A Compartment Burning Rate Model for Various Scales

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ABSTRACT

A model is presented that explains the mass loss rate in a compartment as a function of scale. The effect of ventilation is included in the model by the inclusion of the ambient oxygen concentration in the lower layer that results due to vent mixing. The model is executed in BRI2002, a zone model, capable of computing species and thermal conditions in the upper and lower compartment gas layers. Computations show good agreement with two different scale-down compartment fires for liquid fuel. The results can accurately distinguish scale effect from these experiments and allow us to focus on fundamentals of fire phenomena.

KEYWORDS: compartment fires, fire growth, modeling

NOMENCLATURE LISTING

A	area (m^2)
$A_{F,b}$	burning fuel area
c_p	specific heat
D	diameter of the fuel pan (m)
f	mixing ratio
g	grabity
H	compartment height (m)
Δh_c	heat of combustion (kJ/kg)
L	heat of gasification (kJ/kg)
$\dot{m}''_F$	mass loss rate per unit area (kg/ m^{2}s)
$\dot{m}$	mass flow rate (kg/ s)
N	neutral plane height
$\dot{q}''_{External}$	external radiation heat flux per unit area (kW/m^2)
$\dot{q}_{External}$	external radiation heat flux (kW)
$\dot{q}''_f$	flame heat flux (kW/m^2)
$\dot{q}''_{net}$	net heat to the fuel surface (kW/m^2)
$\dot{q}''_{r,i}$	incident heat flux due to walls and smoke (kW/m^2)
r	stoichiometric oxygen to fuel mass ratio
S	window sill height
s	stoichiometric air to fuel mass ratio
T	temperature (K)
W_o	opening width
Y	mass fraction
Z	layer interface
ε	emmisivity
ϕ	equivalence ratio
κ	extinction-absorption coefficient of the flame
σ	Stefan-Boltzmann coefficient

subscripts

c	convection
e	entrained
exp	experiment
F	fuel
f	flame
q	smoke layer
i	incident
l	lower layer
mix	entraining from upper layer
N	natural
net	net
o	ambient or opening, free burning
ox	oxygen
r	radiation
u	upper layer
v	vaporization
w	wall
∞	ambient

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INTRODUCTION

CFD models are now considered to be mature in fire applications and give the most complete prediction; however, the drawback of CFD technique is that it is computationally demanding and lack adequate validation. Especially for predicting the burning rate, the potential errors are reported caused by uncertainty in the absorption coefficient and flame temperature [1].

The calculating mass loss rate model for zone models has been validated for under-ventilated compartment fires for pool fires by authors [2]. It is consisted of two parts; radiant heat flux from the flame and external radiation heat flux. Instead of calculating the flame radiation, the mass loss due to the flame is expressed by multiplying the free burning rate by surrounding oxygen mass fraction considering ventilation effect. In this research, the dimensionless correlations for large liquid pool fires by Babrauskas [3] are used in the model for estimating free burning rate per unit exposed area. And based on entering air jet approach, the entrainment model is generated to doorway and window openings to predict air vitiation properly.

The mass loss due to the external radiation feedback is also important. In a ventilation-limited condition, it has been reported from experiments that the fuel mass loss rate is directly related to mass flow through the vent. However, this result excludes a recognition of the thermal circumstances which turns out to be a really the controlling factor in small scale and less-charring fires. To support this claim, the effect of fuel type on the mass loss rate reported by Bullen and Thomas [4] (Fig. 1) shows the lack of completeness of this correlation with ventilation expressed by $A_o\sqrt{H_o}$. For this reason, although a lot of fully developed fire studies have primarily been performed at small scales for security and economical reasons, the results have not been fully trusted. In our model, the mass loss due to the external radiation is validated properly as a function of trans-missivity of the flame, so it is believed to contribute much on enhancing small and less-charring fires but not on enhancing large sooty fires.

The current study will use the experimental base of compartment fire experiments described by Utiskul [5] and Naruse. An early modeling attempt using a single zone (uniform compartment gas property) model had success in describing the features of the experiments. The experimental work also has served a basis to validate CFD modeling (using the NIST FDS code) with a prescribed fuel mass loss rate, Hu et al [6]. Herein, a dynamic burning algorithm will be described that is styled for use in a zone model (a two-layer control volume approach for the compartment gases). The model will not only show global fire dynamics, but also promote more effective use of small scale experiments.

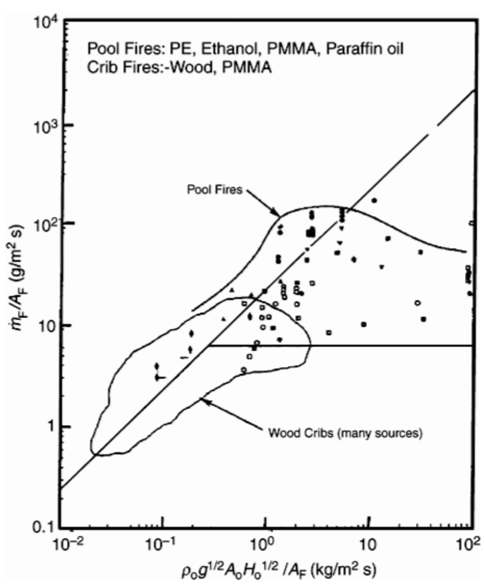


Fig. 1. Fuel mass loss rate versus ventilation parameter in fully developed fires [4]

DESCRIPTION OF EXPERIMENT

The experimental set-up corresponds to two scaled-down cubic-shaped compartments that communicate to the exterior through an adjustable wall vent arrangement (Fig. 2). The compartments sizes are 40 x 40 x 40 cm and 80 x 80 x 80 cm. The wall vent arrangement consists of two vents of equal size located at the top and bottom of one of the compartment vertical walls. The vent's width varies between 2 and 40 cm (1/6 scale), 2 and 80 cm (1/3 scale) respectively; the vents height varies between 1 and 3 cm (1/6 scale), 1 and 6 cm (1/3 scale) respectively; the corresponding total venting area ranges from 4 to 240 cm2 (1/6 scale), 4 to 960 cm2 (1/3 scale) respectively. One wall is equipped with a viewing glass window and allows for direct flame observation. The heptane fuel is placed in a round-shaped pool located at the center of the compartment floor. The fuel pans are modified Pyrex® glass containers of different size, with diameters ranging from 6.5 to 19 cm (1/6 scale), 12 to 36 cm (1/3 scale) respectively; the corresponding fuel source area varies between 33.2 and 283.5 cm2 (1/6 scale), 113.0 and 1017.4 cm2 (1/3 scale) respectively.

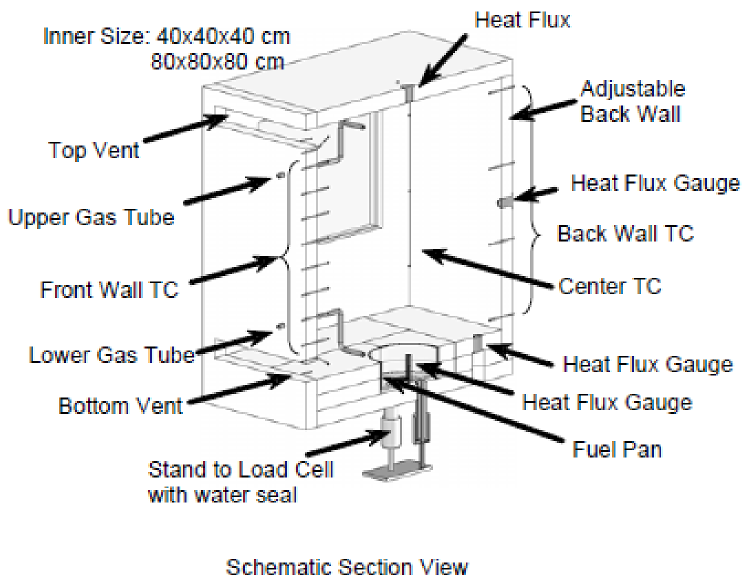


Fig. 2. Experimental configuration

The compartment instrumentation includes a load cell system, an array of 19 thermocouple, 4 heat flux gauges, 2 pressure transducers, and a gas analysis system (Fig. 2). The load cell is installed below the fuel pan and is used to monitor total fuel mass consumption, thereby providing the time history of the fuel mass loss rate; the load cell data are corrected for pressure variations inside the compartment. Thermocouples are used to monitor gas temperatures at various locations, including near the compartment floor and ceiling. Heat flux gauges are used to quantify the thermal feedback to the heptane pool, as well as the heat transfer to the inert wall surfaces; the gauges are water-cooled at a temperature approximately equal to 65℃. Pressure transducers are used near the top and bottom vents, thereby providing an estimate of the flow rates across the vents. Gas sampling probes are installed near the compartment floor and ceiling, and are used to monitor the concentrations of important chemical species, such as oxygen, carbon dioxide and carbon monoxide; the gas analysis data are time-corrected for the delays associated with sampling and detection.

ZONE MODEL DISCRIPTION

The zone model described by Tanaka and Yamada [7], known as BRI2002, will be used as the basis of our calculations (Fig. 3). The physics and mathematics for computing the zone properties for a prescribed mass loss rate are well documented [7]. However, a dynamic fuel mass loss rate model is now included. That model addresses (1) the effects of thermal and oxygen feedback due to the confined compartment gases on the mass loss rate of the exposed fuel, (2) mixing between the upper and lower layers to allow for the reduction of oxygen supply to fuel in the lower layer, typically on the floor, and (3) the phenomenon of flame extinction using a critical flame temperature.

This new mass loss algorithm has been added to BRI2002, and tested against data from small-scale compartment experiments involving the burning of heptane pool fires in a compartment with a distinct floor and ceiling slit-vent [5].

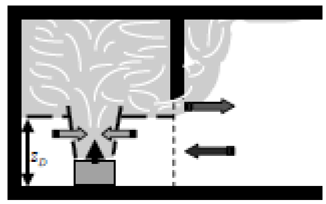


Fig. 3. Basic Zone model for a fire

NEW FIRE ALGORITHM

The new algorithms added to the zone model are described here. First, the mass loss rate is expressed in terms of the normal ambient free burning rate, linearly adjusted by the lower layer oxygen mass fraction, and augmented by the external radiant heat flux to the pool from the compartment. The governing equation is:

$$\dot{m}_F = \dot{m}''_{F,o} A_{F,b} \frac{Y_{ox,l}}{Y_{ox,o}} + \frac{\dot{q}_{External}}{L} \qquad (1)$$

where $A_{F,b}$ is the burning fuel area, $\dot{m}''_{F,o}$ is the free burning rate per unit area in a quiescent air environment, and $Y_{ox,o}$ is the oxygen fraction in normal air equal to 0.233. The first term, the mass loss rate due to the flame, is a very useful form because it is based on the free burning rate that can be available from experiments or empirical correlations. The second term, the thermal effect, consists of the enhanced mass loss rate due to incident radiation from the heated compartment, and the attenuation of the flame radiation. The incident heat flux ($\dot{q}''_{r,i}$) due to the walls and hot smoke to the fuel pan is computed in the BRI zone model. However the flame attenuates this incident heat flux over the portion of the fuel area that is burning, $A_{F,b}$. The external heating rate is then computed in Eq. (1) as

$$\dot{q}_{External} = \dot{q}''_{r,i}(A_F - A_{F,b}) + (1-\varepsilon_f)\dot{q}''_{r,i} A_{F,b} \qquad (2)$$

FUEL PROPERTIES

The fuel in this case is heptane floated on water. The most problematic property is the heat of gasification. Based on free burn experiments it was, surprisingly, found that the heat of gasification at steady burning was not the thermodynamic value for the heptane, 0.48 J/g. After careful tests with and without the water, it was determined that the water caused a significant heat loss that increased the apparent heat of gasification to 1.4 J/g [8], therefore this value was used in all of the computations as it conformed to the experimental conditions for the compartment. The other necessary fuel properties are listed below:

Heat of combustion	41.2 kJ/g	
Free burning rates per unit area	11g/m2s	(D = 6.5cm ~ 12.0cm)
	$101(1-e^{-1.1D(m)})\ g/m^2 s$	(D > 18.0cm)

where D is the pan diameter, and the factor in the parenthesis is the flame emissivity, ε_f for Eq. (2).

MIXING CORRELATION

In addition to the free burning rate, the concentration of the oxygen feeding the flame ($Y_{ox,l}$) needs to be computed. In room fires when the vent is small and the smoke layer descends close to the floor, the smoke, due to buoyancy and shear mixing near the vent, can contaminate the entering cold fresh air stream (Fig. 4). This phenomenon, called vent mixing, leads to the reduction in oxygen feeding the flame. It is the mechanism responsible for the effect of ventilation on the fuel mass loss rate in compartment fires. We used an empirical model of this mixing for the slit vents [1], but here we make it to general for various configurations of vent.

Zukoski et al. [9, 10] developed a correlation for the mixing rate based on saltwater simulation experiments. It was based on an assumption that the cold incoming flow through the opening would behave like a point source buoyant plume entraining the hot gas in the upper layer and then descending downward to the lower layer. A similar assumption was made for the outflow emerging from an opening into another room impinging upon its ceiling. We keep this "Point source approach" for the outflow, But for the reasons that, the plume theory was develop to describe the far field of a weakly buoyant, axisymmetric plume while the doorway plume is not axisymmetric and that, the doorway incoming flow has initial momentum which is not always negligible, we employed "Entering air jet approach"[11] for incoming doorway mixing.

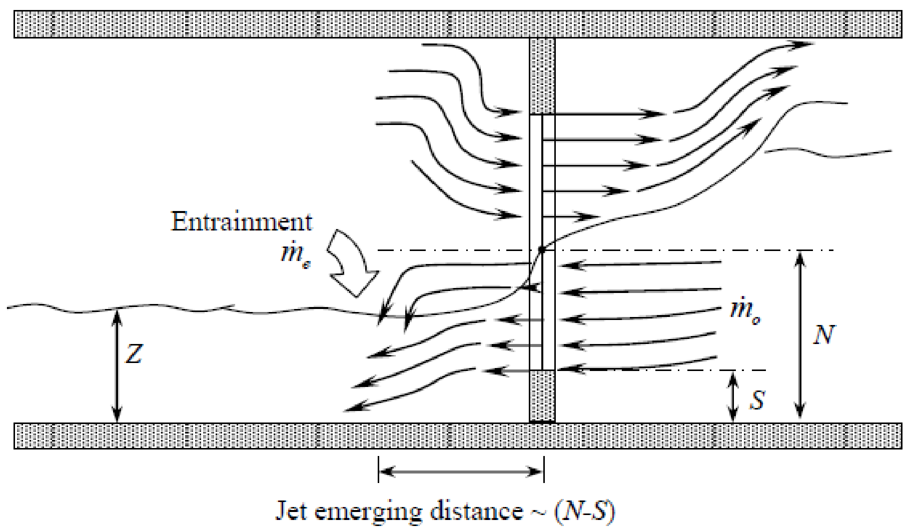


Fig. 4. Schematic showing mixing with entering jet approach

The concept was that the incoming cold air behaved like a jet entering the doorway with a characteristic velocity, expanding horizontally, and diffusing downward because of buoyancy. While the cold air descended, the surrounding hot gas was entrained with a velocity that is proportional to the incoming flow characteristic velocity.

$$\frac{\dot{m}_e}{\dot{m}_o} \sim \left(\frac{T_o}{T}\right)\left(1+\frac{N-S}{W_o}\right)\left(\frac{N-Z}{N-S}\right) \quad (3)$$

where $\dot{m}_e$ is the net rate of mass entrained, $\dot{m}_o$ is the total incoming air flow rate, T and T_o are the temperature of the hot gas in the upper layer and the incoming air flow respectively, N is the neutral plane height and S is the window sill height, Z is the layer interface, and W_o is the opening width. And Utiskul found a linear relationship up to an apparent asymptote for the mixing ratio of 1.28 [8]. This can be put into an expression for the mixing ratio as follow:

$$
\begin{aligned}
&\frac{\dot{m}_e}{\dot{m}_o} = 1.14\left(\frac{T_o}{T}\right)\left(1+\frac{N-S}{W_o}\right)\left(\frac{N-Z}{N-S}\right) && for\ \left(\frac{T_o}{T}\right)\left(1+\frac{N-S}{W_o}\right)\left(\frac{N-Z}{N-S}\right) < 1.1 \\
&\frac{\dot{m}_e}{\dot{m}_o} = 1.28 && for\ \left(\frac{T_o}{T}\right)\left(1+\frac{N-S}{W_o}\right)\left(\frac{N-Z}{N-S}\right) \geq 1.1
\end{aligned} \tag{4}
$$

EXTINCTION MODEL

By Quintiere [12], the extinction of a diffusion flame from a condensed phase fuel can be determined from a critical flame temperature. The flame temperature in terms of imposed external radiation, and surrounding temperature and oxygen mass fraction can be give as

$$
c_p\left(T_f - T_l\right) = \frac{\Delta h_c - L + c_p\left(T_v - T_l\right) + \dfrac{\dot{q}_{Ext}}{\dot{m}_F}}{1+\left(r/Y_{ox,l}\right)} \tag{5}
$$

where T_f is the flame temperature, T_l is the lower layer gas temperature, $Y_{ox,l}$ is the lower layer oxygen mass fraction, r is the stoichiometric mass of oxygen to fuel ratio, $\dot{q}_{Ext}$ is the net external heat feedback in the flaming area given in Eq. (2). This equation assumes negligible flame radiation at extinction and applies generally to a diffusion flame due to condensed phase burning. The criterion for extinction is that T_f must be less than a critical flame temperature of 1300 ºC [12]. By rewriting Eq. (5) as

$$
c_p\left(T_f - T_l\right) = \frac{\Delta h_c + c_p\left(T_v - T_l\right) - L\left\{1 - \dfrac{\dot{q}_{Ext}}{\dot{m}_F L}\right\}}{1+\left(r/Y_{ox,l}\right)} \tag{6}
$$

It can be recognized that the quantity in the brace can take on values between zero and 1, from Eqns. (1) and (2). For extinction (when the mass loss rate is controlled solely by the external heat flux) it is zero, and it is 1 at the free burning condition with no external radiation. As a consequence, for heptane, a flammability diagram is presented in Figure 5 as principally depending on the surrounding temperature and oxygen conditions, nearly independent of the external heat flux. At 25 ºC, the critical oxygen is about 12 %, while at 600 ºC it is about 7 %.

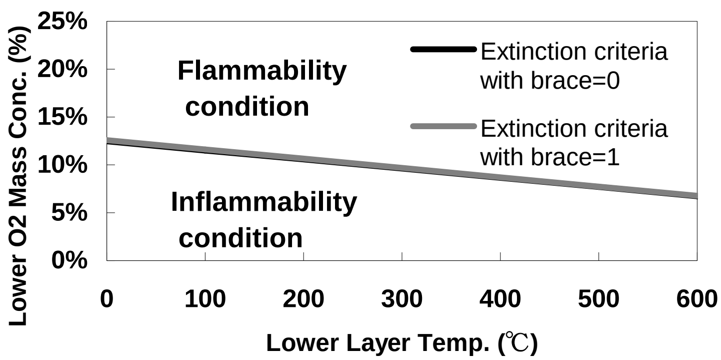


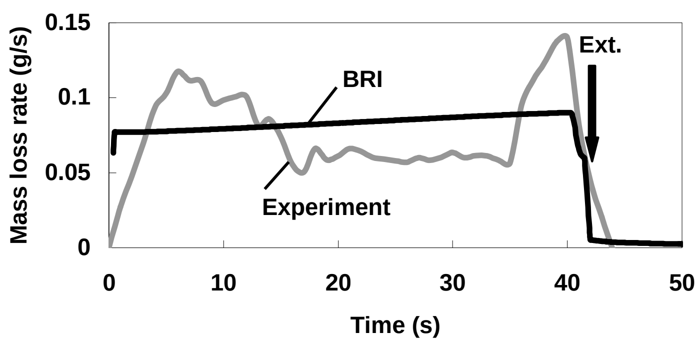
Fig. 5. Flammability diagram for heptane

RESULTS

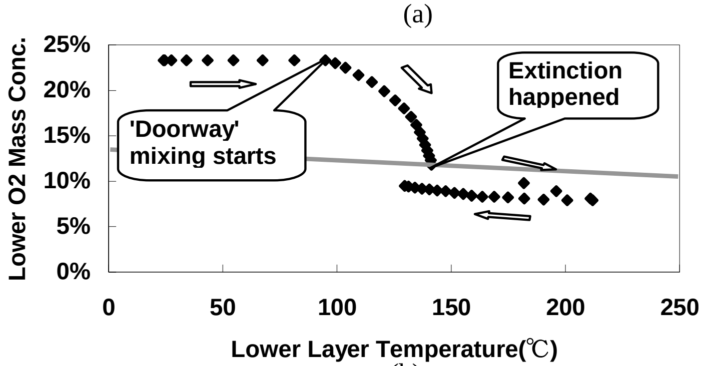
The BRI2002 zone model was executed for the conditions of the cubical two-slit vent compartment experiments using the new fire algorithm. Results were computed over time for each test case, and the mass loss rate is predicted along with the properties of the upper and lower layers. In order to demonstrate the ability of the new algorithm, some selective dynamic results will be presented that are indicative of the burning regimes. Later, overall results will be examined for the ensemble of mass loss rate data, using an appropriate average value.

Dynamic results

Figure 6(a) compares the fuel mass loss rates predicted by BRI and experiment for the case where a small vent leads to extinction. The model is able to predict flame extinction at 42 s and shows good quantitative agreement with fuel mass loss rate. Figure 6(b) is a flammability diagram that indicates that the effect of the mixing model in reducing the lower layer oxygen to a value where extinction occurs. The flammability diagram traces (by symbols) the instantaneous value of the lower layer oxygen concentration and temperature as they change in time. The light grey line is the theoretical limit condition that marks the boundary between burning and extinction as illustrated in Fig. 5. Once the flammability line is crossed, the state of the fire never returns to the flammability region.



(a)



(b)

Fig. 6. Fuel mass loss rate and flammability diagram predicted by BRI for extinction case

Overall results

We assess how well the model can predict the overall burning behavior in the compartment. The average mass loss rate is plotted as in Fig. 1 to compare the trends of the data and predictions in terms of ventilation factor.

Figure 7 shows the effect of the fire intensity. The computed results agree well with experiment. The horizontal line shows the free burning rate. The mass loss rate is reduced as the ventilation is reduced. This is caused by oxygen vitiation in the lower layer due to the mixing model. In this region, burning rate is controlled by the mass flow from the vent and emits less heat flux, which reduces the mass loss rate.

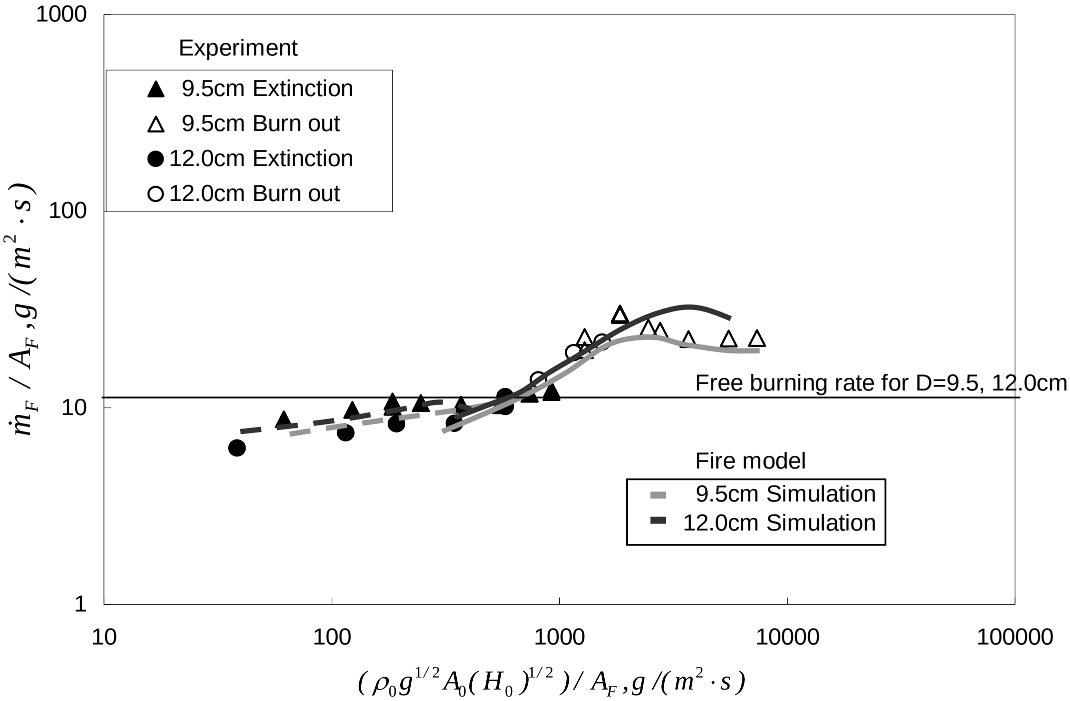


Fig. 7. Compartment fuel mass loss rate versus ventilation parameter (1/6 Scale)

Figure 8 shows the scale effect of the fuel pan size. The mass loss rate is going to be along the free burning rate asymptotically as the ventilation is increased and the condition is transferred into over-ventilated condition. And notice that the free burning rate per unit area is different by the fuel pan size when it is larger than 0.18m.

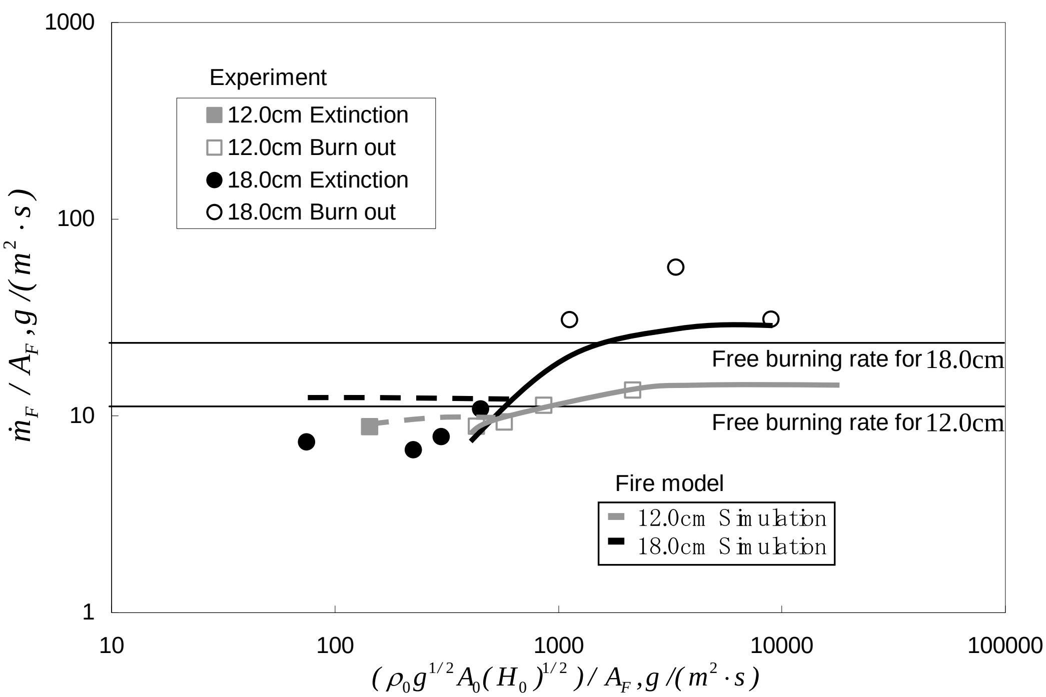


Fig. 8. Compartment fuel mass loss rate versus ventilation parameter (1/3 Scale)

Figure 9 shows the scale effect of the compartment size. In these small scale and less-charring pool fires, trans-missivity of the flame is relatively large, so the external heat flux plays a roll in mass loss rate (2nd term in mass loss rate model). So in the boundary condition between under- and over-ventilated condition, the mass loss rate is largely exceeded the free burning rate. But this bulge becomes scale down as the compartment size is increased. In the condition, the oxygen is supplied enough to keep burning; in addition, the generated heat is kept in the compartment. So both terms in mass loss rate model take a big value. And the heat is accumulated easily when the compartment size is small.

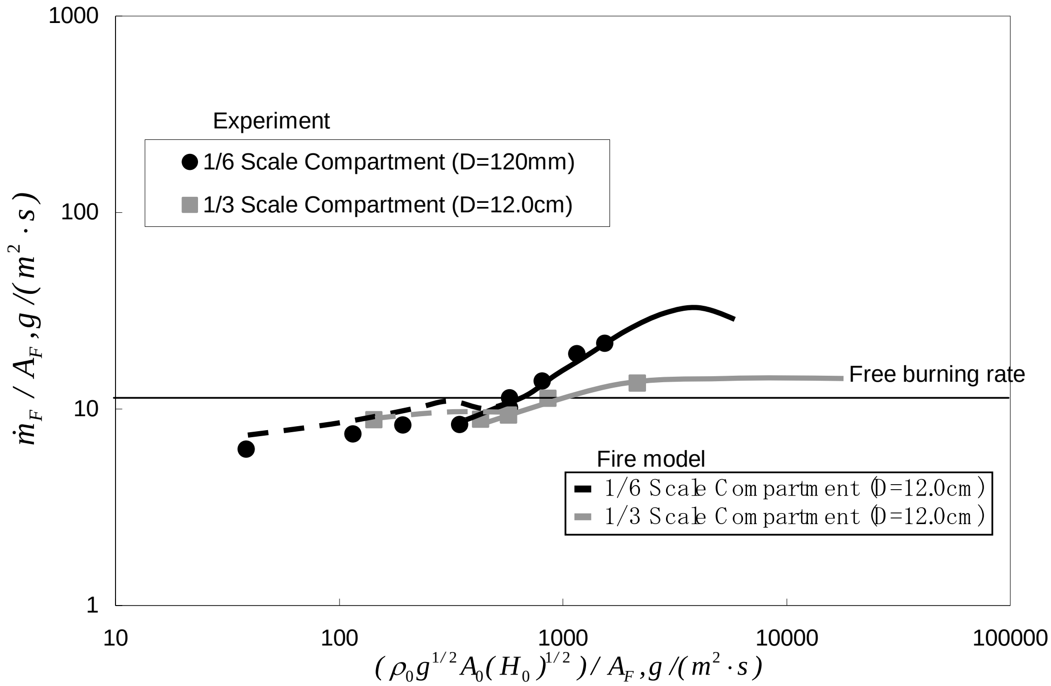


Fig. 9. Compartment fuel mass loss rate versus ventilation parameter (D=12.0cm)

CONCLUSIONS

A general theory for fuel mass loss rate has been presented. Some special features for ventilation-limited condition such as vent mixing model and extinction model are added two-layer zone model. Calculation results have been demonstrated by experimental data and new model has successfully captured the extinction. In addition, the fuel mass loss rate has been discovered in the wide range of ventilation parameter for liquid fuel by using the new model, and it explained the relationship between mass loss rate and ventilation parameter, and also explained scale effect on mass loss rate.

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