J. APPLIED FIRE SCIENCE, Vol. 17(4) 295-310, 2007-2008

RELIEF—A SIMPLE ZONE MODEL TO PREDICT FIRE BEHAVIOR IN ENCLOSURES WITH WALL LININGS

RAJIV KUMAR

SUNIL K. SHARMA

Central Building Research Institute
(Council of Scientific & Industrial Research), India

ABSTRACT

Lining materials are classified on the basis of their heat release rate in room corner tests [1]. They enhance the spread of fire and contribute toward higher temperature in the enclosure fires [2]. Depending upon the heat release rates by the wall and ceiling lining materials in an enclosure, temperatures can be predicted to design the fire protection system. Although zone models are available for such predictions, they are complex in nature. A simple, user-friendly mathematical zone model named RELIEF (Risk Estimation due to Linings In Enclosure Fires) has been developed to predict the temperature of upper gas layer in the enclosure, when lining materials along with source fuel burn and contribute in the fire spread and its growth.

INTRODUCTION

Fire propagation and growth in compartment depends on a number of factors, such as fire load, its location, ventilation size, etc. Normally the walls do not make a significant contribution during the fire in enclosures. However, if lining materials are used on the walls, specially the combustible ones, rapid fire spread is observed. Combustible lining materials along the walls and ceiling require relatively small ignition source for ignition but they contribute significantly

doi: 10.2190/AF.17.4.a
http://baywood.com

toward the growth of fire [2]. A small fire load along with the combustible lining materials behave as a high fire load would. A number of international studies ("Fire Hazard—Fire Growth in Compartments in the Early Stages of Development -Pre-flashover," jointly by Lund University, the Swedish National Testing and Research Institute, and the Swedish Institute for wood Technology Research [3], "EUREFIC —EUropean REaction to FIre Classification" [4], and studies by Dembsey and Williamson [5] and Magnusson and Sundstrom [6] etc.) have been conducted with the interior lining materials developed in those countries. Due to burning of lining material concurrent with the source of ignition, a decrease in the time to onset of flashover is observed. The onset of flashover leads to inclusion of majority of combustibles available in the fire.

A number of researchers [3, 7, 8] developed mathematical models for contribution of lining materials in growth of fire with source burner placed in corners in enclosures and validated the same with the help of the test results of Magnusson and Sundstrom [6]. Lattimer et al. [9] developed a fire spread model and used it in conjunction with CFAST model [10] for predicting heat release rate as well the temperatures in the enclosure with interior finish material and validated it with the corner test (ISO 9705) data [1]. Although CFAST [10], HARVARD [11], or FIRST [12] models represent a detailed and comprehensive zone model and have a great deal of utility in predicting the fire behavior in single as well as multi-room scenarios, yet these are complex model. To operate these, expertise in fire engineering is needed. Most of the developed models predict temperature and rate of flame spread over the lining surface but in conjunction with other models. Therefore, a simple yet effective user-friendly model to provide an engineering approximation of the time varying conditions created by fire in an enclosure with lining, that may be subjected to hot layer venting, needs to be developed. Kanury [13] suggested that one can obtain an approximate model satisfactorily by progressively complicating a simple model. The simpler is the model yielding reasonable results, the easier, elegant, and beautiful would be the explanation of the phenomenon. In the present article, an effort has been made to evolve a simple yet effective model to provide an engineering approximation of the time varying conditions created due to burning of lining materials and ignition source in an enclosure with wall and ceiling linings that may be subjected to hot layer venting. The model is named RELIEF (Risk Estimation due to Linings In Enclosure Fires). There are two approaches to develop a simple model, capable of providing engineering solutions to problems related to fires in compartments. First approach is to simplify an existing complex model such as CFAST [10], HARVARD [11], or FIRST [12]. An alternate approach is to upgrade an existing simple model to meet the requirements or develop the model by deriving the governing equations of mass, momentum, and energy to predict temperature and layer depth in a dynamic environment and casting these equations into computer code to obtain the solution. In case of development of RELIEF, the governing equations of mass and energy to predict temperature and layer depth in a dynamic environment in the enclosure with combustible lining materials have been derived, which are cast into computer code to obtain the solution. RELIEF has been validated with the experimental data of one of the EUREFIC study reported by Kokkala et al. [4] and will be reported in a subsequent communication.

DEVELOPMENT OF MATHEMATICAL MODEL

Combustion products released during a fire reach the ceiling and spread below it to form hot layer or upper layer. In an enclosure lined with lining material(s) on walls and ceiling, if a fire source is placed either near a wall or in a corner of the enclosure, flames from the ignition source and radiations from the hot layer cause heating of the wall lining. When the temperature of wall lining reaches ignition temperature, it gets ignited and starts releasing energy, flame, and gaseous products, thus contributing significantly to the spread and growth of fire. Gaseous combustion products that are released from the lining material move upward along with the combustion products released by fire source used for ignition. This adds mass and energy to the hot layer formed by the gases generated from the ignition source. On reaching the ceiling these hot combustion products form a near-ceiling horizontal outward flow, called ceiling jet. However, the gases are unable to move outward and start descending as more and more gases are released by the burning combustibles because of confinement due to the walls. A layer of hot gas is formed in the upper portion of the compartment whose temperature and thickness increases with time. The upper layer continues to descend till it reaches the soffit of the opening and then starts moving out. Flow rate of the hot gases through the opening depends upon the pressure difference between inside and outside the compartment. There is a clear interface between the hot upper layer and the cold lower layer. A neutral plane exists near the interface, where the pressure difference between hot layer and cold layer is zero. Cold air from the atmosphere flows into the compartment below the neutral plane while the hot gases from the upper layer move out, above the neutral plane. The locations of the neutral plane as well as the interface change with time until a steady state is reached. The upper region entrainment and the jet flow activities provide a stirring effect which mixes the gases in the upper region. Thus, the gas layer can be approximated as a zone with uniform properties. It is assumed that the distribution of temperature and other properties are uniform throughout each layer. Figure 1 is a schematic representation of fire phenomenon in a compartment with combustible linings on wall and ceiling. The room is modelled as two-zone or two-control volumes scenario, viz. upper layer and lower layer. This two layer approach is based upon the observation of stratification of gases in real fire experiments [14]. While there are some variations within the layers, these are often too small to be ignored. Zone models have shown their usefulness in producing reasonable simulations of average layer temperature and depth within a room. In the development of the present mathematical model, the following assumptions have been made.

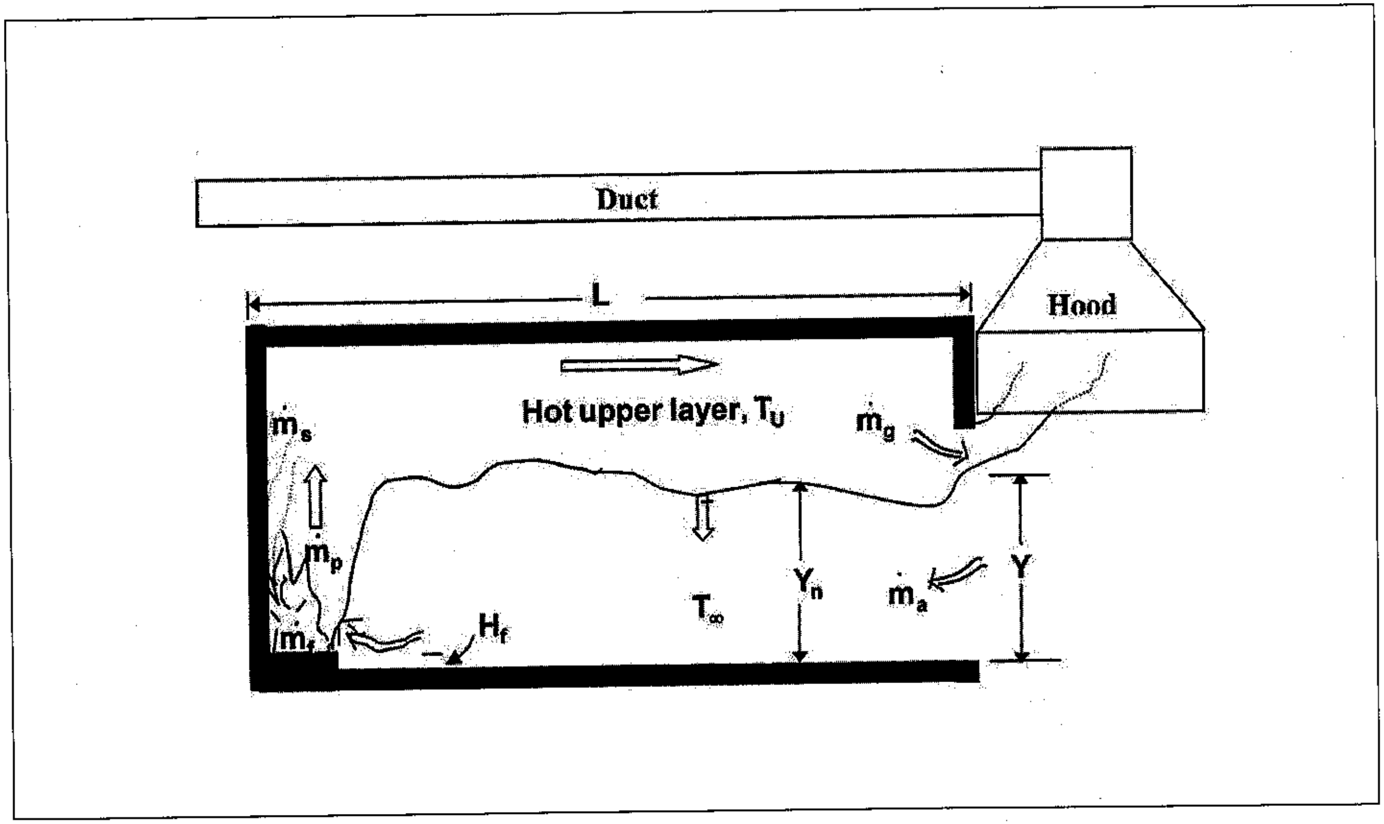

Figure 1. Schematic of room fire phenomenon with lining.

1. Applicability of Ideal Gas Law.
2. Equal and constant values of specific heat of air and gases.
3. Uniformity of temperature in the upper hot gas layer.
4. Equal values of discharge coefficient for incoming air and outgoing gases.
5. Fire source is treated as a strong plume generated by finite size source.

Let $\dot{Q}$ be the amount of energy added into the enclosure due to ignition source and λ_r be the fraction of $\dot{Q}$ lost by radiation from the flame zone and the plume of ignition source. The fraction $\dot{Q}_c = [(1-\lambda_r)\dot{Q}]$, which effectively drives the plume gases upwards, is added to upper hot gas layer. It is known as convective heat release rate. Cooper [15] has indicated that the flaming fires exhibit λ_r values between 0 and 0.6, smaller values are used for small methane fires and transparent flames while for sooty fires higher values are used. $\dot{Q}_s$ is the amount of energy added into the enclosure due to burning of lining materials of wall and ceiling after the lining material gets ignited. The total energy added to upper layer is $\dot{Q}_T$ $(=\dot{Q}_c + \dot{Q}_s)$.

The overall energy balance around the upper layer provides the following equation:

$$\frac{d}{dt}[(H-Y)A_F\rho_u C_p T_u] = \dot{Q}_c - \lambda_c \dot{Q}_c + \dot{Q}_s - \lambda_c \dot{Q}_s - \dot{m}_g C_p T_u + (\dot{m}_p + \dot{m}_s) C_p T_\infty \quad (1)$$

where λ_c is the instantaneous fraction of total heat release rate, which is lost through boundaries. Cooper [16] has provided guidelines for selecting the value of λ_c, which lies in the range of 0.6-0.9. The lower value corresponds to high aspect ratio spaces (ratio of ceiling span to room height) with smooth ceilings and fires positioned far away from the wall. The intermediate to high values correspond to low aspect ratio spaces, rooms with irregular surfaces or rooms in which the fire is within one ceiling height of the wall. The heat loss fraction for a room with insulated boundaries (wall and ceilings) or boundaries with linings with insulated materials will be lower than the fraction for the same room with un-insulated boundaries. If the properties such as thermal conductivity (k) etc. of boundaries and lining material are known, λ_c can be calculated as per the procedure described later on. A_F is the floor area (m^2), C_p is the specific heat ($kJ/kg-K$), and $\dot{m}_p$ is the plume mass entering into the hot upper layer. While moving upward, the plume entrains the relatively quiescent surrounding air which is at ambient temperature and mixes with it. As a result of the air entrainment, the total upward mass flux in the plume, m_p, increases continuously with height, while its temperature decreases. $\dot{m}_s$ is the rate of burning of lining material which is zero till the time (t_i) when the lining material gets ignited.

The time to ignition of lining t_i can be calculated with the help of the following equation by assuming lining material as thermally thick [3, 7]:

$$t_i = \frac{\pi k \rho C (T_s - T_\infty)^2}{4 \dot{q}_f''^2} \tag{2}$$

where k is the thermal conductivity (kW/m-K), ρ is the density (kg/m^3), and C is the thermal capacity (kJ/kg-K) of the lining material, T_s and T_i are the surface and ignition temperature of lining material. $\dot{q}_f''$ is the heat flux (kW/m^2) falling on the surface of lining material at any time, t and $\dot{q}_i''$ is minimum heat flux (kW/m^2), required to ignite the lining material. At ignition, $t = t_i$, $q_f'' = q_i''$ and $T_s = T_i$.

For $0 < t < t_i$, $\dot{m}_s = 0, \dot{Q}_s = 0$. According to Quintiere [7] and Thomas [17], the value of $\dot{q}_f''$ is 30 to 50 kW/m^2 for most of the lining materials. According to Thomas [17], 25 to 30 kW/m^2 seems appropriate for smaller fire size (less than 1 m). Cleary and Quintiere [18] has taken $\dot{q}_f''$ equal to 30 kW/m^2 in their analysis for all materials.

We know

$$\dot{Q}_T = \dot{Q}_c + \dot{Q}_s \tag{3}$$

$\dot{Q}_T$ is the total heat release rate measured at exhaust duct of the hood by oxygen consumption method. It also includes the heat released by ignition source. The value of heat released by surface linings, $\dot{Q}_s$, is determined by the equation (3).

So, equation (1) becomes

$$\frac{d}{dt}[(H-Y)A_F\rho_u C_p T_u] = \dot{Q}_T - \lambda_c \dot{Q}_T - \dot{m}_g C_p T_u + (\dot{m}_p + \dot{m}_s) C_p T_\infty \tag{4}$$

Equation (4) can be rearranged to have

$$\frac{dY}{dt} = -\frac{(1-\lambda_c)\dot{Q}_T}{A_F \rho_\infty T_\infty C_p} + \frac{\dot{m}_g P}{A_F \rho_\infty} - \frac{(\dot{m}_p + \dot{m}_s)}{A_F \rho_\infty}, \tag{5}$$

where $P = \dfrac{T_u}{T_\infty}$ (6)

The overall mass balance provides,

$$\frac{d}{dt}[(H-Y)A_F\rho_u] = \dot{m}_p + \dot{m}_s - \dot{m}_g \tag{7}$$

$$\text{or} -\rho_u \frac{dY}{dt} + (H-Y)\frac{d\rho_u}{dt} = \frac{(\dot{m}_p + \dot{m}_s - \dot{m}_g)}{A_F} \tag{8}$$

or, simply,

$$(H-Y)\frac{d\rho_u}{dt} = \frac{(\dot{m}_p + \dot{m}_s - \dot{m}_g)}{A_F} + \rho_u \frac{dY}{dt}. \tag{9}$$

The ideal gas law provides,

$$\rho_u = \rho_\infty \frac{T_\infty}{T_u} = \frac{\rho_\infty}{P}. \tag{10}$$

Differentiating ρ_u, we get,

$$\frac{d\rho_u}{dt} = -\rho_\infty P^{-2} \frac{dP}{dt}. \tag{11}$$

Combining (9) and (11), we have

$$\frac{dP}{dt} = -\left[\frac{(\dot{m}_p + \dot{m}_s - \dot{m}_g)P}{A_F \rho_\infty} + \frac{dY}{dt}\right]\frac{P}{(H-Y)}. \tag{12}$$

Equations (5) and (12) form the set of model equations, and can be solved with the help of any Runge-Kutta class of methods or Predictor-Corrector class of methods. Equations (5) and (12) can be used to obtain the values of Y and P respectively. One can note from equations (5) and (12) that the value of $\dot{m}_g$ is zero until the hot gas layer reaches the upper edge of the door/window. Once the hot gas layer reaches the door's upper edge, it starts moving out of the enclosure. Similarly, $\dot{m}_s$ and $\dot{Q}_s$ are zero till ignition of surface lining takes place.

$\dot{m}_p$ is the mass entering into the hot gas layer at the interface level. In Room/corner test, different quantities of propane are burned in the burner having significant dimensions to produce fires of varying strengths. Thus, the fuel enters into the flame with different rates of momentum. The plume thus formed moves under the action of buoyancy as well as inertia. Therefore, for the fire sources having significant dimensions which generate the strong plume, plume model given by Heskestad [19] has been used for the plume mass calculation.

Heskestad [19] correlated experimental data to produce two relations to determine the values of plume mass flow rates at any height, Z, above the fire source. One pertains to the non-reacting plume region extending above a limiting elevation, Z_1. The other pertains to the reacting region at elevation lower than Z_1. The limiting elevation, Z_1, is an elevation in the plume, which corresponds closely to the mean flame height. Z_1 has been calculated as follows:

$$Z_1 = Z_o + 0.166\dot{Q}_c^{2/5}, \tag{13}$$

where $\dot{Q}_c$ is the convective fraction of the heat release rate. Z_o is the location of the virtual origin and is given as below:

$$Z_o = -1.02D + 0.083\dot{Q}^{2/5}. \tag{14}$$

D is the diameter of fire source and $\dot{Q}$ is the total heat release rate. The value of Z_o may be negative or positive, depending upon the $\frac{\dot{Q}^{2/5}}{D}$ ratio.

For $Z \geq Z_1$,

$$\dot{m}_p = 0.071 \dot{Q}_c^{1/3} (Z - Z_o)^{5/3} [1 + 0.026 \dot{Q}_c^{2/3} (Z - Z_o)^{-5/3}], \tag{15}$$

while, for $Z < Z_1$,

$$\dot{m}_p = 0.0054 \dot{Q}_c \frac{Z}{Z_1}, \tag{16}$$

where Z is the height at which mass flow rate is required.

The solution of model equations (5) and (12) require initial conditions to start. At $t = 0$

$$Y = H \text{ and } P = 1 \tag{17}$$

One can note from equations (5) and (12) that it is not possible to solve equation (12) with the help of equation (5). We have to formulate another equation in place of equation (12) to provide value of P at the end of first time step, Δt. This can be done with the help of following plume equation, due to Heskestad [19]:

$$\Delta T_u = 9.1 \left(\frac{T_\infty}{g C_p^2 \rho_\infty^2} \right)^{1/3} \dot{Q}_c^{2/3} (Y - H_f)^{-5/3} \tag{18}$$

Also,

$$\dot{Q}_c = (1 - \lambda_r) \dot{Q}, \tag{19}$$

$$\Delta T_u = (T_u - T_\infty) = T_\infty (P - 1) \tag{20}$$

$$P = 1 + \frac{9.1}{T_\infty} \left[\frac{T_\infty}{g C_p^2 \rho_\infty^2} \right]^{1/3} (Y - H_f)^{-5/3} \dot{Q}_c^{2/3} \tag{21}$$

$$P = 1 + 9.1 \left[\frac{1}{g C_p^2 \rho_\infty^2 T_\infty^2} \right]^{1/3} (1 - \lambda_r)^{2/3} (Y - H_f)^{-5/3} \dot{Q}^{2/3} \tag{22}$$

$$P = 1 + C_1 (Y - H_f)^{-5/3} \dot{Q}_c^{2/3}, \tag{23}$$

where

$$C_1 = 9.1 (1 - \lambda_r)^{2/3} \left[\frac{1}{g C_p^2 \rho_\infty^2 T_\infty^2} \right]^{1/3}. \tag{24}$$

Differentiating equation (23), we can have

$$\frac{dP}{dY} = \left(-\frac{5}{3}\right) C_1 \dot{Q}^{2/3} (Y - H_f)^{-8/3} \tag{25}$$

Also,

$$\frac{dP}{dt} = \frac{dP}{dY}\frac{dY}{dt} \tag{26}$$

$$\frac{dP}{dt} = \left(-\frac{5}{3}\right) C_1 \dot{Q}^{2/3} (Y - H_f)^{-8/3} \frac{dY}{dt} \tag{27}$$

At $Y = H$,

$$\frac{dP}{dt} = \left(-\frac{5}{3}\right) C_1 \dot{Q}^{2/3} (H - H_f)^{-8/3} \frac{dY}{dt} \tag{28}$$

Equations (5) and (28) can be used to obtain the values of Y and P respectively, at the end of first time step, Δt. Thereafter, equations (5) and (12) are solved. Equation (5) requires the value of $\dot{m}_g$, for which the location of the neutral plane (Y_n) should be known. Following strategy has been adopted to determine the value of Y_n and $\dot{m}_g$. We know from simple mass balance that

$$\dot{m}_g = \dot{m}_a + \dot{m}_f + \dot{m}_s \tag{29}$$

$\dot{m}_a$ is the mass of air entering into the compartment through the opening, and $\dot{m}_f$ is the mass of combustion products generated by ignition source. $\dot{m}_f$ can be had from

$$\dot{m}_f = \frac{\dot{Q}}{\Delta H_c}, \quad \text{kg/s} \tag{30}$$

ΔH_c is the heat of combustion of igniting fuel (*kJ/kg*).
$\dot{m}_s$ is the mass of surface lining material burned and is given by

$$\dot{m}_s = \frac{\dot{Q}_s}{\Delta H_{CL}}, \quad \text{kg/s,} \tag{31}$$

where, ΔH_{CL} is the heat of combustion of surface lining material and $\dot{Q}_s$ is the rate of heat release contributed by the surface lining material.

The model for fresh air inflow ($\dot{m}_a$) and hot gas outflow ($\dot{m}_g$) through the doorway uses Rockett's [20] two zone model approach. The temperature difference between the room and its environment creates a pressure difference, which causes fluid flow through the opening. Applying Bernoulli's equation relating the pressure differences to the mass flow rates, and Euler's equation relating the fluid pressure to height, the following inflow and outflow correlations are developed.

$$\dot{m}_a = \frac{2}{3} C_i W_o \rho_\infty \sqrt{2g} \sqrt{\left(1-\frac{1}{P}\right)(Y_n - Y)} \left(Y_n + \frac{Y}{2}\right) \tag{32}$$

$$\dot{m}_g = \frac{2}{3} C_o W_o \rho_\infty \frac{1}{P} \sqrt{2g(P-1)}\, (H_o - Y_n)^{3/2} \tag{33}$$

C_i and C_o are the discharge coefficients for in-flow and out-flow fluids through the door. The door way coefficients (C_i and C_o) are measures of how effectively the pressure difference of the fluid across the opening is converted into velocity head. A coefficient of zero represents complete resistance to flow in and out of the compartment. A value of unity is equivalent to an ideal opening where fluid flows without restriction. From the experimental data available in the literature, C_o seems to be nearly constant and has an average value close to 0.7. For the free burning fires, C_i may be estimated to be within the range of 0.5-0.7. Prahl and Emmons [21] suggested the values of coefficients C_i and C_o to be equal to 0.68.

Now equation (32) and (33) can be written for $C_i = C_o = C_d$ as follows:

Let $\dot{m}_x = \frac{2}{3} C_d W_o \rho_\infty \sqrt{2g}$ (34)

Equation (32) can be written as

$$\dot{m}_a = \dot{m}_x \sqrt{\left(1-\frac{1}{P}\right)(Y_n - Y)} \left(Y_n + \frac{Y}{2}\right) \tag{35}$$

Equation (33) can be written as

$$\dot{m}_g = \dot{m}_x \frac{1}{P} \sqrt{(P-1)}\, (H_o - Y_n)^{3/2} \tag{36}$$

$$\dot{m}_g = \dot{m}_x \sqrt{\frac{1}{P}\left(1-\frac{1}{P}\right)} (H_o - Y_n)^{3/2} \tag{37}$$

Now equation (29) can be rewritten as follows:

$$FUN = \dot{m}_x \sqrt{\frac{1}{P}\left(1-\frac{1}{P}\right)} (H_o - Y_n)^{\frac{3}{2}} - \dot{m}_x \sqrt{\left(1-\frac{1}{P}\right)(Y_n - Y)} \left(Y_n + \frac{Y}{2}\right) - \frac{\dot{Q}}{\Delta H_c} - \frac{\dot{Q}_s}{\Delta H_{CL}} \tag{38}$$

FUN is a function whose value is zero. Equation (38) is solved iteratively in conjunction with equations (5) and (12) for each time step, such that $FUN \leq 0.0001$.

The loss fraction through the boundaries, λ_c, can be calculated as follows:

$$\lambda_c = \frac{\dot{Q}_{Loss}}{\dot{Q}_T} \tag{39}$$

$$\dot{Q}_{Loss} = UA_T\,(T_u - T_\infty) \tag{40}$$

where, $\dot{Q}_{Loss}$ is the heat lost through the area A_T of the boundaries (includes the ceiling and wall) in contact of upper hot gas layer and given by

$$A_T = WxL + 2(H - Y)\,(W + L) \qquad \text{for } Y \geq H_o \tag{41}$$

$$A_T = WxL + 2(H - Y)\,(W + L) - (H_o - Y)\,W_o \qquad \text{for } Y < H_o \tag{42}$$

U is the overall heat transfer coefficient for heat loss from boundary area, A_T and is given by

$$U = \frac{1}{\frac{1}{h_i} + \frac{X_L}{k} + \frac{X_w}{k_w} + \frac{1}{h_o}}, \text{kW/m}^2\text{-K} \tag{43}$$

where, k and k_w are the conductivities (kW/m-K) of surface lining materials and wall, respectively. X_L and X_w are the thickness (m) of surface lining materials and wall, respectively. h_o is outside heat transfer coefficient and h_i is inside heat transfer coefficient. According to Emmons [22], the value of outside heat transfer coefficient, h_o, is assumed constant (i.e., .005 kW/m^2-K) while h_i, inside heat transfer coefficient, varies between .005 to .050 kW/m^2-K and is given by

$$h_i = Min[0.050, 0.005 + .045(T_u - T_\infty)/100], \text{kW/m}^2\text{-K} \tag{44}$$

VALIDATION OF RELIEF

RELIEF has been validated with the data of Kokkala et al. [4]. The validation has been presented in another paper of the authors [23].

INPUTS REQUIRED FOR VALIDATION

The data required as input to RELIEF, have been given in Table 1. Room size door size, boundary loss fraction, radiation loss fraction, heat release rate by ignition source and by lining materials are the input parameters. The properties of various lining materials such as thermal conductivity (k), density (ρ), and thermal capacity (C) are to be used as input to the model. These properties are required for calculating the losses through boundaries by equation (39). The value

Table 1. Input Data to RELIEF

Sl. No.	Input parameter
1	Room size
2	Door size
3	Fire height
4	Fire diameter
5	Boundary loss fraction (λ_c)
6	Radiative loss fraction (λ_r)
7	Heat release rate of ignition source (Propane)
8	Total heat release rate measured
9	Heat of combustion of ignition source
10	Properties of lining material:
	(i) Thermal conductivity (k), kW/m-K,
	(ii) Density (ρ), kg/m^3,
	(iii) Thermal capacity (C), kJ/kg-K
	(iv) Ignition temperature (°C)
	(v) Thickness (mm)
	(vi) Heat of combustion (MJ/kg)
	(vii) Minimum heat flux required for ignition of lining material (q''_i), kW / m^2

of product of these properties ($k\rho C$) is required to calculate ignition time of lining materials by equation (2).

The experimental heat release rates (both burner's heat release rates and measured heat release rates) are taken as input to RELIEF. When measured HRR (heat release rate) is larger than the burner output, it is given as input to the RELIEF for total heat release rate, but if the measured HRR (heat release rate) is lower than the burner output, it means that there is no significant contributions by the lining material. Burner output is given as input to RELIEF for ignition source's heat release as well as for total heat release rate (which includes HRR of lining and ignition source).

CONCLUSIONS

A simple mathematical model, RELIEF, has been developed and discussed to predict the temperatures and heights of the hot upper layer formed beneath the ceiling in an enclosure with lining materials taking into consideration the effect of lining materials. RELIEF predicts neutral plane heights, mass of outgoing gases, and mass of air entering into the enclosure through the ventilation opening. RELIEF can also predict time to ignition of lining materials and time to reach onset of flashover.

RELIEF is essentially an extension of the previously developed CALTREE model [14, 24], whereas CALTREE (**CAL**culate **T**emperatures for **R**isk **E**stimation in **E**nclosures) equations are limited to predict temperatures in ventilated room scenarios without taking into account the contribution of lining materials. RELIEF equation (1) and equation (7) formulated for energy and mass conservations in upper hot layer, respectively, include the heat and mass contribution from lining materials in addition to mass and energy added from ignition burner which is placed either in the corner or near to wall. RELIEF accepts the steady heat release rate as well as time dependant values of heat release rate. However, there is need to further improve this model, as two heat release rates (HRR of pilot fire source as well that from lining materials) are required as input. For that, it can be used in conjunction with Quintiere model [7] developed to calculate the rate of heat release from the burning lining by modeling the fire spread over the lining surfaces.

ACKNOWLEDGMENT

Authors are grateful to Director, Central Building Research Institute, Roorkee for his kind support and encouragement, and also for granting permission for the publication of this research work.

NOMENCLATURE

A_F	Floor area, equal to *LxW*, m^2.
A_T	Boundary area in contact of upper hot gas layer, m^2.
C	Thermal capacity of lining material, kJ/kg-K.
C_d	Discharge coefficient (≈ 0.68).
C_i	Discharge coefficient for incoming air.
C_o	Discharge coefficient for outgoing gases.
C_1	Constant.
C_p	Specific heat of gases (taken equal to air), kJ/kg-K.
D	Fire Diameter, m
g	Acceleration due to gravity, equal to 9.81 m/s^2.
h_i	Inside heat transfer coefficient, kW/m^2-K.
h_o	Outside heat transfer coefficient, kW/m^2-K.
H	Compartment Height, m.
H_f	Fire source height, m.
H_o	Height of door/ window, m.
k	Thermal conductivity of surface lining material, kW/m-K.

k_w	Thermal conductivity of boundary material, kW/m-K.
L	Length of the compartment, m.
$\dot{m}_a$	Rate of air entering into the compartment, kg/s.
$\dot{m}_f$	Rate of burning of fuel, kg/s.
$\dot{m}_g$	Rate of gas flowing out through the opening, kg/s.
$\dot{m}_p$	Plume mass entering into the hot gas layer at the interface level, kg/s.
$\dot{m}_s$	Rate of burning of surface lining, kg/s.
P	A dimensionless parameter, equal to $\frac{T_u}{T_\infty}$.
$\dot{q}''_f$	Heat flux falling on linings from the flame of ignition source, kW/m^2.
$\dot{q}''_i$	Minimum heat flux required to ignite surface lining, kW/m^2.
$\dot{Q}$	Rate of heat released by fuel in compartment, kW.
$\dot{Q}_c$	Convective Heat Release Rate, equal to $(1-\lambda_r)\dot{Q}$, kW.
$\dot{Q}_{Loss}$	Losses through boundaries in contact of upper hot layer, kW.
$\dot{Q}_s$	Heat Release Rate by surface linings, kW.
$\dot{Q}_T$	Total Heat Release Rate (Sum of heat release rate by lining and ignition source), kW.
t	time, s.
t_i	Ignition time of surface lining, s.
T_u	Upper gas layer temperature, K.
T_∞	Ambient air temperature, K.
T_s	Surface temperature of lining material, K.
U	Overall heat transfer coefficient for losses through boundaries, kW/m^2-K.
W	Width of the compartment, m.
W_o	Width of door/window, m.
X_L	Thickness of surface lining materials, m.
X_W	Thickness of boundary materials, m
Y	Height of interface level, m.
Y_n	Height of neutral plane, m.
Z	Height above the fire source, m.
Z_o	Location of the virtual origin below finite fire source, m.
Z_1	Mean flame height, m

Greek Letters

ΔH_c	Heat of combustion of ignition fuel, kJ/kg.
ΔH_{CL}	Heat of combustion of surface lining material, kJ/kg.
ΔT_u	Excess upper layer temperature above ambient, $T_u - T_\infty$, K.
λ_c	Fraction of total heat lost through the boundaries , varies between 0.6-0.9.
λ_r	Radiative heat loss fraction.
ρ	Density of surface lining material, kg/m^3.
ρ_u	Density of upper gas, kg/m^3.
ρ_∞	Density of ambient air, kg/m^3.

REFERENCES

1. ISO 9705:1993(E), International Standards for Fire Tests—Full Scale Room Test for Surface Products, International Organization for Standardization, Geneva, Switzerland, 31 pp., 1996
2. J. Quintiere, Growth of Fire in Building Compartments, *Fire Standards and Safety, ASTM STP 614*, A. F. Robertson (ed.), American Society for Testing and Materials, Philadelphia, 0, pp. 131-167, 1977.
3. B. Karlsson, Models for Calculating Flame Spread on Wall Lining Materials and the Resulting Heat Release Rate in a Room, *Fire Safety Journal, 23,* pp. 365-386, 1994.
4. M. Kokkala, U. Goransson, and J. Sodderbom, Five Large-Scale Room Fire Experiments, *VTT Publications 104,* Technical Research Centre of Finland, Espoo. VTTPUBS 109, 1992.
5. N. A. Dembsey and R. B. Williamson, The Effect of Ignition Source Exposure and Specimen Configuration on the Fire Growth Characteristics of a Combustible Interior Finish Material, *Fire Safety Journal, 21,* pp. 313-330, 1993.
6. S. E. Magnusson and B. Sundstrom, *Combustible Linings and Room Fire Growth—A First Analysis*, Fire Safety: Science and Engineering, ASTM STP 882, T. Z. Harmathy (ed.), American Society for Testing and Materials, Philadelphia, 0, pp. 45-69, 1985.
7. J. G. Quintiere, A Simulation Model for Fire Growth on Materials Subject to a Room-Corner Test, *Fire Safety Journal, 20,* pp. 313-339, 1993.
8. B. Karlsson, A Mathematical Model for Calculating Heat Release Rates in the Room Corner Test, *Fire Safety Journal, 20,* pp. 93-113, 1993.
9. B. Y. Lattimer, S. P. Hunt, M. Wright, and U. Sorathia, Modeling Fire Growth in a Combustible Corner, *Fire Safety Journal, 38,* pp. 771-786, 2003.
10. W. W. Jones, A Multi-Compartment Model for the Spread of Fire, Smoke and Toxic Gases, *Fire Safety Journal, 9,* pp. 55-79, 1985.
11. J. A. Rockett, *Using the HARVARD/NIST Mark VI Fire Simulation,* NISTIR 4464, National Institute of Standards and Technology, Gaithersburg, Maryland, 1990.
12. H. E. Mitler and J. Rockett, *A User's Guide to FIRST, A Comprehensive Single Room Fire Model,* NBSIR 87-3595, National Institute of Standards and Technology, Gaithersburg, Maryland, 1987.
13. A. M. Kanury, On the Craft of Modeling in Engineering and Sciences, *Fire Safety Journal, 12,* pp. 65-74, 1987.
14. R. Kumar, *Studies on Compartment Fires*, Ph.D. thesis, Department of Chemical Engineering, Indian Institute of Technology Roorkee, India, 2004.
15. L. Y. Cooper, Estimating the Environment and the Response of Sprinkler Links in Compartment Fires with Draft Curtains and Fusible Link-Actuated Ceiling Vents Theory, *Fire Safety Journal, 16,* pp. 137-167, 1990.
16. L. Y. Cooper, A Mathematical Model for Estimating Available Safe Egress Time in Fires, *Fire and Materials, 6*(3&4), pp. 135-144, 1982.
17. P. H. Thomas, On Concurrent Upward Surface Spread of Flame, *Fire Safety Journal, 22,* pp. 89-99, 1994.
18. T. G. Cleary and J. G. Quintiere, *A Framework for Utilizing Fire Property Tests. Fire Safety Science*—Proceedings of the Third International Symposium: International Association for Fire Safety Science, 0, pp. 647-656, 1991.
19. G. Heskestad, Engineering Relations for Fire Plumes, *Fire Safety Journal, 7,* pp. 25-32, 1984

20. J. A. Rockett, Fire Induced Gas Flow in an Enclosure, *Combustion Science and Technology, 12,* pp. 165-175, 1976.
21. J. Prahl and H. W. Emmons, Fire Induced Flow Through an Opening, *Combustion and Flame, 25,* pp. 369-385, 1975.
22. H. E. Emmons, *The Prediction of Fire in Buildings,* 17th International Symposium on Combustion, pp. 1101-1111, 1978.
23. R. Kumar and S. K. Sharma, Experimental Validation of RELIEF—A Zone Model to Predict Fire Behavior in Enclosures with Wall Linings, *Journal of Applied Fire Science, 17*(4), pp. 311-336, 2007-2008.
24. A. K. Gupta, R. Kumar, and S. Kumar, Compartment Fires: A Simple Mathematical Model, *Journal of Applied Fire Science, 11*(1), pp. 53-74, 2002-03.

Direct reprint requests to:

Rajiv Kumar, Ph.D.
Fire Research Division
Central Building Research Institute
Roorkee, India
e-mail: rajivkgoel@gmail.com