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THE ROLE OF THERMAL RADIATION ON THE INITIATION OF FLASHOVER IN A COMPARTMENT FIRE

by

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Abstract

Importance of thermal radiation for transition to flashover in a compartment fire will be demonstrated. A one zone model is developed with the objective of capturing the key mechanisms responsible for the initiation of flashover, i.e. physics of flashover. Thermal radiation is shown to be a key point and the inclusion of a three-dimensional radiation model is essential in the development of an accurate understanding of flashover. The

heat transfer from the bounding wall of the compartment, the particulate concentration in the hot layer and the ventilation opening are shown to be key parameters which can lead to thermal instability and the resulting initiation of flashover.

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_{wx} = surface area of the wall element x of the compartment (x = l, r, i, o, t, b, v stand for the left, right, inner, outer, top, bottom wall and vent opening respectively)

b = an exponential coefficient used in Eq. (5)

c_p = specific heat of hot gas/particulate layer

c_w = specific heat of wall

C_2 = the second radiation constant

D = fractional height of the discontinuity plane

f_v = particulate volume fraction

$f_{v,0}$ = particulate volume fraction at the final steady state

g = gravitational constant

G = rate of energy gain of the hot gas/particulate layer

h_t = heat transfer coefficient from the hot layer to the wall

h_o = external heat transfer coefficient from the wall to the ambient

H_C = heat of combustion

H_R = height of the cubical compartment

H_{vap} = heat of vaporization

H_V = height of the vertical vent

$\dot{H}_o$ = net enthalpy flow rate out of the vent defined by Eq. (10)

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 = 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

T_f = flame temperature

T_{wx} = temperature of wall component x (x = l, r, i, o, t, b, v)

V_f = flame spread rate

V_w = volume of wall

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

$\dot{H}_o$ = 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

$\dot{q}_{f,surr}$ = heat flux from the surrounding (hot layer and walls) to the fire base

$\dot{q}_{wx}$ = radiative heat flux to wall component x of the compartment (x = l, r, i, o, t, b, v)

$\dot{Q}_w$ = heat loss from the hot layer to the wall

$\dot{Q}_{w,c}$ = convective heat loss from the hot layer to the wall

$\dot{Q}_{w,r}$ = radiative heat loss from the hot layer to the wall

gs_x = exchange factor between the hot layer and wall element x (x = l, r, i, o, t, b, v)

$s_x s_y$ = 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

ρ_w = density of wall

ε = emissivity

κ = absorption coefficient evaluated at the hot layer temperature

κ_{wt} = absorption coefficient evaluated at the temperature of wall component t

κ_a = absorption coefficient evaluated at the ambient temperature

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.

While flashover has been observed frequently, there is currently only a limited understanding on the basic mechanisms leading to a flashover. For example, three criteria were commonly accepted by the fire safety community as conditions for flashover. They are:

a. upper gas layer temperature exceeds 600 C
b. heat flux at the floor exceeds 20 kW/m^2
c. flame coming out of openings

While these criteria are generally supported by experimental observation such as those reported by different studies [3-12], there is little understanding of the fundamental basis of these criteria especially the first two, as both appeared to be related more on heat transfer than combustion. For example, it is not clear that whether one or both of these two criteria are required for the onset of flashover. Since these criteria are not explicitly stated out in most fire codes, it is difficult to use them as a basis for fire safety design.

Over the years, 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]. Even with the increased computational power available in recent years, the zone model remained the preferred approach (over a direct numerical simulation based on solution to the relevant field equations) in the study of flashover because of the difficulty in modeling the complex combustion physics in a full solution of the field equations. While the zone model cannot predict localized spatial behavior of field variables such as temperature, mass concentration of various species and velocity, the model is generally expected to be sufficiently good in illustrating the key mechanisms leading to flashover, provided that all relevant physical processes are simulated with sufficient accuracy. Another advantage of the zone model is that it can be readily adapted to a nonlinear analysis using computational techniques of non-linear dynamics [16-19], which can be a powerful approach both in identifying and understanding the key mechanisms leading to flashover.

Physically, the radiant feedback to a fuel surface has been recognized as an important mechanism leading to the onset of flashover [13-17]. Indeed, without the presence of a radiation source such as the compartment wall or soot particulates within the hot gas, a gas layer temperature of 600 C might not be insufficient to generate the required floor heat flux of 20 kW/m^2 required for flashover. For example, if convection is the only heat transfer mechanism, a heat transfer coefficient of 33 $W/(m^2\text{-}K)$ is required to generate a floor heat flux of 20 kW/m^2 from a 600 C gas layer. This value exceeds the range of heat transfer coefficient generally expected in a compartment fire environment (natural convection and low speed force convection). An accurate radiation model, accounting for the effect of surface radiation from the compartment walls and the radiative emission of the hot gas/particulate layer, is thus an important component of an effective zone model in the simulation of flashover. Radiative heat transfer in a multi-dimensional combustion medium, however, is a complex physical phenomenon which is difficult to simulate numerically in an accurate and efficient manner. Historically, the lack of an accurate and computationally efficient simulation of radiative heat transfer is probably the primary factor limiting the effectiveness of many existing zone models in the analysis and prediction of flashover.

Over the past ten years, significant advances have been 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]. Together with the increased computational power currently available to the design engineers, the development of an accurate and computationally efficient zone model accounting for the realistic effect of radiation is now a practical possibility. A number of works have appeared in the literature illustrating the effect of radiation heat transfer in fire and other general combustion environments [26-30].

In the present work, a zone model is developed with the implementation of two specific aspects of radiative heat transfer. First, a zonal model for radiative exchange [21] is implemented to determine the radiative exchange between the compartment wall, the hot gas/particulate layer in the compartment and the fuel surface. This exchange process is essential in the determination of the radiative feedback to the fuel surface which is expected to be a controlling mechanism for flashover. It is important to note that even in a simple one zone fire model, the radiative exchange process in the compartment is three dimensional and the effect of the intervening absorbing and emitting gas/particulate layer is significant. The zonal method for radiative exchange can simulate this exchange process accurately with excellent computational efficiency. Second, a realistic approximation of the absorption/emission characteristic of the gas/particulate layer is utilized. In nearly all of the existing zone models for compartment fire, the effect of radiative absorption and emission from the hot gas layer is characterized empirically by the specification of an “absorption coefficient” or “emissivity” which is usually left to be an adjustable parameter of the model. Since the absorption coefficient and emissivity of a combustion medium depend strongly on parameters such as temperature, pressure and the particulate volume fraction, a model in which the hot gas emissivity is an adjustable empirical parameter is ineffective in illustrating the transient effect of radiative feedback on the combustion process. In the present model, radiative heat transfer in the hot gas/particulate layer is characterized by fundamental parameters such as temperature and particulate volume fraction. The direct influence of the transient behavior of these parameters on the radiant feedback to the fuel surface and the occurrence of flashover can thus be illustrated.

In the remainder of this paper, the mathematical description of the model is presented in section 2. The approximate models used in the characterization of combustion and convective heat and mass transfer are similar to those used by many existing models. The current approach to the modeling of radiative heat transfer within the compartment will also be described. In section 3, the model is applied to assess the thermal instability of a compartment fire, from the perspective of the transient behavior of the temperature of the hot layer. Three parameters are shown to have an important influence on the behavior of the instability. These parameters are the external heat transfer from the compartment wall, the particulate volume fraction in the hot layer and the vent opening available from the compartment. Radiative heat transfer is shown have the dominant effect on the onset of instability in all cases. Finally, some concluding remarks are presented in section 4.

2. Analysis

A simplified one 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 identify the onset of thermal instability leading to 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. The set of conservation equations is similar to those developed in a previous work [22]. They are repeated here for completeness. Specifically, the temperature of the hot gas/particulate layer is governed by

$$\frac{dT}{dt} = \frac{G - L}{c_p m} \tag{1}$$

The energy gain rate of the hot layer, G, 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

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

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

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

where $\dot{q}_{ff}$ is the heat flux from the fire to the fire base, $\dot{q}_{f,surr}$ 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

$$A_f = \pi R^2 \tag{4}$$

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.

It is important to note that the rate of heat gain from combustion is proportional to the volatilization rate only in a fuel controlled fire when there is sufficient air flow into the compartment. When the air flow is limited, the fire becomes ventilation controlled and G is independent of the volatilization rate, and is also independent of the heat transfer from the surrounding to the fire base, $\dot{q}_{f,surr}$. A ventilation controlled fire is thus insensitive to the radiative feedback to the fuel surface.

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

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

where a is the total potential heat flux generated by the free burning fire and b is an exponential coefficient. The formulation of $\dot{q}_{f,surr}$ 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 defined as

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

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

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

The rate of energy loss from the hot layer is given by

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

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

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

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

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

$\dot{Q}_w$ is the heat loss from the hot gas/particulate layer to the wall which can be written as

$$\dot{Q}_w = \dot{Q}_{w,r} + Q_{w,c} \qquad (12)$$

with $Q_{w,c}$ being the convective heat loss given by

$$\begin{aligned}\dot{Q}_{w,c} = {} & A_{wt}h_t\left[T - T_{wt}\right] + A_{wl}h_t\left[T - T_{wl}\right] + A_{wr}h_t\left[T - T_{wr}\right] \\ & + A_{wi}h_t\left[T - T_{wi}\right] + A_{wo-v}h_t\left[T - T_{wo-v}\right]\end{aligned} \qquad (13)$$

The expression for the radiative heat transfer to the wall, $\dot{Q}_{w,r}$, depends on the radiation model and will be discussed in the next section. The convective heat transfer coefficient to the different walls is assumed to be the same, even though the temperature of the different walls can be different (because of the different radiative exchange between the fuel surface, the hot gas/particulate layer and the different walls). Note that in Eq. (11), the net mass flow into the compartment is assumed to be zero and the mass of the hot gas/particulate layer is given by

$$m = \rho_0 L_R W_R \left(H_R - Z_d \right) \tag{14}$$

In Eq. (14), 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 layer temperature rises and the particulate concentration increases, it is retained in the present work for simplicity. From the perspective of developing a zone model for the study of thermal instability, 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 [16]

$$\frac{dR}{dt} = V_f \left[1 - e^{\frac{R - R_{\max}}{R_{edge}}} \right] \tag{15}$$

where R_{edge} is the distance over which the effect of the edge of the fuel is felt and R_{max} is the maximum radius, representing the size of the fuel sample. V_f is the flame spread rate which can be taken as [24]

$$V_f = \frac{K_f \dot{m}_a}{\rho_0 W_v N H_v} \tag{16}$$

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 is used for simplicity.

2.2 The 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 empirically to be one of the important observed phenomena in the occurrence of flashover. The effect of gaseous radiation on flashover is thus expected to be 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]

$$a_\lambda = \frac{36\pi f_v}{\lambda} \frac{n\kappa}{\left(n^2 - \kappa^2 + 2\right)^2 + 4n^2\kappa^2} \tag{17}$$

where n and κ are optical constants for soot which are known function of λ. The emittance of a soot cloud of thickness L is

$$\varepsilon\left(T, L\right) = \frac{1}{\sigma T^4} \int_0^\infty e_{\lambda b}\left(T\right)\left(1 - e^{-a_\lambda L}\right) d\lambda \tag{18}$$

Eq. (18), together with Eq. (17), have been evaluated for soot generated by some common fuel (acetylene and propane) and numerically, it was shown [24] that the emittance can be approximated by an equivalent gray model as

$$\varepsilon\left(T, L\right) = 1 - e^{-\kappa L} \tag{19}$$

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

$$\kappa = \frac{3.6 k f_v T}{C_2} \tag{20}$$

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.

In the present work, a gray soot model with an absorption coefficient given by Eq. (20) 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.

Since the size of the fire grows with a growth rate given by Eq.. (15), the volume fraction of the hot gas/particulate layer is assumed to be proportional to the fire radius R. Specifically, the current model assumes

$$f_v = \frac{R}{R_{\max}} f_{v,0} \tag{21}$$

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

$$L_f = \sqrt{\pi} R \tag{22}$$

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 [21]. The definition of exchange factor and its mathematical properties are described in the same reference. For a cubic enclosure with $W_R = L_R = H_R = 0.4$ m, $Z_d = 0$ (i.e. the hot layer fills the whole compartment) and a fire base with $L_f = 0.3$ 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 ($g s_t$) are shown in Figs. 2a, 2b and 2c respectively. 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, the wall temperatures and the particulate volume fraction.

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

$$A_f\dot{q}_{f,surr} = \sigma T^4 gs_f\left(\kappa\right) + \begin{bmatrix} \sigma T_{wt}^4 s_t s_f\left(\kappa_{wt}\right) + \sigma T_{wl}^4 s_l s_f\left(\kappa_{wl}\right) \\ +\sigma T_{wr}^4 s_r s_f\left(\kappa_{wr}\right) + \sigma T_{wi}^4 s_i s_f\left(\kappa_{wi}\right) \\ +\sigma T_{wo}^4 s_{o-v} s_f\left(\kappa_{wo}\right) \end{bmatrix} + \sigma T_a^4 s_v s_f\left(\kappa_a\right) \quad (23)$$

$gs_f\left(\kappa\right)$ is the exchange factor between the hot layer and the fire base. $s_x s_f\left(x = t,l,r,i,o-v,v\right)$ 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 (f) respectively. The subscript o-v stands for the outer wall section minus the vent opening. The subscript $wx\left(x = t,l,r,i,o-v,v\right)$ in the absorption coefficient κ indicates the wall temperature, T_{wx}, at which the absorption coefficient is evaluated. In a similar manner, the expression for $\dot{Q}_{w,r}$ is given by

$$\dot{Q}_{w,r} = \sigma T^4 \begin{bmatrix} gs_t\left(\kappa\right) + gs_b\left(\kappa\right) \\ +gs_l\left(\kappa\right) + gs_r\left(\kappa\right) \\ +gs_i\left(\kappa\right) + gs_o\left(\kappa\right) \end{bmatrix} - \begin{bmatrix} \sigma T_{wt}^4 gs_t\left(\kappa_{wt}\right) + \sigma T_{wb}^4 gs_{b-f}\left(\kappa_{wb}\right) \\ +\sigma T_{wl}^4 gs_l\left(\kappa_{wl}\right) + \sigma T_{wr}^4 gs_r\left(\kappa_{wr}\right) \\ +\sigma T_{wi}^4 gs_i\left(\kappa_{wi}\right) + \sigma T_{wo-v}^4 gs_{o-v}\left(\kappa_{wo}\right) \end{bmatrix} - \sigma T_a^4 gs_v\left(\kappa_a\right) \quad (24)$$

where the subscript b stands for the bottom floor.

2.3 Transient Thermal Analysis of the Compartment Walls

In the previous work [22], the wall temperature is set parametrically to be between the ambient temperature and the hot layer temperature and the model is used to assess the consistency of the two criteria of flashover. While that approach was effective for the previous objective, a more realistic model of wall temperature is needed for the present consideration of thermal instability since the radiative feedback from the wall is an important effect leading to flashover. Specifically, the present work uses a lump capacitance model is determine the transient temperature rise of the compartment walls. The energy equation for the compartment wall is given by

$$\rho_w c_w \frac{V_w}{A_w} \frac{dT_{wx}}{dt} = h_t \left(T - T_{wx} \right) + \dot{q}_{wx} - h_o \left(T_{wx} - T_a \right) \tag{25}$$

where h_o is the external heat transfer coefficient which is assumed to be identical for the different walls and $\dot{q}_{wx}$ is the radiative heat flux to the particular compartment wall. For the top wall, for example, it is given by

$$L_R W_R \dot{q}_{wt} = \sigma T^4 g s_t \left(\kappa \right) + \sigma T_a^4 s_v s_t \left(\kappa_a \right) + \begin{bmatrix} \sigma T_{wb}^4 s_{b-f} s_t \left(\kappa_{wb} \right) + \sigma T_{wl}^4 s_l s_t \left(\kappa_{wl} \right) \\ + \sigma T_{wr}^4 s_r s_t \left(\kappa_{wr} \right) + \sigma T_{wi}^4 s_i s_t \left(\kappa_{wi} \right) \\ + \sigma T_{wo}^4 s_{o-v} s_b \left(\kappa_{wo} \right) + \sigma T_f^4 s_f s_t \left(\kappa_{wf} \right) \end{bmatrix} \tag{26}$$

Similar expressions can be written for the radiative heat flux to the other walls. The wall is assumed black in the development of Eq. (26). This assumption is expected to be reasonable for a surface exposed to the severe conditions of a combustion environment.

3. Results and Discussion

Parametric studies are generated to demonstrate the behavior of the hot layer's temperature in the compartment and its stability behavior due to the variation of three parameters, the external heat transfer coefficient h_o, the particulate volume fraction $f_{v,0}$ and the compartment vent opening W_v. These parameters are selected because there are parameters which can be adjusted by compartment design and/or fire suppression measures to prevent flashover. For example, the particulate volume fraction can be controlled by the choice of materials allowed in a building and the vent opening can be controlled by the prescription of appropriate building design regulations. The effect of external heat transfer coefficient can give valuable insights to both fire fighting strategy and building design. Values for other parameters are kept constant and similar to those utilized in previous works [16, 22]. They are listed in Table 1.

3.1 The effect of the external heat transfer coefficient

Numerical data are generated for cases with $f_{v,0} = 10^{-7}$ and W_v = 0.2 m. The small particulate volume fraction is chosen to limit the effect of radiative absorption and, therefore, highlight the effect of the radiation feedback from the wall. The transient behavior of the layer temperature and the top wall temperature at different values of external heat transfer coefficient are shown in Figure 3a. These results show a classical instability behavior as the steady state temperature shows a rapid increase over a small change in the external heat transfer coefficient in a neighborhood of a critical heat transfer coefficient (about 50 W/m^2) and a corresponding critical hot layer temperature (about 900 K). The temperature escalation is suppressed when the combustion becomes ventilation controlled (due to the finite vent opening of W_v = 0.2 m). The behavior of the rate of temperature increase (dT/dt) as a function of the hot layer temperature for three different external heat transfer coefficient (h_o = 10, 50, 100 W/m^2) is shown in Figure 3b. The behavior of the steady state hot layer temperature at different external heat transfer coefficient is shown in Figure 3c.

Physically, the reduction in the external heat transfer coefficient leads to an increase of the temperature of the wall and an increase of the radiant feedback to the fuel surface. The behavior of the hot layer temperature relative to the change in the external heat transfer coefficient is inherently unstable as illustrated by plots of the energy rate as shown in Figures 3d, 3e and 3f. For the case with sufficient heat loss from the wall (Figures 3d and 3e), there is an equilibrium hot layer temperature generated by a balance between $G-H_o$ and $Q_{w,r}+Q_{w,c}$. As the external heat transfer coefficient decreases, there is a critical value below which the heat addition ($G-H_o$) is always greater than the heat loss ($Q_{w,r}+Q_{w,c}$), as shown in Figure 3f. The layer temperature increases at an increasing rate until the combustion becomes ventilation controlled and the burning rate is bounded by the inlet air flow. The heat release G becomes bounded while the ventilation heat loss H_o continues to increase. This leads to a reduction of the curve $G-H_o$ and the system comes to an equilibrium temperature as shown in Figure 3f.

3.2 The effect of the particulate volume fraction

Numerical data are generated for cases with h_o = 1000 W/m^2 and W_v = 0.2 m. The high external heat transfer coefficient is chosen to ensure a "cold" wall and thus minimize the effect of the radiation feedback from the wall. The effect of radiative emission and absorption from the hot layer is demonstrated by the variation of the particulate volume fraction. The transient behavior of the layer temperature and the top wall temperature at different values of the particulate volume fraction, $f_{v,0}$, are shown in Figure 4a. Similar to Figure 3a, the numerical data shows an instability behavior. The steady state hot layer temperature shows a rapid increase over a small change in particulate's volume fraction in a neighborhood of a critical volume fraction (about 10^{-6}) and a corresponding critical gas layer temperature (about 800 K). The behavior of the rate of temperature increase (dT/dt) as a function of the hot layer temperature for four different particulate volume fraction ($f_{v,0} = 10^{-7}, 10^{-6}, 3\times10^{-6}, 10^{-5}$) is shown in Figure 4b. The behavior of the steady state hot layer temperatures at different particulate volume fraction is shown in Figure 4c.

The instability behavior is further illustrated by the energy rate plots as shown in Figures 4d, 4e and 4f. As the particulate volume fraction increases, the radiative feedback due to emission from the hot layer increases. The "equilibrium" temperature increases and the temperature escalates to a high value near the critical volume fraction of about 10^{-6}. The transition from a fuel controlled combustion to a ventilation controlled combustion again provides a limit to the combustion and a limit on the hot layer temperature.

3.3 The effect of the vent opening

One of the important questions in the development of fire fighting strategies is the effect of the vent opening on a fire. Does the breaking of windows and doors (which increase the vent opening) increase or decrease the possibility of a flashover?

To illustrate the effect of vent opening in the presence of wall radiation, steady state temperature for the hot layer and the wall generated for cases with $f_{v,0} = 10^{-7}$ at different vent opening are shown in Figure 5a. When the external heat transfer coefficient is large (h_o = 1000 W/m^2) and the wall is "cold", convection is the dominant heat transfer mechanism. An increase in the vent opening leads to an increase in the venting heat loss ($\dot{H}_o$) and a reduction of the layer temperature. When the external heat transfer coefficient is small (h_o = 10 W/m^2), the radiant feedback from the hot wall to the fuel surface is the controlling heat transfer mechanism. An increase in the vent opening delays the transition from a fuel controlled combustion to a ventilation controlled combustion and this leads to an increase in the steady state layer temperature. For the considered geometry, the wall radiation effect appears to be sufficiently strong that it overwhelms the effect of the increase in the venting heat loss. The layer temperature increases monotonically with increasing vent opening in the "hot" wall case. It is important to emphasize that results in Figure 5a illustrate that the inclusion of the radiation effect can lead to a completely different interpretation on the effect of vent opening on flashover. While increasing the vent opening will reduce the possibility of flashover in a convection-controlled fire, it increases the possibility of flashover in a radiation-controlled fire.

To illustrate the effect of vent opening (vent width in this paper) in the presence of radiative absorption and emission of the hot layer, numerical results are generated with a large external heat transfer coefficient (h_o = 1000 W/m^2) and shown in Figure 5b. When the effect of radiation becomes significant ($f_{v,0} > 10^{-7}$), the layer temperature first increases and then decreases as the vent width increases. Physically, an increase of the vent opening from an initially small value leads to a delay in the transition from a fuel controlled combustion to a ventilation controlled combustion. The radiant feedback from the emission of the hot layer increases the combustion rate and the hot layer temperature. But unlike cases with wall radiation, the radiation feedback from the hot layer is limited by the radiative heat loss from the layer to the surrounding wall. At a sufficiently large vent opening, the increase in the venting heat loss ($\dot{H}_o$) becomes significant and this leads to a reduction of the layer temperature. While the effect of the radiation feedback from the hot layer is not as strong as that from the wall, results in Figure 5b show again that the inclusion of radiation effect can change the perception of the effect of vent opening on flashover. Depending on the particulate volume fraction and the vent width, an increase in the vent width can either increase or decrease the possibility of flashover.

Results in Figures 5a and 5b show readily that radiation plays an important role in the assessment of the effect of vent opening on the hot layer temperature and the subsequent flashover. The effectiveness of many existing models [13-19] which do not have an accurate radiation model is thus highly uncertain.

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 generate misleading conclusion about the effect of various design parameters on flashover.

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 external heat transfer coefficient on the transient temperature rise and flashover. Both the external heat transfer coefficient and the particulate volume fraction are shown to be parameters which can lead to thermal instability and, subsequently, flashover. The size of the vent opening also has a significant effect on the hot layer temperature and wall temperature during a fire. An accurate radiation model is key to the accurate assessment of these effects.

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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Table 1: Specified parameters in numerical examples.

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Compartment Parameters	Fluid Parameters
H_R = 0.4 m W_R = 0.4 m L_R = 0.4 m $H_V = H_R$ = 0.4 m	C_D = 0.7 ρ_0 = 1.25 kg/m^3 T_a = 300 K c_p = 1003.2 J/kg-K
Fuel Parameters	**Heat Transfer Parameter**
R_{max} = 0.15 m R_{edge} = 0.01 m K_f = 1/2000 Sr = 8.25 H_{vap} = 1,008,000 J/kg H_c = 24,900,000 J/kg T_f = 1300 K	h_t = 7 W/m^2-K χ = 0.65 a = 102,000 W/m^2 b = 1.12 m^{-1} $\rho_w C_w \frac{V_w}{A_w}$ = 100 J/(m^2-K)

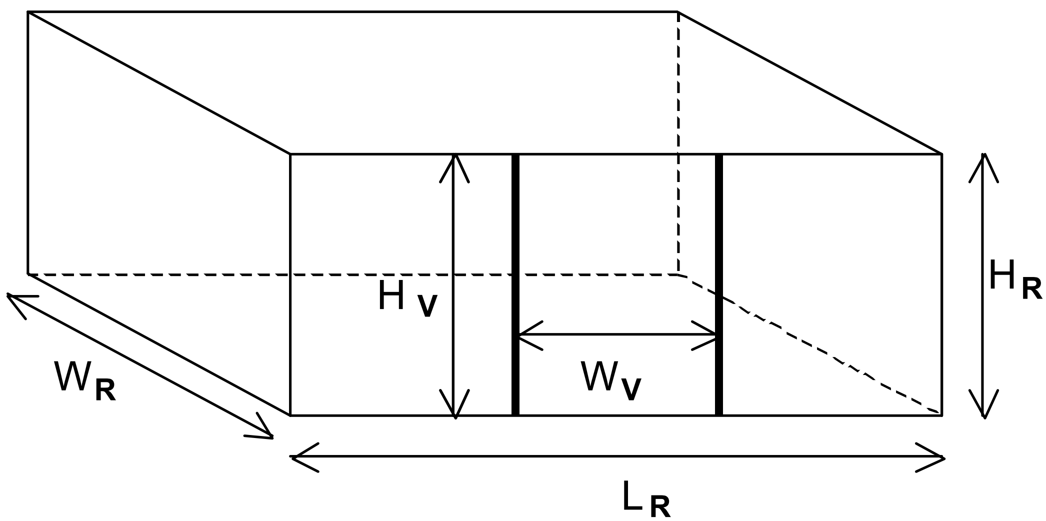

Figure 1: Geometry and dimensions of the cubical compartment.

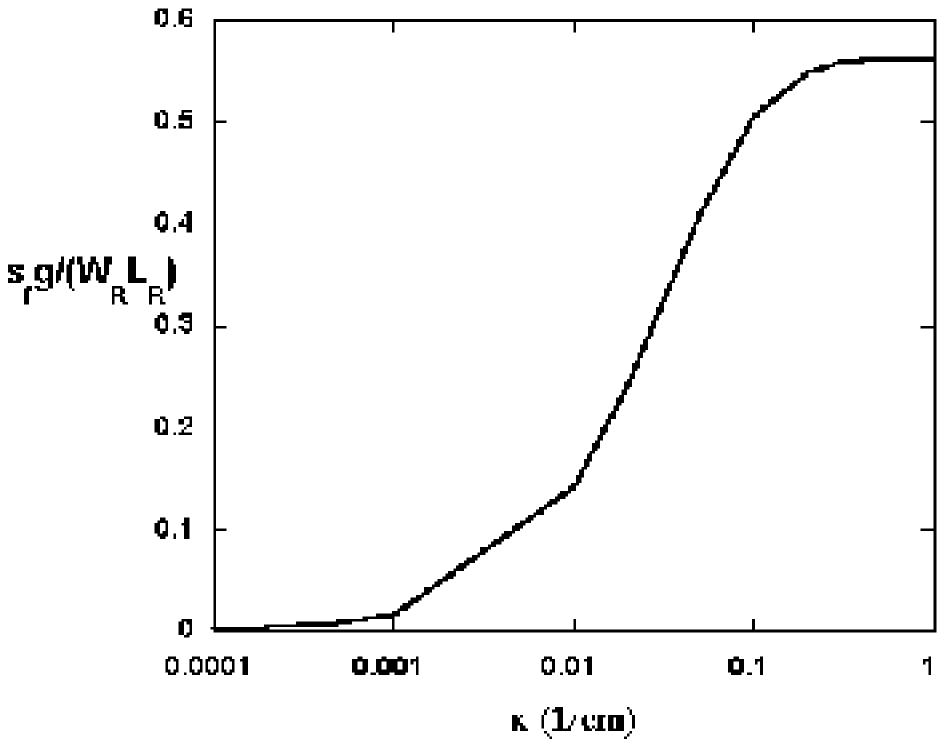

Figure 2a: Exchange factor between the fire base and the hot layer (with $W_R = L_R = H_R =$ 40 cm, L_f = 30 cm, and Z_d = 0).

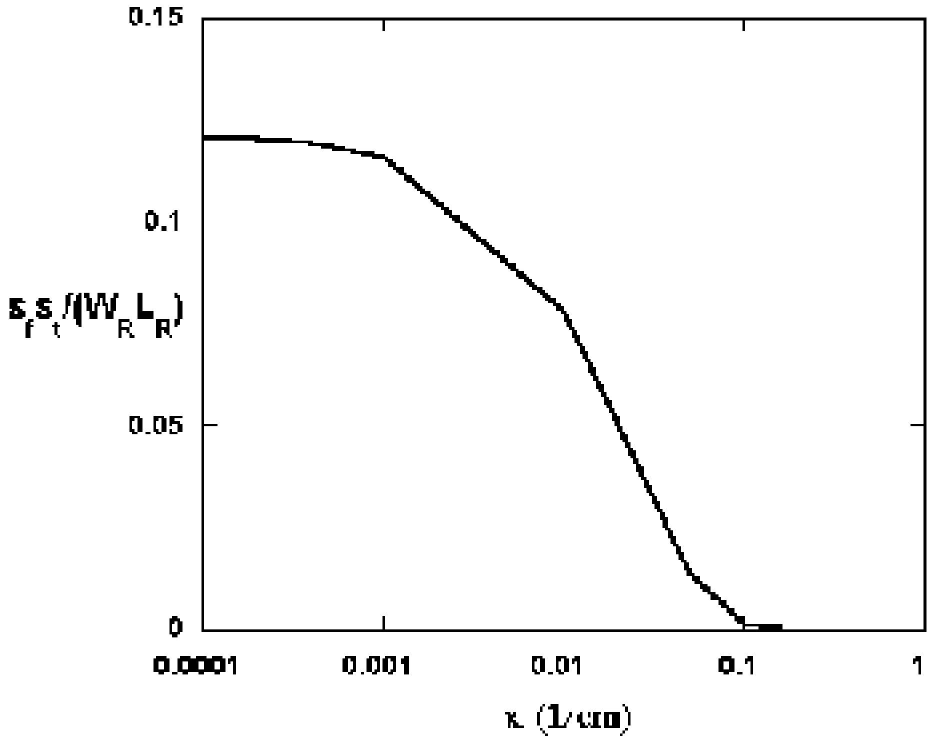

Figure 2b: Exchange factor between the fire base and the top wall (with $W_R = L_R = H_R =$ 40 cm, $L_f = 30$ cm, and $Z_d = 0$).

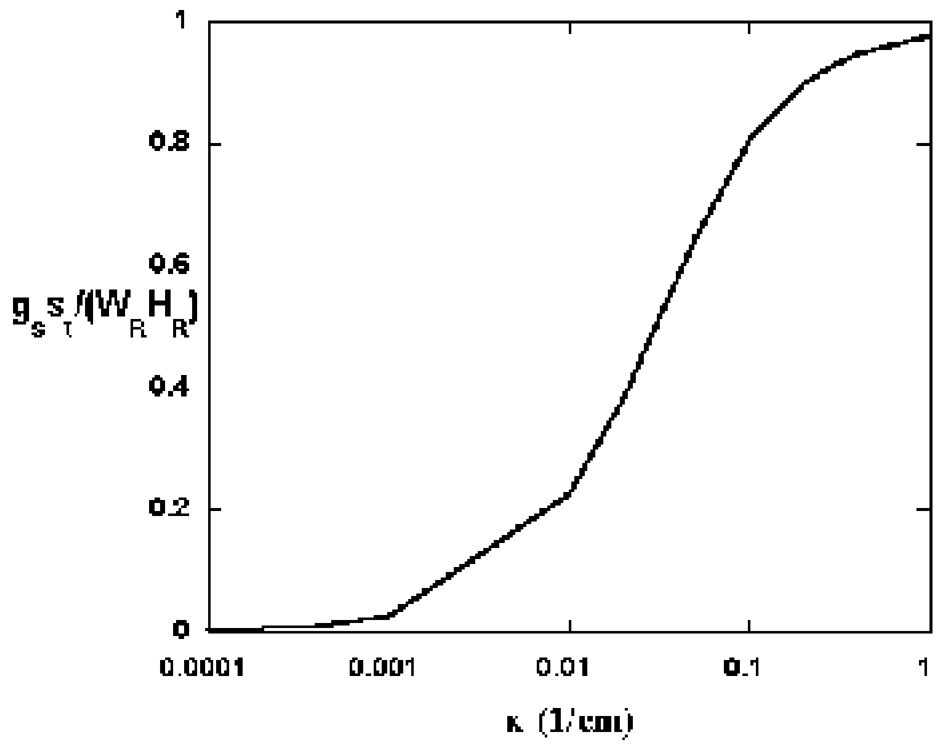

Figure 2c: Exchange factor between the hot gas layer and the top wall (with $W_R = L_R = H_R = 40$ cm, $L_f = 30$ cm, and $Z_d = 0$).

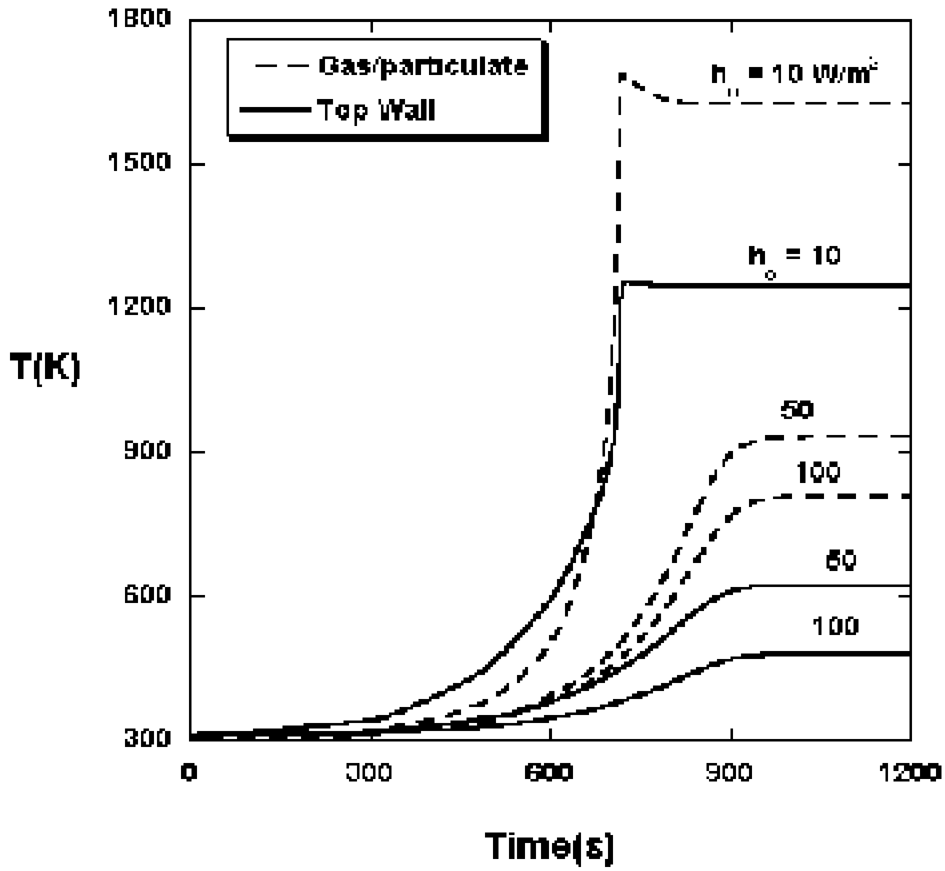

Figure 3a: Temperature of the hot layer and top wall for W_v = 0.2 m and $f_{v,0} = 10^{-7}$ with different external heat transfer coefficient.

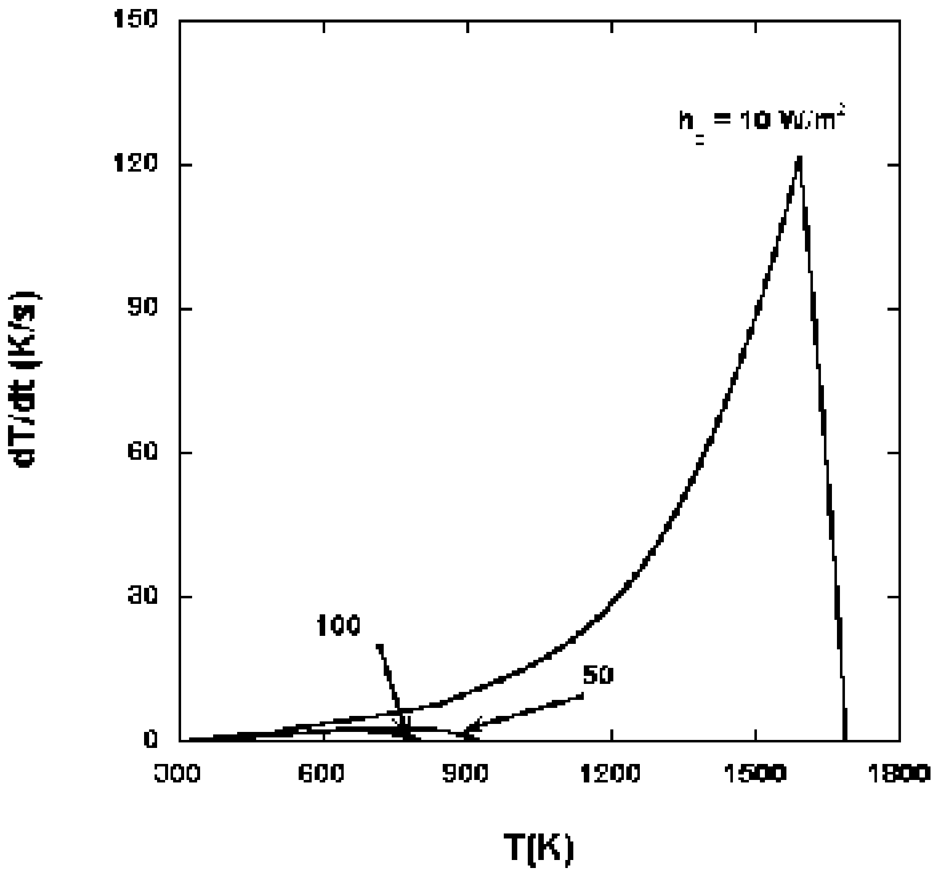

Figure 3b: Rate of the hot layer temperature increase for W_v = 0.2 m and $f_{v,0} = 10^{-7}$ with different external heat transfer coefficient.

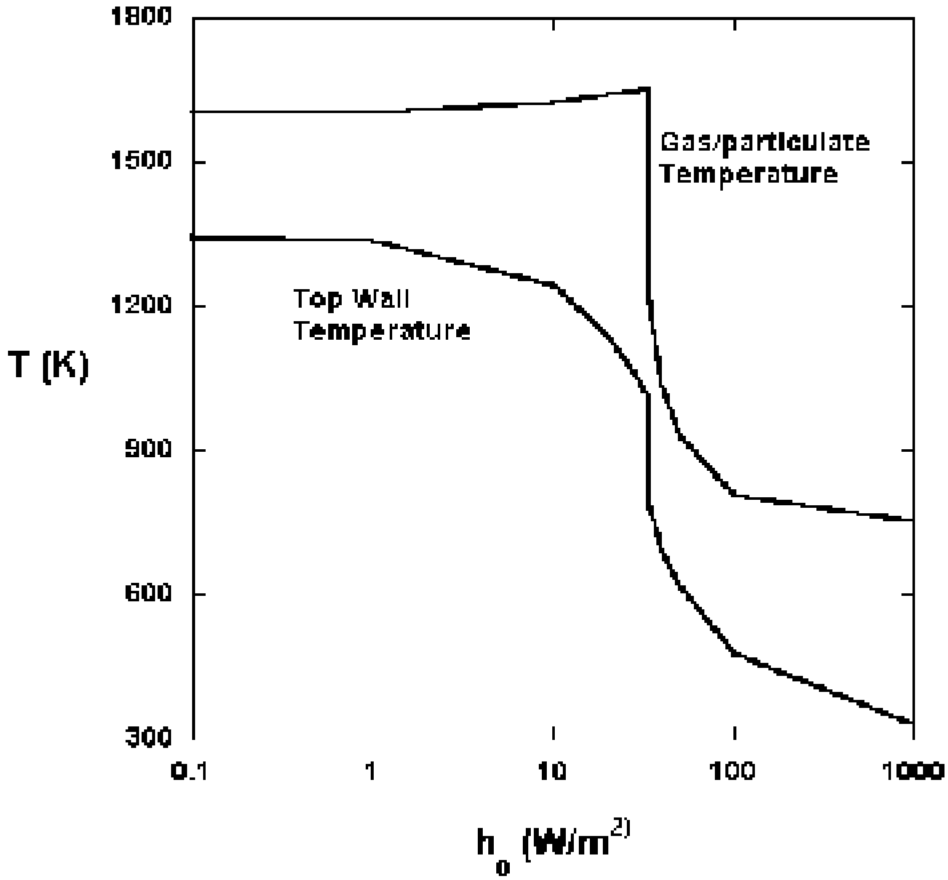

Figure 3c: Steady state temperature for W_v = 0.2 m and $f_{v,0} = 10^{-7}$ with different external heat transfer coefficient

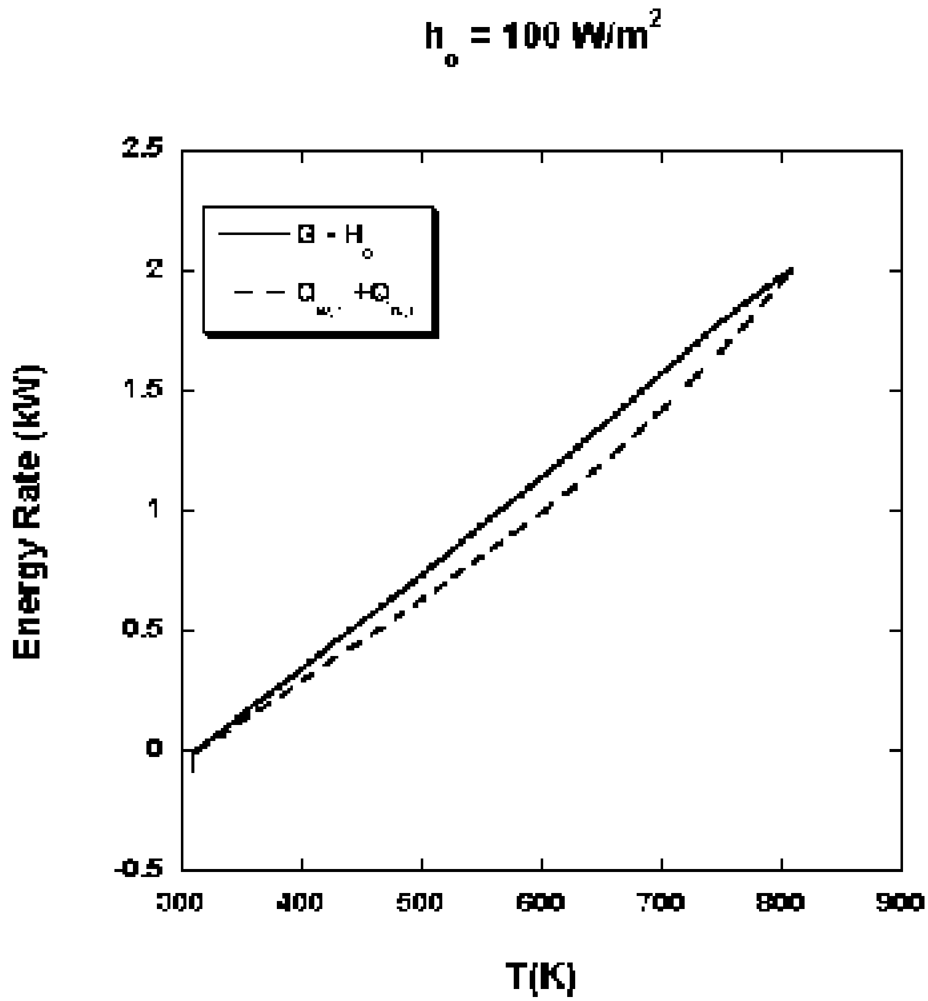

Figure 3d: Behavior of the dependence of energy rates on the hot layer temperature for W_v = 0.2 m, $f_{v,0} = 10^{-7}$ and h_o = 100 W/m^2.

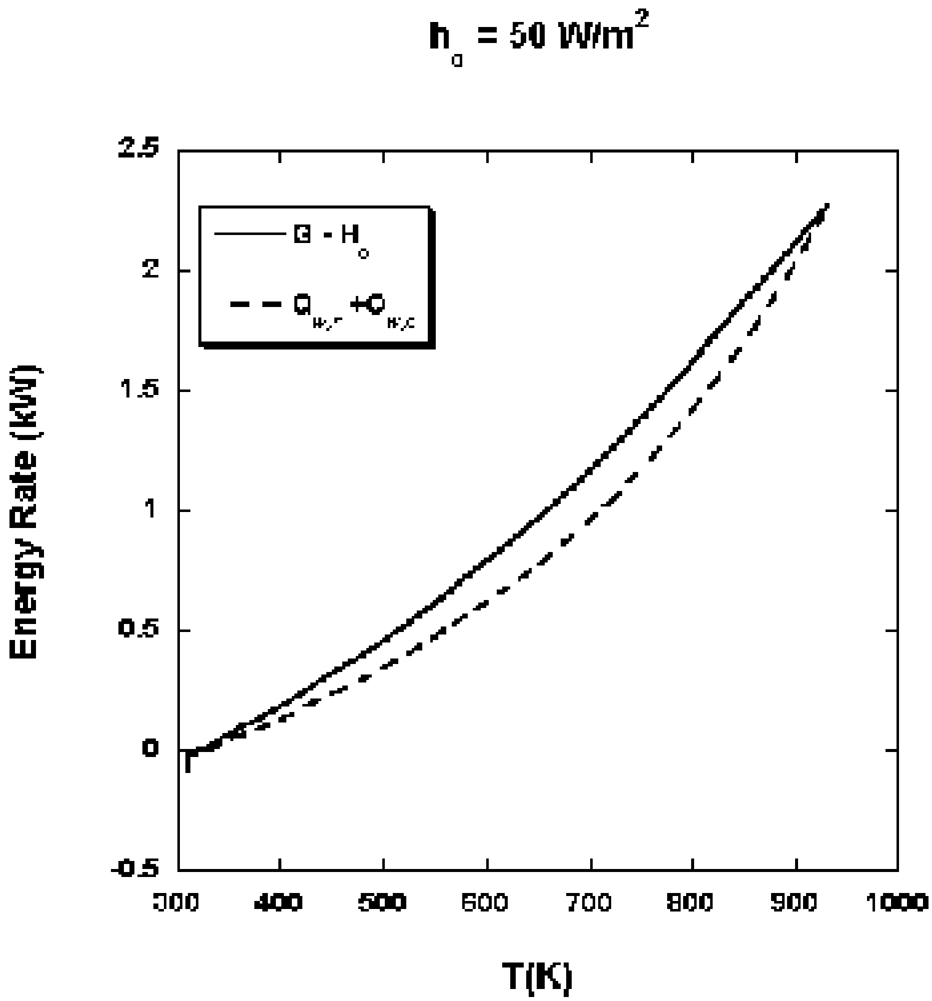

Figure 3e: Behavior of the dependence of energy rates on the hot layer temperature for $W_v = 0.2$ m, $f_{v,0} = 10^{-7}$ and $h_o = 50$ W/m^2.

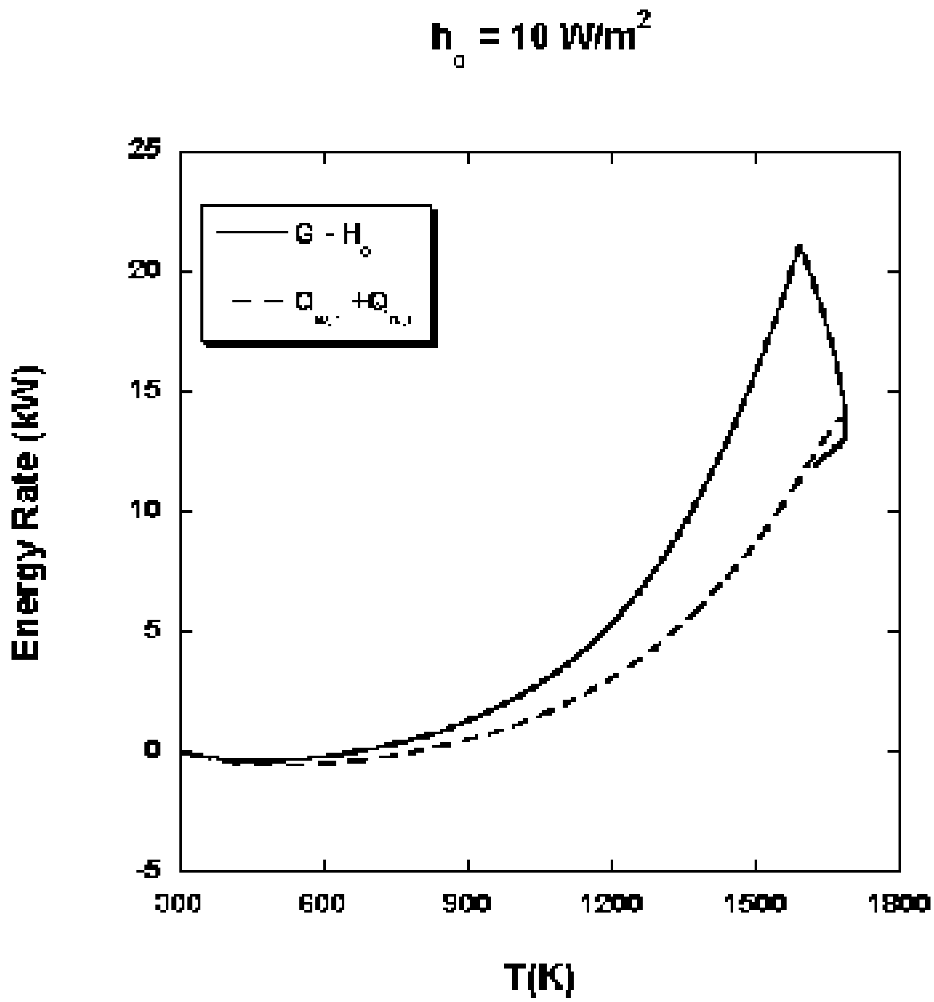

Figure 3f: Behavior of the dependence of energy rates on the hot layer temperature for

$W_v = 0.2$ m, $f_{v,0} = 10^{-7}$ and $h_o = 10$ W/m^2.

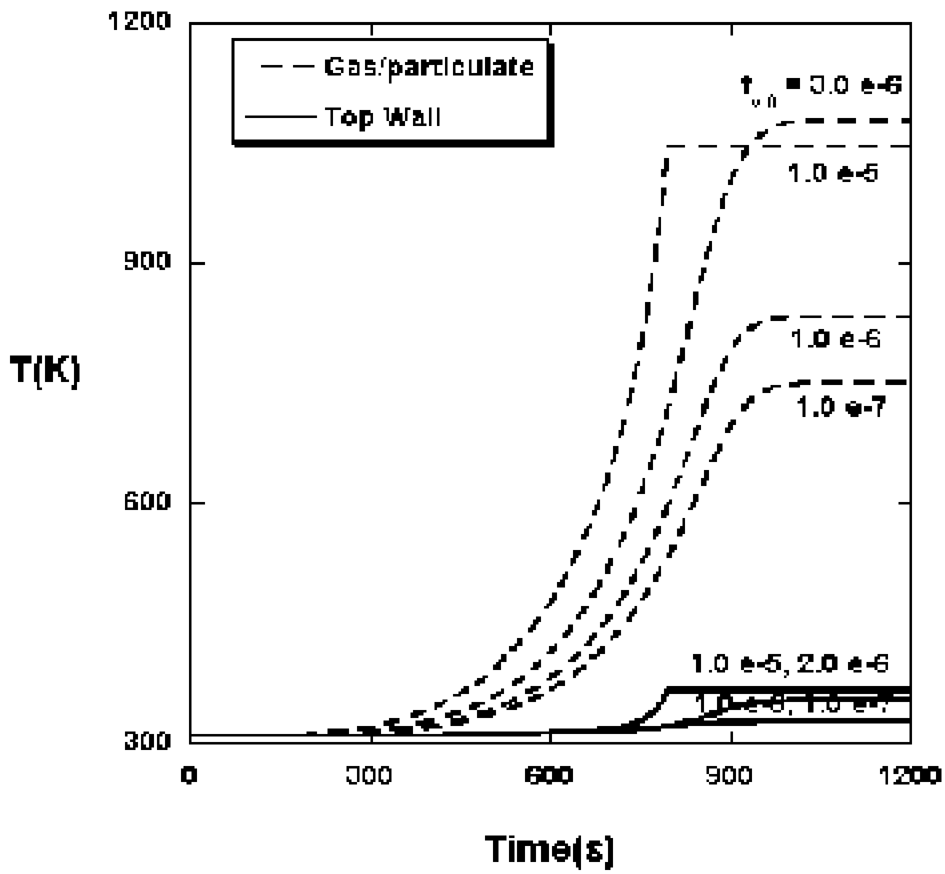

Figure 4a: Temperature of the hot layer and top wall for W_v = 0.2 m and h_o = 1000 W/m^2 with different particulate volume fraction.

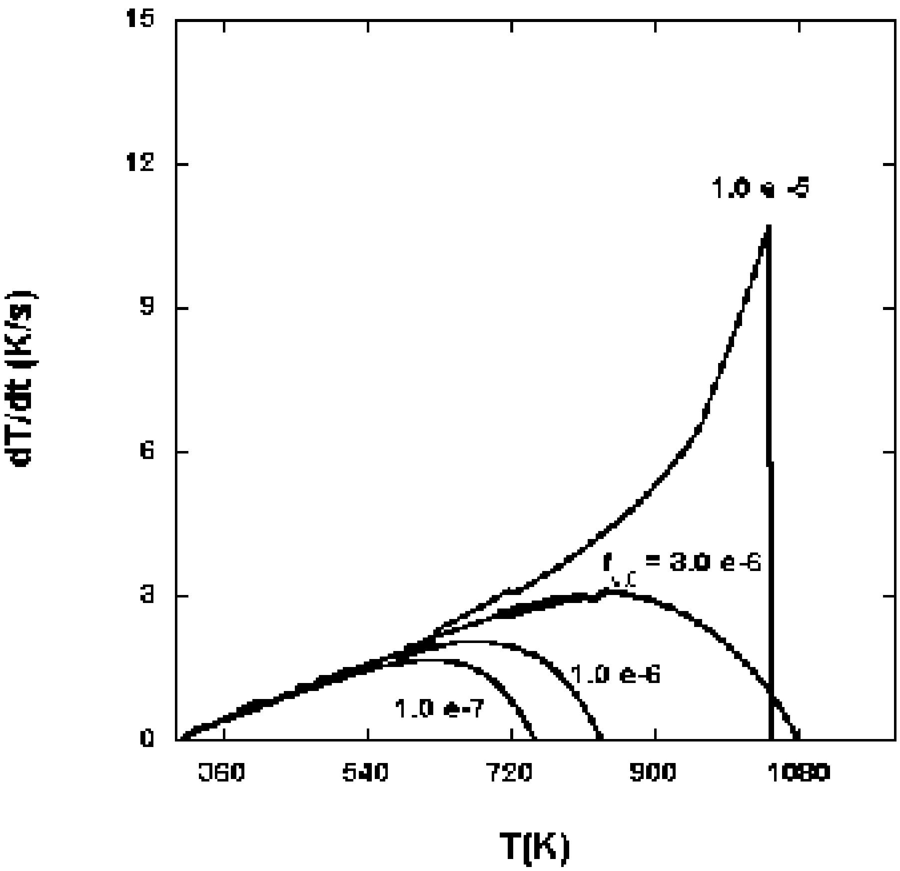

Figure 4b: Rate of the hot layer temperature increase for W_v = 0.2 m and h_o = 1000 W/m^2 with different particulate volume fraction.

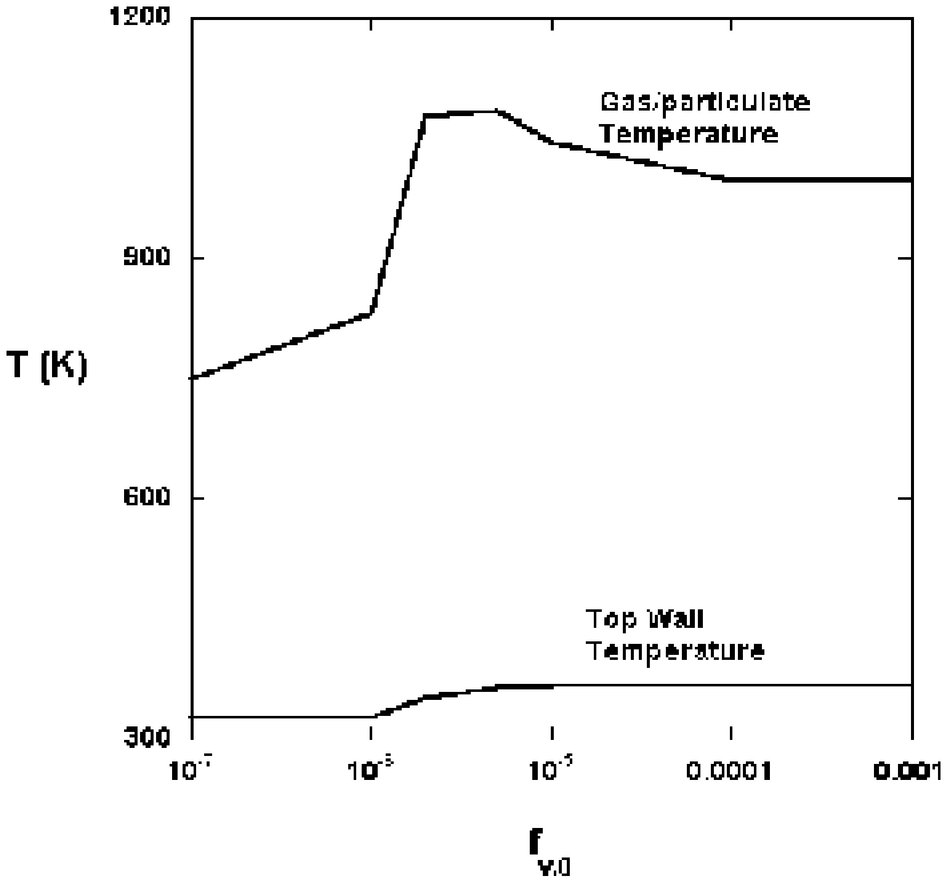

Figure 4c: Steady state temperature for W_v = 0.2 m and h_o = 1000 W/m^2 with different particulate volume fraction.

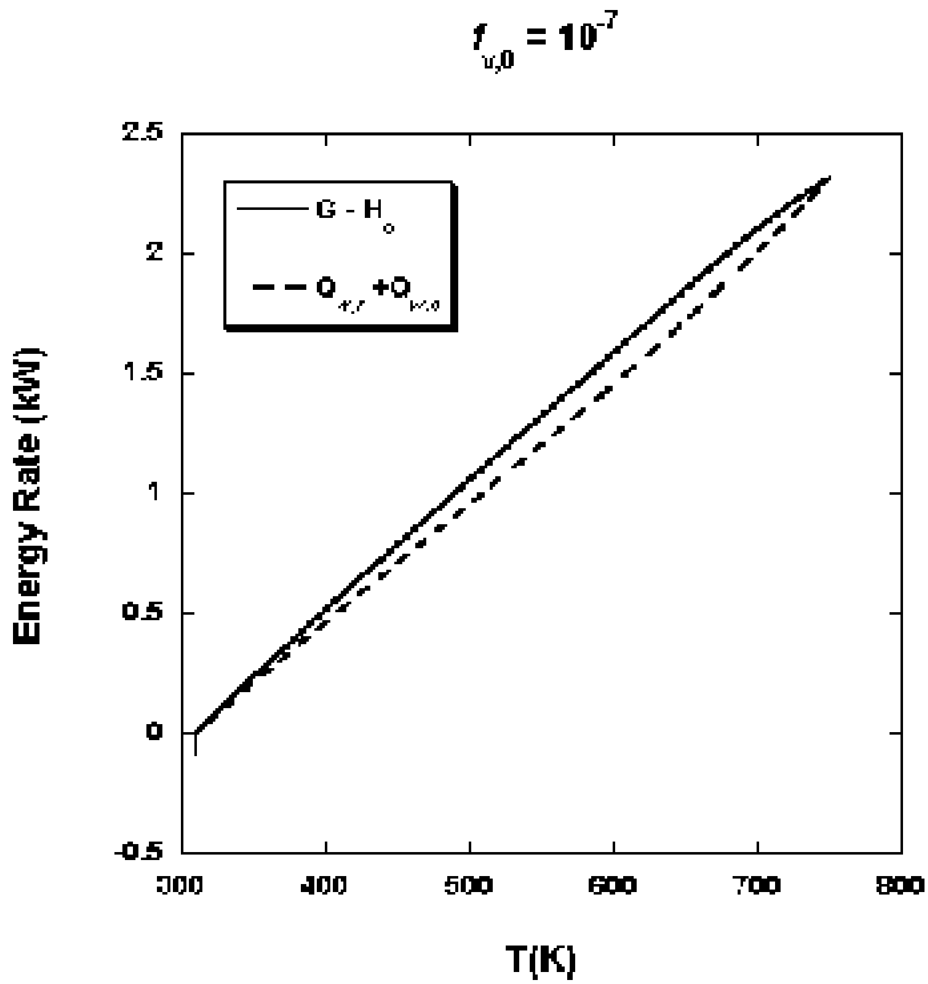

Figure 4d: Behavior of energy rates for $W_v = 0.2$ m, $h_o = 1000$ W/m^2 and $f_{v,0} = 10^{-7}$.

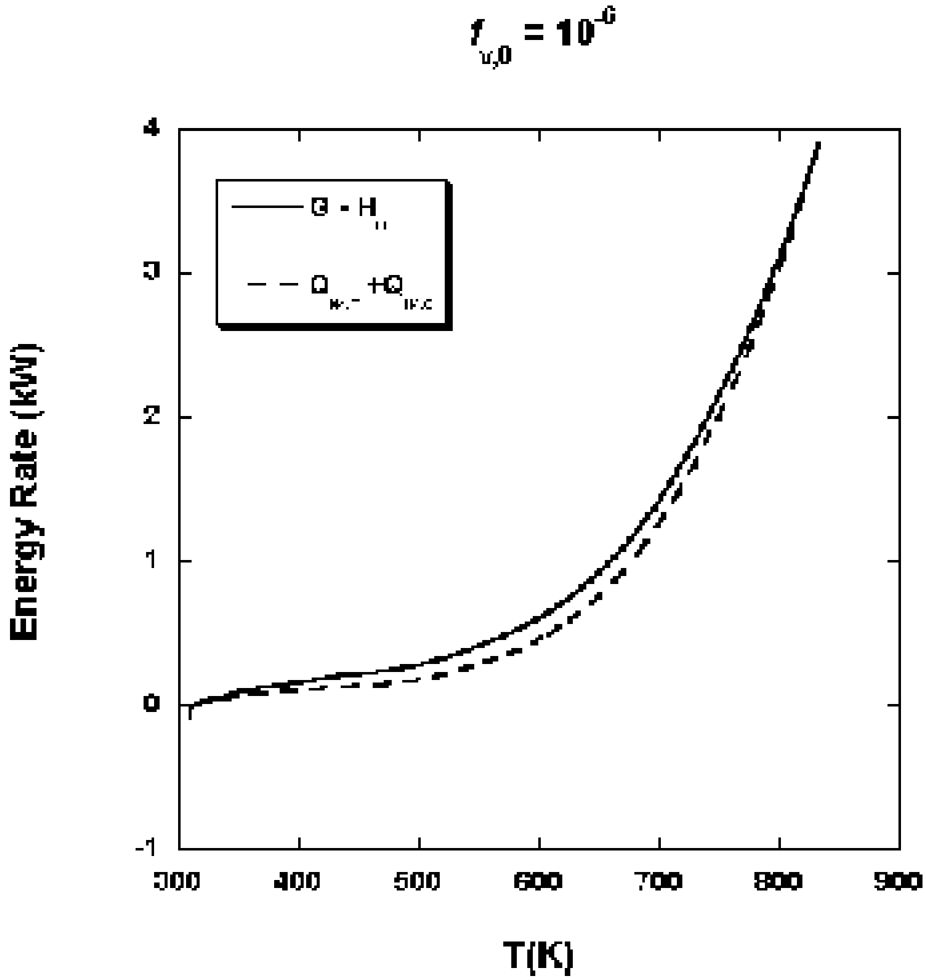

Figure 4e: Behavior of energy rates for $W_v = 0.2$ m, $h_o = 1000$ W/m^2 and $f_{v,0} = 10^{-6}$.

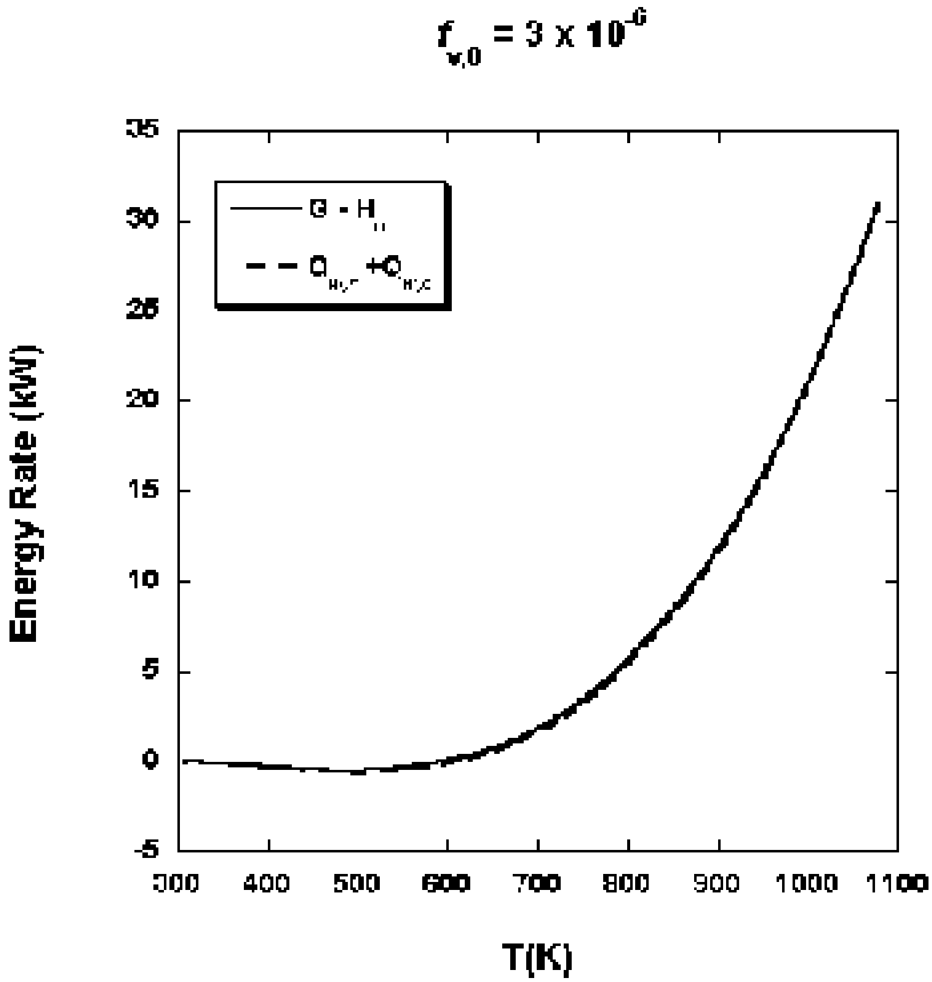

Figure 4f: Behavior of energy rates for $W_v = 0.2$ m, $h_o = 1000$ W/m^2 and $f_{v,0} = 3\times10^{-6}$.

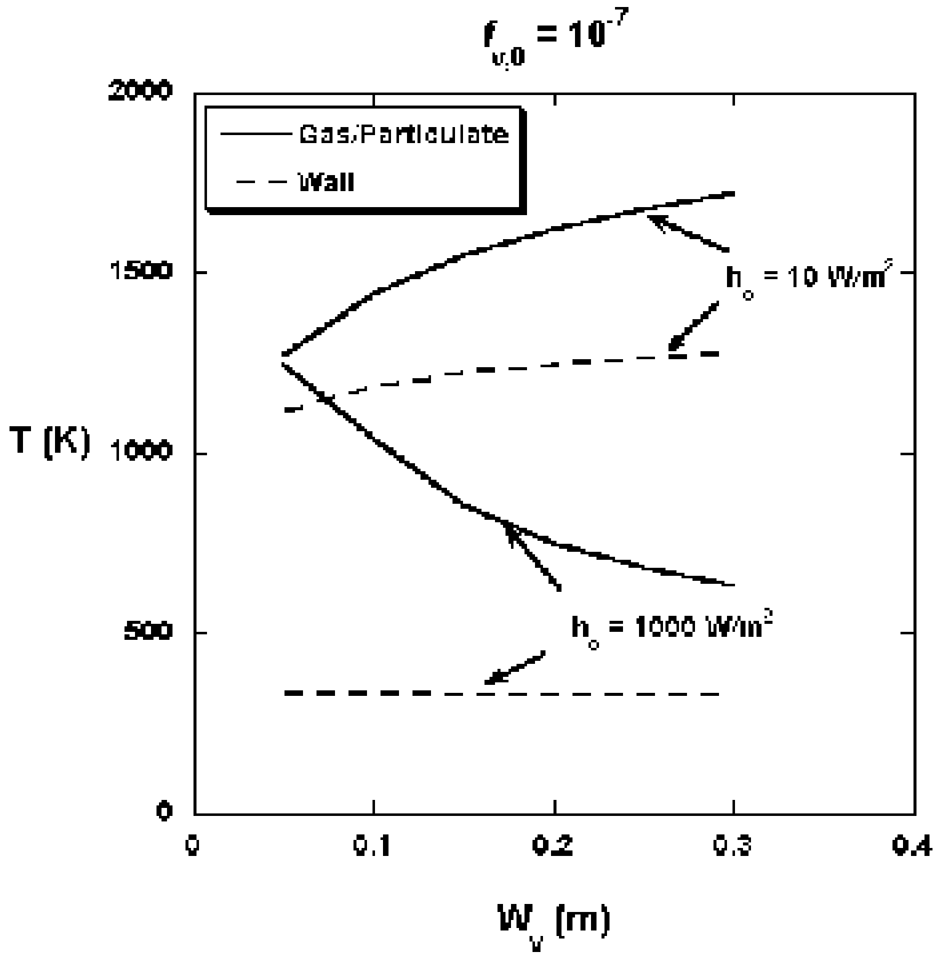

Figure 5a: Temperature of the hot layer and the wall at different external heat transfer coefficient and vent width.

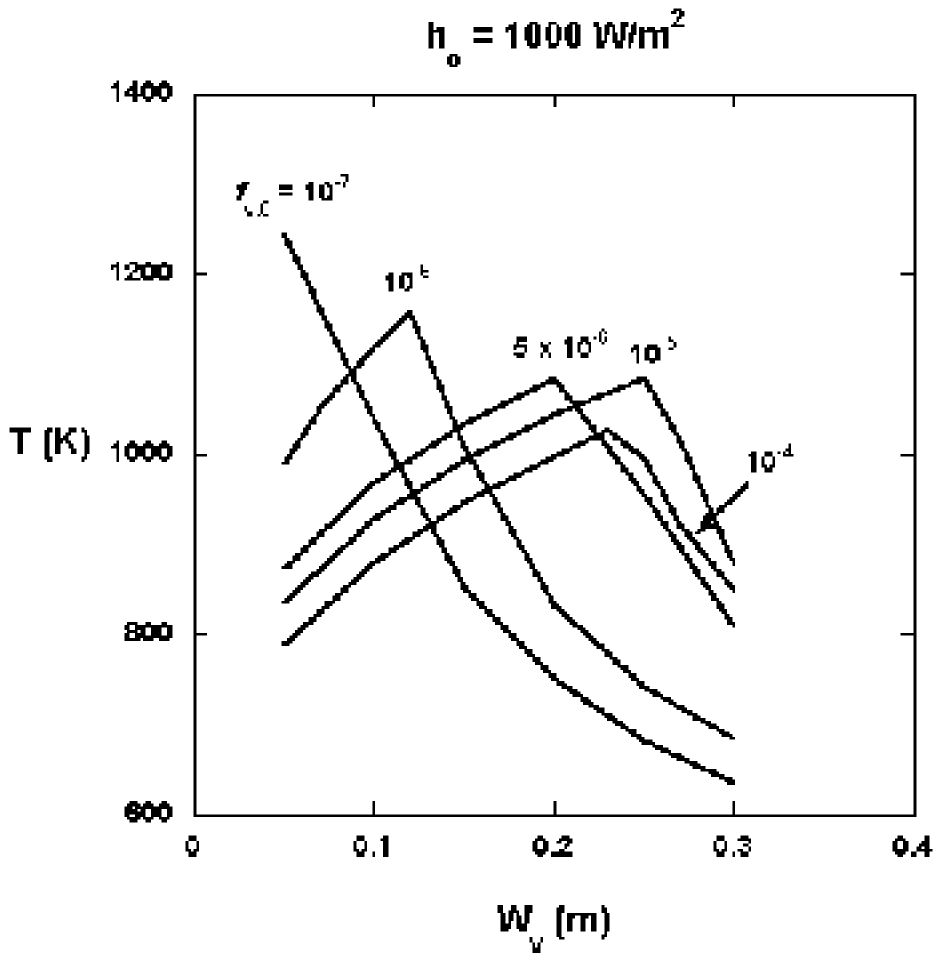

Figure 5b: Temperature of the hot layer at different particulate volume fraction and vent width (the wall temperature is at 300 K due to the high external heat transfer coefficient).