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COMPUTING RADIATIVE HEAT TRANSFER OCCURRING IN A ZONE FIRE MODEL

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ABSTRACT

Radiation, convection and conduction are the three mechanisms which a zone fire model must consider when calculating the heat transfer between fires, wall surfaces and room gases. Radiation dominates the other two modes of heat transfer in rooms where there are fires or hot smoke layers. The computational requirements of a radiation model can also easily dominate the work required to calculate other physical sub-models in a zone fire model.

This paper presents algorithms for efficiently computing the radiative heat exchange between four wall surfaces, several fires and two interior gases. A two-wall and a ten-wall radiation model are also discussed. The structure of this radiation model is exploited to show that only a few configuration factors need to be calculated directly (two rather than 16 for the four-wall model and eight rather than 100 for the ten-wall model) and matrices needed to solve for the net radiative flux striking each surface are shown, after the appropriate transformation is taken, to be diagonally dominant. Iterative methods may then be used to solve the linear equations more efficiently than direct methods such as Gaussian elimination.

INTRODUCTION

Radiation is an important heat transfer mode to represent in a zone fire model due to the high temperatures attained in rooms with fires or hot smoke layers. It can easily dominate convective and conductive heat transfer. A radiative heat transfer calculation can also easily dominate the computation in any fire model. This is because radiation exchange is a global phenomena. Each portion of an enclosure interacts radiatively with every other portion that it 'sees'. It is therefore important to design radiation exchange algorithms that are *efficient* as well as *accurate*.

Most zone fire models use two wall segments to model radiation exchange. Harvard V [1], FIRST [2], BRI [3, 4] and FAST [5] are some examples. FAST/FFM [6] on the other hand uses many surface segments in order to model the radiative interaction between wall surfaces and furniture elements. Harvard V, FIRST, BRI and FAST model the two wall segments as an extended floor and ceiling. The extended ceiling consists of the ceiling plus the four upper walls. The upper wall is the portion of a wall above the layer interface. Likewise, the lower wall is below the interface. The extended floor consists of the floor plus the four lower walls. The purpose of the work described in this paper then is to enhance two wall radiation exchange algorithms by considering more wall segments. In particular for the four-wall case, this allows the ceiling, the upper wall segment, the lower wall segment and the floor to transfer radiant heat independently.

This paper describes three related algorithms for computing radiative heat transfer between the bounding surfaces of a compartment containing upper and lower layer gases and point source fires. The first algorithm uses two wall segments, the second uses four wall segments and the third uses ten wall segments. These algorithms each use the net radiation equation as described in Siegel and Howell [7, Chapter 17] which is based on Hottel's work in [8]. An enclosure is modeled with N wall segments (for our case N will be 2, 4 or 10) and an interior gas. A two layer zone fire model, however, requires treatment of an enclosure with two uniform gases (the upper and lower layer). Hottel and Cohen [9] developed a method to handle this case by dividing an enclosure into a number of wall and gas volume elements. Treatment of the fire and the interaction of the fire and gas layers with the walls is based upon the work of Yamada and Cooper [10, 11] on N-wall radiation exchange models. They model the fire as a point source of heat radiating uniformly in all directions and use the Lambert-Beer law to model the interaction between heat emitting objects (fires, walls or gas layers for example) and gas layers.

The two, four and ten wall algorithms are implemented as FORTRAN 77 subroutines named RAD2, RAD4 and RAD10. The routines, RAD2 and RAD10, take advantage of the modular structure of RAD4 by using a number of its routines. It should be pointed out that the computational requirements of a general N-wall radiation model are too great for now to justify incorporating it into a zone fire model. By implementing the net radiation equation for particular N (two, four or ten walls), significant algorithmic speed increases were achieved by exploiting the structure of the simpler problems.

THE PROBLEM

N Wall Segment Radiation Exchange

The N-wall radiation model described here considers radiative heat transfer between wall segments, point-source fires and two gas layers. An enclosure or room is partitioned into N wall segments where each wall segment emits, reflects and absorbs radiant energy. The interior of the enclosure is partitioned into two volume elements; an upper and a lower layer. The problem then is to determine the net radiation flux emitted by each wall segment and the energy absorbed by each layer given the temperature and emittance of each wall segment and the temperature and absorptance of the two gas layers.

These calculations can be performed in conjunction with a zone fire model such as CFAST[12]. Typically, the solution (wall temperatures, gas layer temperatures *etc*) is known at a given time t. The solution is then advanced to a new time, $t + \Delta t$. The calculated radiation fluxes along with convective fluxes are used as a boundary condition for an associated heat conduction problem in order to calculate wall temperatures. Gas layer energy absorption due to radiation contributes to the energy source terms of the associated zone fire modeling differential equations. The time step, Δt, must be chosen sufficiently small so that changes in wall temperatures are small over the duration of the time step.

Modeling Assumptions The following assumptions are made in order to simplify the radiation heat exchange model and to make its calculation tractable.

iso-thermal Each gas layer and each wall segment is assumed to be at a uniform temperature. This assumption breaks down where wall segments meet.

equilibrium The wall segments and gas layers are assumed to be in a quasi-steady state. The wall and gas layer temperatures are assumed to change slowly over the duration of the time step of the associated differential equation.

fire source The fire is assumed to radiate uniformly in all directions from a single point giving off a fraction, χ, of the total energy release rate to thermal radiation.

radiators The radiation emitted from a wall surface, a gas and a fire is assumed to be diffuse and gray. In other words, the radiant fluxes emitted by these objects are independent of the direction and the wavelength. They can depend on temperature, however. Since both the emittances and the temperatures of wall segments are inputs to the radiation algorithms, it is assumed that the emittances are consistent with the corresponding wall temperatures. Diffusivity implies that $\epsilon_\lambda = \alpha_\lambda$ for each wavelength λ while the gray gas/surface assumption implies that ϵ_λ is constant for all wavelengths. These assumptions allow us to infer that the emittance, ϵ and absorbance, α are related *via* $\epsilon = \alpha$. A discussion of this assumption can be found in [13, p. 589–590].

opacity The wall surfaces are assumed to be opaque. When radiation encounters a surface it is either reflected or absorbed. It is not transmitted through the surface. Equation (1), found below, would have to be modified to account for the loss (or gain) of energy through semi-transparent surfaces.

geometry Rooms or compartments are assumed to be rectangular boxes. Each wall is either perpendicular or parallel to every other wall. Radiation transfer through vent openings, doors, *etc* is neglected.

The Net Radiation Equations Net radiation refers to the difference between outgoing and incoming radiation at a wall surface. As illustrated in Figure 1, incoming radiation consists of gray-body surface radiation emitted from all other surfaces, radiating point-source fires and emission from the two gas layers. Outgoing radiation consists of gray-body surface radiation and incoming radiation that is in turn reflected. Integrating the net radiation equation in Segel and Howell[7, Chapter 17] over all wavelengths, we obtain an equation for the net radiation at each wall surface k given by

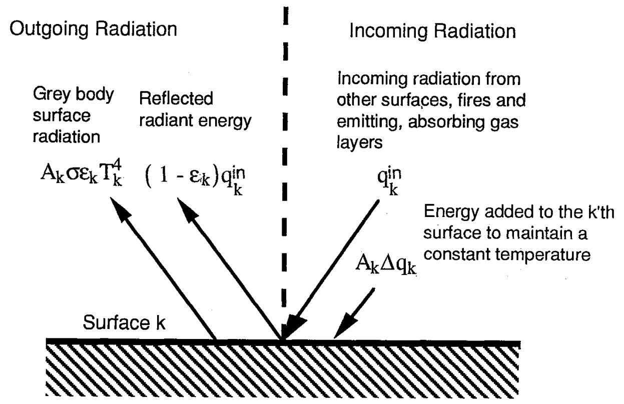

FIGURE 1: Input and Output Energy Distribution at the k'th Wall Surface

$$\frac{\Delta q''_k}{\epsilon_k} - \sum_{j=1}^{N} \frac{1-\epsilon_j}{\epsilon_j} \Delta q''_j F_{k-j} \tau_{j-k} = \tag{1}$$

$$\sigma T_k^4 - \sum_{j=1}^{N} \sigma T_j^4 F_{k-j} \tau_{j-k} - \frac{c_k}{A_k}$$

where $\Delta q''_k$ is the unknown radiative flux and c_k/A_k, accounts for radiative flux striking the k'th wall surface due to point source fires and gas layers and is given by

$$\frac{c_k}{A_k} = \sum_{f=1}^{N_{fire}} q''^{fire}_{f-k} + \sum_{j=1}^{N} \left(q''^{L,gas}_{j-k} + q''^{U,gas}_{j-k} \right). \tag{2}$$

Other terms are defined in the nomenclature. Wall openings (vents, doors, *etc*) can be modeled by replacing T_j in equation (1) with $\hat{T}$ where

$$\hat{T}^4 = T_j^4 - \frac{A_v}{A_j}(T_j^4 - T_{amb}^4),$$

A_v is the vent area and T_{amb} is the ambient temperature. Figure 2 presents a surface plot showing the effect of this equation. It plots the absolute temperature difference, $(T - \hat{T})$, versus relative vent area, A_v/A_j, and temperature, T. Note that over this broad range of temperatures and vent area fractions that the absolute change

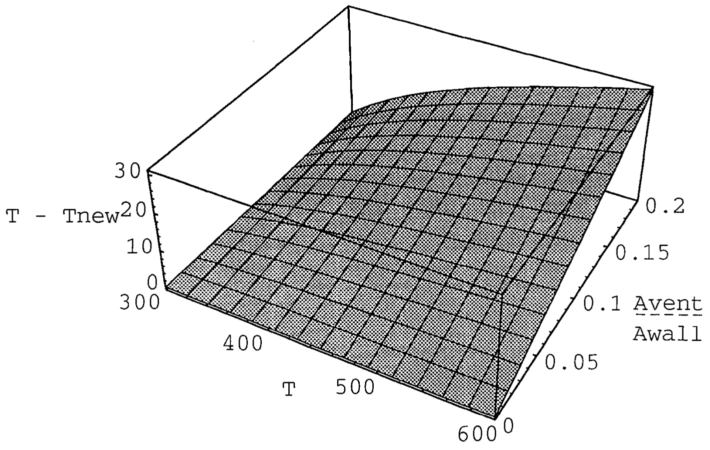

FIGURE 2: Surface plot of temperature difference (original temperature and equivalent temperature accounting for vents and doors) as a function of fractional vent area and temperature showing the effect of vent openings on computing radiation heat transfer.

in T required to account for vent openings is small. For large temperatures T or large vent fractions A_v/A_j then vent openings need to be taken into account.

Subsequent sections discuss the computation of terms in (1) and (2).

Heat Flux Striking a Wall Segment In general, every possible path between two wall segments should be considered in order to compute the total radiant heat transfer between these segments. This is not practical in a zone fire model due to the excessive computational costs. The approach taken here is to model this heat transfer using just one path. For a typical path there are four cases to consider. A path from wall segment j to k can start in either the upper or lower layer and finish in either the upper or lower layer. A fraction, $\alpha = 1 - \tau$, of the energy encountering a layer is absorbed. The rest, τ, passes through unimpeded. Table 1 gives formulas for the heat flux striking the k'th wall segment due to point source fires and heat emitting gas layers.

Heat Flux Striking a Wall Segment Due to a Point Source Fire If the gas layers are transparent then the flux striking the k'th surface due to the f'th fire is

$$q''^{fire}_{f-k} = \frac{\chi q^{fire}_{total} \omega_{f-k}}{4\pi A_k}$$

where the total energy release rate of the fire is q^{fire}_{total}, χ is the fraction of this energy that contributes to radiation and $\omega_{f-k}/(4\pi A_k)$ is the fraction of the radiant energy leaving the f'th fire that is intercepted by the k'th wall segment, *ie* a configuration factor. On the other hand, if the gas layers are not transparent then there are four cases to consider. The fire can be in the upper or lower layer and the surface can be in the upper or lower layer. Figure 3 shows how radiation from a fire is absorbed by each layer when the fire is in the lower layer and the surface k is in the upper layer. The other three cases are handled similarly. These four cases are summarized in the first column of Table 1. This column give formulas

Table 1: Radiative Heat Flux Striking the k'th Rectangular Wall Segment

Path	Fire	Gas Layer	
	q''^{fire}_{f-k}	$q''^{L,gas}_{j-k}$	$q''^{U,gas}_{j-k}$
in upper	$\tau^U_{f-k} \frac{\chi q^{fire}_{total} \omega_{f-k}}{4\pi A_k}$	0	$F_{k-j} \sigma \alpha^U_{j-k} T^4_U$
from upper to lower	$\tau^U_{f-k} \tau^L_{f-k} \frac{\chi q^{fire}_{total} \omega_{f-k}}{4\pi A_k}$	$F_{k-j} \sigma \alpha^L_{j-k} T^4_L$	$F_{k-j} \sigma \alpha^U_{j-k} T^4_U \tau^L_{j-k}$
from lower to upper	$\tau^L_{f-k} \tau^U_{f-k} \frac{\chi q^{fire}_{total} \omega_{f-k}}{4\pi A_k}$	$F_{k-j} \sigma \alpha^L_{j-k} T^4_L \tau^L_{j-k}$	$F_{k-j} \sigma \alpha^U_{j-k} T^4_U$
in lower	$\tau^L_{f-k} \frac{\chi q^{fire}_{total} \omega_{f-k}}{4\pi A_k}$	$F_{k-j} \sigma \alpha^L_{j-k} T^4_L$	0

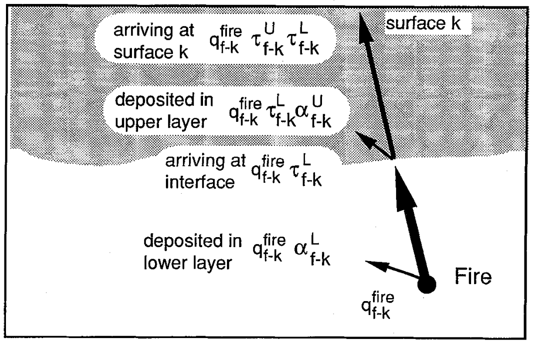

FIGURE 3: Schematic illustrating energy deposited into the lower layer, $q''^{fire}_{f-k}\alpha^L_{f-k}$, deposited into the upper layer, $q''^{fire}_{f-k}\alpha^U_{f-k}\tau^L_{f-k}$, and arriving at the $k'th$ wall surface, $q''^{fire}_{f-k}\tau^L_{f-k}\tau^U_{f-k}$ due to the $f'th$ fire.

for the flux striking a surface k due to a point source fire.

Heat Flux Striking a Wall Segment Due to an Emitting Gas Layer The energy emitted by the i'th layer (i=upper, or i=lower) along the j-k'th path is

$$q''^{i,gas}_{j-k} = \alpha^i_{j-k}\sigma T_i^4$$

where $\alpha^i_{j-k} = 1 - \tau^i_{j-k}$. The emittance of the gas in this equation is the same as the absorptance due to the gray gas assumption. Again four cases must be considered to calculate the flux striking a wall segment. The last two columns of Table 1 gives formulas for radiation striking the k'th wall segment due to lower/upper gas layer heat emissions for each possible path.

Gas Absorbance The energy absorbed by the gas layers may be due to radiating wall segments, emission from other gas layers and radiation from fires. Tables 2 and 3 summarize the formulas used to compute gas layer energy gain/loss due to these phenomena. Again, there are four cases to consider, since an arbitrary path may start in either the lower or the upper layer and end in the lower or upper layer. Figure 4 illustrates the heat absorbed by the gas layers due to surface rectangle emission where the "from" wall segment is in the upper layer and the "to" wall segment is in the lower layer. The other three cases are handled similarly.

Configuration Factor Properties A *configuration factor*, F_{j-k}, is the fraction of radiant energy leaving a surface j that is intercepted by a surface k. The following symmetry and additive properties (see [7, Chapter 7]) are used later to reduce the number of computations in the four-wall and ten-wall model

$$\begin{aligned} A_j F_{j-k} &= A_k F_{k-j} && (3) \\ F_{i-j\oplus k} &= F_{i-j} + F_{i-k} && (4) \\ A_{i\oplus j} F_{i\oplus j-k} &= A_i F_{i-k} + A_j F_{j-k} && (5) \\ \sum_{k=1}^{N} \mathrm{F}_{\mathrm{j-k}} &= 1,\ j = 1, \ldots, N && (6) \end{aligned}$$

where $i \oplus j$ denotes the union of two wall surfaces i and j. If four wall segments are configured as illustrated in Figure 5 then it can be shown that

$$A_1 F_{1-4} = A_2 F_{2-3}\ . \qquad (7)$$

Table 2: Radiant Heat Absorbed by the Upper Layer

Path through the Gas	Due to Heat Emitting Wall Surface $q^{out}_{j-k} = A_j F_{j-k}\left(\sigma T_j^4 - \frac{1-\epsilon_j}{\epsilon_j}\Delta q''_j\right)$	Due to Gas Layer Emission $q''^{i,gas}_{j-k} = \alpha^i_{j-k}\sigma T_i^4$ $q^{i,gas}_{j-k} = q''^{i,gas}_{j-k} A_j F_{j-k}$	Due to Point Source Fire $q''^{fire}_{f-k} = \frac{\chi q^{fire}_{total}\omega_{f-k}}{4\pi A_k}$
from the upper to either the lower or upper layer	$q^{out}_{j-k}\alpha^U_{j-k}$	$-q^{U,gas}_{j-k}$	$q''^{fire}_{f-k}\alpha^U_{f-k}$
from the lower to the upper layer	$q^{out}_{j-k}\tau^L_{j-k}\alpha^U_{j-k}$	$q^{L,gas}_{j-k}\alpha^U_{j-k} - q^{U,gas}_{j-k}$	$q''^{fire}_{f-k}\alpha^U_{f-k}\tau^L_{f-k}$
from the lower to the lower layer	0	0	0

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