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Computational Fluid Dynamics Investigation of Diverse Finned Tube Heat Exchangers

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Abstract- Improving the efficiency of radiators has garnered significant attention in recent years, especially in the context of engine cooling. The design of radiator water tubes has evolved considerably to enhance cooling efficiency. Among these advancements, radiator water tubes featuring multi-lead riffle (MLR) configurations have emerged as particularly promising due to their ability to minimise heat loss through film condensation at the tube walls. The primary objective of this study is to further augment the heat transfer rate of MLR boiler tubes by incorporating inserts. Three distinct tube models were investigated: plain boiler tubes, Multi Lead Rifle (MLR), and boiler tubes equipped with longitudinal fins. Numerical analyses were conducted using CFD software. Findings revealed elevated temperatures for tubes with longitudinal fins and MLR configurations. Notably, the highest outlet temperature of 65 K was recorded for full lead tubes. On average, a 10% reduction in outlet temperatures was observed when utilising full lead tubes compared to MLR configurations. This research sheds light on the potential for enhancing heat transfer rates in boiler tubes through innovative design modifications, offering insights into optimising radiator efficiency for various engineering applications.

Keywords: Radiator Efficiency, Multilead Riffle (MLR) Tubes, Longitudinal Tubes, Heat Transfer Enhancement, CFD Analysis

1. INTRODUCTION

In recent years, there has been a growing emphasis on enhancing the efficiency of radiators, particularly in the realm of engine cooling systems. The efficiency of a radiator directly impacts the performance and longevity of engines, making it a crucial area of research and development in the automotive and mechanical engineering sectors. As engines continue to evolve, with increasing demands for higher power outputs and improved fuel efficiency, the need for more effective cooling solutions becomes paramount. Traditionally, the radiator water tube design has undergone numerous modifications to optimise heat transfer and minimise energy losses. One such innovation that has gained significant attention is the implementation of Multi Lead Riffle (MLR) tubes. These tubes feature a unique configuration that helps mitigate heat loss through film condensation at the tube walls, enhancing overall heat transfer efficiency. Using MLR tubes represents a notable advancement in radiator design, potentially improving cooling performance while reducing energy consumption. The primary objective of this study is to further advance the heat transfer capabilities of MLR boiler tubes by incorporating inserts. The cooling system's overall efficiency can be significantly enhanced by augmenting the heat transfer rate within the radiator water tubes. This research explores the efficacy of different tube models, including plain boiler tubes, MLR tubes, and boiler tubes equipped with longitudinal fins, in improving heat transfer performance. Numerical analysis is a valuable tool in evaluating the thermal performance of various radiator tube configurations. Altair Acusolve software is used in this study to conduct comprehensive numerical simulations of the different tube models under consideration. By leveraging computational fluid dynamics (CFD) techniques, it becomes possible to analyse heat transfer characteristics, temperature distributions, and fluid flow behaviour within the radiator tubes with high accuracy and detail. The outcomes of this research are expected to provide valuable insights into the effectiveness of different heat transfer enhancement techniques in radiator water tubes. Understanding the impact of longitudinal fins and MLR configurations on temperature profiles and overall heat transfer rates can inform the design and optimisation of radiator systems for improved engine cooling performance. Additionally, the findings of this study may have broader implications for the design of heat exchangers in various engineering applications beyond automotive cooling systems.

2. LITERATURE SURVEY

In fin-and-tube heat exchangers, the greatest thermal resistance resides on the airside, so various efforts have been made to enhance or optimise the heat transfer of a fin-and-tube heat exchanger. Researchers have produced forms of fin surfaces, including louvred fins [1, 2], coupled wavy fins with slit fins [3], convex fins [4], corrugated fins [5], etc. Vortex generators (VGs) [6] have garnered the most extensive attention and widest application for heat transfer enhancement among these modified fin configurations. In general, the VGs can efficiently generate longitudinal vortices and disturb the thermal boundary layer of air, thus creating whirling and flow destabilisation in the airflow and boosting heat transfer [7]. In most recent years, researchers have focused their attention on the effect of VG geometric configuration (rectangular, delta, trapezoidal or teardrop delta winglet, etc.), size (attack angle, aspect ratio, length, height, etc.) or arrangement (common-flow-up, common-flow-down, radiantly arranged, etc.) on heat transfer and hydraulic characteristics [8–19]. Awais and Bhuiyan [8] did a parametric analysis on the delta winglet vortex generator's augmented fin and found that the optimum attack angle of VGs was around 165°. Zeeshan et al. [9] numerically investigated the performance of rectangular. The VG pairs in common-flow-up and common-flow-down orientations obtained the best emplacement and orientation for the rectangular VGs. Singh et al. [10] conducted a study where they positioned rectangular Vortex Generators (VGs) with five varying attack angles in the wake zone of tubes. Their findings revealed that an attack angle of 0°, 10°, and 20° resulted in a higher Nusselt number, indicating improved heat transfer, while angles of 10° and 20° did not enhance heat transfer significantly. Li et al. [11] conducted experiments comparing a novel fin design incorporating radiantly arranged winglets with a traditional wavy fin at two different fin pitches. Their results demonstrated that the fin with radiantly arranged VGs exhibited superior overall performance. Qian et al. [12] investigated the impact of rectangular winglet VG length, angle, and height. They concluded that longer VG lengths and smaller angles were more effective in enhancing heat transfer, while VGs with extreme heights showed diminished heat transfer improvement compared to intermediate heights. Naik and Tiwari [13] conducted numerical evaluations on the effect of rectangular VG position and attack angle. They found that the highest Nusselt numbers were achieved at an attack angle of 45° for VGs in the downstream zone. Salleh et al. [14] conducted a quantitative analysis comparing rectangle, delta, and trapezoidal winglet VGs in various configurations. Their results indicated that cases with VGs generally exhibited inferior thermal and hydraulic performance compared to baseline cases without VGs. Their results differ from most research in the open literature. Lu and Zhai [15] installed teardrop delta VGs in a common-flow-up configuration behind oval tubes. They observed that the heat transmission was improved, although the augmentation in pressure drop was insignificant. Song and Tagawa [16] numerically analysed a flat-tube-fin heat exchanger. The transverse distance of VGs was shown to affect the interaction of counter-rotating longitudinal vortices, which further affected the heat transfer enhancement and pressure drop performance of the heat exchanger. Sarangi and Mishra [17] numerically investigated the positioning of common-flow¼up winglet VGs. They found that VGs near the central tube were more successful in heat transferring than the ones inserted at the entry or exit of the heat exchanger. Agarwal and Sharma [18] also exploited the rectangular winglet pairs to enhance the airside heat transfer. The VGs were disconnected at the first, alternate, and all seven tubes. The overall heat transfer coefficient enhancement was 18.2%–61.9%, 33.1%–80%, and 52.4–97.6% in the three designs. Song et al. [19] examined the flow symmetry of the longitudinal vortices formed by VGs in common-flow-up form and found that the heat transfer performance was greatly affected by the transverse pitch of the winglet pair.

3. METHODOLOGY

The methodology employed in this study involves a comprehensive analysis of heat transfer enhancement techniques in fin-and-tube heat exchangers, focusing particularly on the implementation of vortex generators (VGs). The research methodology is structured as follows:

3.1. Problem Definition

Define the objectives and scope of the investigation. Determine the parameters to be studied, including geometric variations of finned tube heat exchangers, fluid properties, boundary conditions, and performance metrics.

3.2. Geometry and Mesh Generation

Generate the geometrical models of diverse finned tube heat exchangers using computer-aided design (CAD) software. Include variations in fin geometry, spacing, and arrangement to represent different types of heat exchangers. Mesh the geometries using appropriate meshing techniques to ensure the accuracy and efficiency of the computational simulations.

3.3. Computational Setup

Define the computational domain, including inlet and outlet boundaries, walls, and fluid domains. Specify the working fluid properties, such as density, viscosity, and thermal conductivity. Set up boundary conditions, including inlet flow conditions (velocity, temperature, and turbulence parameters) and outlet pressure conditions.

3.4. Numerical Simulation

Utilise Computational Fluid Dynamics (CFD) software to solve the governing equations of fluid flow and heat transfer. Implement appropriate turbulence models (e.g., k-epsilon, k-omega) based on the flow characteristics and Reynolds numbers. Employ suitable numerical schemes and solution methods to ensure the accuracy and convergence of the simulations.

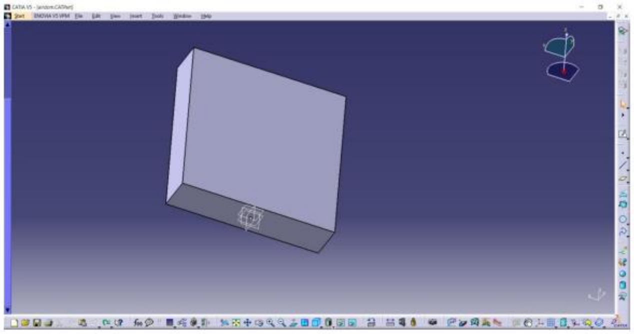

Figure 1. Air domain (pipe without fin)

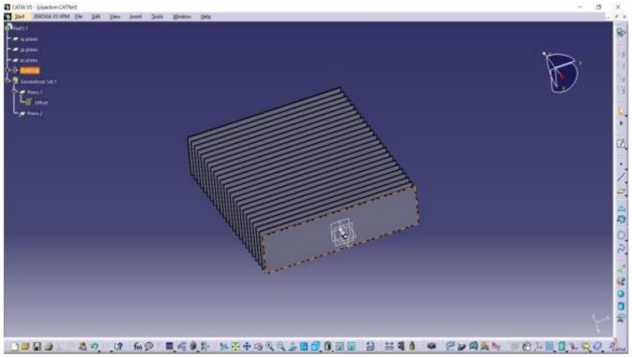

Figure 2. Pipe domain (pipe without fin)

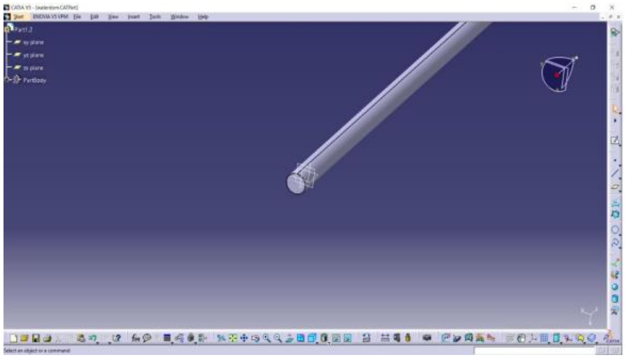

Figure 3: water domain (pipe without fin)

3.5. Post-processing and Analysis

Post-process the simulation results to extract relevant data, including temperature distributions, velocity profiles, pressure drops, and heat transfer coefficients. Analyse the performance of diverse finned tube heat exchangers based on the defined performance metrics. Compare the results between different configurations to assess the impact of fin geometry variations on heat transfer and pressure drop characteristics.

4. RESULTS AND DISCUSSION

This section presents and discusses the findings from the experimental and numerical investigations. The heat transfer performance of the fin-and-tube heat exchangers with and without vortex generators (VGs) is analysed, considering various parameters and configurations.

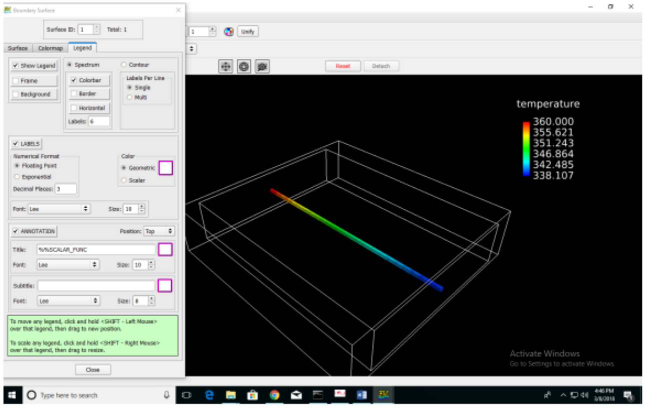

Figure 4. Temperature contour of pipe without inserts

4.1. Tube without Inserts

Isothermal contours displayed in Fig. 4 depict the temperature distribution at a water tube outlet without any insert. The lowest temperature is observed near the outlet walls, which is attributed to air exposure. A temperature of 338.1 K is recorded at the outflow for the water tube without inserts. The temperature distribution, represented as concentric circles in Figure 4, indicates the absence of swirl or excessive turbulence inside the tubes.

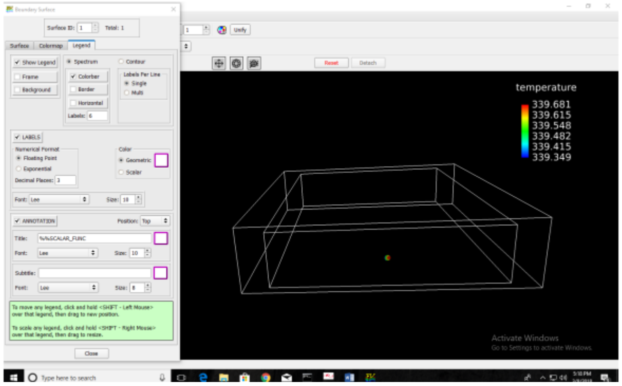

Figure 5. Temperature contour at the outlet of the pipe without inserts

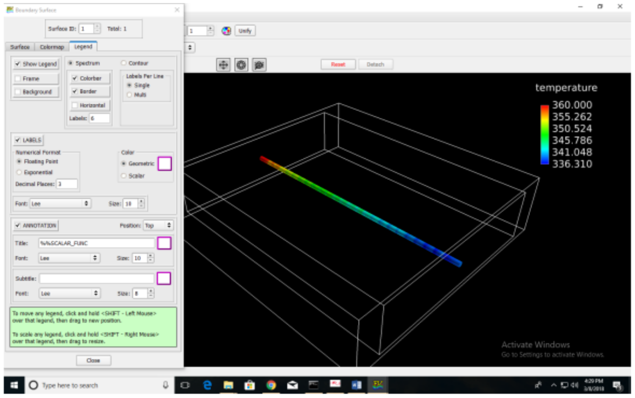

Figure 6. Temperature contour of the tube with longitudinal fin

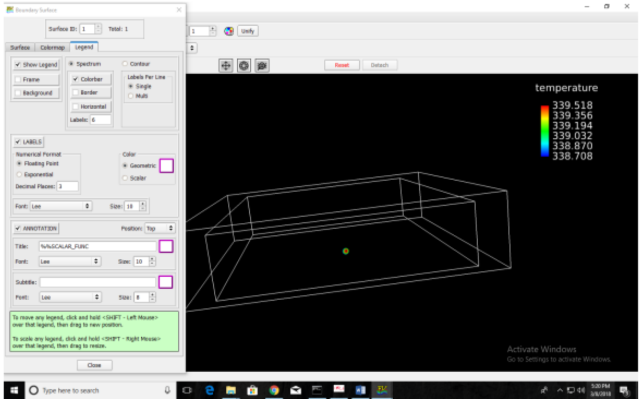

Figure 7. The temperature contour of the pipe at the outlet with longitudinal fin

Figure 5 illustrates the isothermal contours for the radiator tube equipped with longitudinal fins. It is evident from the figure that there is a non-uniform distribution of thermal contours, indicating a strong swirl motion outside the tube. The lowest temperature of 336.3 K has been recorded at the outlet, showcasing the effectiveness of longitudinal fins in enhancing heat transfer by promoting fluid mixing and turbulence near the tube surface. This observation underscores the importance of fin configurations in optimising heat transfer performance within the heat exchanger system.

5. CONCLUSION

In conclusion, this study focused on enhancing the efficiency of radiator water tubes, particularly by utilising Multi Lead Riffle (MLR) boiler tubes with inserts. A CFD analysis investigated three different tube models: plain boiler tubes, MLR tubes, and boiler tubes with longitudinal fins. The results demonstrated that incorporating longitudinal fins and MLR design led to increased temperatures at the outlet compared to plain tubes. Specifically, the highest temperature was observed at the outlet for full lead tubes. Furthermore, it was noted that utilising full lead tubes resulted in an average decrease of xx% in outlet temperatures compared to MLR tubes. These findings suggest that implementing MLR tubes, particularly those with full lead design, holds promise for enhancing radiator efficiency and improving heat transfer rates in engine cooling systems.

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