# Fin Convection Experiment

## Thermal Network Solution with TNSolver

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# Outline

- Fin Convection Experiment
- Math Model
- Thermal Network Model Analysis
- Calculations

# Fins to be Studied

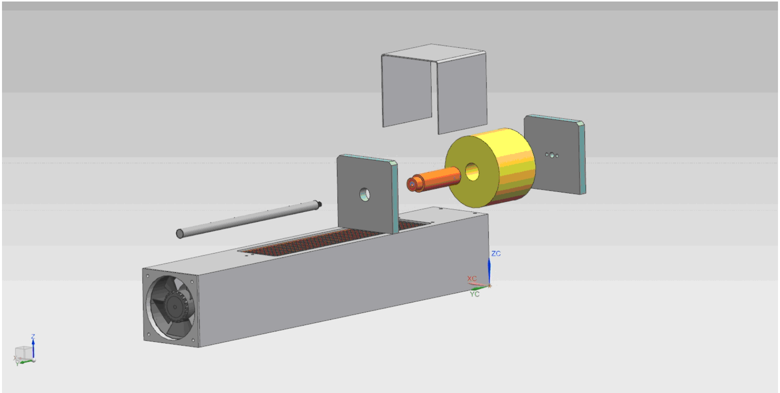
## Fin Convection Experiment

- Four uniform cross section fins will be studied
- Steady state, forced and natural convection
- Three are circular, ●, and one is diamond shaped ◆ (a square, rotated 45°)

| Fin Material | Dimensions | k (W/m-K) |
|---|---|---|
| Aluminum Alloy 6061-T6 | 0.5” ⌀ X 11.22” L | 167.0 |
| Copper Alloy 110 | 0.5” □ X 11.22” L | 388.0 |
| Copper Alloy 110 | 0.5” ⌀ X 6.77” L | 388.0 |
| Stainless Steel Alloy | 0.375” ⌀ X 11.22” L | 16.0 |

# Test Fixture Assembly

## Fin Convection Experiment



# Measurements

## Fin Convection Experiment

The following measurements are made:

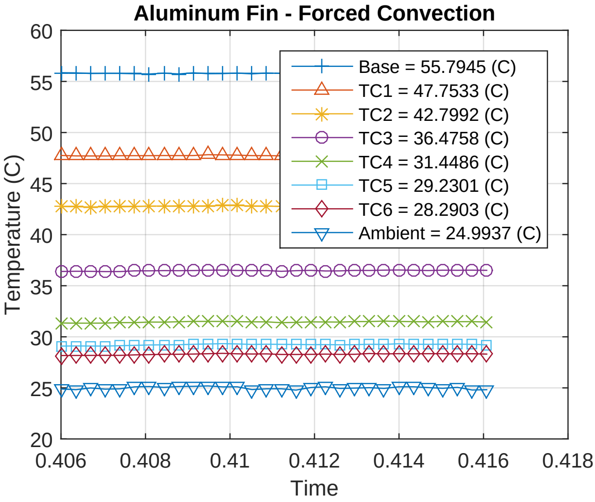
- Base temperature of the fin
- Heater power
- Ambient air temperature
- Fin temperatures along the length of the fin
  - Thermocouples are located at the center line of the fin
- Flow velocity for forced convection

A typical data set is shown for the aluminum fin, for both forced and natural convection.

# Aluminum Fin - Forced Convection

## Fin Convection Experiment

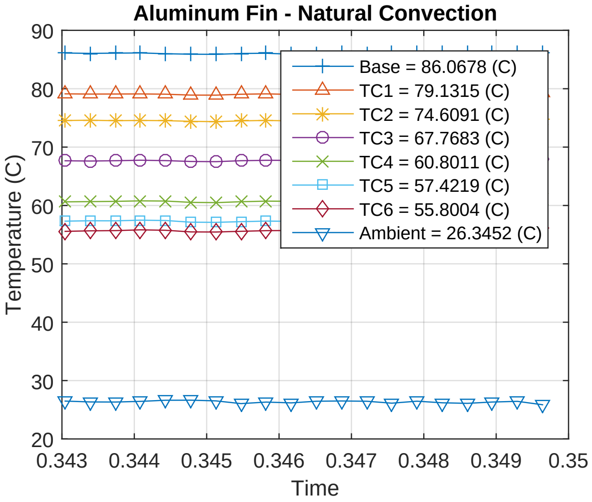
Heater Power = 10.53 W



# Aluminum Fin - Natural Convection

## Fin Convection Experiment

Heater Power = 10.53 W



- Conduction
- Forced Convection Correlations
- Natural or Free Convection Correlations
- Surface Radiation

# Heat Conduction: Cartesian Coordinates (Plane Wall)

## Math Model

The rate of heat transfer, $Q_{ij}$, due to conduction, between the two temperatures $T_i$ and $T_j$, separated by a distance $L$ and area $A$, is:

$$Q_{ij} = \frac{kA}{L}\left(T_i - T_j\right)$$

The heat flux, $q_{ij}$, is:

$$q_{ij} = \frac{Q_{ij}}{A} = \frac{k}{L}\left(T_i - T_j\right)$$

where $k$ is the thermal conductivity of the material.

# Convection Correlations

## Math Model

The convection heat flow rate is:

$$Q = hA(T_s - T_\infty)$$

where $h$ is the heat transfer coefficient, $T_s$ is the surface temperature and $T_\infty$ is the fluid temperature

# External Forced Convection over a Cylinder

## Math Model

Correlation is (Equation (17.69), page 504 in [KK58]):

$$\overline{Nu}_D \equiv \frac{\bar{h}D}{k} = C Re_D^m Pr^{1/3}$$

where $D$ is the diameter of the cylinder and the Reynolds number is $Re_D = \rho VD/\mu = VD/\nu$.

| $Re_D$ | $C$ | $m$ |
|---|---|---|
| 0.4–4 | 0.989 | 0.330 |
| 4–40 | 0.911 | 0.385 |
| 40–4,000 | 0.683 | 0.466 |
| 4,000–40,000 | 0.193 | 0.618 |
| 40,000–400,000 | 0.027 | 0.805 |

Table 17-5, page 505 in [KK58]

# External Forced Convection over a Noncircular Cylinder

## Math Model

For the case of a gas flowing over noncircular cylinders in crossflow (see [SAT04]):

| Geometry | $Re_D$ | $C$ | $m$ |
|---|---|---|---|
| $\rightrightarrows \blacklozenge$ $D = \sqrt{2H^2}$ | 6,000–60,000 | 0.304 | 0.59 |
| $\rightrightarrows \blacksquare$ $D = H$ | 5,000–60,000 | 0.158 | 0.66 |

Note that the fluid properties are evaluated at the film temperature, $T_f$:

$$T_f = \frac{T_s + T_\infty}{2}$$

# External Natural Convection over a Horizontal Cylinder

## Math Model

Correlation is (see [CC75]):

$$\overline{Nu_D} = \frac{\bar{h}D}{k} = \left\{ 0.60 + \frac{0.387 Ra_D^{1/6}}{\left[ 1 + (0.559/Pr)^{9/16} \right]^{8/27}} \right\}^2$$

valid for $Ra_D \leq 10^{12}$, $Pr \geq 0.7$, where $D$ is the diameter of the cylinder and the Rayleigh number, $Ra$, is:

$$Ra_D = GrPr = \frac{g\rho^2 c\beta D^3 (T_s - T_\infty)}{k\mu} = \frac{g\beta D^3 (T_s - T_\infty)}{\nu\alpha}$$

Note that the fluid properties are evaluated at the film temperature, $T_f$:

$$T_f = \frac{T_s + T_\infty}{2}$$

# Surface Radiation

## Math Model

Radiation exchange between a surface and *large* surroundings
The heat flow rate is (Equation (1.32), p. 32 in [LL16]):

$$Q = \sigma \epsilon_s A_s (T_s^4 - T_{sur}^4)$$

where $\sigma$ is the Stefan-Boltzmann constant, $\epsilon_s$ is the surface emissivity and $A_s$ is the area of the surface.
Note that the surface area, $A_s$, must be *much* smaller than the surrounding surface area, $A_{sur}$:

$$A_s \ll A_{sur}$$

Note that the temperatures must be the absolute temperature, $K$ or $^\circ R$

# Radiation Heat Transfer Coefficient

## Math Model

Define the radiation heat transfer coefficient, $h_r$ (see Equation (2.29), p. 74 in [LL16]):

$$h_r = \epsilon\sigma(T_s + T_{sur})(T_s^2 + T_{sur}^2)$$

Then,

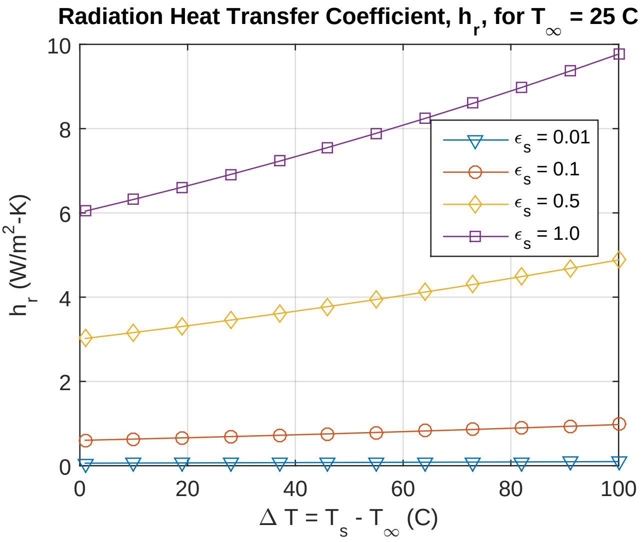
$$Q = h_r A_s (T_s - T_{sur})$$

Note:

- $h_r$ is temperature dependent
- $h_r$ can be used to compare the radiation to the convection heat transfer from a surface, $h$ (if $T_{sur}$ and $T_\infty$ have similar values)

# Range of Radiation Heat Transfer Coefficient

## Math Model



# Thermal Network Terminology



- Geometry
  - Control Volume
    - Volume property, $V = \int_V dV$
    - Node: ●, $T_{\text{node}} = \int_V T(x_i)dV$
  - Control Volume Surface
    - Area property, $A = \int_A dA$
    - Surface Node: ○, $T_{\text{surface node}} = \int_A T(x_i)dA$
- Material properties
- Conductors
  - Conduction, convection, radiation
- Boundary conditions
  - Boundary node: ▲

# TNSolver Input Files

## Thermal Network Model Analysis

The supplied TNSolver input files for each fin model:

| Fin | Forced Convection | Natural Convection |
|---|---|---|
| Aluminum, 11.22” | `Al_fin_FC.inp` | `Al_fin_NC.inp` |
| Round Copper, 6.77” | `Cu_fin_FC.inp` | `Cu_fin_NC.inp` |
| Square Copper, 11.22” | `sqCu_fin_FC.inp` | `sqCu_fin_NC.inp` |
| Stainless Steel, 11.22” | `SS_fin_FC.inp` | `SS_fin_NC.inp` |

Edit each file to set appropriate boundary conditions (Tc, Tr and base) and flow velocities (forced convection models) for your specific experimental data set

# TNSolver Input Files for Estimating h

## Thermal Network Model Analysis

The supplied TNSolver input files for each fin model to be used with `ls_fin_h.m`:

| Fin | Convection |
|---|---|
| Aluminum, 11.22” | `Al_fin_C.inp` |
| Round Copper, 6.77” | `Cu_fin_C.inp` |
| Square Copper, 11.22” | `sqCu_fin_C.inp` |
| Stainless Steel, 11.22” | `SS_fin_C.inp` |

Edit each file to set appropriate boundary conditions (Tc, Tr and base) for your specific experimental data set

# Running a TNSolver Model

## Thermal Network Model Analysis

The MATLAB/Octave command to run the aluminum fin, forced convection model is:

```
>>tnsolver('Al_fin_FC');
```

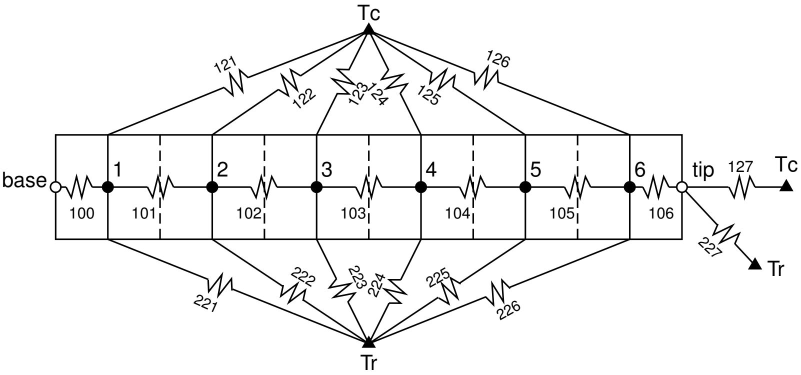
Note that you supply the base of the input file name (`AL_fin_FC`, in this example), without the `.inp` extension

The results output file will be the base name with the extension `.out` (`Al_fin_FC.out`, in this example)

# 11.22” Fin Thermal Network Model

## Thermal Network Model Analysis

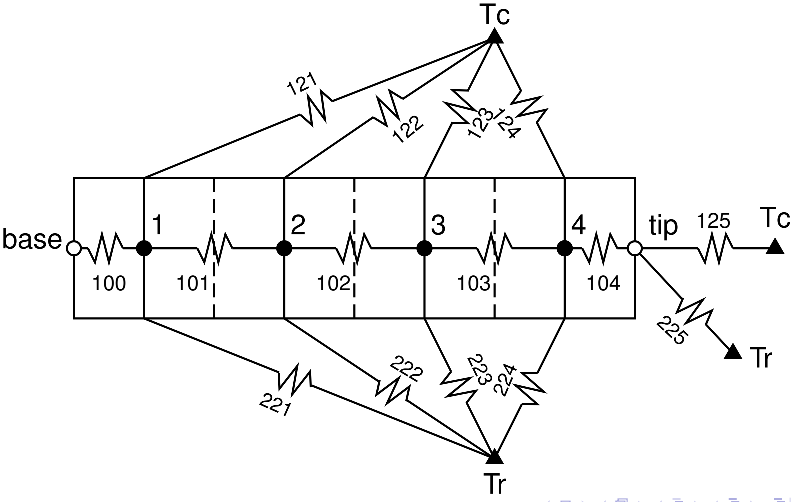
For the 11.22” long fin, there are six thermocouples:



# 6.77” Fin Thermal Network Model

## Thermal Network Model Analysis

For the 6.77” long fin, there are four thermocouples:



# Surface Radiation Properties

## Thermal Network Model Analysis

| Fin Material | Emissivity, $\epsilon$ (dimensionless) |
|---|---|
| Aluminum Alloy 6061-T6 | 0.09 |
| Copper Alloy 110 | 0.12-0.15 |
| Stainless Steel Alloy | 0.5-0.7 |

See Table 10.1, page 530, in [LL16]

# Verification with Analytical Solution

## Thermal Network Model Analysis

Table 3.4, page 161 in [BLID11], Temperature distribution and heat loss for fins with a uniform cross section

| Case | Tip Condition | Temperature, $\theta/\theta_b$ | Fin Heat Transfer Rate, $Q$ |
|---|---|---|---|
| A | Convection | $\frac{\cosh m(L-x)+(h/mk)\sinh m(L-x)}{\cosh mL+(h/mk)\sinh ml}$ | $M\frac{\sinh mL+(h/mk)\cosh mL}{\cosh mL+(h/mk)\sinh mL}$ |
| B | Adiabatic | $\frac{\cosh m(L-x)}{\cosh mL}$ | $M\tanh mL$ |
| C | Specified T | $\frac{(\theta_L/\theta_b)\sinh mx+\sinh m(L-x)}{\sinh mL}$ | $M\frac{\cosh mL-(\theta_L/\theta_b)}{\sinh mL}$ |
| D | $L=\infty$ | $e^{mx}$ | $M$ |

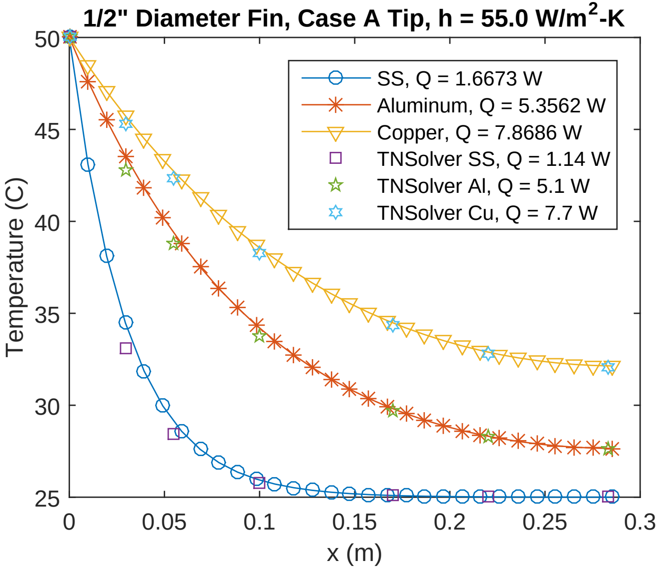
$\theta = T - T_\infty$ $\quad m = \sqrt{hP/kA_c}$

$\theta_b = \theta(0) = T_b - T_\infty$ $\quad M = (\sqrt{hPkA_c})\theta_b$

For circular fins: $P = \pi D$ and $A_c = \pi(D/2)^2$
For square/diamond fins: $P = 4H$ and $A_c = H^2$

# Comparison with TNSolver Network Model

## Thermal Network Model Analysis



# Calculations

## Calculations

For the four forced convection experimental data sets:

1. Using forced convection correlations, determine $h$ and $h_r$ for each fin
   - `EFCcyl` and `EFCdiamond` conductors
2. Using least-squares fit, estimate $\epsilon$, using forced convection correlations
   - `ls_fin_emiss.m` function
3. Using least-squares fit, estimate $h$, using estimated $\epsilon$ and forced convection correlations
   - `ls_fin_h.m` function

How does the estimated $h$ compare to the correlation?

How does the estimated $\epsilon$ compare to the material property table value?

# Calculations (continued)

## Calculations

For four free convection experimental data sets:

1. Using free convection correlations, determine *h* and $h_r$ for each fin
   - `ENChcyl` conductor
2. Using least-squares fit, estimate $\epsilon$, using free convection correlation
   - `ls_fin_emiss.m` function
3. Using least-squares fit, estimate *h*, using estimated $\epsilon$ and free convection correlation
   - `ls_fin_h.m` function

How does the estimated *h* compare to the correlation?

How does the estimated $\epsilon$ compare to the material property table value?

# Least Squares Estimation
## Calculations

Least squares estimation of a parameter $\theta$, for $n$ data points, is:

$$R = \sum_{i=1}^{n} \left(\theta^{i}_{\text{exp}} - \theta^{i}_{\text{model}}\right)^2$$

The closest model parameter is determined by the index $i$, of the minimum $R$

Function to estimate emissivity, $\epsilon$, is: `ls_fin_emiss.m`

Function to estimate convection coefficent, $h$, is: `ls_fin_h.m`

# Conclusion

- Fin convection experiment overview
- Conduction, convection and surface radiation math model
- Thermal network model analysis
- Calculations using the experimental data

Questions?

# Appendix

# Heat Transfer Analysis

## Thermal Network Model

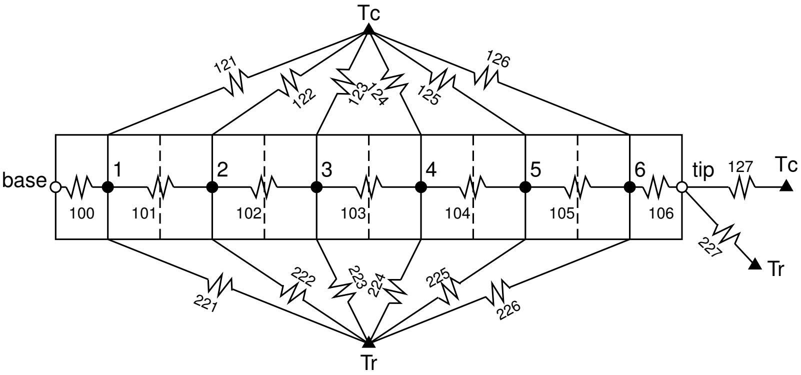
- Energy conservation: control volumes
- Identify and sketch out the control volumes
- Use the conductor analogy to represent energy transfer between the control volumes and energy generation or storage
  - Conduction, convection, radiation, other?
  - Capacitance
  - Sources or sinks
- State assumptions and determine appropriate parameters for each conductor
  - Geometry, material properties, etc.
- Which conductor(s)/source(s)/capacitance(s) are important to the required results?
  - Sensitivity analysis
- What is missing from the model? - peer/expert review

# Thermal Network Terminology

## Thermal Network Model

- Geometry
  - Control Volume
    - Volume property, $V = \int_V dV$
    - Node: $\bullet$, $T_{\text{node}} = \int_V T(x_i) dV$
  - Control Volume Surface
    - Area property, $A = \int_A dA$
    - Surface Node: $\circ$, $T_{\text{surface node}} = \int_A T(x_i) dA$
- Material properties
- Conductors
  - Conduction, convection, radiation
- Boundary conditions
  - Boundary node: $\blacktriangle$

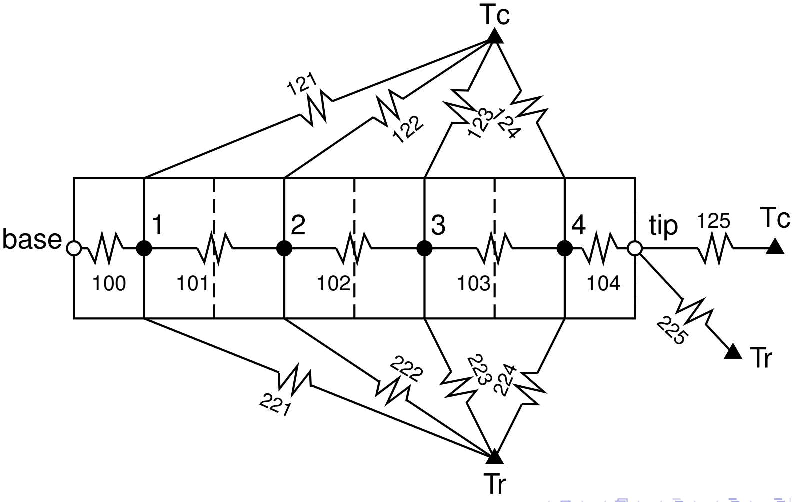
For the 11.22" long fin, there are six thermocouples:



# Thermal Network Analysis

## Thermal Network Model

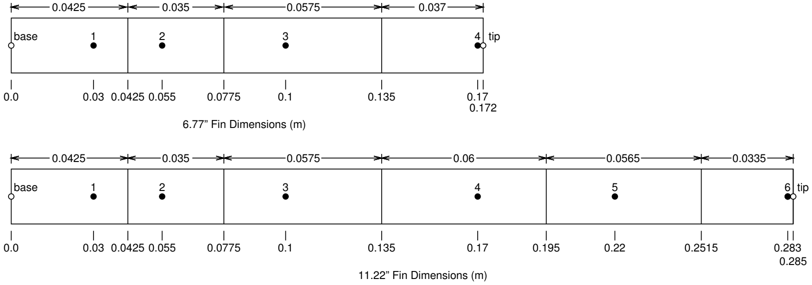
For the 6.77” long fin, there are four thermocouples:



# Control Volume Geometry

## Thermal Network Model

Scale drawing of thermocouple locations and control volume lengths:




Note that the control volume boundaries are located midway between the thermocouple locations

# Round Fin, 11.22" Long, Conduction Geometry

## Thermal Network Model

Axial conduction in the fin, L = 11.22" = 0.285 m
D = 0.5" = 0.0127 m and r = 0.25" = 0.00635 m:

$$L = \text{distance between TC} \qquad A = \pi r^2$$

| Conductor | Length ($m$) | A ($m^2$) |
|---|---|---|
| 100 | 0.030 | 0.00012667 |
| 101 | 0.025 | 0.00012667 |
| 102 | 0.045 | 0.00012667 |
| 103 | 0.070 | 0.00012667 |
| 104 | 0.050 | 0.00012667 |
| 105 | 0.063 | 0.00012667 |
| 106 | 0.002 | 0.00012667 |

# Round Fin, 11.22” Long, Convection Geometry

## Thermal Network Model

Surface convection area:

$$A = L_{CV} P = L_{CV} \pi D$$

D = 0.5” = 0.0127 m

| Conductor | $L_{CV}$ $(m)$ | $A$ $(m^2)$ |
|---|---|---|
| 121 | 0.0425 | 0.001696 |
| 122 | 0.0350 | 0.001396 |
| 123 | 0.0575 | 0.002294 |
| 124 | 0.0600 | 0.002394 |
| 125 | 0.0565 | 0.002254 |
| 126 | 0.0335 | 0.001337 |

# Round Fin, 6.77” Long, Conduction Geometry

## Thermal Network Model

Axial conduction in the fin, L = 6.77” = 0.172 m
D = 0.5” = 0.0127 m and r = 0.25” = 0.00635 m:

$L =$ distance between TC $\qquad A = \pi r^2$

| Conductor | Length ($m$) | A ($m^2$) |
|---|---|---|
| 100 | 0.030 | 0.00012667 |
| 101 | 0.025 | 0.00012667 |
| 102 | 0.045 | 0.00012667 |
| 103 | 0.070 | 0.00012667 |
| 104 | 0.002 | 0.00012667 |

# Round Fin, 6.77” Long, Convection Geometry

## Thermal Network Model

Surface convection area:

$$A = L_{CV} P = L_{CV} \pi D$$

D = 0.5” = 0.0127 m

| Conductor | $L_{CV}$ $(m)$ | $A$ $(m^2)$ |
|---|---|---|
| 121 | 0.0425 | 0.001696 |
| 122 | 0.0350 | 0.001396 |
| 123 | 0.0575 | 0.002294 |
| 124 | 0.0370 | 0.001476 |

# Square Fin, 11.22” Long, Conduction Geometry



Axial conduction in the fin, L = 11.22” = 0.285 m, H = 0.5” = 0.0127 m

$$L = \text{distance between TC} \qquad A = H^2$$

| Conductor | Length ($m$) | A ($m^2$) |
|---|---|---|
| 100 | 0.030 | 0.000016129 |
| 101 | 0.025 | 0.000016129 |
| 102 | 0.045 | 0.000016129 |
| 103 | 0.070 | 0.000016129 |
| 104 | 0.050 | 0.000016129 |
| 105 | 0.063 | 0.000016129 |
| 106 | 0.002 | 0.000016129 |

# Square Fin, 11.22” Long, Convection Geometry

## Thermal Network Model

Surface convection area:

$$A = L_{CV} P = L_{CV} 4H$$

H = 0.5” = 0.0127 m

| Conductor | $L_{CV}$ $(m)$ | $A$ $(m^2)$ |
|---|---|---|
| 121 | 0.0425 | 0.002159 |
| 122 | 0.0350 | 0.001778 |
| 123 | 0.0575 | 0.002921 |
| 124 | 0.0600 | 0.003048 |
| 125 | 0.0565 | 0.0028702 |
| 126 | 0.0335 | 0.0017018 |

# Conduction Conductor

## Thermal Network Model

$$Q_{ij} = \frac{kA}{L}(T_i - T_j)$$

```
Begin Conductors

! label type        nd_i nd_j    k     L         A
  100   conduction   base    1    x.x  0.030  0.00012667
  101   conduction    1      2    x.x  0.025  0.00012667
  102   conduction    2      3    x.x  0.045  0.00012667
  103   conduction    3      4    x.x  0.070  0.00012667
  104   conduction    4      5    x.x  0.050  0.00012667
  105   conduction    5      6    x.x  0.063  0.00012667
  106   conduction    6     tip   x.x  0.002  0.00012667

End Conductors
```

# Convection Conductor

## Thermal Network Model

$$Q_{ij} = hA(T_s - T_\infty) = hA(T_i - T_j)$$

```
Begin Conductors

! label   type       nd_i nd_j  h       A
   121   convection   1    Tc   x.x   0.001696
   122   convection   2    Tc   x.x   0.001396
   123   convection   3    Tc   x.x   0.002294
   124   convection   4    Tc   x.x   0.002394
   125   convection   5    Tc   x.x   0.002254
   126   convection   6    Tc   x.x   0.001337
   127   convection tip    Tc   x.x   0.00012667

End Conductors
```

# Forced Convection Over Cylinder Conductor

## Thermal Network Model

Heat transfer coefficient, h, is evaluated using the correlation.

```
Begin Conductors

! label type   nd_i   nd_j fluid  V     D         A
  121   EFCcyl   1     Tc    air   x.x  0.0127   0.001696
  122   EFCcyl   2     Tc    air   x.x  0.0127   0.001396
  123   EFCcyl   3     Tc    air   x.x  0.0127   0.002294
  124   EFCcyl   4     Tc    air   x.x  0.0127   0.002394
  125   EFCcyl   5     Tc    air   x.x  0.0127   0.002254
  126   EFCcyl   6     Tc    air   x.x  0.0127   0.001337
  127   EFCcyl  tip    Tc    air   x.x  0.0127   0.00012667

End Conductors
```

Note that Re, Nu and h are reported in the output file.

# Forced Convection Over Diamond Conductor

## Thermal Network Model

Heat transfer coefficient, h, is evaluated using the correlation.

```
Begin Conductors

! label type       nd_i   nd_j fluid  V    D        A
  121   EFCdiamond   1     Tc    air  x.x  0.018    0.002159
  122   EFCdiamond   2     Tc    air  x.x  0.018    0.001778
  123   EFCdiamond   3     Tc    air  x.x  0.018    0.002921
  124   EFCdiamond   4     Tc    air  x.x  0.018    0.003048
  125   EFCdiamond   5     Tc    air  x.x  0.018    0.0028702
  126   EFCdiamond   6     Tc    air  x.x  0.018    0.0017018
  127   EFCdiamond  tip    Tc    air  x.x  0.0127   0.00012667

End Conductors
```

Note that Re, Nu and h are reported in the output file.

# Natural Convection Conductor

## Thermal Network Model

Heat transfer coefficient, h, is evaluated using the correlation.

```
Begin Conductors

! label type   nd_i   nd_j fluid  D         A
  121   ENChcyl  1     Tc    air  0.0127  0.001696
  122   ENChcyl  2     Tc    air  0.0127  0.001396
  123   ENChcyl  3     Tc    air  0.0127  0.002294
  124   ENChcyl  4     Tc    air  0.0127  0.002394
  125   ENChcyl  5     Tc    air  0.0127  0.002254
  126   ENChcyl  6     Tc    air  0.0127  0.001337
  127   ENChcyl tip    Tc    air  0.0127  0.00012667

End Conductors
```

Note that Ra, Nu and h are reported in the output file.

# Surface Radiation Conductor

## Thermal Network Model

$$Q_{ij} = \sigma \epsilon_i A_i (T_i^4 - T_j^4)$$

```
Begin Conductors

! label type    nd_i nd_j emissivity     A
  221   surfrad  1     Tr     x.xx      0.001696
  222   surfrad  2     Tr     x.xx      0.001396
  223   surfrad  3     Tr     x.xx      0.002294
  224   surfrad  4     Tr     x.xx      0.002394
  225   surfrad  5     Tr     x.xx      0.002254
  226   surfrad  6     Tr     x.xx      0.001337
  227   surfrad tip    Tr     x.xx      0.00012667

End Conductors
```

Note that $h_r$ is reported in the output file.

# Boundary Conditions

## Thermal Network Model

```
Begin Boundary Conditions

!  type          Tb       Node(s)
  fixed_T      x.xx       Tc    ! fluid T
  fixed_T      x.xx       Tr    ! surrounding radiation T
  fixed_T      x.xx       base  ! fin base T

End Boundary Conditions
```

# TNSolver Input Files
## Thermal Network Model

The supplied TNSolver input files for each fin model:

| Fin | Forced Convection | Natural Convection |
|---|---|---|
| Aluminum, 11.22” | `Al_fin_FC.inp` | `Al_fin_NC.inp` |
| Round Copper, 6.77” | `Cu_fin_FC.inp` | `Cu_fin_NC.inp` |
| Square Copper, 11.22” | `sqCu_fin_FC.inp` | `sqCu_fin_NC.inp` |
| Stainless Steel, 11.22” | `SS_fin_FC.inp` | `SS_fin_NC.inp` |

Edit each file to set appropriate boundary conditions (Tc, Tr and base) and flow velocities (forced convection models) for your specific experimental data set

# Running a TNSolver Model

## Thermal Network Model

The MATLAB/Octave command to run the aluminum fin, forced convection model is:

```
>>tnsolver('Al_fin_FC');
```

Note that you supply the base of the input file name (`AL_fin_FC`, in this example), without the `.inp` extension

The results output file will be the base name with the extension `.out` (`Al_fin_FC.out`, in this example)

# Screen Output When Running TNSolver

## Thermal Network Model

```
*********************************************************
*                                                       *
*          TNSolver - A Thermal Network Solver          *
*                                                       *
*            Version 0.2.0, October 28, 2014            *
*                                                       *
*********************************************************

Reading the input file: Al_fin_FC.inp

Initializing the thermal network model ...

Starting solution of a steady thermal network model ...

     Nonlinear Solve
  Iteration    Residual
  ---------  ------------
        1      52.9978
        2      0.0309635
        3      1.21353e-05
        4      5.09316e-09

Results have been written to: Al_fin_FC.out

All done ...
```

# View TNSolver Output File For Results

## Thermal Network Model

Open `Al_fin_FC.out` in your favorite text editor

```
********************************************************
*                                                      *
*          TNSolver - A Thermal Network Solver         *
*                                                      *
*           Version 0.2.0, October 28, 2014            *
*                                                      *
********************************************************

Model run finished at 10:05 AM, on October 29, 2014

*** Solution Parameters ***

  Title: Aluminum Fin - Forced Convection

  Type                            =  steady
  Units                           =  SI
  Temperature units               =  C
  Nonlinear convergence           =  1e-008
  Maximum nonlinear iterations    =  15
  Gravity                         =  9.80665 (m/s^2)
  Stefan-Boltzmann constant       =  5.67037e-008 (W/m^2-K^4)
```

# View TNSolver Output File For Results (continued)

## Thermal Network Model

*** Nodes ***

| Label | Material | Volume (m^3) | Temperature (C) |
|---|---|---|---|
| 1 | N/A | 0 | 47.1038 |
| 2 | N/A | 0 | 42.202 |
| 3 | N/A | 0 | 36.0832 |
| 4 | N/A | 0 | 31.0199 |
| 5 | N/A | 0 | 29.207 |
| 6 | N/A | 0 | 28.4181 |
| Tc | N/A | 0 | 25 |
| Tr | N/A | 0 | 25 |
| base | N/A | 0 | 55.8 |
| tip | N/A | 0 | 28.416 |

# View TNSolver Output File For Results (continued)

## Thermal Network Model

```
*** Conductors ***

                                                    Q_ij
   Label       Type       Node i      Node j        (W)
---------- ---------- ---------- ---------- ----------
       100 conduction       base          1    6.13192
       101 conduction          1          2    4.14771
       102 conduction          2          3    2.87638
       103 conduction          3          4    1.53011
       104 conduction          4          5   0.766993
       105 conduction          5          6   0.264889
       106 conduction          6        tip  0.0229109
       121     EFCcyl          1         Tc    1.96157
       122     EFCcyl          2         Tc    1.25717
       123     EFCcyl          3         Tc    1.33172
       124     EFCcyl          4         Tc   0.755085
       125     EFCcyl          5         Tc   0.496864
       126     EFCcyl          6         Tc   0.239463
       127     EFCcyl        tip         Tc  0.0226728
       221    surfrad          1         Tr  0.0226511
       222    surfrad          2         Tr  0.0141605
       223    surfrad          3         Tr  0.0145417
       224    surfrad          4         Tr 0.00803642
       225    surfrad          5         Tr 0.00523996
       226    surfrad          6         Tr 0.00251536
       227    surfrad        tip         Tr 0.000238156
```

# View TNSolver Output File For Results (continued)

## Thermal Network Model

```
*** Conductor Parameters ***

surfrad: Surface Radiation

                 h_r
   label      (W/m^2-K)
 ---------- ----------
       221    0.60422
       222   0.589676
       223   0.571949
       224   0.557634
       225   0.552586
       226   0.550402
       227   0.550396

EFCcyl: External Forced Convection - Cylinder

                                          h
   label     Re Number  Nu Number  (W/m^2-K)
 ---------- ---------- ---------- ----------
       121    2832.69    24.7609     52.325
       122    2869.36    24.9192    52.3515
       123    2917.02    25.1207    52.3789
       124    2958.53    25.2909    52.3941
       125    2973.94    25.3526    52.3974
       126    2980.75    25.3797    52.3984
       127    2980.77    25.3798    52.3984
```

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