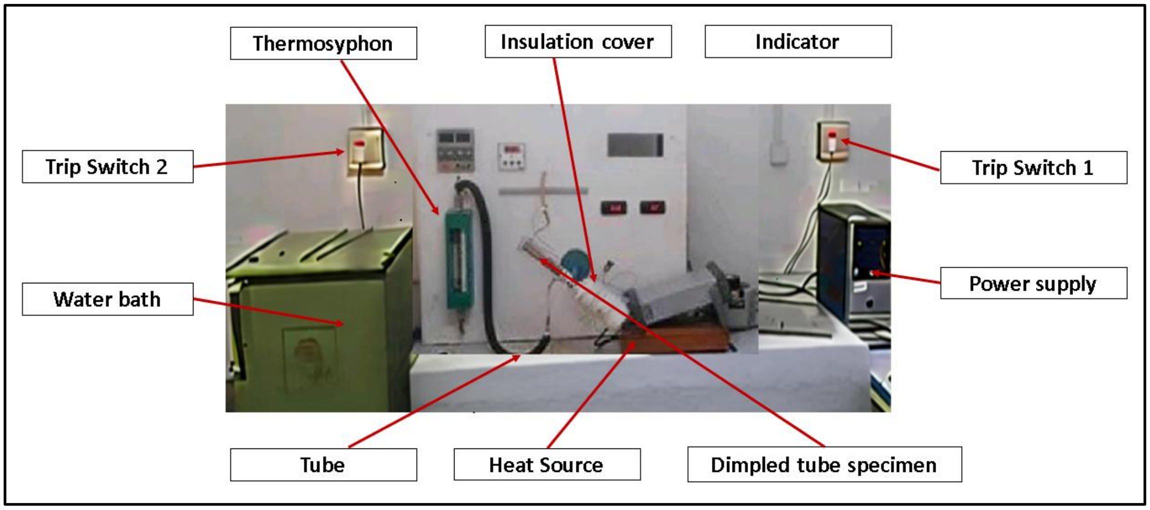

Figure 3: Experimental set up

It is important to note that dimples were intentionally not provided in the inlet section of the pipe as they cause excessive pressure losses. Therefore, a straight entrance length was maintained upstream of the heat transfer section to allow the flow to become hydrodynamically and thermally fully developed. Under fully developed flow conditions, the interaction between the dimples and the fluid is more controlled, enabling enhanced mixing and consistent heat transfer performance. Consequently, keeping the inlet region free from dimples ensures stable flow conditions, minimise undesirable losses, and allows the dimpled section to operate efficiently. A copper tube of suitable standard diameter was selected, and dimples of the required dimensions were fabricated on the tube surface. The experimental setup was then assembled using the selected heat source, dimpled tube, smooth tube, and the necessary measuring instruments. All test sections were adequately insulated to minimise heat loss to the surroundings. The flow rate of the heat transfer fluid was set to a predetermined value and continuously monitored throughout the experiment. Thermocouples were installed at specified axial locations along the tube length to measure temperature variations, ensuring identical placement for both dimpled and smooth tubes. The heat source was activated to maintain a constant temperature difference between the tube wall and the working fluid. Temperature data were recorded at regular intervals until steady-state conditions were achieved. The heat transfer coefficient was subsequently calculated using the inlet and outlet temperature measurements. Finally, the thermal performance of the dimpled tube was evaluated and compared with that of the smooth tube. To ensure reliability and accuracy, experiments were repeated over a range of flow rates and temperature differences to assess the influence of operating parameters on heat transfer characteristics. The selected dimensions of the dimpled tubes, based on the standard pipe diameter and dimple geometry, are presented in **Table 1**.[28]

Table 1: Dimensions of the pipe

S. No	Parameter	Value
1	Length of tube	1.5 m
2	Entry length	1m
3	Diameter of pipe	12.7 mm
4	Length of dimpled tube	0.5 mm
5	Thickness of tube wall	0.8 mm
6	Depth of dimple in tube	3 mm
7	Diameter of dimple	4 mm
8	Number of dimpled made on tube	42

For entry length, correlation utilized are as follows:

Laminar Flow (Re <2300) : $\frac{Le}{D} = 0.06\,Re$ (2)

Turbulent flow (Re > 4000) :

$$\frac{L_e}{D} = Re^{0.167} \quad (3)$$

It was found that 1 m length is enough entry length for all Reynolds numbers. Using the Hagen-Poiseuille equation, pressure drop for simple tube laminar flow, just for reference of future experiments was found

$$\triangle P = \frac{32Ul\mu}{d^2} \quad (4)$$

Taking l =0.5, d=0.00127m, μ = 0.000855 and U as per 20000 Reynolds Number.

$$\triangle P = \frac{32x20000x0.000855x0.5}{(0.00127)^2}$$

= 114.545 Pascal

Since the pressure difference is small, hence density should be comparable to water. Thus, Silicon MSDS oil (with properties shown in Table 2) can be used as working fluid in manometer.

Table 2: Properties of silicon oil [31]

S. No	Parameter	Values
1	Boiling point	315°C at 1013 hPa
2	Density	1.04 g/cm^3 (at 20°C)
3	Flash point	295°C
4	Dimpled tube	0.5 m
5	Ignition temperature	460°C
6	Vapor Pressure	47 hPa (at 20°C)

Now, heat transfer coefficient is expressed using the equation:

$$h = \frac{Q}{A_s\,(T_1 - T_2)} \quad (5)$$

where T_1 and T_2 are the thermocouples reading at the inlet and outlet respectively. Taking temperature; T_1 = 165°C and T_2 = 30°C, Assume Q = 0.4KW area of tube is $A_s = 1.2 \times 10^{-8}$ mm^2, which gives the values of heat transfer coefficient h = 48.59 KW/m^2,which within permissible range of experimental values of dimpled tubevalues.

5. Results and Discussion

Considering the values of heat transfer coefficient (h), Reynolds Number (Re) and Nusselt Number (Nu) results were tabulated for simple and dimpled tube for inline as well as staggered arrangement.

(1) **Inline arrangement**

(a) Simple tube

Table 3: Variations of Re and Nu for Simple tubes

Reynold Number (Re)	Nusselt Number (Nu)
100	3.67
150	3.68
200	3.69
250	3.70
300	3.72

Table 4: Variations of Re v/s h for simple tube

Reynold Number (Re)	Convective Coefficient (h)
100	43.85
150	43.92
200	43.95
250	43.98
300	44.12

(b) Dimpled Tube

Table 5: Variations of Re v/s Nu for dimpled tube

Reynold Number (Re)	Nusselt Number (Nu)
100	3.91
150	3.97
200	4.02
250	4.07
300	4.12

Table 6 Variations of Re v/s h for dimpled tube

Reynold Number (Re)	Convective Coefficient (h)
100	47.12
150	47.56
200	48.24
250	48.75
300	49.23

(2) Staggered Arrangement of tubes

(a) Simple tube

Table 7: Variation of Re v/s Nu for simple pipes

Reynold Number (Re)	Nusselt Number (Nu)
100	3.67
150	3.68
200	3.69
250	3.70
300	3.72

Table 8: Variation of Re v/s h for simple pipes

Reynold Number (Re)	Convective Coefficient (h)
100	43.85
150	43.92
200	43.95
250	43.98
300	44.12

(b) Dimple tubes

Table 9: Variation of Re v/s Nu for dimples tube

Reynold Number (Re)	Nusselt Number (Nu)
100	3.90
150	3.91
200	3.96
250	4.05
300	4.12

Table 10: Variation of Re v/s h for dimpled tube

Reynold Number (Re)	Convective Coefficient (h)
100	46.74
150	47.33
200	48.12
250	48.67
300	49.06

Table 11: Variation of Nusselt Number, Pressure drop with number of dimples on tube

Dimple Count	Nusselt Number (Nu)	Pressure Drop (ΔP)
0	100	1.0
10	120	1.2
20	150	1.5
30	180	2.0
40	190	2.5
50	185	3.0

Accordingly, graphs were plotted as per tabulated values for different values of Re, Nu and h.

(1) For Inline Arrangement

(a) Simple tube

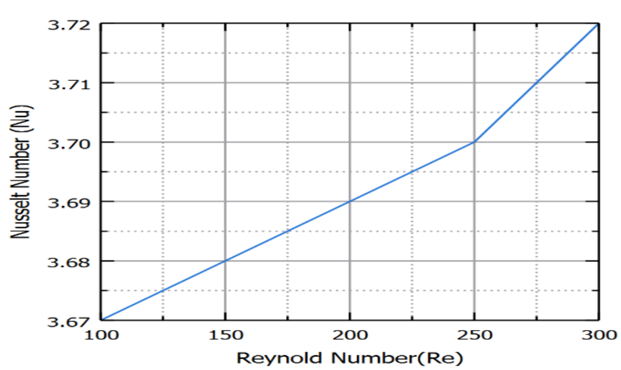

Figure 3: Plot of Reynold Number (Re) v/s Nusselt Number (Nu)

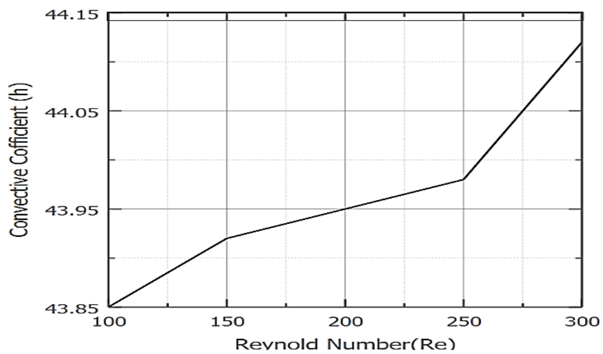

Figure 4: Plot of Reynold Number (Re) v/s Convective Coefficient(h)

(2) Staggered arrangement

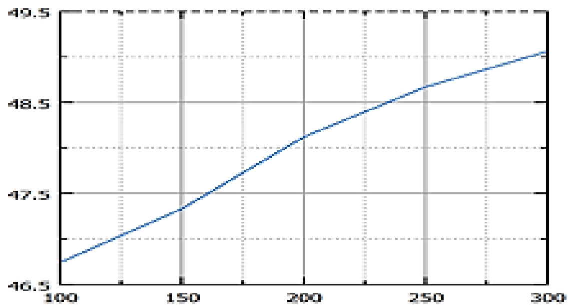

Figure 5: Plot of Reynold Number (Re) and convective heat coefficient(h)

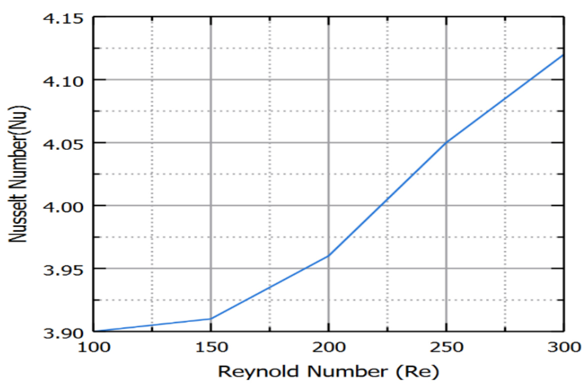

Figure 6: Plot of Reynold Number (Re) and Nusselt Number (Nu)

(b)Dimpled Tubes

(a) Plots for inline arrangement of tubes

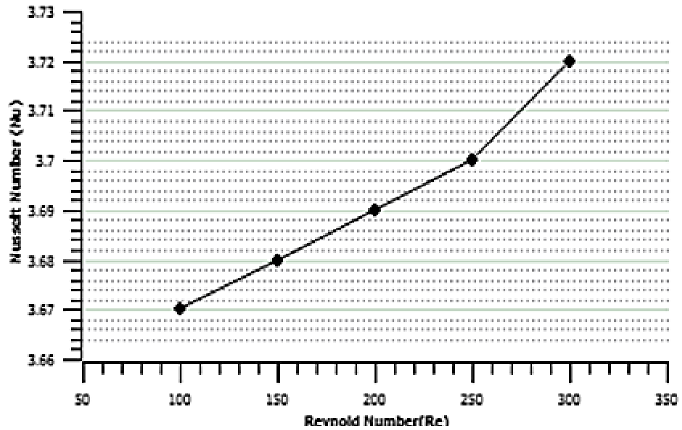

Figure 7: Nusselt and Reynold Number variation plot for inline arrangement

(b) Plots of staggered tubes arrangement

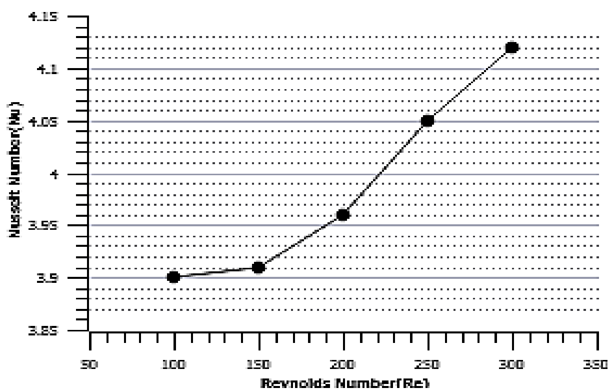

Figure 8: Reynold v/s Nusselt Number variation plot for staggered arrangement

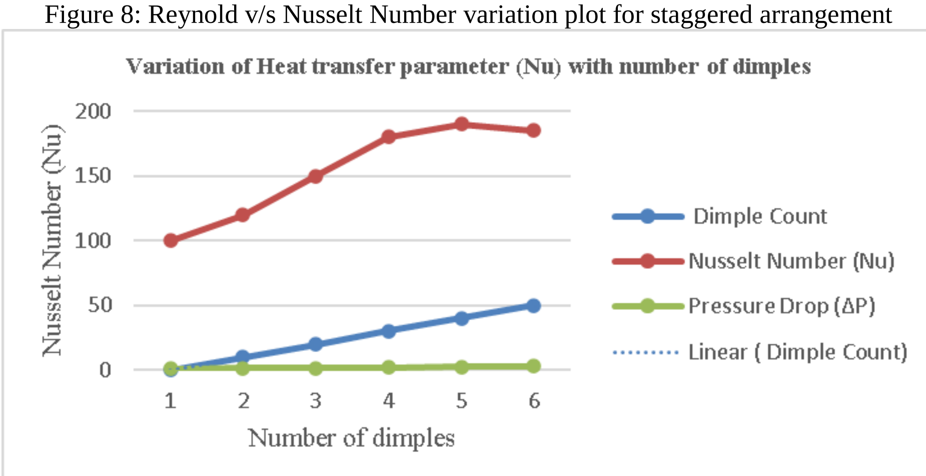

Figure 9: Variation of Nusselt Number (Nu), Pressure drop (ΔP) with the increase in number of dimples on tube

From the tabulated values (Table 3 to 10) and graphical representations (Figure 3 to 9), following inferences can be made:

(1) Dimples modify the cross-sectional temperature distribution, producing a higher core temperature gradient at dimpled sections compared to smooth sections, which indicates enhanced heat transfer.

(2) The presence of dimples reduces thermal stratification and promotes a more uniform temperature field across the tube cross-section, especially downstream of the dimple cavities.

(3) Dimples disturb the incoming flow, generating upstream and downstream vortices along with secondary flows, which disrupt the thermal boundary layer and enhance near-wall mixing. The enhanced turbulence and fluid mixing at dimpled sections result in higher local and average Nusselt numbers than those of smooth tubes.

(4) Flow disturbances caused by dimples increase friction factor and pressure drop; however, the overall thermal performance factor remains greater than unity over the investigated Reynolds number range.

(5) Heat transfer enhancement is more pronounced at lower Reynolds numbers, where the strengthening effect of dimples dominates the flow behavior.

(6) For comparable pressure values, cross-combined dimple tubes exhibit superior overall thermal–hydraulic performance compared to traditional single ellipsoidal dimple tubes.

Overall, the cross-combined dimple configuration proves to be an effective passive heat transfer enhancement technique suitable for compact heat exchanger applications.

6. Conclusion and Future Scope

This research focuses on enhancing heat transfer in thermal systems through the use of tubes with modified inner surfaces incorporating aligned and staggered dimple arrangements. Such configurations are particularly relevant to industrial applications involving heat exchangers and evaporators. The results indicate that the introduction of dimples on the inner surface of the tube leads to a substantial improvement in heat transfer performance when compared with smooth tubes. This enhancement is primarily attributed to the increased turbulence intensity and improved fluid mixing in the near-wall region induced by the presence of dimples. Accordingly, dimpled tubes may be considered an effective design option for improving heat exchanger performance. The study also identifies several practical challenges, including the need to ensure dimensional uniformity during dimple fabrication and the development of a safe and cost-effective U-tube differential manometer employing silicone oil for accurate pressure-drop measurements. In addition, the results show that staggered dimple arrangements provide slightly higher heat transfer enhancement than inline configurations, even when different dimple geometries are employed.

References

[1]. Abed, A. M., H. S. Majdi, Z. Hussein, et al. "Numerical Analysis of Flow and Heat Transfer Enhancement in a Horizontal Pipe with P-TT and V-Cut Twisted Tape." Case Studies in Thermal Engineering, vol. 12, 2018, pp. 749–758.

[2]. Aroonrat, K., and S. Wong wises. "Experimental Study on Two-Phase Condensation Heat Transfer and Pressure Drop of R-134a Flowing in a Dimpled Tube." International Journal of Heat and Mass Transfer, vol. 106, 2017, pp. 437–448.

[3]. Bergles, A. E., and M. K. Jensen. "Enhanced Single-Phase Heat Transfer for OTEC Systems." Proceedings of the Fourth Annual Conference on Ocean Thermal Energy Conversion, New Orleans, Louisiana, 1977, pp. 41–54.

[4]. Chen, J., H. Müller-Steinhagen, and G. G. Duffy. "Heat Transfer Enhancement in Dimpled Tubes." Applied Thermal Engineering, vol. 21, 2001, pp. 535–547.

[5]. Cheraghi, Mohammad Hassan, Mohammad Ameri, and Mohammad Shahabadi. "Numerical Study on the Heat Transfer Enhancement and Pressure Drop inside Deep Dimpled Tubes." International Journal of Heat and Mass Transfer, vol. 147, 2020, article 118845.

[6]. Corcoles-Tendero, J. I., J. F. Belmonte, A. E. Molina, et al. "Numerical Simulation of the Heat Transfer Process in a Corrugated Tube." International Journal of Heat and Mass Transfer, vol. 126, 2018, pp. 125–136.

[7]. Eiamsa-Ard, S., K. Wongcharee, P. Eiamsa-Ard, et al. "Heat Transfer Enhancement in a Tube Using Delta-Winglet Twisted Tape Inserts." Applied Thermal Engineering, vol. 30, 2009, pp. 310–318.

[8]. García, A., J. P. Solano, P. G. Vicente, et al. "The Influence of Artificial Roughness Shape on Heat Transfer Enhancement: Corrugated Tubes, Dimpled Tubes, and Wire Coils." Applied Thermal Engineering, vol. 35, 2012, pp. 196–201.

[9]. Giovannini, A., B. Ferries, and B. Lotado. "Aerothermal Performances of Enhanced Heat Transfer Tubes in Transitional Regime for Compact Heat Exchangers: Problems Associated with Dimensioning Criteria." Entropie, Seminar no. 9, 1991, pp. 93–98.

[10]. Hærvig, J., K. Sørensen, and T. J. Condra. "On the Fully Developed Heat Transfer Enhancing Flow Field in Sinusoidally, Spirally Corrugated Tubes Using Computational Fluid Dynamics." International Journal of Heat and Mass Transfer, vol. 106, 2017, pp. 1051–1062.

[11]. Kalinin, E. K., G. A. Dreitser, N. V. Paramonov, et al. "Comprehensive Study of Heat Transfer Enhancement in Tubular Heat Exchangers." Thermal and Fluid Engineering, vol. 4, 1991, pp. 656–666.

[12]. Kumar, P., A. Kumar, S. Chamoli, et al. "Experimental Investigation of Heat Transfer Enhancement and Fluid Flow Characteristics in a Protruded Surface Heat Exchanger Tube." Experimental Thermal and Fluid Science, vol. 71, 2016, pp. 42–51.

[13]. Li, M., T. S. Khan, E. Al-Hajri, et al. "Single-Phase Heat Transfer and Pressure Drop Analysis of a Dimpled Enhanced Tube." Applied Thermal Engineering, vol. 101, 2016, pp. 38–46.

[14]. Li, M., T. S. Khan, E. A. Hajri, et al. "Geometric Optimization for Thermal–Hydraulic Performance of Dimpled Enhanced Tubes for Single-Phase Flow." Applied Thermal Engineering, vol. 103, 2016, pp. 639–650.

[15]. Li, R., Ya-Ling He, Yuan G. Lei, Y. B. Tao, and P. Chu. "A Numerical Study on Fluid Flow and Heat Transfer Performance of Internally Roughened Tubes with Dimples." Journal of Enhanced Heat Transfer, vol. 16, no. 3, 2009.

[16]. Mahmood, G. I., M. L. Hill, D. L. Nelson, et al. "Local Heat Transfer and Flow Structure on and above a Dimpled Surface in a Channel." Journal of Turbomachinery, vol. 123, 2001, pp. 115–123.

[17]. Marto, P. J., D. J. Reilly, and J. H. Fenner. "An Experimental Comparison of Enhanced Heat Transfer Condenser Tubing." Advances in Enhanced Heat Transfer, ASME, 1979, pp. 1–9.
[18]. Navickaite, K., L. Cattani, C. R. H. Bahl, et al. "Elliptical Double Corrugated Tubes for Enhanced Heat Transfer." International Journal of Heat and Mass Transfer, vol. 128, 2019, pp. 363–377.
[19]. Nkurikiyimfura, Innocent, Yongcheng Wang, and Zhen Pan. "Heat Transfer Enhancement by Magnetic Nanofluids—A Review." Renewable and Sustainable Energy Reviews, vol. 21, 2013, pp. 548–561.
[20]. Pethkool, S., S. Eiamsa-Ard, S. Kwankaomeng, et al. "Turbulent Heat Transfer Enhancement in a Heat Exchanger Using a Helically Corrugated Tube." International Journal of Heat and Mass Transfer, vol. 38, 2010, pp. 340–347.
[21]. Saysroy, A., and S. Eiamsa-Ard. "Enhancing Convective Heat Transfer in Laminar and Turbulent Flow Regions Using Multi-Channel Twisted Tape Inserts." International Journal of Thermal Sciences, vol. 121, 2017, pp. 55–74.
[22]. Sun, Ming, and Ming Zeng. "Investigation on Turbulent Flow and Heat Transfer Characteristics and Technical Economy of Corrugated Tube." Applied Thermal Engineering, vol. 129, 2018, pp. 1–11.
[23]. Suresh, S., M. Chandrasekar, and S. C. Sekhar. "Experimental Studies on Heat Transfer and Friction Factor Characteristics of CuO/Water Nanofluid under Turbulent Flow in a Helically Dimpled Tube." Experimental Thermal and Fluid Science, vol. 35, 2010, pp. 542–549.
[24]. Tao, W., Y. He, Q. Wang, et al. "A Unified Analysis on Enhancing Single-Phase Convective Heat Transfer with the Field Synergy Principle." International Journal of Heat and Mass Transfer, vol. 45, 2002, pp. 4871–4879.
[25]. Wang, W., Y. Zhang, B. Li, et al. "Numerical Investigation of Tube-Side Fully Developed Turbulent Flow and Heat Transfer in Outward Corrugated Tubes." International Journal of Heat and Mass Transfer, vol. 116, 2018, pp. 115–126.
[26]. Webb, R. L. "Performance Evaluation Criteria for Use of Enhanced Heat Transfer Surfaces in Heat Exchanger Design." International Journal of Heat and Mass Transfer, vol. 24, no. 4, 1981, pp. 715–726.
[27]. Xie, G., J. Liu, P. M. Ligrani, et al. "Numerical Analysis of Flow Structure and Heat Transfer Characteristics in Square Channels with Different Internal-Protruded Dimple Geometrics." International Journal of Heat and Mass Transfer, vol. 67, 2013, pp. 81–97.
[28]. Xie, G., and B. Senden. "Numerical Predictions of Augmented Heat Transfer of an Internal Blade Tip-Wall by Hemispherical Dimples." International Journal of Heat and Mass Transfer, vol. 53, 2010, pp. 5639–5650.
[29]. Xie, S., Z. Liang, J. Zhang, et al. "Numerical Investigation on Flow and Heat Transfer in Dimpled Tube with Teardrop Dimples." International Journal of Heat and Mass Transfer, vol. 131, 2019, pp. 713–723.
[30]. Zheng, Lu, Di Zhang, Yonghui Xie, and Gongnan Xie. "Thermal Performance of the Crimpled/Protruded Circular and Annular Microchannel Tube Heat Sink." Journal of the Taiwan Institute of Chemical Engineers, 2016, pp. 342–351.
[31]. Merck Millipore, "Silicone Oil (CAS No. 68083-14-7)., Product no. 107742", retrieved from webpage on 11 January 2026,https://vww.merckmillipore.com/INen/product/Silicone-oil,MDACHEM-107742.