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Influence of Tube Geometry and Spacing on Thermal Performance in Automobile Radiators

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ABSTRACT
This study investigates the influence of tube geometry and spacing on the heat transfer performance of automobile radiators using MATLAB and Simulink simulations. Despite innovations in heat exchanger designs, the impact of practical geometries like circular and rectangular tubes on radiator efficiency remains underexplored. The study examines heat exchanger performance by comparing outlet temperatures for circular and rectangular tubes at inlet temperatures of 310 K to 360 K, and analyzing the effectiveness-NTU relationship, highlighting geometric and operational impacts on efficiency. The NTU method was used to predict fluid outlet temperatures and also validated the simulations. In the case of tube shaping, the rectangular tubes achieve outlet temperatures of 307–347 K, compared to 308–351 K for circular tubes. For tube spacing, circular tubes stabilize at 334 K (2–15 tubes), while rectangular tubes drop to 323 K (up to 140 tubes) but rise to 340 K at 198 tubes due to flow limitations. The effectiveness of rectangular tubes rises sharply to 0.75 at NTU of 1, approaching 1 with minimal gains beyond NTU of 5. The NTU method predicts outlet temperatures of 309 to 359K, closely matching circular tubes but overestimating rectangular performance. This research identifies optimal tube configurations, contributing to improved thermal management. The findings have applications in automotive cooling systems, with future studies recommended for transient behavior analysis.

Keywords: Automobile Radiators, Heat Transfer, Tube Geometry, Thermal Performance, Simulation, NTU.

1. Introduction

Automobile engines generate considerable heat during operation, requiring efficient cooling systems to prevent overheating. The radiator, a key component, dissipates this heat to maintain optimal engine temperature. Enhanced radiator designs are crucial due to increasing engine power and efficiency demands. Numerous studies have been conducted to introduce the various methods and models as well. Kays and London [1] highlighted the importance of tube shape in optimizing heat exchanger performance, while Webb and Kim [2] expressed the improvement of heat transfer with innovative tube shapes. This study also noted that wasp-waisted tubes can enhance heat transfer by up to 10.6% through improved flow dynamics. However, the geometry and arrangement of radiator tubes play a significant role in heat transfer efficiency. Traditional shapes like circular and elliptical tubes are preferred for their structural strength and manufacturability [3, 4]. Oliet et al. [5] found that optimizing tube and fin geometry could increase heat transfer rates by up to 8%. Lotfi and Sundén [6] demonstrated that elliptical tubes effectively reduce pressure drops while maintaining high thermal efficiency. This study focuses on easily manufacturable geometries and examines the less studied impact of tube spacing on performance. The coolant choice and material selection are critical for improving the heat transfer rate. Nanofluids, containing suspended nanoparticles, have shown promise in enhancing radiator performance. Said et al. [7] reported a 24.21% increase in heat transfer with nanofluids, while Bejan et al. [8] found that ethylene glycol-based coolants with metal oxide nanoparticles significantly lowered operating temperatures. The innovations in high-conductivity alloys and coatings have also improved thermal performance and durability [9, 10]. Heat transfer in radiators involves conduction through the tube walls and convection with the surrounding air. Mahmoudi et al. [11] highlighted that air-side thermal resistance contributes to over 60% of the total resistance, making airflow optimization essential. Enhancing air-side fins has increased convective heat transfer rates by 12% [12], aligning with this study's emphasis on optimizing tube spacing for improved airflow efficiency. Though all these works have shown that nanofluids, advanced tube materials, and compact designs are revolutionizing radiator efficiency [9-12]. Again, the NTU-effectiveness method is widely used to evaluate heat exchanger performance. Guo et al. [13] validated its utility in predicting outlet temperatures under various conditions, and Korzeń and Taler [14] refined the method with transient models that better reflect real-world scenarios, showing that minor flow rate variations can significantly affect effectiveness.

Above mentioned studies highlight the role of tube shape and arrangement in improving heat transfer rates. There is limited research that examines the effect of conventional geometries, such as circular and rectangular tubes by exploring the research gaps in tube shape and spacing on radiator performance. Despite advancements in tube geometries, practical designs like circular and rectangular tubes still need to be explored. This study evaluates the impact of tube shape and spacing on key performance metrics, such as heat transfer rate, effectiveness, and overall heat transfer coefficient. The MATLAB and Simulink simulations model different radiator designs, using the NTU method to validate outlet temperature predictions. This research aims to identify

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optimal designs for improving heat transfer efficiency without increasing radiator size or cooling power consumption. The future scope is to investigate by combining advanced materials with optimized geometries that could benefit from incorporating dynamic engine loads and varying coolant properties for enhanced prediction accuracy.

2. Method

The proposed radiator models have been developed in Onshape and validated through MATLAB simulations under steady-state conditions. MATLAB and Simulink are used to model the heat transfer performance of radiators with varying tube shapes (circular, rectangular) and spacing. The key parameters have been calculated to assess design impacts, including the overall heat transfer coefficient (U), effectiveness (ϵ), and NTU. Assumptions include steady-state conditions and constant specific heat capacity of the thermal liquid (water).

2.1 Physical models

This study models the heat transfer performance of automobile radiators using MATLAB and Simulink. The circular and rectangular tube radiators are presented in Fig. 1 and Fig. 2, respectively. The Onshape software is used to visualize the radiator and create a model with circular and rectangular tubes. Figs.1 and 2 have been drawn by inspiration from the literature. The rectangular tube dimensions have been provided, and the internal cross-sectional area is to be calculated. This internal area is then used to determine an equivalent circular tube configuration, ensuring that both setups (rectangular and circular) maintain the same internal heat transfer area in a tube for consistent comparison within the radiator system.

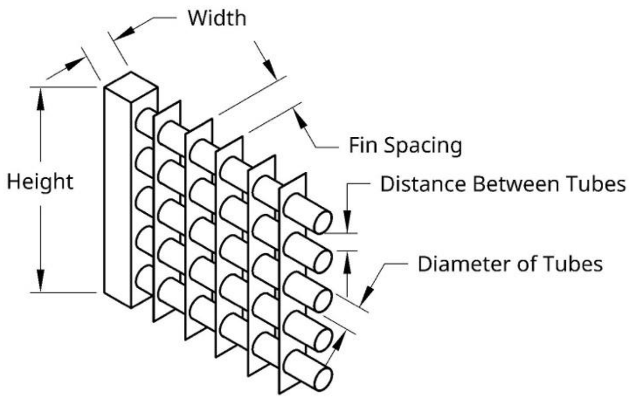

Fig.1 Illustration for radiator with circular tubes.

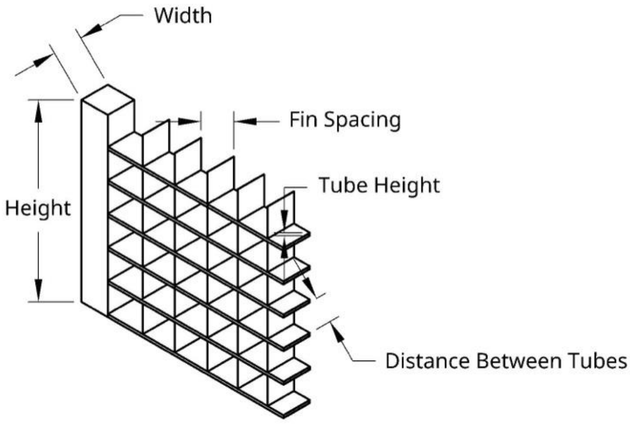

Fig.2 Illustration for radiator with rectangular tubes.

In the case of circular tubes, the maximum number of tubes (for the same internal cross-section area of the rectangular tube):

$$No.of\ Tube_{max} = \frac{Radiator\ height}{External\ dia.of\ pipe} = \frac{0.3}{0.005} = 60$$

Due to the lack of spacing between the pipes, the maximum number of tubes will be 55, and the minimum number will be 2.

Again, in the case of rectangular tubes, the maximum number of tubes:

$$No.of\ Tube_{max} = \frac{Radiator\ height}{External\ height\ of\ pipe} = \frac{0.3}{0.0015} = 200$$

So, the number of rectangular tubes fitted for the same height has increased by almost 3.33 times that of the circular tubes.

2.2 Numerical simulation

Fig. 3 shows the schematic diagram of the simulation setup, highlighting critical components like the fluid flow rate source, heat exchanger block, and temperature sensors at the inlet and outlet. This figure is made by using the MATLAB and Simulink. The setup simulates the thermal liquid (water) flow through a radiator, analyzing the heat transfer to the surrounding air. The model includes a thermal liquid subsystem representing the fluid flow through circular and rectangular tubes and a moist air subsystem simulating airflow across the radiator.

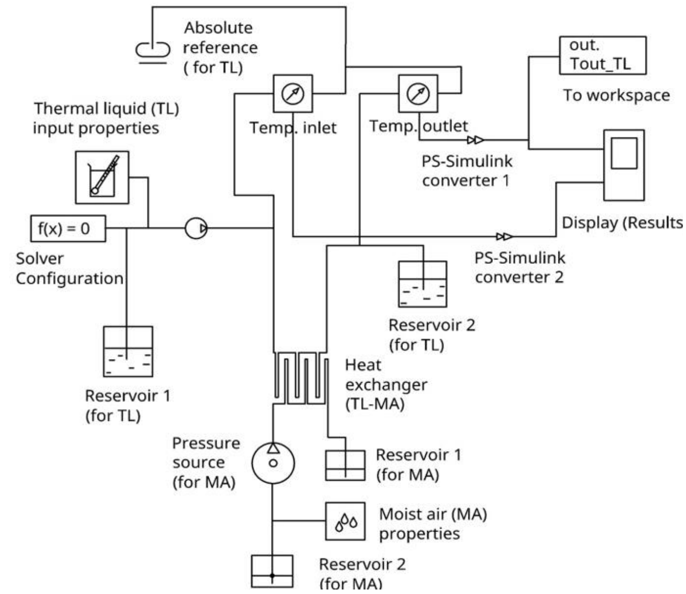

Fig.3 Schematic diagram of the simulation setup for this study.

Thermal liquid (TL) flows from reservoir 1 (TL), passing through a flow rate source and being measured by a temperature sensor, which compares it with the reference in the absolute reference block. The thermal liquid input properties block receives the thermal liquid properties (water) inputs. The thermal liquid flows through circular or rectangular tubes of the radiator and moves to reservoir 2 (TL). The outlet temperature from the radiator is measured with a temperature sensor named temp-outlet. Both inlet and outlet temperatures are converted using a Simulink converter block, displayed in the results block. Outlet temperatures are taken to the workspace to determine the effectiveness, NTU, efficiency, etc. Moist air from reservoir 2 (MA) flows through a pressure source to simulate air pressure and travels through the tube gaps and over the fins to reservoir 1 (MA). By the way, Table 1 shows the parameters considered for the simulation.

Table 1 Simulation setup parameters

Parameter	**Value**
Radiator length (m)	0.5
Radiator width (m)	0.015
Radiator height (m)	0.3
Tube height (m)	0.0015
Fin Spacing (m)	0.002
Wall thickness (m)	0.0001
Wall conductivity, W/(m·K)	240
Specific heat capacity of thermal liquid (water), J/(kg·K)	4181
Convective heat transfer coefficient of fluid, W/(m²·K)	500
Convective heat transfer coefficient of air, W/(m²·K)	50
Fin efficiency	0.7
Mass flow rate of thermal liquid (kg/s)	0.1
Pressure differential for moist air, MPa	0.0005
Reservoir temperature (thermal liquid), K	340
Reservoir temperature (moist air), K	290

2.3 Equations

The following equations provide a theoretical basis for modeling radiator performance, focusing on heat transfer metrics, effectiveness, and NTU for comparative analysis. The heat transfer rate (Q) is calculated based on the fluid's measured inlet and outlet temperatures [15], which is expressed as follows:

$$Q = \dot{m} \times C_p \times (T_{inlet} - T_{outlet}) \quad (1)$$

The overall heat transfer coefficient (U) is a critical factor that quantifies the efficiency of the heat exchanger [17]. It is calculated using empirical data from the simulation by applying the following formula:

$$U = \frac{Q}{A \times \Delta T_{lm}} \quad (2)$$

The number of transfer units (NTU) method is used to predict the outlet temperature of the fluid [18]. The NTU method relates the heat transfer effectiveness (ε) to the capacity rate of the fluids and the overall heat transfer coefficient. The NTU is calculated using the equation [19]:

$$NTU = \frac{UA}{C_{min}} \quad (3)$$

Where, $C_{min} = \dot{m} \times C_p$

The NTU method predicts the outlet temperature for varying tube shapes and gaps, allowing for a thermal performance comparison under different conditions [20].

The effectiveness (ε) of the radiator is a measure of its efficiency as a heat exchanger and is defined as the ratio of the actual heat transfer to the maximum possible heat transfer:

$$\varepsilon = \frac{Q}{Q_{max}} \quad (4)$$

Where, $Q_{max} = T_{rtl} \times T_{rma}$

Also, the effectiveness **(ϵ)** of a heat exchanger can be determined using the effectiveness-NTU method for a cross-flow (single pass-both fluids unmixed) radiator [24, 25].

$$\epsilon = 1 - \exp\left(\frac{exp-(-C_{rel} \times NTU^{.78}) - 1}{C_{rel} \times NTU^{-.22}}\right) \quad (5)$$

Where, $C_{rel} = \frac{C_{min}}{C_{max}}$

2.4 Assumptions

Several assumptions were made to simplify the simulation and ensure computational efficiency. The specific heat capacity of the thermal liquid (water) is 4181 J/kg·K [15]. The convective heat transfer coefficient of the fluid is assumed to be 500 W/m²·K, while that of the air is 50 W/m²·K [16]. The fin efficiency is estimated at 0.7, based on typical values for automotive radiators. The mass flow rate of thermal liquid is set at 0.1 kg/s, and the mass flow rate of moist air is at 0.05 MPa. While these assumptions allowed for an efficient simulation, they may limit the model's ability to fully capture dynamic behavior in real-world applications. For example, assuming constant properties for the thermal liquid may not reflect variations in coolant behavior under extreme temperatures. Future studies using more complex transient simulations should address these limitations.

3. Results and discussion

3.1 Validation and error analysis

Fig. 4 shows the air flow rate cooling capacity as a function of air flow rate by which this work (360 kg/h coolant flow) has been compared with Oliet et al.'s works (500 kg/h coolant flow). The observed results align with Oliet et al. (2007), confirming the impact of optimized geometries on heat transfer. However, deviations in outlet temperatures can be attributed to differences in coolant flow rates and fin arrangements [5]. The discrepancy in mass flow rates between this study and the referenced work by Oliet et al. is attributed to differences in radiator scale and design. This study examines a smaller radiator core with a wider fin spacing of 2 mm, compared to Oliet et al.'s radiator, which features a finer fin pitch of 1.19 mm. The selected flow rate of 360 kg/h aligns with the operational conditions of smaller-scale radiators, ensuring relevance to practical applications. With air flow cooling capacity increases steadily to approximately 5.5 kW at 0.4 kg/s in Oliet et al. where it stabilizes at somewhat less than 0.8 kW with little sensitivity to air flow in this study. It is expected that this difference arises because of the smaller size and poorer thermal performance of this radiator. Furthermore, the higher temperature of the coolant inlet temperature applied by Oliet et al. (95°C, compared to 67°C used here) adds a greater temperature gradient, driving up their cooling performance.

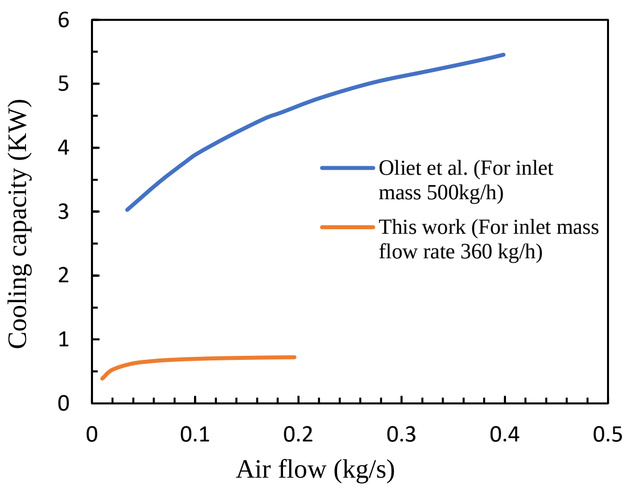

Fig. 4 Air mass flow influence on the thermal and fluid-dynamic performance of the automotive radiator

3.2 Effect of tube shape

Fig. 5 illustrates the impact of tube shape on the outlet fluid temperature for a fixed number of tubes (40). This study evaluates the outlet temperatures of a liquid traversing through a heat exchanger utilizing both circular and rectangular tubes, under varying inlet temperatures ranging from 310 to 360 K. However, the circular tube geometries consistently resulted in higher outlet temperatures compared to rectangular tubes across all inlet temperatures. For an inlet temperature of 360 K, the outlet temperature for circular tubes was 351 K, whereas it was 347 K for rectangular tubes. This difference can be explained by the streamlined flow dynamics in circular tubes, which reduce flow resistance and enhance heat transfer efficiency. Although rectangular tubes provide more surface area for heat exchange, the increased flow resistance caused by sharp edges and a higher surface area-to-volume ratio disrupt the flow, reducing outlet temperature. This observation suggests that rectangular tubes provide enhanced heat transfer efficiency, as indicated by the comparatively lower outlet temperatures in relation to those of circular tubes.

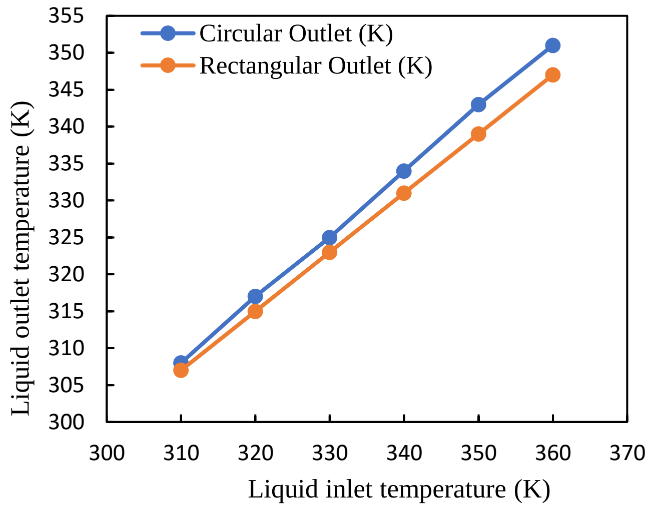

Fig.5 Effect of inlet temperature and tube shape on outlet temperature

3.3 Impact of tube spacing

Figs. 6 and 7 explore the relationship between tube spacing (number of tubes) and heat transfer performance. These figures are separated as the number of tubes fitted to the fixed-height radiator varies. The maximum number of circular tubes is 60, whereas the maximum number of rectangular tubes is 200. For both cases, the liquid inlet temperate has to be considered as 340K for clear understanding. The analysis focused on two key aspects: For the first case of the circular shown in Fig. 6, the tube counts from 2 to 55, and the outlet temperature decreases initially from 337 K (at 2 tubes) to 335 K (at 15 tubes), stabilizing in two stages at 335 K to 334 K as the tube count increases further. This stability suggests that increasing the surface area through more tubes does not significantly enhance heat transfer beyond a certain point, as airflow restrictions limit the cooling effect that causes the sudden drops of temperature from 335 K to 334 K. Again, for the second case of the rectangular tubes shown in Fig. 7, the trend is similar, but rectangular tubes show greater sensitivity to changes in spacing. For fewer tubes (e.g., 40 to 80), the outlet temperature decreases, reaching a minimum at around 140 tubes (323 K), but rising again almost to 340 K at 198 tubes due to flow limitations of the airflow resistance at higher tube counts.

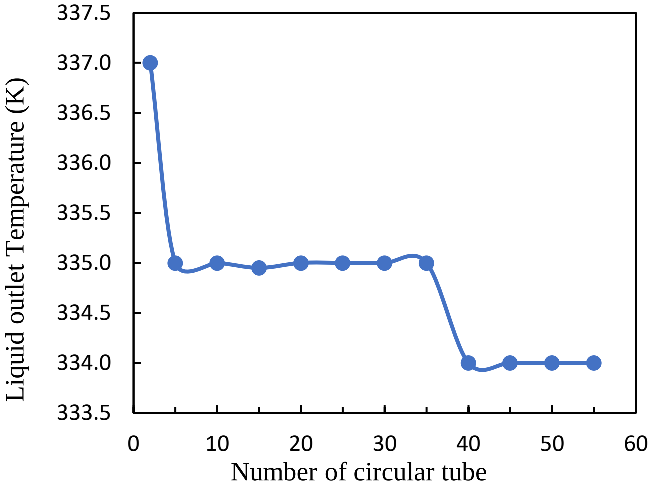

Fig.6 Impact of tube spacing on heat transfer rate for circular tube

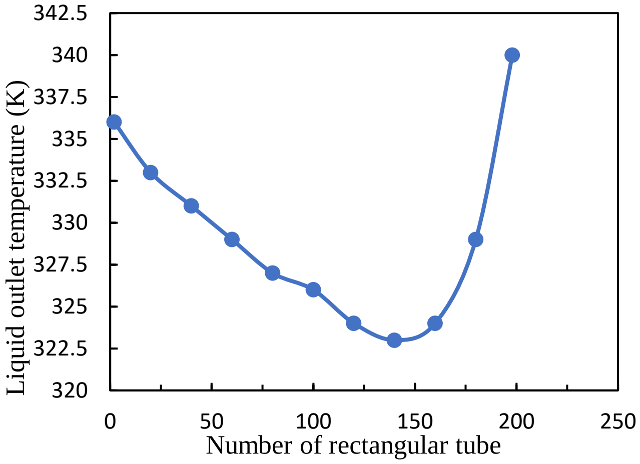

Fig.7 Impact of tube spacing on heat transfer rate for rectangular tube

3.4 Effectiveness (ε) vs. NTU

Fig. 8 shows the relationship between the effectiveness of a heat exchanger and the number of transfer units (NTU) for the rectangular tubes. The effectiveness increases rapidly with increases in the NTU, demonstrating a major improvement in heat transfer capability. This trend is even more visible for low NTU values where even a small increase in NTU makes full use of the effectiveness. At near zero NTU, the effectiveness is approximately zero, indicating no heat transfer. When NTU reaches one, the effectiveness rises sharply to about 0.75. Although the curve becomes flat gradually and asymptotically approaches a maximum value near 1 as NTU increases. As NTU increases further, the effectiveness gradually approaches its maximum value of one, with minimal improvement observed beyond NTU values around five. This trend highlights the diminishing returns in performance with higher NTU values.

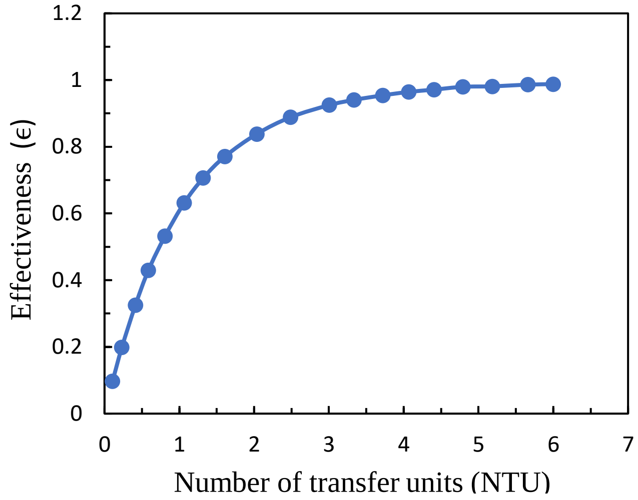

Fig.8 Effectiveness (ε) vs. NTU

3.5 Comparison

Fig. 9 compares simulated outlet temperatures against predictions made using the NTU method. The study examines heat exchanger performance by comparing outlet temperatures for circular and rectangular tubes and theoretical predictions using the NTU method at inlet temperatures from 310 to 360 K. The simulated outlet temperatures for circular tubes range from 308 K to 351 K, while rectangular tubes show slightly lower values, ranging from 307 K to 347 K, indicating improved heat transfer efficiency. The NTU method predicts outlet temperatures between 309 K and 359 K, closely aligning with circular tube results but consistently overestimating compared to rectangular tubes, highlighting the geometric impacts on performance. However, the close agreement between predicted and simulated values supports the accuracy of the chosen assumptions, such as constant fluid properties and steady-state conditions. The effectiveness increases with higher NTU values but reaches a plateau, indicating diminishing returns in heat transfer gains beyond certain radiator sizes. The analysis supports using optimized tube shapes and spacing configurations to enhance heat transfer performance, contributing to better thermal management in automotive cooling systems.

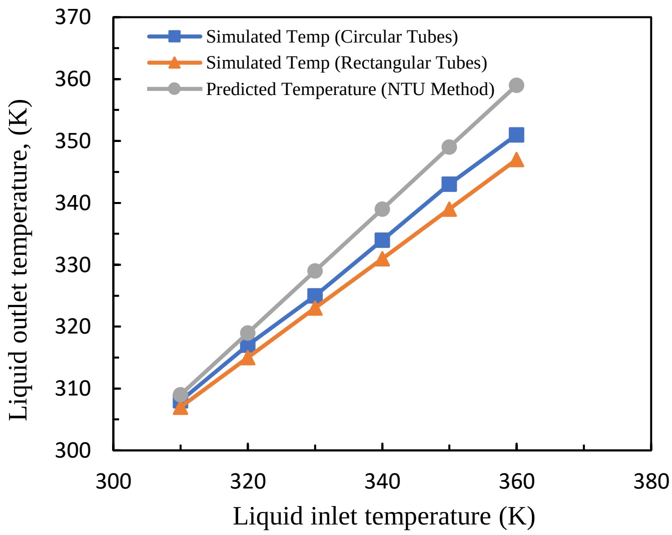

Fig.9 Predicted vs simulated temperature

4. Conclusion

This study evaluated the effects of tube geometry and spacing on the heat transfer performance of automobile radiators using MATLAB and Simulink simulations. The study underscores the significance of optimizing tube configurations in automotive radiator design, paving the way for more effective and energy-efficient thermal management systems. The specific results are as follows:

- For tube shaping, the rectangular tubes achieve outlet temperatures ranging from 307 to 347K, compared to circular tubes from 308 to 351K.
- For tube spacing, circular tubes reduce outlet temperatures from 337 to 334K (2 to 15 tubes) before stabilizing. While rectangular tubes decrease from 336 to 323K (up to 140 tubes) but rise to 340K at 198 tubes due to flow limitations.
- The effectiveness of rectangular tubes rises sharply to 0.75 at NTU of 1 and approaches a maximum of 1, with minimal gains beyond NTU of 5.
- The NTU method predicts outlet temperatures between 309 to 359K, closely aligning with circular tube results but consistently overestimating rectangular tube performance.

Furthermore, the NTU-effectiveness method is closely aligned with the simulated data, validating the model's reliability for steady-state analysis. Future research should focus on transient simulations, comparing radiator weights between circular and rectangular tubes, and experimental validation under varying engine loads to better capture the dynamic behavior of real-world cooling systems.

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NOMENCLATURE

ṁ	:	Mass flow rate of the coolant, kg/s
C_p	:	Specific heat capacity of the fluid, J/kg·K
T_{inlet}	:	Temperature at the inlet, K
T_{outlet}	:	Temperature at the outlet, K
Q	:	Heat transfer rate, W
A	:	Total surface area of the heat exchanger tubes, m^3
ΔT_{lm}	:	Logarithmic mean temperature difference between the coolant and air, K
T_{rtl}	:	The reservoir temperature for the thermal liquid
T_{rma}	:	The reservoir temperature for the moist air
C_{max}	:	Max (Thermal liquid heat capacity rate * Air heat capacity rate)
C_{min}	:	Min (Thermal liquid heat capacity rate * Air heat capacity rate)
Q_{max}	:	Maximum possible heat transfer, W