Improving Reliability Of Air Cooled Power Electronic Devices Through Heat Sink Optimization

How to increase reliability of air cooled products by maximizing heat transfer rate of heat sinks subject to volumetric constraints

Nikesh Dhar

ROAD MAP

- Heat Transfer Mechanism in Heat Sinks
- Analytical Approach and Problem Setup
    - Optimization Problem subject to constraints
- Case Study
    - Case study to validate analytical findings
- Numerical Approach
    - Numerical Setup
    - Numerical Results
- Future Work
- Summary and Conclusions

Heat Sinks

- Power Electronic Components are cooled/maintained at a particular temperature using suitably sized heat sinks
- Heat Transfer in heat sinks is through combined <u>conduction</u> and <u>convection</u> effects
- It is desired to <u>maximize</u> heat transfer rate in order improve components reliability
- One method to enhance heat transfer rate is to optimize heat sink design
  - This paper examines the effect of number of fins <u>keeping everything else constant</u>

Analytical Optimization

- First Limit
  - Case1: $\lim_{n\to\infty}$
    - Gap between channels extremely small
    - Fully developed flow
    - Fluid Outlet Temperature will approach T_{wall}
  - Fluid velocity for fully developed flow well defined

$$U_\infty = \frac{D^2}{12\mu}\frac{\Delta P}{L}$$

  - Heat transfer rate is given by

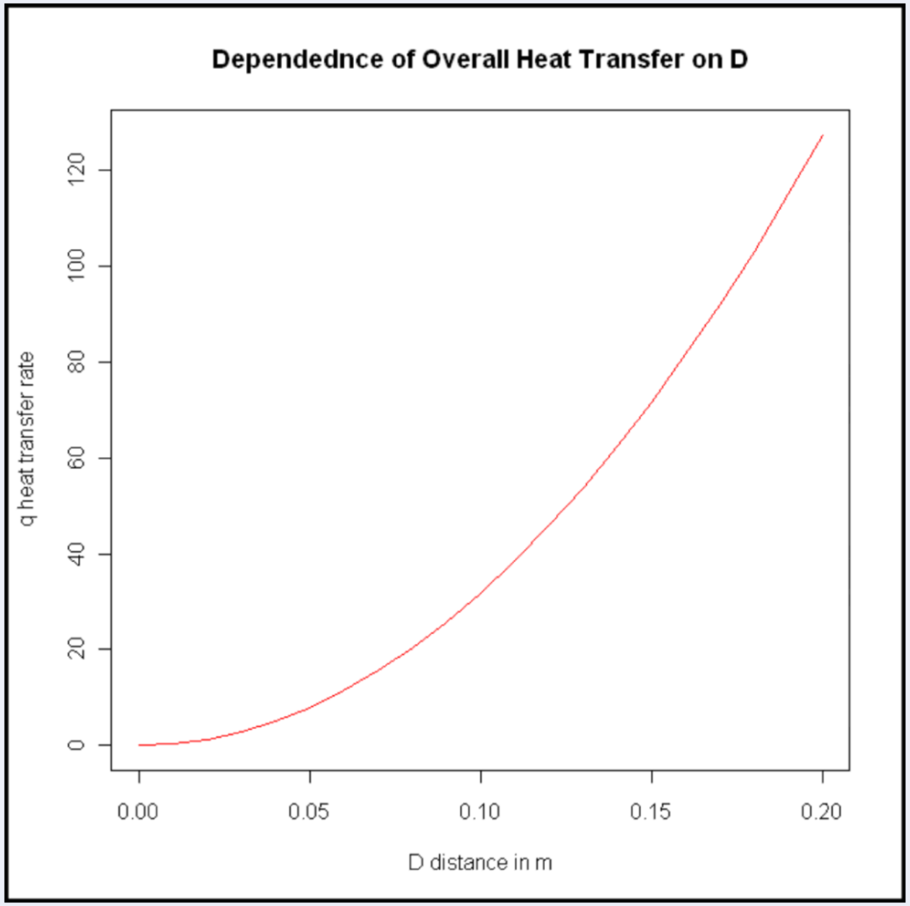
$$\dot{q} = \dot{m} c_p \theta$$
$$\theta = T_{wall} - T_\infty$$

  - Substituting for mass flow rate and free stream velocity we get overall heat transfer rate as

$$\dot{q} = \rho_{air} BH \frac{D^2}{12\mu}\frac{\Delta P}{L} \times C_p \times (T_{wall} - T_\infty)$$

  - In this first limiting case we have

$$\boxed{\dot{q} \propto k_1 D^2 \ldots\ldots\ldots.(1)}$$



Second Limit

- **Problem Setup**
  - Case2: $\lim_{n \to 2}$
    - Gap between channels extremely large compared to boundary layer thickness
    - Free stream velocity unknown
  - Resulting Fluid velocity from N.S/Force Balance Equations

$$U_\infty = \left(\frac{1}{1.328} \frac{\Delta PB}{nL^{1/2} \rho \gamma^{\frac{1}{2}}} \right)^{\frac{2}{3}}$$

  - Heat transfer rate is calculated using Nusselt Number Definition

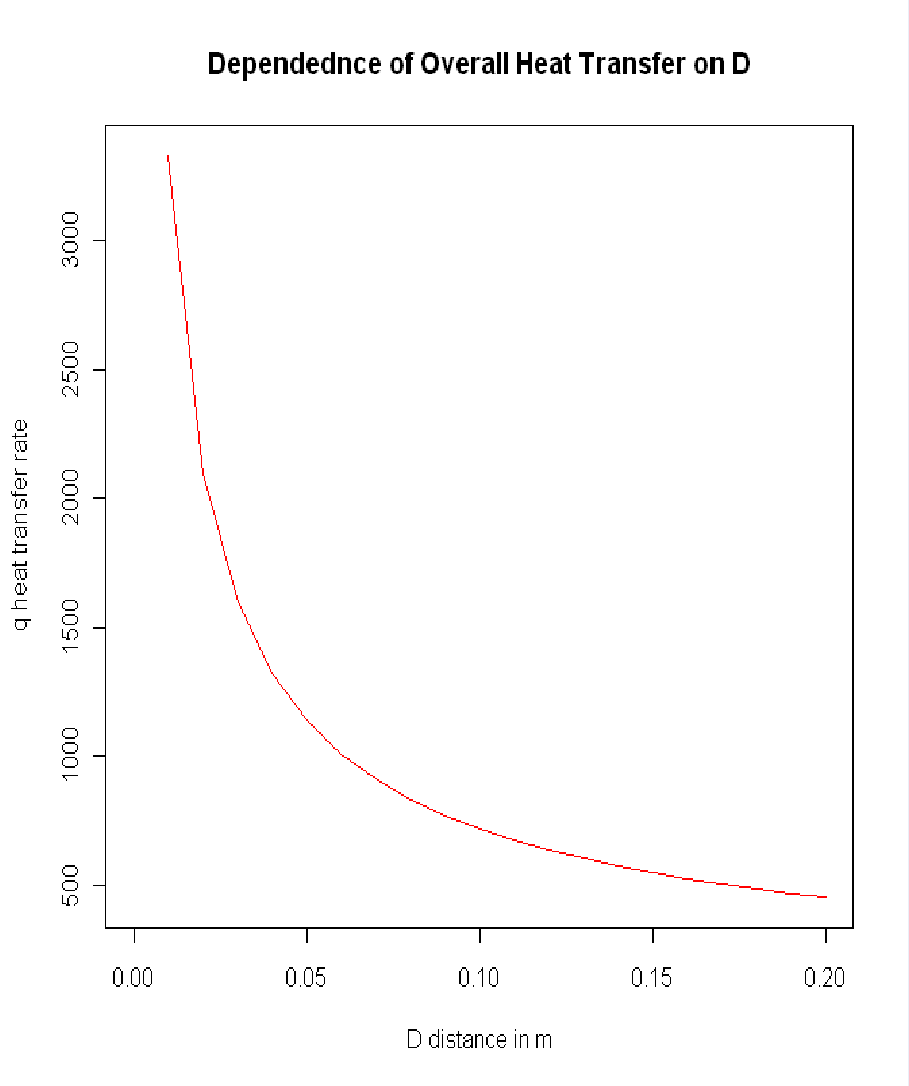
$$\frac{\bar{h} L}{k} = 0.664 \,\mathrm{Pr}^{1/3} \,\mathrm{Re}^{1/2}$$

  - Substituting for mass flow rate and free stream velocity we get overall heat transfer rate as

$$\dot{q} = \frac{1.208 k (T_{wall} - T_\infty) H \,\mathrm{Pr}^{1/3} L^{1/3} \Delta p^{1/3}}{\rho^{1/3} \gamma^{2/3} D^{2/3}}$$

  - In this second limiting case we have

$$\boxed{\dot{q} \propto k_2 D^{-2/3} \ldots\ldots\ldots(2)}$$



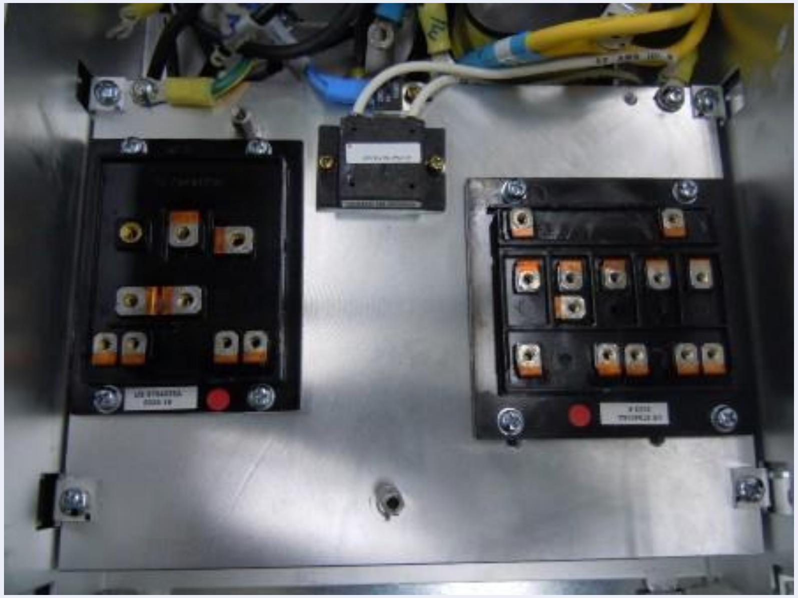
OPTIMAL SOLUTION

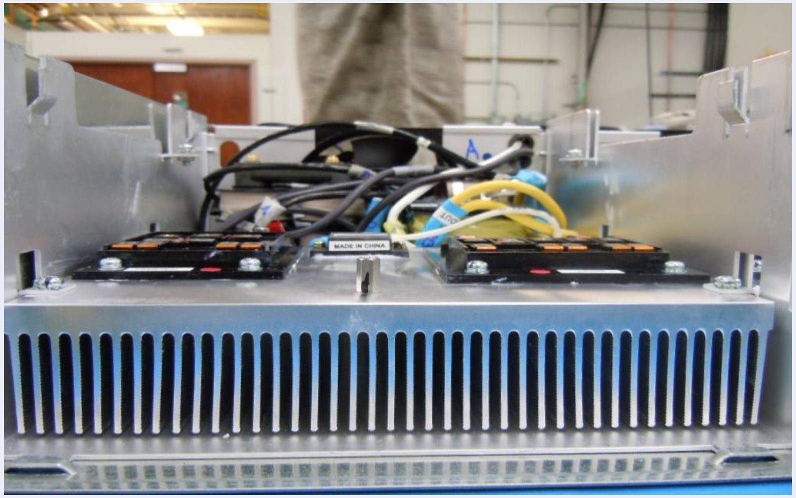
Solving the asymptotes represented in Eq-1 and Eq-2 we get optimal spacing (keeping every other geometric aspect constant) required to maximize heat transfer rate

$$\boxed{D_{opt} \approx 2.7\left(\frac{\mu\alpha}{\Delta p}\right)^{1/4} L^{1/2} \ldots\ldots\ldots\ldots (3)}$$

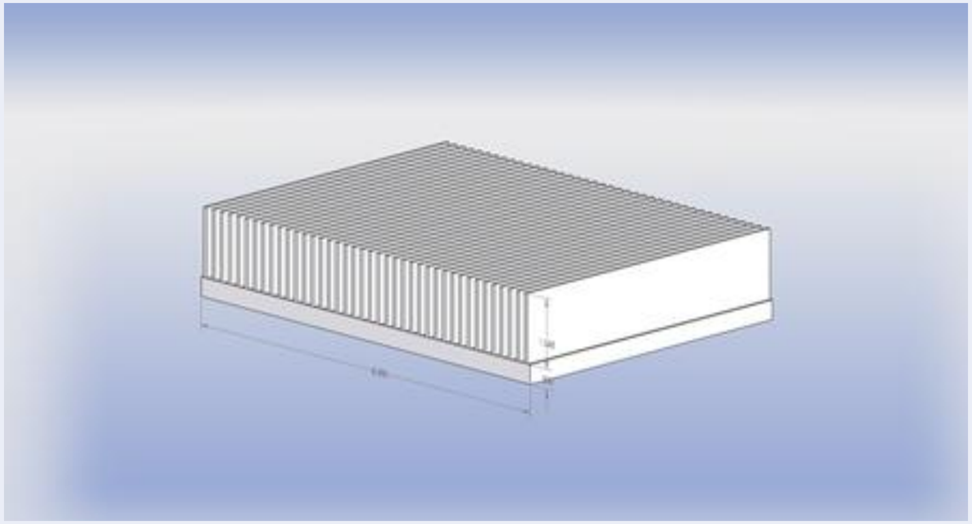
CASE STUDY

- Application
  - Air cooling of Power Hybrids
  - Requires dissipation in the order of 10's of Watts
    - Hybrid critical component for generators operation
    - High failure rate(~20% of generator failures are attributed to hybrid failures)
    - Particular application required dissipation of roughly ~30W
    - Desired to maintain die/$T_j \ll 430K$
    - Lower the die temperature greater the reliability of the hybrid
    - Hybrids demonstrate classical Arrhenius mechanism i.e. AF behaves exponentially with temperature





CASE STUDY

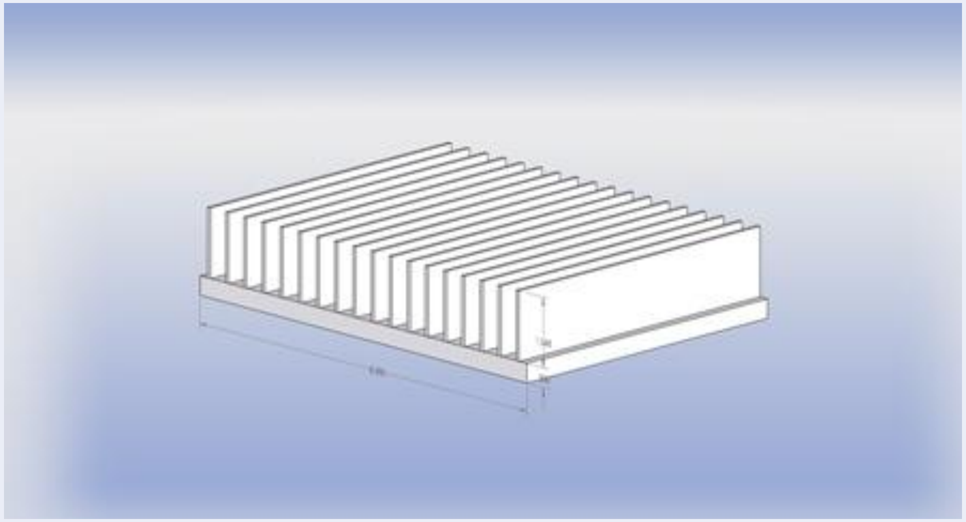


- Current Heat Sink Geometry
  - L=0.15m(in the direction of free stream)
  - B=0.2m
  - H=0.04m
  - n=40(D=0.003m)

- Based on Eq 3

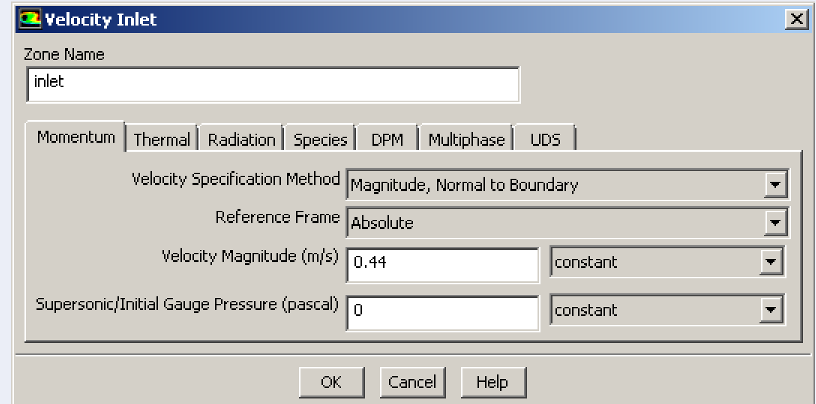
$$D_{opt} \approx 2.7\left(\frac{\mu\alpha}{\Delta p}\right)^{1/4} L^{1/2}$$

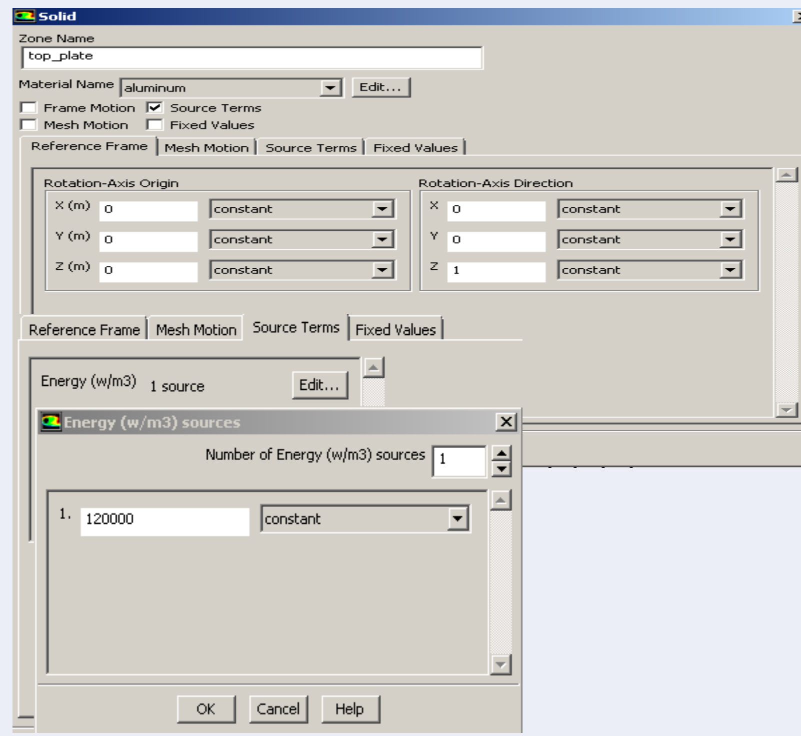
  - n=18 (D_{opt}=0.0106m- not taking into account fin thickness t<<B)
  - n=16 (taking into account fin thickness t)



Numerical Setup

- FLUENT Setup
  - Modeled a steady state conjugate heat transfer problem
  - Current Case assumed
    - Laminar conditions ($R_e < 2000$ and $Pr < X$)
    - Fluid flow was fully developed (achieved by having entrant length greater than 6 X D_{hyd})
    - Cooling fluid was air and was assumed to be an incompressible ideal fluid
    - A total of 32W was applied to the heat sink volume
    - A fan equivalent of X cfm was modeled at the inlet (velocity inlet)
    - In all three cases the area average base plate temperature was monitored
    - In each of the following cases mass conservation($^{kg}/_{s}$) and energy conservation (W) was verified
  - 3 models
    - 40 fins
    - 8 fins $\lim_{n \to \infty}$
    - 18 fins D_{opt} $\lim_{n \to 2}$





Numerical Results

40 fins

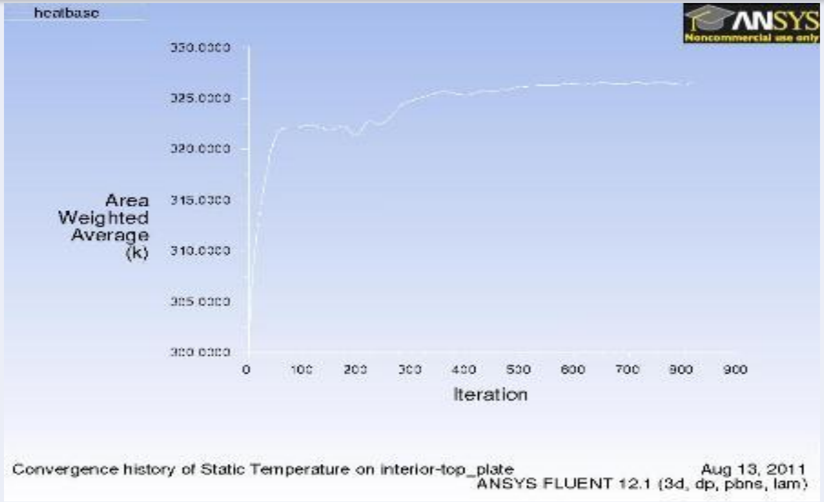
- $T_{base-avg} \sim 327K$
- Mass Conservation

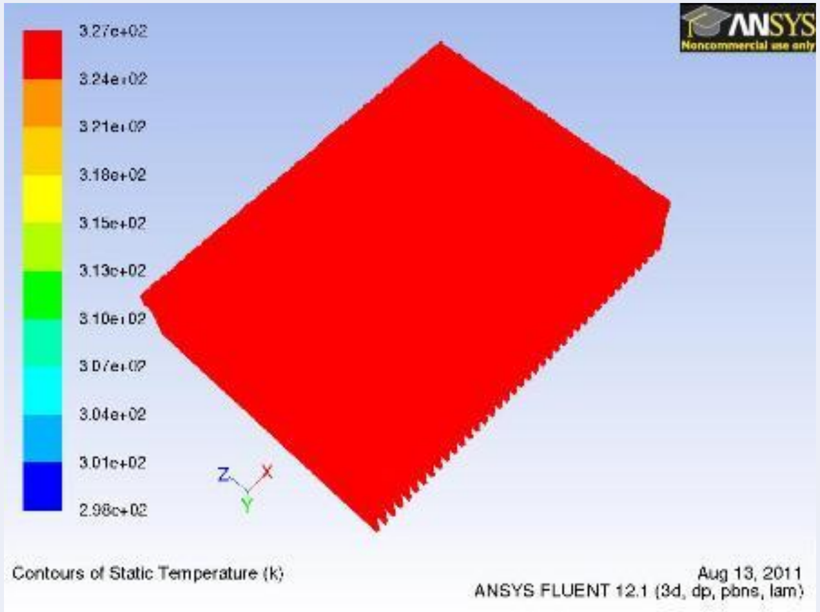
"Flux Report"

Mass Flow Rate	(kg/s)
inlet	0.078181687
outlet	-0.078188458
Net	-6.771e-07

- Heat Transfer Rate

Total Heat Transfer Rate	(w)
inlet	-11.802659
outlet	-20.59948
Net	-32.402139





Numerical Results

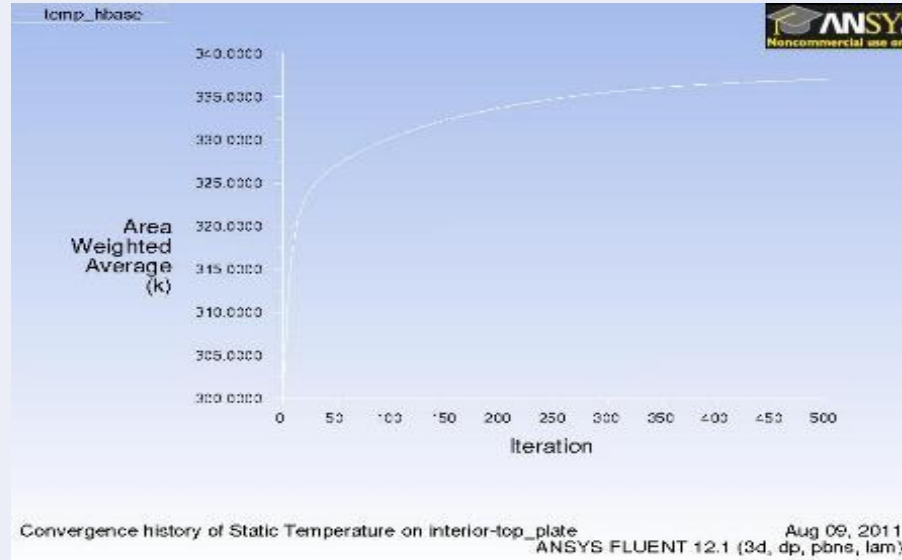
8 fins

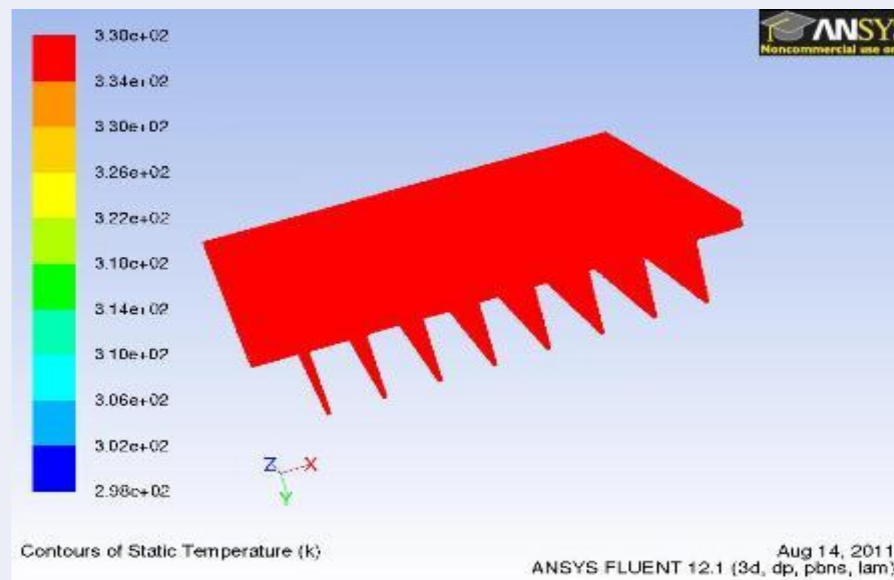
- $T_{base-avg} \sim 337K$
- Energy Conservation

```
                    "Flux Report"

        Total Heat Transfer Rate                    (w)
-------------------------------- --------------------
                           inlet           -11.802659
                          outlet           -20.573757
                ---------------- --------------------
                             Net           -32.376416
```

- Mass Conservation

```
                    "Flux Report"

                  Mass Flow Rate               (kg/s)
-------------------------------- --------------------
                           inlet          0.078181687
                          outlet         -0.078181726
                ---------------- --------------------
                             Net              -3.9e-08
```





Numerical Results

18 fins

- $T_{base-avg} \sim 320K$

- Mass Conservation

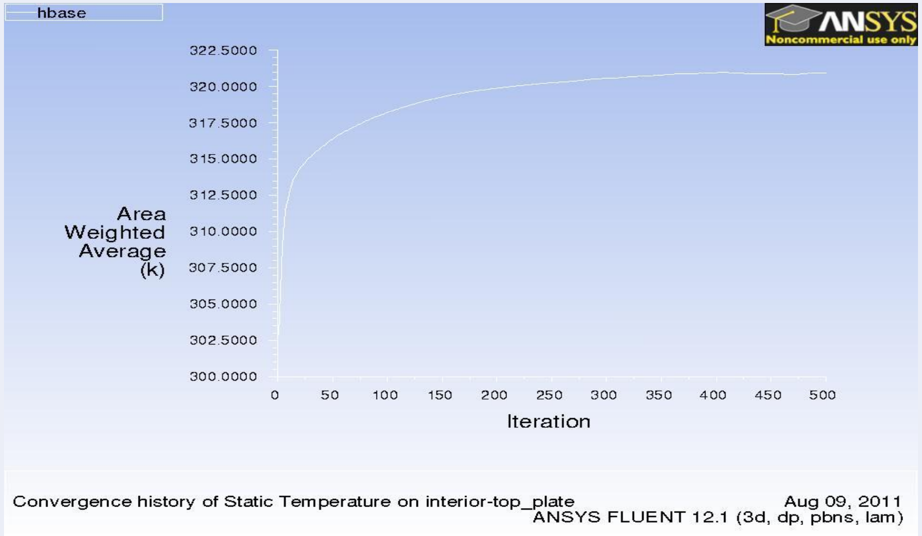
"Flux Report"

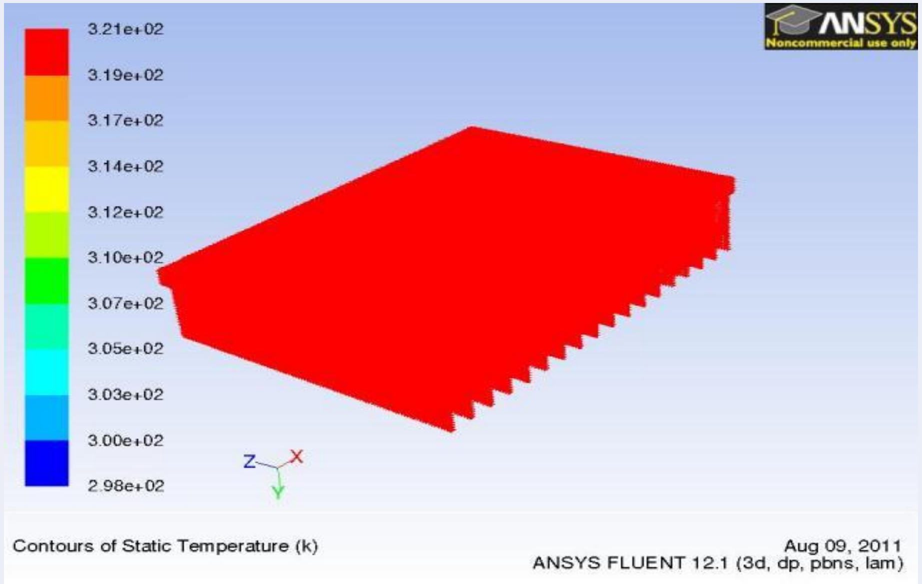
Mass Flow Rate	(kg/s)
inlet	0.078181687
outlet	-0.078182107
Net	-4.2e-07

- Energy Conservation

"Flux Report"

Total Heat Transfer Rate	(w)
inlet	-11.802659
outlet	-20.627146
Net	-32.429805





Acceleration Factor Calculation

Sample Calculation

- Thermal acceleration factor calculation using Arrhenius Equation

- **Assumptions**
  - Activation Energy=1eV

- **Equation**

$$A_T = \exp\{E_a/k \times \{(1/T_u) - (1/T_A)\}\} = L_{Tu} / L_{TA}$$

- 8 fins

$$A_T = \exp\{1/8.617\times10^{-5} \times \{(1/298) - (1/337)\}\} = 90.62$$

Case	T_{amb} (K)	T_{stress} (K)	AF
1.	298	327	31.61
2.	298	337	90.62
3.	298	320	14.54

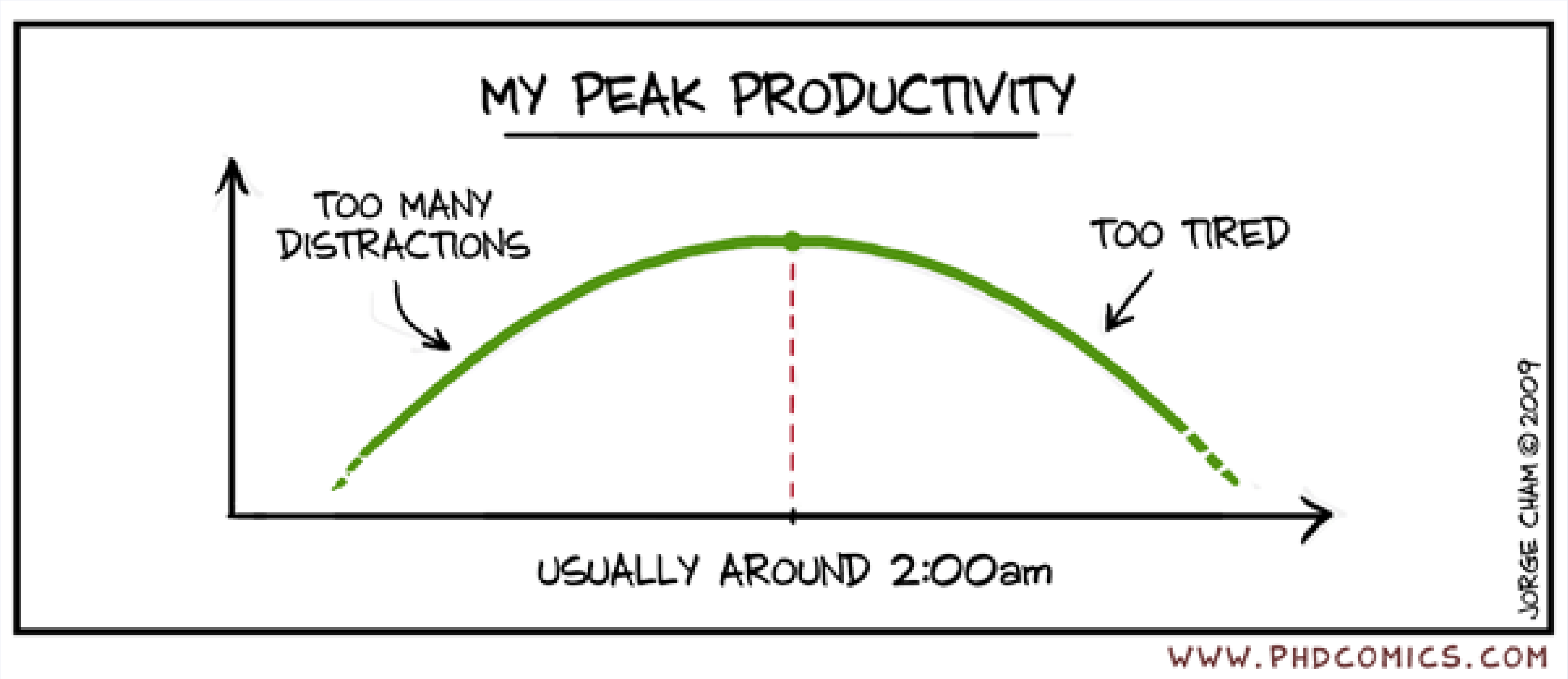
Future Work

- Experimental Verification
  - It is desired to verify the above numerical results experimentally
- Local Heat Sinking
  - Instead of applying a uniform heat to the heat sink surface, it is desired to model the exact hybrid positions and simulate local heat sinking/hot spots
- Larger Q applications
  - Optimization becomes more effective with increase in power dissipation, AF ratios would be much greater, a plot of Q vs. AF ratio would be meaningful
- Turbulence and Transient
  - Present case study involves steady state laminar conditions, it would be interesting to extend this analysis to transient and turbulent conditions and verify if conclusion drawn still remain valid.

Summary and Conclusion

- It is possible to maximize heat transfer rate of heat sinks subject to spatial(volume) constraints
- Maximum heat transfer is desired to not only remove heat from power electronic components as fast as possible but also to lower the steady state temperature at which the component operates at
- For given spatial (volume) constraint it is possible to find the optimum number of fins, keeping every other variable constant
- Numerical approach was followed to verify analytical findings
- Reliability implications of electronic power devices are understood in terms of Acceleration Factor calculations i.e. the optimal fin case resulted in the lowest acceleration factor indicating minimal thermal stress
- Future work to better understand and validate the current hypothesis is also presented

QUESTIONS


MY PEAK PRODUCTIVITY
TOO MANY DISTRACTIONS
TOO TIRED
USUALLY AROUND 2:00am
JORGE CHAM © 2009
WWW.PHDCOMICS.COM