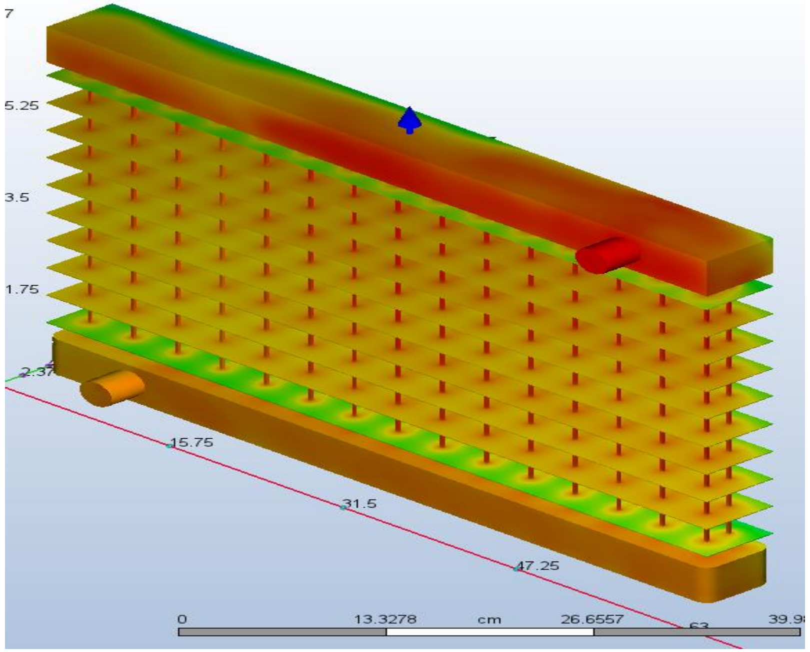
Theoretical Basis for Thermal Performance and Manufacturing of Radiator core



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Introduction

- Car radiators are important for keeping the automobile engine cool in order to maintain suitable operating conditions
- We will be looking at the comparison between theoretical and simulated results for the tube banks.
- Subsequently we will break down the cost of manufacturing the optimized radiator from our last presentation

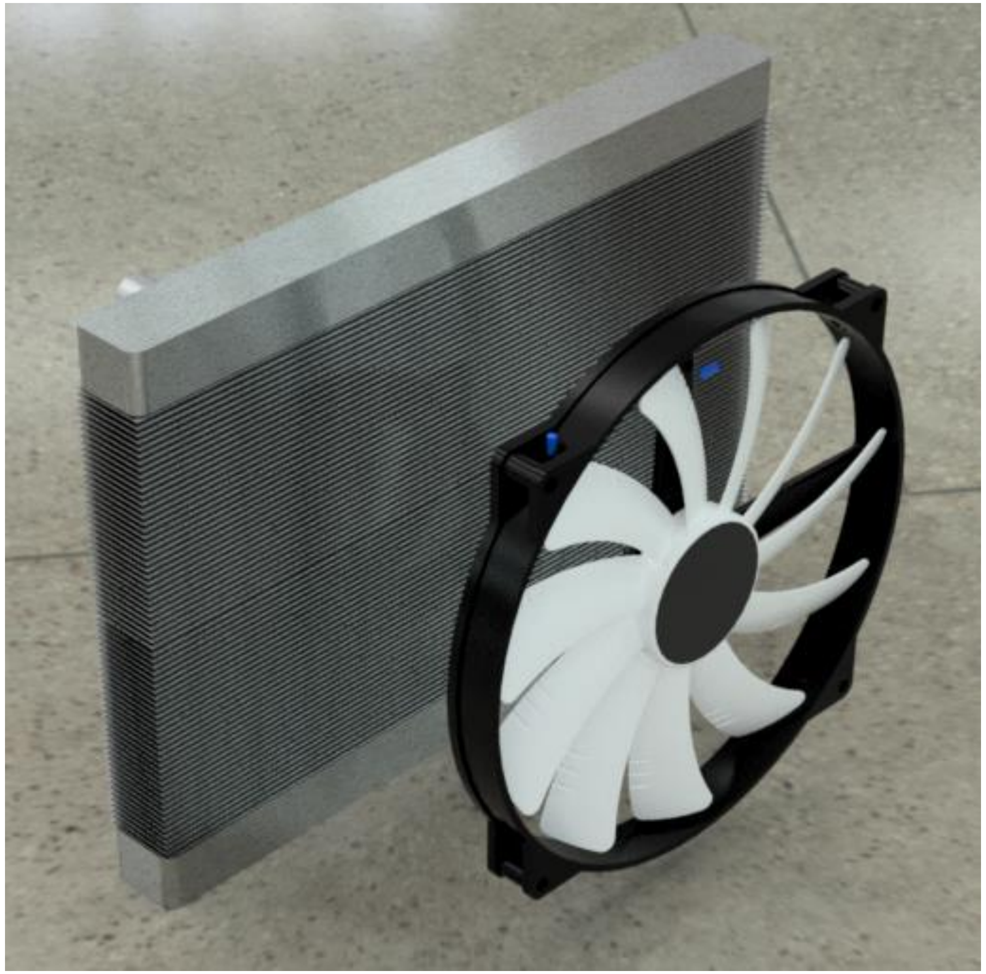


Fig 1. Optimized car radiator

Aim and Objectives

Aim

- The aim of this project is to create virtual laboratories to train and educate engineering students

Objectives

- To show correlation between theoretical and simulation results
- To provide material and manufacturing cost
- To show difference between our optimized and market radiators
- Exploring 3D printed radiators

Previous Presentation

Radiator Label

1. Radiator fin
2. Tubes/Pipes
3. Radiator row
4. Number of columns
5. Fin thickness

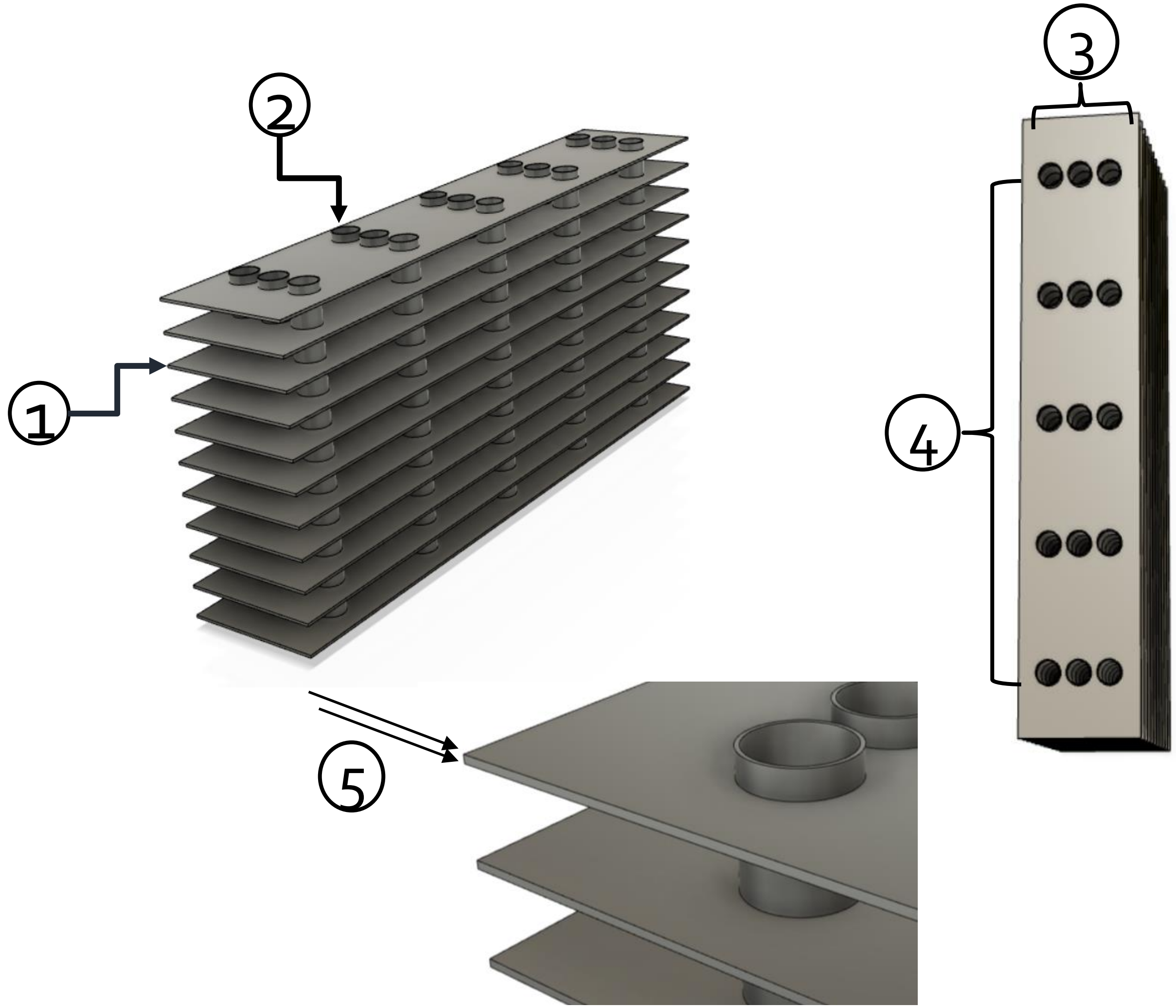


Fig 2. Car radiator

Previous Presentation

Summary

From our last presentation we were able to identify our optimal radiator geometry from a list of parameters. This consisted of

- A square profile
- 70 fins with 0.1 mm fin thickness
- 15 columns with a staggered arrangement
- Outlet temperature of 74.5℃

Theory

Tube Geometry

We found that the reason why different geometries having equal cross-sectional area have different thermal performance is due to a combination of three factors

- Surface area
- Hydraulic diameter
- Generated turbulence

The flow in the radiator consists of internal flow through the tube and external crosswise flow over the tube. By exploring these we can see why the square profile performs best.

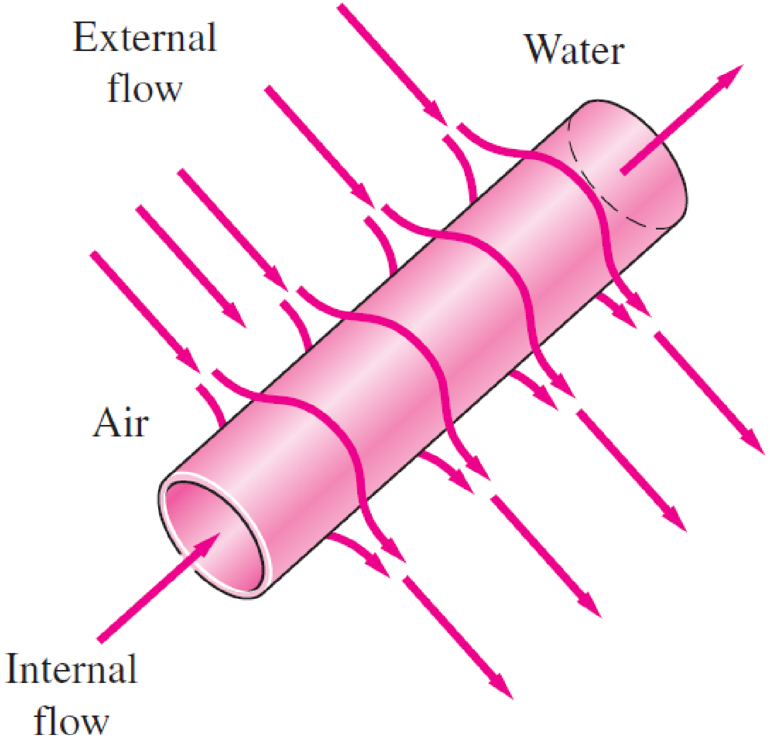


Fig 3. Flow through and across a tube

Theory

Tube Geometry

For external flow the major deciding factor is surface area where there is heat exchange between the pipe and the air occurs

Convective heat transfer is given by $Q = hA_s(T_s - T_\infty)$

Where

Q = power

h = convective heat coefficient

A_s = external surface area

T_s = surface temperature
T_∞= Ambient temperature

For all the shapes tested the square had the highest external surface area, this explains its optimal heat removal in cross flow.

Theory

Tube Geometry

Hydraulic diameter ,D_h, is a commonly used term when handling flow in non-circular tubes and channels. Using this term, one can calculate many things in the same way as for a round tube. When the cross-section is uniform along the tube or channel length, it is defined as

$D_h = 4A/P$

$D_h = 4 R_h$

$h = N_u k / D_h$

R_h is the hydraulic radius.

where

k is the thermal conductivity of the fluid

D_h is the hydraulic diameter of the channel.

h is the convective heat coefficient

The Nusselt number (N_u) for fully developed laminar flow in a square channel under constant heat flux conditions.

So h varies inversely with D_h . Which is why although the square tube has the same cross sectional area as the circular and slot tubes, it is able to dissipate more heat due to its lower hydraulic diameter.

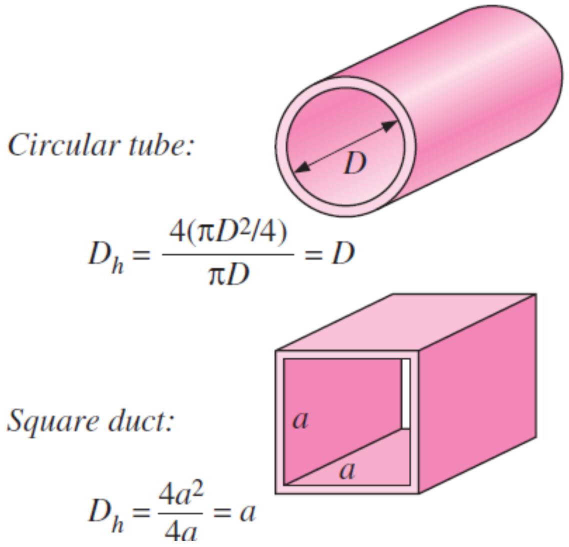


Fig 4. Hydraulic diameter

Theory

Tube Geometry

TURBULENCE

We observed that airflow over the tubes played a role in heat transfer. The square tube generated the most turbulent flow which aided heat transfer. Turbulent flow leads to the creation of eddies leading to higher heat transfer rates due to mixing of fluid layers.

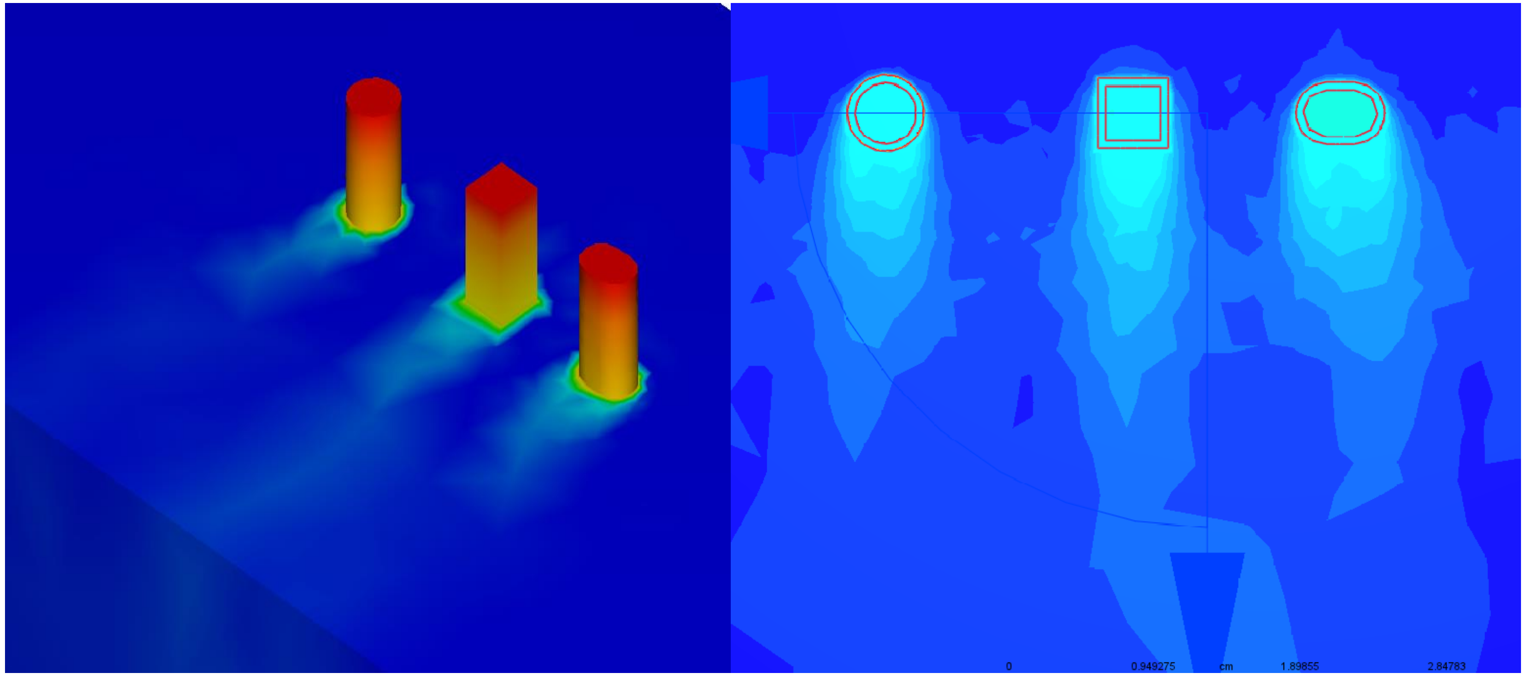


Fig 5. Heat transfer across tubes

Theory

Inline Vs Staggered Arrangement

Flow through tube banks is usually determined experimentally.

We are primarily interested in the average heat transfer coefficient for the entire tube bank which depends on the number of tube rows along the flow as well as arrangement and size of the tubes.

The Nusselt number is the primary deciding factor. This is given as

$$N_u = CRe_D^m Pr^n (Pr/Pr_s)\text{^}0.5$$

where the values of the constants *C*, *m*, and *n* depend on value Reynolds number.

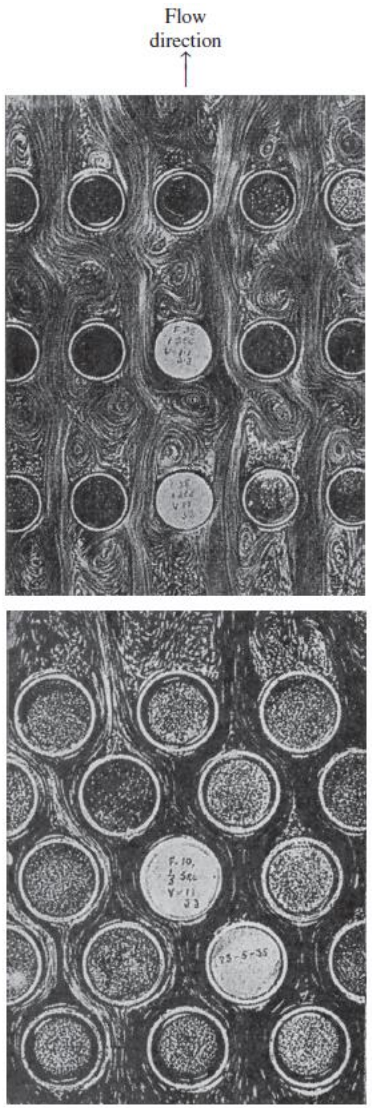


Fig 6. Cross flow through tube banks showing streamlines

Manufacturing

The radiator consists of four major components

1. Upper reservoir
2. Lower reservoir
3. Fins
4. Tubes

The material used for all of the components is aluminum due to its light weight and good thermal conductivity. All the components are then soldered together.

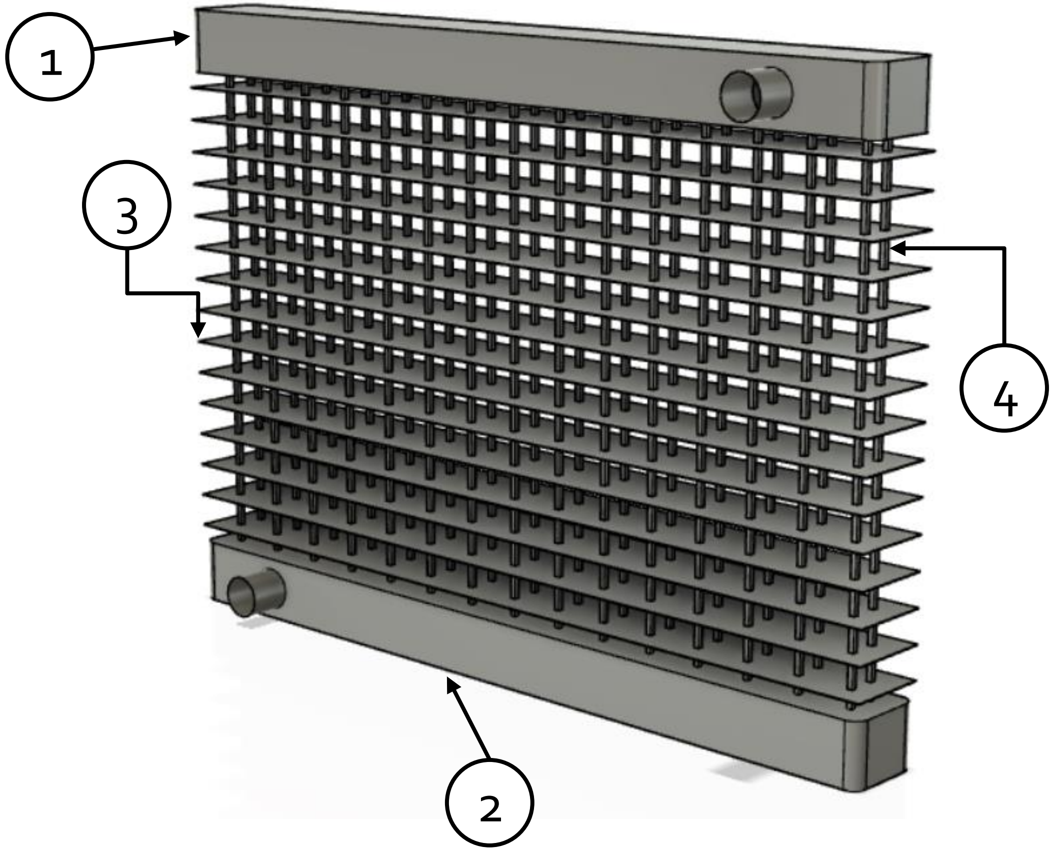


Fig 7. Labelled car radiator

Manufacturing

Upper reservoir

- This has a similar geometry with the lower reservoir.
- The reservoir was designed using Fusion 360 sheet metal and a flat pattern was created.
- This can be CNC plasma cut for low production runs or sheet metal stamped for higher runs.
- The flanges are bent and then soldered together to form a close body.
- The fillets from the sides have been removed for easier manufacturing
- The number of bends is reduced without its inclusion.

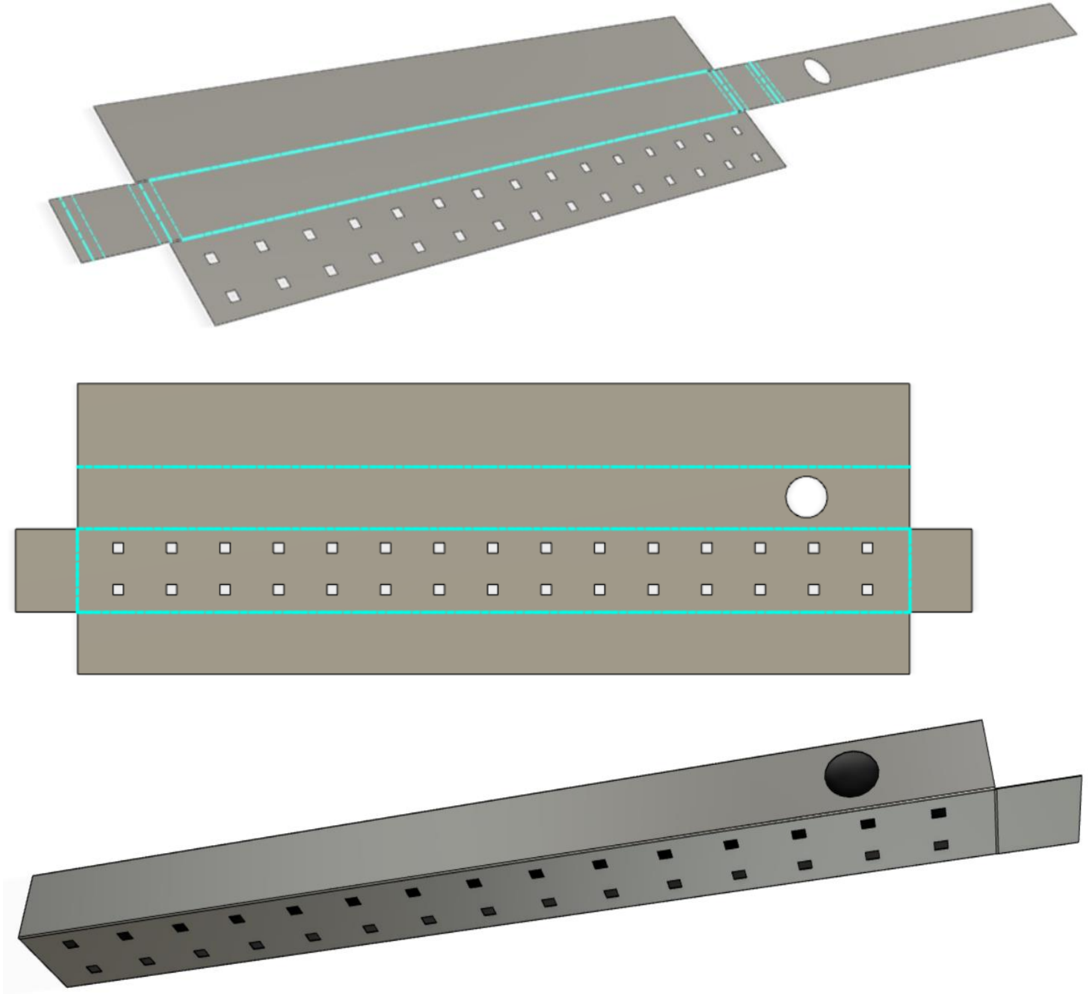


Fig 8. Sheet metal development of upper reservoir

Manufacturing

Fins and tubes

The fins are made from 0.1mm aluminum sheet metal.

The sheets should be plasma cut, but for production runs it will be more suitable to stamp them out.

The tubes are to be plasma cut and then bent into shape using a metal break.

The ends will be wielded together to form a closed outer profile.

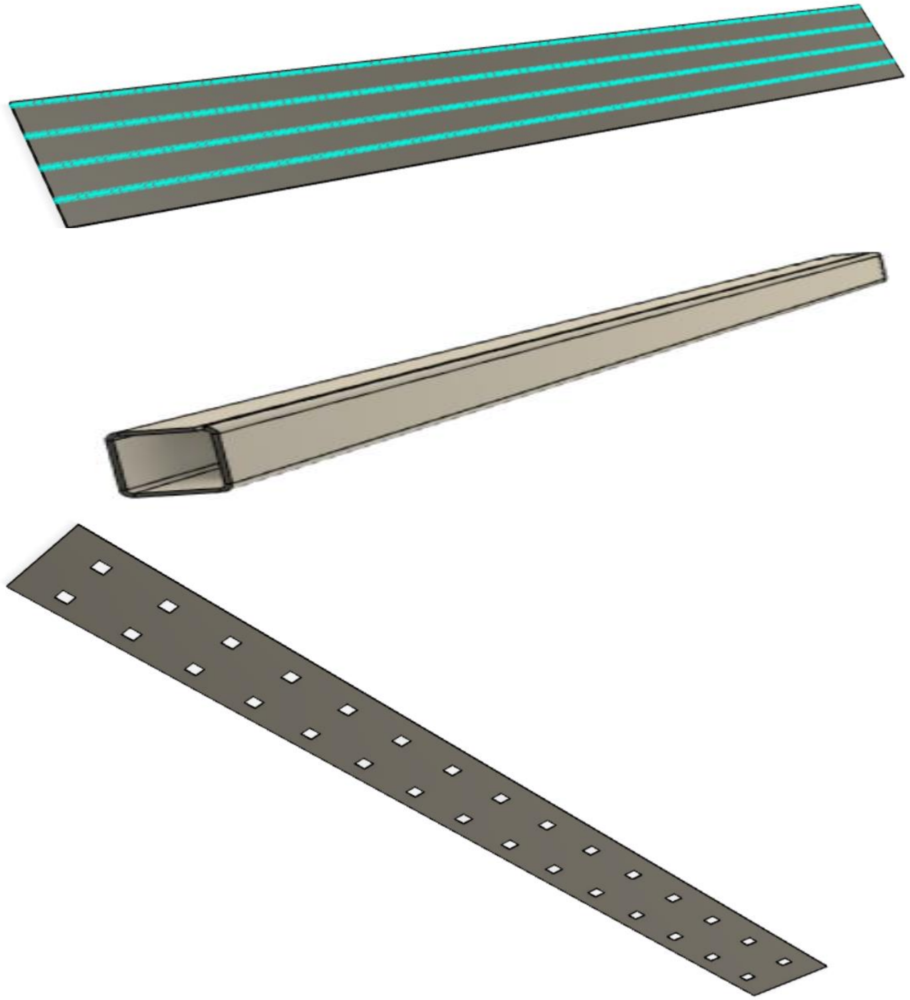


Fig 9. Sheet metal development of radiator tubes

Cost Analysis

COMPONENT	AMOUNT	UNIT PRICE(₦)	TOTAL(₦)
Upper reservoir	1	5377	5377
Lower reservoir	1	5377	5377
Fins	70	397	27,790
Tubes	30	230	6900
			45,444

COMPONENT	MANUFACTURING(₦)
Upper reservoir	3000
Lower reservoir	3000
Fins	7000
Tubes	6000
	19000

The total cost to manufacture the radiator is ₦64,444. Typical production radiators of similar performance cost between N40,000 to N45,000. This isn't a suitable comparison as production radiators have been optimized for manufacturing cost and ease.

Differences

- The two major differences between our optimized radiator and market radiator is fin arrangement and tube profile.

- We wanted to know why there were not many variations of the straight fins configuration in the market.

- The square tubing was the optimal for heat removal but we couldn't find any in use.

- The slotted profile dominated the market

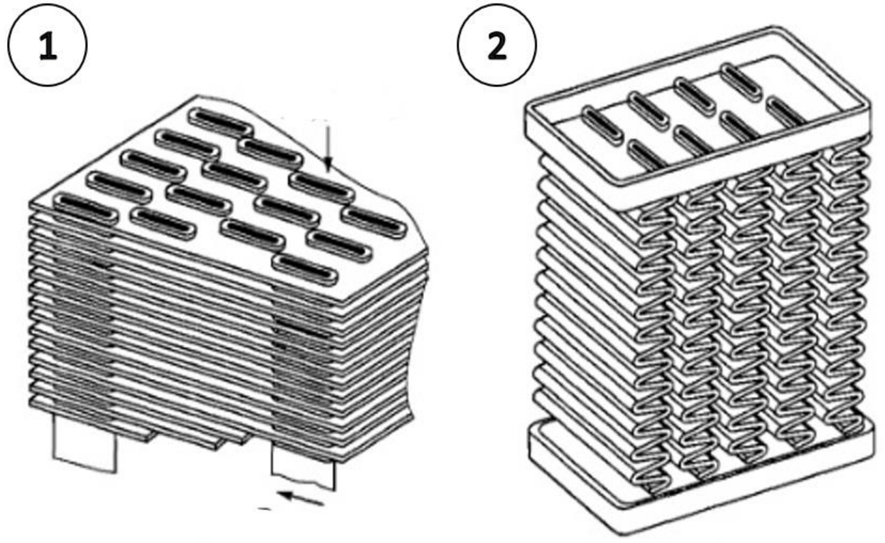


Fig 10. Fin arrangement, (1) Straight fins, (2) Coiled fins

Differences

Fin Arrangement

- **Structure**:

Aluminum fins become difficult to handle at thickness less than 1mm. The strength of the straight fins is weak compared to coiled fins. The coiled fins are easier to handle during assembly and they take up less space in the radiator core

- **Pressure drop**:

The straight tubes offer more resistance to flow across them compared to the coiled fins, this means that with the same air flow rate the coiled fins will be able to remove more heat.

- **Thermal Stress and expansion**:

The aluminum fins expand when they are heated up, straight fins tend to push the tubes laterally i.e. perpendicular to wind flow which can lead to cracks in the core, this is mitigated with coiled fins because they expand along the axial direction i.e. parallel to air flow

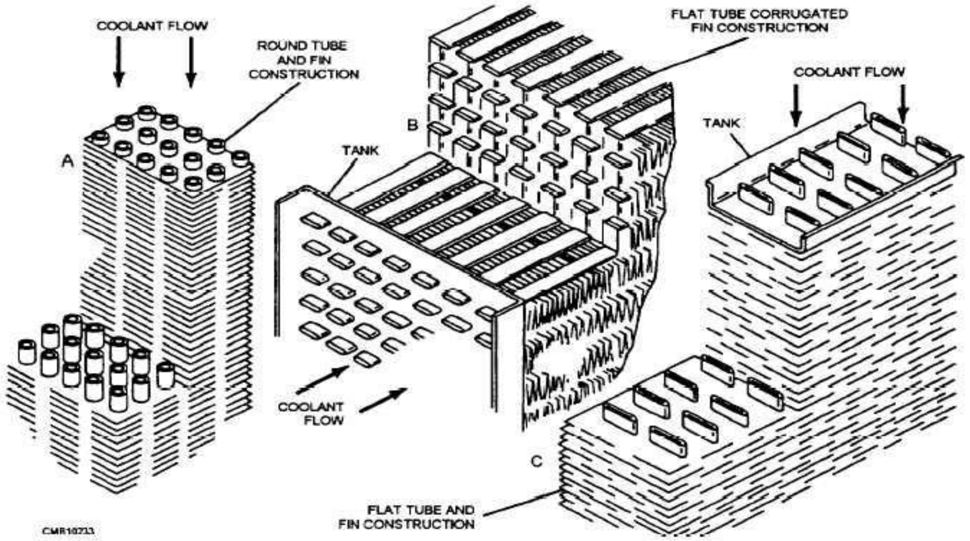


Fig 11. Fin arrangements

Differences

Tube profile

- **Strength**: The slotted profile is selected due to it ability to resist torsional stresses which arise from thermal expansion, it provides a more rigid connection to the upper and lower reservoirs than the square or circle profiles.
- **Ease of manufacturing**: At thicknesses of 1mm and below it becomes hard to form aluminum into circles or square. This is due to complications of welding the profiles. Slotted profiles are easier to weld because overlaps are more easily controlled, this allows for solder to flow easily sealing the tube.
- **Assembly**: The radiator core and fins are joined together using solder, the flat edge of the slot provides a good surface for the fins to be soldered to the core. If any other profile was used then there would be no need for the coiled fins.

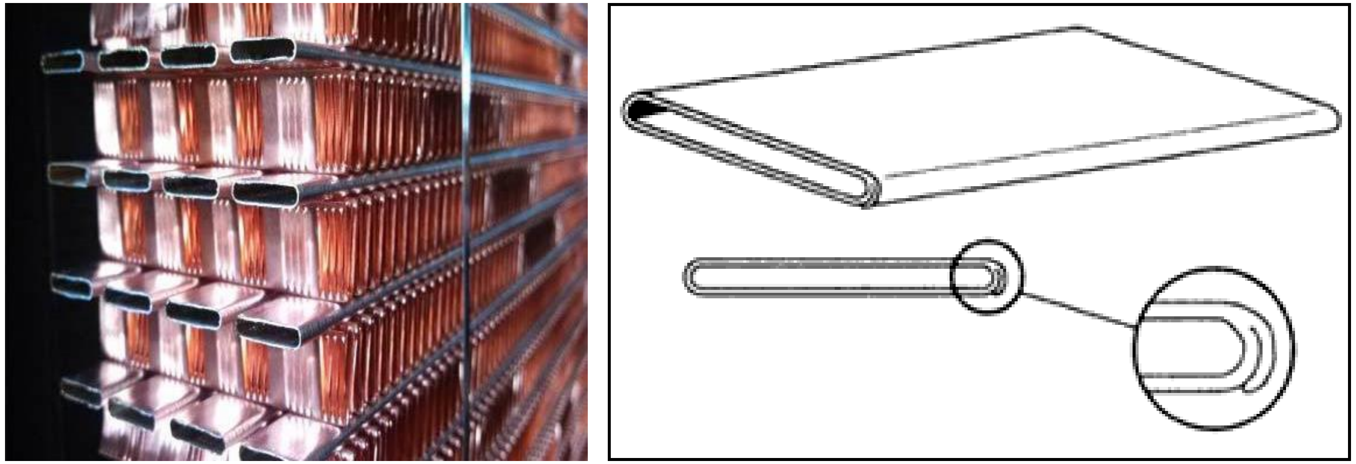


Fig 12. radiator core showing slotted tube

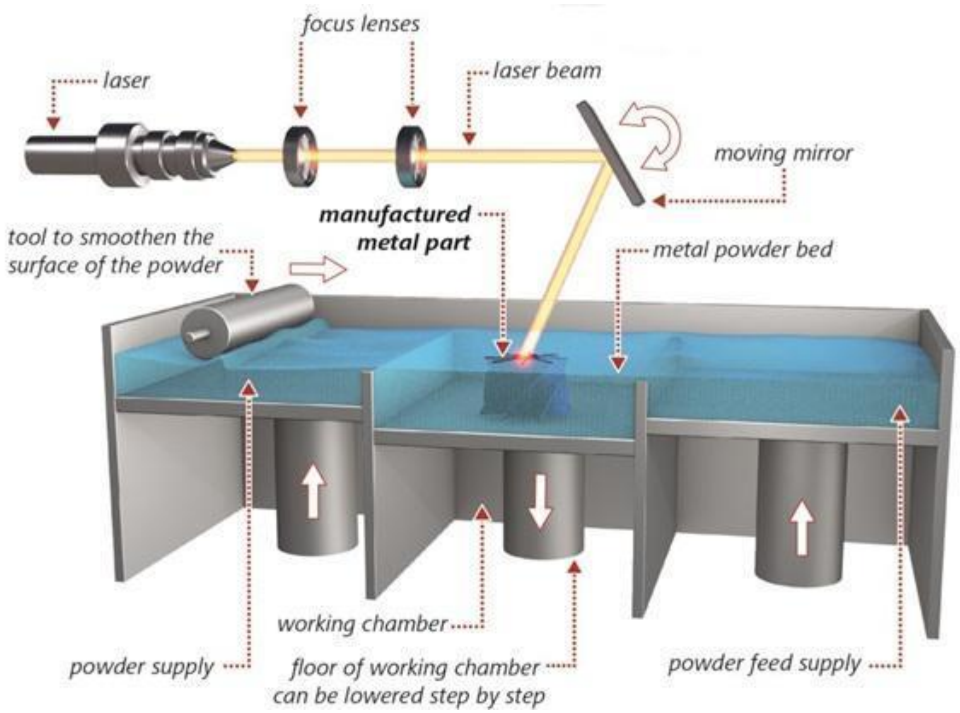
3D Printed Radiators

- The design of radiators have been limited by the manufacturing techniques available. Radiators are designed under the assumptions that they can easily be manufactured with conventional processes. This thought process leads to starting off with a limited design and working to optimize it.
- With 3d printed radiators it is finally possible to design without having to think about manufacturing limitations. The fluid flow paths can be optimized for lower resistance and the fins can be placed around the flow path for greater heat removal

Fig 13. 3D printed heat exchangers

3D Printed Radiators

- There are several methods of 3d printing the radiator, these includes binder jetting, selective laser sintering (SLS) and directed energy deposition (DED)
- SLS is most widely adopted, it involves melting a thin layer of metal power with a powerful laser, this fuses the metal at the point of contact creating a homogeneous bond, this process is repeated for multiple layers until the total geometry is complete.



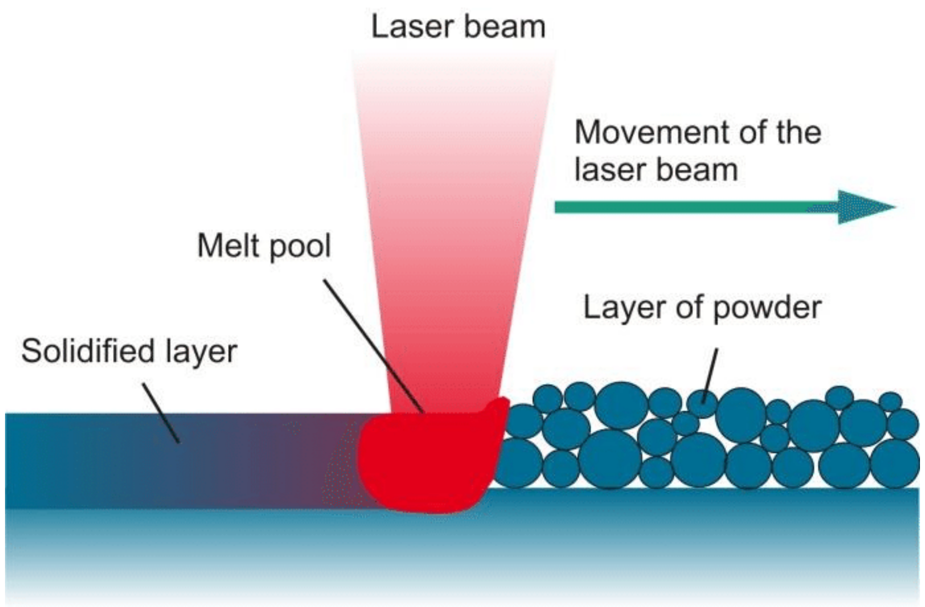


Fig 14. Selective laser Sintering (SLS)

3D Printed Radiator

- The design of 3d printed radiators involves utilizing generative design to come up with the lattice structure required for heat removal, this lattice is then warped around the tubes as efficiently as possible. This is a manual process and our goal for future studies is to automate it.
- We plan on exploring this option further due to the potential cost savings, reduction in weight and improved thermal efficiency.

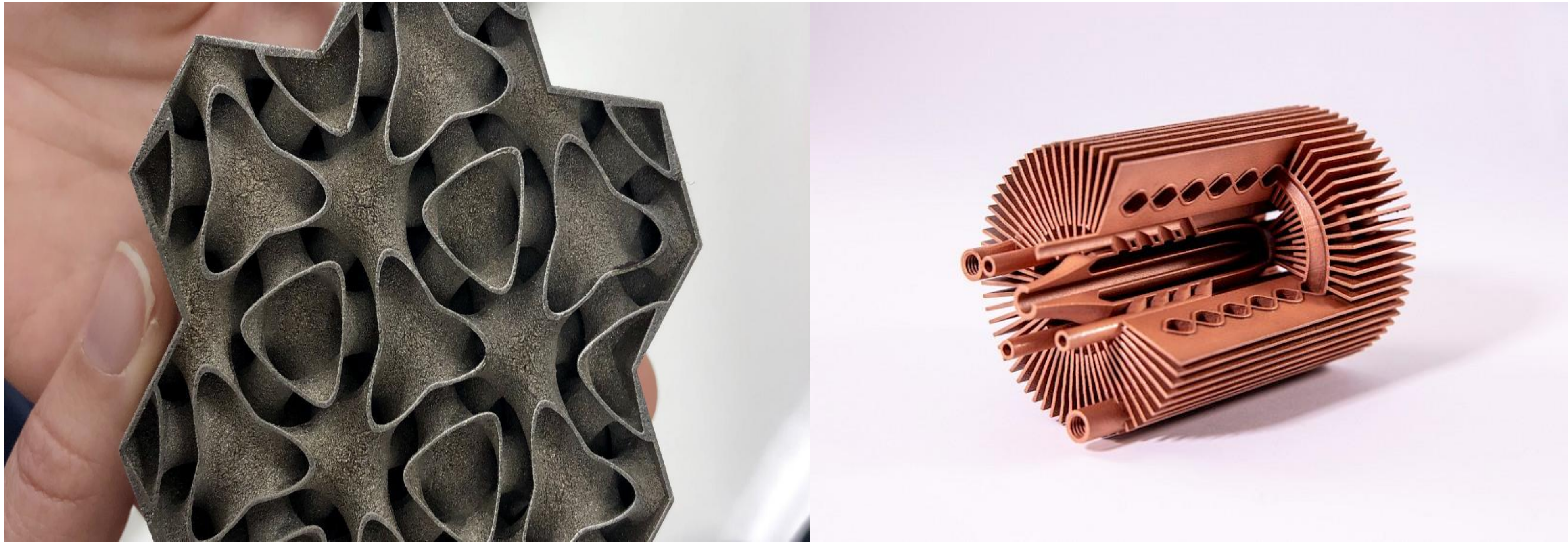


Fig 15. 3d printed radiators showing lattice structure

Conclusion

We have been able to show the correlation between simulated results and theory, furthermore we also looked at the manufacturing of the radiator as well as some of the limitations in the design and why production radiators are made with coiled fins and slotted tubes. Finally we looked at metal 3D printing and how it allows for radiator geometry optimization.