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A Comprehensive Analysis of Dimpled Tube Heat Exchanger Performance with the variations in Reynolds and Nusselt Number

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Abstract - Heat exchangers play a crucial role in various industries, including power generation, chemical processing especially ventilation and air conditioning. Performance and efficiency of heat exchangers is observed to have dependent on various fluid flow parameters like Nusselt and Reynold numbers. In this research work, an attempt is made to investigate the performance of dimpled tube heat exchangers under different flow conditions, characterized by the Reynolds number and Nusselt Number. Results show that dimpled tubes outperform smooth tubes, with significant improvements in heat transfer rates and moderate increases in pressure drop. 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. This research has important implications for industries that rely on heat exchangers, offering a potential solution to improve their efficiency and reduce energy consumption which can aid in developing more efficient and sustainable heat transfer systems.

Key Words: heat transfer coefficient (h), dimpled tube, nusselt Number (Nu), reynolds Number (Re), smooth tubes

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 as in Fig.1.

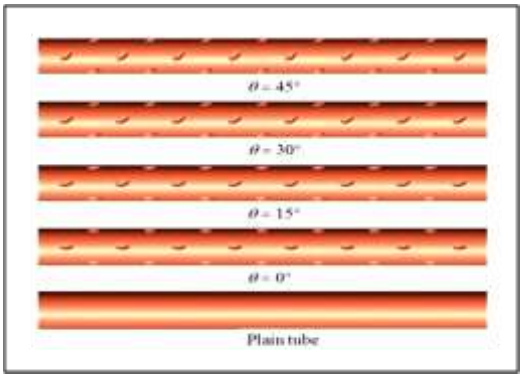

Fig.- 1: Dimpled tube and Plain (Smooth tube)

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 Fig. 2.

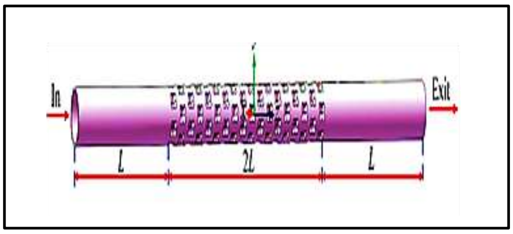

Fig.- 2: Geometry of dimpled tube

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.

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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,

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

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 development of high-performance thermal systems has stimulated interest in methods to improve heat transfer. The study of improved heat transfer performance is referred to as heat transfer augmentation, enhancement, or intensification. A great deal of research has focused on various augmentation techniques with emphasis on rough surfaces, transverse or spiral ribs, transverse grooves, knurling, corrugated and spirally corrugated tubes, straight fins, and spiral and annular ribs. In this investigation, augmented surface has been achieved with dimples strategically located in a pattern along the tube of a double-pipe heat exchanger with the increased area on the tube side. Generally, the options of enhancing heat transfer are categorized into two types consisting of active and passive techniques. 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. METHODOLOGY & EXPERIMENTAL SET UP

To estimate the heat transfer enhancement achieved through the use of dimpled tubes compared to smooth tubes, the following set up was made consisting of dimpled tubes (test specimens) and smooth tubes (control specimens). Heat source was arranged outside with thermocouples or temperature sensors arranged over the test specimen. Flow rate measurement devices(rotameter) and pressure measurement devices (manometer) with cladding of insulation material were installed. There were kept provisions of water or heat transfer fluid within the set up in order to prevent overheating. It is pertinent to mention that the dimples are not provided at the inlet of the pipe because the fluid entering the pipe has not yet settled into a stable flow pattern. At this stage, the flow is still developing, which means the velocity and temperature of the fluid can vary significantly across the pipe. Inlet disturbances caused by bends, fittings, or sudden changes in cross-section further contribute to this uneven behavior. Also, if the dimples were added right at the inlet, their effect on heat transfer would be unpredictable. Fig- 3 shows the experimental setup.

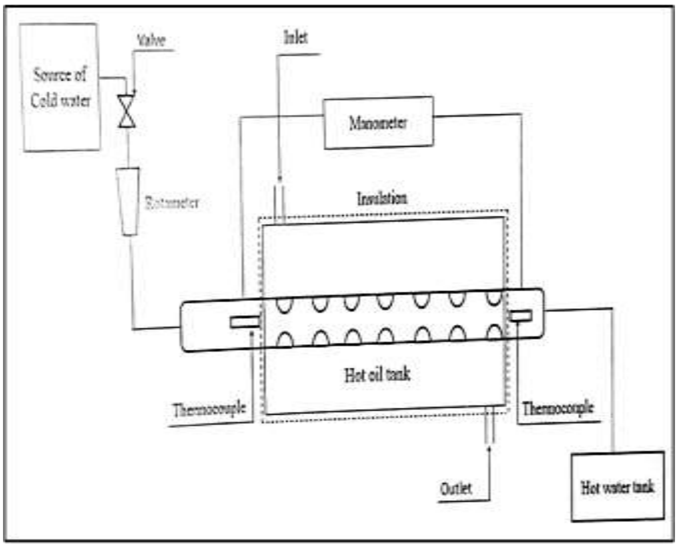

Fig- 3: Experimental set up

Since the flow itself is unstable, the dimples may not enhance heat transfer effectively and could instead cause unnecessary pressure losses. In simple terms, the surface features would be trying to improve heat transfer before the flow is ready to respond to them properly. By providing a straight length of pipe before the heat transfer section, the fluid is given enough space to develop a smooth and uniform velocity and temperature profile. Once the flow becomes fully developed, its behavior is more consistent along the pipe length. Under these conditions, the dimples can interact with the flow in a controlled way, promoting better mixing and more reliable heat transfer enhancement. Therefore, keeping the inlet region free of dimples helps ensure stable flow conditions, reduces unwanted losses, and allows the dimpled section of the pipe to perform efficiently and consistently.

First of all, select the suitable size of copper pipe and make dimples of required dimensions on it. Assemble the experimental setup with the selected heat source, dimpled tube, and necessary instrumentation. Ensure that the tubes are properly insulated to minimize heat loss to the surroundings. Set the flow rate of the heat transfer fluid to a predetermined value. The flow rate is monitored and controlled throughout the experiment. Thermocouples or temperature sensors are placed at specific locations along the length of the tubes to record temperature data. Ensure uniform placement for both the dimpled and smooth tubes. Start the heat source to maintain a constant temperature difference between the fluid and the tube wall. Record temperature data at regular intervals until steady-state conditions are reached. Finally calculate the heat transfer coefficient using the thermocouples reading at the inlet and outlet respectively. The heat transfer performance between dimpled and smooth tubes are then evaluated and compared. It is advised to perform multiple experiments under different flow rates and temperature differences to precisely assess the impact of varying parameters on heat transfer rate. Table 1 shows the dimensions of dimpled tubes which are selected on the basis of the standard diameter of pipe available and the dimensions of the dimples.[28]

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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:

(a) Laminar Flow (Re <2300):

$$\frac{Le}{D} = 0.06\,Re \qquad (2)$$

(b) Turbulent flow (Re > 4000):

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

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 as below:

$$\Delta P = \frac{32 U l \mu}{d^2} \qquad (4)$$

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

$$\Delta P = \frac{32 \times 20000 \times 0.000855 \times 0.5}{(0.00127)^2}$$

= 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:

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

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 lies within the permissible range of experimental values of dimpled tube values.

4. RESULTS AND DISCUSSIONS

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

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(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

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

(1) Plots For Inline Arrangement

(a) Simple tube

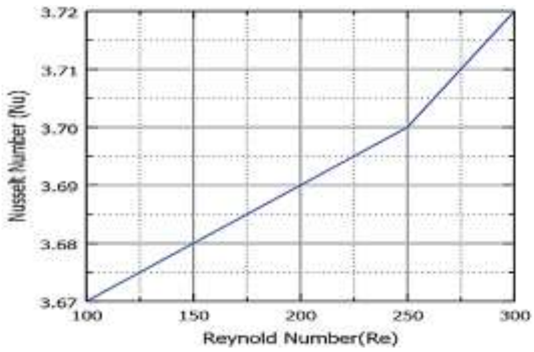

Fig.- 3: Plot of Reynold Number (Re) v/s Nusselt Number (Nu)

(b) Dimpled tube

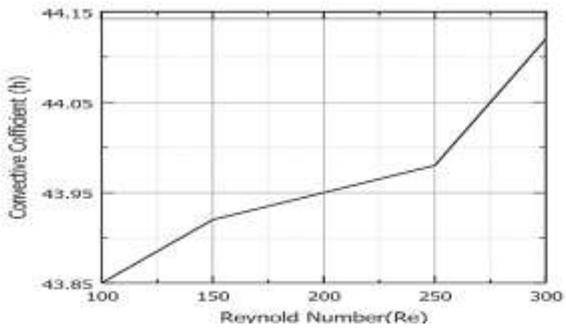

Fig.- 4: Plot of Reynold Number (Re) v/s Convective Coefficient(h)

(2) Staggered arrangement

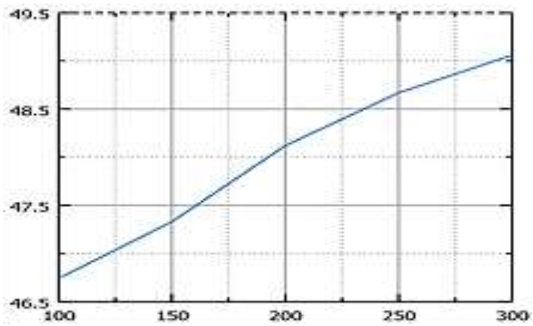

Fig.- 5: Plot of Reynold Number (Re) and convective heat coefficient(h)

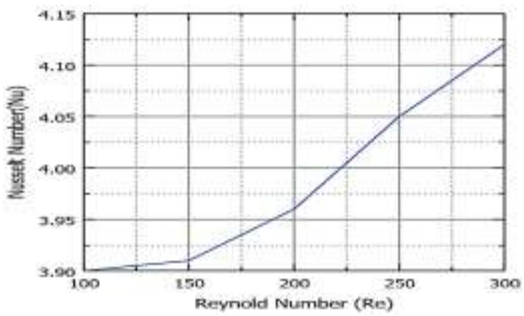

Fig.- 6: Plot of Reynold Number (Re) and Nusselt Number (Nu)

(b)Dimpled Tubes

(a) Plots for inline arrangement of tubes

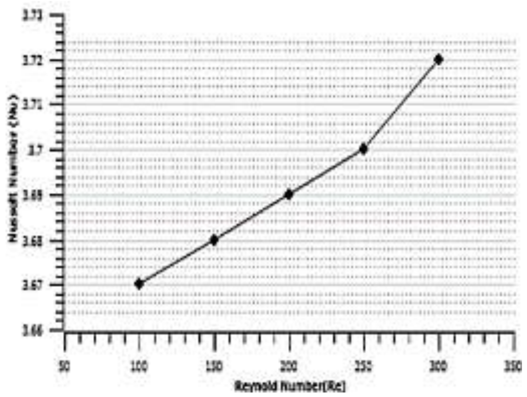

Fig.- 7: Nusselt and Reynold Number variation plot for inline arrangement

(b) Plots of staggered tubes arrangement

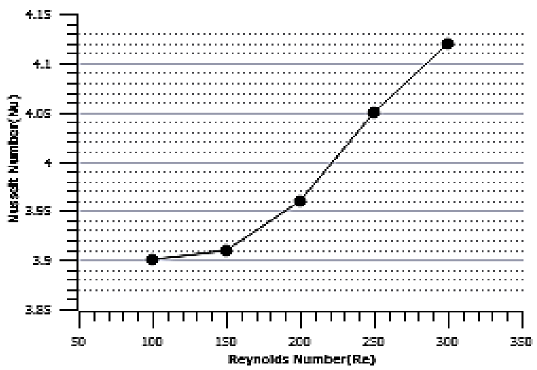

Fig.- 8: Reynold v/s Nusselt Number variation plot for staggered arrangement

From the tabulated values (Table.3-10) and graphical representations (Fig.3 - 8), 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.

5. CONCLUSIONS

This research work focuses on improving heat transfer in thermal systems by using tubes with modified inner surfaces containing aligned and staggered dimples. Such tubes are widely applicable in industries where heat exchangers and evaporators are commonly used. The study clearly shows that introducing dimples on the inner surface of a tube significantly enhances heat transfer compared to a smooth tube. This improvement is mainly due to increased turbulence and better fluid mixing near the tube wall caused by the dimples. Therefore, dimpled tubes can be considered an effective design option for improving heat exchanger performance. However, the study also identifies practical challenges, such as maintaining uniformity during dimple manufacturing and developing a safe, economical U-tube differential manometer using silicone oil for accurate pressure-drop measurement. In addition, it was observed that a staggered dimple arrangement offers a slightly higher heat transfer enhancement than an inline arrangement, even when different dimple shapes are used.

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REFERENCES

1. Abed, A.M., Majdi, H.S., Hussein, Z., 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 12 (2018) 749–758
2. Aroonrat, K., Wong wises, S.: 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 106 (2017) 437–448
3. Bergles, A.E., Jensen, M.K.: Enhanced single-phase heat transfer for OTEC systems. In: Proceedings of the Fourth Annual Conference on Ocean Thermal Energy Conversion, New Orleans, LA (1977) 41–54
4. Chen, J., Müller-Steinhagen, H., Duffy, G.G.: Heat transfer enhancement in dimpled tubes. Applied Thermal Engineering 21 (2001) 535–547
5. Cheraghi, M.H., Ameri, M., Shahabadi, M.: Numerical study on the heat transfer enhancement and pressure drop inside deep dimpled tubes. International Journal of Heat and Mass Transfer 147 (2020) 118845

6. Corcoles-Tendero, J.I., Belmonte, J.F., Molina, A.E., et al.: Numerical simulation of the heat transfer process in a corrugated tube. International Journal of Heat and Mass Transfer 126 (2018) 125–136
7. Eiamsa-Ard, S., Wongcharee, K., Eiamsa-Ard, P., et al.: Heat transfer enhancement in a tube using delta-winglet twisted tape inserts. Applied Thermal Engineering 30 (2009) 310–318
8. García, A., Solano, J.P., Vicente, P.G., et al.: The influence of artificial roughness shape on heat transfer enhancement: corrugated tubes, dimpled tubes and wire coils. Applied Thermal Engineering 35 (2012) 196–201
9. Giovannini, A., Ferries, B., Lotado, B.: Aerothermal performances of enhanced heat transfer tubes in transitional regime for compact heat exchangers: problems associated with dimensioning criteria. Entropie, Semin. 9 (1991) 93–98
10. Hærvig, J., Sørensen, K., Condra, T.J.: 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 106 (2017) 1051–1062
11. Kalinin, E.K., Dreitser, G.A., Paramonov, N.V., et al.: Comprehensive study of heat transfer enhancement in tubular heat exchangers. Thermal and Fluid Engineering 4 (1991) 656–666
12. Kumar, P., Kumar, A., Chamoli, S., et al.: Experimental investigation of heat transfer enhancement and fluid flow characteristics in a protruded surface heat exchanger tube. Experimental Thermal and Fluid Science 71 (2016) 42–51
13. Li, M., Khan, T.S., Al-Hajri, E., et al.: Single-phase heat transfer and pressure drop analysis of a dimpled enhanced tube. Applied Thermal Engineering 101 (2016) 38–46
14. Li, M., Khan, T.S., Hajri, E.A., et al.: Geometric optimization for thermal–hydraulic performance of dimpled enhanced tubes for single-phase flow. Applied Thermal Engineering 103 (2016) 639–650
15. Li, R., He, Y.-L., Lei, Y.G., Tao, Y.B., Chu, P.: A numerical study on fluid flow and heat transfer performance of internally roughened tubes with dimples. Journal of Enhanced Heat Transfer 16(3) (2009)
16. Mahmood, G.I., Hill, M.L., Nelson, D.L., et al.: Local heat transfer and flow structure on and above a dimpled surface in a channel. Journal of Turbomachinery 123 (2001) 115–123
17. Marto, P.J., Reilly, D.J., Fenner, J.H.: An experimental comparison of enhanced heat transfer condenser tubing. In: Advances in Enhanced Heat Transfer, ASME (1979) 1–9
18. Navickaite, K., Cattani, L., Bahl, C.R.H., et al.: Elliptical double corrugated tubes for enhanced heat transfer. International Journal of Heat and Mass Transfer 128 (2019) 363–377
19. Nkurikiyimfura, I., Wang, Y., Pan, Z.: Heat transfer enhancement by magnetic nanofluids—A review. Renewable and Sustainable Energy Reviews 21 (2013) 548–561
20. Pethkool, S., Eiamsa-Ard, S., Kwankaomeng, S., et al.: Turbulent heat transfer enhancement in a heat exchanger using a helically corrugated tube. International Journal of Heat and Mass Transfer 38 (2010) 340–347
21. Saysroy, A., Eiamsa-Ard, S.: Enhancing convective heat transfer in laminar and turbulent flow regions using multi-channel twisted tape inserts. International Journal of Thermal Sciences 121 (2017) 55–74
22. Sun, M., Zeng, M.: Investigation on turbulent flow and heat transfer characteristics and technical economy of corrugated tube. Applied Thermal Engineering 129 (2018) 1–11
23. Suresh, S., Chandrasekar, M., Sekhar, S.C.: 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 35 (2010) 542–549
24. Tao, W., He, Y., Wang, Q., et al.: A unified analysis on enhancing single-phase convective heat transfer with the field synergy principle. International Journal of Heat and Mass Transfer 45 (2002) 4871–4879
25. Wang, W., Zhang, Y., Li, B., 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 116 (2018) 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 24(4) (1981) 715–726
27. Xie, G., Liu, J., Ligrani, P.M., 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 67 (2013) 81–97
28. Xie, G., Senden, B.: Numerical predictions of augmented heat transfer of an internal blade tip-wall by hemispherical dimples. International Journal of Heat and Mass Transfer 53 (2010) 5639–5650
29. Xie, S., Liang, Z., Zhang, J., et al.: Numerical investigation on flow and heat transfer in dimpled tube with teardrop dimples. International Journal of Heat and Mass Transfer 131 (2019) 713–723
30. Zheng, L., Zhang, D., Xie, Y., Xie, G.: Thermal performance of the crimpled/protruded circular and annular microchannel tube heat sink. Journal of the Taiwan Institute of Chemical Engineers (2016) 342–351
31. Merck Millipore: Silicone oil (CAS No. 68083-14-7), product no. 107742. Online (2026)