Trinity College Dublin
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Design and Development of Novel Heat Exchanger Shapes

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Assignment 1
5B3 Advanced Thermal Fluids Design

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1 Executive Summary

Access to adequate and reliable heating is one of the essentials of human needs. Since Ancient Roman times, there has been a market for centralised heating systems to enhance living standards. Today, there exists a large marketplace for centralised heating systems in both temperate and continental climates. Hydronic radiators that use water as a working fluid are ubiquitous in centralised heating systems. The global market for radiators is forecasted for high growth each year, with population growth and construction projects serving as the primary factors for growth. The key market drivers in home heating are efficiency and cost; aesthetic appeal and functionality are mostly overlooked. Traditional systems are bulky and unaesthetically pleasing as the market is stagnant with high technological maturity halting innovation. We, at ThermoShelf, have developed an exciting new product that will upend the traditional market dynamics. Our solution encompasses contemporary, sleek design with key dual functionality that maximises household space utilization. The design is multifunctional and incorporates a high-performance heat exchanger, capable of emitting $1000W$, combined with an efficient shelving unit for household items.

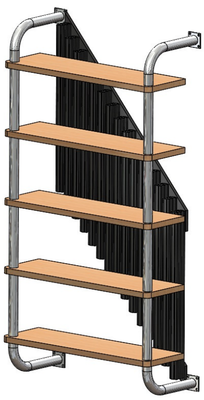


Figure 1.1: ThermoShelf High-Performance heating system

With your financial assistance ThermoShelf can breakthrough the market norms and produce a highly functional home heating system priced at N633, allowing for a 25% markup to target the masses. With these figures, it is estimated the business will become profitable at around 110k units. However, the price point could be increased targeting a higher-end market. While the break-even seems high, the primary potential stakeholder sells over 8 million units a year, indicating the commercial potential for mass production with reduced material and labour costs.

2 Proposed Technical Approach

2.1 Problem Statement and target market

Adequate heating is an essential human necessity. Ever since the introduction of the first centralised heating systems, known as a 'hypocaust' in Ancient Rome over 2000 years ago, such systems have been continuously implemented in public and residential buildings to enhance living standards and hygiene. In a contemporary setting, radiators are omnipresent in central heating systems for homes and businesses in cold and temperate climates.

In 2021, the global radiator market size was estimated to be $4.46 billion, and is expected to rise to $6.6 billion in 2030, with a compound annual interest rate of 4.5% [3]. The market is expected to rise due to expected due to the growth of populations and expansion of cities in temperate climates, with new office, commercial and residential developments needing adequate heating solutions. Moreover, the effects of climate change are becoming more pronounced globally and radiators can offer a reliable and adequate solutions in regions with large climate fluctuations.

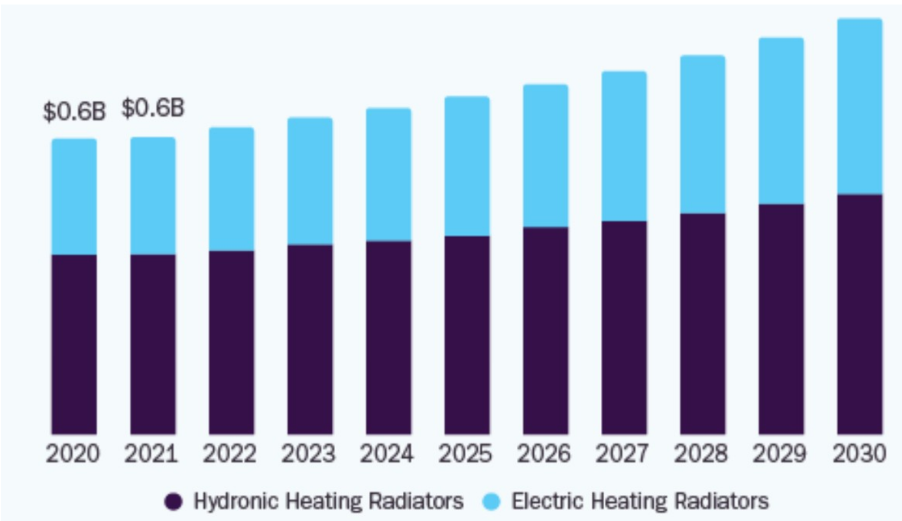


Figure 2.1: Expected Heating Radiator Market Growth in the United States (2020 - 2030)

Europe currently dominates the global radiator market and accounted for the largest revenue share of 34.5% in 2021 [4]. Strict building codes and energy new mandates implemented by the European Commission which legislate more energy efficient heating systems (EU 2024/1103) are expected to cause further growth in the European radiator market. The North American market is expected to rise due to an increased demand for cost-effective and energy efficient solutions. Asia-Pacific is expected to have the highest growth of any region with a compound annual growth rate of 5.4% from 2021 to 2030 due to large population growth and large-scale construction projects [5].

Hydronic radiators controlled 65% of revenue in 2021 and operate by pumping hot water through in-flow tubing, which is extracted from a heat exchanger and naturally convect throughout the room. Hydronic radiators are more economical than electrical radiators and are more energy-efficient than forced air heaters. Hydronic radiators and are also considered safer to use than alternative radiators since there is no fire risk and there is a lower risk of airborne-illnesses for those with allergens and respiratory illnesses as the airflow is not forced. The global hydronic radiator market size was valued at USD 3.85 billion in 2024 [4]. The market is projected to grow from USD 3.93 billion in 2025 to USD 5.43 billion by 2032, exhibiting a compound annual growth rate of 4.73%, driven by primarily green building standards.

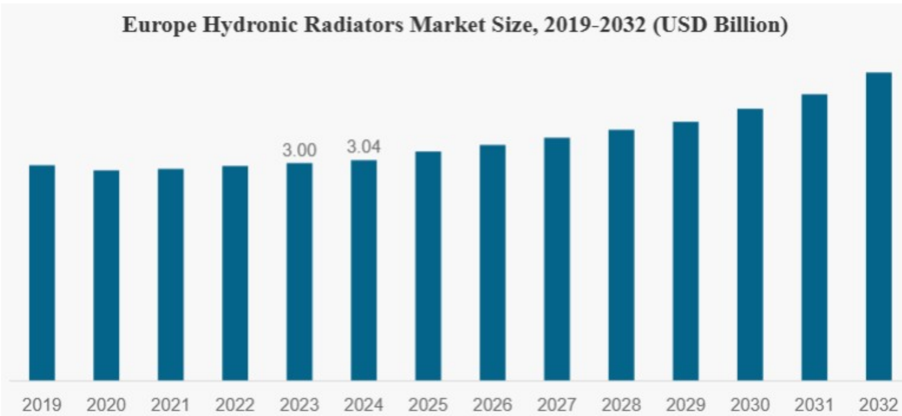


Figure 2.2: Expected Hydronic Radiator Market Growth in Europe (2019 - 2032)

The residential sector dominates the global hydronic radiator market share with 70.73%.The residential sector is expected to experience a compound annual growth rate of 5.1% until 2030 [4]. Hydronic radiators have wide-spread application in hotels, offices, places of worship, schools and other public buildings. Hydronic radiators have many means of distribution to end-users, such as websites, distributors and merchants. The aspects that are important to consumers when purchasing a radiator are cost, performance, make, technology, and availability.

However, the design of radiators has seen little innovation in recent decades. Most hydronic radiators on the market today follow a conventional 'column' or 'panel' design in which flat or profiled mono-colour panels have fins attached at the back which increase the surface area for natural convection. Radiators can occupy a considerable portion of a room and result in *'negative space'*, a term used in architecture to describe empty or unoccupied areas of a room. Negative spaces are generally unusable and are areas unintentionally left-behind of areas with specific purposes. Since radiators only serve the purpose of heating, they often take up large sections of walls in rooms and result in negative space.

Figure 2.3: Conventional Hydronic Radiator Currently on the Market

This report proposes a new radiator design in order to reduce the presence of negative spaces in rooms and to provide consumers with an alternative radiator design to the typical mono-color panel or column radiators currently on the market. The radiator in this report is integrated with a storage shelf which allows the radiator to not result in lost spaces. Storage systems with an integrated heating system are space efficient and can be implemented into multiple sectors, such as residential, commercial, industrial, schools, offices and hotels. Based on their ubiquitous application and unique design to existing radiators currently on the market, the radiator proposed in this report provides investors with a unique opportunity to invest in an secure investment in an industry that is seeing continued growth each year.

2.2 Technology/design overview

The radiator design proposed in this report primarily uses natural convection to transfer heat from the hot working fluid within the radiator to the surroundings. In the radiator there are 15 vertical channels, each with 6 fins. This configuration creates a large surface area for heat to naturally convect heat from the hot radiator surface into the room. It should be noted that the rate of heat transfer is linearly proportional to the surface area. The fins are orientated in the vertical direction for optimal heat transfer due to gravity induced air movement. The calculations of the optimal spacing of the vertical fins are shown in appendix A1.1.

The radiator has a diagonal configuration which creates a unique design point and allows for easier flow of the fluid throughout the pipe from a more even thermal gradient, creating an

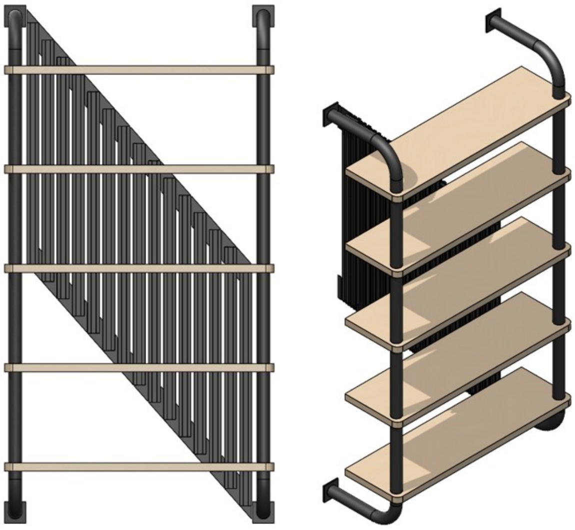


Figure 2.4: Radiator with Storage System Proposal

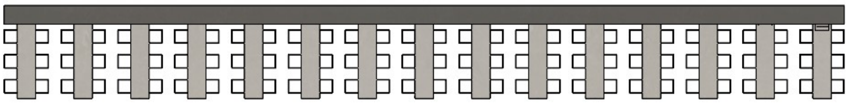


Figure 2.5: Radiator Fins

even temperature distribution as shown in figure 2.12.

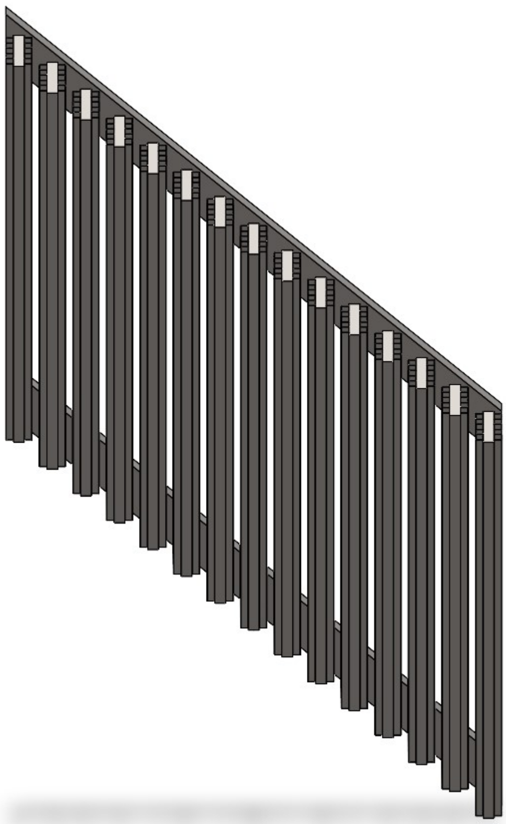


Figure 2.6: Radiator Panels Diagonal Configuration

The shelving on the radiator is modular and can be personalised to fit a customer's particular needs, in a manner which takes inspiration from IKEA furniture, which is renowned for its low cost and intuitive. For example, a customer can use less shelves if they would like to put tall items such as vases, art, sculptures or plants on the shelves. If a customer needs to maximise shelf space for items such as books or photo frames, then more shelves can be added. Clothes drying hooks can also be added to help dry jackets, towels and other items of clothing which can help customers increase their energy efficiency. Figure 2.7 shows an isometric view of the bookshelf radiator. An engineering drawing is available in Appendix A1.5.

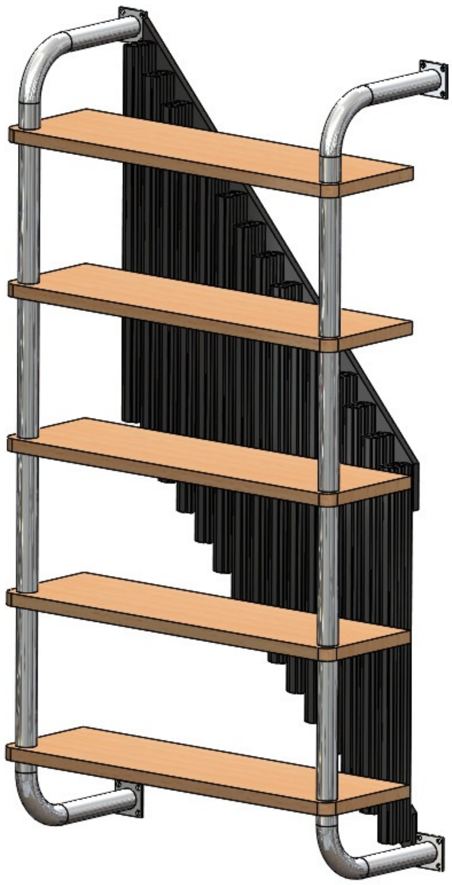


Figure 2.7: Book Shelf Radiator Concept

2.3 Performance prediction methodology performance predictions

2.3.1 Computational Domain and Governing Equations

To avoid any boundary effects and obtain accurate simulation results, the computational domain size was chosen with care as shown in Figure 2.8. It extended to 3 times the length (L) above the heat exchanger and to 1 times the length (L) below it. The lateral dimensions of the domain were similarly set as 1 time the width (W) on both sides of the heat exchanger. The resulting dimensions also provided enough space for developing natural convection flow patterns and prevented interference from the boundaries.

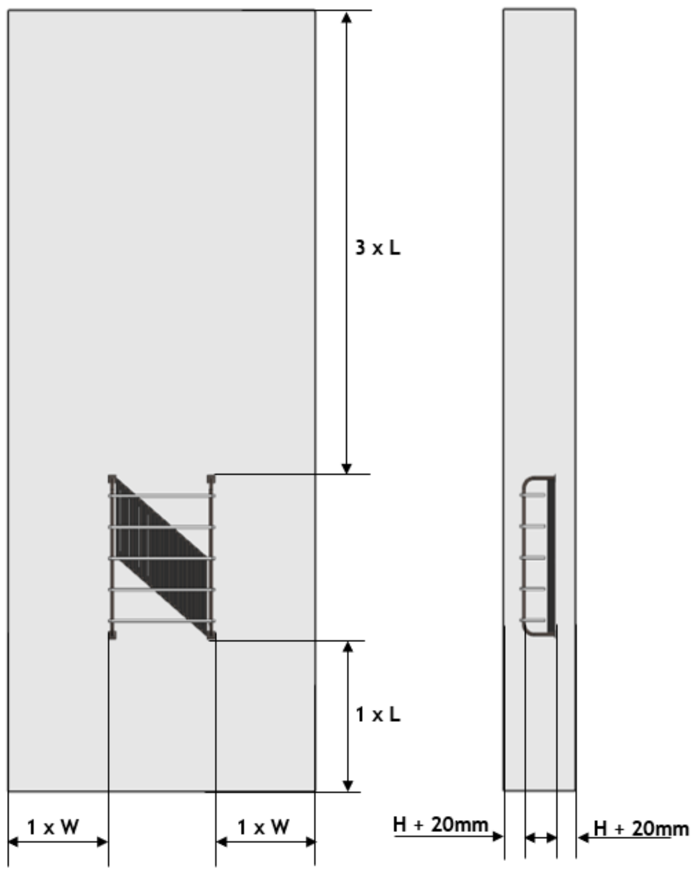


Figure 2.8: Computational domain size

The heat exchanger was subjected to a uniform temperature for the boundary conditions, which simulated the practical heat generation conditions. The heat exchanger was placed in an open environment as shown in Figure 2.9 where the natural convection heat transfer was allowed and the gravity (g) was introduced to simulate buoyancy driven airflow. The simulation was run to see the effect of different thermal loads on power dissipation as the temperature of the heat sink was varied from 60°C to 90°C.

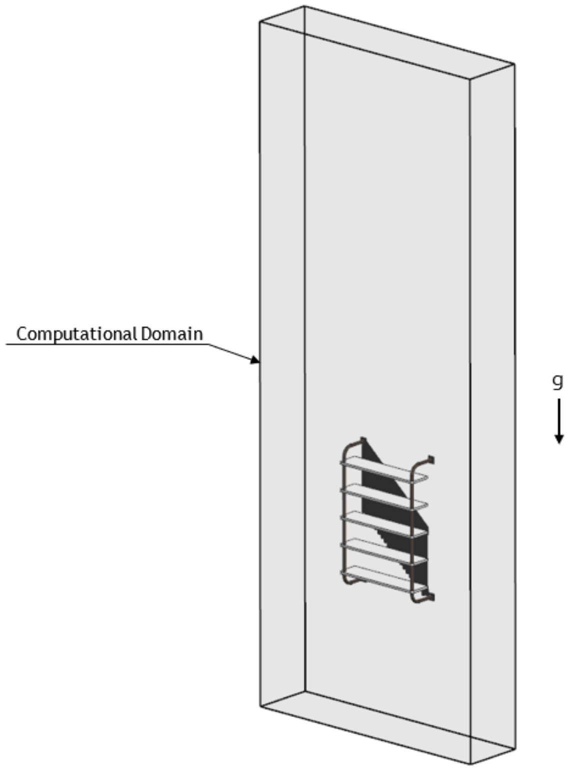


Figure 2.9: Boundary conditions

The computational domain is solved for fluid flow and heat transfer with the k-ϵ turbulence model in FloEFD. The commercial software package FloEFD is used to solve the steady state conservation equations for mass, momentum and energy within the fluid domain. These are follows [6]:

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{2.1}$$

Conservation of Momentum:

$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + \mu \nabla^2 u + F \tag{2.2}$$

Conservation of Energy:

$$\rho \frac{\partial h}{\partial t} + \rho (u \cdot \nabla) h = \nabla \cdot (k \nabla T) + \Phi \tag{2.3}$$

Where,

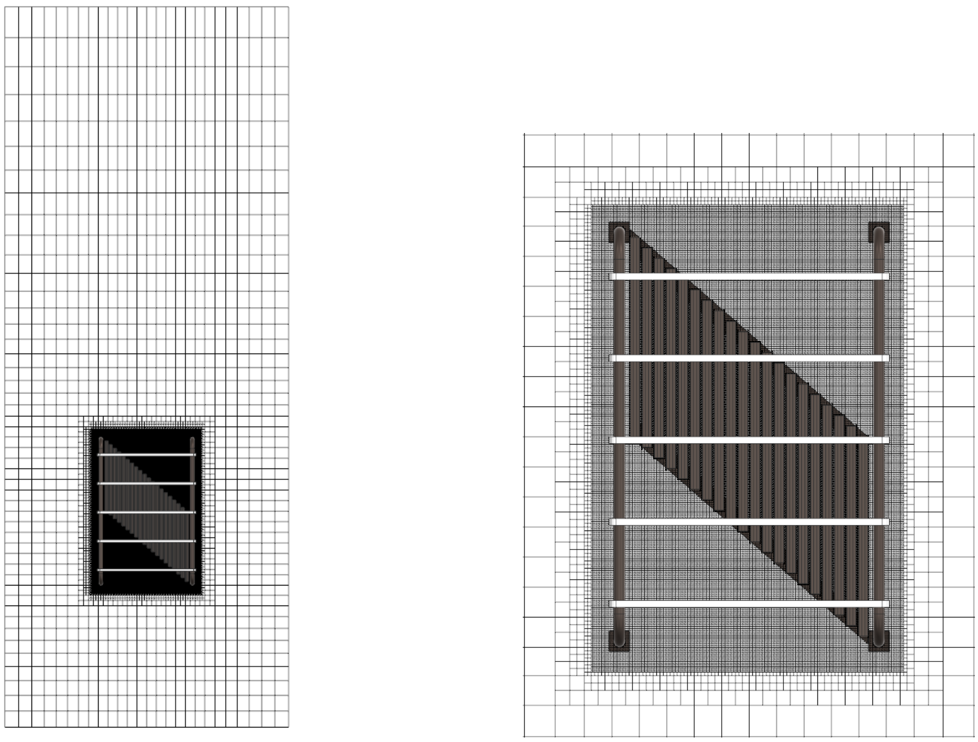
ρ = Fluid density

u = Velocity vector

p = Pressure
μ = Dynamic viscosity
h = Enthalpy
T = Temperature
k = Thermal conductivity

2.3.2 Meshing and Mesh Independence

A mesh independence study was carried out using FloEFD to ensure accurate and reliable simulation results. The mesh density is increased incrementally until the key variables such as heat transfer coefficient and power converge sufficiently. As shown in the Figure 2.10, mesh is divided into two mesh regions to optimize computational resources and precision. To resolve the fine scale thermal and flow gradients, the highest mesh density was used immediately surrounding the fins. This results is consistent with requiring a mesh on the order of 3.53 million cells to achieve accurate and repeatable simulations.



(a) Illustration of computational mesh (b) Localised mesh regions

Figure 2.10: Mesh views

Parameter	Mesh 1	Mesh 2	Mesh 3	Mesh 4	Mesh 5
No of Elements (x10^6)	0.93	2.20	3.43	3.53	04.05
Difference in Heat Transfer Coefficient (%)	-	3.70	2.80	0.71	0.47
Power Difference (%)	-	3.71	2.80	0.71	0.48

Table 2.1: Mesh Independence Study for Thermal Analysis

2.3.3 Simulation Model Verification and Results

CFD simulations were performed to analyze the key performance metrics, being the correlation between the base temperature and the power dissipation and the natural convection from the heat exchanger. Figure 2.11 shows the relationship between base temperature and power dissipation, which is linearly increasing with base temperature from 60°C up to 90°C. The power dissipation of 1001 W is highlighted in blue for reference point at 75°C as per project requirement. It is observed that the trend indicates an increase in convective heat transfer at higher base temperature, which leads to better heat dissipation. Theoretical expectations are met and the design is shown to be feasible in this performance behavior.

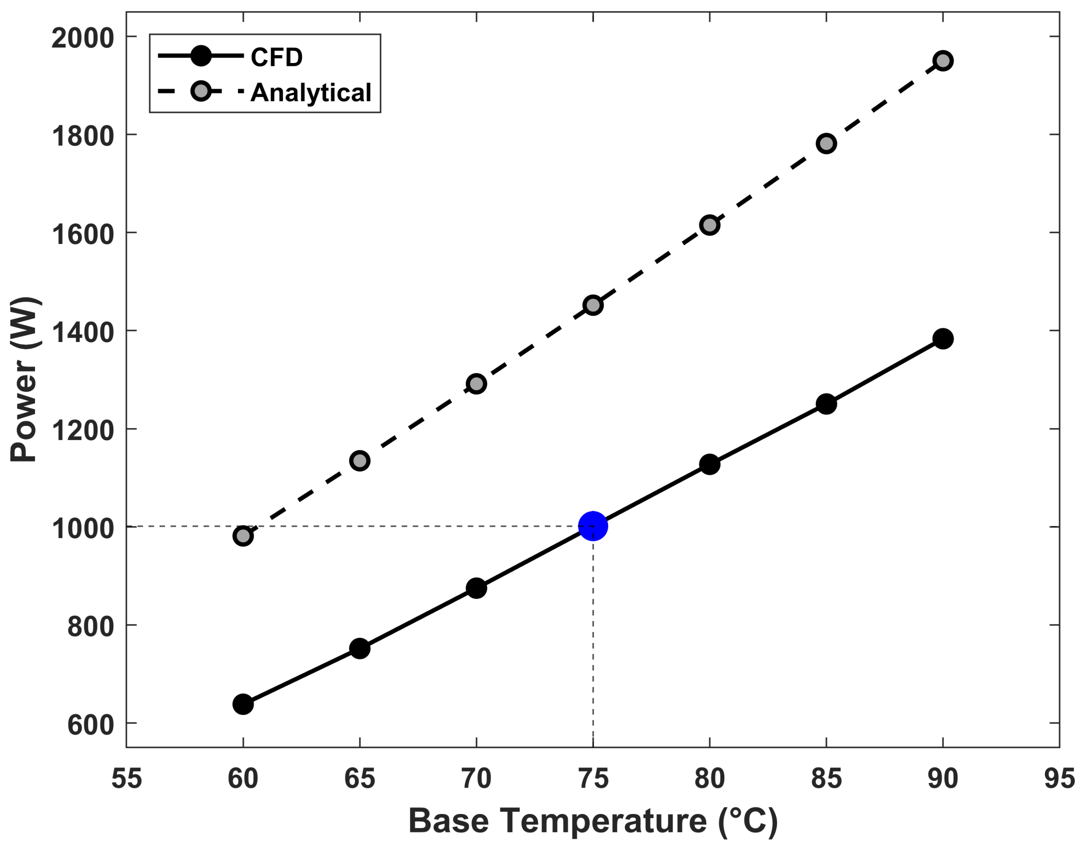


Figure 2.11: Power VS Temperature

Figure 2.12 shows a temperature contour plot of the thermal behavior of heat exchanger in open environment at base temperature of 75°C. It is found that the highest temperature zones are close to the base region, and the temperature decreases gradually with the outer sections, which indicates the effective heat spreading by natural convection. It also shows that the design of the heat exchanger makes efficient thermal dissipation possible and keeps hot spots down.

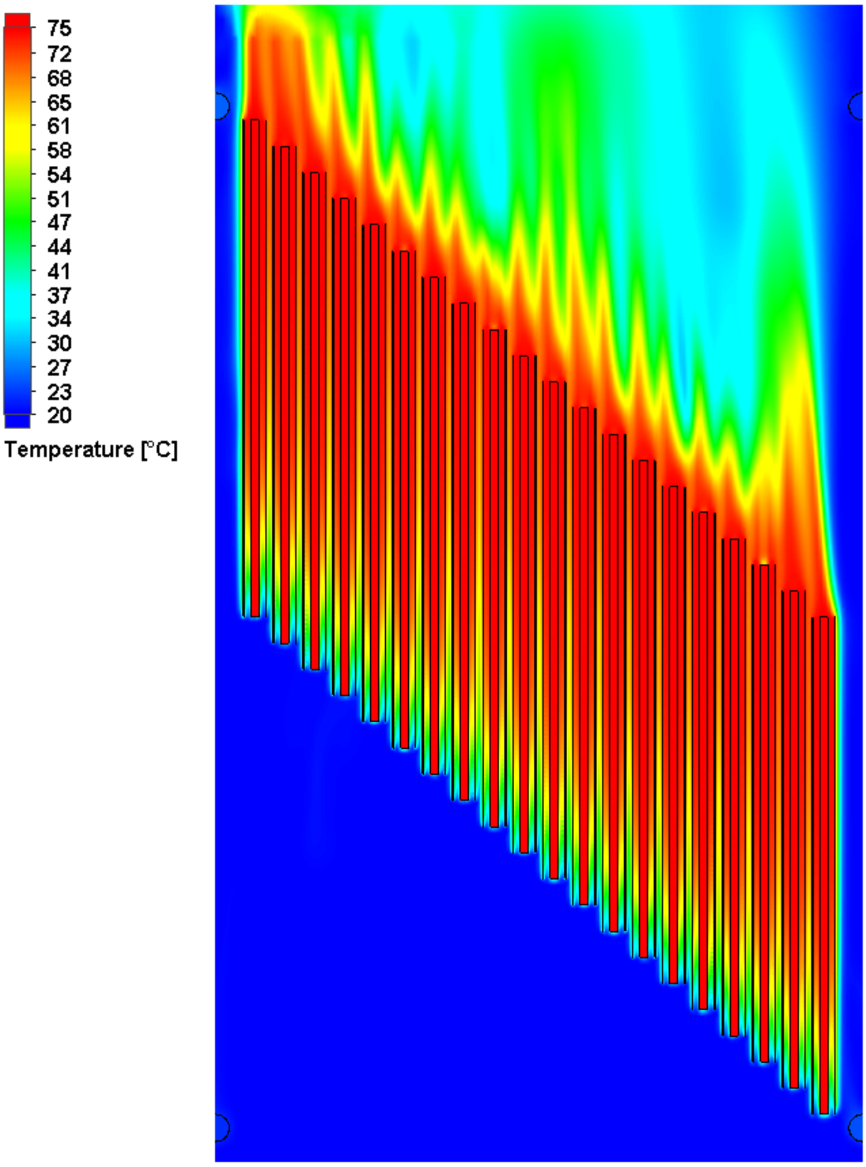


Figure 2.12: Sectioned model plot of temperature

Temperature gradient along the radiator fins, supports the calculation of the optimal fin spacing for improved heat transfer, in agreement with Bar-Cohen's [1] work on the convective cooling efficiency.

2.4 Hydraulic Performance

In order to ensure efficient heat distribution and reduce operational costs, it was imperative to comply with a design constraint of a pressure drop less than $20kPa$. Initial analytical calculations were carried out using flow rates from $0.5 - 3\ LPM$ range corresponding to Reynolds numbers of $(650 - 3900)$. Pressure drop was evaluated using the Darcy-Weisbach equation shown below:

$$\Delta p = f_d \frac{L}{D} \frac{\rho v^2}{2} \tag{2.4}$$

Where:
Δp = Pressure Drop
f_d = Darcy friction factor $(64/Re)$ for $Re < 2100$
D = Hydraulic diameter
μ = Dynamic viscosity
ρ = Fluid density
v = Fluid Velocity

The Darcy friction factor was estimated using the Moody chart (A1.2). This analytical data is useful to compare the numerical hydraulic performance evaluation carried out using SOLIDWORKS Flow simulation. CFD simulations were performed with boundary conditions of a mass flow inlet the top corner of the heat exchanger and an ambient pressure outlet ($101325Pa$ and $70C$)at an extended section of square tube of same internal geometry $(56x8)mm$. Head loss was evaluated isothermally at $70C$, considering only laminar flow, at rates of $0.5 - 3LPM$.

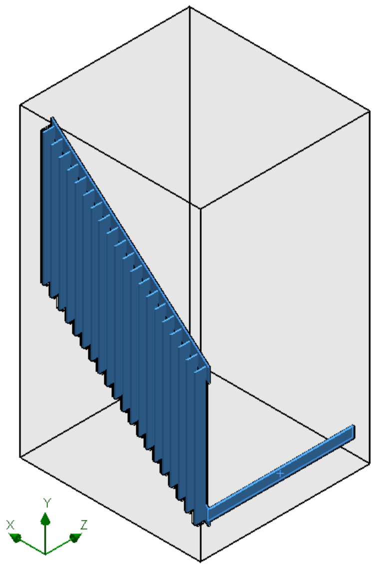


Figure 2.13: Fluid Domain

2.4.1 Meshing and Mesh Independence

Mesh independence was investigated by considering the convergence of evaluated pressure drop (inlet-outlet) at three increasingly refined mesh settings, between 30000 and 305000 elements. Monotonic convergence was experienced with a grid convergence ratio of 0.94.

Parameter	Mesh 1	Mesh 2	Mesh 3
No of Elements (x10^5)	0.78	1.67	3.05
Presure Drop (kPa)	14.426	14.423	14.421
Difference (%)	-	-0.0189	-0.0178

Table 2.2: Mesh Independence Study for Hydraulic Performance

Mesh 2 was chosen to complete further analysis as it balanced reliable results with computational effort required.

2.4.2 Simulation Model Verification and Results

Flow Rate	0.5	1	1.5	2	2.5	3
Reynolds Number (Re)	687.96	1375.92	2063.87	2751.83	3439.79	4127.75
$\Delta P_{\text{friction}}$ (kPa)	18.68	37.36	56.05	74.73	93.41	112.09
ΔP_{minor} (kPa)	10.35	41.40	93.14	165.58	258.72	372.56
ΔP_{total} (kPa)	14.70	14.75	14.82	14.91	15.02	15.16

Table 2.3: Analytical Pressure drop for different flow rates

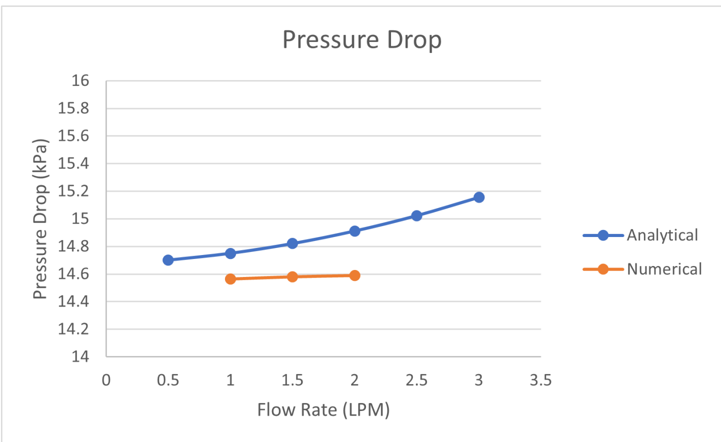


Figure 2.14: Analytical vs Numerical Pressure Drop

There is clear correlation between the numerical and analytical results. The analytical pressure drop evaluated using the Darcy-Weisbach method assumes fully developed flow at the inlet, this is not the case in our CFD simulations. This could be one potential explanation why the analytical friction factor is greater, as the CFD would show smaller frictional losses in the entrance region because the flow is still developing. The analytical result shows a clear upwards quadratic relationship as expected (losses proportionate to v^2). The numerical pressure drop trend showed a less clear relationship with increasing flow rate, the pressure drop plateaued and did not increase with exponential character unless the rates were dramatically increased. This could be as our solver only considered laminar flow, which would have a linear relationship with flow rate Further work must be completed using a turbulent model to further validate our design.

3 Design for Manufacture

3.1 Materials and Manufacturing

3.1.1 Materials

The materials used for this product are aluminium, mild steel, and oak. Additional materials needed are black paint and 5M steel screws with wall anchors if needed. The product comes in two units, the radiator and the bookshelf.

The radiator is mainly constructed of the aluminium. The aluminium is needed in 15mm by 60mm rectangular hollow section with thickness of 2mm for the main water flow and 0.5mm sheet for the square fins that are used to generate more surface area and the radiator mounting plates. Fittings are also needed to connect this radiator to the water supply.

The bookshelf is mainly constructed of the mild steel and oak. The mild steel is used on the 40mm diameter pipe and the 46mm diameter pipe for the fittings as the main structural part of the bookshelf as well as the 5mm wall plates. The oak is used for the individual shelves that can be used for storage.

For finishing and mounting we need the paint and the screws. The black paint is used on the exposed metal parts. The 5M steel screws are used to mount the radiator and the bookshelf units on the wall.

3.1.2 Manufacturing

The manufacturing of the radiator unit involves cutting, drilling, bending, welding, and painting. Volume of radiator is 4696 cm^3. The 20 main water rectangular hollow section as well as the inlet and outlet rectangular hollow section are cut to length with their angled ends. The connection slots between the inlet/outlet rectangular hollow sections and the main rectangular hollow section are cut out. The ends for the rectangular hollow section are cut out of sheet as well. The sheet needed for the fins and the radiator mounting points is cut into size. The sheet then needs to be bent into square corrugations for the fins and right angles for the wall mounts. The fins can at this point be welded onto the main pipes. The

M5 holes for the wall mounts can be drilled. The tops of all the water pipes can be welded on and the main water pipes can be welded on the inlet/outlet pipes. The fitting for connecting the radiator to the water supply can now be welded onto the inlet and outlet pipes. The unit can then be painted.

The manufacturing of the bookshelf unit involves cutting, drilling, bending, threading, welding, painting, sanding, and oiling. The 40mm pipe and the 46mm pipe can be cut into lengths that match the height of a shelf as well as the bended corners that connect to the wall, then threaded and tapped. The necessary sections of this can be bent into 90 degree corners. The 5mm plate can be cut into 65mm squares and the M5 holes can be drilled and countersunk. The ends of the pipes connected to the wall can be welded on to these sections. The wood can be cut into 815mm by 242.5mm by 25mm blocks and the outward facing corners can be ground off. The 40mm holes for the supporting pipe can be drilled into these. The wood can be then sanded and oiled. During assembly, sections of pipe the height of the individual shelf are connected using the wider 46mm pipe fittings. The wooden shelves can then rest on these fittings once assembled.

3.2 Bill of Materials (BOM)

This section includes the total costs of all of the materials required for the products, the quantities of these products needed, and the total cost of the materials needed for manufacturing the product.

Materials or Components	Unit Cost	Quantity	Total Cost
Aluminium Square Pipe (15mm x 60mm)	€14.12 per m	13.00576m	€183.64
Steel Round Pipe (40mm O/D x 2mm)	€8.68 per m	3.714159m	€32.24
Steel Round Pipe (46mm O/D x 4mm)	€8.40 per m	0.25m	€2.10
Aluminium Sheet (0.5mm thickness)	€54.04 per m^2	2.7087m^2	€146.38
Steel Plate (5mm thickness)	€120 per m^2	0.0169m^2	€2.03
Wood (Oak) (210mm x 20mm)	€25.39 per m	4.075m	€103.46
Screws (M5 55mm)	€0.04475 per screw	28 screws	€1.25
Paint (Black)	€6.576 per m^2	5.5404m^2	€36.43
		Total	€507.53

Table 3.1: Bill of Materials for the product.

3.3 Pricing and Price Point

The cost of manufacturing the radiator is €507.53. By analysing the end-of-year financial statement of 'Stelrad Group plc', which is the largest radiator manufacturer in Europe, the annual fixed costs are approximately €10.8 million [7]. These fix costs include machinery, rent, property taxes, staff salaries and administration fees. In order to achieve a sufficient profit from sales, a mark-up of 25% was selected. This results in a retail price of €633. In order to the number of radiators necessary for profit, a breakeven analysis was conducted. The breakeven analysis shows that the radiator with pricing structure that allows for a 25% mark up becomes profitable after 110,000 units. As the project brief specifies an expected 8 million units are to be manufactured, the expected revenue is €4.67 billion.

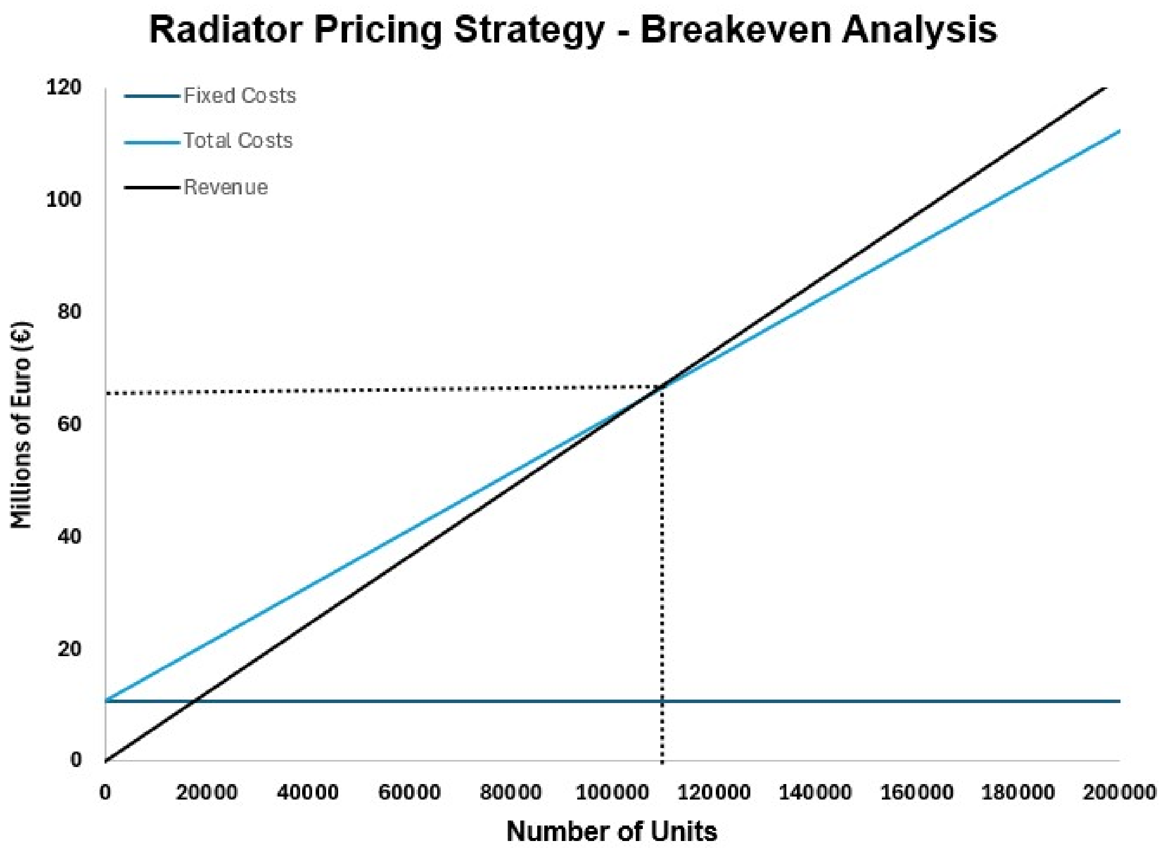


Figure 3.1: Pricing Strategy based on Breakeven Analysis

4 Technology Appropriateness and Outlook

This innovative heat exchanger design combines high efficiency, compactness and aesthetics with manufacturing and economic viability. As the HVAC industry grows and building energy codes tighten, the limitations of traditional radiators are highlighted, while this design offers significant advantages in terms of thermal performance, structural optimisation, cost control and aesthetics.

The design takes into account the needs of the modern HVAC market, with an optimised heat exchanger structure capable of operating at a maximum thermal power output of 1000W and a pressure drop of up to 20kPa. In addition, it adopts natural convection heat dissipation, avoiding the extra energy consumption and maintenance costs of mechanical ventilation, and is suitable for noiseless heating systems in domestic and commercial buildings. At the same time, the wall-mounting solution controls the overall thickness, enabling efficient operation in modern buildings where space is at a premium.

From a manufacturing point of view, the heat exchanger has been manufactured using viable materials and processes such as mild steel and aluminium alloys in order to balance thermal performance and cost control. The processes involved in the design solution (e.g. stamping, welding, painting, etc.) are well established industrial manufacturing methods, ensuring that the product can be mass-produced to meet market requirements for cost and capacity. In addition, the structural innovation of this heat exchanger allows it to fulfil the heat exchange requirements as well as to be decorative, providing higher added value to the consumer as part of the furniture or architecture, compared to traditional designs.

Industry trends show that HVAC equipment is becoming more energy efficient, more aesthetically pleasing and more efficient. Stringent building energy efficiency regulations in Europe (e.g. EU 2024/1103) are driving demand for efficient heating products, while rapid growth in North America and Asia Pacific means greater market potential. The project's heat exchanger design is expected to be in practical use within the next five years due to its superior thermal efficiency, space utilisation and aesthetic properties.

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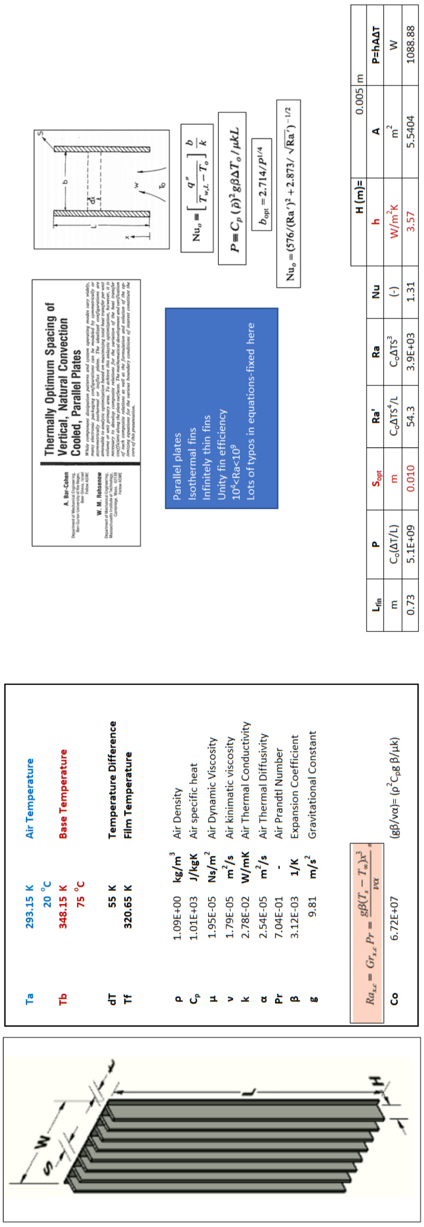
A1 Appendix

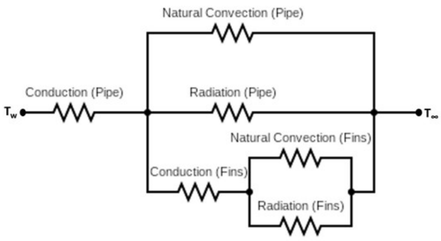
A1.1 Optimum Spacing Calculation (Bar-Cohen [1])



A1.2 Thermal Resistive Network Analytical Calculation

Three forms of heat transfer from radiators:

1. Conduction within Pipes and Fin
2. Natural Convection from Surfaces
3. Radiation from Surfaces



Conduction within Pipes and Fins:

$$R_{cond\ (pipe)} = \frac{\ln\left|\frac{r_2}{r_1}\right|}{2\pi kL} \qquad R_{cond\ (pipe)} = \frac{\ln\left|\frac{0.02}{0.018}\right|}{2\pi(237)(4.22)} = 1.67 \times 10^{-5}\ K/W$$

$$R_{cond\ (fins)} = \frac{L}{kA} \qquad R_{cond\ (fins)} = \frac{(41.6)}{(237)(6.56)} = 0.0268\ \mathrm{K/W}$$

Convection from Pipes and Fins:

$$R_{nat-conv} = \frac{1}{hA} \qquad R_{conv\ (pipe)} = \frac{1}{(5)(0.66)} = 0.303\ \mathrm{K/W}$$

$$R_{conv\ (fins)} = \frac{1}{(5)(6.56)} = 0.0304\ \mathrm{K/W}$$

Radiation with Pipes and Fins:

$$R_{rad} = \frac{1}{\varepsilon\sigma A({T_s}^4 - {T_\infty}^4)}$$

$$R_{rad,pipe} = \frac{1}{(0.9)(5.67 \times 10^{-8})(6.56)(348^4 - 293^4)} = 4.09 \times 10^{-4}\ K/W$$

$$R_{rad,fins} = \frac{1}{(0.9)(5.67 \times 10^{-8})(0.66)(348^4 - 293^4)} = 4.07 \times 10^{-3}\ K/W$$

$$\boxed{R_{TOT} = 0.027\ K/W} \qquad \boxed{Q = 2024.98\ W}$$

Figure A1.1: Thermal Resitive Network

A1.3 Hydraulic Performance

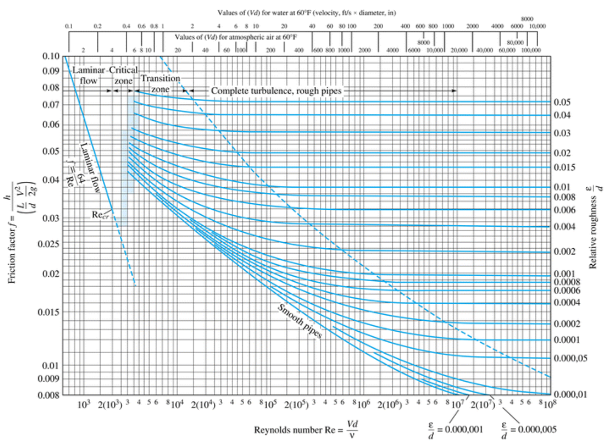


Figure A1.2: Moody Chart [2]

A1.4 Drawing

All Dimentions are in mm

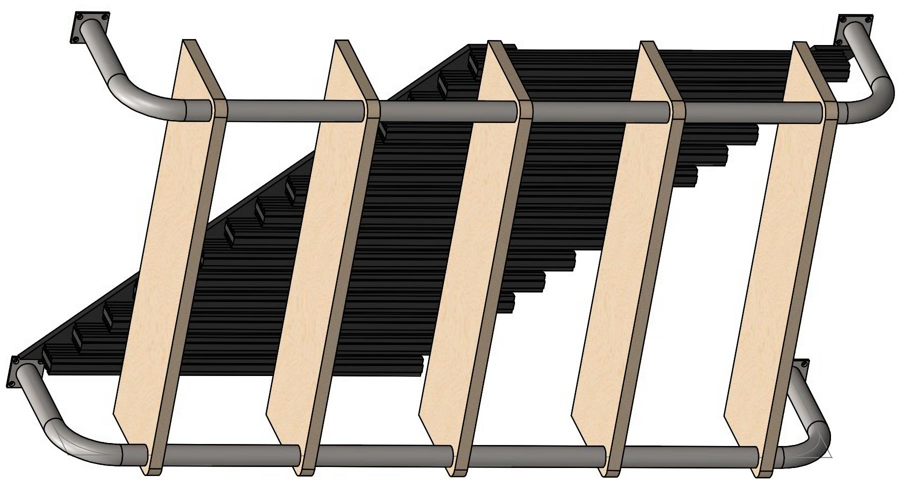
TITLE: Book Shelf Radiator

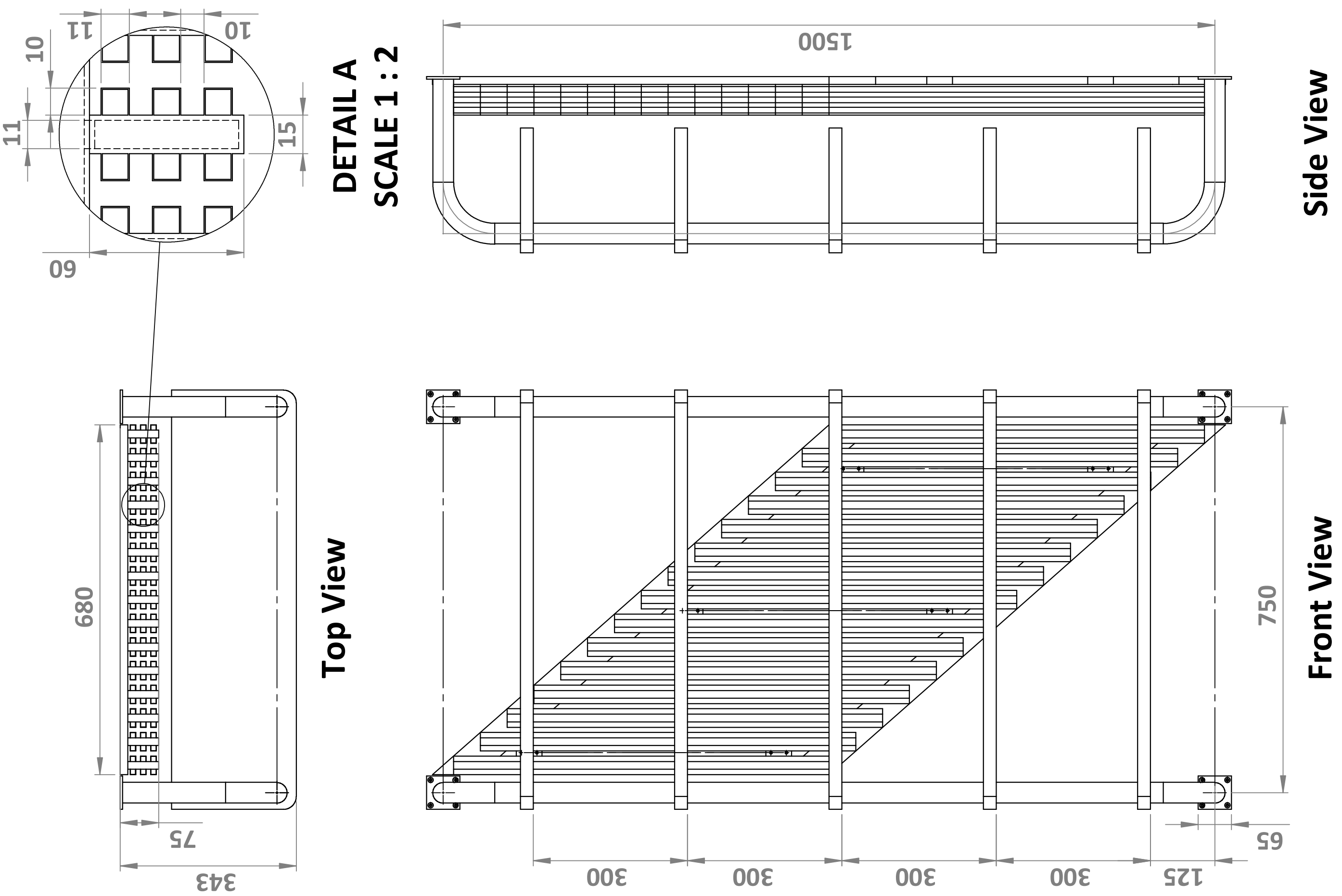
DWG NO. 01

A3

SCALE:1:10

SHEET 1 OF 1





A1.5 Illustration of Book Shelf Radiator in Living Room

Figure A1.3: Living Room Illustration