CL 246 - Course Project

THERMO-ACOUSTIC COOLING FOR THERMAL HOTSPOTS

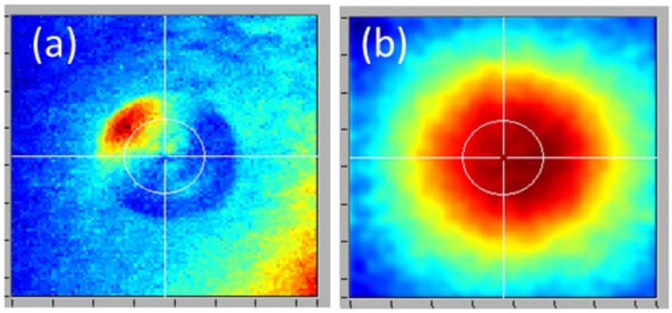

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Image reference : http://surl.li/btzdm

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1. User Story

- Graphics Processing Unit (GPU) chips are widely used in personal electronic devices like mobile phones and personal computers in order to display graphics efficiently.
- They require high power and are often the hottest part of the motherboard. A thermal hotspot is the hottest region of the GPU chip (upto 10-15°C hotter). Due to their small size, a very high heat flux is generated.
- Current cooling strategies are unable to dissipate this heat, which thus creates a bottleneck on chip performance

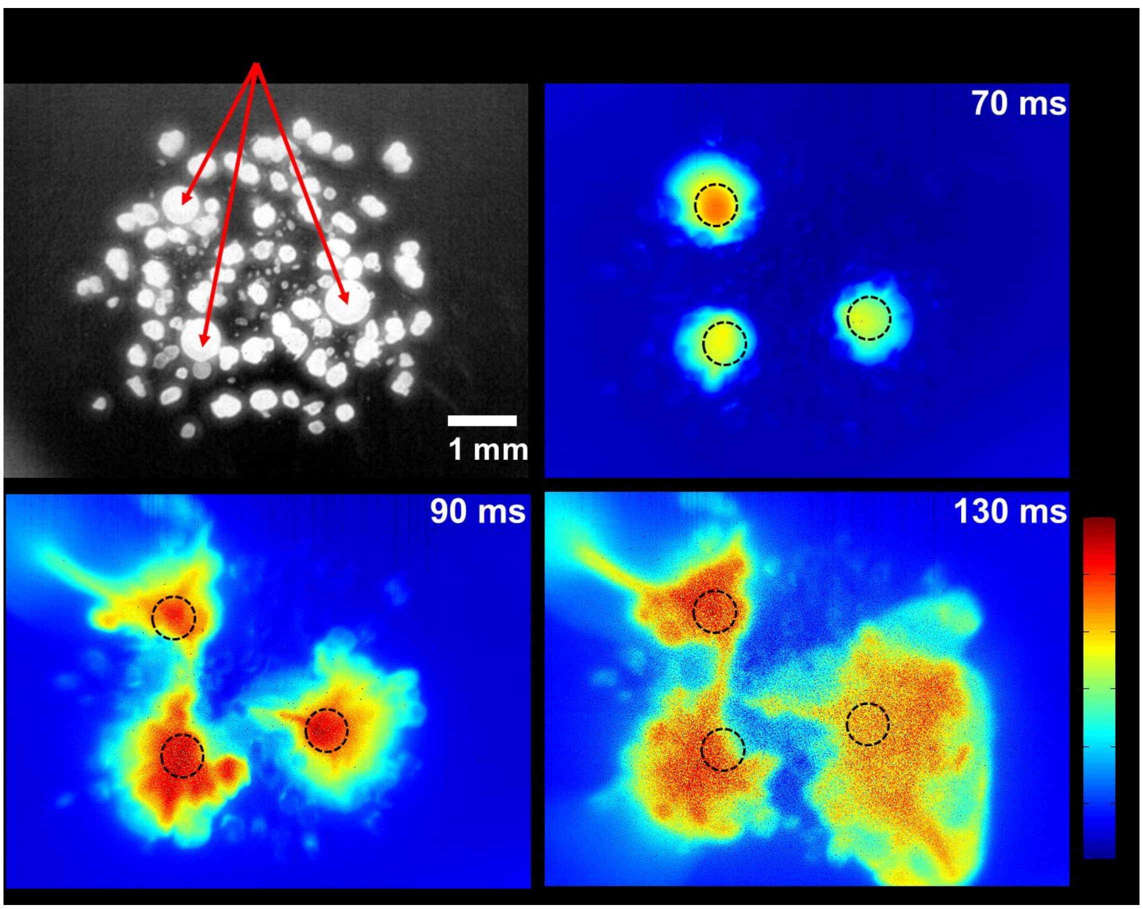

Fig 1 : Thermal hotspots
Reference : https://dlottgroup.web.illinois.edu/drupal8/node/47

2. Technical Problem

Consider a GPU chip having dimensions 50 mm X 50 mm which is at a temperature of 348K. As the GPU heats up, a thermal hotspot of temperature 363 K and size 1 mm X 1 mm gets formed on the chip. This hotspot is cooled using :

(a) passive methods, i.e., free convection and

(b) active methods, i.e., thermoacoustic refrigeration.

The thermoacoustic cooler has a cold end 'A' and a hot end 'B'. It takes in power to maintain a constant temperature difference between these two ends. The heat is first transferred via conduction by means of a wire with cross sectional area equal to that of the hotspot to end A ($T_A = 285$ K). This heat is then transferred to B ($T_B = 345$ K) via thermoacoustic cooling. The heat from B is again carried via conduction to the back of the square laptop screen of diagonal length 15". Assume the ambient temperature to be 298 K and the length of each wire to be 0.25 m. Find the maximum possible heat transfer rate achieved by passive and active cooling mechanisms. Given that $h_{air} = 13.5 \frac{W}{m^2 K}$, $k_{Cu} = 350 \frac{W}{m\ K}$

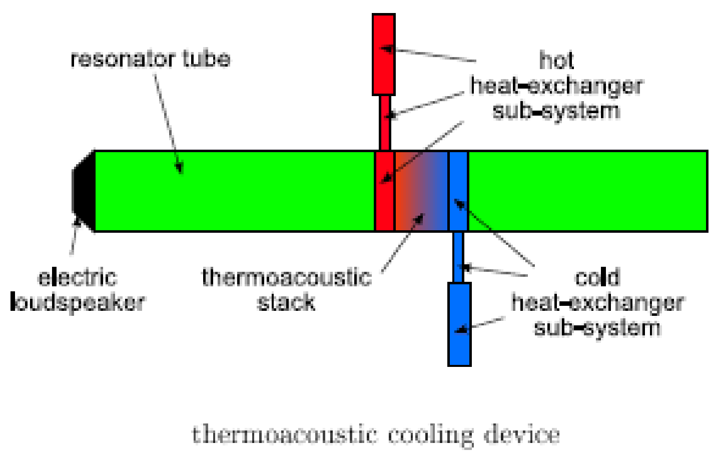

Fig 2: A typical thermoacoustic cooler

Reference: https://www.thesis123.com/wp-content/uploads/2017/07/thermo-acoustic-refrigeration.pd

3. Schematic Diagram

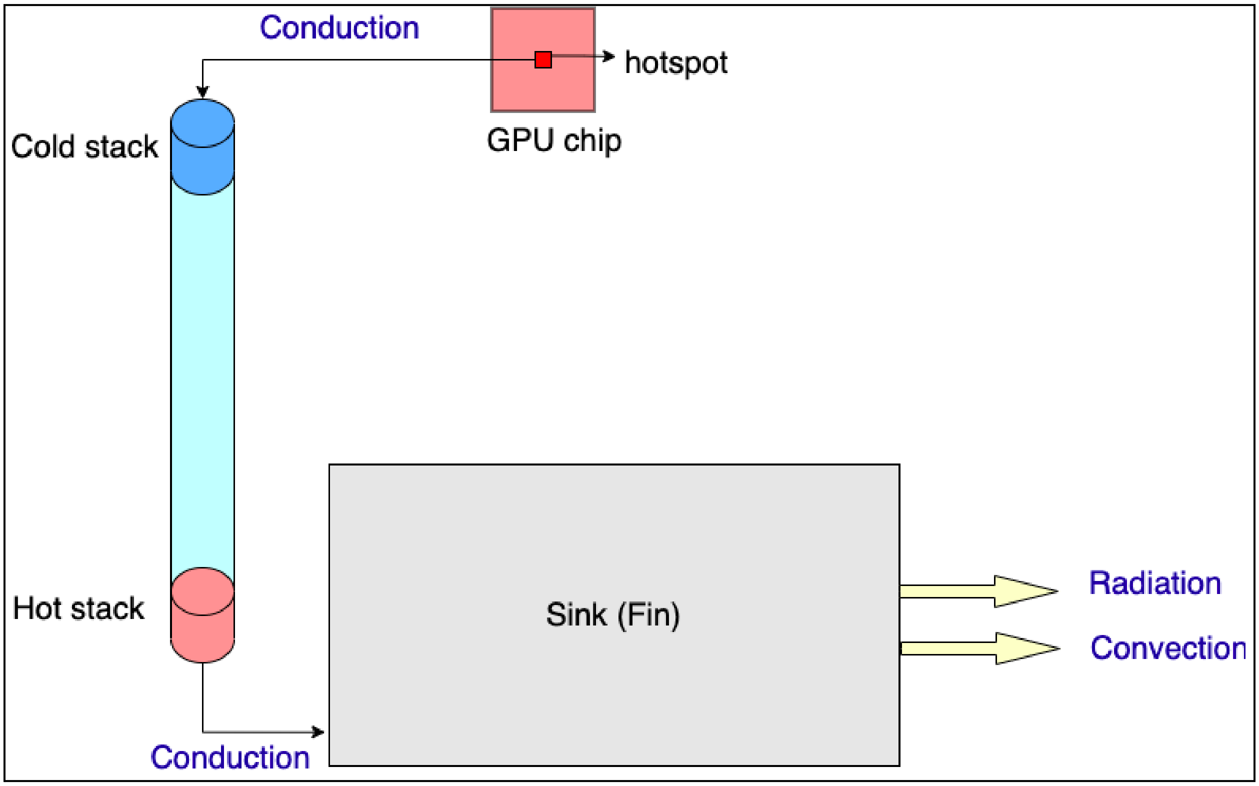

Fig 3. Simplified diagram of proposed solution

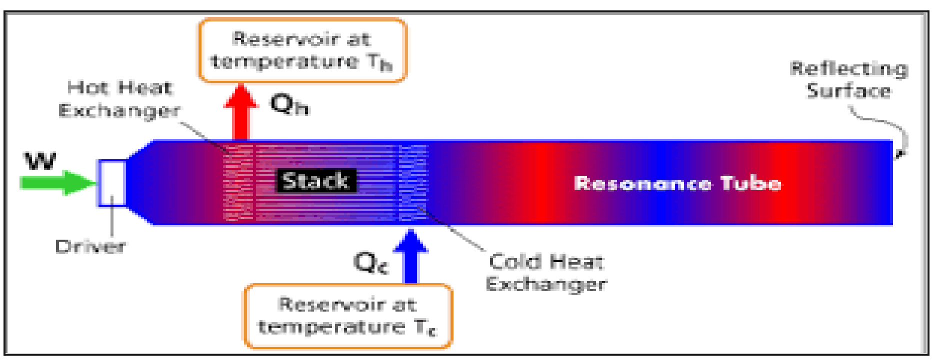

Fig 4. One half of a thermoacoustic cooler (Two such halves are actually coupled in our project)

www.semanticscholar.org/paper/A-Critical-Review-on-Thermoacoustic-Refrigeration-Babu-Sherjin/

4. Approximate estimates

Consider cooling of a thermal hotspot (1mm * 1 mm) at the centre of a GPU chip sized 50 mm * 50 mm. The hotspot is at a temperature of 90°C while the rest of the chip is assumed to be at a uniform temperature of 75°C . Assuming the efficiency of the thermoacoustic engine to be 1, provide estimates of the heat transferred via conduction through the wires and via convection from the back of the laptop screen. Again, assume that radiation losses are negligible and that the entire screen (shaped like a square) is available for convective cooling.

Given the following:

- $T_A = 12°C$
- $T_B = 72°C$
- $T_{air} = 25°C$
- $l_{wire} = 0.25$ m
- $l_{screen} = 15/\sqrt{2}$ in
- $A_{wire} \sim A_{hotspot}$
- $h_{air} = 13.5$ W/mK
- $k_{Cu} = 350$ W/mK

Between hotspot and A:

$q = k_{Cu} * A_{wire} * (T_{hotspot} - T_A)/l_{wire} = 350 * 10^{-6} * (90\text{-}12)/0.25$

$= 109.2$ mW

Between Fins and Atmosphere

$q = 109.2 \text{ mW} = h_{air} * A_{fin} * (T_{Fin} - T_{atmosphere})$

$\Rightarrow T_{Fin} = T_{Atmosphere} + q/(h_{air} * A_{fin}) = 25 + 0.1092/(13.5 * (15/\sqrt{2} * 10^{-2} * 2.54)^2)$

$= 25.03^0C$

Between B and Fin

$q = 0.1092 \text{ W} = k_{Cu} * A_{wire} * (T_B - T_{Fin})/l_{wire} \Rightarrow A_{Wire} = q/(k_{Cu} * (T_B - T_{Fin})/l_{wire})$

$= 0.1092/(350*(72\text{-}25.03)*4) = 1.6606 \text{ mm}^2$

Assuming that the entire heat is thrown out, we have a margin ratio of

$\sim 0.1092/0.000204 = 535.29$,

i.e. we can extract 535 times of what the cooling can be achieved by passive cooling.

On relaxing the assumptions:

$\eta_{thermo\text{-}acoustic} \sim 0.5$, $\eta_{B\rightarrow D} \sim 0.5$

We still have a margin ratio of ~179*0.5*0.5=44.75

Thus, this solution is capable of extracting several times the heat required, and can thereby achieve better cooling and efficiency.

5. Solution Methodology

We have proposed an innovative cooling method to cool thermal hotspots as an alternative to the conventionally existing cooling techniques. Conventional cooling methods aim to cool the entire chip uniformly, and result in lower allowable chip power dissipation or unnecessary overcooling of large areas of the chip. The working of the thermoacoustic cooler is as follows -

- The heat from the hotspot will be directed to a cold stack A via conduction
- Heat is transferred from cold stack A to hot stack B via thermoacoustic refrigeration
- The temperature of Cold stack A and Hot stack B is maintained at a constant value
- Heat from Hot stack B is directed to the back of the laptop screen (sink) via conduction
- Heat is dissipated from the sink to the surroundings via convection

In our analysis we have compared the results obtained by three different cooling mechanisms :

1. Passive cooling (no fans present) i.e. free convection
2. Active cooling (using fans) i.e. forced convection
3. Active cooling (thermoacoustic cooling)

6. Assumptions

a. While calculating the heat transfer rate without a fan
    i. The only hot component in the entire CPU Box is the GPU chip.
    ii. The heat flux from the chip is such that a steady-state is achieved

b. While calculating the heat transfer rate due to fan
    i. The only hot component in the entire CPU is the GPU chip.
    ii. The air flows at a constant and uniform velocity of 1.58 m/s. This was calculated assuming a volume flow rate of 20 ft^3/s.

c. While calculating the heat transfer rate via Thermoacoustic cooler
    i. The wires are perfectly insulated, i.e, no heat is lost during conduction from the GPU to the cooler.
    ii. The heat is finally dissipated from the coil of wire behind the laptop screen, hence it is essentially a 1D problem.
    iii. The thermal hotspot is localised at the centre of the chip. This is a pretty good assumption since we just need to find where the component which heats the most and put the hotspot there.
    iv. Negligible contact resistance.
    v. No heat exchange from the thermoacoustic cooler, except the ends and the source of electricity.

7. Theory and Equations

Theory:

Working of a thermoacoustic cooler:

A thermoacoustic cooler is a heat exchanger that consumes external power to maintain a constant temperature gradient. Its basic geometry can be depicted as shown below -

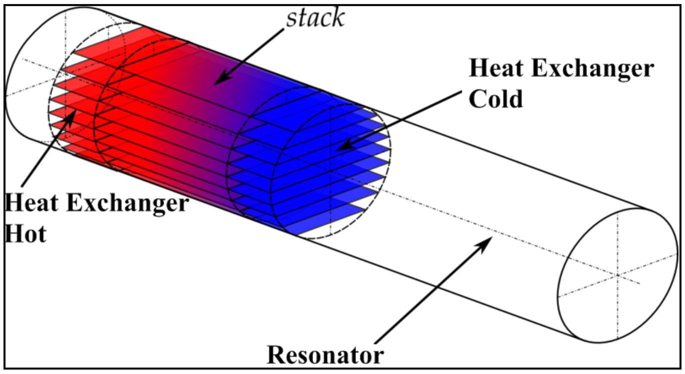

Fig 5. Basic setup of a thermoacoustic cooler

The basic setup includes a glass tube to set up standing waves with stacks placed equidistant from the edges at roughly ⅓ rd of the tube length. The temperature of the stacks do not change with time - this enables us to use it as an active cooling technique.

Equations :

$$Gr = \frac{g*\beta*(T_w - T_{infinity})*L^3}{a}$$

$$Re = \frac{u*L}{\nu}$$

1. Passive cooling:

   Natural convection correlations:

   $$Ra_1 = \frac{Gr}{\nu}$$

   $$Nu_1 = 0.22 * \left(\left(\frac{Pr}{Pr+0.2}\right) * Ra_1\right)^{0.28} * 2.5^{-0.25}$$

   $$h_1 = \frac{Nu_1 * k}{L}$$

   $$q_1 = h_1 * A * (T_h - T_{infinity})$$

2. Active cooling (via fans) :

Forced convection correlations:

$$Ra_2 = \frac{Re^2}{\nu} \;**$$

$$Nu_2 = 0.22 * \left(\left(\frac{Pr}{Pr+0.2}\right) * Ra_2\right)^{0.28} * 2.5^{-0.25}$$

$$h_2 = \frac{Nu_2 * k}{L}$$

$$q_2 = h_2 * A * (T_h - T_{infinity})$$

*** we didn't have an appropriate correlation for forced convection in a narrow channel so we compared the values of Gr and Re^2 . Since Re^2 was much bigger than Gr , we used Re^2 for our calculations .*

To compare the natural and imposed velocities:

$$Re^2 \sim Gr$$

$$\frac{\rho^2 v^2 D^2}{\mu^2} \sim Gr$$

$$v \sim \sqrt{Gr} * \frac{L}{\rho D}$$

$$v_{natural} \sim \sqrt{\frac{g\beta(T_w - T_{infinity})L^3}{a}} * \frac{\mu}{\rho D} = \sqrt{0.4721} * \frac{1.798 * 10^{-5}}{0.05} = 2.4708 * 10^{-4}$$

$$v_{imposed} = 1.58 \frac{m}{s}$$

Observe that $v_{natural} << v_{imposed}$

Thus, we can replace Gr by Re^2 in the above correlation.

3. Active cooling (thermoacoustic)

   a. Conduction in the first wire :

$$q_1 = kA_1 \frac{\Delta T}{\Delta x} = kA_1 \frac{(T_h - T_{cold\ stack})}{L_{wire\ 1}}$$

$$q_1" = k\frac{(T_h - T_{cold\ stack})}{L_{wire\ 1}}$$

   b. Conduction in the second wire :

$$q_2 = kA_2 \frac{\Delta T}{\Delta x} = kA_2 \frac{(T_{hot\ stack} - T_{sink})}{L_{wire\ 2}}$$

$$q_2" = k\frac{(T_{hot\ stack} - T_{sink})}{L_{wire\ 2}}$$

8. Heat Transfer Modes & their Estimates

MODES :

Conduction:

- Hotspot to cold stack
- Hot stack to sink

Convection:

- Sink to surroundings

Radiation:

- Sink to surroundings

ESTIMATES :

For conduction :

$$q_1 = kA_1 \frac{\Delta T}{\Delta x} = kA_1 \frac{(T_{hotspot} - T_{cold\ stack})}{L_{wire\ 1}} = 350 * 10^{-6} * \frac{90-12}{0.25} = 0.342 \text{ W}$$

$$q_2 = kA_2 \frac{\Delta T}{\Delta x} = kA_2 \frac{(T_{hot\ stack} - T_{sink})}{L_{wire\ 2}} = 350 * 1.606*10^{-6}*\frac{72-26}{0.25} = 0.342 \text{ W}$$

For hotspot to cold stack & hot stack to sink :

Area of contact is negligible thus convection and radiation may be neglected.

Total conduction = $q_1 + q_2$= 0.342 + 0.342 = 0.684 W

For sink to surroundings : Comparison between convection and radiation is as follows -

For convection :

$$q = h_a A_{\text{Laptop screen}}(T_{hot\ stack} - T_{sink}) = 13.5*0.0725*1$$
$$= 0.987 \text{ W}$$

For Radiation :

$$q = \varepsilon_{\text{sink}}\sigma A_{\text{Laptop screen}}(T_{hot\ stack} - T_{sink}) = 0.4*5.67*10^{-8}*(299^4-298^4)$$
$$= 0.1749 \text{ W}$$

9. One-Dimensional Model

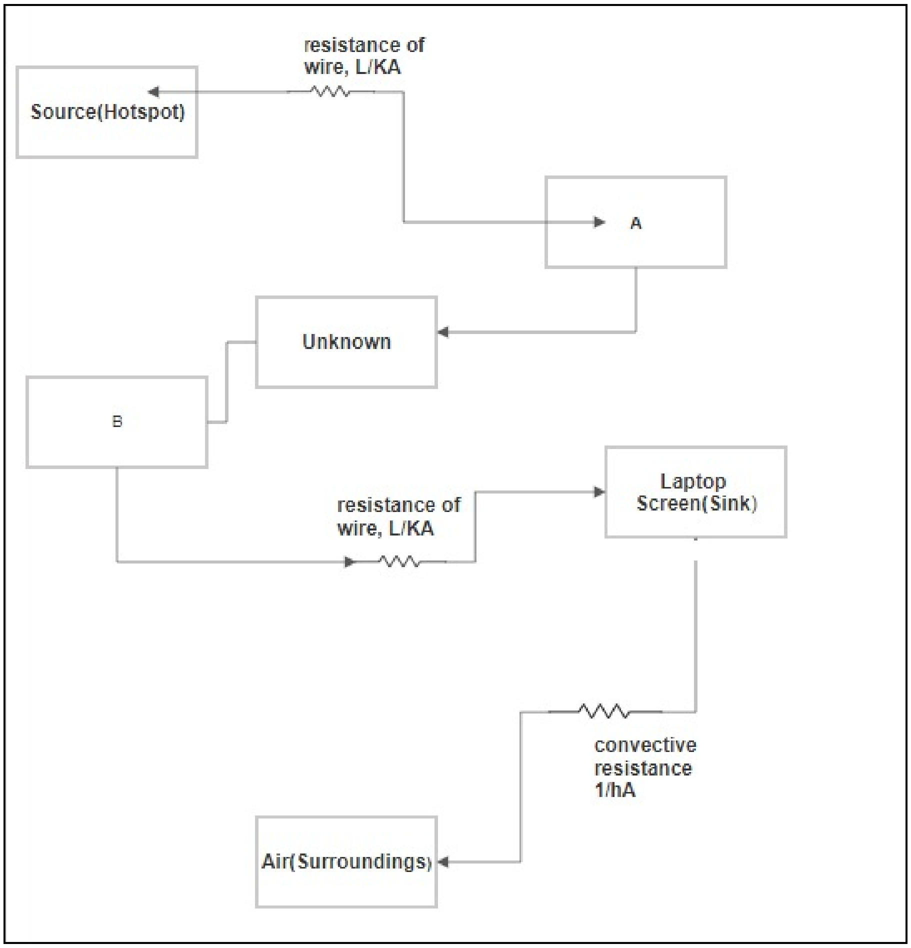

Fig 6 : 1D resistance model for thermoacoustic cooling

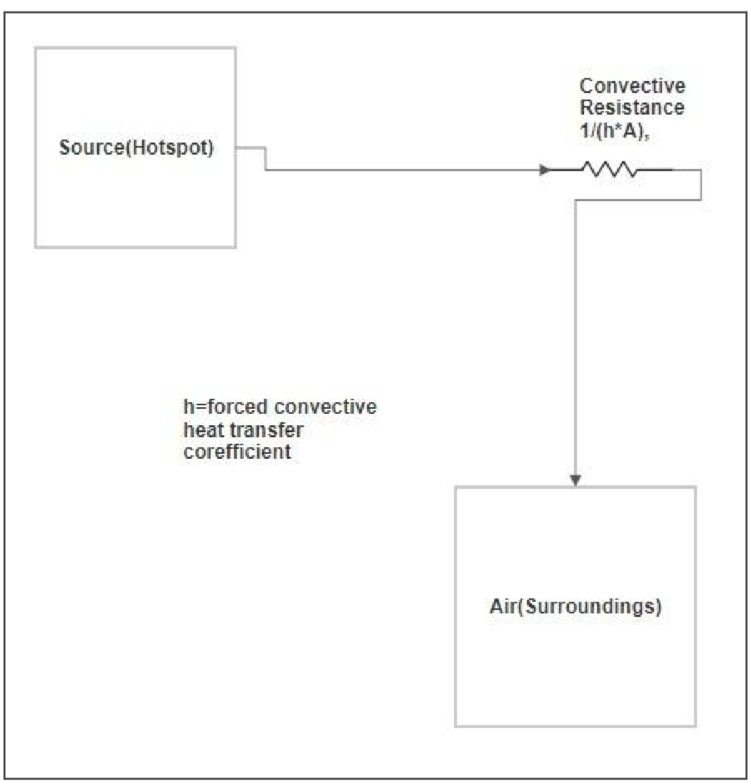

Fig 7: 1D resistance model for passive cooling

10. Simulations and Temperature Profiles

Case 1: Passive cooling

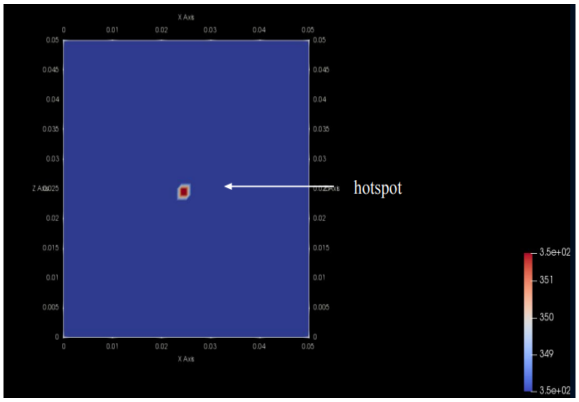

Fig 8 : Top view of temperature profile

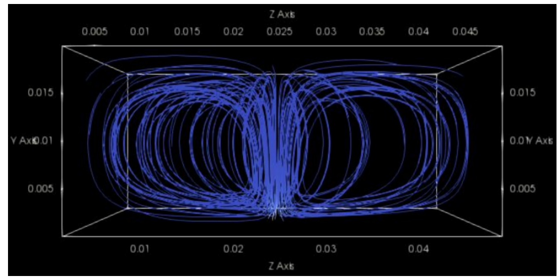

Fig 9 : Front view of streamlines

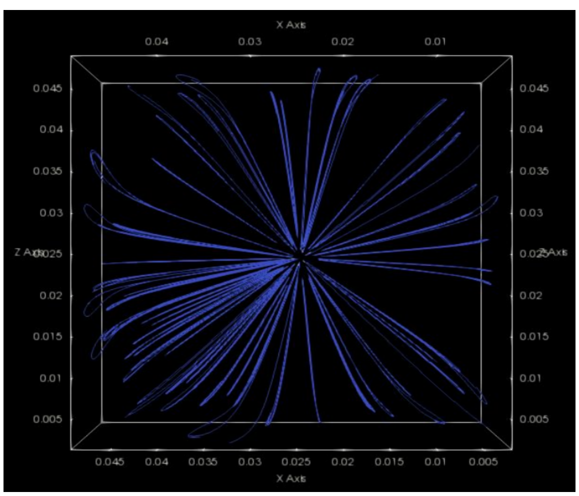

Fig 10 : Top view of streamlines

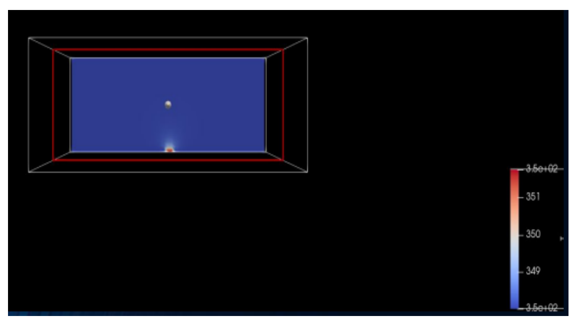

Fig 11 : Front view of temp profile

**Simulations done using OpenFoam*

Case 2: Active cooling using forced convection

This case can be treated like a hot plate with starting unheated length. The thermal and velocity boundary layers are as follows:

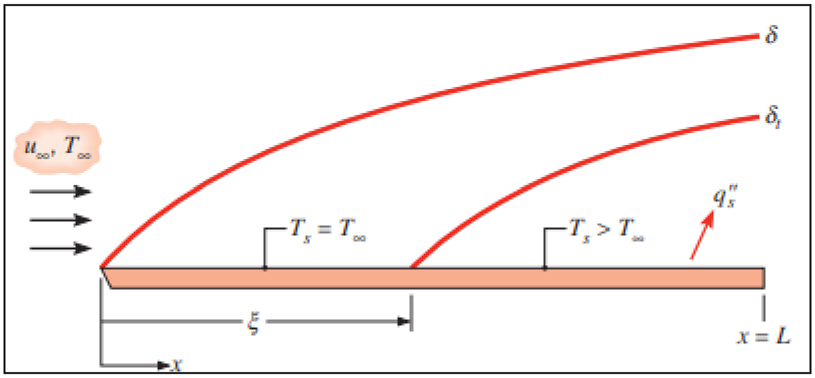

Fig 12: Temperature profile for case 2

Case 3 : Thermoacoustic cooling

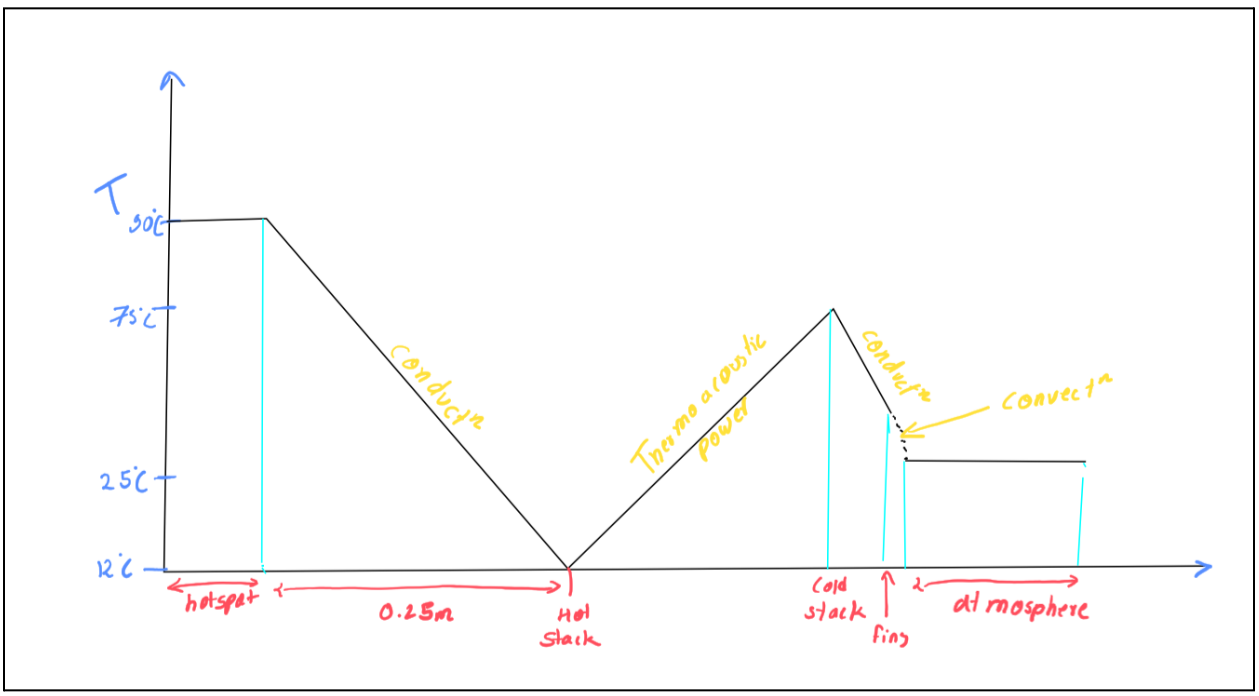

Fig 13 : Temperature profile for case 3

11. Results

Reynolds number $Re = 1.7575 * 10^{3}$
Grashof number $Gr = 0.4721$

For passive cooling:

Rayleigh number $Ra_1 = 2.6257 * 10^{4}$

Nusselt number $Nu_1 = 2.8224$

Convective heat transfer coefficients $h_1 = 3.9627 \frac{W}{m^2K}$

Total heat rate $q_1 = 2.4965 * 10^{-4} W$

For active cooling by fans:

Rayleigh number $Ra_1 = 1.7179 * 10^{11}$

Nusselt number $Nu_2 = 228.5778$

Convective heat transfer coefficients $h_2 = 320.9232 \frac{W}{m^2K}$

Total heat rate $q_2 = 0.0202 W$

For thermoacoustic cooling:

Net heat transfer rate between hotspot and sink = 0.1092 W

12. Economic Analysis

Cost for cooling using conventional active cooling methods :

1. An average quality fan costs approximately 150 Rs
2. Requires more maintenance due to lower efficiency
3. Consumes 1.8 W of power to give 0.02W cooling **

Cost for cooling using thermoacoustic cooling method :

1. There is no significant rise in the expenses, owing to the lack of moving parts
2. Consumes 0.4368 W of power to give 0.11 W cooling **

*** Values obtained from research papers & calculations as cited in references*

Energy consumption Analysis :

We can tally the energy consumption requirements as a ratio of the output cooling power to the input cooling power as follows:

- Conventional cooling $\rightarrow \frac{0.02}{1.8} = 0.011$

  Thus, to give 1 kWh of cooling, $\frac{1}{0.011} = 90$ kWh energy is consumed

  $\rightarrow$ 90 kWh* 8.8 $\frac{Rs}{kWh} = 792\ Rs$

- Thermoacoustic cooling $\rightarrow \frac{0.11}{0.4368} = 0.25$

  Thus, to give 1 kWh of cooling, $\frac{1}{0.25} = 4$ kWh energy is consumed

  $\rightarrow$ 4 kWh* 8.8 $\frac{Rs}{kWh} = 35\ Rs$

Thus, our method is ~ 22.5 times more energy efficient .

Equipment Design & Cost Analysis :

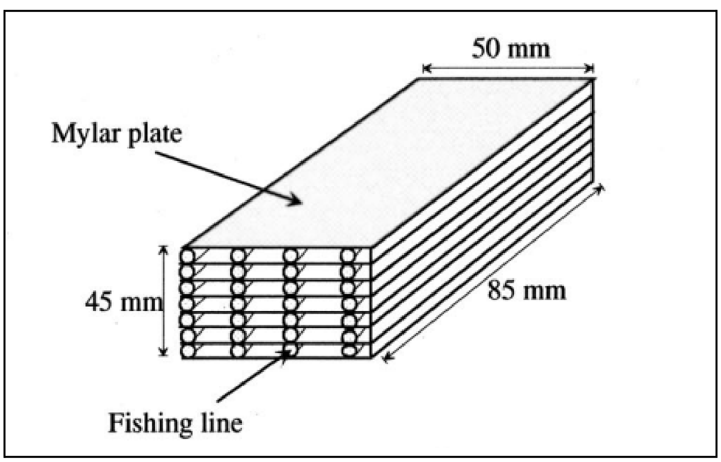

Fig 14 : The basic design for the stacks to be used at the ends of the tube

This design is more economic as compared to the spiral stack design (as shown in the calculations below). Hence we will use the parallel plate stack model for our analysis

The materials required for designing a thermoacoustic cooler & their cost requirements are as follows :

Element	Material	Calculation	Cost
Wire insulation	Thermoplastic (PVC)	Weight = 15kg/km Length = 0.5 m Cost = 115 Rs/kg	0.8625 Rs
		$15*0.5*10^{-3}*115$	
Wire material	Copper	Density = 8.69 g/cm^3 Volume = 50*π* 0.0112/4 cm^3 Cost = 650 Rs/kg	0.0267 Rs
		$8.69*50*\pi*0.0112/4*10^{-3*}650$	
Stack material & Design	Mylar	<u>For Parallel plates stack design:</u> Length = 6 cm Thickness = 0.1 mm Space between stacks = 0.7 mm No. of plates = 45/0.8 = 56 plates Volume = 0.1 * 50 * 85 * 56 mm^3 No. of stacks = 2 ρ = 1390 kg/m^3 Cost = 270 Rs/kg	
		$2 * 2.38 * 10^{-5} * 1390 * 270$	18 Rs
		<u>For spiral stack design:</u> Volume = 3.8 m * 0.06 mm * 6 cm	
		$3.8*0.06*10^{-3}*6*10^{-2}*1390*270$	38 Rs*
Tube material	Glass	Length = 40 cm Internal diameter = 5.3 cm Thickness = 3mm Cost = 1.3k/m^3	0.25 Rs
		$40*\pi*5.3*10^{-4}*3*10^{-3}*1.3*10^{3}$	
Total Cost			20 Rs

**This method is less economical hence not used.*

13. Conclusions

- In this report three methods of cooling hotspot were analysed:
    1. Passive cooling (free convection)
    2. Active cooling (forced convection) using a fan
    3. Active cooling using a thermoacoustic cooler

- This was done by a mixture of CFD and hands calculation methods
  The order of cooling achieved by all three were:
    1. By passive cooling ,we can achieve a cooling rate of 0.00024965 W.
    2. By active cooling using fans we can achieve a cooling rate of 0.0202 W.
    3. Using thermoacoustic cooling we can achieve a cooling rate of 0.11 W.

- Thermoacoustic cooling when compared with other active cooling techniques is :
    1. 22.5 times more energy efficient (in terms of cooling power)
    2. 23 times more cost efficient (in terms of energy consumption costs)
    3. 7.5 times more cost efficient (in terms of hardware costs)

  Hence, Thermoacoustic refrigeration is undoubtedly the most efficient method of the three.

14. References

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