Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Performance Analysis of Corrugated Twisted Tape Inserts for Heat Transfer Augmentation

Anant Sidhappa Kurhade[1,*], Govindarajan Murali[2], Pallavi Abhinandan Jadhav[1], Parimal Sharad Bhambare[3], Shital Yashwant Waware[1], Tushar Gadekar[4], Rahul Shivaji Yadav[4], Ramdas Biradar[5], Prashant Patil[6]

1 Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology, Sant Tukaram Nagar, Pimpri, Pune, 411018, Maharashtra, India
2 Department of Mechanical Engineering Koneru Lakshmaiah Education Foundation Green Fields, Vaddeswaram, Guntur (Dt) Andhra Pradesh 522502, India
3 Department of Mechanical and Industrial Engg, College of Engineering, National University of Science and Technology, Muscat, Oman
4 Department of Mechanical Engineering, Marathwada Mitramandal's College of Engineering, Karvenagar, Pune, 411052, Maharashtra, India
5 School of Engineering & Technology, PCET's Pimpri Chinchwad University, Sate, 412106, Pune, Maharashtra, India
6 Department of Mechanical Engineering, Abhinav Education Society's College of Engineering and Technology, Satara - 412801, Maharashtra India

ARTICLE INFO

Article history:
Received 6 May 2024
Received in revised form 30 August 2024
Accepted 15 September 2024
Available online 30 September 2024

Keywords:
Heat transfer; wavy twisted tape; turbulent; pressure drop

ABSTRACT

This study explores the impact of wavy corrugated twisted tape inserts on enhancing heat transfer and reducing pressure drop in a double pipe heat exchanger. Cu inserts with twist ratios of 3.2, 4.2, and 5.2 were used to create turbulence in the inner tube. Varying water flow rates and measuring bulk mean temperatures at different points revealed significant improvements in heat transfer over smooth tubes. The insert with a 3.2 twist ratio achieved the highest Nusselt number increase (185%) and a 36.33% rise in the friction factor. These results highlight the effectiveness of wavy corrugated twisted tape inserts for optimizing heat transfer, with a 3.2 twist ratio identified as the most effective. Across Reynolds numbers from 4000 to 18000, Nusselt number increases were 77.75% for a 5.2 twist ratio, 167% for a 4.2 twist ratio, and 185% for a 3.2 twist ratio. Friction factors rose by approximately 10.42% for a 5.2 twist ratio, 32.54% for a 4.2 twist ratio, and 36.33% for a 3.2 twist ratio, demonstrating the relationship between twist ratio, heat transfer enhancement.

1. Introduction

Enhancing heat transfer within a duct can be achieved through passive methods, including the use of various rib patterns, indented surfaces, and pin-like protrusions. These techniques are applied in combustion chamber linings, cooling internal turbine blades, solar air heaters, electronic cooling systems, medical equipment, and industrial heat exchangers. Dimpled surfaces are currently favored due to their ability to significantly increase heat transfer rates with minimal

* *Corresponding author.*
E-mail address: a.kurhade@gmail.com

https://doi.org/10.37934/arfmts.121.2.192200

pressure impact. Researchers have explored combining these techniques to further enhance heat transfer efficiency. Extensive literature covers how different parameters of dimples affect heat transfer. The Russian Aerodynamic Society uses dimpled surfaces not only to reduce drag but also to enhance heat transfer. They utilize configurations such as regular arrays of dimples, staggered arrays in annular passages, flow through converging and diverging ducts with a single hemispherical dimple, and narrow ducts with spherical dimples variably positioned on opposing walls. Some studies report up to 150% higher heat transfer compared to flat plates, with a relatively minor pressure increase. Recent research shows heat transfer improvements up to 2.5 times greater than smooth plates across various Reynolds numbers, with a pressure penalty roughly half that of ribbed turbulators. Kurhade *et al.,* [1-4] discussed material selections and computational fluid dynamics (CFD) approaches for thermal cooling, while Patil *et al.,* [5], and Waware *et al.,* [6] provided critical reviews on heat transfer enhancement in heat exchangers. Khot Rahul *et al.,* [7-11] investigated laser welding parameters on the strength of TRIP steel. The present study focuses on enhancing heat transfer using wavy corrugated twisted tape inserts. Luo *et al.,* [12] used three methods—air bubble injection, perforated wavy strip turbulator (PWST), and nanofluids—to enhance thermal performance in a double pipe heat exchanger. Results indicated heat transfer increases of 56% with nanofluids, 53% with PWST, and 14.1% with bubble injection. Combining all three methods boosted heat transfer and exergy losses by 2.15 and 1.82 times, respectively, compared to a plain pipe. Kumar *et al.,* [13] presented experimental analyses on a heat exchanger tube using a newly designed perforated conical ring combined with twisted tape inserts. Aldawi [14] explored the use of twisted tapes in spiral tubes to address significant research gaps, employing a validated mathematical model to understand geometric parameters' effects on heat transfer and exergy efficiency in such configurations. Ahmad *et al.,* [15] found that corrugated geometries exhibit a performance evaluation criterion (PEC) greater than unity, surpassing smooth pipes. Experiments by Afanasyev *et al.,* [16] analyzed friction and heat transfer on surfaces with spherical cavities exposed to turbulent flow, using an aerodynamic test bed to study boundary layer conditions. Bunker and Donnellan [17] demonstrated that heat transfer in circular passages with dimpled surfaces can be enhanced by factors exceeding 2 when the dimple depth is greater than 0.3 and the array density is 0.5 or higher, resulting in friction factor multipliers between 4 and 6. This research provides initial insights into the effects of different concave arrays on heat transfer and friction in turbulent flows. Chyu *et al.,* [18] showed that concave configurations enhance heat transfer approximately 2.5 times more than smooth surfaces for Reynolds numbers between 10,000 and 50,000, comparable to continuous ribbed turbulators, with significantly lower pressure losses, nearly half of those caused by protruding elements. Isaev *et al.,* [19] demonstrated that altering the separation flow structure from symmetric to a single vortex significantly boosts heat transfer, increasing approximately 60% in the region of the spherical dimple and about 45% in its wake. Ligrani *et al.,* [20] presented flow structure characteristics for a channel with a dimpled surface on one wall, both with and without protrusions on the opposite wall. Moon *et al.,* [21] showed that heat transfer enhancement and pressure penalties remain consistent across a wide range of Reynolds numbers and duct heights. Mahmood *et al.,* [22] examined mechanisms for enhancing heat transfer on plain duct surfaces with dimples on one wall, where the duct height was 50% of the dimple print diameter. Syred *et al.,* [23] studied turbulent heat transfer and hydrodynamics in concavely and convexly curved dimples with Reynolds numbers ranging from 1.3×10^5 to 3.1×10^5. Mohadjer *et al.,* [24] showed that the PEC value was increased by only 6.3 %, some of the turbulators reduced this parameter by up to 11.8 %, which is more severe. The worst performance was observed with the Case C (three-bladed) turbulator at a PR value of 11, which reduced the PEC by 11.8 %. Abed *et al.,* [25] suggest that by incorporating bubble injection, adopting the magnetic turbulator, and simultaneously utilizing both methods, there is a significant improvement in heat transfer. Kumar *et al.,* [26] examines the efficiency of a solar thermal air collector called a jet impingement solar thermal air collector (JISTAC) that is fitted with discrete multi-arc-shaped ribs (DMASRs) utilizing soft computing techniques. Ng and Alzakri [27] numerically investigate the thermal performance of laminar flow inside a pipe with a newly designed small twisted tape insert, showing a Nusselt number increase of approximately 0.07-42.7% for the three-small tapes design and 4.7-48.0% for the five-small tapes design compared to a plain twisted tape insert.

Engineers are looking for new ways to improve heat transfer in machines using magnets, like in car engines and refrigerators. Even though there's been a lot of research on improving heat transfer in double pipe heat exchangers with different methods, scientists haven't looked much at how wavy corrugated twisted tape inserts specifically affect how well heat transfers. Most studies focus on plain twisted tapes or other inserts that make the flow more turbulent. So, we don't really understand how the wavy bumps and twists of these special tapes affect heat transfer and pressure changes in turbulent flow. This research aims to fill this gap by thoroughly examining how these inserts perform.

2. Experimental Investigations

2.1 Set Up

Figure 1 and its inset illustrate the layout of the experiment, including the measuring tools used. The key component was a heat exchanger with a copper inner tube and a mild steel outer tube. We used thermocouples to track temperature changes in both the hot and cold water entering and exiting the exchanger. Four thermocouples were used in total: one for each inlet and outlet of both hot and cold water streams. Rotameters measured the flow rate of the water entering the hot and cold sides. Two pumps kept the water circulating, and separate tanks stored the hot and cold water. The hot water tank had a 1500-watt electric heater. A U-shaped manometer measured the pressure difference between the hot water inlet and outlet, while a current meter measured the flow velocity inside the test section. Control valves and bypass valves allowed for adjusting the flow at the inlet of each rotameter. An airflow meter with a restriction (orifice meter) is used to measure how much air is passing through. A valve allows researchers to control the flow rate. They used two temperature sensors (thermocouples) to measure the incoming air temperature and three to measure the outgoing air temperature.

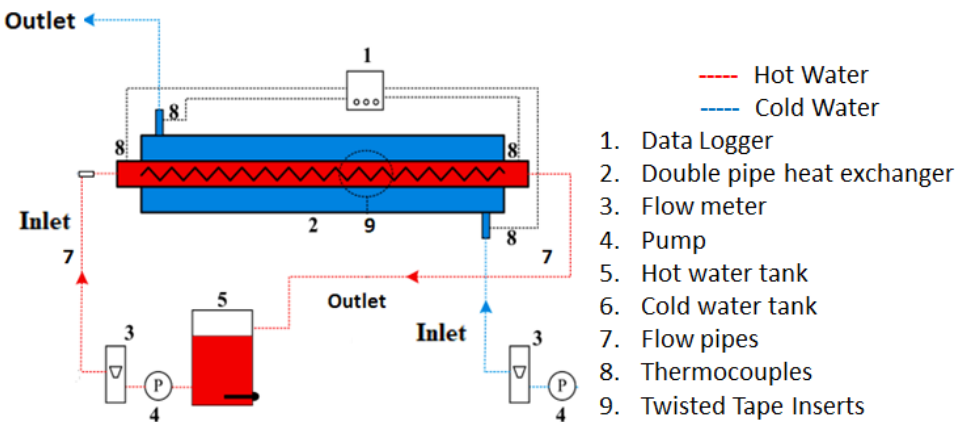
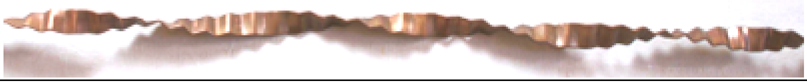


Fig. 1. Experimental set up

2.2 Method

The experiment began by filling the tank with cold water and heating it to 80°C using a heater. Then, a pump and a valve were used to turn on the flow of hot water through a rotameter and into the inner pipe of the heat exchanger. At the same time, cold water from a separate tank was pumped and controlled by a valve to flow through a rotameter and into the outer pipe of the heat exchanger. The cold water flow rate was set to 100 liters per hour (LPH) and held constant throughout the experiment. The hot water flow rate was set to 350 LPH at first. Once the system reached a stable state (steady state), researchers recorded the inlet and outlet temperatures of both the hot and cold water. They also measured the pressure difference across the test section for a plain tube without any inserts. This process was then repeated using three different wavy twisted tapes inserted into the tube. Each tape had a different twist ratio (TR) of 5.2, 4.2, or 3.2 as shown in Table 1. The hot water flow rate was also varied during these tests, ranging from 350 LPH to 850 LPH.

Table 1
Inserts with different Twist Ratios

Sr. No.	Twist Ratio (TR)	Inserts
01	5.2	
02	4.2	
03	3.2	

The instruments used, provide accurate measurements within specified ranges, crucial for detailed performance analysis of heat exchangers with corrugated twisted tape inserts as shown in Table 2.

Table 2
Instruments used with accuracy and range

Sr. No.	Parameter	Measuring Instrument	Accuracy	Range
01	Temperature of Hot Fluid	Thermocouple	±0.5°C	-50°C to 500°C
02	Temperature of Cold Fluid	Thermocouple	±0.5°C	-50°C to 500°C
03	Flow Rate of Hot Fluid	Flow Meter	±1% of full scale	0.1 to 1000 m³/h
04	Flow Rate of Cold Fluid	Flow Meter	±1% of full scale	0.1 to 1000 m³/h
05	Electric Current	Energy Meter	±2%	0 to 100 kW

3. Data Reduction

The bulk mean temperature,

$$T_{bh} = \frac{T_{h1}+T_{h2}}{2} \text{ and } T_{ch} = \frac{T_{c1}+T_{c2}}{2} \tag{1}$$

Heat transfer for hot water and cold water

$$Q_h = m_h.C_{ph}.(T_{h1} - T_{h2}) \text{ and } Q_c = m_c.C_{pc}.(T_{c1} - T_{c2}) \tag{2}$$

Experimental Nusselt Number

$$N_{ui} = \frac{h_i . d_i}{K} \quad (3)$$

Experimental Friction Factor

$$f = \frac{2gdih}{LU_i^2} \quad (4)$$

4. Uncertainty Analysis

The Kline and McClintock's [28] method is used to estimate the uncertainty in their measurements. This method considers the errors associated with each instrument used to collect data. Table 3 shows the largest possible margins of error for the calculated Reynolds number (Re), Nusselt number (Nu), and friction factor (f). These uncertainties are based on the accuracies of the instruments used to measure the original data and the properties of the materials involved.

Table 3
Uncertainties

Sr. No.	Parameters	% Uncertainty
01	Nusselt Number (Nu)	± 1.67
02	Reynold Number (Re)	± 1.67
03	Friction factor (f)	± 1.67

5. Results and Discussion

After analyzing the experiment data, we calculated Nusselt numbers and friction factors for both plain tubes and tubes with wavy inserts. We compared these results to established correlations: the Dittus-Boelter correlation for Nusselt number and the using Blasius's correlation for friction factor [29,30].

$$N_u = 0.023\,(R_e)^{0.8} . (P_r)^{1/3} \quad (5)$$

$$f = 0.0791. (R_e)^{-0.25} \quad (6)$$

Figure 2 shows the relationship between Nusselt number and Reynolds number for the plain tube. The graph reveals a linear trend, indicating that Nusselt number is influenced by Reynolds number. It shows how the Nusselt number (indicating heat transfer rate) changes with Reynolds number (fluid flow rate) for twisted tapes with different twist ratios (TR). The results show that the Nusselt number increases as Reynolds number increases, which means a higher flow rate leads to a greater heat transfer rate. Interestingly, for a specific flow rate (Reynolds number), the twisted tape with the lowest twist ratio (TR=3.2) has the highest Nusselt number. In other words, the lowest twist ratio tape achieved the best heat transfer performance at that flow rate.

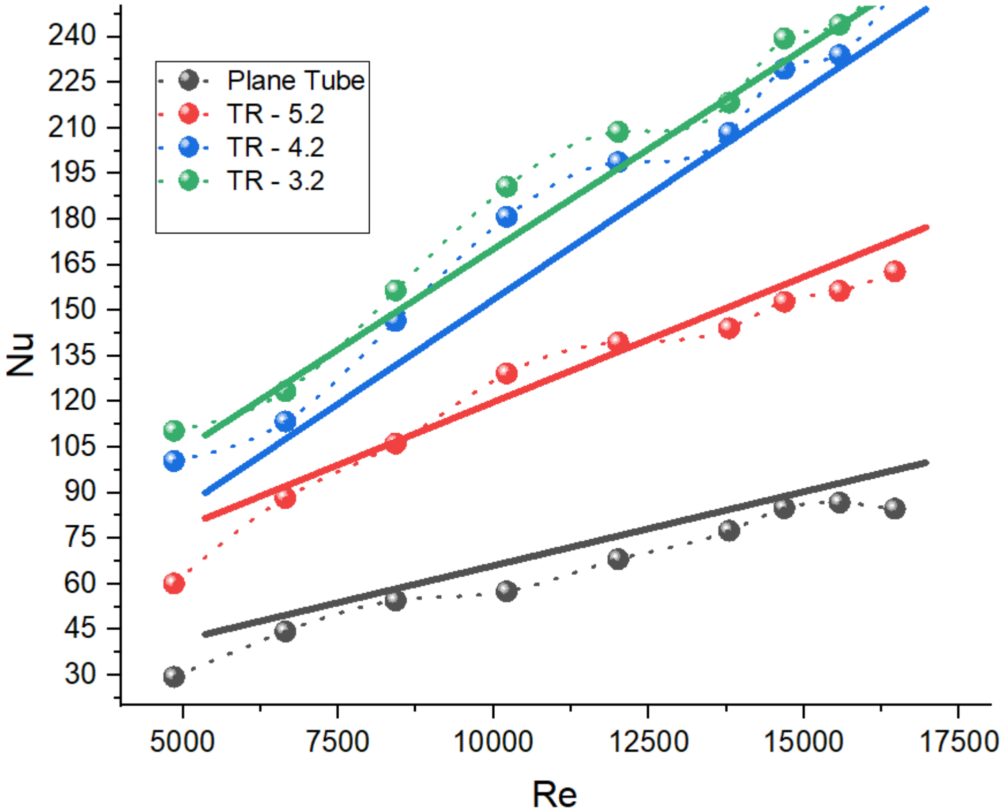


Fig. 2. Nusselt number vs Reynolds number

Figure 3 illustrates the friction factor versus Reynolds number for the plain tube. Here, we see an inverse relationship, meaning that friction factor decreases as Reynolds number increases. The graph shows how the friction factor changes with the flow rate (represented by Reynolds number) for different wavy twisted tape inserts. It reveals that friction factor increases as the twist ratio of the insert goes down. In other words, tapes with lower twist ratios create more friction. Specifically, the insert with the lowest twist ratio (3.2) has the highest friction factor, nearly two times greater than a plain tube. As the twist ratio increases (3.2, 4.2 and 5.2), the friction factor decreases, approaching values closer to a plain tube (1.98, 1.36 and 0.247 times that of a plain tube, respectively). These findings on heat transfer and heat transfer coefficients in a basic tubular heat exchanger are validate with those reported by Waware *et al.,* [31]. This comparison showed a close agreement, with a difference of less than 3% between the two studies, which helps to validate the current experiment's results.

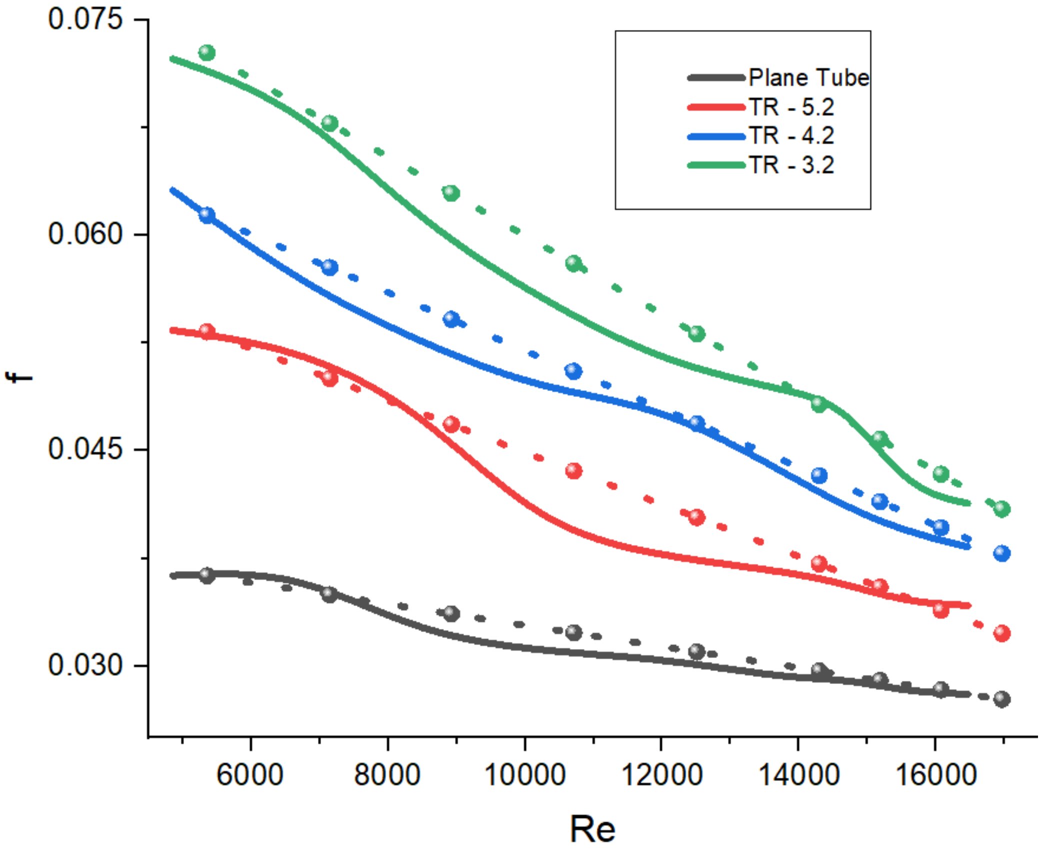


Fig. 3. Friction Factor Vs Reynolds number

6. Conclusion

Researchers and engineers can effectively leverage the benefits of wavy twisted tape inserts to enhance heat transfer in heat exchangers while addressing practical challenges related to friction factors and operational conditions. Future research should delve deeper into corrugated twisted tape inserts by exploring a wider range of geometries (corrugation pitch and height) and operating conditions to identify the optimal configuration for maximizing heat transfer. Additionally, investigating how these inserts synergize with other enhancement techniques like surface roughening or flow inducers could lead to even greater efficiency gains. Rigorous experiments are crucial to validate computational models and confirm real-world effectiveness. Finally, considering practicalities like ease of installation, maintenance, and long-term durability, alongside fostering collaboration between researchers, engineers, and industry, will accelerate the development of innovative heat transfer augmentation technologies through the combined expertise of diverse stakeholders.

Based on the experimental investigation, the following conclusions can be drawn

i. Wavy (corrugated) twisted tape inserts significantly enhance heat transfer, particularly with a twist ratio of 3.2.
ii. Compared to a plain tube, all tested wavy twisted tape inserts showed substantial heat transfer improvements.
iii. Increasing the twist ratio further boosted heat transfer rates while reducing friction factors.
iv. For Reynolds numbers between 4000 and 18000, Nusselt number increases were 77.75% for a twist ratio of 5.2, 167% for 4.2, and 185% for 3.2.
v. The friction factor rose by approximately 10.42% for a twist ratio of 5.2, 32.54% for 4.2, and 36.33% for 3.2.

This design offers a substantial increase in heat transfer compared to plain tubes. While higher twist ratios further enhance heat transfer, also come with a slight increase in friction. Overall, these inserts provide a good balance between improved heat transfer and manageable friction factor.

References

[1] Kurhade, Anant Sidhappa, T. Venkateswara Rao, V. K. Mathew, and Naveen G. Patil. "Effect of thermal conductivity of substrate board for temperature control of electronic components: A numerical study." *International Journal of Modern Physics C* 32, no. 10 (2021): 2150132. https://doi.org/10.1142/S0129183121501321

[2] Kurhade, Anant, Virendra Talele, T. Venkateswara Rao, Archana Chandak, and V. K. Mathew. "Computational study of PCM cooling for electronic circuit of smart-phone." *Materials Today: Proceedings* 47 (2021): 3171-3176. https://doi.org/10.1016/j.matpr.2021.06.284

[3] Kurhade, Anant Sidhappa, and G. Murali. "Thermal control of IC chips using phase change material: A CFD investigation." *International Journal of Modern Physics C* 33, no. 12 (2022): 2250159. https://doi.org/10.1142/S0129183122501595

[4] Kurhade, Anant Sidhappa, G. Murali, and T. Venkateswara Rao. "CFD Approach for Thermal Management to Enhance the Reliability of IC Chips." *International Journal of Engineering Trends and Technology* 71, no. 3 (2023): 65-72. https://doi.org/10.14445/22315381/IJETT-V71I3P208

[5] Patil, Suhas Prakashrao, Sandeep Sadashiv Kore, Satish Suresh Chinchanikar, and Shital Yashwant Waware. "Characterization and Machinability Studies of Aluminium-based Hybrid Metal Matrix Composites-A Critical Review." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 101, no. 2 (2023): 137-163. https://doi.org/10.37934/arfmts.101.2.137163

[6] Waware, Shital Yashwant, Sandeep Sadashiv Kore, and Suhas Prakashrao Patil. "Heat Transfer Enhancement in Tubular Heat Exchanger with Jet Impingement: A Review." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 101, no. 2 (2023): 8-25. https://doi.org/10.37934/arfmts.101.2.825

[7] Khot Rahul, S., and Prasanna Rajendra Kadam. "Structural Behavior of Fillet Weld Joint for Bimetallic Curved Plate Using Finite Element Analysis (FEA)." In *6th International Conference on Advanced Research in Arts, Science, Engineering & Technology, ICARASET - 2021 Proceedings*, Organized by DK International Research Foundation, pp. 23-28. 2021.

[8] Khot Rahul, S., and T. Venkateswara Rao. "Investigation of mechanical behaviour of laser welded butt joint of transformed induced plasticity (TRIP) steel with effect laser incident angle." *International Journal of Engineering Research and Technology* 13, no. 11 (2020): 3398-3403. https://doi.org/10.37624/IJERT/13.11.2020.3398-3403

[9] Khot Rahul, S., T. Venkateswara Rao, Harshad Natu, H. N. Girish, Tadashi Ishigaki, and Puttaswamy Madhusudan. "An Investigation on Laser Welding Parameters on the Strength of TRIP Steel." *Journal of Mechanical Engineering/Strojniški Vestnik* 67, no. 1/2 (2021): 45-52. https://doi.org/10.5545/sv-jme.2020.6912

[10] Khot Rahul, S., and T. Venkateswara Rao. "Effect of Quenching Media on Laser butt Welded Joint on Transformed -Induced Plasticity (TRIP) Steel." *International Journal of Emerging Trends in Engineering Research* 8, no. 10 (2020): 7686-7691. https://doi.org/10.30534/ijeter/2020/1588102020

[11] Khot Rahul, S., T. Venkateswara Rao, Abhishek Keskar, H. N. Girish, and Puttaswamy Madhusudan. "Investigation on the effect of power and velocity of laser beam welding on the butt weld joint on TRIP steel." *Journal of Laser Applications* 32, no. 1 (2020): 012016. https://doi.org/10.2351/1.5133158

[12] Luo, Jie, Muhammad Asadollahzadeh, Bhupendra Singh Chauhan, Ahmed Abdalmonem, Ibrahim Elbadawy, Bashir Salah, Ahmed Farouk Deifalla, and S. P. Ghoushchi. "First and second law analysis of a heat exchanger equipped with perforated wavy strip turbulator in the presence of water-CuO nanofluid." *Case Studies in Thermal Engineering* 54 (2024): 103968. https://doi.org/10.1016/j.csite.2023.103968

[13] Kumar, Anil, Masood Ashraf Ali, Rajesh Maithani, Naveen Kumar Gupta, Sachin Sharma, Sunil Kumar, Lohit Sharma et al. "Experimental analysis of heat exchanger using perforated conical rings, twisted tape inserts and CuO/H_2O nanofluids." *Case Studies in Thermal Engineering* 49 (2023): 103255. https://doi.org/10.1016/j.csite.2023.103255

[14] Aldawi, Fayez. "Efficiency enhancement of flat coiled tube using spiral twisted tape insert with various configurations; thermal, hydraulic and exergetic analysis." *Results in Engineering* 22 (2024): 102098. https://doi.org/10.1016/j.rineng.2024.102098

[15] Ahmad, Foyez, Sajjad Mahmud, M. Monjurul Ehsan, and Musfequs Salehin. "Thermo-hydrodynamic performance evaluation of double-dimpled corrugated tube using single and hybrid nanofluids." *International Journal of Thermofluids* 17 (2023): 100283. https://doi.org/10.1016/j.ijft.2023.100283

[16] Afanasyev, V. N., Ya P. Chudnovsky, A. I. Leontiev, and P. S. Roganov. "Turbulent flow friction and heat transfer characteristics for spherical cavities on a flat plate." *Experimental Thermal and Fluid Science* 7, no. 1 (1993): 1-8. https://doi.org/10.1016/0894-1777(93)90075-T
[17] Bunker, Ronald S., and Katherine F. Donnellan. "Heat transfer and friction factors for flows inside circular tubes with concavity surfaces." *Journal of Turbomachinery* 125, no. 4 (2003): 665-672. https://doi.org/10.1115/1.1622713
[18] Chyu, M. K., Y. Yu, H. Ding, J. P. Downs, and F. O. Soechting. "Concavity Enhanced Heat Transfer in an Internal Cooling Passage." In *Turbo Expo: Power for Land, Sea, and Air*, vol. 78705, p. V003T09A080. American Society of Mechanical Engineers, 1997. https://doi.org/10.1115/97-GT-437
[19] Isaev, Sergey Aleksandrovich, Alexandr Ivanovich Leont'ev, Nikolai Anatol'evich Kudryavtsev, and I. A. Pyshnyi. "The effect of rearrangement of the vortex structure on heat transfer under conditions of increasing depth of a spherical dimple on the wall of a narrow channel." *Heat and Mass Transfer and Physical Gasdynamics* 41, no. 2 (2003): 268-272.
[20] Ligrani, P. M., G. I. Mahmood, J. L. Harrison, C. M. Clayton, and D. L. Nelson. "Flow structure and local Nusselt number variations in a channel with dimples and protrusions on opposite walls." *International Journal of Heat and Mass Transfer* 44, no. 23 (2001): 4413-4425. https://doi.org/10.1016/S0017-9310(01)00101-6
[21] Moon, H. K., T. O'connell, and B. Glezer. "Channel height effect on heat transfer and friction in a dimpled passage." *Journal of Engineering for Gas Turbines and Power* 122, no. 2 (2000): 307-313. https://doi.org/10.1115/1.483208
[22] Mahmood, Gazi I., M. L. Hill, D. L. Nelson, P. M. Ligrani, H-K. Moon, and B. Glezer. "Local heat transfer and flow structure on and above a dimpled surface in a channel." *Journal of Turbomachinery* 123, no. 1 (2001): 115-123. https://doi.org/10.1115/1.1333694
[23] Syred, Nicholas, A. Khalatov, A. Kozlov, A. Shchukin, and R. Agachev. "Effect of surface curvature on heat transfer and hydrodynamics within a single hemispherical dimple." *Journal of Turbomachinery* 123, no. 3 (2001): 609-613. https://doi.org/10.1115/1.1348020
[24] Mohadjer, Ali, Mohammad Hasan Nobakhti, Alireza Nezamabadi, and Seyed Soheil Mousavi Ajarostaghi. "Thermohydraulic analysis of nanofluid flow in tubular heat exchangers with multi-blade turbulators: The adverse effects." *Heliyon* 10, no. 9 (2024). https://doi.org/10.1016/j.heliyon.2024.e30333
[25] Abed, Azher M., Bhupendra Singh Chauhan, Hamdi Ayed, Abir Mouldi, S. P. Ghoushchi, Ahmed Deifalla, and Ibrahim Mahariq. "Heat transfer augmentation in a double pipe heat exchanger by tandem utilization of bubble injection and novel magnetic turbulators methods." *Case Studies in Thermal Engineering* 57 (2024): 104298. https://doi.org/10.1016/j.csite.2024.104298
[26] Kumar, Raj, Nitisha Sharma, Gia Huy Ngo, Amit Kumar Yadav, Daeho Lee, and Tej Singh. "Prediction of jet impingement solar thermal air collector thermohydraulic performance using soft computing techniques." *Case Studies in Thermal Engineering* 55 (2024): 104144. https://doi.org/10.1016/j.csite.2024.104144
[27] Ng, Yee Luon, and Aqilah Alzakri. "Numerical Study of New Small-twist Tape Insert on Heat Transfer and Pressure Drop for Laminar Flow Inside Circular Pipe." *CFD Letters* 15, no. 2 (2023): 87-100. https://doi.org/10.37934/cfdl.15.2.87100
[28] Kline, Stephen J., and F. A. McClintock. "Describing uncertainties in single-sample experiments." *Mechanical Engineering* 75 (1963): 3-8.
[29] Hangi, Morteza, Alireza Rahbari, and Wojciech Lipiński. "Design improvement of compact double-pipe heat exchangers equipped with tube-side helical insert and annulus-side helical strip: Hydrothermal and exergy analyses." *Applied Thermal Engineering* 190 (2021): 116805. https://doi.org/10.1016/j.applthermaleng.2021.116805
[30] Cengel, Yunus A. *Heat and mass transfer: fundamentals and applications*. 5th ed. McGraw-Hill, 2008.
[31] Waware, Shital Yashwant, Sandeep Sadashiv Kore, Anant Sidhappa Kurhade, and Suhas Prakashrao Patil. "Innovative Heat Transfer Enhancement in Tubular Heat Exchanger: An Experimental Investigation with Minijet Impingement." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 116, no. 2 (2024): 51-58. https://doi.org/10.37934/arfmts.116.2.5158