SIMPLE ESTIMATION MODEL ON CEILING TEMPERATURE AND VELOCITY OF FIRE INDUCED FLOW UNDER CEILING

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ABSTRACT

A new simple estimation model was described on excess temperature and velocity of ceiling jet under the flat, horizontal and sloped ceiling of an unconfined room from a t^2 -fire. This simple model was composed of ceiling height (H), distance along ceiling from the impinging point (r), and heat release rate (Q) which was given as a t^2 -fire. This model was verified by the experimental data which were conducted using at^2 model fire with ceiling heights of 2m, 2.1m, 4m, 8m, 15m and 20m. Flat and sloped ceiling with smooth surface was also used as a model ceiling, and those experimental data were used to verify the model. This model can deal with the cases of a corner fire and a wall fire for its early stages, and also verified by the data of corner and wall fires. The model for excess temperature and velocity with suitable RTI gave the estimation on the operation time of heat detector and sprinkler.

Keywords: ceiling jet, excess temperature, velocity, corner fire, wall fire, unconfined ceiling, sloped ceiling, t^2 fire, operation time, RTI model

1.INTRODUCTION

Estimation model on excess temperature and velocity of ceiling jet and flow which was given by a fire is important to assess the operation times of fire heat detector and sprinklers system in the early stage of fire. Operation time of fire detector gives a cue of the start of escape and/or evacuation for residents from a fire, so that the estimation model on excess temperature and velocity of ceiling jet is quite important and useful tool for fire safety. Thomas[1], Alpert [2,3], leading researchers on the ceiling jet behavior, have presented the model on excess temperature and velocity along the ceiling of unconfined dividing the regions into turning and ceiling jets as a function of nondimensional distance from the apparent impinging point, r/H , considering ceiling height and heat release rate, Q. Heskestad [4], and Heskestad and Delichatsios [5] have also presented the model on excess temperature and

velocity of ceiling jet in dimensionless forms. These famous models of FMRC researchers dealt with the ceiling jet under flat and unconfined ceiling. Kung, Spaulding and Stavrianidis[6] and Sugawa et al.[7] presented the experimental results on the ceiling jet using flat and sloped ceiling to obtain the other basic behavior of the ceiling jet.

In this study, we carried out experimental studies using high ceiling of up to 20m and flat and sloped ceiling with usual high ceiling of 2.7m. Based on the experimental data, the model on excess temperature and velocity was established utilizing the Froude modeling with considering dimensionless length of the representative trajectory.

Modeling

In the early stage of fire, with the unconfined fire plume, no physical barriers to restrict air entrainment across the plume boundary, but in a

confined space along the flat ceiling which restrict air entrainment through the area of ceiling side. Thus, air entrainment to the hot ceiling flow is reduced. However, it is expected that Froude modeling is applicable both vertical plume and ceiling flow considering with the suitable relationship between excess temperature and velocity.

Based on McCaffrey's plume model [8] and Alpert's ceiling jet model [2,3], excess temperature for higher part of the plume and for ceiling flow can be modeled by coupled governing two physical terms of traveling distance and HRR. These two terms are necessary to be modified as $-5/3$ power of traveling distance, $(H+r)^{-5/3}$, which includes the traveling distance along the ceiling of r , and $2/5$ power of HRR, $Q^{2/5}$. Thus,

$$\Delta T = a \cdot \left(\frac{H+r}{Q^{2/5}} \right)^{-5/3}, \quad (1-1)$$

$$a = 20 \sim 22 (\text{deg} \cdot \text{kW}^{3/2} \cdot \text{m}^{-3/5});$$

Let us assume that the ceiling flow is driven by the difference of the buoyancy depending on the radial distance along the ceiling, and also assume that apparent boundary length for unit traveling distance is reduced to $1/2$ of that in the vertical plume zone because the ceiling restrict the air entrainment across the boundary of the flow. This reduction implies two times longer traveling distance is needed for the same amount of air entrainment across the horizontal plume boundary. Then, we can estimate the ceiling flow velocity based on the local buoyancy using the local excess temperature, $\Delta T/T_\infty$ and g , and representative length of H . Adopting the suitable coefficient, k , and decreasing rate for radial direction by the dimensionless form of $H/(H+2r)$ adopting as the ratio between the vertical traveling distance and total traveling distance which includes the trajectory along the ceiling, thus the ceiling velocity, v , is expected;

$$v = k \cdot \frac{H}{H+2r} \sqrt{\frac{\Delta T}{T_\infty} \cdot g \cdot H} \quad (1-2)$$

(for an unconfined flat ceiling),

where we also assumed the adiabatic condition to the ceiling so that no remarkable effects is given by the heat loss to the ceiling in and near impinging region.

For the sloped ceiling flow, upslope region in this paper we consider, we also expect the traveling distance along the ceiling is influenced by the slope angle, θ . So that, we can modified equation (1-2) [7] as;

$$\Delta T = a \cdot \left(\frac{H+r}{((4/n) \cdot Q)^{2/5}} \right)^{-5/3}, \quad (2-1)$$

$$a = 20 \sim 22 (\text{deg} \cdot \text{kW}^{3/2} \cdot \text{m}^{-3/5});$$

n : location factor, $n = 4$ for an unconfined and sloped ceiling

$$v = k \cdot \frac{H}{H+2 \cdot (n/4) \cdot r \cdot \cos \theta} \sqrt{\frac{\Delta T}{T_\infty} \cdot g \cdot H} \quad (2-2)$$

(for unconfined and confined ceiling)

If an item is burning against a wall, the area through which air may be entrained is reduced to $1/2$ but its apparent HRR of the item is increased as $(4/2)^{5/2} = (2)^{5/2}$;

$$\Delta T = a \cdot \left(\frac{H+r}{[(4/n) \cdot Q]^{2/5}} \right)^{-5/3}, \quad (3-1)$$

$$a = 20 \sim 22 (\text{deg} \cdot \text{kW}^{3/2} \cdot \text{m}^{-3/5});$$

n : location factor,
 $n = 2$ for a wall and a near wall fire

$$v = k \cdot \frac{H}{H+(n/4) \cdot r} \sqrt{\frac{\Delta T}{T_\infty} \cdot g \cdot H} \quad (3-2)$$

(for unconfined and confined ceiling)

Similarly, if the fire source locates in a corner; with an apparent HRR increased four times of unconfined fire source, excess temperature and horizontal ceiling velocity can be described as;

$$\Delta T = a \cdot \left(\frac{H+r}{[(4/n) \cdot Q]^{2/5}} \right)^{-5/3}, \quad (4-1)$$

$$a = 20 \sim 22 (\text{deg} \cdot \text{kW}^{3/2} \cdot \text{m}^{-3/5});$$

n : location factor,

$n = 1$ for a corner wall fire

$$v = k \cdot \frac{H}{H + (n/4) \cdot r} \sqrt{\frac{\Delta T}{T_\infty} \cdot g \cdot H} \quad (4-2)$$

(for unconfined and confined ceiling)

The consequences regarding heat loss to the ceiling and forming of the hot layer or smoke filling given by wall effect needed to be examined for extended modeling which is applicable to the ceiling flow in the far region from the impinging region.

2. RESULTS AND DISCUSSION

(a) Test Fires in Unconfined Ceiling

Two kinds of test fires composed of wood crib pile and urethane foam mats, which gave flaming combustion with t^2 -growing fire, were used in the respective test rooms with the ceiling height of 4m and 8m (10m $\times$ 10m floor area) and of 15m and 20m (20m $\times$ 20m floor area). Both rooms were assumed as an unconfined ceiling room. Table 1 shows the setting condition adopted in the experiments. Impingement of flame or intermittent flame to the ceiling was not observed in every tests.

Figure 1 shows the representative correlation between excess temperature along the trajectory including the vertical path from the fire source to the ceiling, H , and radial distance along the ceiling surface, r , giving the traveling distance in the normalized by $Q^{2/5}$ in the form of $(H+r)/Q^{2/5}$. The representative results, exp.#3, #9, #33, and

#65 in Table 1 of wood crib pile, are plotted in Figure 1-a. Figure 1-b and 1-c show the similar plots as the previous figure but using a flaming urethane mats fire. These plots were given in time range of 90 - 600sec and 100-300sec, respectively. The hot flow from these model fires reached within several seconds at the most far point even in 20m high ceiling, so that we could treat these hot flow as in quasi-steady flow. The ceiling height, H , was counted from the floor level. Figure 1-a ~ 1-c clearly show that the Equation (1-1) is acceptable to estimate ΔT both in the plume and ceiling flow regions as it flows along the trajectory, and we could evaluate the coefficient of $a=20 \sim 22 (\text{deg} \cdot \text{kW}^{3/2} \cdot \text{m}^{-3/5})$.

We also measured ceiling flow velocities at $r = 1\text{m}, 2\text{m}, 3\text{m}, 4\text{m},$ and 5m from the impinging point (which locates just above the fire source) with gap of a few centimeters between the sensor head of anemometers and ceiling surface. Assuming the local buoyancy along the trajectory drives the ceiling flow radially and adiabatic condition on the ceiling, ceiling flow velocities were simulated using Equation (1-2) and which are plotted against the measured velocity taking the coefficient $k=1$ as shown in Figures 2-a ~ 2-d. The comparison of the experimental data with the prediction using Equation (2-1) shows that the estimation method based on local buoyancy can be used for the ceiling velocity estimation within the ceiling heights of 4m, 15m, and 20m, respectively. These representative figures show clearly that the term of $H/(H+2r)$ is quite valuable and useful to keep Froude number constant for ceiling flow at respective radial distance. If we choose suitable values of RTI and thermal conductivity of the detector (rise-of heat and fixed temperature type) and of sprinkler hear with Equations (1-1, 1-2), we could estimate the activation and/or operation time of these detectors and sprinkler, respectively.

Figure 1-a Excess temperature from a wood crib pile in an unconfined room with ceiling height of 4m - 20m.

Figure 1-b Excess temperature from a polyurethane mats fire in an unconfined room with ceiling height of 15m.

Figure 1-c Excess temperature from a polyurethane mats fire in an unconfined room with ceiling height of 20m.

Table 1 Flaming Test Fires carried out in Unconfined Ceiling [9]

Exp.	Fuel	Ceiling Height (m)	α (kW/sec ²)	Delay time (sec)
Exp.01	Wood, 900mm×900mm,6steps	4	0.0035	100
Exp.03	Wood, 1800mm×1800mm,6steps	4	0.0027	170
Exp.05	Wood, 900mm×900mm,6steps	8	0.0037	100
Exp.07	Wood, 900mm×900mm,6steps	8	0.0362	150
Exp.09	Wood, 1800mm×1800mm,6steps	8	0.0055	150
Exp.11	Wood, 1800mm×1800mm,12steps	8	0.0327	100
Exp.31	Wood, 1800mm×1800mm,6steps	15	0.0057	130
Exp.33	Wood, 1800mm×1800mm,12steps	15	0.0414	125
Exp.40	Wood, 1800mm×1800mm,6steps	20	0.0093	150
Exp.41	Wood, 1800mm×1800mm,12steps	20	0.0573	110
Exp.13	Urethane foam, 500mm×500mm×80mm	4	0.0041	80
Exp.14	Urethane foam, 500mm×1000mm×80mm	4	0.0099	120
Exp.16	Urethane foam, 1000mm×1000mm×80mm	8	0.0192	125
Exp.17	Urethane foam, 1000mm×1000mm×120mm	8	0.0496	100
Exp.52	Urethane foam, 1000mm×1000mm×120mm	15	0.0265	115
Exp.53	Urethane foam, 1000mm×1000mm×160mm	15	0.0214	85
Exp.55	Urethane foam, 1000mm×1000mm×120mm	20	0.0225	100
Exp.57	Urethane foam, 1000mm×1000mm×160mm	20	0.0316	115

Figure 2-a Ceiling velocity measured against ceiling velocity estimated based on Eq. 1-2.

Figure 2-b Ceiling velocity measured against ceiling velocity estimated based on Eq. 1-2.

Figure 2-c Ceiling velocity measured against ceiling velocity estimated based on Eq. 1-2.

Figure 2-d Ceiling velocity measured against ceiling velocity estimated based on Eq. 1-2.

Figure 3-a Temperature measured and calculated by Eq.(2-1) for fast growing fire of $Q=0.0468t^2$.

(b) Wall Fire

In the case of a fire source is set beside the walls, the wall effects on air entrainment into the hot flow resulted in the apparent increase of HRR as well as apparent decrease of reducing rate on excess temperature and velocity along the trajectory. Modification on these behavior must be considered and which are evaluated as

Figure 3-b Velocity measured and calculated by Eq.(2-1) for fast growing fire of $Q=0.0117t^2$.

Equation (2-1). Figure 3-a shows the temperatures measured using the fast growing fire of $Q=0.0468t^2$ and calculated ones by Eq.(2-1). Figure 3-b shows the velocities measured [10] using a medium growing fire of $Q=0.0117t^2$ and calculated ones using Equation (2-2). In both figures, solid lines are given by Equations (2-1) and (2-2), respectively. Heskestad-Delichatsios's

model (HD-model) gave almost the same evaluation but the Alpert's model gave smaller values for both temperature and velocity cases. Even in the case of wall fire, the dimensionless term on positioning with modification on HRR, $H/(H+(2/n)r)$, acts effectively as the keeper on the Froude number constant along the trajectory. These results show that the Equation (2-1) and (2-2) are useful to estimate the temperature and velocity of the ceiling flow given by a wall fire based on the HRR, height to ceiling, H , and distance from the wall, r .

(c) Detached Wall Fire

Vettori[10] have also conducted the experiments of detached wall fire using a gas diffusion burner setting off from the wall keeping the same space of fire source size, i.e., $S/D=1$. Flame extension behavior and air entrainment coefficient as a function of distance from a corner were investigated by Sugawa et. al [11] changing the separation distance between the fire source and wall(s). They reported that little wall effect on air entrainment was found in the far area of the dimensionless separation distance, S/D , is greater than 2. This implies that the detached wall fire by Vettori locates at $S/D=1$ and is still within the region of wall fire behavior. Free boundary condition for the models of Equations (1-1) and (1-2) are not applicable to the Vattori's test but Equations (2-1) and (2-2) are applicable to estimate these physical values as assuming unconfined ceiling condition. Figure 4-a and 4-b show the comparison between the excess temperatures and ceiling velocities of measured and calculated ones, respectively based on Equations (2-1) and (2-2). Temperature is correlated well by Equation (2-1) and which is almost the same correlation by HD-model, however, Alpert's model gave little smaller values than the these two models. The similar trend is also observed in the ceiling velocity estimation. It is seemed that the velocity measured are obtained between the two groups;

the first group of lines are given by Equations (2-2) and HD-model, and the second one is given by Alpert's model, can be used to provide estimates of the ceiling flow temperature and velocity from a detached wall fire source.

Figure 4-a Comparison of temperature measured and calculated by Equation (2-1) for a detached wall fire.

Figure 4-b Comparison of ceiling velocity measured and calculated by Equation (2-2) for a detached wall fire.

Figure 4-c Comparison of temperature measured and calculated by Equation (2-1) for a detached wall fire.

Figure 4-d Comparison of ceiling velocity measured and calculated by Equation (2-2) for a detached wall fire.

Figure 5-a Comparison of temperature measured and calculated by Equation (4-1) for a corner fire with slow growing.

Figure 5-b Comparison of temperature measured and calculated by Equation (4-2) for a corner fire with slow growing.

Figure 5-c Comparison of temperature measured and calculated by Equation (4-1) for a corner fire with fast frowning.

Figure 5-d Comparison of temperature measured and calculated by Equation (4-1) for a corner fire with medium frowning.

Figure 5-e Comparison of temperature measured and calculated by Equation (4-2) for a corner fire with fast frowning.

Figure 5-f Comparison of temperature measured and calculated by Equation (4-2) for a corner fire with medium frowning.

(d) Corner Fire

In the case of a fire located in a right angle corner, both walls give blocking effect on air entrainment into hot flow resulting in the flame extension and deformation of its cross section from circular shape to L-shape as the hot current goes up. This blocking on air entrainment by walls brought about the apparent 4 times greater HRR to a fire source. Equation (4-1) is applied to estimate the excess temperature along the trajectory from a corner fire and is illustrated in Figure 5-a with temperatures measured using a slow growing propane fire of $Q=0.00293t^2$. [10] Temperature along the ceiling surface is correlated well as shown in Figure 5-a by the Equation (4-1), though there is a general tendency to underpredict the temperature rise by the model by Equation (4-1) and by HD model. And there is also underpredict by Alpert's model.

Froude modeling has been employed to estimate the ceiling flow velocity with dimensionless positioning factor of $H/(H+2r)$ for a corner fire, and that is given by Equation (4-2) as are shown in Figure 5-b. These experimental data are also adopted from Vettori[10]. The other cases of fast and medium growing fires located in a corner are also adopted and plotted in Figures 5-c, 5-d, 5-e, and 5-f with calculated ones by Equation (4-2), HD-model, and Alpert's model. In the case of corner fire, Equation (4-1) and (4-2) give better simulation than HD-model and Alpert model.

SUMMARY

Utilizing Froude model, ceiling velocity is modeled based on excess temperature and with positioning factor of $H/(H+2r)$. For a sloped ceiling, radial path of r is modified with the slope angle as $r \cos \theta$. For a corner fire and wall fire (and detached but near wall), it is needed to modify on an apparent HRR as $(4/n Q)^{2/5}$ with $n=2$ for a wall fire and $n=1$ for a corner fire.

Estimation models presented here have respective dimensions, such as temperature in °C

or K and velocity in m/sec, so that which are not only quite useful and convenient to simulate these physical value using HRR, ceiling height, and radial trajectory which are given in the designing, but also are convenient to estimate the activation times of heat detector and sprinkler.

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