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A Model for Naturally Ventilated Cavities on the Exteriors of Opaque Building Thermal Envelopes

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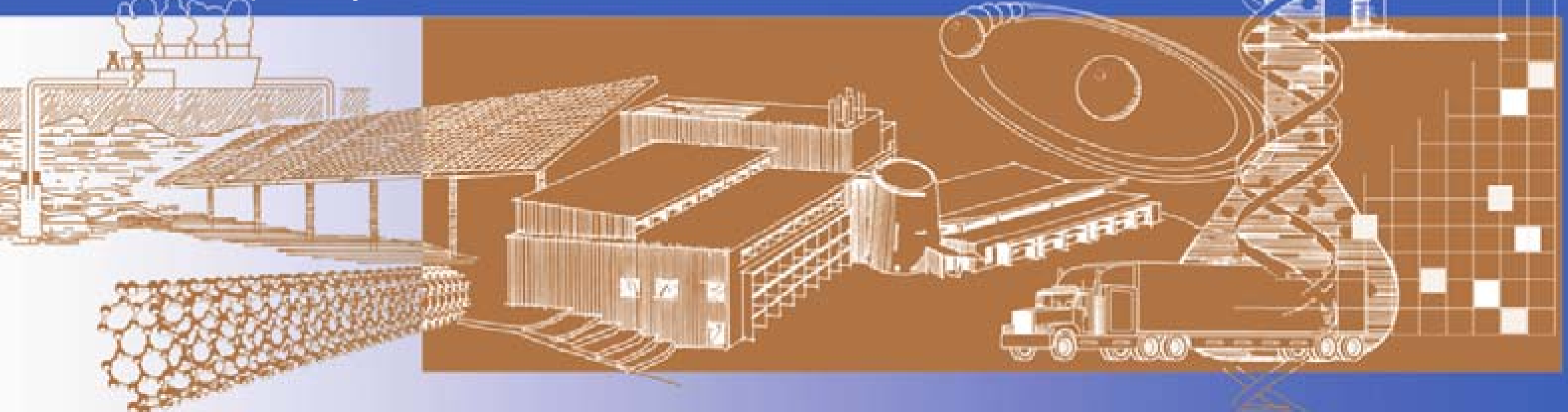

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A MODEL FOR NATURALLY VENTILATED CAVITIES ON THE EXTERIORS OF OPAQUE BUILDING THERMAL ENVELOPES[1]

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ABSTRACT

This paper describes a model for naturally ventilated cavities that are formed by lightweight baffles on the exteriors of opaque building thermal envelopes. The model can be used for building components that are slightly detached from the main envelope (but do not connect to the interior), such as photovoltaic panels, double roofs, rain screens, and unglazed transpired collectors. The model provides values for baffle surface temperature as well as exterior boundary conditions for convection and radiation to use in modeling heat transfer in the underlying surface. Two quasi-steady energy balances are used to solve for temperatures: one for the baffle surface and the other for the air in the cavity. The model assumes that the heat capacity in the baffle can be neglected, since it is much lower than the underlying mass surface. Natural ventilation rates are calculated with simplistic correlations that are based on user-provided discharge coefficients. Convection coefficients inside the cavity are based on those used for window gaps as documented in ISO (2003) Standard 15099. Radiation coefficients are linearized. The model has been implemented in EnergyPlus.

INTRODUCTION

Buildings form complicated systems and present numerous modeling challenges for whole-building energy simulation programs. The exterior surfaces that form the thermal envelope of buildings are fundamental elements of whole-building simulation programs. Most building simulation programs intended for modeling annual energy performance treat surfaces as solid constructions with uniform (one-dimensional) heat flows. Boundary conditions for modeling surface heat transfer are also treated as uniform across the area. For the outside face of exterior surfaces, the boundary conditions typically represent the surrounding weather. Building simulation programs often provide mechanisms for other boundary conditions on the outside faces of exterior surfaces, such as for ground contact and neighboring thermal zones.

Many wall and roof constructions used in buildings can be considered solid, but in special cases surfaces are constructed such that their exteriors are not solid with the rest of the assembly. They instead have cavities underneath that are partially vented to the outside. Examples include vented roof tiles, certain rain screens, photovoltaic mounting configurations with standoffs (e.g., roof paver systems from PowerLight[tm], see www.powerlight.com), unglazed transpired solar collectors (e.g., solar ventilation preheat systems such as Solar Wall[tm], see www.solarwall.com), and various other double-skin designs that have been proposed for alternative, low-energy architecture. Such constructions share the following characteristics:

- Air-filled cavities located toward the exterior
- A solid portion of the construction assembly located toward the interior
- Opaque outer layers on the exterior with openings that allow airflow in and out of the cavities.

This paper presents a simple model for exterior surfaces with these characteristics. Ciampi et. al. (2003) studied such systems for opaque facades and developed a simple analytical model that predicts the impact that ventilation has on the thermal load. However, whole-

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building simulation programs do not appear to provide explicit models for vented exterior cavities. Advanced users who need to model such systems could, for example, modify surface and material properties to attempt to account for changes in thermal performance. However, little guidance is available. Ideally, an explicit model would be available for building simulation. In the case of ventilated photovoltaic modules, having a more detailed model is especially important because the resulting temperature affects the device's performance. This model was originally developed to represent unglazed transpired solar collectors when they are not being actively operated for solar ventilation preheat (but are still present on the facade).

MODEL FORMULATION

The Exterior Naturally Vented Cavity model is provided as a special case for the outside boundary conditions of opaque heat transfer surfaces when they include a multi-skin exterior. Figure 1 shows the overall configuration. From the thermal envelope's point of view, a vented cavity on the outside of the surface modifies the conditions experienced by the underlying heat transfer surfaces. This exterior cavity acts as a radiation and convection baffle situated between the exterior environment and the outside face of the underlying heat transfer surface. The actual outer surface is referred to as the "baffle." The modeling here assumes that the heat capacity in the outer baffle can be neglected, since it is much lower than the underlying mass surface. This assumption may not hold for ventilated exterior facade systems that use a more massive outer layer, such as heavy tiles; the model should not be used for these cases without modification.

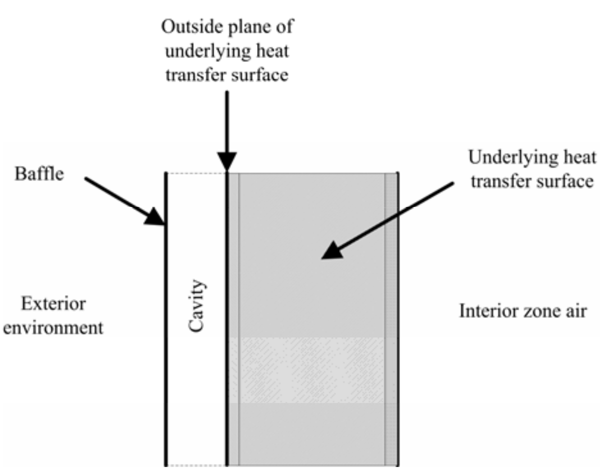

Figure 1 Overall configuration

Baffle Heat Balance

The baffle is assumed to be thin and have high enough conductivity that it can be modeled with a single temperature (for both sides and along its area). This temperature $T_{s,baff}$ is determined by formulating a heat balance on a control volume that just encapsulates the baffle surface. The heat balance is diagrammed in Figure 2.

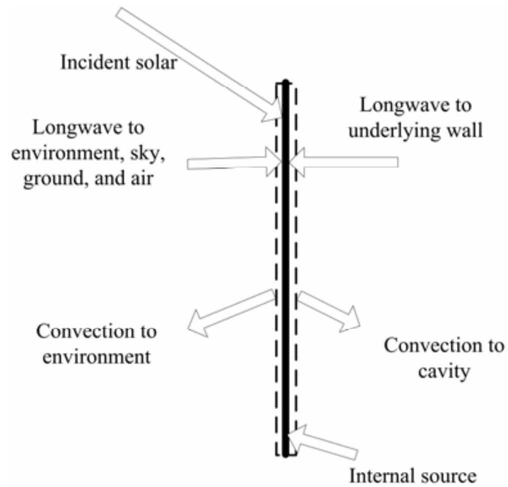

Figure 2 Baffle surface heat balance

The heat balance on the baffle surface's control volume is:

$$q''_{\alpha sol} + q''_{LWR,Env} + q''_{conv,Env} + q''_{LWR,cav} + q''_{conv,cav} + q''_{source} = 0 \quad (1)$$

Where,

$q''_{\alpha sol}$ is absorbed direct and diffuse solar (short wavelength) radiation heat flux,

$q''_{LWR,Env}$ is net long wavelength (thermal) radiation flux exchange with the air and surroundings,

$q''_{conv,Env}$ is surface convection flux exchange with outside air,

$q''_{LWR,cav}$ is net long wavelength (thermal) radiation flux exchange with the outside face of the underlying surface(s),

$q''_{conv,cav}$ is surface convection flux exchange with cavity air,

q''_{source} is a source/sink term that accounts for energy exported out of the control volume when the baffle is a hybrid device such as a photovoltaic module or an active thermal collector.

All terms are positive for net flux to the baffle. Each heat balance component is introduced briefly here.

External SW Radiation

$q''_{\alpha sol}$ is calculated by using models for sky conditions, solar radiation, shading, and reflections that are typical of building simulation, and generally includes both direct and diffuse incident solar radiation that is absorbed by the surface face . This is influenced by location, surface facing angle and tilt, shading surfaces, surface face material properties, weather conditions, etc. The sky, solar, and shading models used in the current implementation are documented in the engineering reference for EnergyPlus (DOE 2006).

External LW Radiation

$q''_{LWR,Env}$ is formulated as the radiation exchange between the surface, the sky, the ground, and the atmosphere, which is typical of building simulation. In the current implementation, radiation heat flux is calculated from the surface absorptivity, surface temperature, sky, air, and ground temperatures, and sky and ground view factors (DOE 2006). Linearized coefficients, rather than the full fourth-order relation, are typically used to model radiation coefficients to greatly simplify solving Eq. 1.

External Convection

$q''_{conv,Env}$ is modeled with the classical formulation: $q''_{conv,Env} = h_{co}\left(T_{amb} - T_{s,baff}\right)$, where h_{co}, is the convection coefficient. The value for h_{co} is treated in the usual way for surfaces that are exposed to exterior (weather) conditions. In addition, when it is raining, the current implementation of this model assumes the baffle becomes wet and models the rain-enhanced surface heat transfer by using a large value for h_{co} of 1000.0 $W/m^2 \cdot K$. In the current implementation, this value is fixed inside the program and was selected to be consistent with what EnergyPlus uses for rain on normal exterior surfaces. This arbitrary and high value for h_{co} drives the baffle temperature to be very close to the outdoor air temperature. This is consistent with the assumptions that the baffle is lightweight and the rain drops area at the outdoor temperature.

Cavity LW Radiation

$q''_{LWR,cav}$ is modeled with a radiation exchange formulation between the baffle surface and the underlying heat transfer surface across the cavity. Radiation across the cavity is also modeled with linearized coefficients.

Cavity Convection

$q''_{conv,cav}$ is modeled with the classical formulation: $q''_{conv,cav} = h_{c,cav}\left(T_{a,cav} - T_{s,baff}\right)$, where $h_{c,cav}$, is the convection coefficient. Although ventilation air exchanges will affect the actual airflow patterns within the cavity, a simple model would have great difficulty predicting the consequences of this on surface convection rates. Therefore, we assume that the cavity's geometry and temperature regimes are similar to the gaps found inside the glazing units used in windows. ISO (2003) standard 15099 provides a concise collection of accepted correlations for $h_{c,cav}$ that were selected because they were the best identified. The correlations were synthesized from a large number of relevant engineering studies. They cover a wide range of tilts providing a set of correlations that apply to arbitrary angles, including vertical and horizontal orientations.

Baffle Temperature

Substituting models into (1) and solving for $T_{s,baff}$ yields the following equation:

$$T_{s,baff} = \frac{\begin{pmatrix} I_s\alpha + h_{co}T_{amb} + h_{r,atm}T_{amb} + h_{r,sky}T_{sky} + \\ h_{r,gnd}T_{amb} + h_{r,cav}T_{so} + h_{c,cav}T_{a,cav} + q''_{source} \end{pmatrix}}{\left(h_{co} + h_{r,air} + h_{r,sky} + h_{r,gnd} + h_{r,cav} + h_{c,cav}\right)} \quad (2)$$

where,

I_s is the incident solar radiation of all types [W/m^2],

α is the solar absorptivity of the baffle [dimensionless],

$h_{r,atm}$ is the linearized radiation coefficient for the surrounding atmosphere [$W/m^2 \cdot K$],

T_{amb} is the outdoor dry bulb from the weather data, also assumed for ground surface [ºC],

$h_{r,sky}$ is the linearized radiation coefficient for the sky [$W/m^2 \cdot K$],

T_{sky} is the effective sky temperature [ºC],

$h_{r,gnd}$ is the linearized radiation coefficient for the ground [W/m^2·K],

$h_{r,cav}$ is the linearized radiation coefficient for the underlying surface [W/m^2·K],

T_{so} is the temperature of the outside face of the underlying heat transfer surface [ºC],

h_{co} is the convection coefficient for the outdoor environment [W/m^2·K],

$h_{c,cav}$ is the convection coefficient for the surfaces facing the cavity [W/m^2·K], and

$T_{a,cav}$ is the dry bulb temperature for air in the cavity [ºC].

Cavity Heat Balance

The *cavity* is the volume of air between the baffle and the underlying heat transfer surface. The cavity air is modeled as well-mixed. The uniform temperature of the cavity air, $T_{a,cav}$, is determined by formulating a heat balance on a control volume of air as diagrammed in Figure 3.

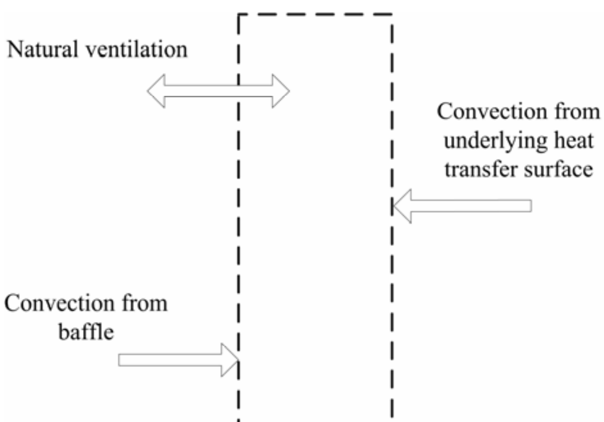

Figure 3 Cavity heat balance

The heat balance on the plenum air control volume is:

$$\dot{Q}_{vent} + \dot{Q}_{co} + \dot{Q}_{c,baff} = 0 \tag{3}$$

where,

$\dot{Q}_{vent}$ is the net rate of energy added from natural ventilation, where outdoor ambient air exchanges with the cavity air.

$\dot{Q}_{co}$ is the net rate of energy added by surface convection heat transfer with the underlying surface.

$\dot{Q}_{c,baff}$ is the net rate of energy added by surface convection heat transfer with the baffle.

Cavity Temperature

Substituting into Eq. (3) yields the following equation:

$$T_{a,cav} = \frac{\left(\begin{array}{c} h_{c,cav} A T_{so} + \dot{m}_{vent} c_p T_{amb} \\ + h_{c,cav} A T_{s,baff} \end{array} \right)}{\left(h_{c,cav} A + \dot{m}_{vent} c_p + h_{c,cav} A \right)} \tag{4}$$

where,

A is the surface area [m^2]

$\dot{m}_{vent}$ is the air mass flow from natural forces [kg/s]

Modeling natural ventilation air exchanges in a general way is challenging. Therefore, simplistic engineering models are used to model $\dot{m}_{vent}$ resulting from natural buoyancy and wind forces. Reasoning that the configuration is similar to single-side natural ventilation, we elect to use correlations for natural ventilation presented as Eq. (29) and (30) in Chapter 26 of ASHRAE HOF (2001).

$$\dot{m}_{vent} = \rho \dot{V}_{\text{tot}} \tag{5}$$

where,

ρ is the density of air [kg/m^3], and

$\dot{V}_{\text{tot}} = \dot{V}_{\text{wind}} + \dot{V}_{\text{thermal}}$ is the total volumetric flow rate of air ventilating in and out of the cavity from wind-driven and buoyancy-driven flows, where,

$$\dot{V}_{\text{wind}} = C_v A_{in} U_{\infty} \tag{6}$$

$$\dot{V}_{\text{thermal}} = C_D A_{in} \sqrt{2 g \Delta H_{NPL} \frac{\left(T_{a,cav} - T_{amb} \right)}{T_{a,cav}}} \tag{7}$$

(if $T_{a,cav} > T_{amb}$)

$$\dot{V}_{\text{thermal}} = C_D A_{in} \sqrt{2 g \Delta H_{NPL} \frac{\left(T_{amb} - T_{a,cav}\right)}{T_{amb}}} \qquad (8)$$

(if $T_{amb} > T_{a,cav}$ and baffle is vertical).

C_v is the effectiveness of the openings and depends on opening geometry and the orientation with respect to the wind. ASHRAE HoF (2001) indicates values of 0.25−0.6. This value is user input.

C_D is the discharge coefficient for the opening and depends on opening geometry. This value is user input.

Mass continuity arguments lead to modeling the area of the openings as one-half the total area of the openings, so we have:

$$A_{in} = \frac{A_{vent\ openings}}{2}$$

g is the gravitational constant taken as 9.81 [m/s^2].

ΔH_{NPL} is the height from midpoint of lower opening to the neutral pressure level. This value is user input.

If the cavity is horizontal and $T_{amb} > T_{a,cav}$, then $\dot{V}_{\text{thermal}} = 0$ because this is a stable situation.

SAMPLE RESULTS AND DISCUSSION

The model was implemented in EnergyPlus. In this implementation, the Heat Balance Model with conduction transfer functions was used to model the underlying heat transfer surface. The exterior cavity model provides a method of updating the boundary conditions that are exposed to the outside plane of the underlying heat transfer surfaces. The interdependence of Eqs. 2 and 4 is handled with sequential substitution.

An example of using the model is presented for the case of photovoltaic roof paver systems. One common configuration for membrane roofs involves mounting the photovoltaic modules to interlocking foam boards with standoffs that raise the modules away from the underlying foam. This allows outside air to naturally ventilate the cavity under the modules. To demonstrate the model and its implementation, we present results for the two configurations diagrammed in Figure 4. The vented cavity configuration is compared to a similar configuration, but without the standoffs that raise the module. In both cases, the photovoltaic modeling is thermally coupled so that the electrical energy converted by the photovoltaics is exported from the system and the module operating temperatures are obtained from the heat transfer modeling.

The model was run for Chicago with TMY2 weather, and results are presented for a single representative sunny day of July 8. The exterior cavity model used the following input data: vent area fraction of 0.03, thermal emissivity of 0.84, solar absorptivity of 0.92, cavity thickness of 0.05 m, C_v of 0.25, and C_D of 0.5, and a length scale of 0.05 m for buoyancy. The two roof assemblies cover the same interior thermal zone. The empirical model from Sandia National Laboratories (King et. al. 2004) was used to model photovoltaic module performance. The panels are BP Solar model BP275.

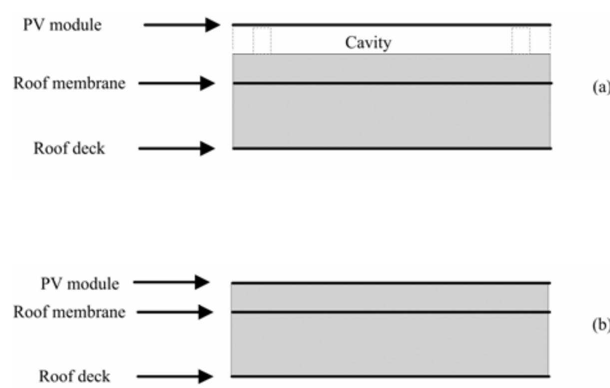

Figure 4 Photovoltaic roof configurations, (a) with ventilated cavity and (b) with integrated surface mounting.

Figure 5 shows the results for dry bulb temperatures on July 8, including the outdoor air, the cavity air, the baffle surface, the underlying surface, and the integrated surface for comparison. In the beginning of the day, the baffle heats more quickly than the integrated roof assembly and then cools more quickly. The underlying surface's outside temperature is lower than the unventilated integrated surface during the daytime, but is slightly warmer during the night as it cools more slowly. For this day, the thermal protection of the vented configuration makes the inside surface (facing the interior) under the roof deck below the ventilated configuration about 1.6ºC cooler than below the integrated collector, shown in Figure 6. This indicates the importance of including an exterior cavity model when modeling the thermal impacts of ventilated roofs.

The photovoltaic panel efficiencies are also affected by the module temperatures (see Figure 7).

The model results for the underlying surface temperature are much higher than the cavity air temperatures. This indicates that radiation heat transfer is the dominant heat flow mechanism. Figure 8 explains this result by showing the calculated heat transfer coefficients. The correlations from ISO (2003) standard 15099 appear to produce relative low values for convection coefficients, which limits the rate of ventilation-driven cooling. Most results for convection coefficients (for this rooftop paver configuration) are being capped at a lower threshold of 0.534 W/m^2-K. This indicates that the ISO 15099 convection correlations are not very dynamic for horizontal cavities in these operating ranges and further investigation on convection correlations is warranted.

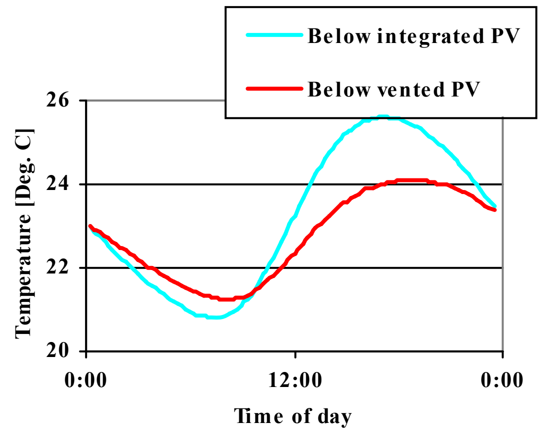

Figure 6 Interior temperature results

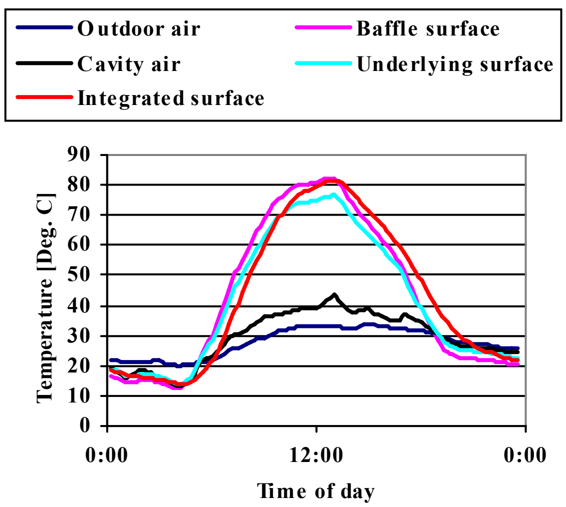

Figure 5 Exterior temperature results

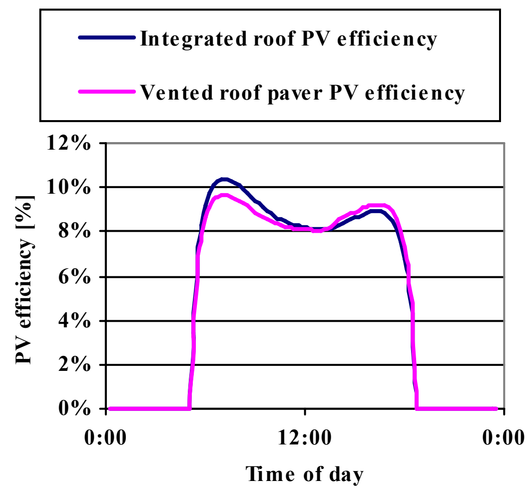

Figure 7 Photovoltaic efficiency results

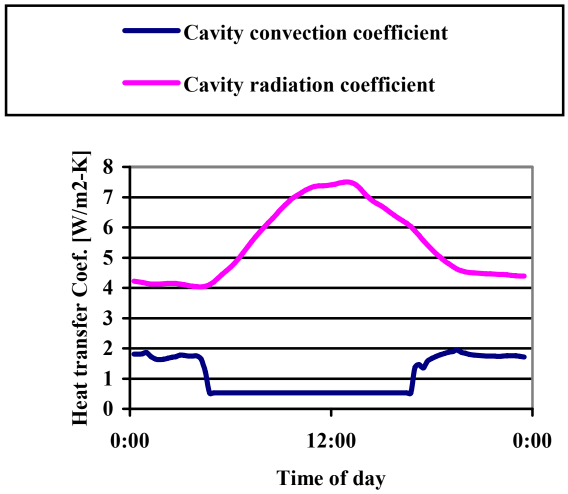

Figure 8 Heat transfer coefficient results

CONCLUSION AND FUTURE WORK

A model was presented for use in building simulation programs for the special case where opaque envelope surfaces have ventilated cavities on their exterior. The model forms separate heat balances on a baffle and a cavity that are used to determine boundary conditions for modeling heat transfer in a more massive underlying surface.

The model is suggested as an appropriate mathematical framework for subsequent research to derive input data from empirical measurements. The model developed is based on engineering first principles and has not been experimentally validated. There are currently very few appropriate input data to use with the model. Experimental and field research efforts are needed to characterize appropriate input values for the ventilation opening areas and discharge coefficients for various types of systems. Cavity convection coefficients were modeled with accepted correlations for window glazings; however, this needs to be revisited because the correlations may not be performing well for some configurations.

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14. ABSTRACT *(Maximum 200 Words)*
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