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The Effect of Different Types of Air-Cooled Heat Exchangers on Cooling Performance in Vehicles

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Özet

Bu proje, motorlu taşıtlarda kullanılan radyatörlerin soğutma performansı üzerindeki etkilerini kapsamlı bir şekilde incelemektedir. Araştırmanın temel amacı, radyatör tasarımında kullanılan boru sayısı ve kanatçık bulunması gibi parametrelerin, ısı transferi ve basınç kayıplarına olan etkilerini değerlendirmek ve bu parametrelerin sistem performansı üzerindeki rolünü anlamaktır. Çalışmada farklı tasarım seçenekleri modelleme ve teorik hesaplama yöntemleriyle analiz edilmiştir. Ayrıca bu analizler, termal performansı ve enerji verimliliğini artırmayı hedefleyen tasarım yaklaşımlarına katkı sağlamayı amaçlamaktadır.

Elde edilen sonuçlar, boru sayısının artırılmasının toplam ısı transfer yüzeyini genişlettiğini ve böylelikle termal performansı olumlu yönde etkilediğini göstermiştir. Bununla birlikte, boru sayısındaki artışın sıvı akış hızını düşürdüğü ve sistemdeki basınç kayıplarını artırdığı gözlemlenmiştir. Kanatçıklı radyatör tasarımları, yüzey alanını daha da genişleterek ısı transferini önemli ölçüde artırmıştır. Bu tasarımların seçimi, sistem gereksinimlerine ve enerji verimliliği hedeflerine göre optimize edilmelidir.

Bu kapsamlı araştırma, radyatör tasarımında termal performans ve basınç kaybı arasındaki dengeyi optimize etmenin önemini vurgulamaktadır. Çalışma, enerji verimliliği yüksek, radyatör tasarımlarına zemin hazırlamayı amaçlamakta ve otomotiv sektöründe verimli uygulamalara katkıda bulunmayı hedeflemektedir.

Abstract

This project comprehensively examines the effects of radiators used in motor vehicles on cooling performance. The primary objective of the research is to evaluate the impact of design parameters, such as the number of tubes and the presence of fins, on heat transfer and pressure losses, as well as to understand the role of these parameters on system performance. Different design options were analyzed using modeling and theoretical calculation methods. Additionally, these analyses aim to contribute to design approaches that enhance thermal performance and energy efficiency.

The results indicate that increasing the number of tubes expands the total heat transfer surface area, thereby positively affecting thermal performance. However, it was observed that an increase in the number of tubes reduces the fluid flow velocity and increases pressure losses within the system. Finned radiator designs further enhance heat transfer by increasing the surface area. The selection of these designs should be optimized based on system requirements and energy efficiency goals.

This comprehensive research highlights the importance of optimizing the balance between thermal performance and pressure losses in radiator design. The study aims to provide a foundation for developing energy-efficient radiator designs and contribute to effective applications in the automotive sector.

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ŞEKİLLER DİZİNİ

1. Introduction

Radiators are heat exchangers that facilitate energy transfer between fluids of different temperatures and serve as a fundamental component of the thermal management system in motor vehicles. Their primary function is to dissipate the excess heat generated by the engine to the environment, thereby preventing engine overheating. Additionally, by remaining inactive during low temperatures, they allow the engine to reach its optimal operating temperature quickly, positively influencing engine efficiency.

The effective design of radiators has a positive impact on engine performance and efficiency. Consequently, the design, production, and optimization of radiators hold significant importance in automotive engineering.

In this study, the effects of different design parameters, including the number of tubes and fin types, on the thermal performance and pressure losses of vehicle radiators are examined. The primary aim of the study is to evaluate various designs in terms of thermal efficiency and hydraulic losses and to highlight the impact of these parameters on the system.

1.1. Heat Exchangers and General Definition

Heat exchangers are devices that facilitate energy transfer between fluids of different temperatures. These devices are used across a wide range of applications, from industrial processes to automotive systems, to ensure energy management, efficiency, and thermal balance. The operating principle of heat exchangers is to maximize energy transfer. In this process, the primary goals of design are to minimize energy losses and enhance thermal efficiency.

Radiators used in motor vehicles hold a special place among heat exchangers. They play a critical role in ensuring that vehicle engines operate at optimal temperatures, reducing fuel consumption, and minimizing exhaust emissions.

Figure 1.1. Automobile Radiator

1.2. Classification of Heat Exchangers

Heat exchangers are categorized based on their structures, flow arrangements, and transfer mechanisms.

- **Tubular Heat Exchangers:** Systems where fluids are transported through tubes. These designs are widely used in power plants and the petrochemical industry due to their high pressure resistance.
- **Plate Heat Exchangers:** Compact structures that provide high efficiency under low-temperature differentials. They are commonly preferred in the food processing and pharmaceutical industries.
- **Finned Surface Heat Exchangers:** Designs equipped with additional fins to increase surface area. Vehicle radiators fall into this category, providing high performance in limited spaces.
- **Regenerative Heat Exchangers:** Systems that store energy between hot and cold fluids for reuse. These are particularly favored in energy recovery systems.

Radiators belong to the category of finned surface heat exchangers and are critical components for the automotive industry.

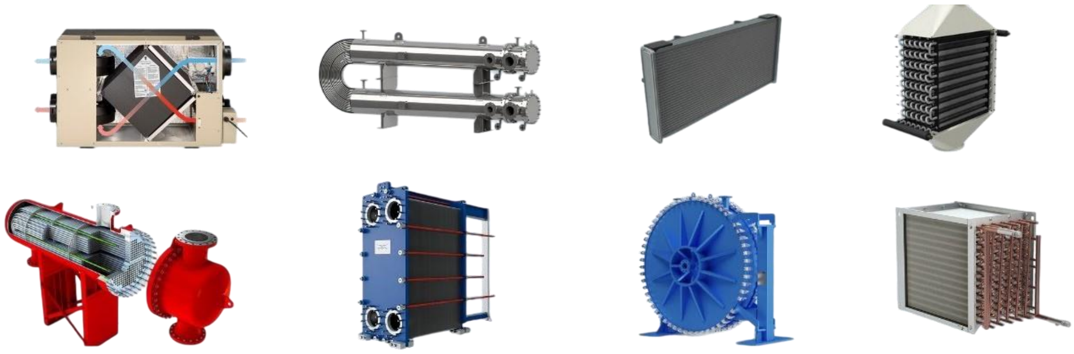


Figure 1.2. Types of Heat Exchangers

1.3. Definition and Working Principle of Radiators

Radiators are heat exchangers used in motor vehicles to prevent engine overheating and maintain temperature balance. The excess heat generated during engine operation is absorbed by the coolant and transported to the radiator. Within the radiator, the coolant's heat is transferred to the incoming airflow through its tubes. This process ensures that the engine operates at an optimal temperature level, enhancing efficiency. Radiators are typically made of lightweight materials with high thermal conductivity, such as aluminum, though copper is also used occasionally due to its superior thermal conductivity.

The efficient operation of radiators is significantly influenced by the number of tubes and the structure of the fins. Tubes can be designed with microchannel structures to provide more surface area, which enhances heat transfer while allowing for a reduction in size. Fins, on the other hand, direct the airflow and help dissipate heat to the surroundings. Modern radiators feature optimized designs that minimize pressure losses and improve energy efficiency. Balancing these design parameters carefully is essential for ensuring the efficient operation of the engine and prolonging the system's lifespan.

1.4. Aim of the Thesis

The primary objective of this study is to thoroughly investigate the effects of different tube counts and fin types used in vehicle radiators on thermal performance and pressure losses. In this context, the impact of various design parameters on the heat transfer efficiency of radiators will be evaluated, and the relationship between these parameters and system pressure losses will be analyzed.

During the research process, various radiator designs will be modeled virtually using Catia software, and theoretical calculations will be performed based on these models. These calculations will provide a better understanding of the effects of tube count and fin geometries on cooling capacity and hydraulic losses.

This study aims to expand the existing knowledge in the literature and establish a significant foundation for the development of more efficient and optimized radiator designs, particularly for the automotive sector. As a result, it seeks to enable the creation of new approaches for designing radiators that consume less energy, are more compact, and are environmentally friendly.

1.5. Materials Used in Radiators

The materials used in radiators are carefully selected considering factors such as heat transfer capacity, durability, corrosion resistance, and cost. Each material used in the radiator directly affects the system's performance and lifespan. Today, the most commonly used materials are aluminum, copper-brass alloys, and composite materials.

Aluminum Materials:

Aluminum is the most widely used material in modern radiators due to its lightweight, high corrosion resistance, and economic advantages. It naturally forms an oxide layer, making it resistant to corrosion. Its low density helps reduce the overall weight of the vehicle, thereby improving fuel efficiency. Although its thermal conductivity is slightly lower than that of copper, this drawback can be mitigated through designs such as microchannel tubes and thin fin arrangements. Aluminum also offers economic benefits due to its low-cost production methods and ease of processing. These characteristics make aluminum an ideal material for the automotive industry. [Nurettin Uzun, 1999]

Figure 1.3. Aluminum and Copper Vehicle Radiators

Copper-Brass Materials:

Copper offers high thermal conductivity, optimizing heat transfer in radiators. Its high-temperature resistance and excellent heat conductivity make it a preferred choice for industrial applications and systems requiring high performance. However, copper's weight and cost are higher compared to aluminum, limiting its use in the automotive sector. Another advantage of copper-brass alloys is their excellent solderability, which simplifies repair and assembly processes. Despite these benefits, cost considerations have made aluminum the more widespread option in the industry.

Composite Materials:

Composite materials combine lightweight and durability, making them an attractive choice for specialized applications, such as in electric vehicles. While their thermal conductivity is lower than that of metallic materials, they offer significant advantages in mechanical strength and low weight. Composite materials are particularly suitable for radiators used in harsh conditions due to their high durability and low maintenance requirements. They are often preferred in modern automotive technologies, especially for eco-friendly and energy-efficient designs.

In conclusion, the choice of material for radiators should be based on the intended application and design requirements. While aluminum stands out for its lightweight and cost-effectiveness, copper-brass alloys and composite materials provide distinct advantages for specific applications.

1.6. The Impact of Design Parameters on Performance

The design parameters used in radiators are critical factors that directly influence heat transfer efficiency and pressure losses within the system. Optimizing these parameters not only enhances the thermal performance of the radiator but also improves the overall efficiency and reliability of the system.

1.6.1. Number and Diameter of Tubes

The number and diameter of tubes are critical design parameters that determine the heat transfer surface area of the radiator. Increasing the number of tubes provides a larger surface area, enhancing heat transfer. However, this can also lead to higher pressure losses in the system. As the tube diameter increases, the flow velocity of the fluid decreases, reducing pressure losses but potentially limiting thermal efficiency.

Thinner designs, such as microchannel tubes, offer increased surface area, which enhances heat transfer, while smaller diameters tend to minimize pressure losses. Therefore, balancing the number and diameter of tubes is essential for achieving a high-performance radiator design.

[Ahmet Serhan CANBOLAT, Burak TÜRKAN 2016]

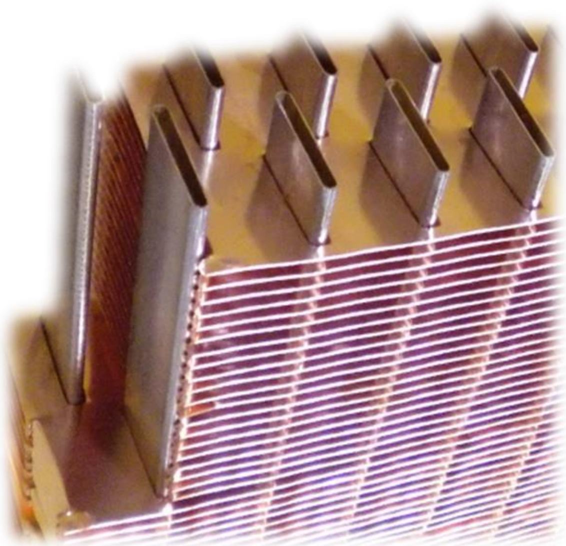


Figure 1.4. Radiator Fins and Tubes

1.6.2. Fin Types

Fins act as thin metal plates that increase the heat transfer surface area of radiators. Different types of fins balance thermal performance and pressure loss. The main types of fins are:

- **Flat Fins:** Simple and cost-effective designs, though their thermal performance is limited.
- **Wavy Fins:** Improve heat transfer by increasing fluid turbulence. These fins cause moderate pressure loss.
- **Louvered Fins:** Direct airflow to renew boundary layers and achieve higher thermal efficiency. These fins are ideal for high-performance applications.
- **Offset Fins:** Continuously generate turbulence for maximum heat transfer but may lead to significant pressure losses. This design is preferred in situations requiring intense cooling.

The selection of fin types should be based on cooling requirements and the system's energy efficiency goals.

1.6.3. Airflow

Optimizing airflow has a significant impact on the heat transfer efficiency of radiators. Efficiently directed airflow, particularly through forced airflow (using fans), is an effective method to enhance heat transfer. Fans direct the airflow onto the radiator surface, facilitating the rapid and efficient transfer of heat to the environment.

However, excessively increasing the airflow speed can also lead to higher pressure losses. Therefore, achieving a balance between airflow speed and direction is critical for maximizing radiator efficiency. [Hasan ACÜL, Fırat BOLAZAR 2009]

1.7. Coolants and Their Effects on Performance

Coolants used in radiators play a critical role in ensuring effective heat transfer. The selection of coolant directly impacts the system's thermal efficiency, durability, and overall performance. Different coolants can enhance heat transfer capacity, improve viscosity, optimize freezing and boiling points, and prevent corrosion. Below is an explanation of the main types of coolants commonly used in radiators and their characteristics:

1.7.1. Water and Ethylene Glycol Mixtures

Water, with its excellent thermal conductivity, is widely used as a coolant. However, the freezing point of pure water is unsuitable for engine cooling systems. To address this, ethylene glycol is added to water, lowering the freezing point and raising the boiling point of the mixture. Ethylene glycol also offers corrosion-inhibiting properties, protecting the metal surfaces of the engine. The ratio of water to ethylene glycol can be adjusted based on operating conditions; for example, a higher proportion of ethylene glycol is used in colder climates.

1.7.2. Nanofluids

Nanofluids are created by adding nanoscale metal oxide particles to water or glycol-based mixtures. These particles enhance the thermal conductivity of the fluid, thereby improving heat transfer. Compared to traditional coolants, nanofluids provide a higher heat transfer coefficient, increasing radiator efficiency. Additionally, they offer benefits such as lower energy consumption, compact designs, and reduced pressure losses.

1.7.3. Additive Fluids

Additive fluids are produced by incorporating chemical additives into base coolants. These additives enhance the fluid's corrosion resistance, prevent foaming, and inhibit sediment accumulation. Corrosion inhibitors play a crucial role in the long-term protection of metal surfaces, reducing maintenance costs. Additive fluids also optimize freezing and boiling points, ensuring effective cooling even at low temperatures. These fluids are commonly used in heavy-duty engines and industrial machinery.

1.8. Components of Radiators and Their Functions

Radiators are devices composed of multiple components that perform critical functions in the cooling systems of motor vehicles. Each part complements the others to ensure the efficient operation of the radiator. The design, material, and arrangement of these components directly influence the radiator's overall efficiency and performance.

1.8.1. Tubes

Tubes are one of the fundamental components of radiators. As the coolant flows through the tubes, the excess heat generated by the engine is absorbed and transferred to the surroundings. The surface area of the tubes has a direct impact on heat transfer efficiency. Increasing the number of tubes expands the surface area, thereby enhancing thermal performance. However, a higher tube count can also result in increased pressure losses.

Thinner designs, such as microchannel tubes, provide greater surface area for more efficient heat transfer, although they may contribute to higher pressure losses. The design of the tubes also regulates the fluid flow, enabling uniform heat transfer. Tubes are typically made from materials with high thermal conductivity, which ensures the effective operation of the radiator.

[Bahadır Gemicioğlu, Tolga Demircan 2020]

1.8.2. Fins

Fins form the most crucial heat transfer surfaces of radiators. These thin metal plates, placed on the tubes, increase the surface area and transfer heat to the surroundings. The design of fins has a significant impact on system efficiency. For instance, wavy fins enhance heat transfer by increasing fluid turbulence, but this also leads to higher pressure losses. Offset fins provide maximum heat transfer, though at the cost of increased pressure loss.

The selection of fin materials is critical to improving thermal conductivity and ensuring corrosion resistance. Additionally, the geometry and arrangement of fins optimize airflow, thereby enhancing cooling capacity.

[Bahadır Gemicioğlu, Tolga Demircan 2020]

1.8.3. Manifolds

Manifolds are vital components that regulate the entry and exit of coolant in the radiator. By ensuring the even distribution of coolant, they enable more effective heat dissipation. The design of manifolds optimizes fluid flow and enhances the heat transfer efficiency of the radiator. Manifolds are typically made from materials resistant to high temperatures, ensuring the uniform distribution of coolant throughout the system.

1.8.4. Cooling Fans

Fans are essential components that support heat transfer in radiators. They are used to provide forced airflow, typically accelerating airflow over the radiator surface. This increases cooling performance and allows the coolant to be cooled more efficiently. The speed and placement of the fan must be carefully designed to optimize cooling efficiency. Electric fans are particularly effective at providing cooling even at low vehicle speeds, though they may consume more energy at high speeds.

1.8.5. Thermostat

The thermostat regulates the temperature levels of the coolant in the radiator system, ensuring the engine operates within its optimal temperature range. When the coolant temperature reaches a specific level, the thermostat activates to control the flow of the fluid into the radiator. This mechanism prevents the engine from overheating and enhances engine efficiency. The proper functioning of the thermostat is crucial for the effective operation of the system.

2. Literature Review

2.1. Purpose of the Literature Review

The primary purpose of the literature review is to compile and analyze existing studies that examine the effects of radiator design parameters (such as the number of tubes, fin types, and cooling fluids) on pressure loss and thermal performance. In this context, the focus will be on research regarding the design criteria and thermal performance optimization of radiators used in the automotive sector, while evaluating gaps and conflicting findings in the literature.

2.2. Examination of Radiator Design and Parameters

In radiator design, it is well known that the number of tubes, their diameter, the structure of fins, and the cooling fluids used directly affect both the thermal performance and hydraulic efficiency of the system. Studies have shown that these parameters are interrelated, and each modification contributes to the overall system performance in different ways. Increasing the number of tubes enhances heat transfer by expanding the surface area, but it may also increase pressure loss. Fin types influence thermal performance by regulating airflow; it has been reported that the use of wavy and microchannel fins provides significant improvements in heat transfer.

2.3. The Impact of Cooling Fluids on Performance

Cooling fluids play a critical role in the efficient operation of radiators. While traditional water and ethylene glycol mixtures are commonly used, next-generation cooling fluids such as nanofluids have the potential to enhance thermal conductivity. It has been noted that fluids containing nanoparticles deliver high performance even at lower temperatures. These fluids not only optimize pressure loss but also contribute to energy efficiency.

2.4. Modern Design Approaches

Traditional radiator designs are increasingly being replaced by more compact and efficient models. Microchannel radiators offer higher heat transfer capacity in confined spaces while aiming to minimize pressure loss. The use of lightweight materials with high thermal conductivity, such as aluminum, not only reduces production costs but also contributes to environmental sustainability.

2.5. Gaps in the Literature and Future Research Directions

It has been observed that studies focusing on tube and fin optimization in radiator design are limited. In particular, more data is needed on the long-term effects of various cooling fluids and the practical performance of nanofluids. Additionally, detailed analyses of the thermal performance and corrosion resistance of different material types could help address existing knowledge gaps in this field.

2.6. Conclusion

Studies in the literature emphasize the importance of optimizing the balance between thermal performance and pressure loss in radiator design. These studies have served as a guide, particularly for energy efficiency and environmentally friendly designs in the automotive industry. However, advancing research in this field with a broader scope will contribute to both theoretical knowledge and practical applications

3. Heat Transfer Calculations

3.1. Fundamental Principles of Heat Transfer

Heat transfer is the energy transfer from one medium to another due to a temperature difference. This energy transfer occurs through three main mechanisms:

1. Conduction
2. Convection
3. Radiation

Since conduction and convection mechanisms are predominant in automobile radiators, these aspects will be examined in detail.

3.1.1. Conduction

Conduction is the transfer of heat through a solid material due to temperature differences, occurring via molecular vibrations and the movement of free electrons. Conduction is defined by Fourier's Law of Heat Conduction:

$$q_x = -k\frac{dT}{dx} \tag{3.1}$$

Here:

- q_x: Heat flux by conduction per unit area (W/m²)
- k: Thermal conductivity of the material (W/m·K)
- dT/dx: Temperature gradient (K/m)

The total heat transferred for heat transfer through a flat wall is calculated by integrating Fourier's law as follows:

$$Q = \frac{k.A.(T_1 - T_2)}{L} \tag{3.2}$$

Here:

- Q: Total heat transferred (W)
- A: Heat conduction surface area (m²)
- $T_1 - T_2$: Temperatures on the two surfaces of the wall (K veya °C)
- L: Thickness of the wall (m)

3.1.2. Convection

Convection is the heat transfer that occurs due to temperature differences during the movement of a fluid. Convection is expressed by Newton's Law of Cooling:

$$q = h.A.\left(T_{surface} - T_{fluid}\right) \tag{3.3}$$

Burada:

- q: Heat flux by convection per unit area (W/m²)
- h: nvective heat transfer coefficient (W/m²·K)
- A: Convection surface area (m²)
- $T_{surface}$: Surface temperature (K or °C)
- T_{fluid}: Fluid temperature (K or °C)

Convection is divided into two main categories

1. **Forced Convection:** The fluid is moved by an external force, such as a fan or a pump. For example, in a car radiator, air flow is provided with the help of a fan.
2. **Free/Natural Convection:** Fluid motion is caused by density differences

3.1.2.1 Nusselt Number (Nu) for Forced Convection

In forced convection, the dimensionless Nusselt number is used to calculate the convection coefficient. This number represents the ratio of heat transfer by convection to heat transfer by conduction:

$$Nu = \frac{h.D}{k_{fluid}} \tag{3.4}$$

Here:

- h: Convection heat transfer coefficient (W/m²·K)
- D: Hydraulic diameter (m)
- k: Thermal conductivity of the fluid (W/m·K)

In the case of turbulent flow, the Nusselt number is calculated using experimental correlations:

$$Nu = 0{,}023\ .\ Re^{0{,}8}\ .\ Pr^{0{,}3} \tag{3.5}$$

In laminar flow (for a straight pipe):

$$Nu=366 \tag{3.6}$$

it is calculated

3.1.2.2. Reynolds Number for Forced Convection (Re)

The Reynolds number is used to determine whether the flow is turbulent or laminar. It is the ratio of inertial forces to viscous forces of the fluid:

$$Re = \frac{\rho v D}{\mu} \tag{3.7}$$

Here:

- ρ: Density of the fluid (kg/m³)
- v: Average flow velocity (m/s)
- *D:* Hydraulic diameter (m)
- μ: Dynamic viscosity of the fluid (Pa·s veya N·s/m²)

Hydraulic diameter

- For a circular pipe: D=D_d
- In a rectangular cross-section channel:

$$D = \frac{4A_{section}}{P_{perimeter}} \tag{3.8}$$

Laminar and Turbulent Flow:

- *Re*<2300: Laminar flow
- *Re*>4000: Turbulent flow
- 2300 < *Re* <4000: Transitional region

  Note: Since the flow in car radiators is typically turbulent, Re > 4000 is assumed.

3.1.2.3. Prandtl Number (Pr)

The Prandtl number gives the ratio between the momentum diffusion (viscosity) and heat diffusion (thermal conductivity) of the fluid:

$$Pr = \frac{c_\rho . \mu}{k} \tag{3.9}$$

Here:

- c_ρ: Specific heat capacity of the fluid (J/kg·K)
- μ: Dynamic viscosity (Pa·s or N·s/m²)
- k: Thermal conductivity of the fluid (W/m·K)

Prandtl Interpretation of the number:

Small Pr (Pr < 1): Heat diffusion is fast (e.g., gases).
Large Pr (Pr > 1): Momentum diffusion dominates (e.g., liquids).

Typical Values:

● Water (25°C): Pr ≈ 7

● Air (25°C): Pr ≈ 0.7

3.1.3. Combined Evaluation of Convection and Conduction

We mentioned that heat transfer in a radiator occurs in three basic stages. These stages are evaluated along with the total thermal resistance approach. To calculate the total heat transfer coefficient, the resistance of each mechanism is added in series.

3.1.3.1. Total Thermal Resistance Model

Total heat transfer is expressed by the following equation:

$$Q = \frac{\Delta T_{total}}{R_{total}} \tag{3.10}$$

Here:

- Q: Total heat transferred (W)
- ΔT_{total} : Temperature difference (K)
- R_{total} : Total thermal resistance (K/W)

Total thermal resistance is the sum of the convective and conductive resistances:

$$R_{total} = R_{liquid} + R_{conduction} + R_{air} \tag{3.11}$$

3.1.3.2. Definition of Each Resistance

1. Fluid-side convective resistance (R_{liquid})

   Fluid-side convective resistance is defined using Newton's Law of Cooling:

$$R_{R_{liquid}} = \frac{1}{h_{liquid} \cdot A_{inside}} \tag{3.12}$$

Here:

- h_{liquid}: Fluid-side convective heat transfer coefficient (W/m²·K)
- A_{inside}: Inner surface area of thetube m²)

Convection coefficient (h_{liquid}):

In forced convection, the fluid-side convection coefficient h_{liquid}, is calculated by relating it to the Nusselt number:

$$h_{liquid} = \frac{Nu \;.\; k_{liquid}}{D_{inside}} \tag{3.13}$$

2. **Conduction Resistance ($R_{conduction}$)**
   Conduction through the pipe material is defined by Fourier's Law. For a circular pipe, the conduction resistance is calculated as follows:

$$R_{conduction} = \frac{ln(\frac{D_{outside}}{D_{inside}})}{2\pi k_{material} L} \tag{3.14}$$

Here:

- $D_{dış}$: Outer diameter of the pipe (m)
- $D_{iç}$: Inner diameter of the pipe (m)
- $k_{malzeme}$: Thermal conductivity coefficient of the pipe material (W/m·K)
- L: Length of the pipe (m)

3. **Air-side convective resistance (R_{air})**
   is defined as the convective resistance from the outer surface of the pipe to the air as follows:

$$R_{air} = \frac{1}{h_{air} \, . \, A_{outside}} \tag{3.15}$$

Here:

- h_{hava}: Air-side convective heat transfer coefficient (W/m²·K)
- $A_{dış}$: Outer surface area of the pipe (m²)

Convection coefficient(h_{air}):
The air-side convection coefficient is calculated from experimental values or using the Nusselt number:

$$h_{air} = \frac{Nu \, . \, k_{air}}{D_{outside}} \tag{3.16}$$

Result: Combination of Heat Transfer Mechanisms

Total heat transfer in a radiator is expressed by the following equation:

$$Q = \frac{\Delta T_{total}}{R_{total}} \tag{3.17}$$

With this equation, the mechanisms of convection from the fluid to the pipe, conduction through the material, and convection to the air can be calculated in a single model.

3.2. Heat Transfer Models in Radiators

Car radiators function as cross-flow compact heat exchangers that facilitate energy transfer from the fluid to the air. Heat transfer occurs through the combined action of convection and conduction mechanisms in the radiator. The heat transfer models in the radiator are analyzed using the total heat transfer coefficient (U) approach and consist of the following stages:

3.2.1. Total Heat Transfer Coefficient (U) Approach

Total heat transfer in a radiator relies on the combined effects of convection and conduction mechanisms. The total heat transfer coefficient (U) is derived from the thermal resistances on the fluid, material, and air sides:

$$\frac{1}{U} = \frac{1}{h_{liquid}} + \frac{t}{k} + \frac{1}{h_{air}} \tag{3.18}$$

Here:

h_{fluid}: Convective heat transfer coefficient of the coolant on the inner surface of the pipe (W/m²·K)

t: Thickness of the pipe wall (m)

k: Thermal conductivity coefficient of the pipe material (W/m·K)

h_{hava}: Convective heat transfer coefficient of the air on the outer surface of the pipe (W/m²·K)

These coefficients are determined through experimental or empirical correlations depending on the radiator design. The fluid and air convection coefficients depend on the physical properties of the fluid and the flow conditions (Reynolds and Nusselt numbers).

3.2.2. Calculation of Heat Transfer Surface Area

The total heat transfer performance of the radiator is directly related to the size of the surface area. Pipes and fins constitute the total heat transfer surface:

1. **Pipe Surface Area (A_{tube}):**
   Heat transfer by convection along the outer surface of the pipes:

$$A_{tube} = N_{tube}.2.(w+h).L \tag{3.19}$$

Here:

$N_{tüp}$: Number of tube

w: Width of the yube (m)

h: Height of the tube (m)

L: Length of thetube (m)

2. **Fin Surface AreaAlanı (A_{fin}):**
   Fins improve heat transfer by increasing the radiator's surface area:

$$A_{fin} = n_{fin}\ .\ l_{fin}\ .\ b_{fin} \tag{3.20}$$

Here:

- n_{fin}: Number of fins
- l_{fin}: Length of the fin (m)
- b_{fin}: Width of the fin (m)

Total Surface Area (A):

$$A_{total} = A_{tube} + A_{fin} \tag{3.21}$$

3.2.3. Logarithmic Mean Temperature Difference (LMTD) Model

In radiators, the temperature difference between the fluid and air is the driving force for energy transfer. In a crossflow radiator, the temperature difference exhibits a logarithmic variation based on the inlet and outlet temperatures:

$$\Delta T_{log} = \frac{(T_{fluid\ in} - T_{air\ in}) - (T_{fluid\ out} - T_{air\ out})}{ln(\frac{T_{fluid\ in} - T_{air\ in}}{T_{fluid\ out} - T_{air\ out}}} \tag{3.22}$$

Burada:

- $T_{fluid,in}$: Inlet temperature of the fluid (°C)
- $T_{fluid,out}$: Outlet temperature of the fluid (°C)
- $T_{air,in}$: Inlet temperature of the air (°C)
- $T_{air,out}$: Outlet temperature of the air (°C)

3.2.4. Gnielinski Correlation

The Gnielinski correlation is a formula used to calculate the convection heat transfer coefficient more accurately under turbulent flow conditions. Compared to the Dittus-Boelter correlation, it has a broader range of applications and incorporates the friction factor. The equation is expressed as follows:

$$Nu = \frac{(f/8).(Re - 1000).Pr}{1 + 12{,}7.(f/8)^{0{,}5}.(Pr^{0{,}667} - 1)} \tag{3.23}$$

Here:

- Nu: Nusselt number
- f: Friction factor
- Re: Reynolds number
- Pr: Prandtl number

Friction Factor (f):
For turbulent flow, it is calculated using the following formula:

$$f = 0{,}079.(Re)^{-0{,}25} \tag{3.24}$$

3.2.5. NTU-ε Method

The NTU-ε method is used to analyze the performance of crossflow heat exchangers. This method directly calculates the total heat transfer (Q) by utilizing the heat transfer effectiveness (ϵ) and NTU values. The equations are expressed as follows:

$$\epsilon = \frac{Q_{real}}{Q_{max}} \tag{3.25}$$

$$Q_{max} = C_{min}.(T_{intake\ liquid} - T_{intake\ air}) \tag{3.26}$$

$$NTU = \frac{U.A}{C_{min}} \tag{3.27}$$

In Counterflow Configuration, Effectiveness is Expressed by the Following Equation:

$$\epsilon = \frac{1 - e^{-NTU.(1-Cr)}}{1 - Cr.e^{-NTU.(1-Cr)}} \tag{3.28}$$

$$Cr = \frac{C_{min}}{C_{max}} \tag{3.29}$$

3.2.6. Heat Transfer Equation

The total heat transfer of a radiator is calculated by combining all these parameters as follows:

$$Q = U.A.\ \Delta T_{log} \tag{3.30}$$

Burada:

- Q: Total heat transferred (W)
- U: Overall heat transfer coefficient (W/m²·K)
- A: Total heat transfer surface area (m²)
- ΔT_{log}: Logarithmic temperature difference ((K)

3.2.7 Calculation of Fin Efficiency (η_k)

Fin Efficiency is calculated to evaluate the thermal performance of the fins using the following formula:

$$\eta_k = \frac{tanh(m.h_k)}{m.h_{k)}} \tag{3.31}$$

And:

$$m = \left(\frac{2.h_{air}}{k_k.t_k}\right)^{0,5} \tag{3.32}$$

- h_k: *Height of the fin*
- h_{air}: *Convection coefficient of air*
- k_k: *Thermal conductivity of the fin material*
- t_k: *Thickness of the fin*

3.2.8. Behavior of Crossflow Heat Exchangers

Radiators typically operate as crossflow heat exchangers. This design facilitates a system where the fluid and air flows intersect, enabling maximum energy transfer.

- **Flow Directions:**
    - **Crossflow:** Air and fluid flows move at right angles to each other.
    - Crossflow offers a compact design with high heat transfer performance.
- **Effective Surface Area and Fin Geometry:**
    - Fin geometry enhances turbulence, increasing the air-side convection coefficient (h_{air}).
    - The spacing and shape of the fins affect pressure loss.

Crossflow designs effectively balance compactness and performance, making them suitable for high-efficiency radiator systems.

3.3. The Effect of Radiator Design Parameters on Heat Transfer

In this section, the effects of tube count, fin configuration, and material selection on the overall heat transfer performance of the radiator are examined. All calculations have been conducted under specific assumptions, and the key design parameters affecting the thermal performance of the radiator are comparatively analyzed.

3.3.1. General Approach and Comparison Criteria

This section investigates the impact of tube count and fin configuration on the total heat transfer performance of the radiator. All analyses have been performed under certain assumptions, with a comparative focus on the fundamental design parameters influencing the radiator's thermal performance

3.3.1.1. Criteria to be Examined

1. **Effect of Tube Count (With Fixed Geometry)**

   - The geometry of the tubes used will remain constant:
     - Height (h): 5 mm (0.005 m)
     - Width (w): 20 mm (0.02 m)
     - Length (L): 80 cm (0.8 m)
   - Two different tube count configurations will be examined::
     - 50 tubes: Lower total surface area and convective performance.
     - 100 tubes: Higher total surface area and potential convective performance
   - Increasing the number of tubes expands the total surface area, allowing for greater heat transfer. However, this also impacts the flow velocity and pressure loss on the fluid sid.

2. **Effect of Finned and Non-Finned Configurations (With 100 Tubes)**

- **Finned Radiator:**
  - Fins are added around the tubes, increasing the total surface area:

    $$A_{fin} = n_{fin} \cdot\ l_{fin} \cdot\ b_{fin} \tag{3.33}$$

  - The finned configuration enhances the convective heat transfer coefficient (h_{air}) on the air side. However, it may also increase pressure losses on the air side..

- **Non-Finned Radiator:**
  - Heat transfer occurs only through the tubes. Due to the lower surface area, the convective heat transfer coefficient on the air side is reduced.

2. Assumptions and Fixed Parameters

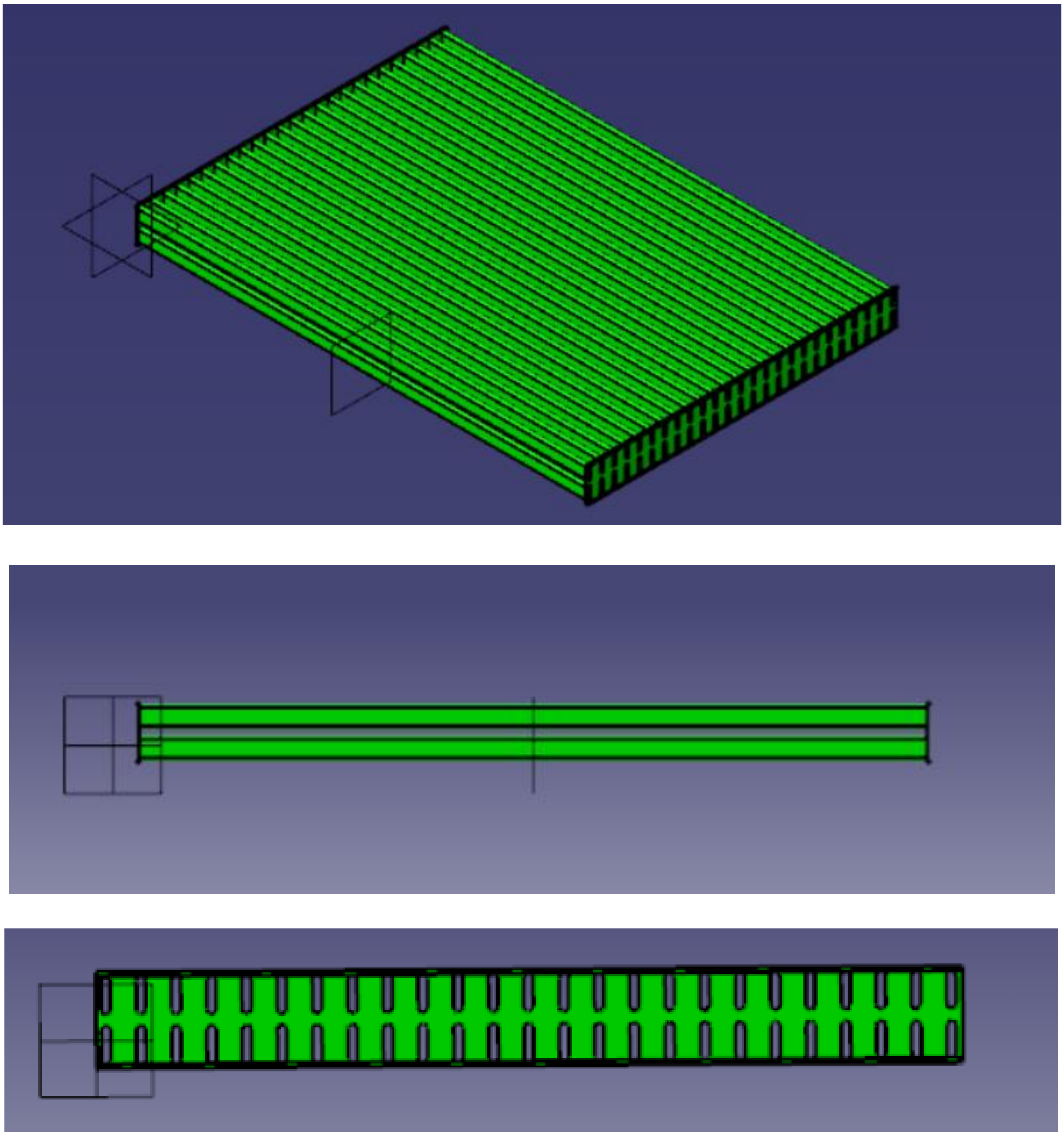
To ensure the calculations are comparable and consistent, the following assumptions have been made::

1. **Properties of Water:**
    - **Cooling Fluid Used:** Water
    - Physical Properties of Water:
        - Density (ρ): 965 kg/m^3(90°C')
        - Specific Heat (c_p): 4208 J/kg.K
        - Thermal Conductivity (k): 0.6 W/m.K
        - Dynamic Viscosity (μ): 0.000355 Pa.s
    - Inlet Temperature ($T_{fluid,inlet}$,): 90°C.
    - Outlet Temperature ($T_{fluid,outlet}$,): 70°C.
    - Flow Rate (V): It is kept constant.
2. **Properties of Air:**

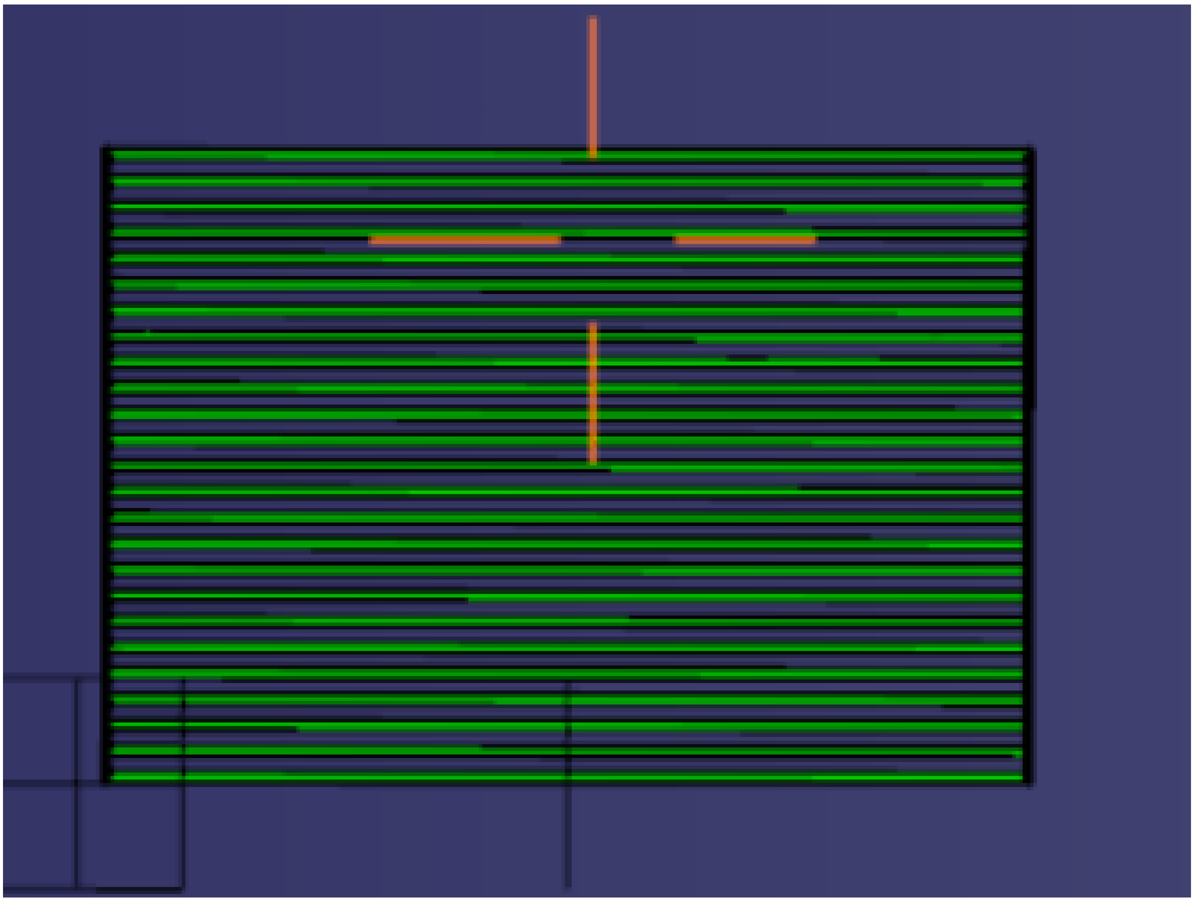
- Air Inlet Temperature($T_{air,inlet}$): 30°C.
- Airflow Velocity**:** Assumed constant:
- Physical Properties of Air:
    - Density (ρ): 1,2 kg/m^3(30°C')
    - Specific Heat (c_p): 1005 J/kg.K
    - Thermal Conductivity (k): 0,026 W/m.K
    - Dynamic Viscosity (μ): 0.000018 Pa.s

3.3.2. The Effect of Tube Count on Heat Transfer Performance

In this section, the impact of tube count on the overall heat transfer performance of the radiator is analyzed in detail. Calculations were first performed for the 50-tube configuration, followed by the same methodology applied to the 100-tube configuration. The analysis examines the effect of increasing the number of tubes on surface area, convective heat transfer coefficient, and outlet temperature.



50 Tube Design



50 Tube Design

3.3.2.1. Heat Transfer Calculations for the 50-Tube Configuration

1. **Calculation of Reynolds, Prandtl, Friction Factor, and Nusselt Numbers:**

ReynoldsNumber (Re)

Values used:

- Density(ρ): 965 kg/m^3
- Average velocity(v): 0,417 m/s
- Hydtraulic diameter(Dh): 0.008 m
- Dynamic viscosity (μ\): 0.000355 Pa.s

$$Re = \frac{965.0.417.0,008}{0,000355} = 9014 \quad (3.34)$$

SinceRe>4000, the flow is fully turbulent.

Prandtl Number (Pr):

Values used:

- Specific heat (c_p): 4186 J/kg.K
- Dynamic viscosity (μ): 0.000355 Pa.s
- Thermal conductivity of fluid ($k_{sıvı}$): 0.665 W/m.K

$$Pr = \frac{4186.0{,}000355}{0{,}665} = 2{,}23 \tag{3.35}$$

Friction Factor (f)

For turbulent flow, the friction factor is calculated using the formula:

$$f = 0{,}079.(9014)^{-0{,}25} = 0{,}008107 \tag{3.36}$$

Nusselt Number (Nu):

Substituting the values:

$$Nu = \frac{(0{,}008107/8).(9014 - 1000).2{,}23}{1 + 12{,}7.(0{,}008107/8)^{0{,}5}.(2{,}23^{0{,}667} - 1)} = 11{,}13 \tag{3.37}$$

This value indicates the convective heat transfer enhancement due to the turbulent flow regime.

2. **Convective Heat Transfer Coefficient (h_{fluid})**

Values used:

- Nusselt number (Nu): 11,13
- Thermal conductivity of the fluid ($k_{sıvı}$): 0.665 W/m.K
- Hydraulic diameter: 0.008 m

$$h_{fluid} = \frac{11{,}13.0{,}665}{0{,}008} = 926\, W/m^2K \tag{3.38}$$

3. Overall Heat Transfer Coefficient (U):

$$\frac{1}{U} = \frac{1}{926} + \frac{0,001}{205} + \frac{1}{100} = 0,01108 \tag{3.39}$$

Taking the reciprocal gives

$$U = 90,1\ W/m^2.K \tag{3.40}$$

This value represents the overall heat transfer efficiency of the radiator, accounting for the contributions from the fluid, wall, and air resistances..

4. Total Heat Transfer Calculation Using the NTU-ϵ Method

$$NTU = \frac{90,1.4}{1,5*1005} = 0,239 \tag{3.41}$$

$$Cr = \frac{m_{air}.c_{p,air}}{m_{fluid}.c_{p,fluid}} \tag{3.42}$$

$$Cr = \frac{1,5.1005}{2.4186} = 0,18 \tag{3.43}$$

$$\epsilon = \frac{1-e^{-0,239.(1-0,18)}}{1-0,18.e^{-0,239.(1-0,18)}} = 0,2088 \tag{3.45}$$

$$Q = 0,2088 * 1,5 * 1005 * 60 = 18888\ W \tag{3.46}$$

5. Logarithmic Mean Temperature Difference (ΔT_{log})

$$\Delta T_{log} = \frac{(T_{fluid,inlet} - T_{air,inlet}) - (T_{fluid,outlet} - T_{air,outlet})}{ln(\frac{T_{fluid,inlet} - T_{air,inlet}}{T_{fluid,outlet} - T_{air,outlet}})} \tag{3.47}$$

Values Used:

- Water inlet temperature($T_{fluid,inlet}$): 90°C
- Water outlet temperature ($T_{fluid,outlet}$,): 70°C
- Air inlet temperature ($T_{air,inlet}$,): 30°C
- Air outlet temperature ($T_{air,outlet}$,): 30°C

$$\Delta T_{log} = \frac{(90-30)-(70-30)}{ln(\frac{90-30}{70-30})} = 49{,}38K \quad (3.48)$$

It is found as.

6. **Total Heat Transfer Calculation (Using Logarithmic Mean Temperature Difference):**

Values Used:

- *U=90.1 W/*$m^2 . K$
- *A=4* m^2
- *ΔTlog=49.38 K*

$$Q = 90{,}1 \,.\, 4 \,.\, 49{,}38 = 17796\, W \quad (3.49)$$

Outlet Temperature Calculation (T_{outlet}):

$$T_{outlet} = 90 - \frac{17796}{2.4208} = 87{,}87°C \quad (3.50)$$

According to the theoretical results obtained from the calculations, the total heat transfer in the tubes was found to be 19.59 kW. The water outlet temperature from the radiator was calculated as $87{,}66°C$ Now, using the calculated T_{outlet} value, we will reperform the calculations to determine the actual heat transfer and outlet temperature.

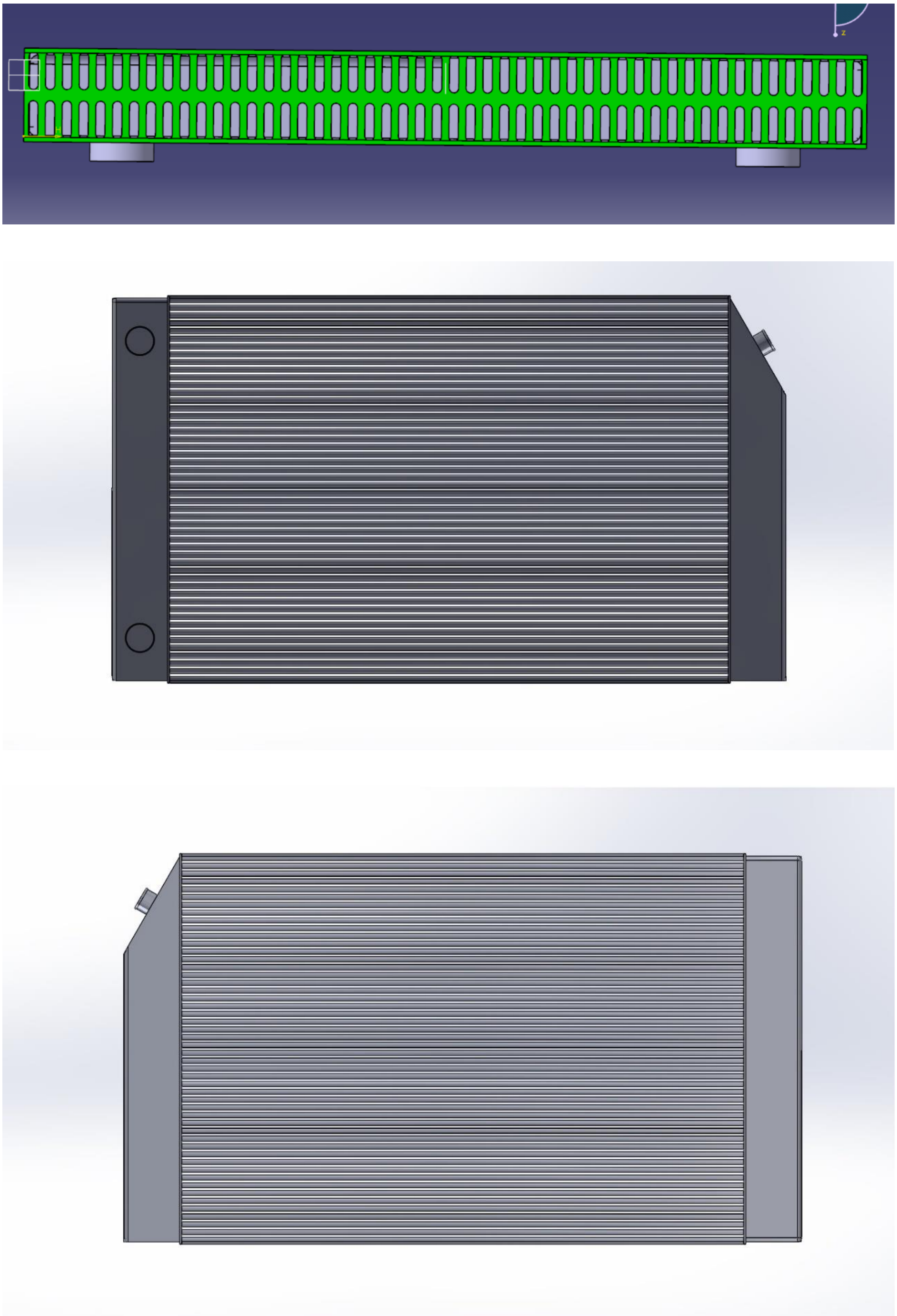
$$\Delta T_{log} = \frac{(90-30)-(85{,}74-30)}{ln(\frac{90-30}{85{,}74-30})} = 57{,}84\ K \quad (3.51)$$

$$Q = 98.1 \cdot 4 \cdot 57.84 = 22696\, W \quad (3.52)$$

$$T_{outlet} = 90 - \frac{22696}{2.4208} = 87{,}28°C \quad (3.53)$$

Has been determined.

3.3.2.2. Heat Transfer Calculations for the 100-Tube Configuration



100 Tube Design

1.Total Surface Caluclulation ($A_{tüp}$)

Values Used:

- Number of Tubes ($N_{tüp}$): 100
- Tube Witdh (w): 0.02m
- Tube Height(h): 0.005 m
- Tube Length (L): 0.8 m

$$A_{tube} = 100.2.0{,}025.0{,}8 = 8m^2 \quad (3.53)$$

2. Average Flow Velocity Per Tube (v_{tibe})

In the 100-tube system, the total flow is divided as follows::

$$v_{tube} = \frac{v_{total}}{N_{tube} \cdot A_{surface}} \quad (3.54)$$

And there is:

- Volumetric Flow Rate (v_{total}): 0.00208 m^3/ (sabit)
- Tube Cross-Sectional Area ($A_{cross\ sectional}$): w·h=0.02·0.005=0.0001 m^2
- **Number of Tubes**
- (N_{tube}): 100

$$v_{tube} = \frac{0{,}00208}{100.0.0001} = 0{,}208\ m/s \quad (3.55)$$

3: Calculation of the Reynolds Number

Values Used:

- Density (ρ): 965 kg/m^3
- Average Velocity (v): 0,208 m/s
- Hydraulic Diamete (Dh): 0.008 m
- Dynamic Viscosity (μ\): 0.000355 Pa.s

$$Re = \frac{965.0.208.0{,}008}{0{,}000355} = 4507 \quad (3.56)$$

Since Re>4000, the flow is turbulent.

4: Calculation of the Friction Factor

$$f = 0{,}079.\,(4507)^{-0{,}25} = 0{,}009641 \tag{3.57}$$

5: Calculation of the Nusselt Number

$$Nu = \frac{(0{,}009641/8).(4507-1000).2{,}23}{1+12{,}7.(0{,}009641/8)^{0{,}5}.(2{,}23^{0{,}667}-1)} = 7{,}189 \tag{3.58}$$

6: Calculation of the Convective Heat Transfer Coefficient (h_{fluid})

$$h_{fluid} = \frac{7{,}189.0{,}665}{0{,}008} = 597{,}59\ W/m^2K \tag{3.59}$$

7: Calculation of the Overall Heat Transfer Coefficient (U)

$$\frac{1}{U} = \frac{1}{597{,}59} + \frac{0{,}001}{205} + \frac{1}{100} = 0{,}0116782 \tag{3.60}$$

and

$$U = 85{,}6\ W/m^2K \tag{3.61}$$

is found.

8: Total Heat Transfer Calculation Using the NTU-ϵ Method

$$NTU = \frac{85{,}6.8}{1{,}5.1005} = 0{,}454 \tag{3.62}$$

$$Cr = \frac{m_{hava}.c_{p,hava}}{m_{sıvı}.c_{p,sıvı}} \tag{3.63}$$

$$Cr = \frac{1{,}5.1005}{2.4186} = 0{,}18 \tag{3.64}$$

$$\epsilon = \frac{1-e^{-0{,}454.(1-0{,}18)}}{1-0{,}18.e^{-0{,}454.(1-0{,}18)}} = 0{,}3548 \tag{3.65}$$

$$Q = 0{,}3548 * 1{,}5 * 1005 * 60 = 32091\ W \tag{3.66}$$

9: Calculation of Heat Transfer (Q) Using the Overall Heat Transfer Coefficient

Values Used:

- U=85.6 W/m^2K
- A=8 m^2
- ΔTlog=49.38 K

$$Q = 85{,}6\,.\,8\,.\,49{,}38 = 33827\,W \tag{3.67}$$

Is founded.

10: Calculation of the Outlet Temperature ($T_{fluid,out}$)

Values Used:

- $T_{fllidt,inlet}$: 90°C
- Q=33815.93 W
- m˙=2 kg/s
- cp=4186 J/kg.K

$$T_{outlet} = 90 - \frac{33815}{2.4208} = 85{,}96°C \tag{3.68}$$

According to the theoretical results obtained, the total heat transfer in the tubes was found to be 33.81 kW. The water outlet temperature from the radiator was calculated as $85{,}96°C$ Now, using the calculated $T_{çıkış}$ value, let's recompute the actual heat transfer and outlet temperature.

$$\Delta T_{log} = \frac{(90-30)-(85{,}96-30)}{ln(\frac{90-30}{85{,}96-30})} = 57{,}95\,K \tag{3.69}$$

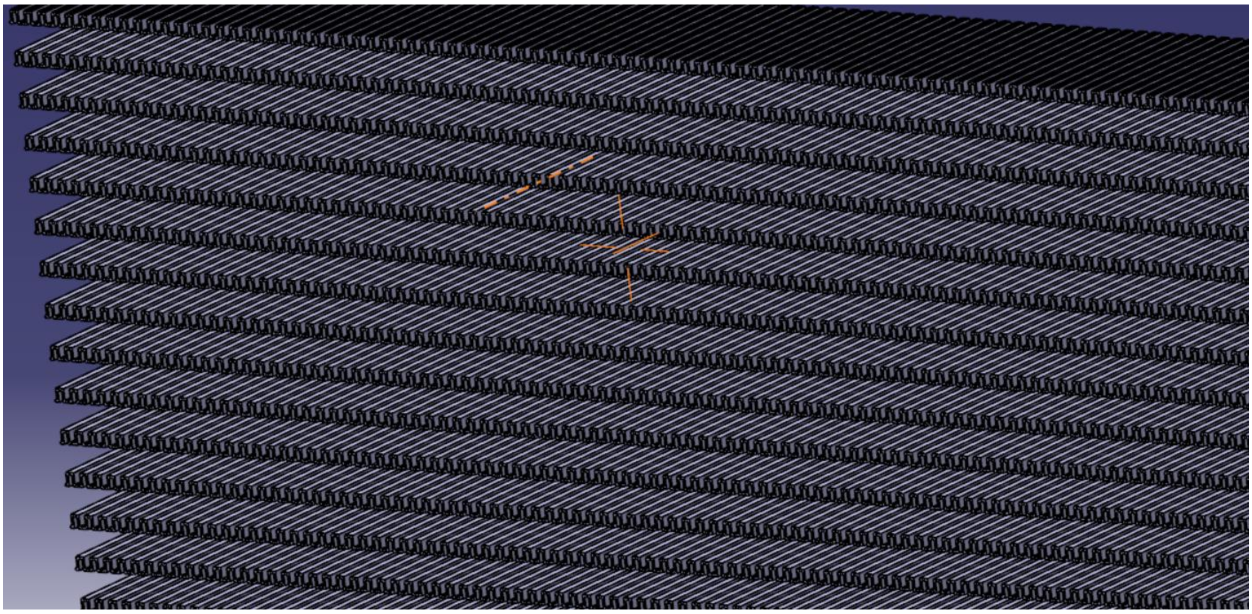
$$Q = 85{,}6 \cdot 8 \cdot 57.64 = 39688\,W \tag{3.70}$$

$$T_{outlet} = 90 - \frac{39688}{2.4208} = 85{,}25°C \tag{3.71}$$

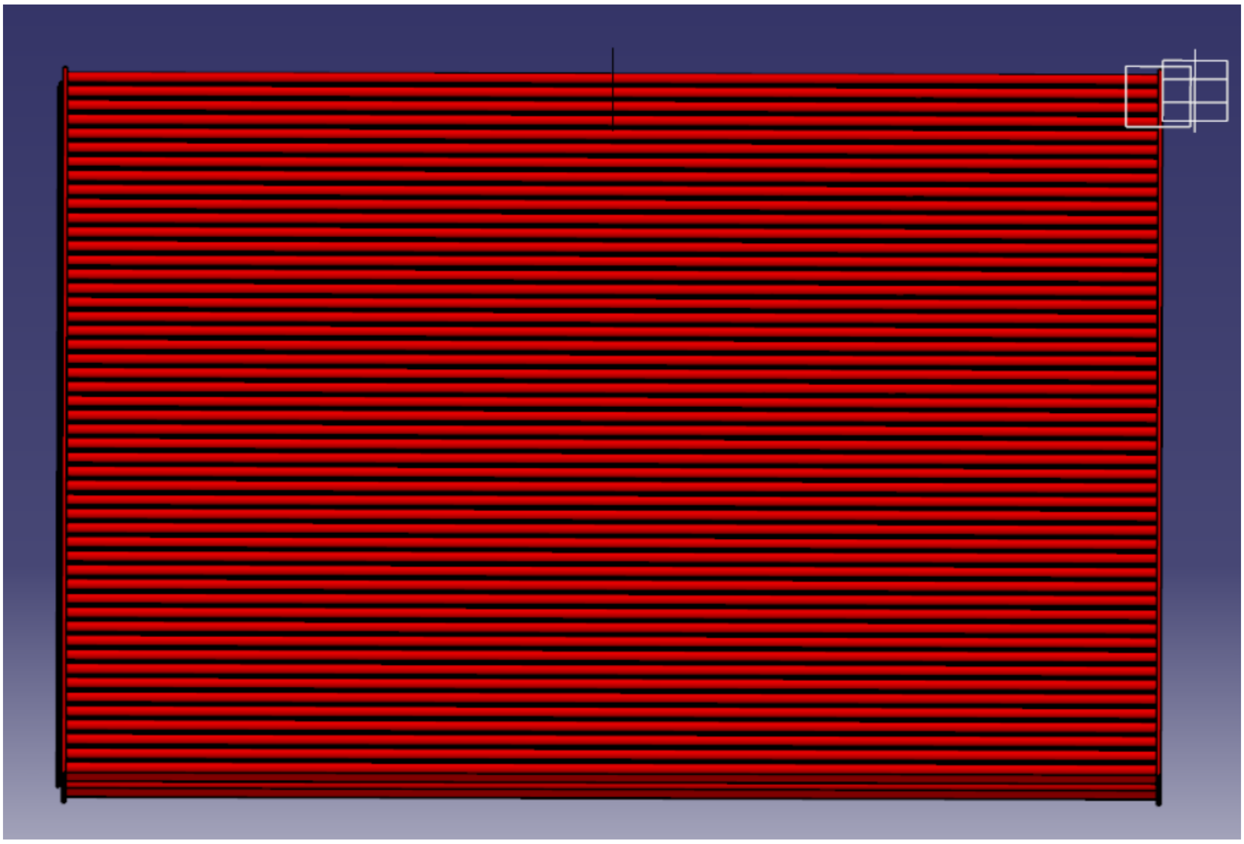
This is the recalculated actual outlet temperature and heat transfer.

3.3.2.2. Heat Transfer Calculations for Finned Design

100 Tube Finned Design



100 Tube Finned Design



100 Tube Finned Design

1. Calculation of Total Surface Area

The finned surface area is found by adding the surface area of the tubes and the total surface area of the fins.

$$A_{finned} = A_{tube} + A_{fin} \quad (3.72)$$

Given Values:

- Surface Area of the Tubes: $A_{tube} = 8m^2$
- Surface Area of the Fins: $A_{kanat}fin$ =9,43m^2

$$A_{finned} = 8 + 9{,}43 = 17{,}43m^2 \quad (3.73)$$

2 Calculation of Fin Efficienc (η_k)

The fin efficiency is a measure of how effectively the fins contribute to heat transfer. It is calculated using the following formula:

$$m = (\frac{2.100}{205.0{,}0005})^{0{,}5} = 44.17 \quad (3.74)$$

$$44{,}17.0{,}00298 = 0{,}1316 \quad (3.75)$$

Fin Efficiency:

$$\eta_k = \frac{tanh(0{,}1316)}{0{,}1316} = 0{,}994 \quad (3.76)$$

Fin Efficiency has been found to be 0.994.

7. Calculation of the Overall Heat Transfer Coefficient

$$\frac{1}{U} = \frac{1}{h_{fluid}} + \frac{t}{k} + \frac{1}{h_{air} \cdot \eta_k} \quad (3.77)$$

$$\frac{1}{U} = \frac{1}{597{,}59} + \frac{0{,}0005}{205} + \frac{1}{100.0{,}994} = 0{,}011736 \quad (3.78)$$

From this, the overall heat transfer coefficient U is found to be 85.2 W/m^2*K

Total Heat Transfer:

$$85{,}2 * 17{,}43 * 57{,}95 = 86057\,W \tag{3.79}$$

Is founded.

8. **Water Outlet Temperature**

$$T_{outlet} = 90 - \frac{86057}{2.4186} = 79{,}72°C \tag{3.80}$$

4. Pressure Loss in the Tubes

Another aim of this study is to analyze the pressure losses occurring in radiator designs, identify the major sources of these losses, and propose effective strategies to minimize them. During the study, pressure loss calculations will be performed using numerical methods, and the obtained results will be compared based on various criteria.

4.1 Determination of Parameters

- **Fluid Density**:): 965 kg/m^3
- Flow Velocity: 0,208 m/s (in 100 tubes)
- **Flow Velocity**: 0,417 m/s (in 50 tubes)
- **Reynolds Number** : 9046 (in 50 tubes)
- **Reynolds Number** : 4523 (in 100 tubes)

4.2 Pressure Losses

Pressure Loss for 100-Tube Design:

$$\mu_{max} = \mu_{max} \frac{S_T}{S_T - D} \tag{3.81}$$

$$Re = \frac{\rho v D}{\mu} \tag{3.82}$$

$$\mu_{max} = 0{,}4 \frac{11}{11-8} = 1{,}466 \tag{3.83}$$

$$\Delta P = \frac{0{,}008107 * 100 * (967{,}1 * 1{,}4)^2 * 8}{2967{,}1} = 6146 \text{ Pa} \tag{3.84}$$

Pressure Loss for 50-Tube Design:

$$\Delta P = \frac{0{,}008107 * 50 * (967{,}1 * 1{,}4)^2 * 8}{2967{,}1} = 3073 \tag{3.85}$$

Is founded.

5. Evaluation and Interpretation of Results

In this study, the effects of different design parameters on heat transfer performance and pressure losses in vehicle radiators were examined in detail. According to the theoretical results obtained, design changes significantly affect radiator performance. Increasing the number of tubes has expanded the total surface area, thereby increasing the heat transfer capacity. The heat transfer in the 50-tube design was 22.69 kW with an outlet temperature of 87.28°C, whereas in the 100-tube design, heat transfer increased to 36.68 kW with an outlet temperature of 85.25°C. In the 100-tube finned design, the heat transfer was 86.08 kW, with the outlet temperature reaching 79.72°C. However, the increase in the number of tubes also raised the pressure losses, which impacted hydraulic performance. Therefore, determining the number of tubes is critical for balancing performance and energy efficiency. Finned radiators, by providing a larger surface area, significantly increased heat transfer performance. The fin efficiency calculations highlighted the need for optimizing fin geometry for high-performance designs. However, the pressure losses caused by the fins must also be considered. The pressure loss in the 50-tube design was calculated to be 3073 Pa, while it increased to 6146 Pa in the 100-tube design. These results demonstrate that increasing the number of tubes affects not only thermal performance but also hydraulic resistance.

Configuration	Heat Transfer (kW)	Outlet Temperature (°C)
50 Tubes	22.69	87.28
100 Tubes	39.68	85.25
100 Tubes with Fins	86.05	79.72

Table 5.1 Total Heat Transfer and Outlet Temperature

Configuration	Pressure Loss
50 Tubes	3073
100 Tubes	6146

Table 5.2 Total Pressure Loss

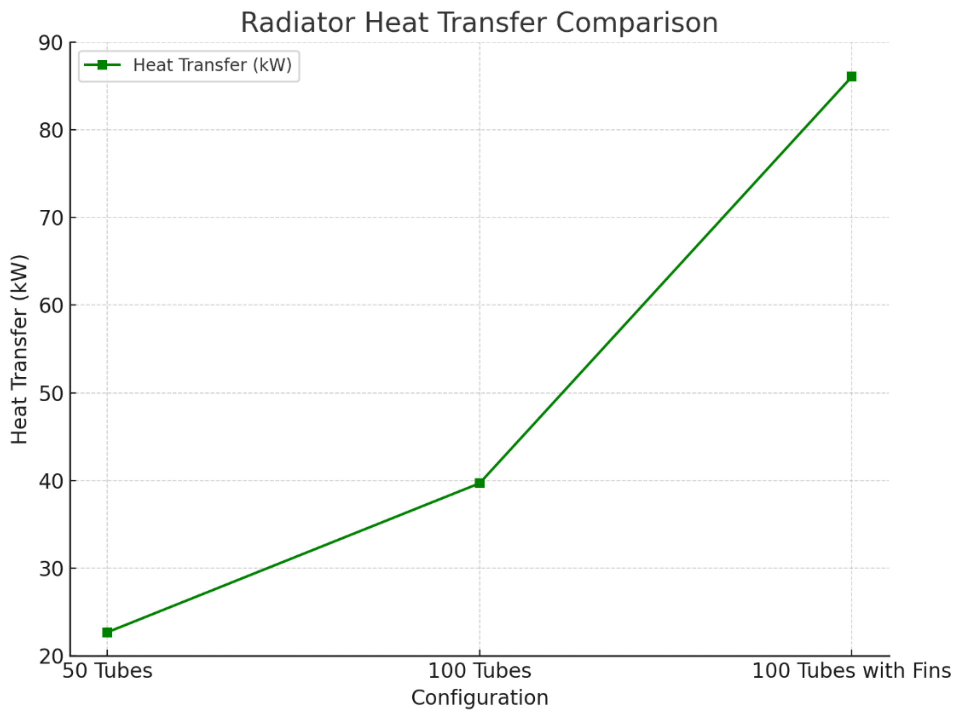


Table 5.3 Exit Temperature Comparison

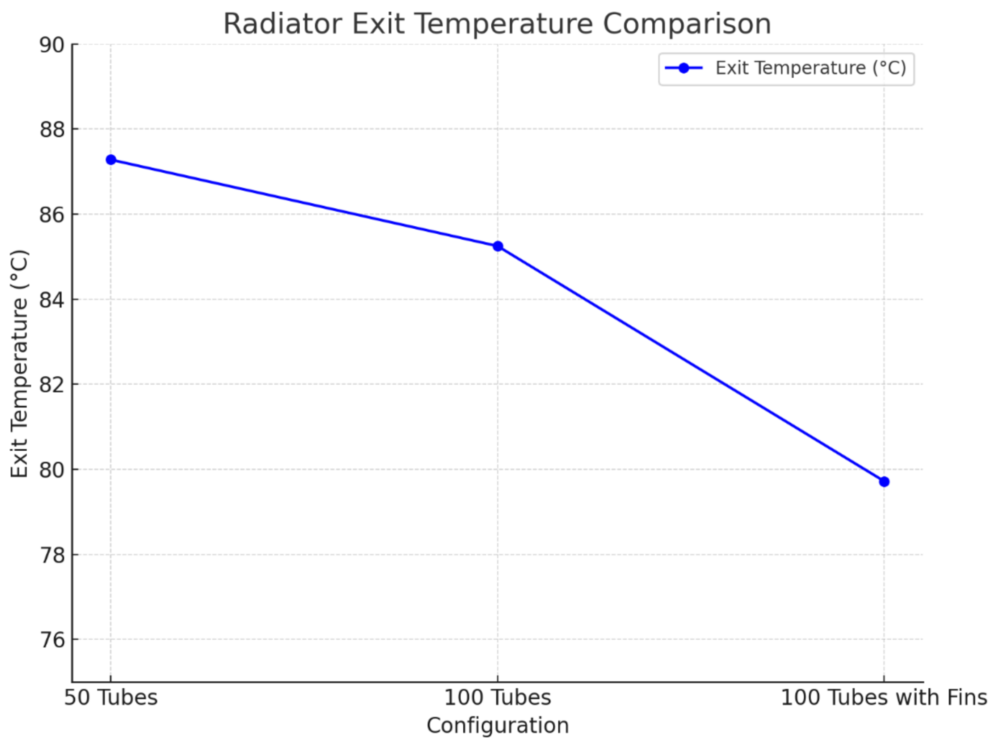


Table 5.4 Heat Transfer Performance

6. APPENDICES

T (K)	P (bar)	ρ (kg/m^3)	h_{sb} (kJ/kg)	c_p kJ/kgK	$\mu \cdot 10^3$ Ns/m^2	$\nu \cdot 10^6$ (m^2/s)	$k \cdot 10^3$ (W/mK)	$\alpha \cdot 10^6$ (m^2/s)	Pr	$\sigma \cdot 10^3$ (N/m)	$\beta \cdot 10^6$ (K^{-1})
273.15	0.00611	1000	2502	4.217	1.750	1.75	569	0.135	13.0	75.5	-68.05
275	0.00697	1000	2497	4.211	1.652	1.652	574	0.136	12.1	75.3	-32.74
280	0.0099	1000	2485	4.198	1.422	1.422	582	0.139	10.3	74.8	46.04
285	0.01387	1000	2473	4.189	1.225	1.225	590	0.141	8.7	74.3	114.1
290	0.01917	999	2461	4.184	1.080	1.081	598	0.143	7.6	73.7	174
295	0.02617	998	2449	4.181	0.959	0.961	606	0.145	6.6	72.7	227.5
300	0.03531	997	2438	4.179	0.855	0.858	613	0.147	5.8	71.7	276.1
305	0.04712	995	2426	4.178	0.769	0.773	620	0.149	5.2	70.9	320.6
310	0.06221	993	2414	4.178	0.695	0.7	628	0.151	4.6	70	361.9
315	0.08132	991.1	2402	4.179	0.631	0.637	634	0.153	4.2	69.2	400.4
320	0.1053	989.1	2390	4.18	0.577	0.583	640	0.155	3.8	68.3	436.7
325	0.1351	987.2	2378	4.182	0.528	0.535	645	0.156	3.4	67.5	471.2
330	0.1719	984.3	2366	4.184	0.489	0.497	650	0.158	3.1	66.6	504
335	0.2167	982.3	2354	4.186	0.453	0.461	656	0.160	2.9	65.8	535.5
340	0.2713	979.4	2342	4.188	0.420	0.429	660	0.161	2.7	64.9	566
345	0.3372	976.6	2329	4.191	0.389	0.398	668	0.163	2.4	64.1	595.4
350	0.4163	973.7	2317	4.195	0.365	0.375	668	0.164	2.3	63.2	624.2
355	0.51	970.9	2304	4.199	0.343	0.353	671	0.165	2.1	62.3	652.3
360	0.6209	967.1	2291	4.203	0.324	0.335	674	0.166	2.0	61.4	697.9
365	0.7514	963.4	2278	4.209	0.306	0.318	677	0.167	1.9	60.5	707.1
370	0.904	960.6	2265	4.214	0.289	0.301	679	0.168	1.8	59.5	728.7
373.15	1.0133	957.9	2257	4.217	0.279	0.291	680	0.168	1.7	58.9	750.1
375	1.0815	956.9	2252	4.22	0.274	0.286	681	0.169	1.7	58.6	761
380	1.2869	953.3	2239	4.226	0.260	0.273	683	0.170	1.6	57.6	788
385	1.5233	949.7	2225	4.232	0.248	0.261	685	0.170	1.5	56.6	814
390	1.794	945.2	2212	4.239	0.237	0.251	686	0.171	1.5	55.6	841
400	2.455	937.2	2183	4.256	0.217	0.232	688	0.172	1.3	53.6	896
410	3.302	928.5	2153	4.278	0.200	0.215	688	0.173	1.2	51.5	952
420	4.37	919.1	2123	4.302	0.185	0.201	688	0.174	1.2	49.4	1010
430	5.699	909.9	2091	4.331	0.173	0.19	685	0.174	1.1	47.2	-
440	7.333	900.9	2059	4.36	0.162	0.18	682	0.174	1.0	45.1	-
450	9.319	890.5	2024	4.4	0.152	0.171	678	0.173	1.0	42.9	-
460	11.71	879.5	1989	4.44	0.143	0.163	673	0.172	0.9	40.7	-
470	14.55	868.1	1951	4.48	0.136	0.157	667	0.172	0.9	38.5	-
480	17.9	856.9	1912	4.53	0.129	0.151	660	0.170	0.9	36.2	-
490	21.83	844.6	1870	4.59	0.124	0.147	651	0.168	0.9	33.9	-

Table 6.1: Thermophysical Properties of Saturated Water

T (K)	P (bar)	ρ (kg/m³)	h_{sb} (kJ/kg)	c_p kJ/kgK	$\mu \cdot 10^3$ Ns/m²	$\nu \cdot 10^6$ (m²/s)	$k \cdot 10^3$ (W/mK)	$\alpha \cdot 10^6$ (m²/s)	Pr	$\sigma \cdot 10^3$ (N/m)	$\beta \cdot 10^6$ (K⁻¹)
500	26.4	831.3	1825	4.66	0.118	0.142	642	0.166	0.9	31.6	-
510	31.66	818.3	1779	4.74	0.113	0.138	631	0.163	0.8	29.3	-
520	37.7	803.9	1730	4.84	0.108	0.134	621	0.160	0.8	26.9	-
530	44.58	788.6	1679	4.95	0.104	0.132	608	0.156	0.8	24.5	-
540	52.38	772.8	1622	5.08	0.078	0.101	594	0.151	0.7	22.1	-
550	61.19	755.9	1564	5.24	0.073	0.097	580	0.146	0.7	19.7	-
560	71.08	738	1499	5.43	0.069	0.094	563	0.140	0.7	17.3	-
570	82.16	718.4	1429	5.68	0.065	0.091	548	0.134	0.7	15	-
580	94.51	697.8	1353	6	0.061	0.088	528	0.126	0.7	12.8	-
590	108.3	674.8	1274	6.41	0.057	0.084	513	0.119	0.7	10.5	-
600	123.5	648.9	1176	7	0.053	0.081	497	0.109	0.7	8.4	-
610	137.3	620.3	1068	7.85	0.048	0.077	467	0.096	0.8	6.3	-
620	159.1	586.5	941	9.35	0.042	0.072	444	0.081	0.9	4.5	-
625	169.1	562.4	858	10.6	0.039	0.07	430	0.072	1.0	3.5	-
630	179.7	538.8	781	12.6	0.036	0.067	412	0.061	1.1	2.6	-
635	190.9	516.8	683	16.4	0.033	0.064	392	0.046	1.4	1.5	-
640	202.7	481.9	560	26	0.028	0.059	367	0.029	2.0	0.8	-
645	215.2	425.4	361	90	0.023	0.054	331	0.009	6.2	0.1	-
647.3[k]	221.2	315.5	0	∞	0.014	0.045	238	-	-	0	-

Table 6.2: Thermophysical Properties of Saturated Water (Continued)

T (K)	ρ (kg/m^3)	c_p (kJ/kgK)	$\mu \cdot 10^7$ ($N\ s/m^2$)	$\nu \cdot 10^6$ (m^2/s)	$k \cdot 10^3$ (W/mK)	$\alpha \cdot 10^6$ (m^2/s)	Pr
Hava							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.075	338.8	68.10	52.4	98.0	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709
850	0.4097	1.110	384.3	93.80	59.6	131	0.716
900	0.3868	1.121	398.1	102.9	62.0	143	0.720
950	0.3666	1.131	411.3	112.2	64.3	155	0.723
1000	0.3482	1.141	424.4	121.9	66.7	168	0.726
1100	0.3166	1.159	449.0	141.8	71.5	195	0.728
1200	0.2902	1.175	473	162.9	76.3	224	0.728
1300	0.2679	1.189	496	185.1	82	238	0.719
1400	0.2488	1.207	530	213	91	303	0.703
1500	0.2322	1.230	557	240	100	350	0.685
1600	0.2177	1.248	584	268	106	390	0.688
1700	0.2049	1.267	611	298	113	435	0.685
1800	0.1935	1.286	637	329	120	482	0.683
1900	0.1833	1.307	663	362	128	534	0.677
2000	0.1741	1.337	689	396	137	589	0.672
2100	0.1658	1.372	715	431	147	646	0.667
2200	0.1582	1.417	740	468	160	714	0.655
2300	0.1513	1.478	766	506	175	783	0.647
2400	0.1448	1.558	792	547	196	869	0.630
2500	0.1389	1.665	818	589	222	960	0.613
3000	0.1135	2.726	955	841	486	1570	0.536

Table 6.3: Thermophysical Properties of Air

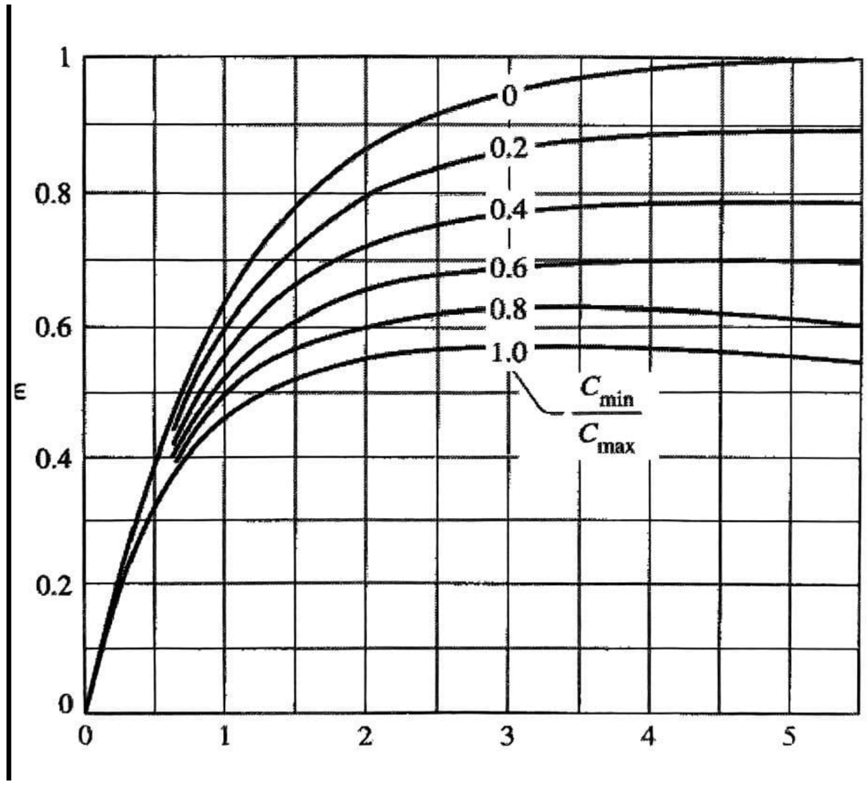


Table 6.4: Effectiveness of Single-Pass Crossflow Heat Exchanger with Fluid Mixing

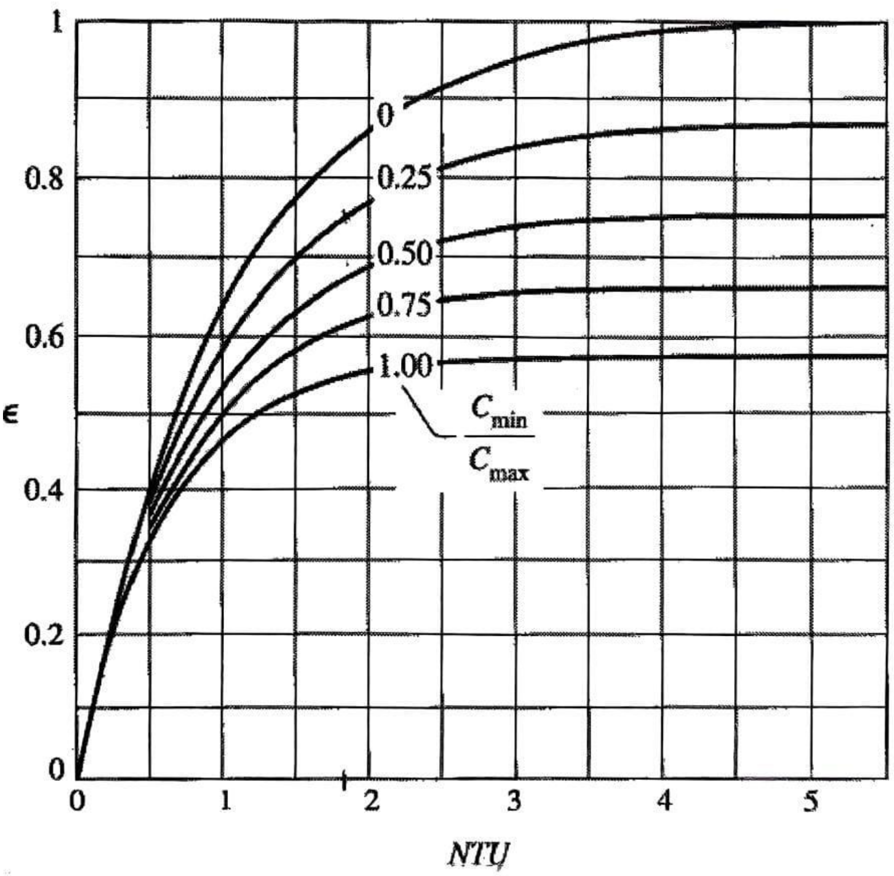


Table 6.5: Effectiveness of Single-Shell, Two or More Tube Pass Heat Exchanger

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