Thermal Analysis of Electronics Cabinet

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Introduction

Increasing demand for enhanced functionality and smaller form factor has led to significant increases in the power consumed by today's electronic control modules. Consequently, improved thermal management of individual components and control modules is now a primary consideration to ensure continued, long term device operation. In industrial applications, multiple, individual control modules are often packaged in enclosures that group functioning modules together to provide a protective environment and the required inter-module connectivity.

To minimize the propensity for continued maintenance of fans and other approaches for active cooling, thermal dissipation in these cabinets generally occurs by passive means. With the increased power density of individual modules, the need to understand and control the passive dissipation of thermal energy in an enclosed cabinet has come under increased focus.

Modules of differing functionality and power density are often packaged in small enclosures to limit the physical footprint, but this can restrict the ability to dissipate heat to the surrounding environment. Depending on the size of the enclosure and the power density of the individual modules, dissipation of heat is governed by a combination of conduction, convection and radiation; the resulting conjugate heat flow represents a challenging multiphysics problem.

A fully coupled heat transfer and fluid flow analysis of heat sources in a confined cabinet has been conducted using COMSOL Multiphysics® to identify the significance of conduction, convection and radiation in dissipating thermal energy and the impact that cabinet volume has on locally constraining fluid flow due to natural convection. The results of the analyses predict the thermal gradients existing within cabinets containing distributed heat sources and identify the relative importance of conduction, convection and radiation in dissipating thermal energy to the local environment. The influence of volumetric constraints on flow due to natural convection has also been investigated.

Keywords

Conjugate heat transfer, Conduction, Convection, Radiation

Governing equations

Heat transfer in solid domains is generally described by the heat equation:

$$\rho\, c_p \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T\right) \qquad (1)$$

Where
ρ is the density of the solid or fluid material
c_p is the specific heat capacity
T is the temperature
λ is the thermal conductivity

The fluid domain is modeled as air in which the fluid flow physics are described by the conservation of mass, momentum, and energy according to the following equations:

$$\nabla \cdot \left(\rho\, \mathbf{u}\right) = 0 \qquad (2)$$

$$\rho\, \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left(\eta\left(\nabla \mathbf{u} + \left(\nabla \mathbf{u}\right)^T\right) - \frac{2}{3}\eta\left(\nabla \cdot \mathbf{u}\right)\mathbf{I}\right) + \rho\, \mathbf{g} \qquad (3)$$

$$\nabla \cdot \left(-k \nabla T\right) = Q - \rho\, c_p \mathbf{u} \qquad (4)$$

The viscous heating and pressure work terms are neglected in the energy equation. In the above equations, ρ is the density, $\mathbf{u}$ is the velocity vector, p is the pressure, η is the dynamic viscosity, $\mathbf{g}$ is the gravitational acceleration vector, k is the thermal conductivity, T is the temperature, Q is a heat source term, and c_p is the specific heat capacity. The viscosity, thermal conductivity, and specific heat capacity are functions of temperature, while the density is a function of both temperature and pressure.

The heat flux at the surface of the part due to radiation is modeled as

$$q_r = \varepsilon_{emis}\left(G_m + F_{amb}\sigma\, T_{amb}^4 - \sigma\, T^4\right) \qquad (5)$$

Where:

ε_{emis} is the emissivity of the surface
G_m is the mutual irradiation from other surfaces
F_{amb} is the ambient view factor
σ is the Stefan-Boltzmann constant
T_{amb} is the far-away ambient temperature
T is the temperature at the surface
G_m is a function of the radiosity

In the presence of mutually irradiating surfaces, the ambient view factor and mutual irradiation are automatically computed.

Computational model

A computational model of an enclosed cabinet containing multiple electronic devices that act as individual heat sources was developed using the COMSOL Multiphysics® Heat Transfer module. The complex geometry and power distribution of the real cabinet was simplified by representing the electronic components as simple blocks with defined volumes to which a specific power could be assigned. The resulting computational model was used to predict the effects of number of heater units, heater power, power distribution between the units, heater unit size and cabinet dimensions on the dissipation of heat within the cabinet.

Simulation Results

Heat from the electronic devices in the cabinet is dissipated into the surrounding environment by:

1. Conduction to the back plane of the cabinet
2. Natural convection of air in the cabinet volume
3. Radiation between surfaces

For a given set of operating conditions, a thermal distribution is established within the cabinet the details of which are dependent on component power and size of the components with respect to the cabinet volume. An example of the thermal distribution in the cabinet is provided in Figure 1.

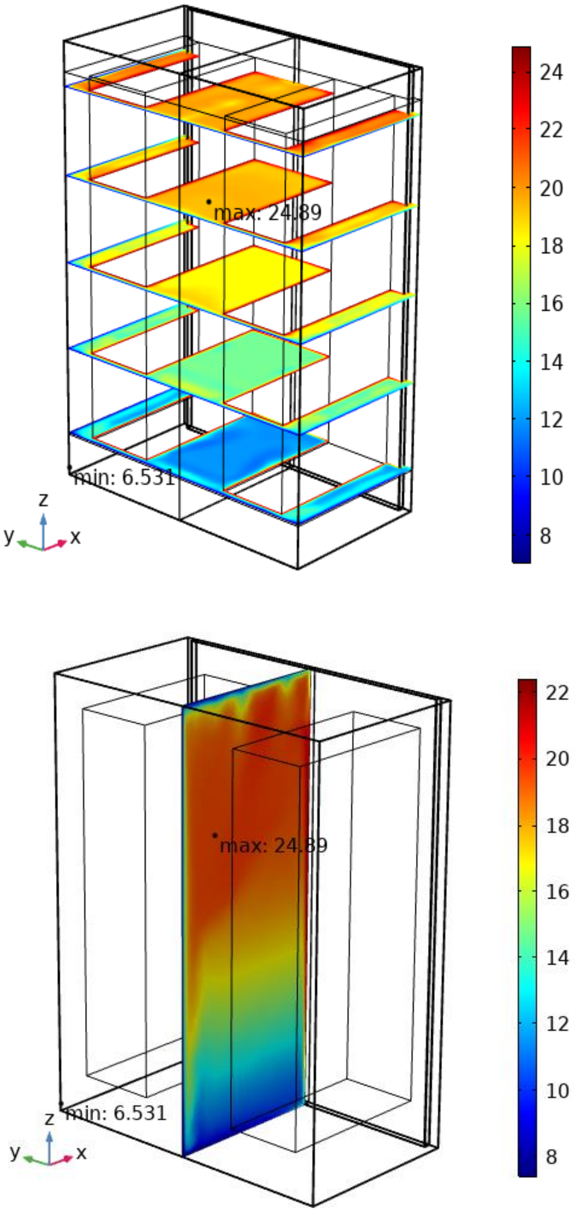

Figure 1. Distribution of temperature (°C) in an enclosed cabinet of fixed size for a given heater power and heater dimensions.

The temperature distribution within the cabinet is primarily influenced by the power applied and the volume and surface area of the heater; these latter items influence the separation between the surface of the heater and the walls of the cabinet. The effect of applied power and spacing between the heater surface and the cabinet walls on the difference in fluid temperature along a vertical center plane is shown in Figure 2.

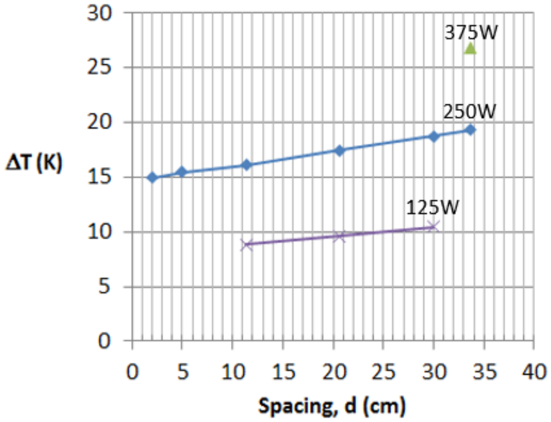

Figure 2. Temperature difference along a vertical plane in the center of the cabinet.

Further details of the temperature distribution are given in Figure 3.

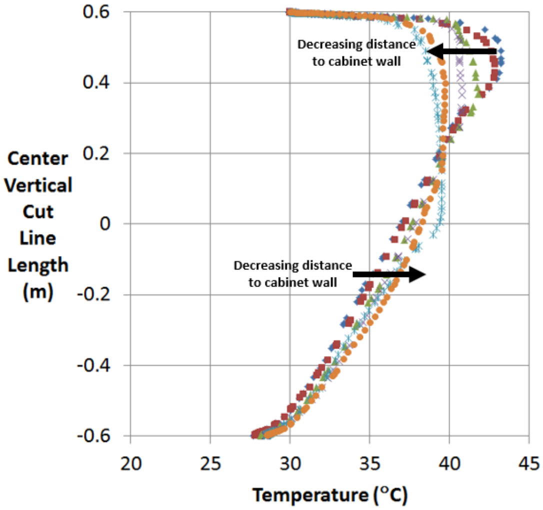

Figure 3. Temperature distribution along vertical plane through the center of the cabinet for a given heater power.

As the separation between the heater surface and the cabinet wall decreases, the maximum fluid temperature increases in the lower half of the cabinet but decreases in the upper half of the cabinet.

The mechanism of thermal dissipation in the cabinet is a complex function of natural convection within the enclosed space, Figure 4, and losses due to thermal radiation.

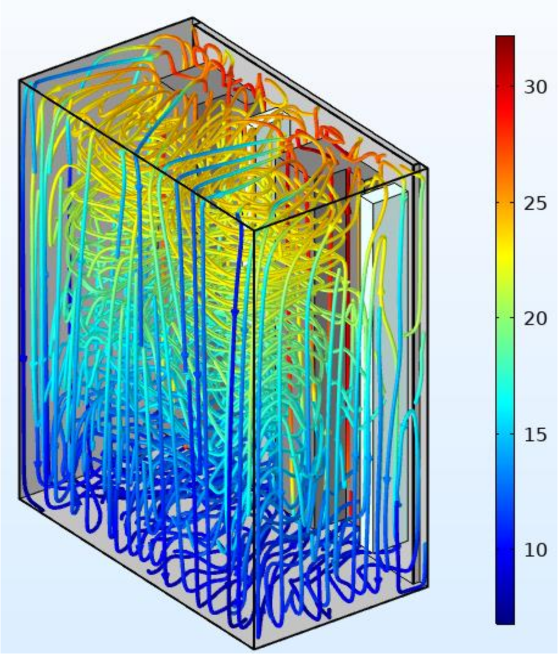

Figure 4. Velocity and temperature (°C) field due to natural convection in the cabinet.

The origin of the observed behavior can be explained by considering the effect of the distance between the heater surface and the cabinet wall on the thermal resistances of the system.

The thermal resistance network for the cabinet is shown schematically in Figure 5.

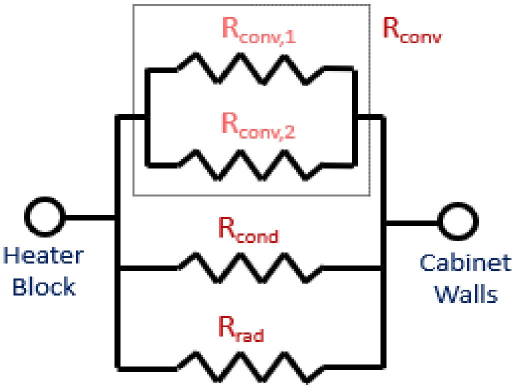

Figure 5. Schematic representation of thermal resistance network of cabinet.

Where the thermal resistances are:

R_{rad}: Radiation between the heater block and the cabinet walls

R_{cond}: Conduction between the heater block to the back plate

R_{conv}: Total convection from the heater block to the cabinet walls

R_{conv1}: Convection from the front face of the heater block

R_{conv2}: Convection from all other faces of the heater block

Figure 6 shows how the maximum heater and air temperatures decrease with decreased separation between the heater surface and the cabinet wall for a given heater power. This indicates that the total thermal resistance between the heater block and the enclosure decreases leading to increased thermal dissipation. Further, since the maximum air temperature is closely related to the heater temperature, the maximum air temperature also decreases as the spacing decreases.

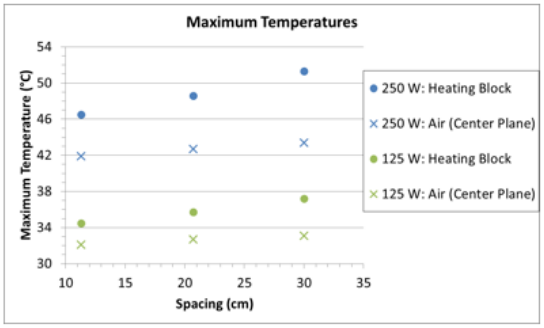

Figure 6. Maximum temperature of heater block and air due to separation between heater surface and cabinet wall.

As the spacing between the heater and the cabinet walls changes, the magnitude of the flow velocity decreases with decreasing distance, Figure 7 and 8. This response is associated with the lower temperature of the heater block that reduces air temperature and thus flow velocity due to convection.

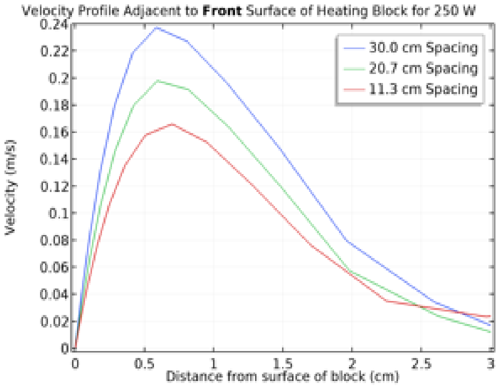

Figure 7. Velocity profile of fluid adjacent to front surface of heating block.

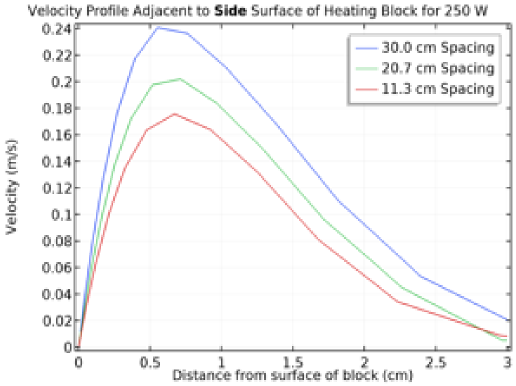

Figure 8. Velocity profile of fluid adjacent to side surface of heating block.

As the spacing between the heater surface and the cabinet walls decreases, the surface area of the block also increases; this is a critical parameter determining the maximum air temperature. Further investigation of the breakdown of the heat transfer characteristics associated with thermal dissipation demonstrates the relative significance of heat transfer due to conduction, convection and radiation, Table 1.

Table 1. Proportion of heat transfer associated with primary mechanisms of thermal dissipation in cabinet.

		Mode of Heat Transfer		
	Spacing (cm)	*Convection*	*Conduction*	*Radiation*
Block 125 W	11.3	25.6 %	20.8 %	53.6 %
	20.7	26.4 %	23.8 %	49.8 %
	30	27.0 %	28.5 %	44.5 %
Block 250 W	11.3	26.8 %	19.7 %	53.5%
	20.7	27.5 %	22.6 %	49.9%
	30	28.1 %	27.1 %	44.8%

For all power levels and distances between the heater surface and the cabinet walls, the dominant mechanism of heat transfer is associated with surface to surface radiation. The maximum temperatures developed in this application are generally less than ~50°C and as such do not reach a level where radiation would intuitively be expected to be significant. However, the detailed analysis shows that even at these relatively low temperatures the dominant mechanism of heat transfer is radiation from the heater surface to the surrounding walls.

Conclusions

A conjugate heat transfer model of an array of heaters in an enclosed cabinet demonstrates the importance of radiation in determining the distribution of temperature in the cabinet.