Thermal Adversity in Solid-state Lighting

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Abstract: COMSOL Multiphysics is used to simulate natural convection and its impact on peak operating temperatures of solid-sate lighting in thermally adverse conditions. PDE modes in the general form are used in conjunction with a thin-surface conduction formulation in the weak form. COMSOL is used to predict both temperatures and heat flows through numerous components of the configuration. Model output is used to evaluate different designs and construct plausible explanations for why different designs behave the way that they do.

Keywords: Solid-state lighting, natural convection

1. Introduction

Solid-state lighting (LEDs) is a rapidly growing area with capacity to provide quality light while significantly reducing electrical consumption on a global scale. The energy savings is particularly substantial in directional lighting, where LEDs are 4 times as efficient as their primary competitor in traditional lighting, the halogen lamp. But unlike halogen lamps which operate above 3000 K, LEDs begin to experience loss of performance when their operating temperatures exceed 100 C. Heat transfer is the critical factor in feasible replacements. As the need for lighting capacity grows in solid-state lighting, cooling strategies become increasingly important. We describe and simulate an especially stringent configuration for directional lighting, the insulated ceiling array shown in Figure 1.

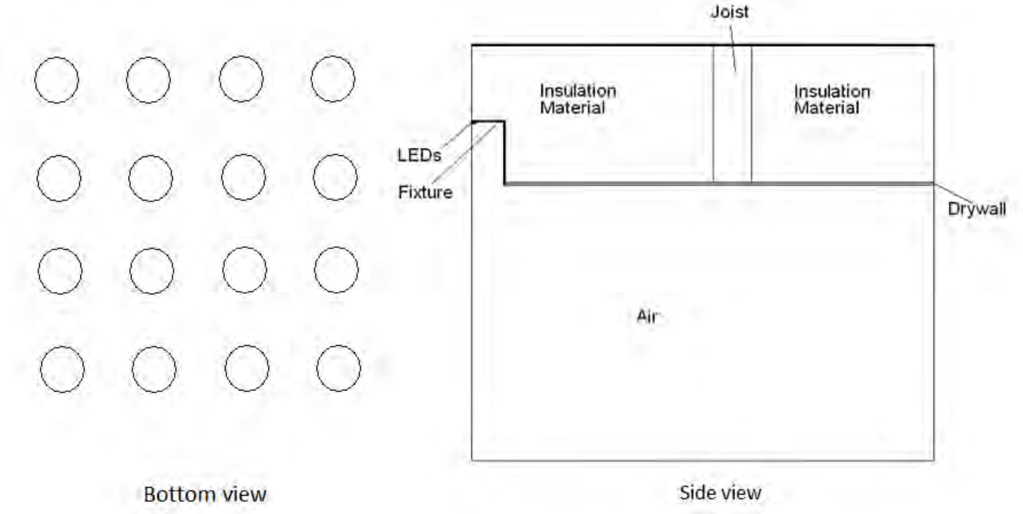

Figure 1: Insulated ceiling array

This configuration involves multiple recessed fixtures in an insulated ceiling. This is a stringent configuration for two reasons: First, insulation material above the ceiling suppresses convection between the fixture and the floor above. Second, additional neighboring ceiling fixtures suppress lateral heat loss in the air below the fixture. The challenge, addressed in different ways by numerous design strategies [1,2,3,4], is to maximize the capacity of the heat to escape from the fixture for a given LED operating temperature. Simulation results using COMSOL are shown which quantify both local temperatures and heat flows in between critical components.

3. Use of COMSOL Multiphysics

The model's mathematical description combines fully-compressible natural convection in the air with heat conduction through the solid materials and radiation from exposed fixture surfaces. For axi-symmetric velocity components $u(r,z)$, $w(r,z)$, density ρ, and temperature T, the governing equations used for convection are

$$\rho ru\frac{\partial u}{\partial r}+\rho rw\frac{\partial u}{\partial z}+2\mu\left(\frac{u}{r}-\frac{\Delta}{3}\right)=-r\frac{\partial p}{\partial r}+\frac{\partial}{\partial r}\left[r\mu\left(2\frac{\partial u}{\partial r}-\frac{2}{3}\Delta\right)\right]+\frac{\partial}{\partial z}\left[r\mu\left(\frac{\partial w}{\partial r}+\frac{\partial u}{\partial z}\right)\right],$$

$$\rho ru\frac{\partial w}{\partial r}+\rho rw\frac{\partial w}{\partial z}=-r\frac{\partial p}{\partial z}-\rho rg+\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial w}{\partial r}+\frac{\partial u}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left[r\mu\left(2\frac{\partial w}{\partial z}-\frac{2}{3}\Delta\right)\right],$$

$$\rho rc_p u\frac{\partial T}{\partial r}+\rho rc_p w\frac{\partial T}{\partial z}=\frac{\partial}{\partial r}\left(r\kappa\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(r\kappa\frac{\partial T}{\partial z}\right),$$

$$u\frac{\partial\rho}{\partial r}+w\frac{\partial\rho}{\partial z}=-\rho\Delta,$$

$$p=\rho R_{air}\left(T+273\right).$$

All units are MKS with temperature in C. The term Δ refers to the dilatation rate, given by

$$\Delta=\frac{1}{r}\frac{\partial(ur)}{\partial r}+\frac{\partial w}{\partial z}.$$

Boundary conditions on air velocity are no-slip and impermeability at each solid surface. Boundary conditions on temperature are imposed ambient temperature at the floor below the domain and at the (higher-story) floor above the domain. In addition, heat loss by radiation is imposed on fixture surfaces. All lateral heat transfer is suppressed. The model is used not just to generate temperature maps but also to obtain the amount of heat that flows between any two arbitrary components, such as the recessed can and the blown insulation. Normally a software package treats heat flow at an interface by setting the boundary temperature equal on each side, and then letting the amount of heat flow float to a consistent value. That heat-flow value is used in the solution of the governing equations but it is not generally accessible in the post processing. In this model we work around that by assigning two different temperatures, say T_1 and T_2 to the temperature on either side of the interface. Then we assign a mixed boundary condition at the interface for each side

$$q=\frac{T_1-T_2}{R_{num}},$$

where q is the heat flux along the interface, and R_{num} is an arbitrarily small numerical value of thermal resistance. This expression forces the two temperatures T_1 and T_2 to become arbitrarily close to each other, and heat flux q can be extracted and integrated along the interface to provide the heat flow in the model output.

COMSOL is used to model the heat generated at the LEDs and flowing through the fixture, the air below the fixture, and the insulation above the fixture. The governing equations above are implemented in the PDE mode using the general form. The fixture and drywall are treated as thin surfaces with lateral conduction implemented in the weak form. Integration of heat flux over internal and external boundaries is used to produce a global energy budget.

4. Results

Simulation of conduction through insulation above the fixture coupled with convection in the air below the fixture is shown in Figure 2. 6 W of heat are supplied in the center of a 5” fixture in an axi-symmetric representation of the insulated ceiling array.

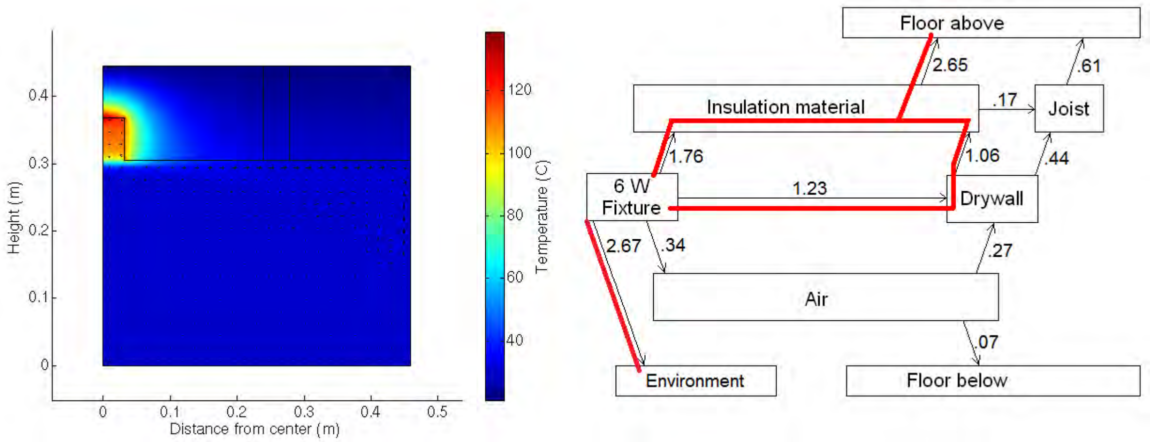

Figure 2: Heat transfer simulation for a cylindrical fixture in the insulated ceiling array. Temperature of all components together with air velocity vectors is shown on the left. A budget of heat flow (W) between components is shown on the right.

The heat-flow budget shows that primary paths of heat loss are by radiation from the fixture and by conduction through the insulation at the floor above, where the temperature is set to ambient. The near-LED temperature of 130 C is too high – modification to this design is needed for a feasible lamp under these conditions.

The model is used to evaluate a modified fixture design, shown in Figure 3 in an axi-symmetric cross section. The fixture is mounted lower so that half of its height protrudes below the ceiling. Then a simple conical fin structure is added to the bottom edge of the fixture. This fin is an extension of the fixture made from the same material, and in good thermal contact.

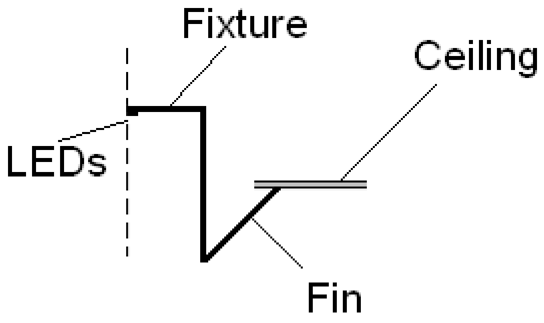

Figure 3: Design modification for improved heat flow. The fixture is lowered to protrude beneath the ceiling, and a conical fin is added to induce buoyant convection on the outside of the fixture.

In this configuration, heat flows from the fixture to the fin, exposing the room air to the fin's hot surface. This induces buoyant convection in which the air flow rises at the fin, and then turns outward along the bottom of the ceiling, carrying the fixture's heat with it and spreading it over the ceiling's full area. Model evaluation of this design is shown in Figure 4.

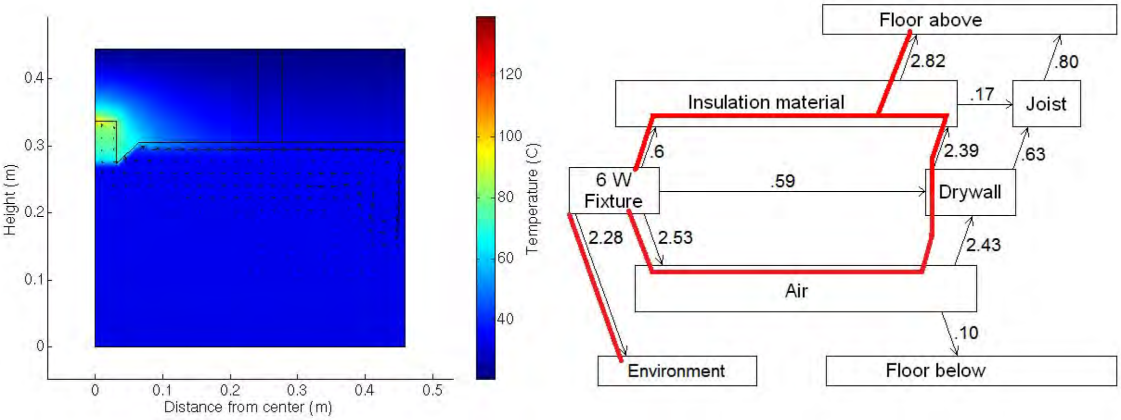

Figure 4: Heat transfer simulation for the modified fixture in the insulated ceiling array. Temperature of all components together with air velocity vectors is shown on the left. A budget of heat flow (W) between components is shown on the right.

The improved heat flow can be understood by comparing the primary paths of heat shown in red in the two heat-flow diagrams of Figure 2 and Figure 4. The fin enables the air to transport 2.5 W of heat from the fixture to the drywall, compared with just 0.3 W in the baseline design. It is natural convection induced by the fin that enables the air to carry the additional heat away from the fixture and spread it along the larger surface area of drywall. Because the fixture loses over 2.5 W of heat to the fin, it loses much less heat directly to the insulation material. Comparing 0.6 W of conducted heat with the fin design with 1.76 W in the baseline design, it is clear from that a much smaller temperature difference should be needed to drive heat from the fixture directly to the insulation. This is why the fin design achieves a far lower peak temperature of 105 C, as shown in Figure 4.

5. Conclusion

Heat-transfer modeling is used to evaluate a new fin design for a recessed LED fixture for use under stringent thermal conditions. These conditions include insulation material above the ceiling which suppresses natural convection there. They also include an array of evenly-spaced fixtures installed in the ceiling, represented in the model by suppressed lateral heat loss from the insulation above the fixture and from the air below the fixture. The model is used to show that the fin design of Figure 3 significantly lowers the fixture temperature by improving the heat flow from the ceiling to the floor above through the insulation material and the wooden joist. This design has the potential to greatly expand the feasible applications of LED fixtures.

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