MATHEMATICAL ANALYSIS AND POSSIBLE APPLICATION OF THE TWO-LAYER ZONE MODEL FIRM

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ABSTRACT

With the possibility of implementing engineering performance-based fire code, it is important to select a design tool for estimating the fire environment. A simple two-layer zone model such as the ASET model should be a good candidate for quick estimation of fire environment. However, there is no opening in the model and air is supplied through leakage. Another model, FIRM was upgraded from ASET to include a vertical opening. It is believed that it is useful for fire hazard assessment. Mathematical derivation of the key equations in FIRM is reviewed in this paper. Possible application is demonstrated by referring to full-scale burning tests in the new PolyU/HEU Assembly Calorimeter.

1. INTRODUCTION

It is quite impossible to update prescriptive codes [e.g. 1-4] for building fire safety quick enough to cope with new architectural feature, new fire safety design, new style of living and use of new building materials and consumable products. Time has to be spent on discussing the new codes with arguments. Proposals might be turned down by the Legislative Council such as the Karaoke Establishments Bill [5]. Putting in fire safety measures by following older versions of fire code without in-depth consideration might even give adverse effect. Installing sprinkler at high headroom atrium while following the FSI code [e.g. 4] is an obvious example [6]. A good solution is to implement 'engineering approach' [7] such as that designated by the government Buildings Department on fire safety design for projects having difficulties in following the prescriptive code. Of course, fire safety management [e.g. 8-10] should be implemented properly to give total fire safety.

'Engineering approach' [7] is not yet performance-based fire code [e.g. 9-12], but very similar in the sense of requiring fire hazard assessment. Estimating the probable fire environment for scenario analysis by carrying out full-scale burning tests is too expensive. There are far too many parameters to preserve for scale model studies. Empirical correlation equations for different buildings are not all verified. Therefore, using fire model [13-17] is a key element in fire hazard assessment, although it is not equivalent to performance-based fire code [18]. Consequences of the identified hazard scenarios can be estimated fairly easily.

A simple fire model such as the pioneer concept of Available Safe Egress Time (ASET) developed by Cooper and coworkers [19-21] is suitable for quick estimation on fire environment. However, there is no opening in this model. Another model, Fire Investigation and Recruitment Method (FIRM) [17] upgraded from ASET with a vertical opening, is a good candidate. As this kind of approach is simple in nature, but include all key fire phenomena. Key equations in FIRM are reviewed in this paper with mathematical derivation reported. Possible application is demonstrated by referring to the full-scale burning experiments at PolyU/HEU Assembly Calorimeter [22]. This is a joint project between The Hong Kong Polytechnic University (PolyU) and Harbin Engineering University (HEU). As proposed earlier [23], symbolic mathematics such as Maple-V [24,25] are used for the ease of checking the equations [15]. Note that there are criticisms by the local professionals that it is difficult to understand the computer program in most fire models. Software on field modelling or Computational Fluid Dynamics [15] is the most obvious example. Even zone models [13-17,19-21] are always regarded as 'black boxes'! Programming with symbolic mathematics [23] would allow professionals to know what happens inside a fire model.

2. KEY EQUATIONS FOR FIRM MODEL

FIRM [17] is a two-layer fire zone upgraded ASET model [19-21] which can estimate fire environment in a room with an opening. Note that ASET allows only a small gap near the floor with air supplied through it. A pictorial presentation is shown in Fig. 1. An upper hot smoke layer at height Z_i is induced by a fire with height Z_f with a lower cool air layer found under it. Heat and mass are transferred through a plume.

Similar to a typical two-layer zone model, there are eleven variables on temperature T_U and T_L; mass m_U and m_L; internal energy E_U and E_L; volume V_U and V_L; density ρ_U and ρ_L of the upper hot and lower cool layers; and room pressure P_{room}. There should be eleven equations with seven physical constraints. The basic equations of FIRM model are similar to those in ASET as the following assumptions are the same:

$$\rho_L = \text{constant} \tag{1}$$

$$T_L = \text{constant} \tag{2}$$

$$\frac{dP_{room}}{dt} = 0 \tag{3}$$

Therefore, the equations are:

$$\frac{dm_L}{dt} = \dot{m}_L \tag{4}$$

$$\frac{dm_U}{dt} = \dot{m}_U \tag{5}$$

$$\dot{q}_L + \dot{q}_U = 0 \tag{6}$$

$$\frac{dE_L}{dt} = \frac{1}{\gamma}\dot{q}_L \tag{7}$$

$$\frac{dE_U}{dt} = \frac{1}{\gamma}\dot{q}_U \tag{8}$$

$$\frac{dV_L}{dt} = \frac{1}{P_{room}\gamma}(\gamma - 1)\dot{q}_L \tag{9}$$

$$\frac{dV_U}{dt} = \frac{1}{P_{room}\gamma}(\gamma - 1)\dot{q}_U \tag{10}$$

In the above equations, $\dot{q}_L$ and $\dot{q}_U$ are the rates of change of enthalpy of the two layers, and γ is the ratio of specific heat capacities C_p and C_v at constant pressure and volume respectively.

Equations (1) to (3) give:

$$\frac{d\rho_U}{dt} = \frac{-1}{C_p T_U V_U}\left(\dot{q}_U - C_p \dot{m}_U T_U\right) \tag{11}$$

$$\dot{q}_L - C_p \dot{m}_L T_L = 0 \tag{12}$$

$$\frac{dT_U}{dt} = \frac{1}{C_p \rho_U V_U}\left(\dot{q}_U - C_p \dot{m}_U T_U\right) \tag{13}$$

The above equations would be reduced to only two equations on Z_i and T_U for both ASET and FIRM. Since FIRM has a vertical opening, the equations concerned are much more complicated. Additional parameters in FIRM are height of the lowest part of the opening Z_b and height of the uppermost part of the opening Z_t as shown in Fig. 1.

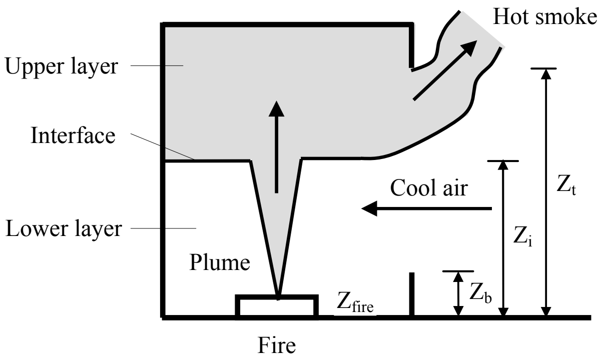


Fig. 1: The two-layer fire zone model FIRM

3. FLOW CONDITIONS THROUGH THE OPENING

Different pressure profiles along the height between indoor and outdoor would give different flow conditions. Five flow conditions are identified [17] in FIRM:

- Flow condition 1

  The smoke layer interface height lies above the opening, i.e. $Z_i > Z_t$.

  Under this condition, indoor cool air will be heated up and flow out of the opening with a mass flow rate $\dot{m}_{VL}$. Pressure variation along the vertical height Z is shown in Fig. 2. Conservation of energy gives an equation in terms of the heat lost coefficient L_c and specific heat capacity of air C_p of value 1004 $kJkg^{-1}K^{-1}$:

$$\dot{m}_{VL} C_p T_L = (1 - L_c)\dot{Q}$$

Rearranging the above equation gives an expression of $\dot{m}_{VL}$:

$$\dot{m}_{VL} = \frac{(1-L_c)\dot{Q}}{C_p T_L} \qquad (14)$$

- Flow condition 2

Smoke layer interface is between the soffit and the sill $Z_b < Z_i < Z_t$; and the inside pressure is higher than outside pressure. Taking Z_n as the minimum height satisfying $P_{in} > P_{out}$, then $Z_n < Z_i$.

In this case, both cool air and hot air are flowing out with rates $\dot{m}_{VL}$ and $\dot{m}_{VU}$ respectively. The pressure variation is shown in Fig. 3. Expressing the pressure difference between inside and outside of the room at height Z in terms of the acceleration due to gravity g of value 9.8 ms^{-2}:

$$\Delta P(Z) = P_{in}(Z) - P_{out}(Z)) \qquad (15)$$

Since

$$P_{out}(Z) = P_{out}(Z_i) - \rho_U g(Z - Z_i)$$

$$P_{in}(Z) = P_{in}(Z_i) - \rho_L g(Z - Z_i)$$

These equations give:

$$\Delta P(Z) \approx \Delta P(Z_i) + g(Z_i - Z)(\rho_L - \rho_U) \qquad (16)$$

In the ASET model, both the upper hot smoke layer and the lower cool air layer are assessed to be ideal gases of equal molecular weight, and the pressure inside the room is unchanged. Ideal gas law gives the air density $\rho(T)$ at any temperature as:

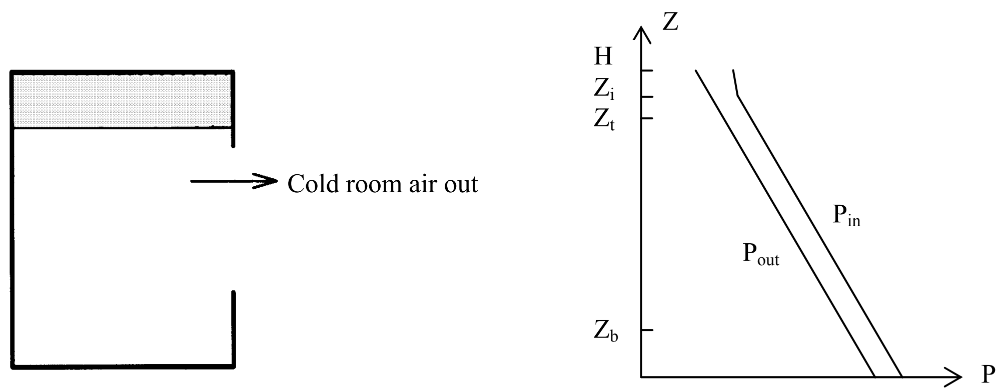
$P = \rho(T)\ RT$

and

$P = \rho_L\ RT_L$

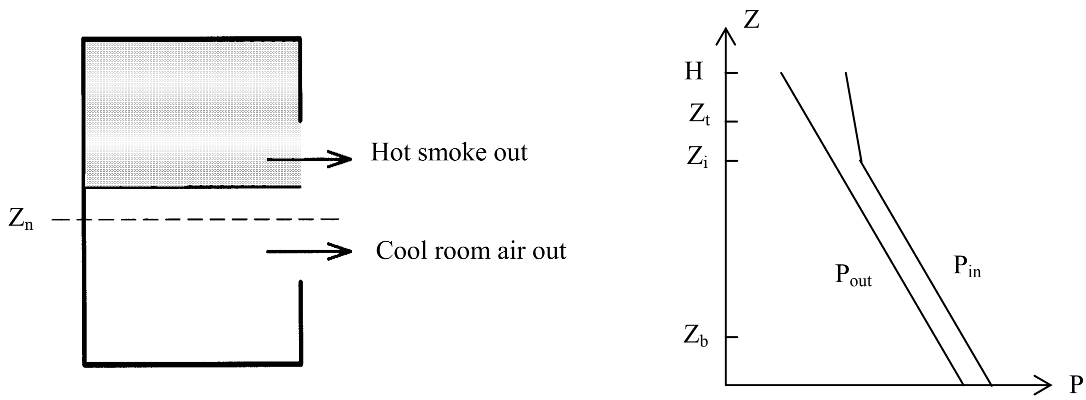
i.e.

$$\rho(T) = \frac{\rho_L T_L}{T} \qquad (17)$$



(a) Physical picture (b) Pressure variation

Fig. 2: Flow condition 1



(a) Physical picture (b) Pressure variation

Fig. 3: Flow condition 2

Taking ρ_L as 1.2 kgm^{-3} and T_L as 294.26 K,

$$\rho(T) = \frac{353}{T} \tag{18}$$

Substituting equation (17) into equation (16):

$$\Delta P(Z) \approx \Delta P(Z_i) + g\rho_L T_L (Z_i - Z)\left(\frac{1}{T_L} - \frac{1}{T_U}\right) \tag{19}$$

For $Z_b < Z < Z_t$, the outflow of upper smoke layer, outflow of lower cool air layer, or inflow of outside cool air can all be considered as an 'opening flow problem' (with $\rho_{in} = \rho_{out} = \rho$) of incompressible fluids at the same horizontal level ($Z_{in} = Z_{out}$). Mass conservation and Bernouilli's equation at any one vertical plane (represented by subscript in) of the room and opening plane (represented by subscript out) give:

$$V_{in} A_{in} = V_{out} A_{out} \tag{20}$$

$$P_{in} + \frac{1}{2}\rho V_{in}^2 = P_{out} + \frac{1}{2}\rho V_{out}^2 \tag{21}$$

Substituting equation (20) into equation (21), the velocity v(Z) at any height Z at the opening plane is:

$$|v(Z)| = C\sqrt{\frac{2|\Delta P(Z)|}{\rho(Z)}} \tag{22}$$

Experiments with salt-water models suggested C to be 0.68 as reported by Prahl and Emmons [26]. In this case, $\dot{m}_{VU}$ is:

$$\dot{m}_{VU} = W_V \int_{Z_i}^{Z_t} \rho_U |v(Z)| dZ \tag{23}$$

Substituting equations (18), (19) and (22) into the above equation gives:

$$\dot{m}_{VU} = W_V \int_{Z_i}^{Z_t} \frac{353}{T_U} C \sqrt{\frac{2\left|\Delta P(Z_i) + g\rho_L T_L (Z_i - Z)\left(\frac{1}{T_L} - \frac{1}{T_U}\right)\right|}{\frac{353}{T_U}}}\, dZ$$

$$= \frac{17.7 W_V C}{X_4}\left[\left(X_3 + X_4(Z_t - Z_i)\right)^{3/2} - X_3^{3/2}\right] \tag{24}$$

W_V is the width of the room opening (in m), X_3 and X_4 are defined as:

$$X_3 \equiv \frac{|\Delta P(Z_i)|}{T_U} \tag{25}$$

and

$$X_4 \equiv \frac{g\rho_L T_L}{T_U}\left(\frac{1}{T_L} - \frac{1}{T_U}\right) \tag{26}$$

Similarly, $\dot{m}_{VL}$ can be expressed as:

$$\dot{m}_{VL} = W_V \int_{Z_b}^{Z_i} \rho_L |v(Z)| dZ \tag{27}$$

Since T_L is the same as the outside air temperature, in the region $Z_t \le Z \le Z_i$:

$$\Delta P(Z) = \Delta P(Z_i) \tag{28}$$

Substituting equations (18), (22) and (28) into equation (27) gives:

$$\dot{m}_{VL} = W_V \int_{Z_b}^{Z_i} \frac{353}{T_L} C \sqrt{\frac{2|\Delta P(Z_i)|}{\frac{353}{T_L}}}\, dZ$$

$$= 26.6 W_V C X_1^{1/2}(Z_i - Z_b) \tag{29}$$

where

$$X_1 \equiv \frac{|\Delta P(Z_i)|}{T_L}$$

Under this condition, there is an unknown $\Delta P(Z_i)$ in equations (24) and (29). An additional equation is required to solve for the opening flow rate. Energy conservation of the whole room gives:

$$\dot{m}_{VL} C_p T_L + \dot{m}_{VU} C_p T_U = C_p \dot{m}_p (T_U - T_L) + C_p \frac{\rho_L T_L}{T_U} A(H - Z_i)\frac{dT_U}{dt} \tag{30}$$

The opening flow rate under this condition can be obtained by equations (24), (29) and (30).

- Flow condition 3

The smoke layer interface height lies within the opening region; and at any height within the region of the lower cool air layer, the pressure inside the room is equal to the pressure outside, i.e. $Z_b < Z_i < Z_t$ and $Z_n = Z_i$.

In this case, there will only be hot air flowing out with rate $\dot{m}_{VU}$ and the pressure variation is shown in Fig. 4. This can be taken as a special case of flow condition 2. Under this situation,

$$\Delta P(Z_i) = 0 \tag{31}$$

Substituting equation (31) into (24):

$$\dot{m}_{VU} = 17.7 W_V C X_4^{1/2} (Z_t - Z_i)^{3/2} \tag{32}$$

Substituting equation (31) into (29) gives:

$$\dot{m}_{VL} = 0 \tag{33}$$

- Flow condition 4

  Smoke layer interface is within the opening region; and at any height within the region of $Z < Z_n$, the pressure inside the room is lower than the pressure outside, i.e. $Z_b < Z_i < Z_t$ and $Z_n > Z_i$.

In this case, there will be outflow of hot air with rate $\dot{m}_{VU}$ and an inflow of outside cool air with rate $\dot{m}_{VA}$. The pressure variation is shown in Fig. 5. The pressure difference $\Delta P(Z)$ at any height above the interface $Z(Z_i \le Z \le Z_t)$ can be expressed as:

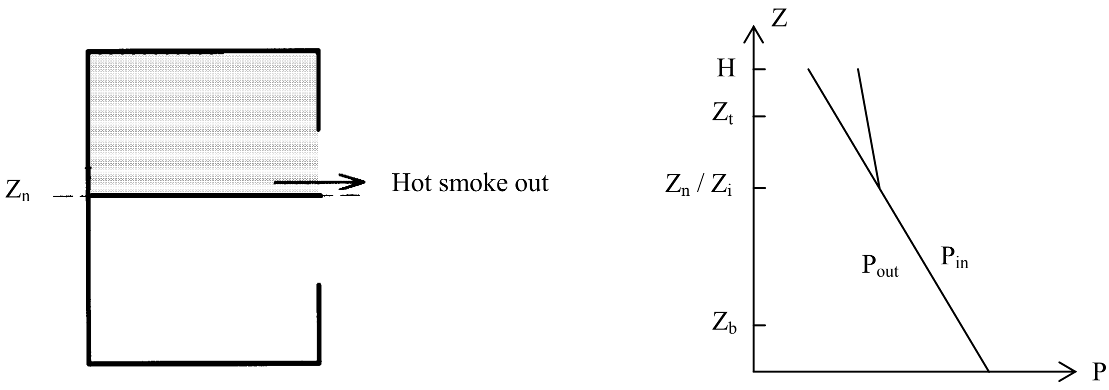
$$\Delta P(Z) \approx g \rho_L T_L (Z_n - Z) \left(\frac{1}{T_L} - \frac{1}{T_U} \right) \tag{34}$$

Since the lower cool air temperature is equal to the outside air temperature, therefore, at any height below the interface ($Z_t \le Z \le Z_i$),

$$\Delta P(Z) = \Delta P(Z_i) \tag{35}$$

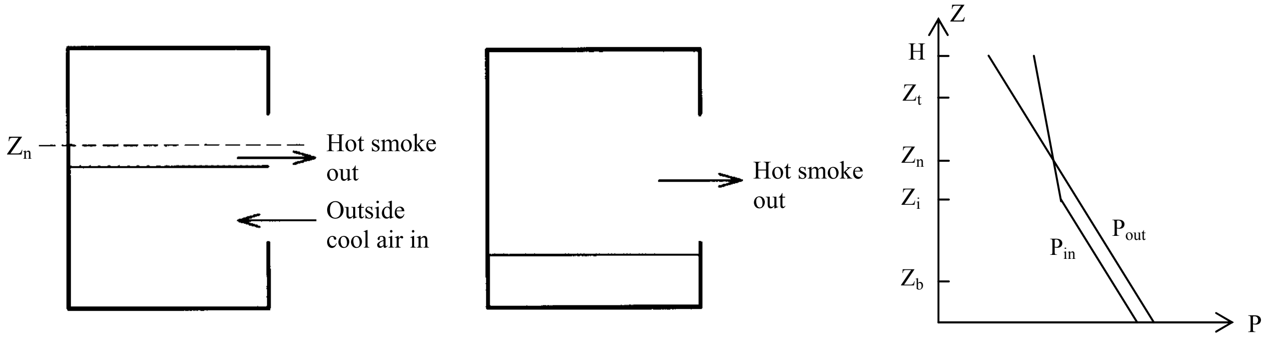
Since there is hot air flowing out only within the region $Z_n \le Z \le Z_t$, $\dot{m}_{VU}$ under this condition is:

$$\dot{m}_{VU} = W_V \int_{Z_n}^{Z_t} \rho_U |v(Z)| \, dZ \tag{36}$$



(a) Physical picture (b) Pressure variation

Fig. 4: Flow condition 3



(a) Flow condition 4 (b) Flow condition 5 (c) Pressure variation

Fig. 5: Flow conditions 4 and 5

Substituting equations (18), (22) and (34) into equation (36) gives:

$$\dot{m}_{VU} = W_V \int_{Z_n}^{Z_t} \frac{353}{T_U} C \sqrt{\frac{2\left|g\rho_L T_L (Z_n - Z)\left(\frac{1}{T_L} - \frac{1}{T_U}\right)\right|}{\frac{353}{T_U}}} dZ$$

$$= 17.7 W_V C X_4^{1/2} \left(Z_t - Z_n\right)^{3/2} \tag{37}$$

In this case, there is outside cool air flowing in within the region $Z_b \le Z \le Z_n$, with $\dot{m}_{VA}$ given by:

$$\dot{m}_{VA} = W_V \int_{Z_b}^{Z_n} \rho_L |v(Z)| dZ$$

$$= W_V \int_{Z_b}^{Z_i} \rho_L |v(Z)| dZ + W_V \int_{Z_i}^{Z_n} \rho_L |v(Z)| dZ \tag{38}$$

Substituting equations (18), (22), (34) and (35) into equation (38) gives:

$$\dot{m}_{VA} = W_V \int_{Z_b}^{Z_i} \frac{353}{T_L} C \sqrt{\frac{2|\Delta P(Z_i)|}{\frac{353}{T_L}}} dZ +$$

$$W_V \int_{Z_i}^{Z_n} \frac{353}{T_L} C \sqrt{\frac{2\left|g\rho_L T_L (Z_n - Z)\left(\frac{1}{T_L} - \frac{1}{T_U}\right)\right|}{\frac{353}{T_L}}} dZ$$

$$= 26.6 W_V C X_1^{1/2} \left(Z_i - Z_b\right) + 17.7 W_V C X_2^{1/2} \left(Z_n - Z_i\right)^{2/3} \tag{39}$$

where

$$X_2 \equiv g\rho_L \left(\frac{1}{T_L} - \frac{1}{T_U}\right)$$

Under this condition, there are two unknowns $\Delta P(Z_i)$ and Z_n in the opening flow rate equations (37) and (39). To solve for the opening flow rate, two additional equations are needed:

(i) Energy conservation of the whole room:

$$\dot{m}_{VU} C_p T_U = C_p \dot{m}_p (T_U - T_L) + C_p \frac{\rho_L T_L}{T_U} A\left(H - Z_i\right)\frac{dT_U}{dt} + \dot{m}_{VA} C_p T_L \tag{40}$$

(ii) Pressure difference $\Delta P(Z)$ between inside and outside of the room at Z_i:

$$\Delta P(Z_i) \approx g\rho_L T_L (Z_n - Z_i)\left(\frac{1}{T_L} - \frac{1}{T_U}\right) \tag{41}$$

Therefore, the opening flow rate under this condition can be obtained from equations (37), (39), (40) and (41).

- Flow condition 5

The interface between the upper smoke layer and the lower cool air layer is below the lowest part of the opening, i.e. $Z_i \le Z_b$.

In this case, there is only hot air flowing out $\dot{m}_{VU}$ through the room opening.

Energy conservation of the whole room gives:

$$\dot{m}_{VU} C_p T_U = C_p \dot{m}_p (T_U - T_L) + C_p \frac{\rho_L T_L}{T_U} A\left(H - Z_i\right)\frac{dT_U}{dt} \tag{42}$$

Rearranging the above equation, $\dot{m}_{VU}$ can be expressed as:

$$\dot{m}_{VU} = \dot{m}_p \frac{T_U - T_L}{T_U} + \rho_L T_L A \frac{H - Z_i}{T_U^2} \frac{dT_U}{dt} \tag{43}$$

4. TOTAL HEAT LOSS COEFFICIENT L_C

There are three components [e.g. 17] in the heat lost coefficient L_c: radiative heat lost, convective heat lost with ceiling, and other heat lost:

$$L_c = L_r + L_{ceiling} + L_{other} \tag{44}$$

The radiative heat loss coefficient L_r would be different for different materials and geometry of the room. In FIRM model, it can be taken as 0.35, or may be determined based on relevant data.

The convective heat loss with ceiling $L_{ceiling}$ is related to the radiative heat loss coefficient L_r, geometry of the room and height of the fire source Z_f as:

$$L_{ceiling} = 0.47 \times (1 - L_r) \times \left[1 - e^{-\frac{0.69R}{H - Z_f}} \right] \quad (45)$$

R is the equivalent diameter of the upper space of the fire source given in terms of the length L, width W and area A of the room as:

$$R = \sqrt{\frac{A + 2.0(L + W)(H - Z_f)}{\pi}} \quad (46)$$

The heat loss coefficient L_{other} due to other factors is mainly related to the smoothness of the ceiling, taking 0.0 for smooth ceiling; 0.05 if the ceiling is not so smooth; and 0.1 if the ceiling is coarse.

It should be noted that the total heat loss coefficient L_c should not exceed 1.0.

5. COMBUSTION

Complete combustion is assumed in ASET model. In real fires, combustion might not be complete and FIRM has been improved to consider incomplete combustion in two aspects:

- Incomplete combustion due to opening

  Under the opening flow condition as in condition 4, as the burning proceeds, the thickness of the upper layer will keep on increasing and the interface height descending, the entrainment of outside cool air will also increase. When the interface has descended to a certain level, entrainment of outside air would reach a maximum and no longer increase. In such case, burning will be affected. In FIRM model, the maximum entrainment of outside cool air as reported in the literature [27,28] is adopted:

$$\dot{m}_{VA} = 0.52 W_V (Z_t - Z_b)^{3/2} \quad (47)$$

  Substituting equation (47) into equation (40), $\dot{m}_{VU}$ at the opening can be written as:

$$\dot{m}_{VU} = \left(\dot{m}_p \frac{T_U - T_L}{T_U} + \rho_L T_L A \frac{H - Z_i}{T_U^2} \frac{dT_U}{dt} \right) + \frac{T_L}{T_U} \dot{m}_{VA} \quad (48)$$

- Incomplete combustion due to plume

  In complete combustion, the heat release rate per unit mass of oxygen is approximated by a constant of value equal to the ratio of the heat release rate of burning fuel $\Delta h_{c,net}$ to the stoichiometric oxygen to fuel ratio s_{stoich}:

$$(\dot{Q})_{max} = \dot{m}_p \left(\frac{\Delta h_{c,net}}{s_{stoich}} \right) \quad (49)$$

  The ratio ($\Delta h_{c,net}/s_{stoich}$) will be different for different burning fuels with some values reported in the literature [e.g. 27]. The value might also be taken as 3030 kJ/(kg air) to give equation (49) as:

$$(\dot{Q})_{max} = 3030 \dot{m}_p \quad (50)$$

  The plume flow rate induced by a point heat source [e.g. 17] is taken as $\dot{m}_p$:

$$\dot{m}_p = \begin{cases} 0.21 \left(\dfrac{g(1 - L_r)\dot{Q}}{C_p T_L} \right)^{1/3} \rho_L^{2/3} (Z_i - Z_f)^{5/3} & Z_i > Z_f \\ 0 & Z_i \le Z_f \end{cases} \quad (51)$$

  Putting in values for the parameters g, C_p, T_L and ρ_L into equation (51) gives:

$$\dot{m}_p = \begin{cases} 0.076 (1 - L_r)^{1/3} \dot{Q}^{1/3} (Z_i - Z_f)^{5/3} & Z_i > Z_f \\ 0 & Z_i \le Z_f \end{cases} \quad (52)$$

  Substituting equation (50) into equation (52) gives the maximum plume flow rate $(\dot{m}_p)_{max}$ as:

$$(\dot{m}_p)_{max} = 1.152 (1 - L_r)^{1/2} (Z_i - Z_f)^{5/2} \quad (53)$$

6. THE TWO KEY EQUATIONS

Besides the above three improvements over ASET on having a ventilation opening; modifying the total heat loss coefficient; and allowing incomplete combustion, prediction of heat release rate and flashover are also proposed. Since only interface height and upper layer temperature are focused in this paper, these phenomena will not be discussed here. These will be considered later with full-scale burning tests.

Anyway, there are only two key equations on Z_i and T_U in FIRM:

- Equation for Z_i:

  Conservation of mass of the lower cool air layer gives:

$$\rho_L A \frac{dZ_i}{dt} = \dot{m}_{VA} - \dot{m}_{VL} - \dot{m}_p \qquad (54)$$

  Rearranging the above equation, the differential equation for Z_i is:

$$\frac{dZ_i}{dt} = \frac{\dot{m}_{VA} - \dot{m}_{VL} - \dot{m}_p}{\rho_L A} \qquad (55)$$

- Equation for T_U

  Conservation of mass of the upper layer gives:

$$\dot{m}_U = \dot{m}_p - \dot{m}_{VU} \qquad (56)$$

  Conservation of enthalpy of the upper layer gives:

$$\dot{q}_U = (1 - L_c)\dot{Q} + C_p \dot{m}_p T_L - C_p \dot{m}_{VU} T_U \quad (57)$$

  Definition of enthalpy of the upper layer gives:

$$\dot{q}_U = \frac{d\left(C_p m_U T_U\right)}{dt} = C_p \dot{m}_U T_U + C_p m_U \frac{dT_U}{dt} \qquad (58)$$

  The upper layer mass m_U is given by:

$$m_U = \rho_U A(H - Z_i) \qquad (59)$$

  Substituting equations (17), (56), (58) and (59) into equation (57) gives the differential equation for T_U as:

$$\frac{dT_U}{dt} = T_U \cdot \frac{(1 - L_c)\dot{Q}(t) + C_p \dot{m}_p T_L}{C_p \rho_L A(H - Z_i) T_L} - T_U^2 \cdot \frac{\dot{m}_p}{\rho_L A(H - Z_i) T_L} \qquad (60)$$

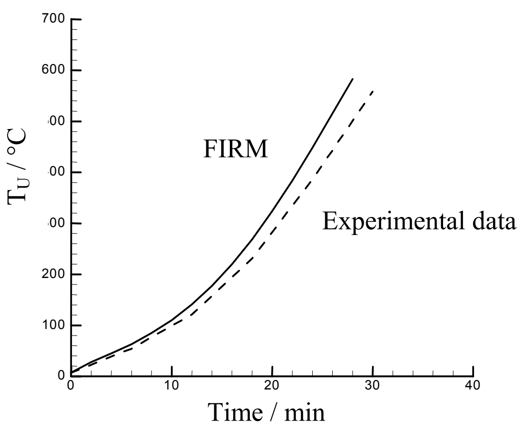
Equations (55) and (60) are solved by symbolic mathematics Maple-V [23-25].

7. APPLICATION

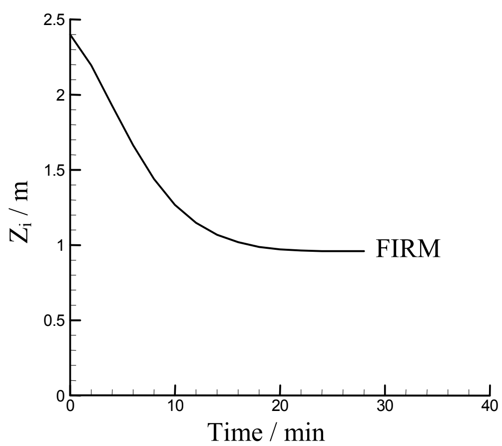
A PolyU/HEU Assembly Calorimeter [22] for studying heat release rate of burning assemblies was constructed at Lanxi, Heilongjiang, China. Exhaust hood, fan and duct section for sampling gases for chemical analysis were developed. The key instruments such as oxygen analyzer and flow measuring devices were calibrated with a standard burner with known heat release rate.

To verify the results predicted by FIRM, preliminary full-scale burning tests were carried out in a room of size similar to the ISO9705 room calorimeter. A polyurethane sofa was burnt with heat release rates measured to be 2253 kW, 668 kW, 668 kW, 133 kW and 133 kW at 46 s, 276 s, 388 s, 696 s and 1636 s respectively. The two key equations for FIRM on Z_i and T_U given by (54) and (59) are solved by Maple-V [23-25].

Predictions on T_U and Z_i are shown in Figs. 6(a) and 6(b) with experimental results on T_U shown. Smoke layer interface heights were not measured and so no comparison was made. It is observed that a very good agreement on T_U was predicted. Note that a burning sofa with the heat release rate taken as input parameter was considered. This gives a much more practical application.



(a) Smoke layer temperature



(b) Smoke layer interface height

Fig. 6: Comparison with results from PolyU/HEU Assembly Calorimeter

8. CONCLUSION

With the increasing demand on getting reliable tools for fire hazard assessment for implementing EPBFC [9-12], a two-layer zone model [13] should be very useful. The two-layer zone model FIRM [17] should be a good candidate as it is relatively simple but includes almost all necessary physical subroutines. Mathematical derivation of the key equations in FIRM including the five flow ventilation conditions identified earlier was reported in this paper. This is useful for local professionals to understand the physics inside such a model. Further, the two key equations are solved by symbolic mathematics Maple-V [24,25]. This allows [23] a more transparent feature to know the computing details inside.

Comparisons on the prediction with preliminary full-scale burning test data [22] at the new PolyU/USTC Assembly Calorimeter are reported. Very good agreement between experiments and FIRM predictions is found. This gives confidence in recommending the use of FIRM for consideration as part of a hazard assessment tool. The model can be further improved [e.g. 16] by including flame spreading model on surface lining materials; and emission of toxic gases such as carbon monoxide.

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