The Effect of Thermal Radiation on the Dynamics of Flashover in a Compartment Fire*

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Flashover is a phenomenon describing a room fire changed from the growth stage to the development stage. There is a rapid increase in size and intensity. The radiant heat flux back to the fuel surface and the floor of the room is known to be one of the key parameters leading to flashover. Indeed, a heat flux (largely due to radiation) of 20 kW/m^2 to the room floor is often taken to be the condition of flashover. To understand the importance of radiation, a zone model is developed to simulate the transient fire growth in a compartment. Heat and mass transfer correlations available in the literature are used to simulate the non-radiative effect. A three-dimensional non-gray soot radiation model is used to simulate the radiative exchange between the fuel surface, the hot gas/particulate layer and the surrounding wall. Results show that the hot layer temperature alone may not be an effective indicator for flashover. Other parameters such as particulate volume fraction in the hot layer, venting area and heat transfer to the surrounding wall are also important in determining the occurrence of flashover.

***Key Words*:** Fire, Flashover, Radiation, Zonal Method

1. Introduction

The importance of the phenomenon of flashover in compartment fire is well known for many years$^{(1)}$. Physically, flashover is a term used to characterize the rapid transition of a relatively small local fire to a large fire in which the whole compartment is involved. When flashover occurs, the fire "jumps" from the growth stage to the development stage, and great damages to the building structure and properties would be resulted. Flashover has been consistently observed in disastrous fires$^{(2)}$ leading to severe losses of human lives and properties.

Experimentally, studies on flashover were reported both in actual fires and in full-scale burning tests. Two quantitative criteria were consistently observed as conditions for the onset of flashover. They are:

a. upper gas layer temperature exceeds 600°C
b. heat flux at the floor exceeds 20 kW/m^2

A summary of the conditions for the onset of flashover reported by different studies is shown in Table 1$^{(3)-(12)}$. Qualitatively, another criterion used to characterize the onset of flashover is the visual observation that at the time immediate prior to flashover, flames begin to come out of the vents.

Numerical and theoretical studies of flashover have focused primarily on predicting the behavior of the gas layer temperature in a compartment fire using various forms of the zone model$^{(13)-(15)}$. The concept of thermal instability in compartment fire was initiated by Thomas et al.$^{(11)}$ This concept led to further works$^{(16),(17)}$ in which the onset of flashover is "predicted" by computational techniques of nonlinear dynamics$^{(18),(19)}$. In all of the existing numerical and

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Table 1 Observations of the flashover criteria

References	Temperature Near the Ceiling (C)	Radiation Heat Flux (kW/m^2)
Hagglund [4]	600	No data
Parker and Lee [5]	No data	20
Fang [6]	450-650	17-33
Lee and Breese [7]	650	17-30
Babrauskas [8]	600	20
Budnick and Klein [9]	673-771, 634-734	15
Fang and Breese [10]	706±92	20
Thomas [11]	520	22
McCaffrey and Quintiere [12]	600	17.7-25

theoretical studies, the gas layer temperature is the primary dependent variable and the gas temperature criterion (>600°C) is used as the quantitative criterion for flashover.

It is interesting to note from Table 1 that in all of the reported flashover in which data for both criteria are available, both the gas temperature and heat flux criteria for the onset of flashover are satisfied. Physically, the heat flux criterion is expected to be more critical since the secondary ignition of the combustibles in a compartment is a major factor leading to flashover. The heat flux to the floor (and more specifically, radiant heat flux) is the main source of energy leading to the secondary ignition. However, gas layer temperature exceeding 600°C without a radiation source (such as the wall or soot particulates which can serve as a radiating medium) is insufficient to generate the necessary floor heat flux required for flashover. To generate a floor heat flux of 20 kW/m^2 for a temperature difference of 600°C based only on convection, for example, would require a heat transfer coefficient of about 33 W/(m^{2}K) if the whole compartment is assumed to be one zone at the same temperature. In general, the lower gas layer is expected to be at a temperature lower than 600°C. The actual heat transfer coefficient required for flashover is thus higher than 33 W/(m^{2}K). This value exceeds the range of heat transfer coefficient generally expected in a compartment fire environment (natural convection and low speed force convection). Therefore, thermal radiation is important.

The importance of the radiant feedback mechanism in the onset of flashover is recognized by almost every theoretical study of flashover(13)–(17). But due to the complexity of radiation and the uncertainty of the radiation model used in the analysis, all of the existing studies do not use the heat flux criterion as a factor in determining the condition of flashover. Over the past ten years, significant advances have achieved both in the understanding of the radiative properties of the various combustion species in a fire and the mathematical modeling of three-dimensional radiative transport in a participating medium(20). These advances can be readily implemented in a zonal model to give an improved assessment of the onset of flashover.

The objective of the present work is to implement two specific advances in radiation heat transfer into a zone model to analyze the transient behavior of a compartment fire and the onset of flashover. Since smoke particulates are expected to be a major component contributing to the radiative emission and absorption of the hot gas/particulate layer in the room during a compartment fire, a simplified model(21) is used to account for the non-gray absorption behavior of the smoke particulates. This model yields a relationship between smoke particulate volume fraction, gas layer temperature with the radiative emission and absorption of the hot layer. Computationally, the three-dimensional radiative exchange between the hot layer, the fire base and the surrounding walls must be evaluated accurately to determine the radiant feedback to the floor. An efficient and accurate zonal method(22), which is shown to be applicable for all participating media in enclosures with three-dimensional geometry, is used. Numerical data are generated to show the importance of various parameters on the onset of flashover both from the perspective of the hot gas/particulate layer temperature and the radiant heat flux to the floor.

Nomenclature

a : the total potential heat flux generated by the free burning fire, parameter used in Eq. (5)
A_f : area of the fuel surface
A_w : surface area of the wall of the compartment
b : an exponential coefficient used in Eq. (5)
c_p : specific heat of hot gas/particulate layer
C_2 : the second radiation constant
D : fractional height of the discontinuity plane
f_v : particulate volume fraction
g : gravitational constant
G : rate of energy gain of the hot gas/particulate layer
H_C : heat of combustion
H_R : height of the cubical compartment
H_{vap} : heat of vaporization
H_V : height of the vertical vent
k : an empirical constant used in the definition of absorption coefficient of hot gas/particulate layer
K_f : a flame spread constant
L : rate of energy loss of the hot gas/particulate layer

L_R : length of the cubical compartment
L_f : equivalent length of the fire base
m : mass of hot gas/particulate layer
n_r : real component of the index of refraction for soot
n_i : imaginary component of the index of refraction for soot
N : fractional height of the neutral plane
R : radius of the fire at the compartment floor
R_{edge} : the distance over which the effect of the edge of the fuel is felt
$R_{\max}$: the maximum radius of the fire
Sr : stoichiometric ratio
t : time
T : temperature of the hot gas/particulate layer
T_a : ambient temperature
V_f : flame spread rate
U_c : an adjustable parameter for the wall temperature
W_R : width of the cubical compartment
W_V : width of the vertical vent
Z_d : discontinuity height
$\dot{H}$: increase in enthalpy of hot gas/particulate layer due to mass increase
$\dot{H}_o I$: net enthalpy flow rate out of the vent
$\dot{m}_a$: mass flow rate of air into the compartment
$\dot{m}_f$: rate of volatilization
$\dot{m}_o$: mass flow rate out of the vent
$\dot{q}_{ff}$: heat flux from the fire to the fire base
$\dot{q}_{f,\mathrm{surr}}$: heat flux from the surrounding (hot layer and walls) to the fire base
$\dot{q}_b$: radiative heat flux to the base of the compartment
gs_x : exchange factor between the hot layer and wall element x (x=l, r, i, t, o, b, v stand for the left, right, inner, outer, top, bottom wall and vent opening respectively)
$s_x s_y$: exchange factor between wall element x and wall element y (x, y=l, r, i, o, t, b, v)
χ : combustion efficiency
ρ_0 : density of hot gas/particulate mixture
ε : emissivity
κ : absorption coefficient

2. Analysis

A simplified two zone compartment fire model(16) is used as the basis of the present study. While this model can give only an overall picture with no fine details, it contains all the relevant physics and is sufficient for the present purpose, which is to illustrate the importance of using an accurate radiation model in assessing flashover.

2.1 Conservation equations

The compartment is assumed to be a cubical enclosure as shown in Fig. 1. The fire is assumed to be a circular region in the center of the floor with radius R. Following the mathematical development of Bishop et al.(16),(19), the temperature of the hot gas/particulate layer is governed by

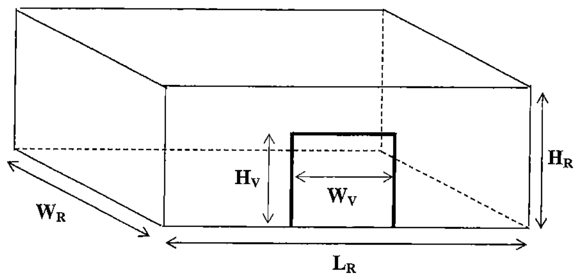

Fig. 1 Geometry and dimensions of the cubical compartment

$$\frac{dT}{dt}=\frac{G-L-\dot{H}}{c_p m} \qquad (1)$$

The energy gain rate of the hot layer depends on whether the ratio of the mass air flow rate to the fuel volatilization rate is greater than (fuel controlled fire) or less than (ventilation controlled fire) the stoichiometric ratio. Assuming that all energy of combustion goes into the hot layer, G is given by

$$G=\begin{cases}\chi \dot{m}_f H_c & \text{if } \dfrac{\dot{m}_a}{\dot{m}_f}\geq Sr \\ \chi \dfrac{\dot{m}_a}{Sr} H_c & \text{if } \dfrac{\dot{m}_a}{\dot{m}_f}< Sr\end{cases} \qquad (2)$$

where χ is the combustion efficiency, $\dot{m}_a$ is the mass flow rate of air into the compartment, $\dot{m}_f$ is the rate of volatilization, H_c is the heat of combustion and Sr is the stoichiometric ratio.

The volatilization rate of fuel depends on the heat transfer from the fire and the compartment surrounding to the fire base. It is given by

$$\dot{m}_f=\frac{(\dot{q}_{ff}+\dot{q}_{f,\mathrm{surr}})A_f}{H_{\mathrm{vap}}} \qquad (3)$$

where $\dot{q}_{ff}$ is the heat flux from the fire to the fire base, $\dot{q}_{f,\mathrm{surr}}$ is the heat flux from the surrounding (hot layer and walls) to the fire base, H_{vap} is the heat of vaporization and A_f is the area of the fuel surface given by

$$A_f=\pi R^2 \qquad (4)$$

The heat loss from the fuel surface (due to convection and radiation) is assumed to be negligible compared to the large incoming heat flux from the flame and the surrounding hot layer.

Following Emmons(13), the fire is assumed to have the form of a cone and the heat flux from the flame to the base is given by

$$q_{ff}=a(1-e^{-bR}) \qquad (5)$$

where a is the total potential heat flux generated by the free burning fire and b is an exponential coefficient. The formulation of $\dot{q}_{f,\mathrm{surr}}$ depends on the radiation model and it will be discussed in the next section.

The mass flow rate of air into the compartment is assumed to be driven by buoyancy flow(23) and is given by

$$\dot{m}_a=\frac{2}{3}C_D\rho_0 W_v H_v^{3/2}\sqrt{2g\left(1-\frac{T_a}{T}\right)(N-D)}\left(N+\frac{D}{2}\right) \quad (6)$$

with D being the fractional height of the discontinuity plane (which is defined as the lower plane of the hot gas layer) given by

$$D=\frac{Z_d}{H_v} \quad (7)$$

where Z_d is the discontinuity height. N is the fractional height of the neutral plane and it is taken empirically to be

$$N=D+\frac{(1-D)^2}{2} \quad (8)$$

Physically, the neutral plane is the plane across the ventilation opening at which the pressure equals the ambient pressure. The hot gas flows out of the compartment above the neutral plane while the cold gas flows into the compartment below the neutral plane. The rate of energy loss from the hot layer is given by

$$L=\dot{H}_o+\dot{Q}_w \quad (9)$$

where $\dot{H}_o$ is the net enthalpy flow rate out of the vent given by

$$\dot{H}_o=\dot{m}_o c_p(T-T_a) \quad (10)$$

with $\dot{m}_o$ being the mass flow rate out of the vent. Assuming that there is no accumulation of mass in the compartment, $\dot{m}_o$ is related to $\dot{m}_a$ and $\dot{m}_f$ by

$$\dot{m}_o=\dot{m}_f+\dot{m}_a \quad (11)$$

$\dot{Q}_w$ is the heat loss from the hot gas/particulate layer to the wall. Its expression depends on the radiation model and will be discussed in the next section. A consequence of Eq.(11) is that there is no mass increase within the compartment. This leads to

$$\dot{H}=0 \quad (12)$$

and the mass of the hot gas/particulate layer is given by

$$m=\rho_0 L_R W_R(H_R-Z_d) \quad (13)$$

In Eq.(13), the density of the hot gas/particulate layer is assumed to be constant at ρ_0. While this assumption is in general not accurate as the gas layer temperature rises and the soot concentration increases, it is retained in the present work so that the current result can be compared with previous works(13)–(17) which used this assumption. From the perspective of illustrating the effect of radiation on flashover, this assumption is not expected to have a significant quantitative impact.

Finally, the differential equation for the rate of change of the fire radius is given by Ref.(16).

$$\frac{dR}{dt}=V_f\left(1-e^{\frac{R-R_{\max}}{R_{\mathrm{edge}}}}\right) \quad (14)$$

where $R_{\max}$ is the maximum radius, representing the size of the fuel sample. Numerically, the empirical parameter R_{edge} is the distance from the edge at which the rate of change of the fire radius is reduced to 0.63 V_f. R_{edge} thus represents the characteristic distance over which the edge effect is felt. The adjustment of V_f is the flame spread rate which can be taken as(24)

$$V_f=\frac{K_f\dot{m}_a}{\rho_0 W_v N H_v} \quad (15)$$

with K_f being a flame spread constant.

Note that Z_d is taken as a constant. Previous experience on zone modeling simulation indicated that the smoke layer interface height depends only on the opening height for a steady burning fire. Since the objective of the paper is to illustrate the importance of thermal radiation, this approach was used for simplicity.

2.2 Radiation model of previous works

In nearly all of the existing theoretical works(13)–(17) on flashover, $\dot{q}_{f,\mathrm{surr}}$ and $\dot{Q}_w$ are generated by assuming a constant value of emissivity, ε, for the gas/particulate layer. For example, Bishop et al.(16) used the following expressions

$$\dot{q}_{f,\mathrm{surr}}=\sigma[\varepsilon T^4+(1-\varepsilon)T_w^4-T_a^4] \quad (16)$$

$$\dot{Q}_w=A_w[\varepsilon\sigma(T^4-T_w^4)+h_t(T-T_w)] \quad (17)$$

with h_t being a convective heat transfer coefficient and A_w is the surface area of the surrounding wall given by

$$A_w=2(L_R W_R)+2(L_R H_R)+2(H_R W_R) \quad (18)$$

To complete the mathematical description of the model, the wall temperature is assumed to be between the layer temperature T and the ambient temperature T_a given by

$$T_w=U_c(T-T_a)+T_a \quad (19)$$

with U_c being an adjustable parameter between 0 and 1.

A fundamental difficulty of this radiation model is that it provides no physical correlation between the layer emissivity ε and measurable parameters such as particulate volume fraction and temperature of the hot layer which are known to have an effect on hot layer emissivity. The model also does not account for the effect of the compartment geometry (dimensions, size of vent and radius of fire base) on the radiation transport.

2.3 The current radiation model

In the current model, particulates in the hot layer are assumed to be the primary species for radiative emission and absorption. While the gaseous species (e.g. CO_2 and H_2O) are known to contribute to the flame radiative emission, their contribution is generally small. For example, a standard furnace 4 m high and 2 m in diameter consisting of a stoichiometric mixture of CO_2 and H_2O (generated from the combustion of methane) at one atmosphere only has an emittance of 0.11(20). Indeed, the presence of soot particulates and luminous radiation from the hot layer are known to be important factors in the occurrence of flashover. The effect of gaseous radiation on flashover is thus secondary compared to that of radiation from the soot particulate.

Assuming that the size of the particulate is small so that the Rayleigh's limit of particle absorption is valid, the absorption coefficient of the hot gas/particulate layer can be written as(20)

$$a_\lambda=\frac{36\pi f_v}{\lambda}\frac{n_r n_i}{(n_r^2-n_i^2+2)^2+4n_r^2 n_i^2} \tag{20}$$

where n_r and n_i are, respectively, the real and imaginary component of the index of refraction for soot which are known functions of λ. The emittance of a soot cloud of thickness L is

$$\varepsilon(T, L)=\frac{1}{\sigma T^4}\int_0^\infty e_{\lambda b}(T)(1-e^{-a_\lambda L})d\lambda \tag{21}$$

Equation (21), together with Eq. (20), have been evaluated numerically for soot generated by some common fuel (acetylene and propane) and, it was shown(21) that the emittance can be approximated by an equivalent gray model as

$$\varepsilon(T, L)=1-e^{-\kappa L} \tag{22}$$

with a being an equivalent absorption coefficient which is determined to be

$$\kappa=\frac{3.6kf_v T}{C_2} \tag{23}$$

where f_v is the particulate volume fraction, k is an empirical constant in the range of 3.5 to 7.5 (depending on the fuel) and C_2 is the second radiation constant. Note that the equivalent absorption coefficient depends on the temperature of the blackbody intensity with which Eq. (21) is evaluated. If κ is used in the evaluation of absorption, it should be evaluated at the temperature of the radiation source.

In the present work, a gray soot model with an absorption coefficient given by Eq. (23) will be utilized. The radiative emission from the gaseous combustion products will be ignored. Analysis with a more detail non-gray soot model and the inclusion of radiation from gaseous species will be considered in future works.

Physically, the particulate volume fraction of the hot layer is expected to increase as the fire grows. As a first order approximation of this effect, the present work assumes a linear relation between the particulate volume fraction and the fire radius. It is written as

$$f_v=\frac{R}{R_{\max}}f_{v,0} \tag{24}$$

with $f_{v,0}$ being a characteristic volume fraction which is a function of the fuel.

Assuming that the fuel surface can be treated as a square of length L_f given by

$$L_f=\sqrt{\pi}R \tag{25}$$

exact expressions for the exchange factor between the fire base, the hot gas/particulate layer and the surrounding wall can be readily obtained either directly by numerical integration or using the tabulated data and superposition procedure as outlined in Yuen and Takara(22). The definition of exchange factor and its mathematical properties are described in Ref. (21). For a cubic enclosure with $W_R=L_R=H_R=40$ cm, $Z_d=0$ (i.e. the hot layer fills the whole compartment) and a fire base with $L_f=30$ cm, for example, the exchange factor between the fire base and the hot layer ($s_f g$), the exchange factor between the fire base and the top wall ($s_f s_t$) and the exchange factor between the hot layer and the top wall (gs_t) are shown in Fig. 2. It is important to note that these factors depend strongly on the absorption coefficient. The radiation transport thus depends strongly on the hot layer temperature and the particulate volume fraction.

Based on the concept of exchange factor, the expression for $\dot{q}_{f,\mathrm{surr}}$ can be written as

$$A_f\dot{q}_{f,\mathrm{surr}}=\sigma T^4 gs_f(\kappa)+\sigma T_w^4\left[\begin{array}{c}s_t s_f(\kappa_w)+s_l s_f(\kappa_w)\\+s_r s_f(\kappa_w)+s_i s_f(\kappa_w)\\+s_{o-v}s_f(\kappa_w)\end{array}\right]+\sigma T_a^4 s_v s_f(\kappa_a) \tag{26}$$

$gs_f(\kappa)$ is the exchange factor between the hot layer and the fire base. $s_x s_f$ ($x=t, l, r, i, o-v, v$) stands for the exchange factor between the top wall (t), left wall (l), right wall (r), inner wall (i), outer wall (o), the vent opening (v) and the fire base respectively. The subscript $o-v$ stands for the outer wall section minus the vent opening. The subscript in the absorption

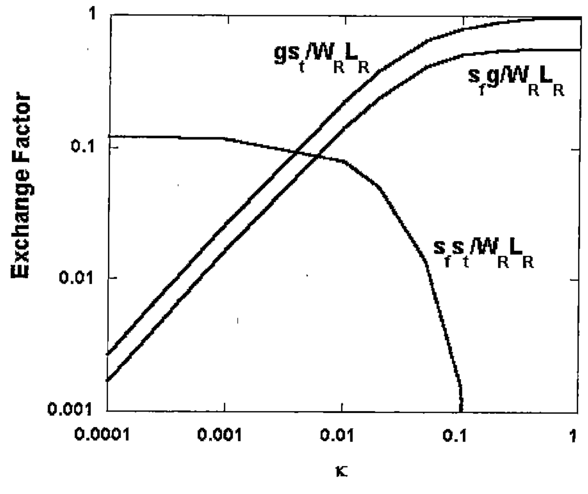

Fig. 2 Typical exchange factor between the fire base, the hot layer and the enclosure walls for the considered compartment with $W_R=L_R=H_R=40$ cm, $L_f=30$ cm, and $Z_d=0$

coefficient κ indicates the temperature (wall, vent or hot layer temperature) at which it is evaluated. In a similar manner, the expression for $\dot{Q}_w$ is given by

$$\dot{Q}_w = \sigma T^4 \begin{bmatrix} gs_t(\kappa)+gs_b(\kappa) \\ +gs_l(\kappa)+gs_r(\kappa) \\ +gs_i(\kappa)+gs_o(\kappa) \end{bmatrix} - \sigma T_w^4 \begin{bmatrix} gs_t(\kappa_w)+gs_{b-f}(\kappa_w) \\ +gs_l(\kappa_w)+gs_r(\kappa_w) \\ +gs_i(\kappa_w)+gs_{o-v}(\kappa_w) \end{bmatrix} - \sigma T_a^4 gs_v(\kappa_a) \quad (27)$$

where the subscript b stands for the bottom floor. Equations (1) to (15), together with Eqs. (20) to (27) constitute a complete mathematical description of the present transient compartment fire model. In addition to predicting the transient behavior of the hot layer temperature, the radiative heat flux to the compartment floor can be readily evaluated by

$$\dot{Q}_b = L_R W_R \dot{q}_b = \sigma T^4 gs_b(\kappa) + \sigma T_a^4 s_v s_b(\kappa_a) + \sigma T_w^4 \begin{bmatrix} s_t s_b(\kappa_w)+s_l s_b(\kappa_w) \\ +s_r s_b(\kappa_w)+s_i s_b(\kappa_w) \\ +s_{o-v} s_b(\kappa_w) \end{bmatrix} \quad (28)$$

Equation (28) can be used as a basis of evaluation for the heat flux criterion of flashover.

For simplicity, the walls of the enclosure are assumed to be black and the hot gas/particulate layer is assumed to be non-scattering in the development of Eqs. (26) to (28). The exchange factors are the "direct exchange factors" between the wall elements and the hot gas/particulate layer. In principle, Eqs. (26) and (28) are also applicable for non-gray walls and a scattering hot gas/particulate layer with the exchange factors interpreted as the "total exchange factor". The evaluation of these total exchange factors, however, is quite complicated. The consideration of non-gray walls and scattering particulate are not essential for the purpose of the present work, which is to identify the effect of radiation on flashover. These effects will be considered in the future extension of the present work.

3. Results and Discussion

Numerical data are generated to examine the effect of vent opening W_v, particulate volume fraction $f_{v,0}$ and the wall temperature parameter U_c on the transient temperature rise of the hot gas/particulate layer and the radiative heat flux to the compartment floor. These parameters are selected because they are expected physically to be important parameters affecting the occurrence of flashover. The effect of other parameters will be investigated in future works. For the value of other parameters, the present work follows the approach of Bishop et al.[16] They are chosen to describe a typical fire burning on a circular PMMA slab developed on a scaled (i.e. 40 cm inside cube) compartment. A listing of the parameters is shown in Table 2. For a direct comparison, numerical data are also generated with the previous radiation model with a layer emissivity of $\varepsilon=0.41$ (value used in Ref. (16)).

Table 2 Specified parameters in numerical examples

Compartment Parameters	Fluid Parameters
$H_R = 40$ cm	$C_D = 0.7$
$W_R = 40$ cm	$\rho_0 = 1.25$ kg/m^3
$L_R = 40$ cm	$T_a = 300$ K
$H_V = H_R = 40$ cm	$c_p = 1003.2$ J/kg-K
Fuel Parameters	Heat Transfer Parameter
$R_{max} = 15$ cm	$h_t = 7$ W/m^2-K
$R_{edge} = 1$ cm	$\chi = 0.65$
$K_f = 1/2000$	$a = 102{,}000$ W/m^2
$Sr = 8.25$	$b = 1.12$ m^{-1}
$H_{vap} = 1{,}008{,}000$ J/kg	
$H_c = 24{,}900{,}000$ J/kg	
$T_f = 1300$ K	

For the case with $U_c=0$ ($T_w=T_a$, the "cold wall" case), the layer temperature and the corresponding heat flux to the compartment floor for different vent openings are shown in Figs. 3(a) to 3(e). The layer temperature illustrates an interesting relation between radiation and vent openings. When the vent opening is small (for example, $W_v=5$ cm) and the fire is ventilation controlled, the primary effect of radiation appears to be the heat loss to the surrounding wall. The case with the smaller particulate volume fraction (hence less radiation heat loss) has the higher layer temperature. An increase in the particulate volume fraction increases the radiative heat loss (to the surrounding) and thus lowers the layer temperature. When the vent opening is large ($W_v>10$ cm) and the fire is fuel controlled, the effect of radiative feedback to the fuel surface appears to be more important. The layer temperature increases with increasing particulate volume fraction. The increased radiative feedback to the fuel surface increases the burning rate and therefore the layer temperature.

It is interesting to note that result of the previous radiation model (which does not depend on particulate volume fraction) agrees with the optically thick (high particulate volume fraction) case for the ventilation controlled fire ($W_v=5$ cm) and it agrees with the optically thin (low particulate volume fraction) case for the fuel controlled fire. This result demonstrates the physical difficulty of the previous radiation model. By assuming a constant emissivity for the hot gas layer and the wall in an ad-hoc fashion, the previous model cannot yield a consistent interpretation of the physics, even in a limiting sense.

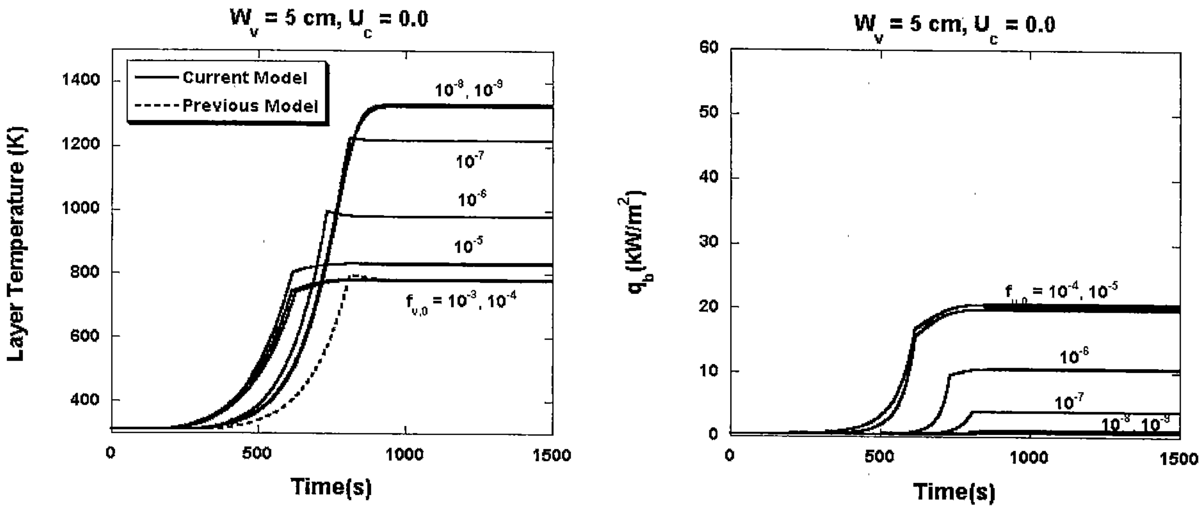

Fig. 3(a) Temperature of the hot layer and radiative heat flux to the floor for W_v=5 cm and U_c=0 with different particulate volume fraction

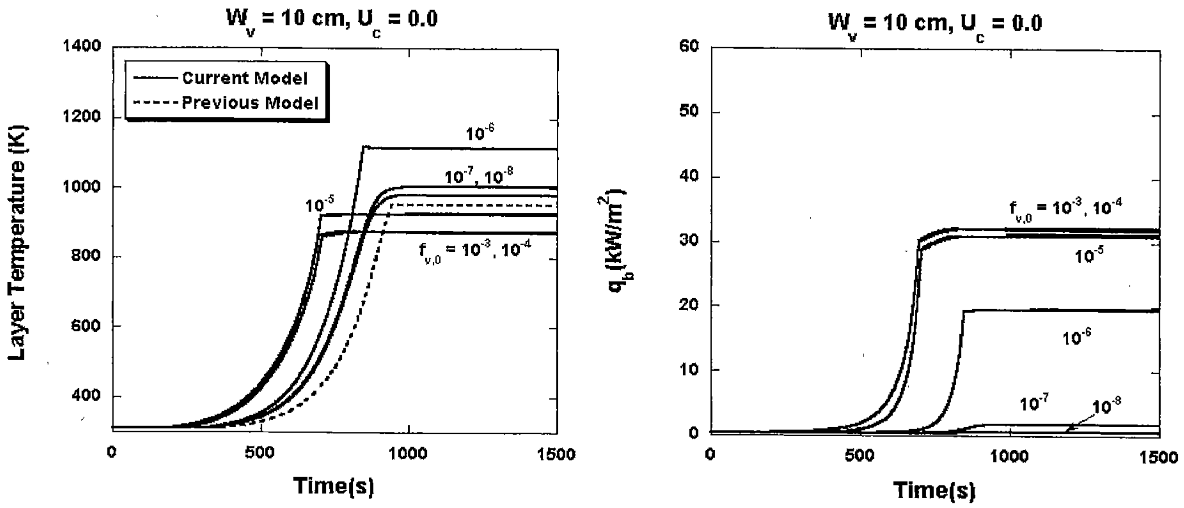

Fig. 3(b) Temperature of the hot layer and radiative heat flux to the floor for W_v=10 cm and U_c=0 with different particulate volume fraction

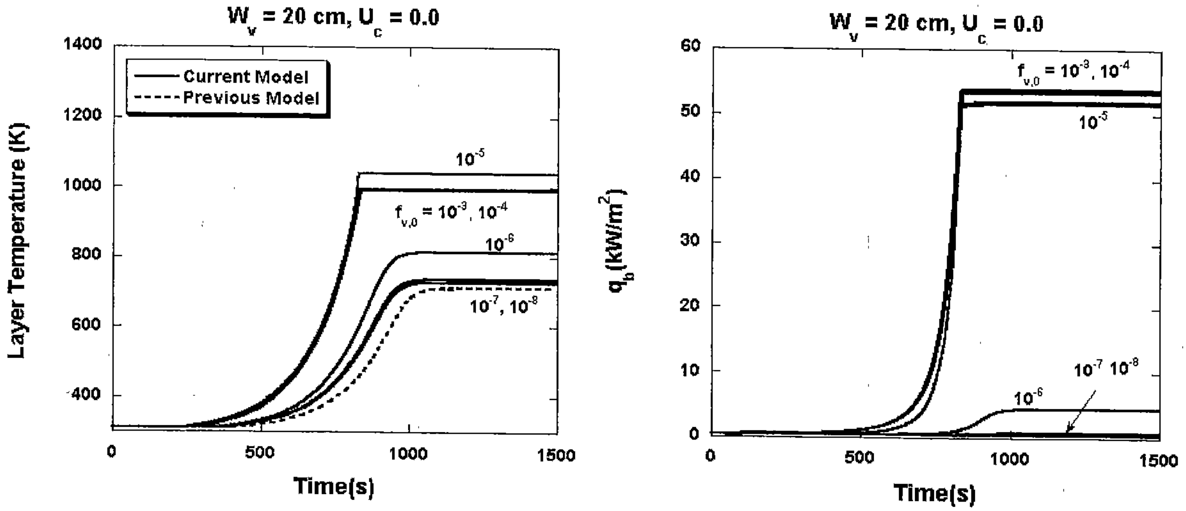

Fig. 3(c) Temperature of the hot layer and radiative heat flux to the floor for W_v=20 cm and U_c=0 with different particulate volume fraction

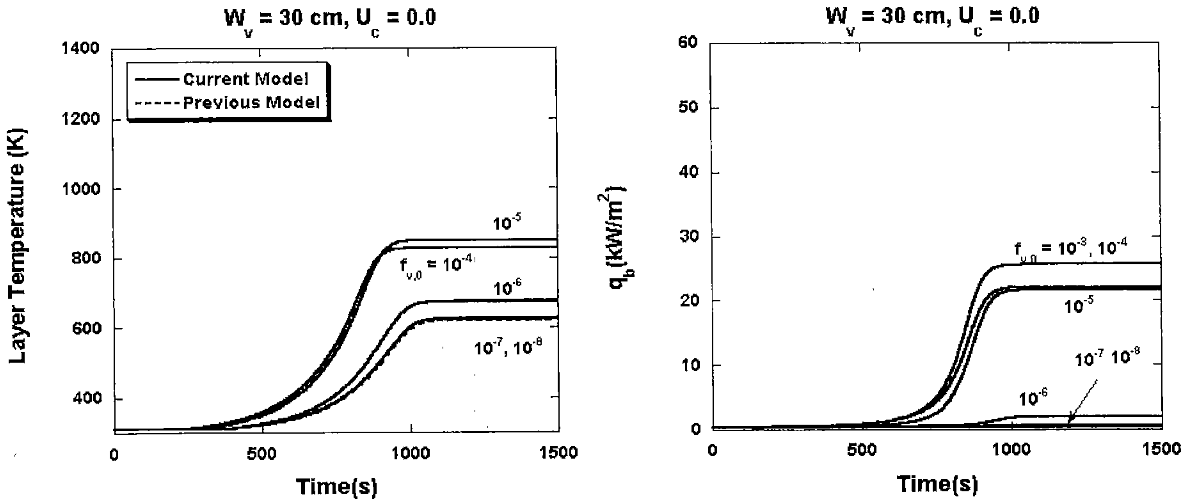

Fig. 3(d) Temperature of the hot layer and radiative heat flux to the floor for W_v=30 cm and U_c=0 with different particulate volume fraction

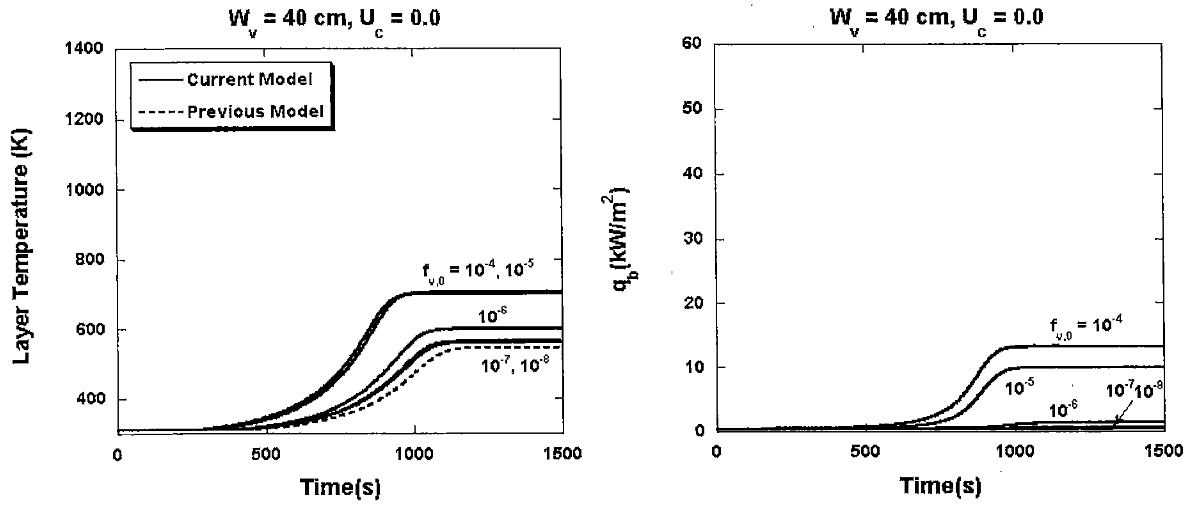

Fig. 3(e) Temperature of the hot layer and radiative heat flux to the floor for W_v=40 cm and U_c=0 with different particulate volume fraction

From the flashover perspective, results in Figs. 3(a) and 3(e) and the temperature criterion (temperature of layer greater than 600°C) would suggest that flashover occurs in the ventilation controlled case with low particulate volume fraction ($f_{v,0} \leq 10^{-6}$ for W_v=5 cm, $f_{v,0} \leq 10^{-5}$ for W_v=10 cm). The temperature criterion is also satisfied for the high volume fraction case ($f_{v,0} \geq 10^{-5}$) with W_v=20 cm. The temperature criterion is never satisfied for all particulate volume fraction for the fuel controlled fire (W_v=30, 40 cm). The conclusion about flashover, however, is quite different if the heat flux criterion is applied to the result of Figs. 3(a) to 3(e). Specifically, heat flux criterion is not satisfied for all particulate volume fraction for the fully ventilation controlled fire (W_v=5 cm) and the fully fuel controlled fire (W_v=40 cm). For the W_v=5 cm case, the high layer temperature is attained when the particulate volume fraction is small. There is insufficient emission and therefore the radiative heat flux to the compartment floor remains low. For the W_v=40 cm case, the temperature of the hot layer is not high enough to generate the necessary radiative heat flux. Results in Figs. 3(b) to 3(d) suggest that flashover occurs in cases with high particulate volume fraction ($f_{v,0}=10^{-3}, 10^{-4}, 10^{-5}$) for fires which are neither totally ventilation controlled nor totally fuel controlled (W_v=10, 20, 30 cm). Note that in the W_v=30 cm case, the heat flux criterion is satisfied even though the hot layer temperature is only about 800 K (500°C). It is important to note that the association of flashover with high particulate volume fraction is consistent with the observation that the presence of smoke and luminous flame is a necessary condition for flashover. Results in Figs. 3(a) to 3(e) demonstrate readily that the temperature criterion alone might not be an adequate condition for the

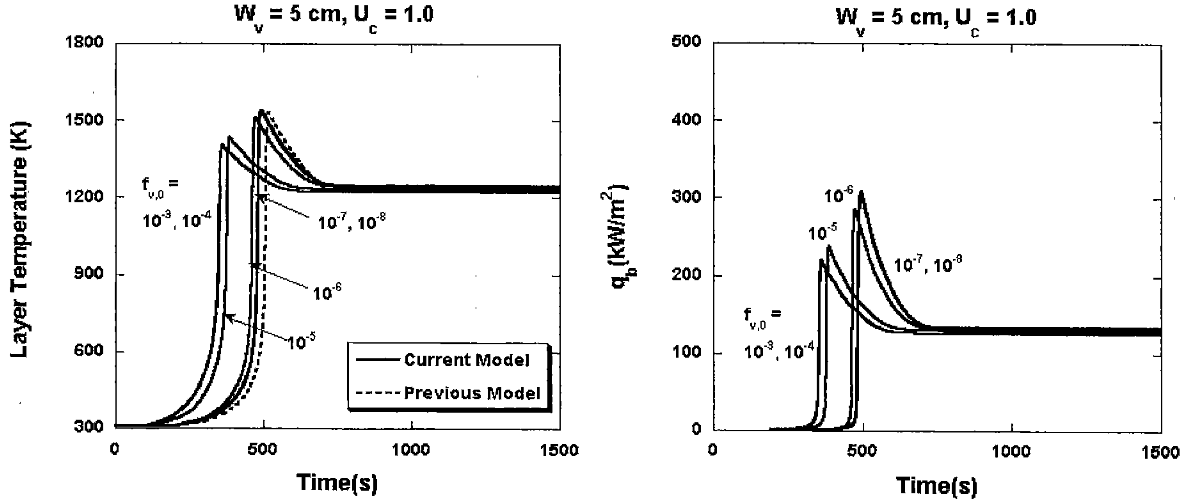

Fig. 4(a) Temperature of the hot layer and radiative heat flux to the floor for $W_v=5$ cm, $U_c=1$ with different particulate volume fraction

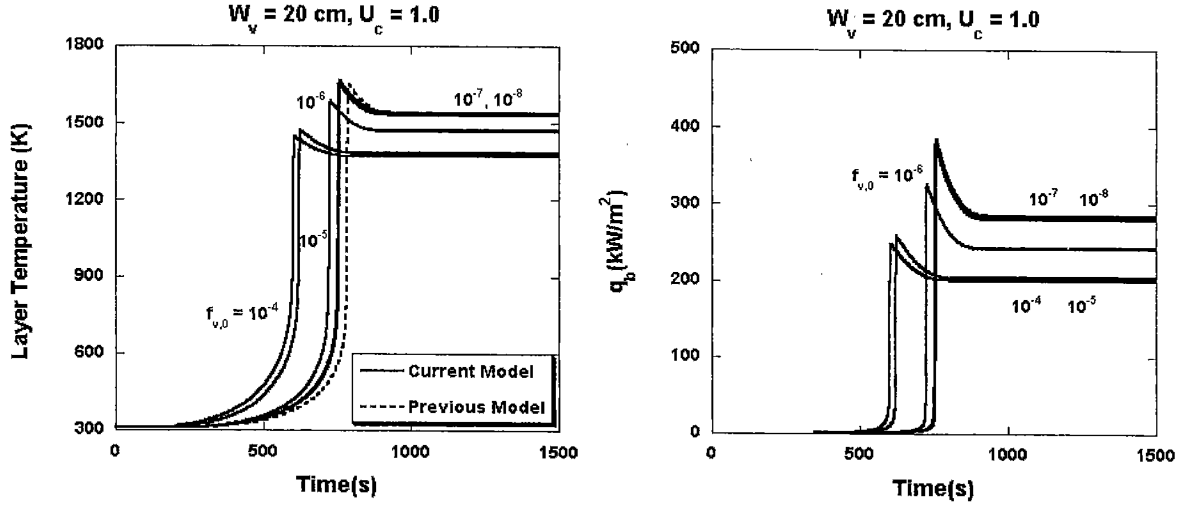

Fig. 4(b) Temperature of the hot layer and radiative heat flux to the floor for $W_v=20$ cm, $U_c=1$ with different particulate volume fraction

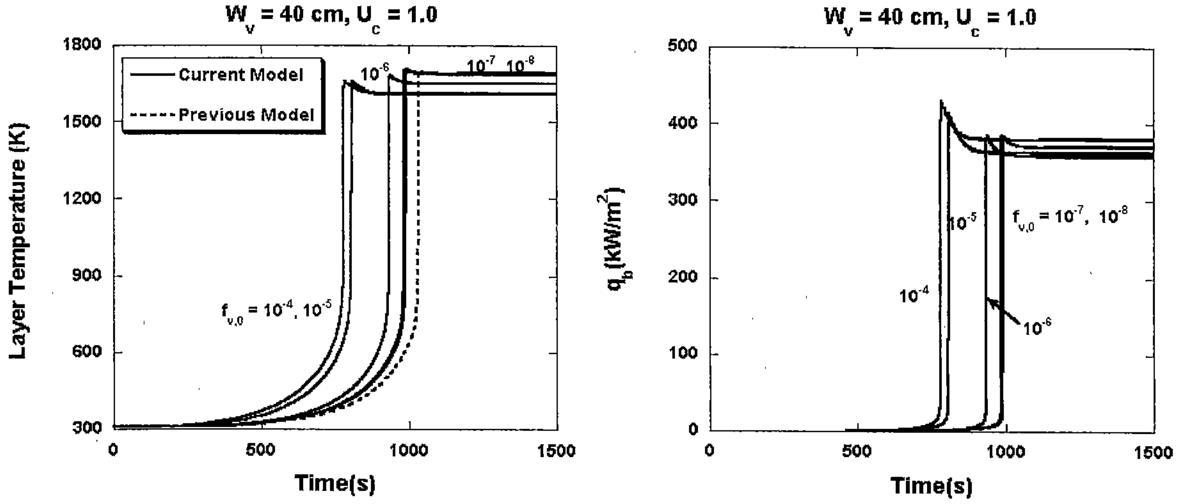

Fig. 4(c) Temperature of the hot layer and radiative heat flux to the floor for $W_v=40$ cm, $U_c=1$ with different particulate volume fraction identification of flashover. An accurate model for thermal radiation heat transfer and a correct assessment of the radiative heat flux to the compartment floor are necessary for an effective assessment of the flashover.

Temperature results and the corresponding heat flux to the compartment floor with $U_c=1$ ($T_w=T$, the "hot wall" case), are shown in Figs. 4(a) to 4(c). The transient temperature behavior for different W_v is quite similar. Since there is no heat loss from the hot layer to the wall, the primary heat loss from the hot layer is due to that from the mass flow out of the vent. For ventilation controlled fire ($W_v=5$ cm), the radiative feedback to the fuel surface is not a controlling factor on the combustion rate, the steady state temperature is independent of the radiative properties of the layer and is thus insensitive of the particulate volume fraction. For fuel controlled fires ($W_v=20$, 40 cm), the radiative feedback effect has a more important effect on combustion and the particulate volume fraction has a stronger effect on the layer temperature. The radiative heat flux to the compartment floor also shows similar behavior for different vent opening and particulate volume fraction. In general, the radiation from the wall dominates the heat transfer and has a major effect on the final steady state hot layer temperature and heat flux to the compartment floor. Because of the large radiative heat flux from the wall, the two flashover criteria are readily satisfied in all cases. It is interesting to observe that all the predicted flashovers are quite "catastrophic" as there is a nearly vertical jump both in the temperature and in the radiative flux to the compartment floor. Physically, this suggests that a fire in a highly insulated compartment will likely lead to a flashover. This is consistent with physical expectation.

4. Concluding Remarks

The present work shows that radiative heat transfer is clearly a dominant factor in the determination of flashover. A theoretical model with an inaccurate model of radiation can lead to conclusions with uncertain accuracy.

Using a non-gray particulate radiation model and the zonal method, a zone model is developed to determine the conditions leading to flashover. Numerical data are presented to illustrate the effect of vent opening, particulate volume fraction and the wall temperature on the transient temperature rise and flashover. Results demonstrate that the hot gas layer temperature alone might not be a sufficient criterion for flashover. Both high temperature in the hot layer and high emissivity from the gas/particulate layer are necessary to generate a heat radiative heat flux to the compartment floor. If the compartment is well insulated, the radiation from the wall can also become a dominant effect leading to flashover.

The present model can be used as a basis for a more detailed non-linear analysis to identify the different type of instabilities and their relation to the transition to flashover. This task is currently under consideration and will be reported in future publications.

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