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Predicting Heat Transfer Enhancement with Twisted Tape Inserts Using Fuzzy Logic Techniques in Heat Exchangers

Anant Sidhappa Kurhade[1]*, Gulab Dattrao Siraskar[2], Milind Manikrao Darade[3], Jyoti R. Dhumal[4], Chaitrali Surendra Kardile[5], Ramdas Biradar[6], Suhas Prakashrao Patil[7] and Shital Yashwant Waware[1]

[1]*Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology, Pimpri, Pune - 411018, Maharashtra, India; a.kurhade@gmail.com*

[2]*Department of Mechanical Engineering, PCET's Pimpri Chinchwad College of Engineering and Research, Ravet, Pune - 412101, Maharashtra, India*

[3]*Civil Engineering Department, Nagnathappa Halge College of Engineering, Parli Vaijnath - 431515, Maharashtra, India*

[4]*Department of Computer Engineering, Sinhgad Institute of Technology, Kusgaon(Bk), Lonavala, Pune - 410401, Maharashtra, India*

[5]*Department of Computer Engineering, Dr. D. Y. Patil Institute of Technology Pimpri, Pune - 411018, Maharashtra, India*

[6]*School of Engineering and Technology, PCET's Pimpri Chinchwad University, Sate, Pune - 412106, Maharashtra, India*

[7]*Department of Mechanical Engineering, Arvind Gavali College of Engineering, Satara - 415015, Maharashtra, India*

Abstract

Fuzzy logic, introduced by Lotfi Zadeh in 1965, is a powerful method for modelling complex experiments. This study utilizes fuzzy logic to simulate and predict heat transfer in a double-pipe heat exchanger equipped with wavy inserts. The inserts, in the form of twisted tapes, have varying twist ratios (TR=9, 7, 6). The study investigates a range of Reynolds numbers (Re) from 6000 to 18000, with friction factors ranging from 0.03620 to 0.08231, and Nusselt numbers (Nu) between 66.13 and 253.28. The results for different twist ratios are compared to the ideal case. The experimental results indicate that the highest heat transfer occurs with a twist ratio of 6, leading to a significant increase of 162% in the Nusselt number and a 36.21% rise in the friction factor compared to the ideal scenario. In the fuzzy logic framework, the input variables are the twist ratio (Tr), temperature, and Reynolds number (Re), while the output variables are the friction factor (f) and Nusselt number (Nu). The study demonstrates that the Mamdani fuzzy inference system is an exceptionally effective tool for predicting experimental outcomes, given its low error rate. Upon analysing the data, it is observed that the graphs plotting the Nusselt number versus Reynolds number and friction factor versus Reynolds number, derived from both experimental data and the fuzzy logic model, exhibit nearly identical trends with a margin of error of just 3%. This high level of accuracy underscores the reliability of the fuzzy logic model in replicating the experimental results.

Keywords: *Fuzzy Logic, Heat Transfer, Mamdani Inference System*

*Author for correspondence

1.0 Introduction

Enhancing heat transfer within a duct can be achieved through passive methods such as various rib patterns, indented surfaces, and pin-like protrusions. These techniques are employed in combustion chamber linings and industrial heat exchangers. Dimpled surfaces are particularly favoured for their ability to significantly increase heat transfer rates with minimal pressure impact. Researchers have combined these techniques to further enhance efficiency, and extensive literature details how different dimple parameters affect heat transfer.

The Russian Aerodynamic Society uses dimpled surfaces to reduce drag and enhance heat transfer, utilizing configurations like regular and staggered dimple arrays in annular passages, converging and diverging ducts with single hemispherical dimples, and narrow ducts with variably positioned spherical dimples. Some studies report up to 150% higher heat transfer compared to flat plates, with relatively minor pressure increases. Recent research indicates heat transfer improvements up to 2.5 times greater than smooth plates across various Res, with pressure penalties roughly half that of ribbed turbulators.

Anant *et al.*[1-6] explored material selection and CFD methods for thermal cooling, while Shital *et al.*[7-9] reviewed techniques for enhancing heat transfer in heat exchangers. Rahul Khot *et al.*[10-14] examined the impact of laser welding parameters on the strength of TRIP steel, with a focus on improving heat transfer using wavy corrugated twisted tape inserts. Jie Luo *et al.*[15] employed air bubble injection, Perforated Wavy Strip Turbulators (PWST), and nanofluids to boost thermal performance in a double-pipe heat exchanger. Their findings indicated a 56% increase in heat transfer with nanofluids, a 53% increase with PWST, and a 14.1% increase with bubble injection. The combined use of all three methods improved heat transfer and exergy losses by 2.15 and 1.82 times, respectively, compared to a plain pipe.

Anil Kumar *et al.*[16] conducted experimental analyses on a heat exchanger tube using a novel perforated conical ring combined with twisted tape inserts. Fayez Aldawi[17] investigated the effects of twisted tapes in spiral tubes using a validated mathematical model to assess how geometric parameters influence heat transfer and exergy efficiency. Foyez Ahmad *et al.*[18] discovered that corrugated geometries offer a Performance Evaluation Criterion (PEC) greater than one, outperforming smooth pipes. V. N. Afanasyev *et al.*[19] analyzed friction and heat transfer on surfaces with spherical cavities subjected to turbulent flow, using an aerodynamic test bed to study boundary layer conditions. Ronald S. Bunker *et al.*[20] showed that heat transfer in circular passages with dimpled surfaces can be enhanced by more than a factor of 2 when the dimple depth exceeds 0.3 and the array density is 0.5 or higher, leading to friction factor multipliers between 4 and 6. This research provides preliminary insights into how different concave arrays affect heat transfer and friction in turbulent flows.

M. K. Chyu *et al.*[21] found that concave configurations improve heat transfer about 2.5 times more than smooth surfaces for Reynolds numbers between 10,000 and 50,000, like continuous ribbed turbulators but with significantly lower pressure losses, nearly half of those caused by protruding elements. S. A. Isaev *et al.*[22] showed that transforming the separation flow structure from symmetric to a single vortex greatly enhances heat transfer, increasing by approximately 60% in the spherical dimple region and about 45% in its wake. P. M. Ligrani *et al.*[23] provided insights into the flow structure characteristics for a channel with a dimpled surface on one wall, with and without protrusions on the opposite wall. Moon *et al.*[24] demonstrated that heat transfer enhancement and pressure penalties remain consistent across a wide range of Reynolds numbers and duct heights. Mahmood *et al.*[25] studied heat transfer mechanisms on plain duct surfaces with dimples on one wall, where the duct height was 50% of the dimple print diameter. N. Syred *et al.*[26] investigated 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.

Ali Mohadjer *et al.*[27] reported a 6.3% increase in PEC value, with some turbulators reducing this parameter by up to 11.8%. The worst performance was observed with the Case C (three-bladed) turbulator at a pressure ratio of 11, which decreased the PEC by 11.8%. Azher M. Abed *et al.*[28] suggested that using bubble injection and magnetic turbulators, either separately or together, significantly improves heat transfer. Raj Kumar *et al.*[29] evaluated the efficiency of a solar thermal air collector, specifically the Jet Impingement Solar Thermal Air Collector (JISTAC) with Discrete Multi-Arc-Shaped Ribs (DMASRs), using soft computing techniques. K. A. Sidhappa *et al.*[30]

explained heat transfer enhancement by using twisted tape inserts with circular holes in forced convection.

This study aims to develop and apply a fuzzy logic model, specifically utilizing the Mamdani fuzzy inference system, to simulate and predict heat transfer characteristics in a double-pipe heat exchanger equipped with wavy inserts in the form of twisted tapes. The model aims to accurately estimate the friction factor and Nusselt number for varying twist ratios (TR=9, 7, 6) across a range of Reynolds numbers (6000 to 18000) and compare these predictions with experimental results. The goal is to assess the effectiveness of fuzzy logic in modelling the heat transfer performance and identify the twist ratio that maximizes heat transfer, with a focus on achieving a low margin of error between the experimental and predicted outcomes.

1.1 Fuzzy Model

Designing a compact heat exchanger that achieves high heat transfer rates with minimal pumping power presents a significant challenge. Fuzzy logic offers a method for modelling experiments, which can potentially reduce costs. These models enable the prediction of experimental outcomes that may be impractical or restricted from actual execution. This study employs fuzzy logic methodology to model and forecast experimental results. A typical fuzzy logic system comprises four primary components: the fuzzification interface, fuzzy rule base, fuzzy inference engine, and defuzzification interface.

While existing literature provides insights into the use of conventional methods to enhance heat transfer efficiency in heat exchangers, such as rib patterns and dimpled surfaces, there is a distinct lack of comprehensive research utilizing fuzzy logic specifically for predicting heat transfer augmentation with corrugated twisted tape inserts. Addressing these gaps will contribute to advancing the understanding and application of fuzzy logic in optimizing heat transfer performance with corrugated twisted tape inserts, potentially offering innovative solutions for enhancing thermal management in various industrial and technological applications. This study aims to utilize fuzzy logic to predict and enhance heat transfer performance in a double-pipe heat exchanger equipped with corrugated twisted tape inserts.

2.0 Experimental Investigations

The experiment commenced with filling the tank with cold water, which was subsequently heated to 75°C using a heater. A pump and valve were then utilized to initiate the flow of hot water through a rotameter into the inner pipe of the heat exchanger. Simultaneously, cold water from a separate tank was pumped through a rotameter into the outer pipe of the heat exchanger, controlled by a valve to maintain a constant flow rate of 100 litres per hour (LPH) throughout the experiment. Initially, the hot water flow rate was set to 350 LPH. Once the system achieved a stable state (steady state), the researchers recorded the inlet and outlet temperatures of both hot and cold water. They also measured the pressure difference across the test section for a plain tube without any inserts. This procedure was then repeated using three different wavy twisted tapes

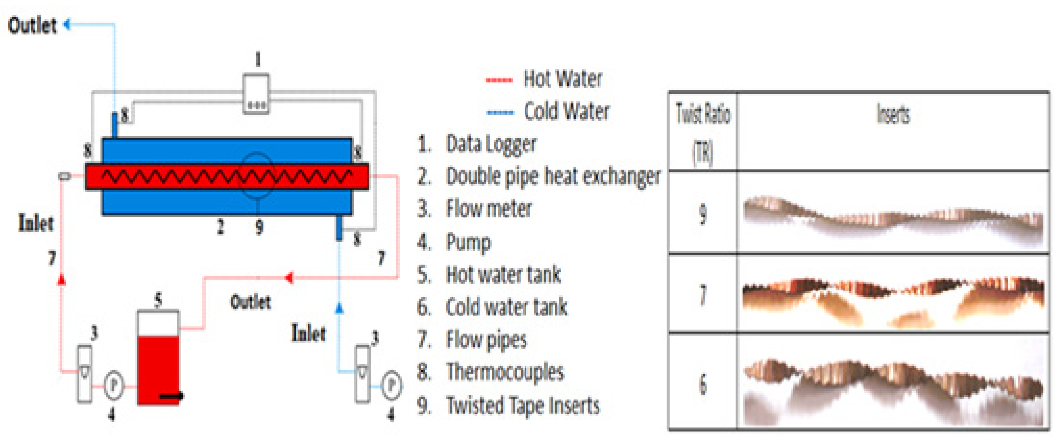

Figure 1. Set up and inserts used.

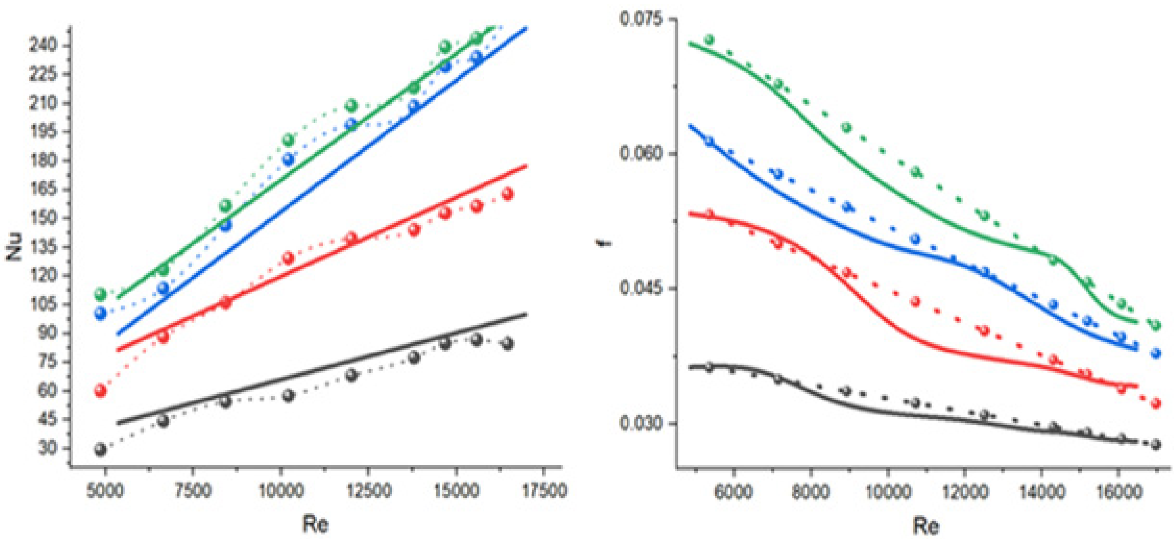

Figure 2. Nu Vs Re and f Vs Re.

inserted into the tube, each tape having a distinct Twist Ratio (TR) of 9, 7, 6 as detailed in Table 1. The hot water flow rate varied between 350 LPH and 850 LPH during these tests.

Wavy twisted tape inserts are highly effective in enhancing heat transfer, especially when configured with a twist ratio of 3.2. Furthermore, increasing the twist ratio not only further enhanced heat transfer rates but also reduced friction factors. Notably, at Res ranging from 6000 to 18000, the Nu increased by 67.75% for a twist ratio of 9, 157% for 7, and 175% for 6. Concurrently, the friction factor saw increments of approximately 10.42% for a twist ratio of 9, 32.54% for 7, and 36.33% for 6.

3.0 Fuzzy Logic Modelling

This research aimed to understand how factors like fluid speed (Reynolds number), the shape of the tube (twist ratio), and temperature influence the flow and heat transfer within a tube. A fuzzy logic system was created to analyze these factors. The system considered fluid speeds between 6000 and 18000 units, temperatures from 35 to 51 degrees Celsius, and tube shapes with twist ratios from 6 to 9. The system determined two outcomes: the friction the fluid experiences and the rate of heat transfer. A specific type of fuzzy logic system called Mamdani was used and is visually explained in Figure 3, while the

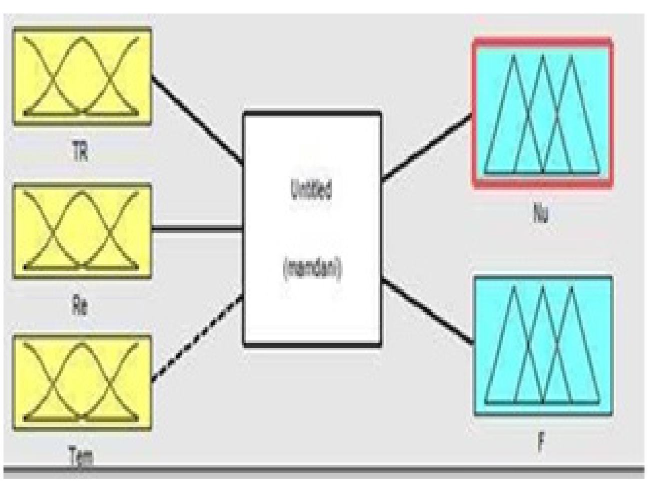

Figure 3. Mamdani inference system.

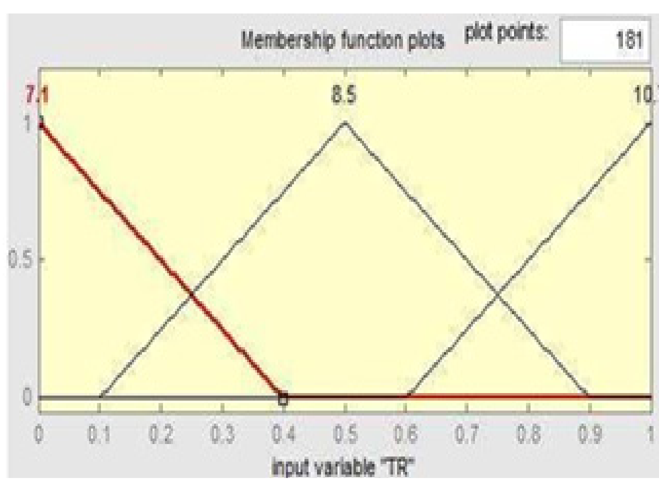

Figure 4. Membership functions plot (TR).

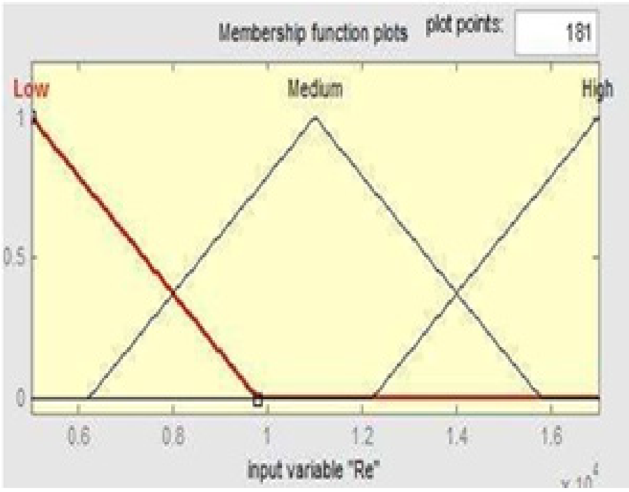

Figure 5. Membership functions plot (Re).

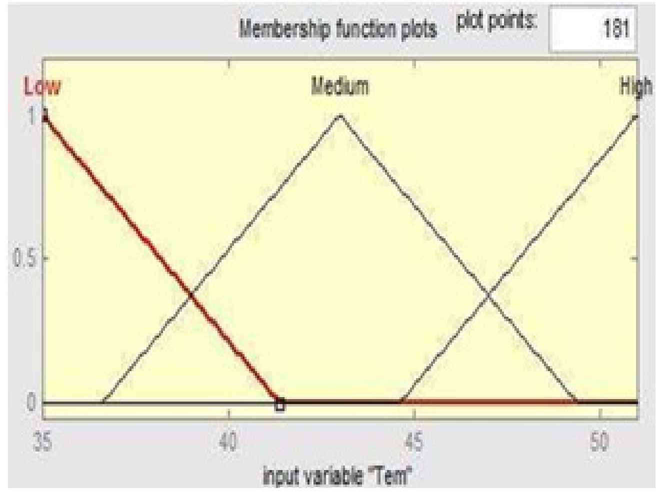

Figure 6. Membership functions plot (Tem).

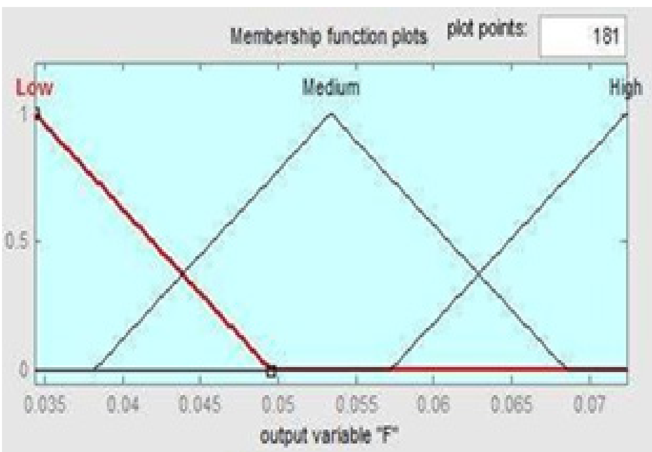

Figure 7. Membership functions plot (friction factor) .

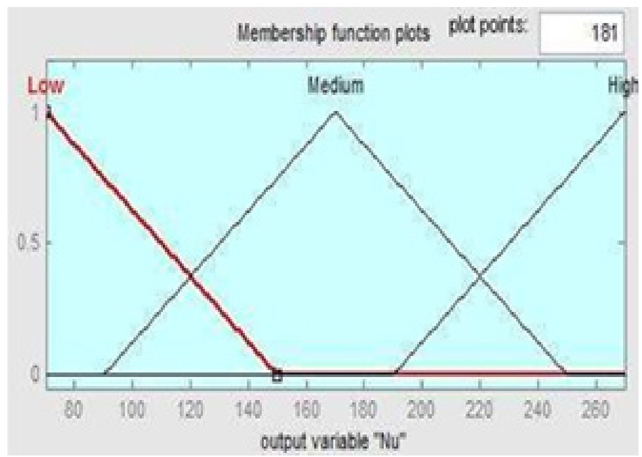

Figure 8. Membership functions plot (Nu).

details of the input factors are shown in Figures 4, 5, and 6. Membership functions for friction factor and Nu are presented in Figures 7 and 8. Selected rules for the fuzzy model are outlined in Figure 9. Three-dimensional graphs depicting the relationships between input variables Re and TR with output variables friction factor and Nu are shown in Figures 10 and 11. The experimental results were effectively modelled using the fuzzy inference system, confirming that Fuzzy Logic is a reliable method for predicting and modelling heat transfer behaviours. According to the fuzzy logic model, an increase in Re corresponds to an increase in Nu.

4.0 Conclusion

Based on the observed data, the graphs showing Nu versus Re and f versus Re, derived from both experimental results and the fuzzy logic model, reveal nearly identical trends with a margin of error of just 3%. All configurations enhanced heat transfer rates compared to the ideal case. As the TR increased, heat transfer improved further while the friction factor (f) decreased. Specifically, the Nusselt number (Nu) increased by approximately 67.75%, 157%, and 175% for twist ratios of 9, 7, and 6, respectively, while the friction factor increased by around 10.42%, 32.54%, and 36.33% for these twist ratios. Fuzzy logic has proven

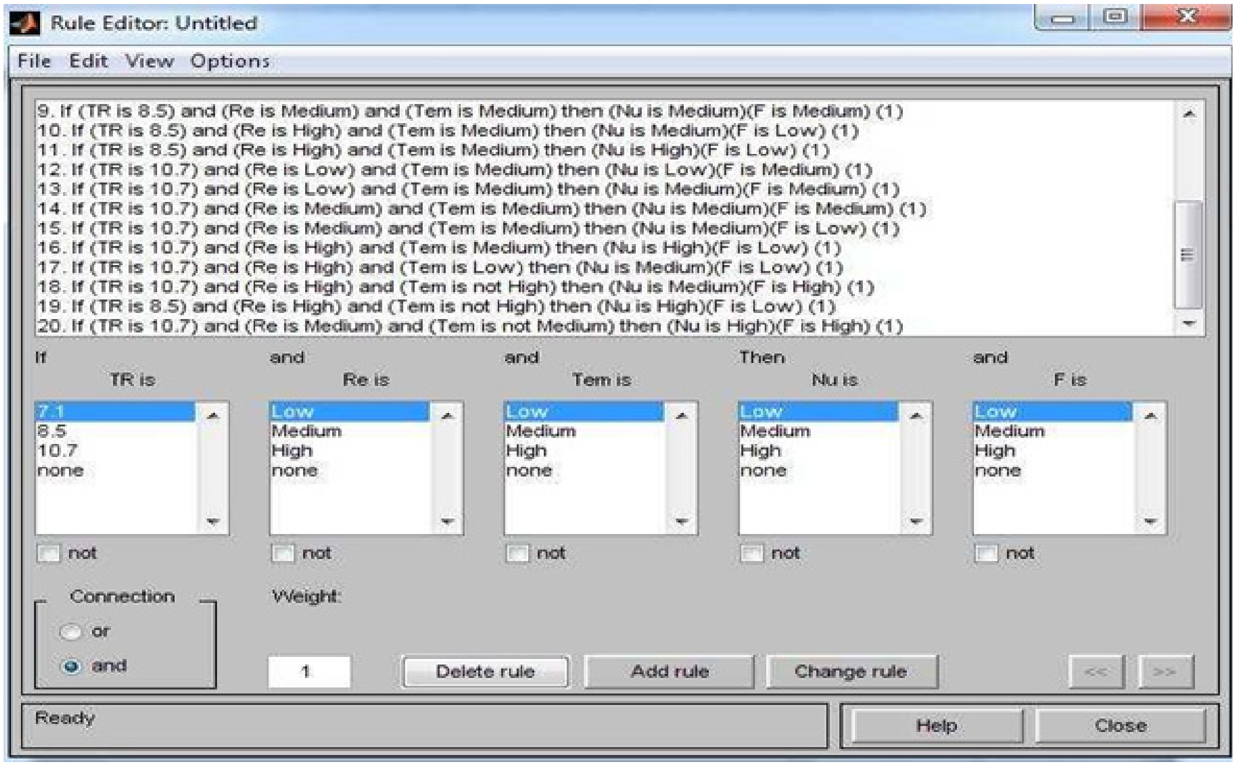

Figure 9. Rule editor window.

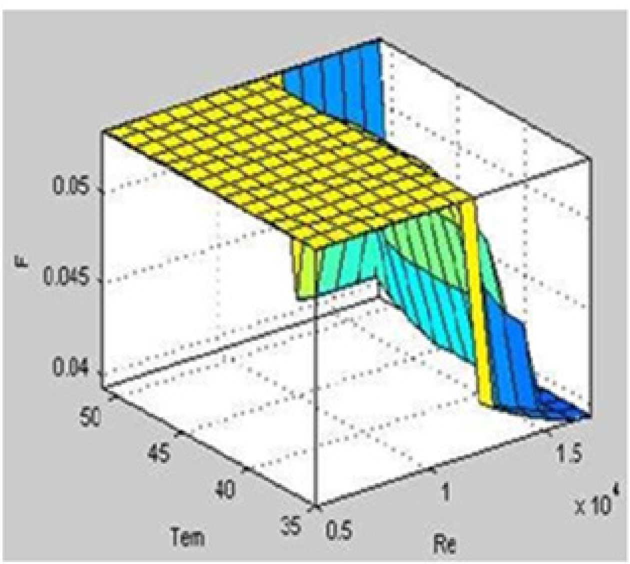

Figure 10. f VS Re.

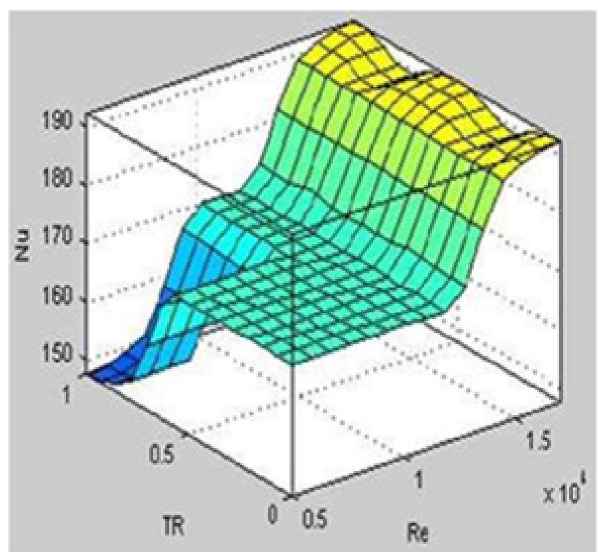

Figure 11. Nu Vs Re.

to be highly accurate in predicting results, making it an effective tool for precise experimental modelling. The successful modelling of experimental outcomes using the fuzzy inference system confirms that fuzzy logic is a reliable method for predicting heat transfer behaviours. According to the fuzzy logic model, an increase in Reynolds number (Re) correlates with an increase in the Nusselt number (Nu). Fuzzy logic techniques enhance the efficiency, reliability, and performance of heat exchangers, making them a crucial tool in modern thermal engineering. The study's findings provide valuable insights for designing more efficient heat exchangers. The use of fuzzy logic enables engineers to predict and optimize performance parameters with high precision, leading to better-informed decisions in the design and operation of heat exchangers with complex geometries or varying operational conditions.

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