New Estimation of the Thermal Interface Height in Forced-Ventilation Enclosure Fires

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ABSTRACT

A new method is proposed to determine the thermal interface height for transient development in forced-ventilation enclosure fires. The method is based on the assumption of a vertical temperature gradient in the hot upper region and is based on mathematical considerations. The results of this new method are compared with the experimental data obtained during recent experiments on forced-ventilation enclosure fires carried out in IPSN facilities. These results are also compared to those obtained by the mass equivalency method [1] and show that the new method leads to better predictions of interface height and temperature profiles.

KEYWORDS : Compartment fire ; Forced ventilation ; Two-zone model ; Interface height ; Temperatures of lower and upper layers ; Vertical temperature gradient.

INTRODUCTION

In nuclear power plants and reprocessing plants, the compartments are well-confined to protect the environment from possible release of radioactive particles due to fire consequences. Therefore, the IPSN is carrying out many experiments with forced-ventilation enclosure fires and is developing a computer code using a zone model methodology [2]. The experimental results presented here have been obtained through a collaboration between the IPSN and COGEMA.

The two-zone model is widely used to predict the development of compartment fires including natural and/or forced ventilation. The basic concept of the zone model assumes two distinct gas layers with uniform temperature and composition : an upper region of hot gases and smoke, and a lower region of relatively cool air. These two regions result from thermal stratification due to buoyancy effects. The main parameters of this approach are the average temperature of the lower and upper layers and the interface height splitting the two zones. A fundamental and well-documented description of zone modeling can be found elsewhere [3,4].

From this, many computer codes have been developed to simulate the fire growth process and smoke movement problem in buildings and industrial installations [5]. These computer codes provide reasonable accuracy of prediction in engineering applications with low CPU time cost.

In order to use the zone model predictions with confidence, the appropriate and meaningful values obtained from experimental data must prove to be in good agreement with the numerical results coming from computer codes. The interface height appears as one of the most important parameters in determining a splitting line between hot gases and relatively fresh air in a fire room [6,7]. The objective of the present study is to propose a new method for the determination of the interface height derived from the measurements of the transient development of a forced-ventilation enclosure fire.

EXPERIMENTAL DESIGN

Experimental set-up

The PLUTON fire test cell facility is 9.0 m long, 6.0 m wide and 7.4 m high, providing a total volume of about 400 m^3 (Figure 1). The fire room is supplied with fresh air through an inlet (0.5 x 0.6 m^2) located against the North wall center and 1.5 m above the floor. This air inlet is directly connected with an open atmosphere. The exhaust (0.5 x 0.8 m^2) of the experimental facility is located near the West wall center and 6.0 m above the floor ; this one is controlled by an industrial-like ventilation network which extracts the combustion products from the fire compartment. The ventilation operating conditions used during the experiments (Table 1) are a volume flow rate of 1200 m^3/h under steady conditions (initial conditions of the experiments).

The South wall surface of the room is covered with fireproof fiber (THERMIPAN, 50 mm in thickness) in order to protect the concrete wall from thermal stresses. The entire fireproof wall is supported by a steel structure.

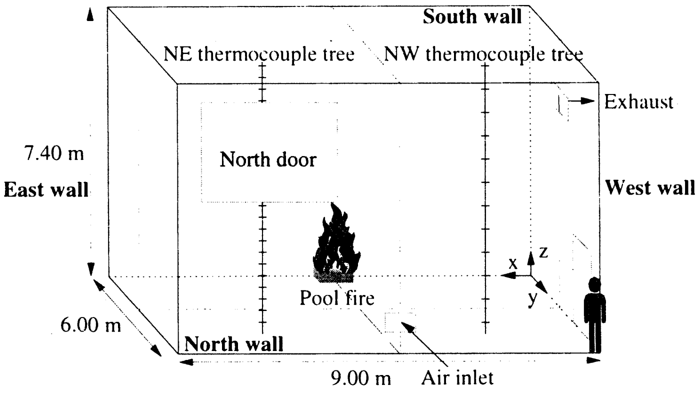

FIGURE 1 : Diagram of the PLUTON fire test room

TABLE 1 : Main characteristics of experiments

Test	Tank geometry	Tank area	Type of fuel	Init. volume of fuel	Mean HRR	Init. forced-ventilation conditions
	-	m²	-	m^3 (x 10^{-3})	kW	m^3/hour
1	square	0.4	TPH/TBP	20	360	1200
1A	square	0.4	Ethanol	20	215	1200
2	square	1	TPH/TBP	50	645	1200
2A	square	1	Ethanol	50	510	1200
3	square	3.2	TPH/TBP	160	2140	1200
4	line	3.2 (0.36 x 8.8)	TPH/TBP	160	-	1200
4 bis	line	3.2 (0.36 x 8.8)	TPH/TBP	160	1680	1200

Fuel

Two types of fuel are used during the experiments. The first one is a mixture of liquid hydrocarbons, 70% Hydrogenated TetraPropylene - [TPH (C_{12} H_{26})] and 30% TriButylPhosphate - [TBP ((C_4 H_9)$_3$ PO_4)] by volume. Its main characteristics are density : $\rho = 816$ kg/m^3 and net heat of combustion : $\Delta H_c = 36$ MJ/kg. The second fuel is ethanol. Table 1 sums up the main parameters (fuels, tanks, heat release rate and ventilation conditions) of the seven experiments carried out.

The average heat release rates (HRR) of pool fires are estimated from the mean mass loss rate as [8] :

$$HRR = \Delta H_c . \dot{m}''. A$$

where ΔH_c is the net heat of combustion, $\dot{m}''$ is the mean mass loss rate and A is the area of the pool fire.

All the tanks are located against the middle of the South wall in the PLUTON fire room (Figure 1). In order to measure the evolution of fuel mass flow, the tanks are placed on one scale for the square pool and on two scales for the line pool. The initial position of the fuel surface is 0.5 m above the floor. The load cell is heat-insulated to minimize thermal stresses due to hot gases filling the fire room.

Temperatures

Temperatures are measured in the room by means of sheathed thermocouples, type K and 0.2 mm in diameter. All the temperatures reported here are uncorrected values. A first vertical thermocouple rake is placed close to the North/East corner, 2.25 m from the East wall and 1.5 m from the North wall (Figure 1). This rake contains 31 vertically aligned thermocouples spaced 0.25 m apart. The bottom thermocouple is 0.05 m above the floor and the top thermocouple is 0.05 m below the ceiling.

A second vertical thermocouple rake is located close to the North/West corner, 2.25 m from the West wall and 1.5 m from the North wall (Figure 1). This rake contains 16 vertically aligned thermocouples spaced 0.50 m apart. Again, the bottom thermocouple is 0.05 m above the floor and the top thermocouple is 0.05 m below the ceiling.

All the temperatures measured are not reported here and are beyond the scope of this paper.

METHOD OF DETERMINATION OF THE INTERFACE HEIGHT, THE LOWER AND UPPER LAYER TEMPERATURES

Transient development of the temperature profiles in the PLUTON fire room (Test 1A)

As soon as the fire starts in the PLUTON fire test room, a plume of hot combustion products impinges on the ceiling and spreads under it. Then, a vitiated hot upper layer begins to fill the fire room and becomes thicker, showing a vertical temperature profile (Figure 2, t = 20 s to 180 s) due to a poor mixing process inside the upper layer [9]. The temperature profiles presented here come from the NE thermocouple tree (Figure 1), the NW thermocouple tree providing quite similar results. Near the floor, the temperature rise is small, compared that near the ceiling. If the fire is under-ventilated with low air-inlet positions, a single-layer profile with a temperature gradient is produced in the fire compartment (Figure 2, t = 300 s to 2000 s) and the lower region is no longer observed [10]. The pool fire self-extinguishes for lack of fuel (ethanol) about 2000 s after the ignition. Then, a cooling phase of the compartment begins and the lower region progressively reappears showing a nearly constant temperature. A vertical gradient temperature is seen again in the hot upper region, which is reduced with time by the cooling of the room (Figure 2, t = 2200 s to 3200 s). The same phenomena are observed for all other experiments described in Table 1.

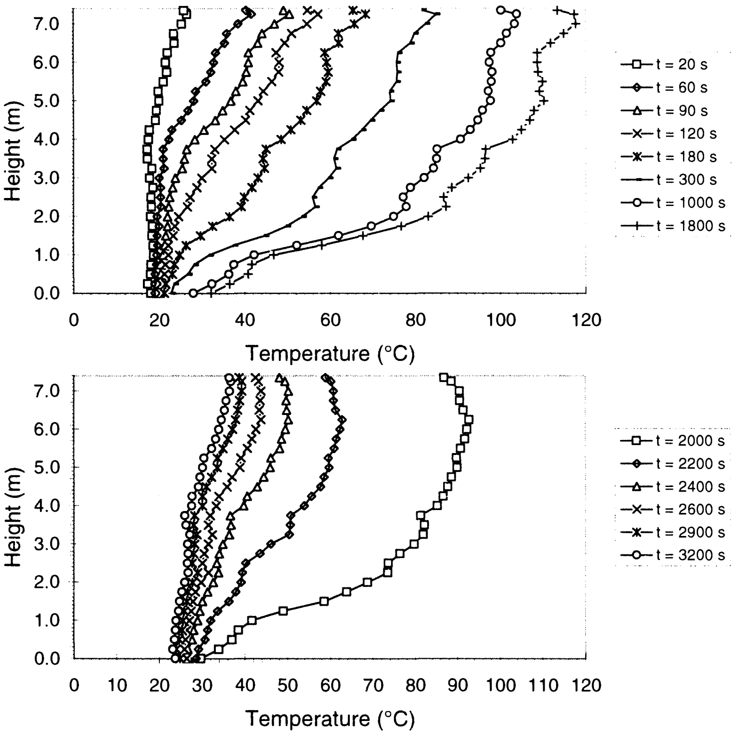

FIGURE 2 : Temperature profiles versus time - Test 1A

Similar results have been previously observed by Backovsky [10] in experiments with forced-ventilation fires in the LLNL fire test cell. The burner supplied with methane gas was located at the center of the room and the heat release rates were in the range of 100 to 400 kW. But, Backovsky didn't investigate the cooling phase of the compartment. Furthermore, the fire growth showing a vertical temperature profile in the upper region and a quasi constant temperature in the lower region has been observed in several experimental studies including natural and/or forced ventilation enclosure fires [10,11,12,13].

Methods proposed in the literature to determine the interface height

Several methods have been proposed to determine the interface height : the N-percentage rule by Cooper [11], the mass equivalency method by Quintiere [1,16], a technique mixing the previous technique and the method used to estimate the neutral plane position by Janssens [14]. More recently, He [7] carried out a detailed analysis of the three previous methods and considered that they are quite subjective or empirical. Thus, He proposed two new interesting techniques to determine the interface height based on mathematical considerations of uniformity and optimization but, at present, further comparisons with experimental data are required. However, all the methods consider that the upper layer temperature is constant which is generally in contradiction with experimental results dealing with transient development of fires [10,13] since a thermal gradient is often observed. Therefore, this study proposes to take into account the production of a thermal gradient in the upper region to determine the interface height.

Mathematical description of the new method

The interface height determination method proposed here (Figure 3) assumes that the estimated lower temperature is constant from the floor to the interface height but that the upper temperature profile has a constant vertical thermal gradient from the interface height to the ceiling of the room.

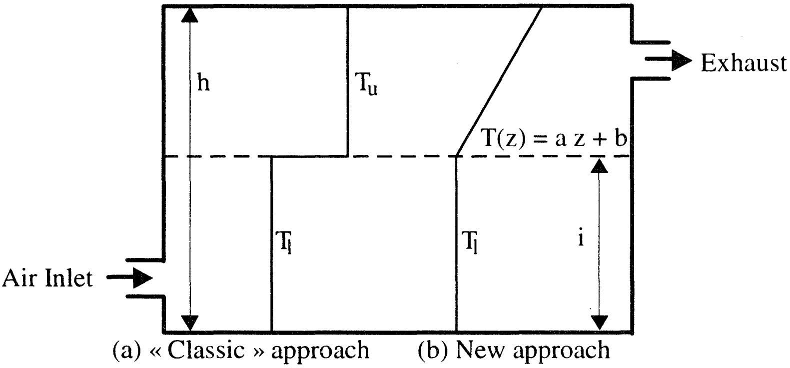

FIGURE 3 : Assumptions of temperature profiles in the fire compartment.

Therefore, the temperature profile is written as :

$$\text{if } z \in \left[0;i\right], \text{ then } T(z) = T_l \,, \qquad (1)$$
$$\text{if } z \in \left[i;h\right], \text{ then } T(z) = a\,z + b \,,$$

where z is the elevation above the floor, i is the interface height, h is the height of the fire room, a and b are the linear function parameters and T_l is the lower layer temperature. The upper layer temperature T_u can be defined as the average of the T(z) function for $z \in \left[i;h\right]$.

This function T(z) is supposed continuous on the region $\left[0;h\right]$ and then :

$$T(z=i) = a\,i + b = T_l \qquad \text{and} \qquad T(z=h) = a\,h + b = T(h) \tag{2}$$

a and b can be estimated with the lower layer temperature, the interface height and the temperature under the ceiling as :

$$a = \frac{T(h) - T_l}{h - i} \qquad \text{and} \qquad b = \frac{h\,T_l - i\,T(h)}{h - i} \tag{3}$$

Now, the problem is to determine the three unknowns T_l, T(h) and i. Using the same approach as the mass equivalency technique [16,1], two integrals of the T(z) function can be defined :

$$I = \int_0^h \frac{dz}{T(z)} \qquad \text{and} \qquad J = \int_0^h T(z)\,dz \tag{4}$$

These two quantities can be estimated from experimental data as :

$$I = \sum_{j=1}^{n} \frac{\Delta z_j}{T(z_j)} \qquad \text{and} \qquad J = \sum_{j=1}^{n} T(z_j)\,\Delta z_j \tag{5}$$

The mass equivalency method provides only two equations for three unknowns ; consequently, we choose to determine T_l from the thermocouples close to the floor of the fire room. Although this choice appears subjective and empirical [7], one can consider that it is quite reasonable because the experimental lower layer temperature (T_l) is probably less « disturbed » than the temperature measured under the ceiling due to ceiling flows. In addition to this, the thermal gradient assumption seems to be more appropriate in rendering the experimental transient vertical temperature profiles clearly and this assumption allows us to expect good results.

From equations (1), (3) and (4), we find :

$$I = \frac{i}{T_l} + \frac{h-i}{T(h)-T_l}\ln\left(\frac{T(h)}{T_l}\right) \qquad \text{and} \qquad J = h\,T(h) + \frac{1}{2}\left(T_l - T(h)\right)\left(i+h\right) \tag{6}$$

Let :

$$x_1 = \frac{i}{h} \text{ with } x_1 \in \left[0;1\right] \qquad \text{and} \qquad x_2 = \frac{T(h)}{T_l} \tag{7}$$

where x_1 is a non-dimensional length and x_2 a non-dimensional temperature.

The relations (6) can then be written as follows :

$$x_1 + \frac{1-x_1}{x_2-1}\ln(x_2) = \frac{IT_1}{h} \qquad \text{and} \qquad x_2(1-x_1) + 1 + x_1 = \frac{2J}{hT_1} \tag{8}$$

Again, let :

$$A_1 = \frac{IT_1}{h} \quad ; \quad A_2 = \frac{2J}{hT_1} \quad ; \quad X = 1 - x_1 = \frac{h-i}{h} \tag{9}$$

X is the ratio between the height of the upper region and the height of the fire room. Introducing (9) into (8) to eliminate x_2 ,we obtain finally :

$$X^2 \ln\left(\frac{X+(A_2-2)}{X}\right) - (A_2-2)X + (A_2-2)(1-A_1) = 0 \tag{10}$$

The solution of (10) can be easily calculated using a Newton-like method [15].

APPLICATION AND DISCUSSION

Interface height and room temperature profiles

Figures 4 and 5 show the evolution of experimental temperature profiles and the interface heights determined from the new method and the Quintiere method (QSC method) for Test 1A (see Table 1). The history of the fire room extends from ignition to the compartment cooling after the pool fire extinction (t = 2000 s). Concerning the interface height (Figure 6), the new method is close to the QSC method at the onset of the fire (t = 20 s). Afterwards, the interface height estimated by means of the new method decreases quickly and reaches the floor of the compartment about t = 200 s. This result is in good agreement with both experimental temperature data (Figure 4) and the single-layer profiles described by Backovsky [10]. At the same time, the QSC method stabilizes the interface height 1.30 m above the floor and, thus, assumes a lower region which is not clearly established regarding temperature profiles. From t = 200 s to 2000 s (fire extinction due to fuel deficiency), a quasi-steady state of the interface height is observed for both methods (Figure 5). The former keeps one single-layer temperature profile and the latter an interface height at the same location (Figure 6). After the fire extinction, the interface height for both methods is seen to increase as the fresh air inlet cools the compartment. The cooling phenomena appears to be processed in a similar way by the two methods, the new method estimating an interface height about 1.5 m smaller than the QSC method.

Concerning the room temperature profiles throughout Test 1A, the temperature distribution estimated by the new method is well-fitted with the experimental data as seen in Figures 4 and 5, especially when the two-layer profiles are observed.

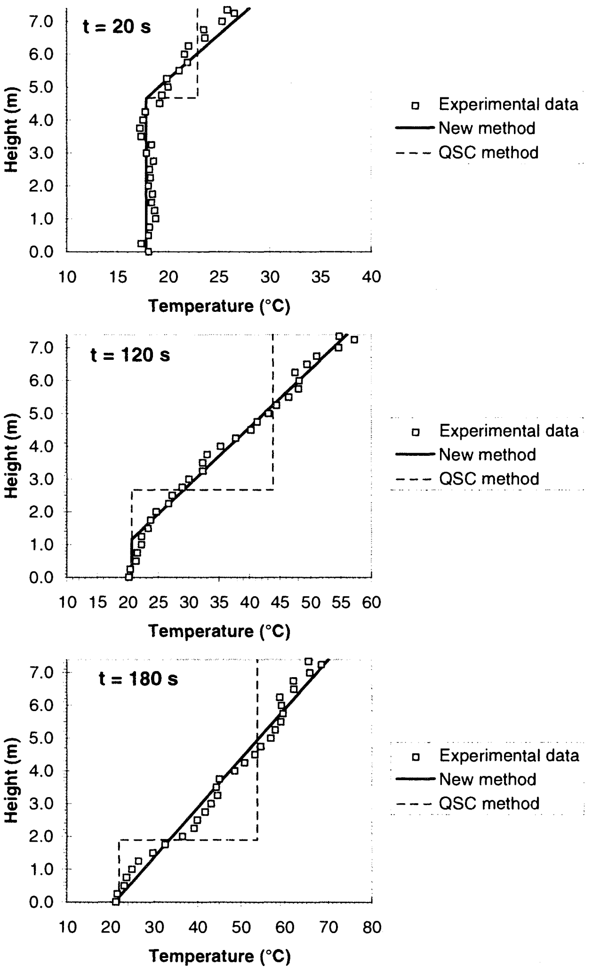

FIGURE 4 : Room temperature profiles from 20 to 180 s - Test 1A

The QSC method is in poor agreement especially in the hot upper layer because the basic assumption assumes a constant temperature in this region. The upper layer temperatures presented in Figure 7 for both QSC and the new method show a quite similar profile. The new method under-estimates the upper layer temperature by 12°C in comparison to the QSC method at t = 1800 s because, for a given temperature distribution, the upper zone temperature is a function of the interface height. Since the interface height is lower in the new method compared to the QSC method, the upper zone temperature is lower for the new method.

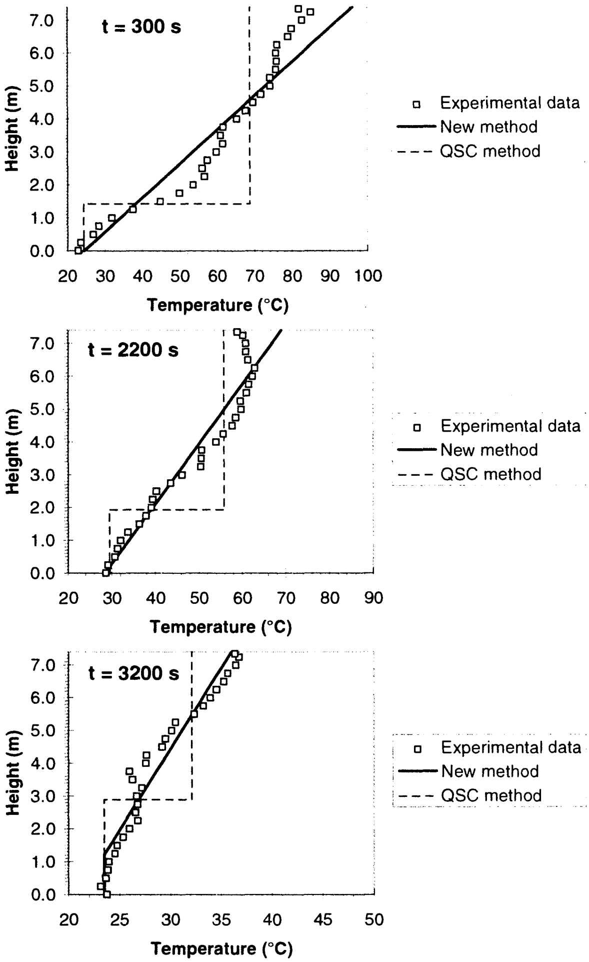

FIGURE 5 : Room temperature profiles from 300 to 3200 s - Test 1A

Limitations

The new method assumes a constant temperature in the lower region of a fire room and a vertical temperature gradient in the upper region. In practice, the last assumption is often observed during the transient development of a fire room [10,11,12,13]. If the fire room reaches a thermal steady state, the temperature distribution can become discontinuous close to the interface height and two distinct regions with uniform temperature can be observed [1]. The new method is then no longer valid.

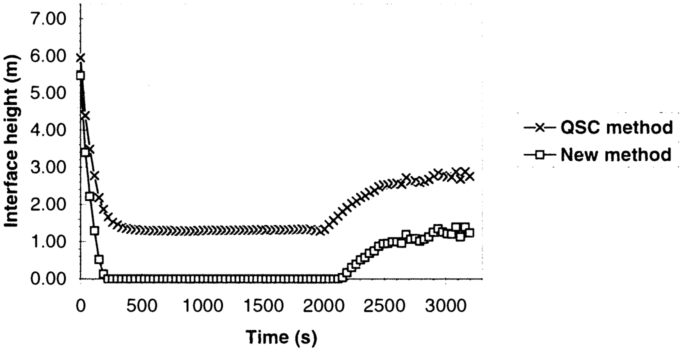

FIGURE 6 : Evolution of interface height - Test 1A

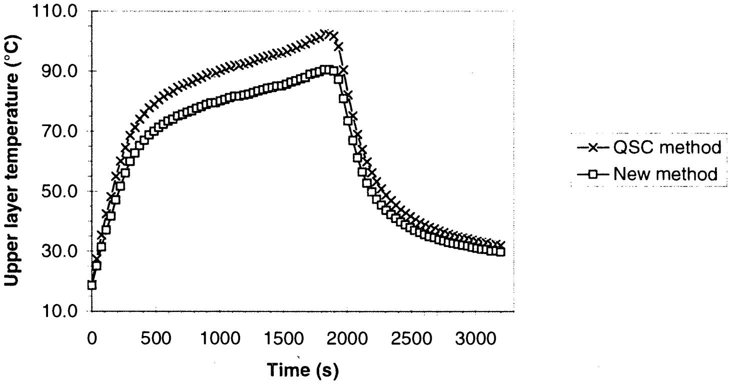

FIGURE 7 : Evolution of the upper layer temperature (T_u) - Test 1A

CONCLUSION

As mentioned above, the knowledge of the interface height in forced-ventilation enclosure fires is of prime interest since it enables us to assess the reliability of zone model computer codes. Existing approaches such as the QSC method [1] show notable discrepancies with the experimental data obtained during recent fire tests carried out by the IPSN. That is why a new method derived from the mass equivalency technique and based on the assumption of a vertical temperature gradient in the hot upper layer has been developed. The results of this new method are compared with the experimental data and with the QSC method. The new method improves the appraising of the interface height and the temperature profiles, especially in the two-layer and the one-layer cases observed in under-ventilated enclosure fires [10]. The new method has provided satisfactory results for all the tests in Table 1 but more investigations are required in order to check the applicability to the transient development of natural ventilation enclosure fires [13].

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