A SIMPLE METHOD FOR PREDICTION OF MASS BURNING RATES IN COMPARTMENT FIRES

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ABSTRACT

In the present paper, the effect of ventilation and burning area on the mass burning rate in compartment fires was studied through the reduce scale model experiments. It was found that they both determine the compartment fire behavior and their common effect could be expressed by the ratio of $\rho_0 g^{1/2} AH^{1/2}/Av$, on the basis of which the regions of various fire characteristics were divided. Based on experimental results, according to steady-state energy balance on fuel surface, a new simple model was proposed in which the mass burning rate can be calculated as a function of ventilation parameter and fuel surface area, and the critical conditions for the transition between various fire characteristics were obtained. The calculated results were in good agreement with the experimental data and the previous researches.

Key Word: Compartment fire, Ventilation-controlled, Fuel-controlled, Ventilation parameter, Fuel surface area.

INTRODUCTION

A large number of experiments has been conducted for fully developed compartment fires ventilated through a single rectangular opening centrally located in one wall. It was indicated that the main factors affecting burning behavior in a compartment were opening condition, fuel bed area, compartment size and shape, thermal conductivity of walls, properties of burning materials, position of fire source and so on, and the effect of ventilation opening size and shape can be expressed by the ventilation parameter $AH^{1/2}$,[1] where A and H are the area and height of the ventilation opening respectively. In addition, it was found that the mass burning rate in compartment depend largely on fuel surface area besides ventilation parameter, and the effects of ventilation parameter and fuel surface area are not independent, as they change, various fire characteristics such as extinction, oscillatory combustion, ventilation-controlled and fuel-controlled combustion occurs. Having analyzed data from a large number of compartment fires, Harmathy[1] indicated that there was obvious difference between ventilation-controlled fires and fuel-controlled fires, which can be distinguished by constant values of $\rho_0 g^{1/2} AH^{1/2}/Av$, where ρ_0 is the density of ambient air, g is the gravitational constant, and Av is the fuel surface area. It is important to be able to distinguish between these two regimes as the fuel-controlled fire is generally less severe except in comparison with fires in which the ventilation is very poor.

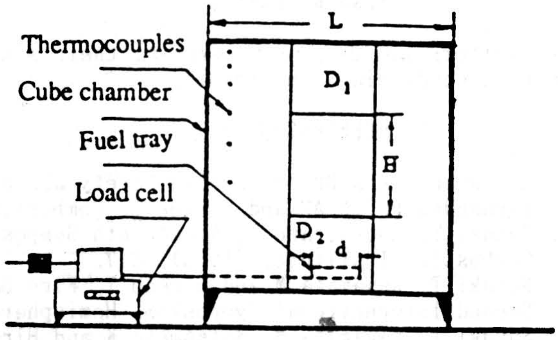

Fig. 1. Schematic diagram of experimental apparatus

H.Takeda[2] examined the effects of ventilation and compartment size on fire behavior for methanol fires using a series of cubic chambers made of asbestos board, and a simple one zone and transient model of compartment fires was established based on the quasi-steady energy balance relationship involving the whole compartment.

In this paper, ethanol fires was studied in a constant cubic chamber with various size opening and fuel tray. a new simple model of compartment fires was presented according to steady-state energy balance relationship on the fuel surface, and the steady mass burning rates of PMMA was predicted successfully. These experimental and calculated results were compared with previous researches in detailed discussion.

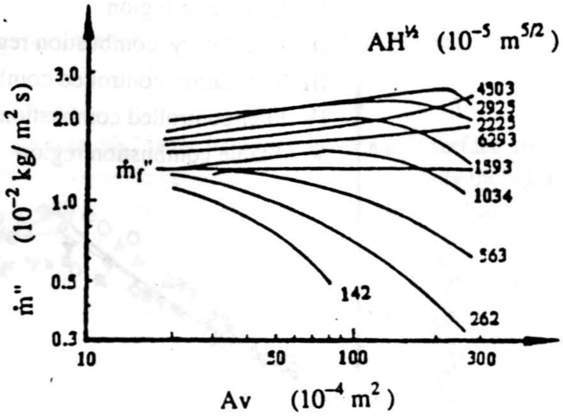

Fig. 2. Experimental results of $\dot{m}''$–Av relation for various $AH^{1/2}$ values

($\dot{m}_f''$— free burning rate in open environment)

EXPERIMENTAL DESCRIPTION AND RESULTS

As shown in Fig. 1, experiments were conducted in the 0.5 m cube chamber made of 2 mm steel board with a rectangular opening of variable height and area. Various size circular fuel tray of 5 cm ~ 20 cm in diameter and 2 cm in depth is installed at the center of the floor, and fuel used is ethanol. The mass burning rates and gases temperatures were measured by load cell and thermocouples respectively.

Experiments showed that the fire characteristics in compartment depend strongly on ventilation parameter $AH^{1/2}$ and fuel tray area Av, when $AH^{1/2}$ is small or Av is large, extinction occurs, and as $AH^{1/2}$ increases or Av decreases, combustion becomes oscillatory and then stable. Fig. 2 shows the experimental results of mass burning rate per unit fuel surface area ($\dot{m}''=\dot{m}/Av$) as a function of Av for various $AH^{1/2}$ values. When $AH^{1/2}$ is certain value, $\dot{m}''$ value rises till maximum and then decreases as Av increases. As $\dot{m}''$ increases and reaches a maximum, it is considered that the fire approaches stoichiometric burning and the fire characteristics transforms from fuel-controlled to ventilation-controlled.

Fig. 3 shows the mass burning rate $\dot{m}$ as a function of Av for various $AH^{1/2}$ values, and the critical curves under which the oscillatory combustion and extinction may be observed in the experiments respectively. Assuming $\xi = \rho_0 g^{1/2} AH^{1/2}/Av$, the critical values of ξ_e, ξ_o and ξ_s, which are corresponding to extinction, oscillatory combustion and maximum $\dot{m}''$ condition respectively, are listed in Table 1.

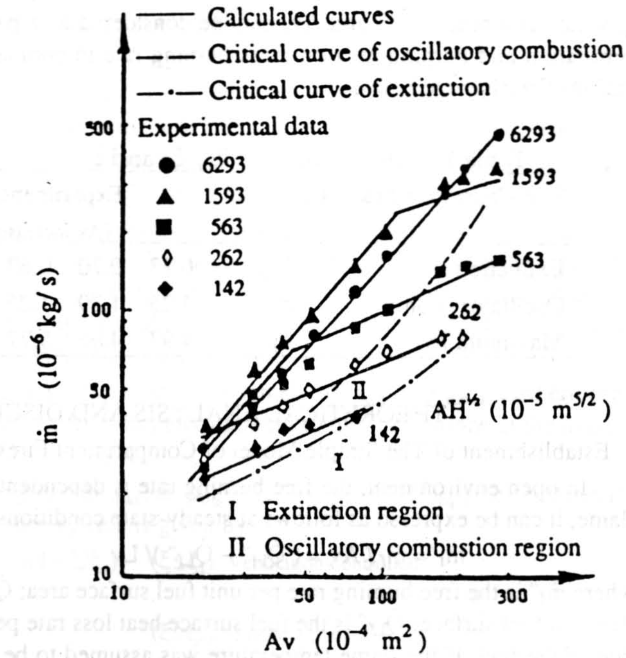

Fig. 3. Relationship between $\dot{m}$ and Av with various $AH^{1/2}$ values and comparison between experimental data and calculated results

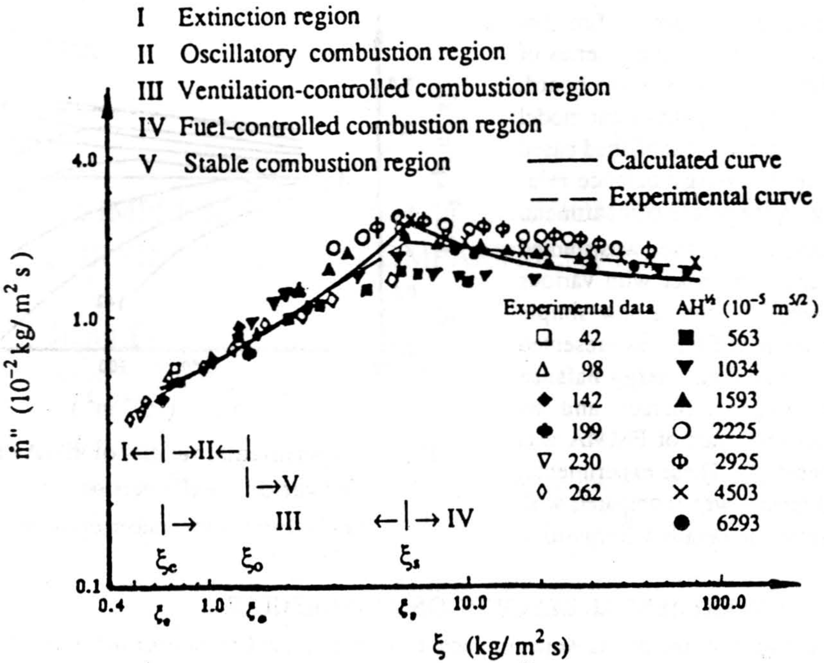

Fig.4. Dependence of $\dot{m}''$ on ξ and regions for various fire characteristics

Fig. 4, plotted as $\dot{m}''$ versus ξ, shows a clear distinction between the ventilation-controlled fires and fuel-controlled fires, and the rigions of various fire characteristics. Besides, this figure demonstrates that the ξ, which combines $AH^{1/2}$ and Av, may be considered as a parameter for indicating the common effect of ventilation and burning area on mass burning rate in compartment fires, and for dividing the regions of various fire characteristics.

Table 1. Critical values of ξ_e, ξ_o and ξ_s

Fire Characteristics	Critical ξ (kg/m²s)	Experimental Data (Av increasing →)					Average Value	Calculated Value
Extinction	ξ_e	0.73	0.70	0.67	0.50	0.46	0.61	0.55
Oscillatory comb.	ξ_o	1.25	1.39	1.23	1.21	1.42	1.30	1.33
Maximum $\dot{m}''$	ξ_s	4.97	4.86	5.77	4.78	5.18	5.11	5.28

THEORETICAL ANALYSIS AND DISCUSSION

1. Establishment of The Simple Model of Compartment Fires

In open environment, the free burning rate is dependent on the heat transfer to the fuel surface from flame, it can be expressd as follows at steady-state conditions:

$$\dot{m}_f'' = \dot{m}_f / Av = (\dot{Q}_{Ff}'' - \dot{Q}_{Lf}'') / Lv \qquad 1$$

where $\dot{m}_f''$ is the free burning rate per unit fuel surface area; $\dot{Q}_{Ff}''$ is the heat flux per unit surface area from flame to fuel surface; $\dot{Q}_{Lf}''$ is the fuel surface heat loss rate per unit surface area, Lv is the heat of gasification of the fuel. If the flame temperature was assumed to be uniform, the $\dot{Q}_{Ff}''$ can thus be approximately writtten as:

$$\dot{Q}_{Ff}'' = \sigma\varepsilon_f F_f(T_f^4 - T_l^4) + h_f (T_f - T_l) \qquad 2$$

where σ is the Stefen-Boltzmann constant, ε_f is the flame emissivity, F_f is the relevant geometric configuration factor, h_f is the fuel heat transfer coefficient, T is the temperature, and the subscript f and l represent flame and fuel surface respectively.

For compartment fires, the mass burning rate per unit fuel surface area can be expressed as follows at steady-state conditions:

$$\dot{m}'' = \dot{m} / Av = (\dot{Q}_F'' + \dot{Q}_E'' - \dot{Q}_L'') / Lv \qquad 3$$

where $\dot{Q}_F''$ is the flame heat flux per unit fuel surface area, $\dot{Q}_L''$ is the heat loss rate per unit surface area, $\dot{Q}_E''$ is the external heat flux per unit surface area from the hot environment to fuel surface, mainly including the radiant heat flux from walls and layer of hot smoky gases, it may be approximately expressed as:

$$\dot{Q}_E'' = \sigma\varepsilon_g F_g (T_g^4 - T_l^4) + \sigma\varepsilon_w F_w (T_w^4 - T_l^4) \qquad 4$$

where ε, F, and T are relevant emissivity, geometric configuration factor and temperature, subscript g, w, and l represent gas, wall, and fuel surface, respectively. The gas emissivity can be expressed as:

$$\varepsilon_g = 1 - \exp(-KL) \qquad 5$$

where K is the absorption coefficient. The wall temperature T_w was assumed empirically as the following expression according to reference [2],

$$T_w = U (T_g - T_0) + T_0 \qquad 6$$

and the coefficient

$$U = (T_f - T_D - T_0) / (T_f - T_0)$$

where T_D is the temperature difference between gas and wall at the maximum burning condition, and T_0 is the ambient temperature.

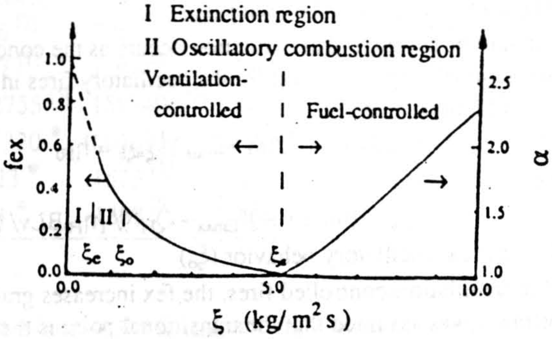

Fig. 5. Dependence of fex and α on ξ

Further, the following relationship mainly for preflashover fires was introduced for the inflow rate of air by ventilation,[1]

$$\dot{m}_{air} = B \rho_0 g^{1/2} A H^{1/2} \qquad 7$$

where B is the empirical constant containing the discharge coefficient and density term.

(1) Mass burning rate

For ventilation-controlled fires ($\rho_0 g^{1/2} A H^{1/2} < \rho_0 g^{1/2} (A H^{1/2})_{eq}$), as the mass burning rate is strongly denpendent on the air supply rate, the heat release rate and flame heat flux to the fuel surface will increase with the mass flow rate of inflow air increasing, so that the proportional relationship between the $\dot{Q}_F''$ and $\dot{m}_{air}$ was assumed as $\dot{Q}_F'' = \varphi' \dot{m}_{air} = \varphi \rho_0 g^{1/2} A H^{1/2}$, furthermore $(\dot{Q}_E'' - \dot{Q}_L'') / Lv = \phi$ =constant.

For fuel-controlled fires ($\rho_0 g^{1/2} A H^{1/2} > \rho_0 g^{1/2} (A H^{1/2})_{eq}$), with the mass flow rate of inflow air increasing, the excessive air supply and the heat loss through the ventilation opening will increase, and the average gas temperature in compartment will decrease, as a result the external heat flux from the hot environment to the fuel surface will reduce. Therefore the inverse proportional relationship between the $\dot{Q}_E''$ and $\dot{m}_{air}$ was assumed as: $\dot{Q}_E'' = \psi' / \dot{m}_{air} = \psi / \rho_0 g^{1/2} A H^{1/2}$, furthermore $(\dot{Q}_F'' - \dot{Q}_L'') / Lv = \dot{m}_f''$.

When $\dot{m}''$ has a maximum ($\rho_0 g^{1/2} A H^{1/2} = \rho_0 g^{1/2} (A H^{1/2})_{eq}$), it was assumed that $\dot{Q}_E'' = \dot{Q}''_{Emax}$ furthermore $(\dot{Q}_F'' - \dot{Q}_L'') / Lv = \dot{m}_f''$. where $\dot{Q}''_{Emax}$ is the heat flux from hot environment to the fuel surface at the maximum burning condition, which may be obtained from Eq. 4.

Based on these assumptions above, and using $\dot{m}'' = \dot{m}''_{max}$, at $\rho_0 g^{1/2} A H^{1/2} = \rho_0 g^{1/2} (A H^{1/2})_{eq}$, the coefficient φ, ϕ and ψ can be obtained. So that the mass burning rate is given by

$$\begin{cases} \dot{m}'' = \dot{m}/Av = \dot{m}_f'' + \dot{Q}''_{Emax}/Lv - (\dot{Q}_{Ff}''/Lv)(1 - \xi/\xi_s) & (\xi \le \xi_s) \text{ Ventilation-controlled} \\ \dot{m}'' = \dot{m}/Av = \dot{m}_f'' + (\dot{Q}''_{Emax}/Lv)(\xi_s/\xi) & (\xi \ge \xi_s) \text{ Fuel-controlled} \end{cases} \qquad 8$$

(2) Excess fuel factor and excess air factor

Bullen and Thomas[1] defined an excess fuel factor as $fex = 1 - \dot{m}_{air} / \gamma \dot{m}$, which is zero for stoichiometric burning and positive if there are unburnt volatiles leaving the compartment, where γ is the stoichiometric air to fuel mass ratio. Using Eqs. 7 and 8, for ventilation-controlled fires, fex can be calculated from Eq. 9.

$$fex = 1 - (BLv\xi/\gamma) / [\dot{m}_f'' Lv + \dot{Q}''_{Emax} - \dot{Q}_{Ff}''(1 - \xi/\xi_s)] \qquad (\xi \le \xi_s) \qquad 9$$

If the excess air factor is described as $\alpha = \dot{m}_{air} / \gamma \dot{m}$ for fuel-controlled fires, which equals unit for stoichiometric burning and can be obtain from Eq. 7 and 8.

$$\alpha = (BLv\xi/ \gamma)/ [\dot{m}_f''Lv + \dot{Q}''_{Emax}(\xi_s/\xi)] \qquad (\xi \geq \xi_s) \qquad 10$$

The relationship between fex, α and ξ are shown in Fig. 5.

(3) Determination of the critical values of ξ for various fire characteristics

A. The transition from ventilation-controlled fires to fuel-controlled fires (ξ_s)

It is considered as the critical condition between ventilation-controlled fires and fuel-controlled fires that combustion becomes stoichiometric combustion. Substitution of fex=0 at $\xi=\xi_s$ into Eq. 9 or $\alpha=1$ at $\xi=\xi_s$ into Eq. 10, gives

$$\xi_s = \rho_0 g^{1/2} (AH^{1/2})_{eq} / Av = (\gamma/ B)(\dot{m}_f'' + \dot{Q}''_{Emax}/ Lv) \qquad 11$$

B. The critical extinction behavior (ξ_e)

It may be assumed that extinction occurs as the concentration of fuel vapor increases to and beyond its upper flammability limit (η_{F0}) for the oscillatory fires in which the ventilation is very poor. Substitution of Eq. 7 and 8 into

$$\eta_F \,|_{\xi=\xi_e} = \dot{m}/(\dot{m} + \dot{m}_{air})\,|_{\xi=\xi_e} = \eta_{F0}$$

gives

$$\xi_e = (\dot{m}_f''Lv + \dot{Q}''_{Emax} - \dot{Q}_{Ff}'')/ [\eta_{F0}BLv/ (1-\eta_{F0}) - \dot{Q}_{Ff}''/ \xi_s] \qquad 12$$

C. The critical oscillatory behavior (ξ_o)

For ventilation-controlled fires, the fex increases gradually then steeply as ξ decreases (See Figure 5), therefore it was assumed that the transitional point is the critical point at which the oscillatory combustion occurs, that is to say

$$(dfex/ d\xi)\,|_{\xi=\xi_o} = -1/ \xi_s \qquad 13$$

Substitution of Eq. 9 into Eq. 13 gives

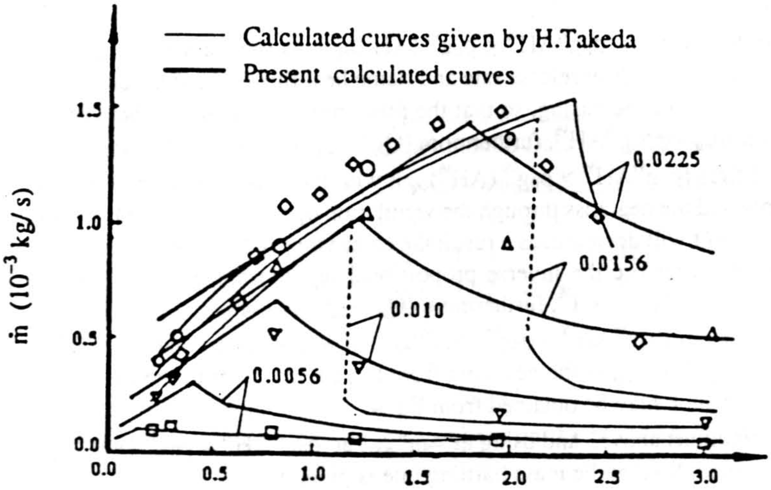

Fig. 6. Calculated results of $\dot{m}$–$AH^{1/2}$ relation for PMMA compartment fires and comparison with previous results (L=0.4 m)

Experimental Data

□ Av=0.0056 m^2 J. Quintiere
▽ Av=0.0100 m^2 J. Quintiere
△ Av=0.0156 m^2 J. Quintiere
○ Av=0.0225 m^2 J. Quintiere
◇ Av=0.0225 m^2 H. Takeda

$$\xi_o = \{[(BLv\xi_s/\gamma)(\dot{m}_f''Lv + \dot{Q}''_{Emax} - \dot{Q}_{Ff}'')]^{1/2} - (\dot{m}_f''Lv + \dot{Q}''_{Emax} - \dot{Q}_{Ff}'')\}(\xi_s/\dot{Q}_{Ff}'') \qquad 14$$

2. Calculation Results and Discussion

The calculation results have been shown in Fig. 3, Fig. 4, Fig. 5 and Table 1 in comparison with experimental data respectively. Besides, according to the experimental conditions of H.Takeda and J.Quintiere,[2,3] the mass burning rate of PMMA was calculated for various $AH^{1/2}$ and Av values, as shown in Fig. 6, and the results were in good agreement with their experimental data and theoretical curves given at the same time for comparison. The data used in calculation are listed in Table 2.

Table 2. Specified parameters for the calculation

			Ethanol	PMMA		Ethanol	PMMA
F_f	0.75 [4]						
F_g	0.56 [4]	h_f (W/m^{2}K)	17.6 [2]	7.0 [3]	T_l (K)	351[5]	543 [1]
F_w	0.42[4]	K (1/m)	0.37 [1]	1.30 [3]	T_0 (K)	298 *	288 [3]
g (m^2/s)	9.81	Lv (J/kg)	932755 [5]	1588400 [3]	ε_f	0.06 [1]	0.25 [1]
T_D (K)	100 [2]	$\dot{m}_f''$ (kg/m^{2}s)	0.01320 *	0.01035[3]	ε_w	0.97 [6]	0.96 [6]
σ (W/m^{2}K^4)	5.67×10^{-8}	T_f (K)	1123 *	1573 [1]	γ	9.00 [5]	8.25 [3]
ρ_0 (kg/m^3)	1.18 [1]	T_{gmax} (K)	773 *	1303 [2]	η_{F0}	0.18 [1]	

✱ Experimental data

In the present model, the critical values of ξ were related to the $\dot{Q}''_{Emax}$ and $\dot{m}_f''$, generally, both of them are dependent on fuel surface area. Howevre, when the fire increases in size to and beyond the point at which interaction with the compartment boundaries becomes significant, the $\dot{Q}''_{Emax}$ is nearly independent of Av. In addition, according to the experimental results of hydrocarbon liquid pool fires given by Blinov and Khudialov,[1] when pool diameter is around 0.1 m or more than 1.0 m the $\dot{m}_f''$ is almost independent of Av. Similarly, the $\dot{m}_f''$ is almost a constant for various fuel tray diameters from 0.05 m to 0.2 m in present experiments (See figure 2). So that it may be approximately considered that the critical values of ξ are dependent only on the fuel type and wall material, and can be used to describe the fire characteristics for fully developed compartment fires.

CONCLUSION

1. Both opening condition and burning area are important factors affecting compartment fire behavior. The various fire characteristics was found to be described by the ratio of $\xi=\rho_0 g^{1/2} AH^{1/2}/Av$ in some specific situations.
2. A new simple model for compartment fires involving liquid or thermoplastic fuel has been established using steady-state energy balance relationship on fuel surface, and also has been proven to be reasonable in comparison with the small-scale experimental data and calculated results given by other model. However, it ought to be compared further with the full-scale compartment fires.

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