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Design & Analysis of Extended Surfaces

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Abstract

This assignment explores the role of fins in enhancing heat transfer through convection, focusing on their design and application across automotive and microprocessor technologies. The report investigates the historical evolution of fins in automotive design, tracing their development over decades. It also examines the integration of extended surfaces in microprocessor cooling, highlighting recent advancements in fin design and their benefits, such as increased surface area and optimised thermal management.

The Report validates the optimum length parameter $mL \approx 2.65$ in ml fin design through a visual representation of the ratio of heat transfer as a function of mL .

Finally, the report analyses four different material rods with finite, optimum, and accurate lengths using the adiabatic tip condition, the optimum length parameter, and the infinite fin condition.

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1 Extended Surfaces

Extended surfaces, also described as fins, are engineered features designed to enhance heat transfer by increasing the surface area available for convection (Cengel, 2002) & (Nagarani, et al., 2014). Their application is critical in fields like automotive design and microprocessor technology, where efficient thermal management directly impacts performance and reliability (Oclon, et al., 2021). In automotive design, heat transfer fins have evolved significantly over the decades to meet the demands of increasingly complex engines and systems (Babu & Lavakumar, 2014). Similarly, in microprocessors, extended surfaces have become essential for dissipating heat as devices shrink and power densities rise (Li, et al., 2021). This investigation explores the historical development of heat transfer fins in automotive design, their integration into microprocessor cooling, and recent advances in extended surface design, highlighting their perceived advantages.

2 Application of Fins in Automotive Design

2.1 Air-Cooled Engines

The use of fins in automotive design began in the early 20th century with the advent of internal combustion engines. Early vehicles utilised air-cooled engines, where fins were cast onto cylinder barrels to enhance convective heat dissipation into the surrounding air. These fins were typically simple, rectangular protrusions made of cast iron or aluminium, chosen for their thermal conductivity and manufacturability (Singh, 2020). A notable example is the 1911 Harley-Davidson model 7D engine, as illustrated in Figure 1. This air-cooled design features an open configuration, prominently displaying the fins cast onto the cylinder barrels. Fins were engineered to enhance convective heat transfer, addressing the critical challenge of preventing engine overheating, a prevalent issue in early automotive engineering as power outputs increased.

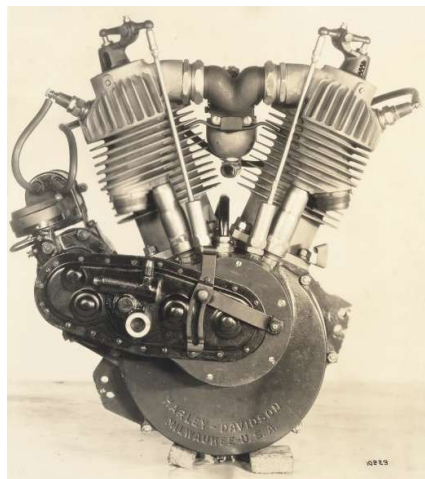


Figure 1 - 1911 Harley-Davidson model 7D engine

During the 1920s and 1930s, air-cooled engines with finned cylinders gained prominence in vehicles like the Franklin automobile and early Volkswagen Beetle prototypes (Figure 2). Franklin improved the cooling system in their automobiles by using copper instead of steel for its superior heat conductivity and oriented the cylinders horizontally for maximum air exposure over the vertical fins (Franklin, 2021).

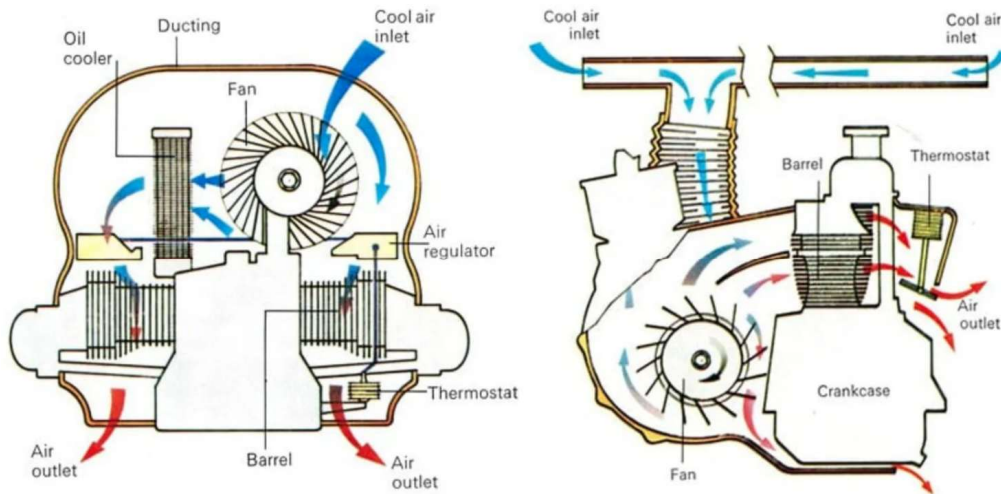


Figure 2 – VW Beetle Engine Diagram

The application of fin technology was not limited to air-cooled engines within the automotive industry. Former Franklin employees, for instance, employed this approach in aviation with the Model 4AC-150, an air-cooled, four-cylinder, horizontally opposed engine developed in 1938 (Figure 3).



Figure 3 – Franklin Model 4AC-150

While air-cooled engines were one solution to dissipate heat from the engine, Wilhelm Maybach devised an alternative: a liquid-cooled engine in which heat transfer fins were utilised in radiators to dissipate heat from coolant. In 1901, Maybach patented a honeycomb design of more than 8000 square tubes (Figure 4), arranged to efficiently remove heat from the coolant. (Motorequipmentnews, 2020).

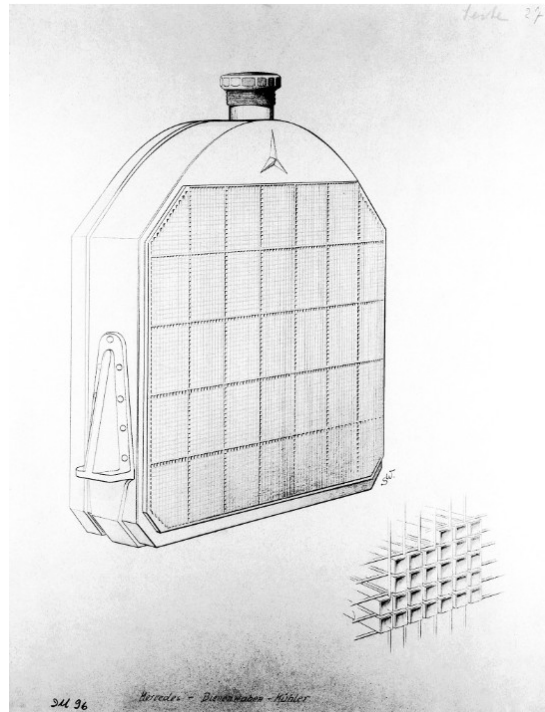


Figure 4 - Mercedes Maybach Radiator (Mercedes-Benz, 2025).

He later enhanced the design by changing the square tube to a round one. Both ends of the tube were shaped into hexagons and joined together using soldering. However, the internal water flow speed within the honeycomb radiator was slow, making it susceptible to accumulation. Additionally, the lengthy welding seams posed a risk of leaks, which led to high costs and complicated maintenance. Consequently, the honeycomb radiator was eventually replaced with tube-fin radiators (Sheradiatortank, 2021).



Figure 5 - Diagram of Round Tube Honeycomb Radiator.

2.2 Finned Tube Radiators

Radiator finned tubes were often flat or corrugated aluminium strips soldered or brazed to coolant pipes, increasing the surface area for heat exchange between the coolant and ambient air (Rundle, 1999). This transition improved cooling efficiency, enabling higher-performance engines in post-war models like the 1950s Chevrolet Bel Air (Figure 6).



Figure 6 – Chevrolet Bel Air Replica Radiator (55belair, 2025)

Early radiators, including those in pre-war and immediate post-war automobiles, often used copper or brass for tubes and fins due to their excellent thermal conductivity. By the 1950s, aluminium started to gain popularity in automotive applications. Although copper has better thermal conductivity, aluminium’s weight, manufacturability, corrosion resistance, and cost benefits made it a more suitable choice for heat dissipation (Carworship, 2024).

Era	Material	Cooling Type	Efficiency	Weight (kg)	Cost (\$)
1920s	Copper	Air	50%	15	100
1950s	Brass	Water	70%	10	80
1980s	Aluminum	Water	85%	7	60
2000s	Aluminum	Hybrid	90%	5	50
2010s	Composite	Hybrid	95%	4	40
2020s	Carbon Fiber	Advanced	98%	3	70

Figure 7 – Material Comparison Table (Carworship, 2024)

2.3 Modern Automotive Cooling Systems

In modern automotive cooling systems design, fin design principles have evolved with computer-aided design (Automotivequest, 2024) and computational fluid dynamics tools. Using computational fluid dynamics can enable simulations to optimise fin designs for thermal performance while also reducing cost through virtual prototyping (Rama, et al., 2022).

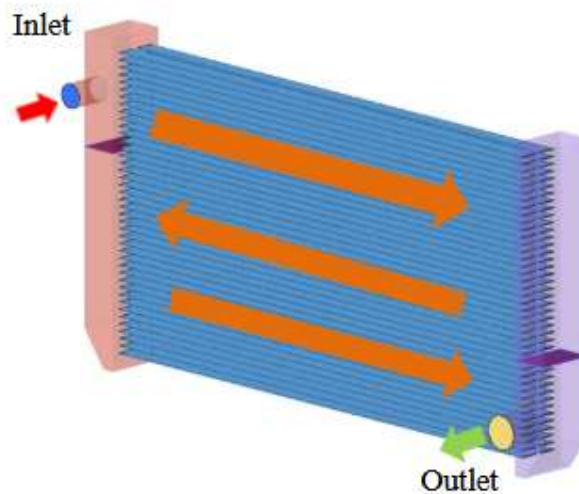


Figure 8 – CFD Radiator Model

Modern radiators routinely use high-performance aluminium alloys that allow for intricate designs (hdautoparts, 2024). In some high-performance or speciality vehicles, nanostructured coatings on fins have even been experimented with to boost heat transfer capabilities further (Kumar, et al., 2024).

Modern manufacturing methods, such as extrusions, stamping, and even additive manufacturing, have facilitated the development of designing fins with micro-optimised geometries (Sun & Shang, 2022). These methods allow engineers to fine-tune the fin profiles to meet specific aerodynamic and thermal resistance criteria.

3 Fins in Microprocessor Cooling

As computers gained popularity for personal use and work-based tasks, the demand for increased computing power output for microprocessors resulted in more significant heat generation. This advancement sparked a heightened emphasis on sophisticated thermal management techniques, adapting the idea of extended surfaces to address the specific cooling requirements in microelectronics.

3.1 Integrated Heat Sinks

In the early stages of microprocessor development, the cooling methods employed were relatively simple. These techniques were primarily focused on passive cooling solutions, which relied on natural convection and conduction to dissipate heat generated by the microprocessors. As processing speeds and power increased, the limitations of these basic cooling methods became apparent, necessitating the exploration of more sophisticated thermal management strategies (Cheung, 2020).

One of the earliest processors to incorporate a heat sink for cooling was the Intel 80486, commonly referred to as the i486, which debuted in 1989 (see Figure 9). A fan was mounted on the heat sink alongside this innovation to enhance cooling through forced convection (see Figure 10).

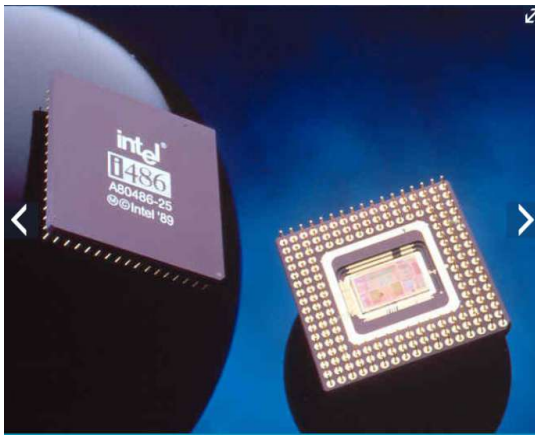


Figure 9 – i486 Processor (Intel, 2025)

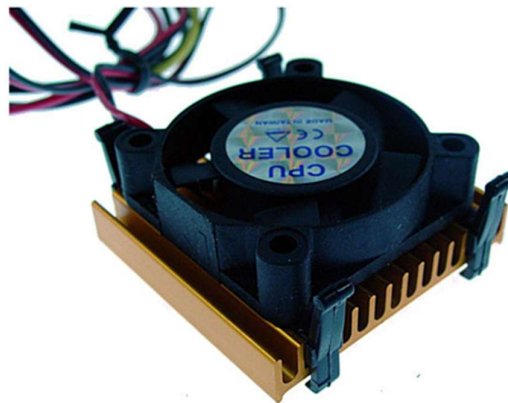


Figure 10 – Heatsink with forced convection (Aerocooler, 2025)

3.2 Compact Extended Surfaces

As computers evolved and form factors became increasingly compact, the microprocessor was required to reduce in size (Figure 11). This advancement also extended to cooling solutions, where traditional bulky heatsinks had to be designed to be more compact and lightweight, incorporating finer fin structures to enhance efficiency. The heat sink concept was still conventional; more fins enhanced the effective surface area, but production constraints required designers to find a balance between fin thickness, spacing, and total weight (Fruci, 2023).



Figure 11 – Compact Heatsink (Aerocooler, 2025)

3.3 Microprocessor Cooling Advances

The arrival of microchannel heat sinks was a significant advancement in microprocessor thermal management (Figure 12). These advanced heatsinks feature tiny channels that are etched or drilled into the material. Liquid coolants travel through the channels, significantly improving the convective heat transfer coefficient. Microchannels provide a significant surface area relative to their volume, which is crucial for effectively removing localised heat from high-performance chips (Kadam & Kumar, 2014).

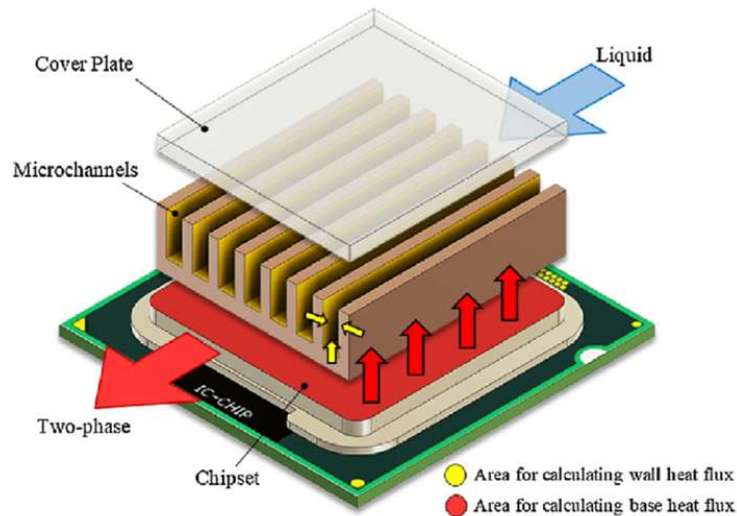


Figure 12 – Micro Channel Heat Sink Diagram (Maghrabie, et al., 2023)

3.4 Pin-Fin Arrays

Micro-scale pin-fin arrays (Figure 13) have been created for use in integrated circuits. These arrays are positioned in non-linear configurations to promote turbulent airflow, which improves convective heat transfer (Pati, et al., 2018). The design takes into account factors such as the density and layout of the pins and the geometry of the fin tips, which can be optimised based on various assumptions, from nearly adiabatic conditions to those that account for actual conduction losses (Mohammadi & Kos, 2020).

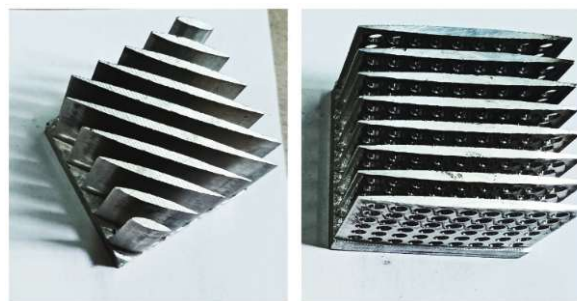


Figure 13 – Aerofoil pin fin array example (Bhaumik, et al., 2023)

3.5 Computational Fluid Dynamics

Computational fluid dynamics is now a widely used design tool for simulating and managing heat dissipation in extended surfaces and heat sinks (Figure 14). Through simulation, various geometries, patterns, and material types can be analysed using realistic heat and fluid flow parameters (Freegah, et al., 2020).

Research indicates that alterations in fin geometries, such as transitioning straight to curved designs or incorporating perforated curves, can substantially enhance heat dissipation. This improvement is attributed to the increased turbulence and augmented surface area that facilitate convective heat transfer (Abdollahi, et al., 2024).

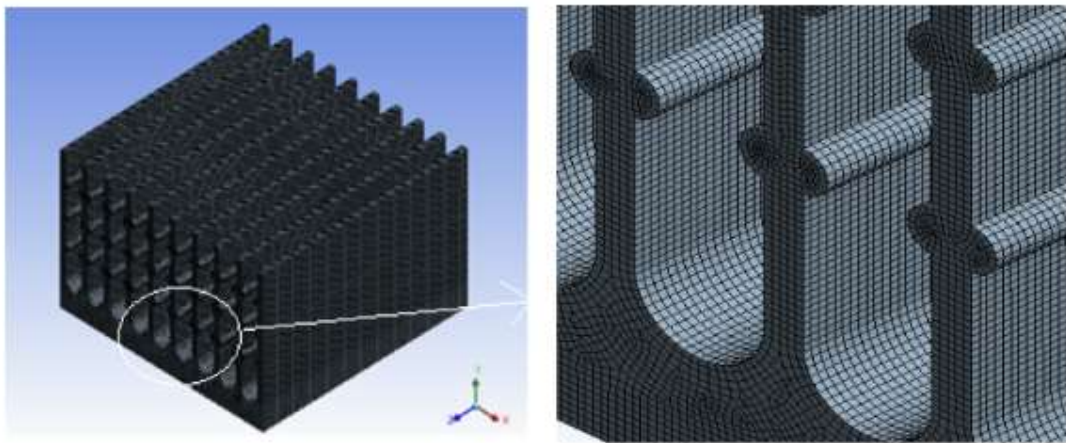


Figure 14 - CFD mesh of modern heat sink design (Freegah, et al., 2020)

4 Recent Advances in Extended Surface Design

Recent technological advances have enabled thermal management to explore new ideas; the following are some of the latest progresses and their perceived advantages.

Nano Particles

Titanium substrates coated in porous copper nanoparticles created by plasma electrolytic oxidation have been identified as a way of improving heat transfer and increasing surface area (Fattah-alhosseini, et al., 2024). Graphene and nano-structured carbon materials are also being utilised as materials in fin design; the exceptional thermal properties are used to boost heat dissipation efficiency (Lin, et al., 2023).

Advanced Manufacturing Techniques

Additive manufacturing has enabled the production of intricate, lightweight structures that were previously unachievable through conventional manufacturing methods. This advancement allows for

the optimisation of surfaces using techniques such as topology optimisation and computational fluid dynamics, facilitating the creation of designs that enhance performance and efficiency (Kivanani, et al., 2024).

Phase-Change Materials (PCM)

Extended surfaces coated with PCM's (paraffin or salt hydrates) are utilised to increase heat absorption and dissipation, especially during transient thermal loads (Yang, et al., 2024).

5 Numerical Analysis

5.1 Governing Equations

Where:

h = Heat transfer coefficient (W/m² K)

P = Perimeter of the rod (m)

k = Thermal conductivity (W/m K)

A_c = Cross-sectional area of the rod (m²)

T_b = Temperature at base (°C)

T_∞ = Air temperature (°C)

L = Finite rod length (m)

x = Distance along the rod (m)

Equation 5-1 (Fin parameter)

$$m = \sqrt{\frac{hP}{kA_c}}$$

Equation 5-2 (Adiabatic tip temperature distribution)

$$T(x) = T_\infty + (T_b - T_\infty) \frac{\cosh[m(L - x)]}{\cosh(mL)}$$

Equation 5-3 (Adiabatic tip heat transfer)

$$\dot{Q}_f = \sqrt{hPkA_c}(T_b - T_\infty) \tanh(mL)$$

Equation 5-4 (Optimum length fin parameter)

$$L = \frac{2.65}{m} \quad (\text{derived from: } mL \approx 2.65)$$

Equation 5-5 (Ratio of heat transfer)

$$\frac{\dot{Q}_f}{\dot{Q}_\infty} = \tanh(mL).$$

Equation 5-6 (Infinite fin temperature distribution)

$$T(x) = T_\infty + (T_b - T_\infty)e^{-mx}$$

Equation 5-7 (Accurate length fin parameter)

$$L = \frac{3.912}{m} \quad (\text{derived from: } e^{-mL} < 0.02 \therefore mL = -\ln(0.02) \therefore L = \frac{-\ln(0.02)}{m})$$

5.2 Fin Parameter

The effectiveness of an extended surface is crucial in enhancing convective heat dissipation. (Incropera, et al., 2006) state that for a fin with an adiabatic tip condition, the heat transfer rate $\dot{Q}_{finite}$ is lower than that of an infinitely long fin $\dot{Q}_{\infty}$ but increases with fin length until reaching an optimal point where further length provides diminishing returns.

Figure 15 illustrates the heat transfer ratio $\frac{\dot{Q}_f}{\dot{Q}_{\infty}}$ as a function of the dimensionless fin parameter, mL as described by the relationship in equation 4-5. The findings confirm the existing literature (Lienhard, 2020) indicating that the optimal fin length is defined as $mL \approx 2.65$.

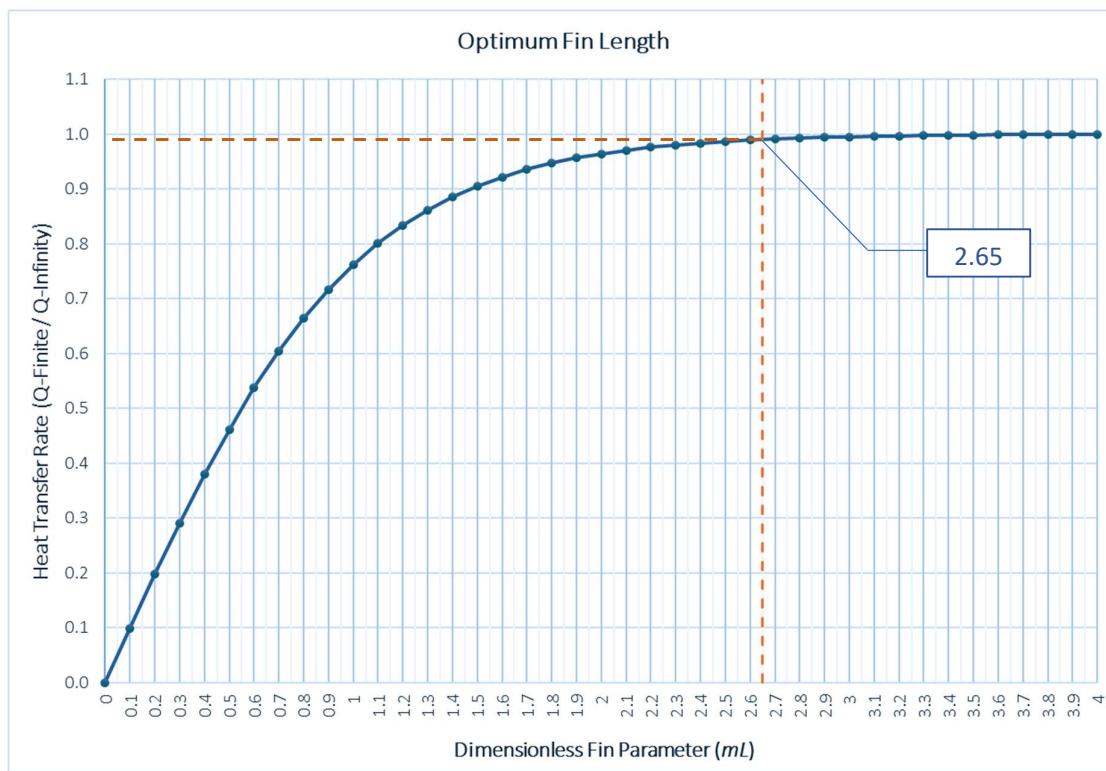


Figure 15 – Optimum fin length

5.2.1 Summary

The findings indicate that the heat transfer ratio $\frac{\dot{Q}_f}{\dot{Q}_{\infty}}$ asymptotically approaches maximum heat dissipation as the fin parameter mL reaches 2.65. At this value, heat dissipation is at approximately 99% of its maximum rate, validating the recommendation from heat transfer literature that this value represents an optimal fin length for practical applications. This finding reinforces the requirement to balance fin length against material and space constraints in extended surface design, ensuring efficient heat dissipation without unnecessary extension of the fin structure.

5.3 Heat Transfer in a Long Rod

This analysis examines the thermal performance of 7.5 mm diameter 'very long rods' made from four different materials, focusing on temperature distribution and heat transfer. The study involves a rod consistently held at a temperature of 110°C at its base while the surface of the rod is exposed to ambient air at 18°C. The analysis also explores determining the optimum and accurate lengths for efficient fin design.

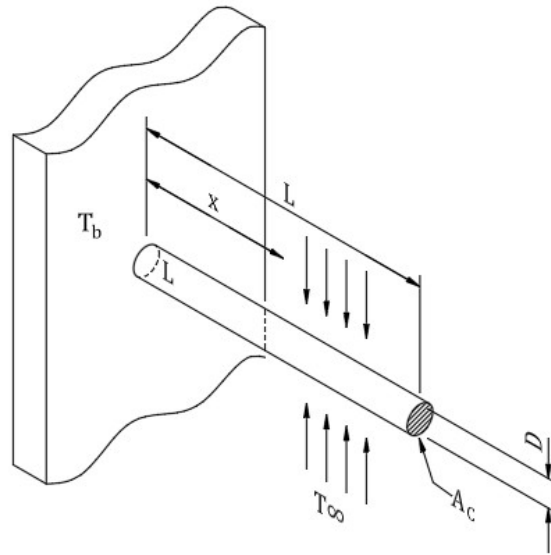


Figure 16 - Very long rod diagram (Harris, 2025)

5.3.1 Methodology

The numerical analysis followed the steps outlined below:

Temperature Distribution and Heat Transfer

Temperature distribution $T(x)$ and heat transfer ($\dot{Q}$) were calculated and tabulated for each material type along the rod, up to 0.4 m in 10 mm increments.

Optimum Rod Length

The four material types' optimum rod length was calculated to maximise heat dissipation. Utilising this length enabled the calculation of the temperature distribution $T(x)$ and heat transfer ($\dot{Q}$) data for comparison of the finite-length rod with the optimum-length rod.

Accurate Rod Length

An accurate length rod was calculated using the relation $e^{-mL} < 0.02$ and further temperature distribution data was calculated for comparison.

5.3.2 Design Parameters and Material Properties

Design Parameters and material property tables were created in Microsoft Excel to aid data collection and evaluation (Tables 1 and 2).

Table 1 – Design parameters

Parameter	Unit	Value
Diameter (D)	m	0.0075
Area (A _c)	m ²	4.41786E-05
Perimeter (P)	m	0.023561945
Air temperature	°C	110
T _∞	°C	18

Table 2 – Material properties

Material	h (W/m ² .K)	k (W/m.K)	m
2024 Aluminium alloy	30	186	9.27
Brass (70 Cu/30 Zn)	30	99	12.71
Copper	15	398	4.48
304 Stainless Steel	7.5	16	15.81

5.3.3 Assumptions

- Steady-state conditions.
- Constant heat transfer coefficient.
- Constant material properties.
- One-dimensional conduction through the rod.
- Negligible radiation exchange.

6 Results

6.1 Finite Length - Temperature Distribution

The following temperature distribution was calculated and plotted using equation 4-2 for an adiabatic tip condition.

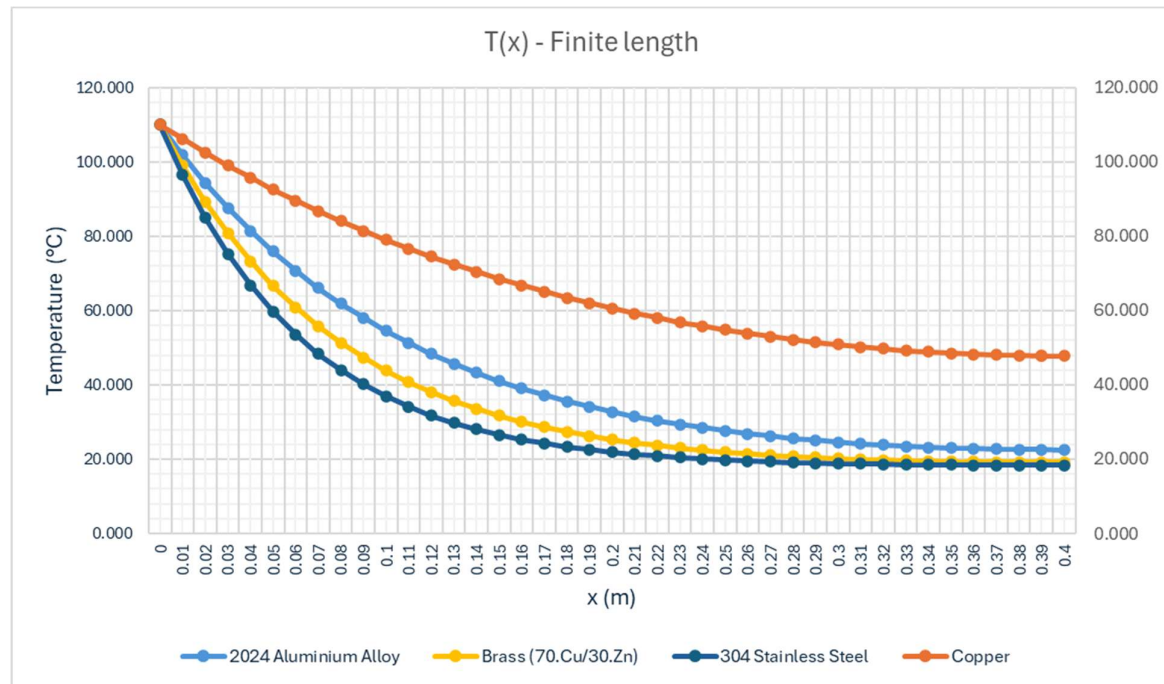


Figure 17 – Temperature distribution for finite-length rods

6.1.1 Summary

The data presented in Figure 10 illustrate a strong relationship between the fin parameter m and temperature distribution values. A higher m value, e.g. 304 Stainless Steel, indicates the fin dissipates heat more rapidly due to high convection relative to conduction. A lower m value, e.g. copper, means the fin effectively spreads heat along its length before losing it to the surrounding fluid. For finite lengths of 0.4 m, this model was unsuitable for copper or stainless steel but moderately suitable for aluminium and brass.

6.2 Finite Length - Heat Transfer

The following heat transfer values were calculated and plotted using equation 4-2 for an adiabatic tip condition.

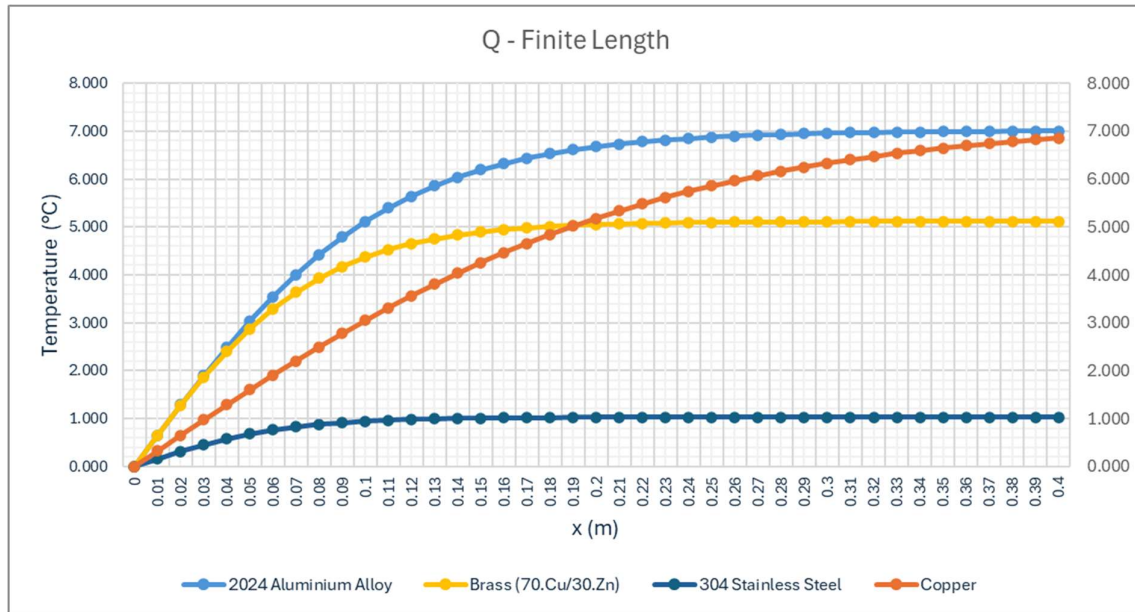


Figure 18 - Heat Transfer - Finite Length

6.2.1 Summary

The data presented in Figures 9 and 10 illustrate that a high k value increases the heat transfer rate. Copper and aluminium display the highest heat transfer due to their high thermal conductivity, whereas stainless steel exhibits poor heat transfer with low thermal conductivity.

6.3 Optimum Length – Heat Transfer

Using equations 4-3 and 4-4, an optimum rod length and corresponding heat transfer values were determined (Table 3).

Table 3 - Optimum length and heat transfer

Material	2024 Aluminium Alloy	Brass (70.Cu/30.Zn)	Copper	304 Stainless Steel
Optimum Length (m)	0.286	0.208	0.591	0.168
Heat Transfer (W)	6.942	5.065	7.180	1.018

The optimum lengths for 2024 Aluminium Alloy, Brass (70 Cu/30 Zn), and 304 Stainless Steel are shorter than the finite length of 0.4 m. For Copper, the optimum length requirement is longer than 0.4 m. These values indicate more appropriate lengths for each material.

6.3.1 Heat Transfer Comparison

The heat transfer values from the initial finite length calculations were used to compare the results with the optimum length values (Table 4 and Figure 19).

Table 4 - Finite and optimum length - Q comparison

Material	Q (Finite)	Q (Optimum)	Difference	Variation (%)	Length Change (%)
2024 Aluminium Alloy	7	6.94	-0.06	-0.86	-16.67
Brass (70 Cu/30 Zn)	5.12	5.07	-0.05	-0.98	-31.48
Copper	6.86	7.18	0.32	4.66	19.28
304 Stainless Steel	1.03	1.02	-0.01	-0.97	-40.94

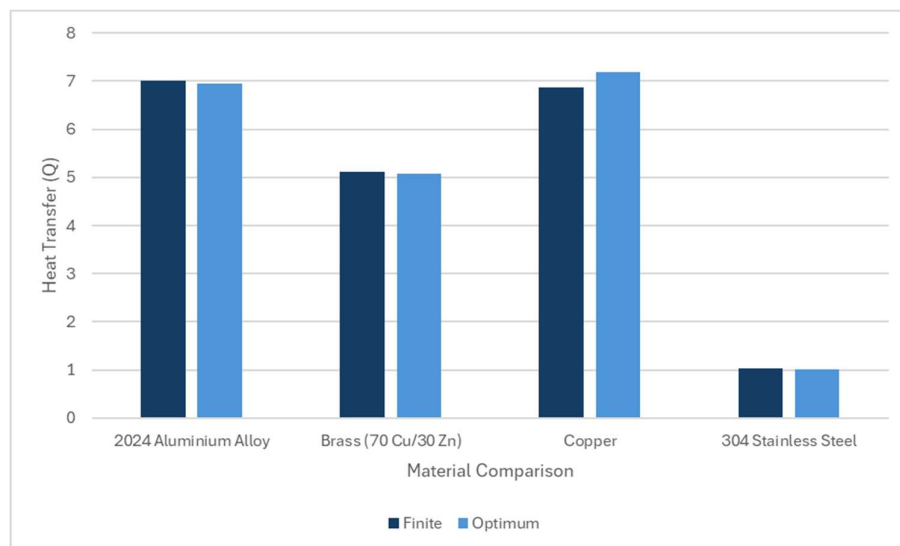


Figure 19 – Heat transfer comparison chart

6.3.2 Summary.

The following mL values were calculated to highlight the relation to the heat transfer value results and summary.

Table 5 – Finite and optimum length mL and $TANH(mL)$ values

Material	Finite mL	Finite $TANH(mL)$	Optimum mL	Optimum $TANH(mL)$
2024 Aluminium alloy	3.710	0.999	2.65	0.990
Brass (70 Cu/30 Zn)	5.085	1.000	2.65	0.990
Copper	1.793	0.946	2.65	0.990
304 Stainless Steel	6.325	1.000	2.65	0.990

2024 Aluminium Alloy, Brass (70 Cu/30 Zn), and 304 Stainless Steel:

Q values decrease slightly for the optimum lengths (percentage variation: -0.86%, -0.98%, -0.97%) as $\tanh(2.65) = 0.990$ is less than the close to 1 value for the finite rods (where $mL > 2.65$). These decreases in heat transfer are considered small when considering the favourable length decreases highlighted in Table 4

Copper:

Heat transfer increases by 4.66%, as the optimum length uses $\tanh(2.65) = 0.990$, compared to the 0.4 m rod, which uses $\tanh(1.793) = 0.946$ allowing more heat dissipation. Copper's high thermal conductivity and lower h result in a larger optimum length, enhancing heat transfer when allowing for the extended Length.

6.4 Optimum Length - Temperature Distribution $T(x)$

The following values (Table 6) were computed for the optimum length temperature distribution utilising equation 4-2, and the results were plotted (Figure 20).

Table 6 - Optimum Length - Temperature Distribution

Material	2024 Aluminium Alloy	Brass (70.Cu/30.Zn)	Copper	304 Stainless Steel
Optimum Length (m)	0.286	0.208	0.591	0.168
Temperature Distribution (°C)	30.935	30.935	30.935	30.935

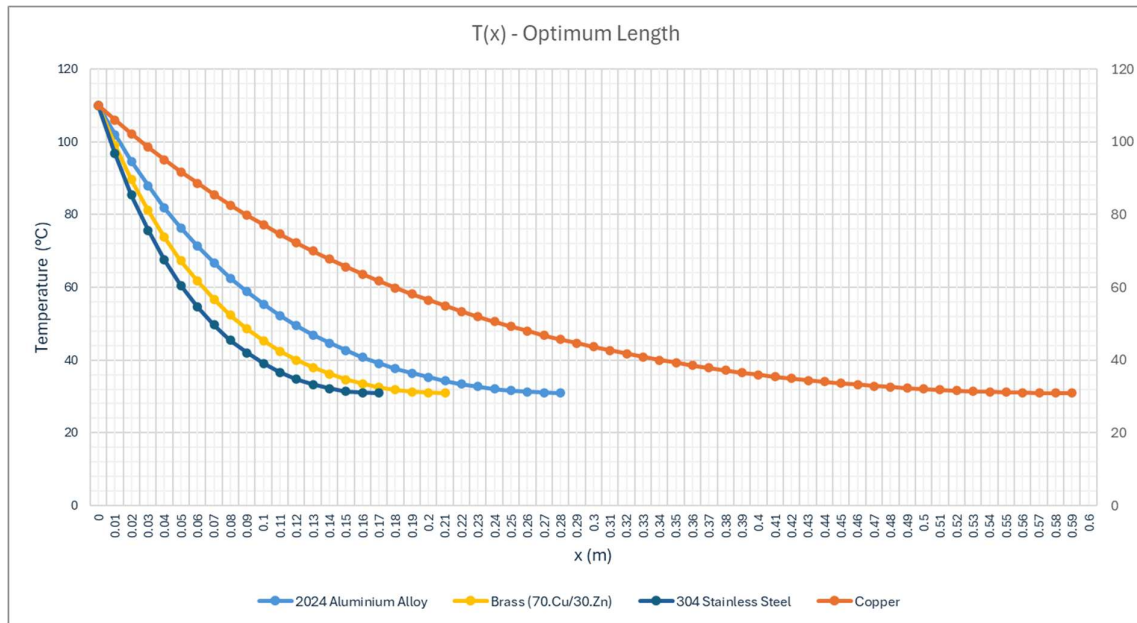


Figure 20 – Optimum length temperature distribution

6.4.1 Comparison

Table 7 – Finite and optimum temperature distribution variation

Material	T(x) Finite (°C)	T(x) Optimum (°C)	Difference (°C)	Variation (%)
2024 Aluminium Alloy	22.500	30.940	8.440	31.587
Brass (70 Cu/30 Zn)	19.140	30.940	11.800	47.125
Copper	48.560	30.940	-17.620	-44.327
304 Stainless Steel	18.330	30.940	12.610	51.187

Table 7 illustrates various significant rises in tip temperature for aluminium, brass, and stainless steel, decreasing thermal performance; however, copper tip temperature decreased by approximately 44%, enhancing heat dissipation due to the increased length.

6.5 Accurate Length

Using equations 4-6 and 4-7, an accurate rod length and corresponding temperature distribution values were determined (Table 8)

Table 8 – Accurate length and temperature distribution values

Material	2024 Aluminium Alloy	Brass (70.Cu/30.Zn)	Copper	304 Stainless Steel
Accurate Length (m)	0.422	0.308	0.873	0.247
Temperature Distribution (°C)	19.840	19.840	19.840	19.840

The Accurate length $T(x)$ values have decreased to within 2% of the ambient temperature ($\dot{Q}_{\infty}$) due to the relationship of $e^{-mL} < 0.02$.

6.6 Temperature Distribution Comparison

Tables 9 and 10 show the percentage variation in values between finite and accurate and optimum and accurate temperature distributions to highlight the differences.

Table 9 – Finite and accurate temperature distribution comparison

Material	T(x) Finite (°C)	T(x) Accurate (°C)	Difference (°C)	Variation (%)
2024 Aluminium Alloy	22.500	19.840	-2.660	-12.565
Brass (70 Cu/30 Zn)	19.140	19.840	0.700	3.592
Copper	48.560	19.840	-28.720	-83.977
304 Stainless Steel	18.330	19.840	1.510	7.912

For Aluminium, brass and stainless steel, there is a moderate change in tip temperature for accurate lengths; however, copper has significantly decreased tip temperature, increasing heat dissipation.

Table 10 - Optimum and accurate temperature distribution comparison

Material	T(x) Optimum (°C)	T(x) Accurate (°C)	Difference (°C)	Variation (%)
2024 Aluminium Alloy	30.940	19.840	11.100	43.718
Brass (70 Cu/30 Zn)	30.940	19.840	11.100	43.718
Copper	30.940	19.840	11.100	43.718
304 Stainless Steel	30.940	19.840	11.100	43.718

For each material of accurate length, there is approximately a 44% decrease in tip temperature.

To visualise the variation in Length and temperature distribution, the following plots were produced for each material (Figures 21 to 24)

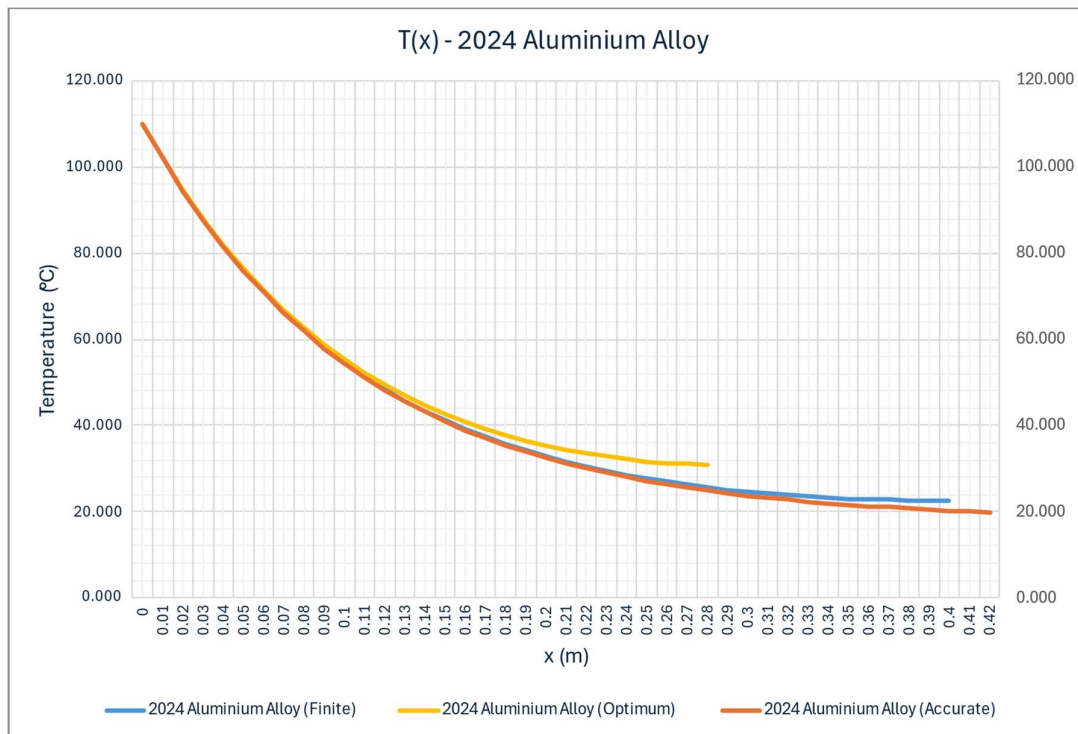


Figure 21 - 2024 Aluminium Alloy $T(x)$ comparison

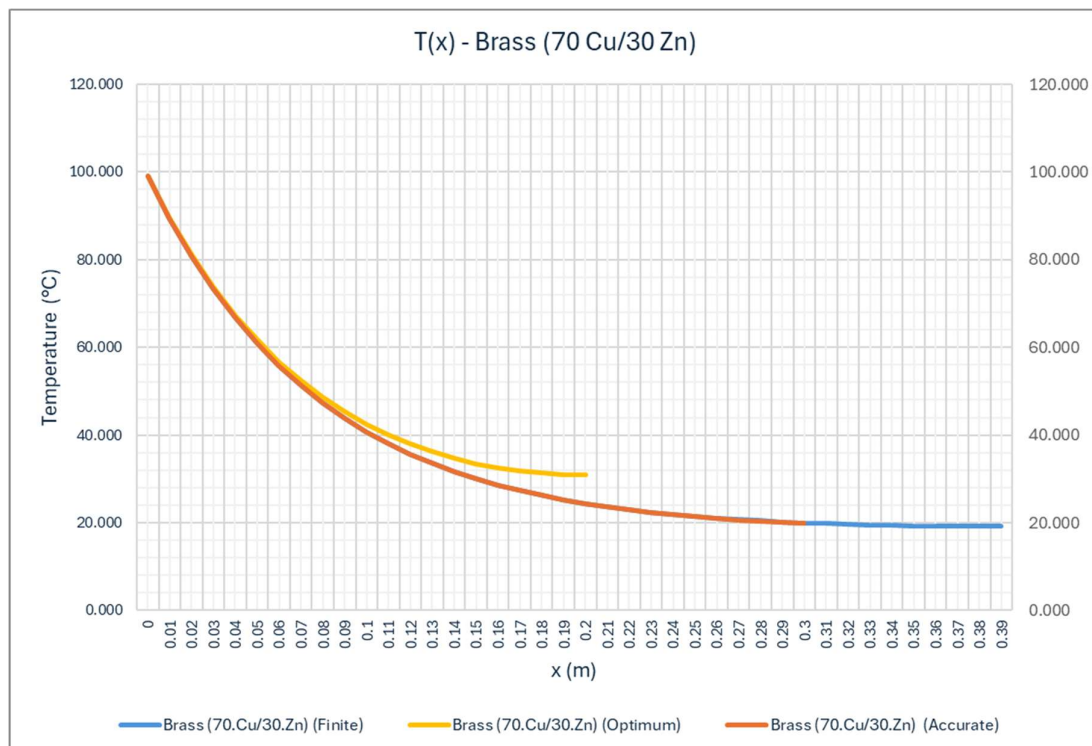


Figure 22 - Brass (70 Cu/30 Zn) $T(x)$ Comparison

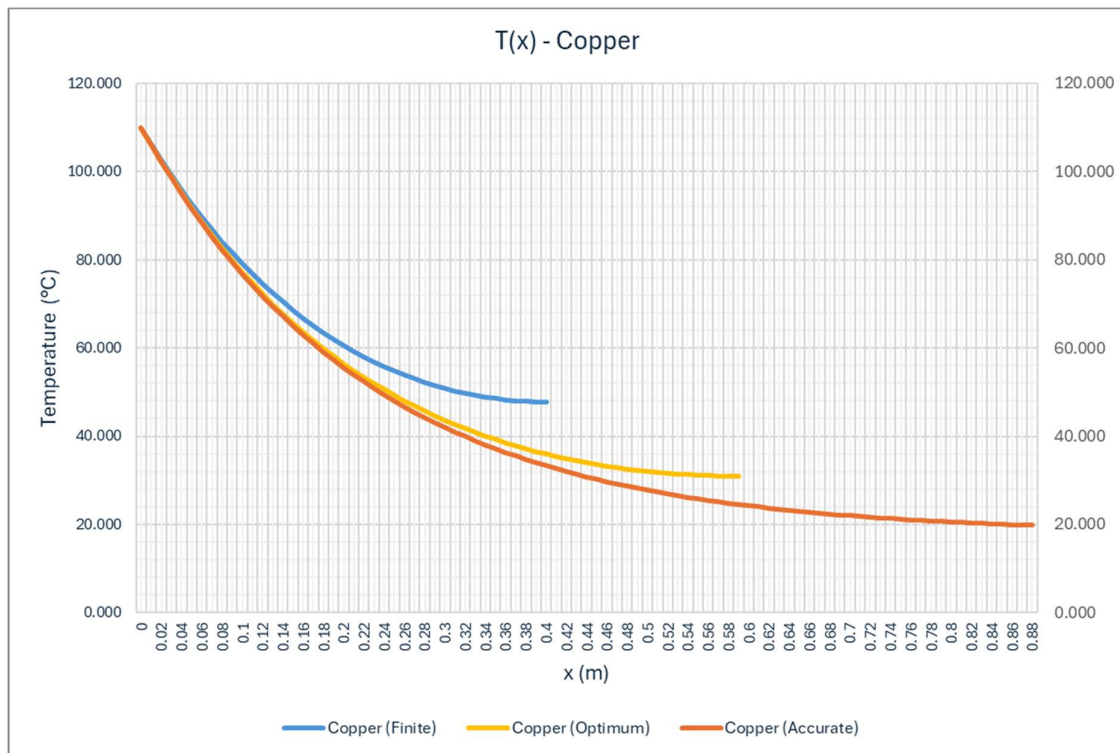


Figure 23 – Copper T(x) comparison

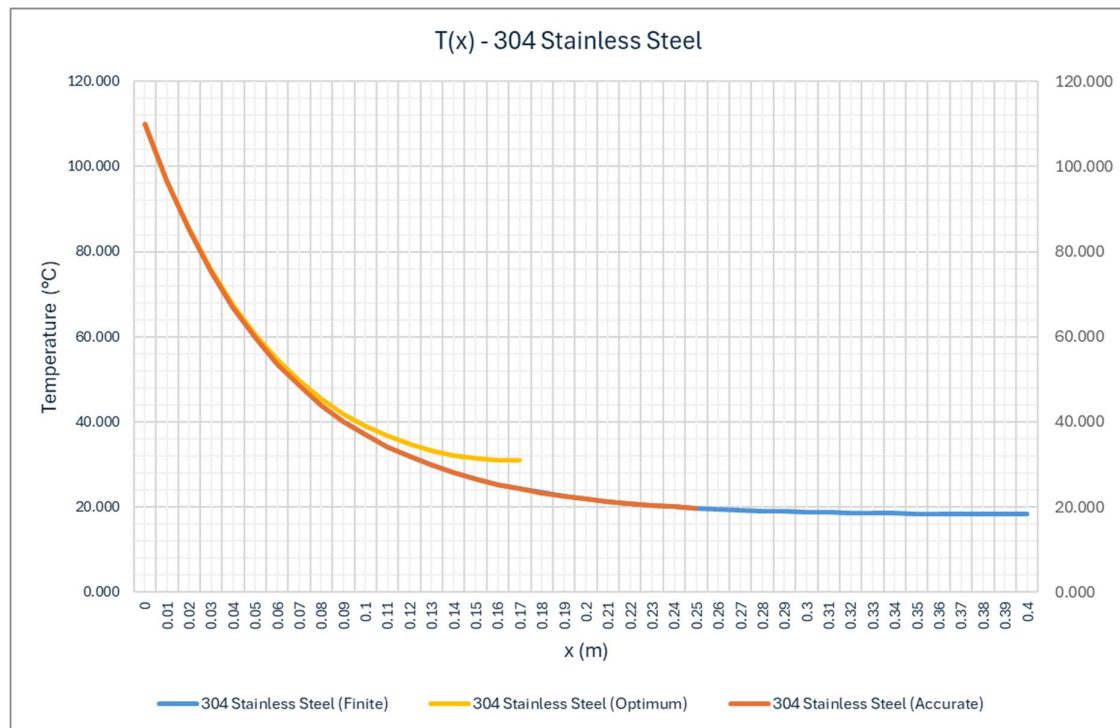


Figure 24 – 304 Stainless Steel comparison

7 Conclusion

The determination of the appropriate calculation method in fin design is conditional upon the specific requirements of the applications outlined below:

The finite length method is applicable in real-world scenarios where geometric parameters determine the fin's length, and the necessary heat transfer values are assessed for suitability. The effectiveness of this method depends on the material properties, potentially leading to inefficient outcomes for materials with significantly high or low thermal conductivity values.

The optimum length method effectively balances material usage with heat transfer needs, minimising the length required in scenarios where insignificant returns do not provide any advantages to the application. This approach is particularly applicable in contexts where space constraints and weight considerations are as critical as efficient heat dissipation.

The accurate length method maximises heat dissipation by approximating an infinite fin to maintain a temperature within 2% of the external fluid temperature. However, this approach results in fins longer than the optimal lengths for smaller returns. This method can be applied in scenarios where maximum heat dissipation is essential or for theoretical analysis.

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