BNL-99409-2013-TECH

C-A/AP/259;BNL-99409-2013-IR

Thermal Analysis for Arc Flash Resistor and Enclosure

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November 2006

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

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for the U.S. Department of Energy

Technical Note

date: October 26th, 2005

to: J. Sandberg, J. Tuozzolo

from: Viorel Badea, Steven Bellavia

subject: Thermal Analysis for Arc Flash Resistor and Enclosure

Discussion:

A steady-state thermal analysis was performed for the proposed Arc Flash Resistor and it's enclosure. Results indicate temperatures in the enclosure in excess of 120 deg Celsius. Several hand calculations, spreadsheets and ultimately a finite element model were utilized.

Geometry, Materials and Assumptions:

The 2.5" x 5" x 10" resistor is housed in a metal enclosure approximately 22" tall, x 22" wide x 19" deep. This enclosure is housed in a larger metal cabinet, approximately 109" tall, 60" wide and 50" deep. See Figure 1. Natural convection, along with radiation and conduction were used.

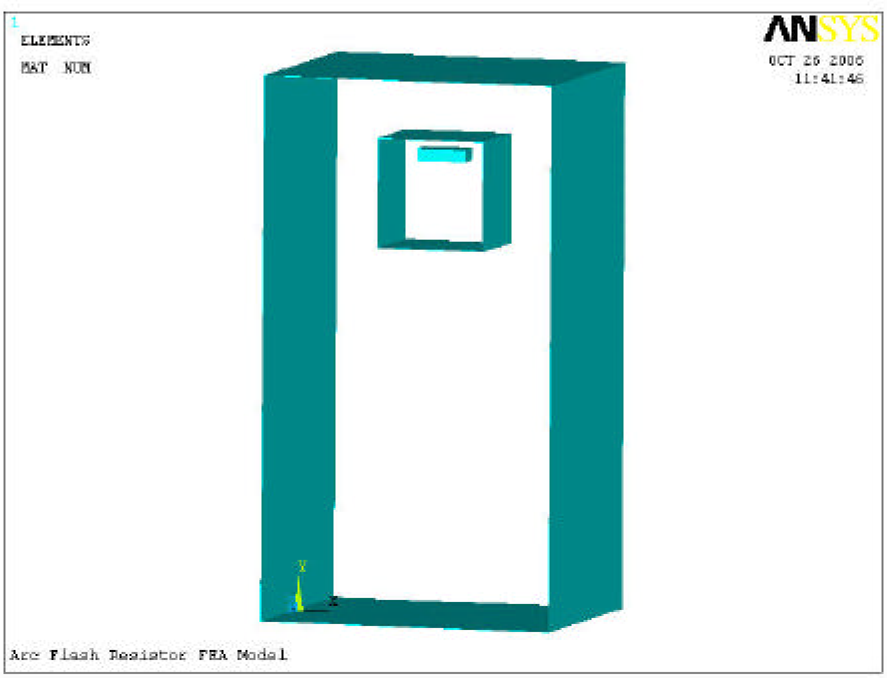


Figure 1. 3-D Model of Arc Flash Resistor and enclosure

Calculations:

Hand Calculations:
Hand calculations were performed. These calculations indicate that the maximum enclosure temperature is between 147 and 217 degrees Celsius. Appendix 1 shows the hand calculations performed.

FEA Modeling:
A finite element model was then developed to determine a more accurate temperature distribution at various locations within the structure.

A quasi-3-Dimensional model was built. See Figure 2. The model used planar elements with the depth option, along with radiation Link elements. This model consisted of a total of 12,468 elements, 12,654 nodes. Appendix 2 lists and describes the elements used and other FEA model parameters.

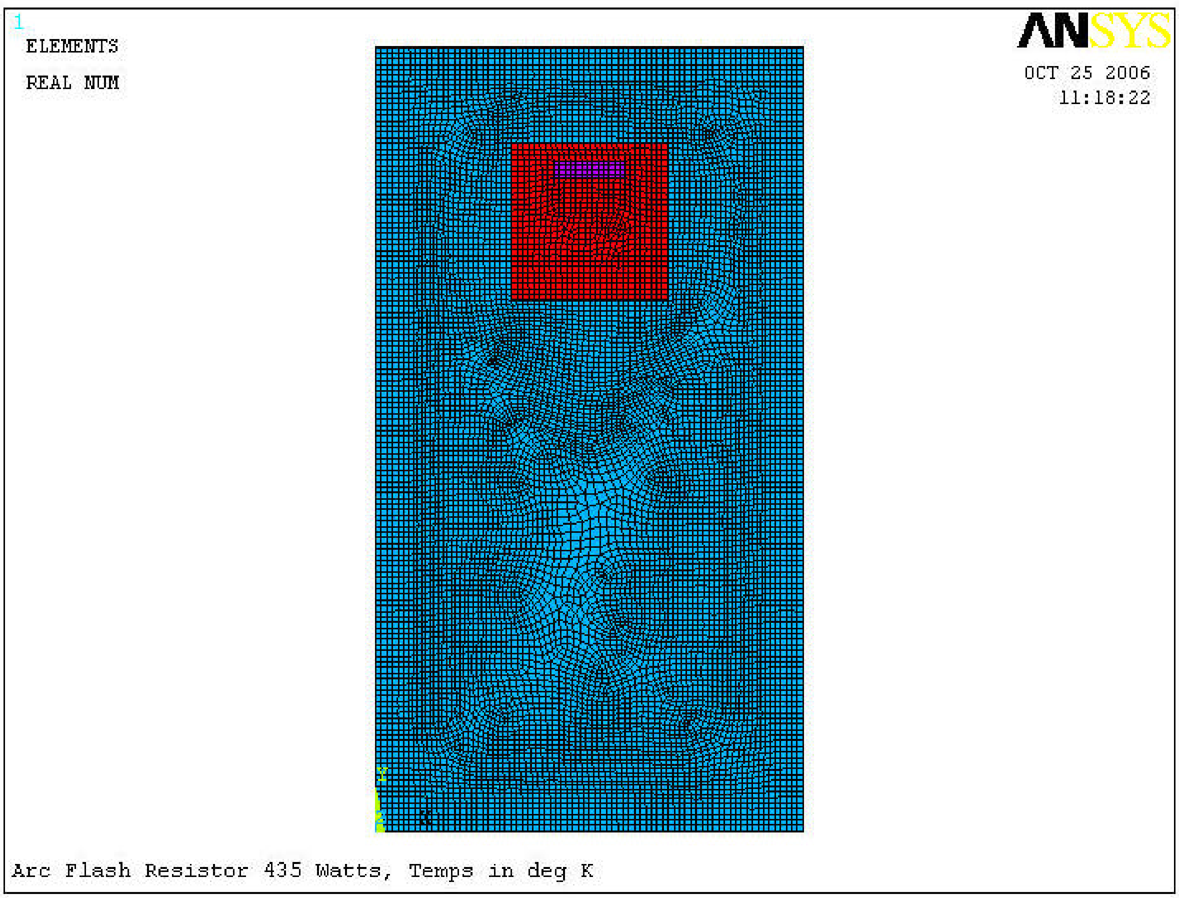


Figure 2. FEA model of electrical cabinet and arc flash resistor and enclosure.

Loads and Boundary Conditions:

Volumetric heat generation was used to apply a heat load of 435W to the resistor. (2.123×10^5 Watts/m^3). The outside of the large cabinet was subjected to a natural convection in 30 deg Celsius ambient air. Appendix 3 shows the film coefficient calculations used. The inner box and heater were also subjected to natural convection. Since this was not a Computational Fluid Dynamics (CFD) model, the convection was lumped into the conduction parameter for the trapped air. Appendix 4 describes the method used to determine the equivalent conduction. Since the calculation for the film coefficient depends on the temperature differential of the surface and bulk fluid temperature, several iterations of the FEA model were required to first obtain the resulting fluid temperature, re-calculating the film coefficient, then running the model again. This required two to three iterations, and converged rather quickly.

Results:

A peak temperature of 228 deg C was reached on the surface of the resistor. The enclosure walls reached 120 deg Celsius. Figure 3 shows the temperatures of the heater, air and metal enclosure. Figure 4 shows the temperatures for the entire cabinet.

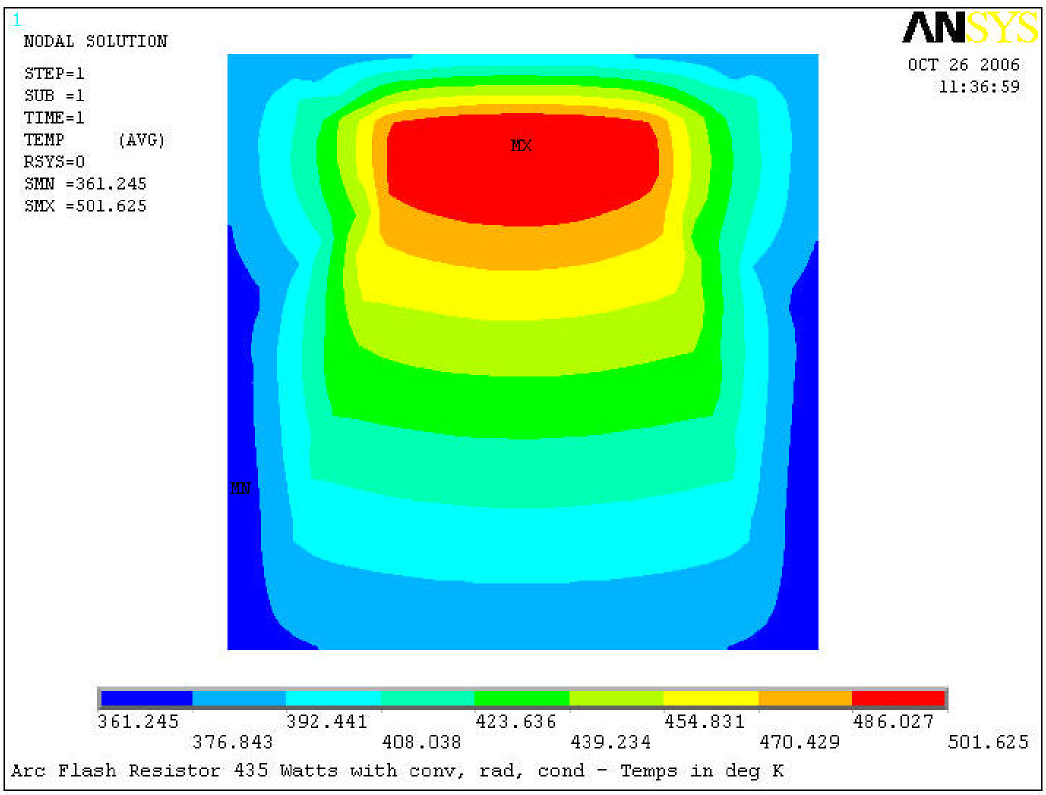


Figure 3: Temperature of heater, air and metal enclosure.

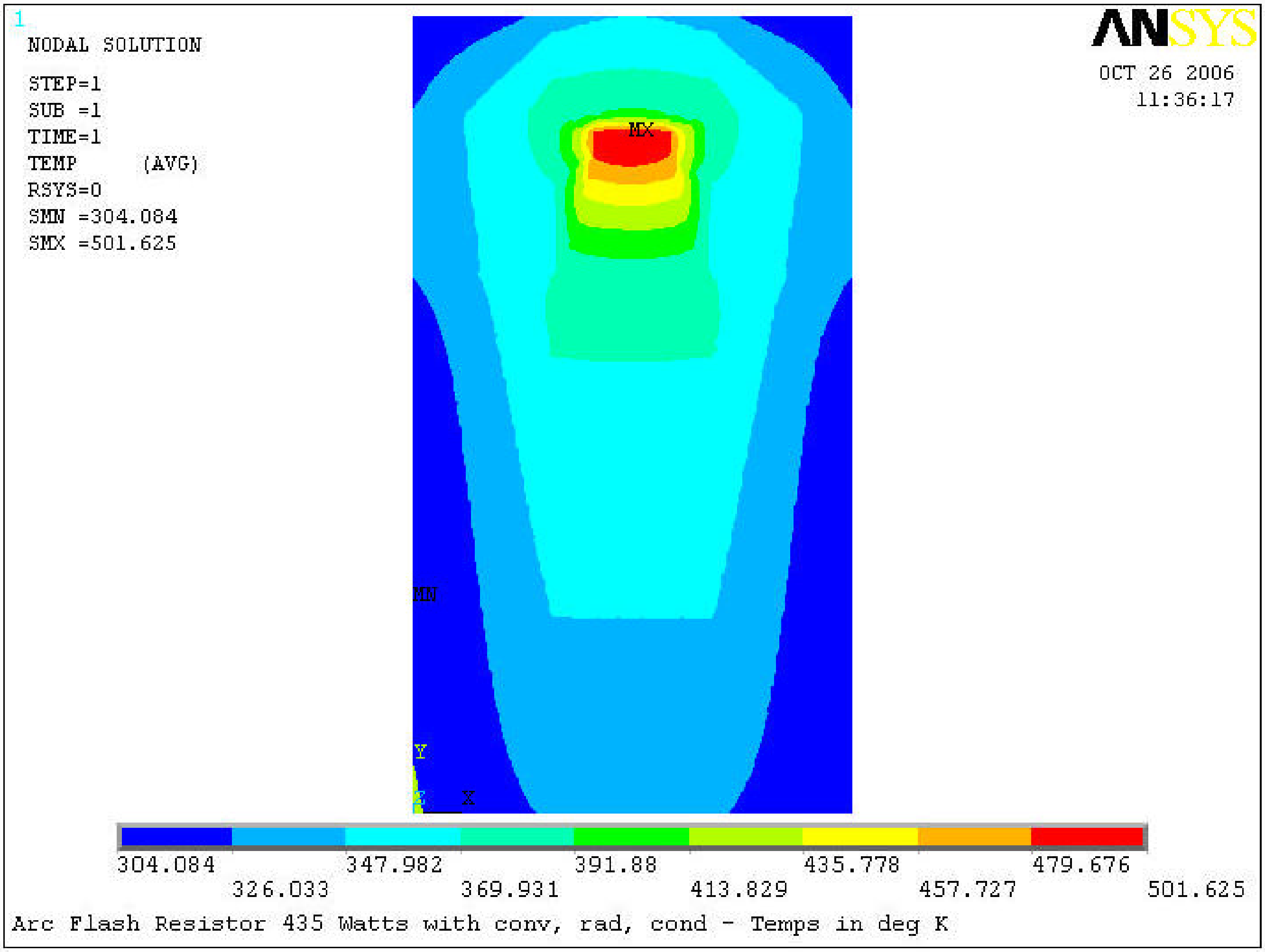


Figure 4: Temperatures of entire electrical cabinet

Summary:

Of the 435 Watts given off by the resistor, approximately 150 Watts is removed by radiation to the nearby enclosure walls. The remaining 285 watts is distributed through natural convection and conduction of the air trapped within the enclosure and cabinet, and ultimately to the outside ambient air by conduction through the cabinet walls. This results in a peak temperature of 228 deg Celsius at the resistor surface and 120 degrees Celsius on the metal enclosure walls.

The FEA model can be used to do more studies and test various heating/cooling scenarios.

Please direct any questions or concerns to Viorel Badea, x7104 or Steven Bellavia, x4846.

Appendix 1: Hand Calculations

1 SVG Oct 24 – 2005

BBC from 120

Middle cubicle of 3

$A_M = A_{front} + A_{rear} + A_{top}$

$A_{front} = 0.559^2 = 0.3125\ m^2$

$A_{rear} = 0.559^2 = 0.3125\ m^2$

$A_{top} = 0.559 \times 0.483 = 0.2699$

$A_M = 0.89499 \sim \boxed{0.895\ m^2}$

Power loss $P_v = 435\ W$

- Heat-dissipating area of cubicle (the middle one) $A_M = 0.895\ m^2$
- large cubicle thing max $\vartheta = 35°C$
- load factor $\alpha = 0.9$

Definition: cubicle > 1 m h; box < 1 m h

Effective power loss $P'_v = \frac{\alpha^2 \cdot P_v}{A_M} = \frac{0.9^2 \times 435}{0.895} = 393.68\ \frac{W}{m^2}$

$\Delta\vartheta = 67.5\ K$ (fig 5-9 extrapolated)

$k = 1.7$ for $h = 90\%$ (upper half of cubicle)

$\Delta\vartheta(90\%h) = 1.5 \times 67.5 = \boxed{114.75\ K}$

$T_K = 114.75 + 303.15 = \boxed{417.9°K}$

Appendix 1: Hand Calculations (continued)

2 CVB Oct 25-2006

for $\alpha = 1.$

$A_{front} = 0.559^2 = 0.3125\ m^2$

$A_{top} = 0.559 \times 0.483 = 0.2699$

$A_M = 0.5824$

- Power loss $P_V = 435\ W$
- large cubicle temp max $\vartheta = 45°C$

Effective power loss $P'_V = \frac{\alpha^2 P_V}{A_M} = \frac{1^2 \times 435}{0.582} =$

746.90 ~

$\Delta\vartheta = 109.58 \sim 110°K$ (fig 5-9) $\boxed{747\ W/m^2}$

$k = 1.7$, for $h = 90\%$ (location of the heater inside the cubicle)

$\Delta\vartheta(90\% h) = 1.7 \times 110 = 187°K$. (or °C)?

Δ_t 187 + 30 = 217 °C (total temp) 490°K

Recommended max temp for equipment not to be higher than 55°C (BBC pag 121)

$\boxed{\Delta_t 187\ K + 303.15 = \boxed{490.15\ °K}}$ - Max. temp inside box

NOT ACCEPTANCE

Appendix 2: FEA Database Summary

TITLE = Arc Flash Resistor FEA Model
ANALYSIS TYPE = STATIC (STEADY-STATE)
NUMBER OF ELEMENT TYPES = 2
12468 ELEMENTS CURRENTLY SELECTED. MAX ELEMENT NUMBER = 12468
12654 NODES CURRENTLY SELECTED. MAX NODE NUMBER = 12654
28 KEYPOINTS CURRENTLY SELECTED. MAX KEYPOINT NUMBER = 28
36 LINES CURRENTLY SELECTED. MAX LINE NUMBER = 36
12 AREAS CURRENTLY SELECTED. MAX AREA NUMBER = 12
6 COMPONENTS CURRENTLY DEFINED
MAXIMUM LINEAR PROPERTY NUMBER = 10
MAXIMUM REAL CONSTANT SET NUMBER = 6
ACTIVE COORDINATE SYSTEM = 0 (CARTESIAN)
NUMBER OF SPECIFIED SURFACE LOADS = 430
NUMBER OF SPECIFIED ELEM BODY FORCES = 52

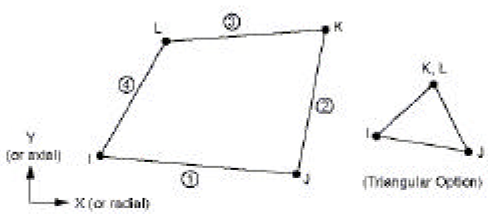
PLANE55 Element Description

PLANE55 can be used as a plane element or as an axisymmetric ring element with a 2-D thermal conduction capability. The element has four nodes with a single degree of freedom, temperature, at each node.

The element is applicable to a 2-D, steady-state or transient thermal analysis. The element can also compensate for mass transport heat flow from a constant velocity field. If the model containing the temperature element is also to be analyzed structurally, the element should be replaced by an equivalent structural element (such as PLANE42). A similar element with midside node capability is PLANE77. A similar axisymmetric element which accepts nonaxisymmetric loading is PLANE75.

An option exists that allows the element to model nonlinear steady-state fluid flow through a porous medium. With this option the thermal parameters are interpreted as analogous fluid flow parameters. See PLANE55 in the *ANSYS, Inc. Theory Reference* for more details about this element.

Figure 55.1 PLANE55 Geometry



PLANE55 Input Data

The geometry, node locations, and the coordinate system for this element are shown in Figure 55.1: "PLANE55 Geometry". The element is defined by four nodes and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. The element coordinate system orientation is as described in Coordinate Systems. Specific heat and density are ignored for steady-state solutions. Properties not input default as described in Linear Material Properties.

Element loads are described in Node and Element Loads. Convection or heat flux (but not both) and radiation may be input as surface loads at the element faces as shown by the circled numbers on Figure 55.1: "PLANE55 Geometry".

Heat generation rates may be input as element body loads at the nodes. If the node I heat generation rate HG(I) is input, and all others are unspecified, they default to HG(I).

A mass transport option is available with KEYOPT(8). With this option the velocities VX and VY must be input as real constants (in the element coordinate system). Also, temperatures should be specified along the entire inlet boundary to assure a stable solution. With mass transport, you should use specific heat (C) and density (DENS) material properties instead of enthalpy (ENTH).

The nonlinear porous flow option is selected with KEYOPT(9) = 1. For this option, temperature is interpreted as pressure and the absolute permeabilities of the medium are input as material properties KXX and KYY. Properties DENS and VISC are used for the mass density and viscosity of the fluid. See the *ANSYS, Inc. Theory Reference* for a description of the properties C and MU, which are used in calculating the coefficients of permeability, with reference to the Z terms ignored. Temperature boundary conditions input with the D command are interpreted as pressure boundary conditions, and heat flow boundary conditions input with the F command are interpreted as mass flow rate (mass/time).

This element can also have a Z-depth specified by KEYOPT(3) and real constant THK. Be careful when using this option with other physics, especially radiation. Radiation view factors will be based on a unit Z-depth (only).

LINK31 Element Description

LINK31 is a uniaxial element which models the radiation heat flow rate between two points in space. The link has a single degree of freedom, temperature, at each node. The radiation element is applicable to a 2-D (plane or axisymmetric) or 3-D, steady-state or transient thermal analysis.

An empirical relationship allowing the form factor and area to multiply the temperatures independently is also available. The emissivity may be temperature dependent. If the model containing the radiation element is also to be analyzed structurally, the radiation element should be replaced by an equivalent (or null) structural element. See LINK31 in the *ANSYS, Inc. Theory Reference* for more details about this element.

Figure 31.1 LINK31 Geometry

LINK31 Input Data

The geometry, node locations, and the coordinate system for this radiation element are shown in Figure 31.1: "LINK31 Geometry". The element is defined by two nodes, a radiating surface area, a geometric form factor, the emissivity, and the Stefan-Boltzmann constant (SBC). For axisymmetric problems, the radiation area should be input on a full 360° basis.

The emissivity may be constant or temperature (absolute) dependent. If it is constant, the value is input as a real constant. If it is temperature dependent, the values are input for the material property EMIS and the real constant value is used only to identify the material property number. In this case the MAT value associated with element is not used. EMIS defaults to 1.0.

The standard radiation function is defined as follows:

$$q = \sigma \varepsilon FA(T(I)^4 - T(J)^4)$$

where:
σ = Stefan-Boltzmann Constant (SBC)
(defaults to 0.119×10^{-10} (BTU/Hr*in^2* °R^4)
ε = emissivity
F = geometric form factor
A = area (Length)^2
q = heat flow rate (Heat/Time)

The nonlinear temperature equation is solved by a Newton-Raphson iterative solution based on the form:

$$[(T(I)^2 + T(J)^2)(T(I) + T(J))]_p(T(I) - T(J))$$

where the $[\ ]_p$ term is evaluated at the temperature of the previous substep. The initial temperature should be near the anticipated solution and should not be zero (i.e., both TUNIF and TOFFST should not be zero).

Appendix 3: Film Coefficient Calculations:

Table 7-2 Simplified equations for free convection from various surfaces to air at atmospheric pressure, adapted from Table 7-1

Surface	*Laminar,* $10^4 < \mathrm{Gr}_f \mathrm{Pr}_f < 10^9$	*Turbulent,* $\mathrm{Gr}_f \mathrm{Pr}_f > 10^9$
Vertical plane or cylinder	$h = 1.42 \left(\frac{\Delta T}{L}\right)^{1/4}$	$h = 0.95(\Delta T)^{1/3}$
Horizontal cylinder	$h = 1.32 \left(\frac{\Delta T}{d}\right)^{1/4}$	$h = 1.24(\Delta T)^{1/3}$
Horizontal plate:		
Heated plate facing upward or cooled plate facing downward	$h = 1.32 \left(\frac{\Delta T}{L}\right)^{1/4}$	$h = 1.43(\Delta T)^{1/3}$
Heated plate facing downward or cooled plate facing upward	$h = 0.61 \left(\frac{\Delta T}{L^2}\right)^{1/5}$	

where h = heat-transfer coefficient, $\mathrm{W/m^2 \cdot {}^\circ C}$
$\Delta T = T_w - T_\infty$, °C
L = vertical or horizontal dimension, m
d = diameter, m

Calculation of Equivalent Conduction:

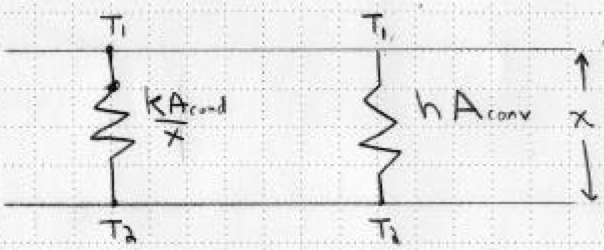
Heat transfer coefficient / equivalent conduction

Region	dT	L	a	b	c	$h=a \times (dT/L^b)^c$	x	K_{air}	Keq	mat'l #
	K	m				W/m^2-K	m	W/m-K	W/m-K	
heater top	106	0.127	1.32	1	0.25	7.094952092	0.0635	0.02624	0.476769	8
heater sides	111	0.127	1.42	1	0.25	7.720904112	0.15	0.02624	1.184376	9
heater bottom	128	0.127	0.61	2	0.2	3.674940742	0.43	0.02624	1.606465	10
box top	87	0.483	1.32	1	0.25	4.835784754	0.335	0.02624	1.646228	5
box sides	31	0.483	1.42	1	0.25	4.01922191	0.483	0.02624	1.967524	6
box bottom	47	0.483	0.61	2	0.2	1.762668138	1.868	0.02624	3.318904	7
cabinet top	44	1.27	1.32	1	0.25	3.202478112				
cabinet sides	31	1.27	1.42	1	0.25	3.156296819				
cabinet bottom	28	1.27	0.61	2	0.2	1.079543018				

Appendix 4: Equivalent Conduction

ENGINEERING ANALYSIS

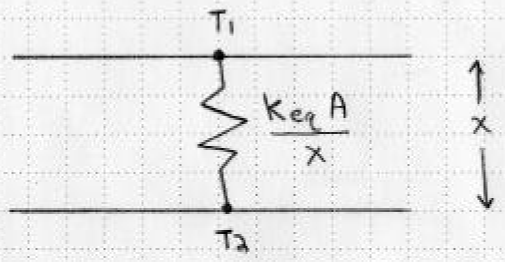
MODEL	SUBJECT: CONVECTION / CONDUCTION	INDEX
ANALYST: S. BELLAVIA	CHECKER	DATE: 10/25/06	PAGE 1 OF



$$q = \frac{kA}{x}(T_1 - T_2) + hA(T_1 - T_2)$$

$$\therefore q = \left(\frac{kA}{x} + hA\right)(T_1 - T_2)$$

Combine into conduction term



if $A_{cond} \approx A_{conv}$

$$q = \left(\frac{k}{x} + h\right)A(T_1 - T_2)$$

mult h by $\frac{x}{x}$

$$q = \left(\frac{k}{x} + \frac{hx}{x}\right)A(T_1 - T_2)$$

$$q = \frac{k_{eq}}{x}A\,(T_1 - T_2)$$

$$k_{eq} = k + hx$$

Example:

Air, @ 500 k $\quad k = .04038$ w/m-k

$x = .127$ m

A_{cond} = cross-sectional area

Convection:

A_{conv} = surface area $\approx$ cross-sectional area (per surface)

heated plate facing up or cooled facing down $\quad h \approx 1.32\left(\frac{\Delta T}{L}\right)^{1/4}$ $\quad$ For $\Delta T = 200°C$, $L = .5$ m

$h \approx 5.9$ w/m²-k

So that $k_{eq} = k + hX$

$$= .04038\,\frac{w}{m\text{-}k} + \left(5.9\,\frac{w}{m^2\text{-}k}\right)(.127\,m)$$

$k_{eq} = .79$ w/m-k $\quad$ (about 20 x conduction)