A FORMULA FOR PREDICTION OF CEILING JET TEMPERATURE IN TWO LAYER ENVIRONMENT

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ABSTRACT

The means for predicting ceiling jet temperature under an unconfined ceiling has been well established by the previous work under an unconfined ceiling. However, a room ceiling is usually enclosed by walls so a fire plume rises in a stratified environment in the event of room fire. Previous work under an unconfined ceiling will not be sufficient to predict the ceiling jet temperature in such a configuration. On the other hand, a two layer zone model is often used for predicting fire temperature in a stratified configuration but it only gives average condition in the upper layer, which is too crude to predict the near ceiling temperature to assess the actuation of ceiling mounted detectors and sprinklers.

In this study, a formula for ceiling jet temperature in a two layer configuration was derived by combining previous work under an unconfined ceiling, upper layer temperature and layer interface height. The validity of the formula was examined by comparing the results of prediction and the experiments using the test fires prescribed in an ISO/TC21/SC3 draft standard. The predicted ceiling temperatures generally exhibit satisfactory agreement with the measured temperatures.

KEY WORDS : ceiling jet, ceiling layer, fire detection, enclosure fire

1. INTRODUCTION

Progress in the area of fire safety engineering in recent decades has induced an irreversible trend towards performance-based design methods of buildings. However, progress towards performance-based assessment of fire detection system until now seems to be slow. The assessment of fire detectors still primarily depends upon prescribed test methods such as EN54-9 [1], a test method for sensitivity to fire of automatic fire detection system and an ISO/TC21/SC3 draft standard [2], a international test method for smoke detector developed based on EN54-9.

However, the response of a detector in an actual fire will differ from one case to another depending on the conditions of the fire source and the room in which the detector is equipped. In order to assess detector response performance in a variety of conditions, it is vital to have a means which one enables to predict the response as a function of fire source and room geometry.

Although consideration needs to be made in many aspects to achieve this goal one of the most important issues is to develop a model to predict the ceiling jet temperature in realistic fire environment. A ceiling in a room is a confined ceiling, bounded by walls so a hot gas layer is expected to develop under the ceiling in the event of fire. The fire plume rising in such a stratified environment entrains hot gases from the upper layer as well as ambient air from the lower layer, which will affect the plume temperature, hence the ceiling jet.

In case of unconfined horizontal ceiling, the well-established equations derived by Alpert [3] is available to predict the ceiling jet temperature and velocity. A formula by Heskestad [4] can be used for the same purpose. In case of unconfined slant ceilings, the prediction methods were also proposed by Sugawa [5] for example.

For the prediction of upper layer temperature, on the other hand, a two layer zone model is usually employed [6][7]. But such a model can only gives layer average temperature, which is too crude to predict near ceiling temperatures for the purpose of assessing detector response.

The prediction of ceiling jet temperature in two layer environment was tried by Evans, who proposed a method of prediction in terms of a set of non-dimensional formulas [8]. Cooper also proposed a method to predict ceiling jet temperature in the same configuration [9]. Yamauchi extended the Evans' method to develop the prediction method for response time of smoke detectors [10]. Hasemi and Sako et al applied the Evans' method to generate the correlation of the ceiling jet temperatures measured in their experiments [11]. These methods seem to exhibit a certain extent of success but most of the calculation procedures basically address steady state conditions and may be somewhat complex for many practitioners.

In this study, a very simple formula for predicting the ceiling jet temperature in two layer environment was derived taking into account the plume entrainment in two layer configuration and combining the Reference [3] equations, upper layer temperature and layer interface height. The predictions by the formula were compared with the transient ceiling jet temperatures measured in the experiments using three of the fire sources prescribed in Reference [1][2]. The agreement was satisfactory in the three experiment cases.

2. THE MODEL

2.1 Ceiling Jet Temperature in Stratified Environment

As illustrated by Fig. 1, a plume rising from the floor of a room is considered. The air in the room is assumed to be stratified into a hot upper layer at temperature T_s and a cold layer at temperature T_a, each of which is uniform in temperature.

Letting $m_p(Z_a)$ be the plume mass flow rate at the height of layer interface Z_a and $m_p(H)$ be the mass flow rate at the height of ceiling H, the energy conservation for the plume is described as

$$c_p T_a m_p(Z_a) + c_p T_s \{m_p(H) - m_p(Z_a)\} + Q_c = c_p \overline{T(H)} m_p(H) \tag{1}$$

where Q_c is the convective component of the heat release rate and $\overline{T(H)}$ is the plume average temperature at the ceiling height H. From Eq.(1), the average temperature rise at the height of H can be obtained as follows:

$$\overline{\Delta T(H)} \equiv \overline{T(H)} - T_a = \left\{1 - \frac{m_p(Z_a)}{m_p(H)}\right\}(T_s - T_a) + \frac{Q_c}{c_p m_p(H)} \tag{2}$$

The second term in the right hand side of Eq.(2) denotes the plume average temperature rise when the plume environment is ambient, or more generally uniform, at the ceiling height, that is,

$$\frac{Q_c}{c_p m_p(H)} = \overline{\Delta T_a(H)} \tag{3}$$

The first term in the right hand side of Eq.(2) denotes the effect of the upper layer, with temperature T_s and interface height Z_a, on the plume temperature rise.

It is assumed here that the plume mass flow rate in the stratified environment is the same as that in uniform environment regardless the condition of stratification and given by Zukoski [12].

$$m_p(Z) = 0.07 Q^{1/3} Z^{5/3} \tag{4}$$

where Q is the heat release rate of the fire source. This assumption will be adequate at least in approximate sense for the early stage of fire where the upper layer temperature is not so high if it may not be completely true.

Using Eq.(4) and (3) in Eq.(2) yields

$$\overline{\Delta T(H)} = \left\{1 - \left(\frac{Z_a}{H}\right)^{5/3}\right\}(T_s - T_a) + \overline{\Delta T_a(H)} \tag{2'}$$

Eq.(2') gives the relationship of the average temperature rise of plume between uniform and stratified plume environment but not the detailed temperature distribution of the plume impinging upon a ceiling. Nevertheless, it is naturally presumed that Eq.(2') may be converted to a relationship to give the ceiling jet temperature in stratified configuration if the second term of the right hand side is replaced with the Reference [3] equations. In other words,

$$\Delta T_c(H,r) = \left\{1 - \left(\frac{Z_a}{H}\right)^{5/3}\right\}(T_s - T_a) + \Delta T_{Alp}(H,r) \tag{5}$$

where $\Delta T_c(H,r)$ is the ceiling jet temperature in the stratified configuration as a function of ceiling height H and the distance from the plume axis r, and $\Delta T_{Alp}(H,r)$ is the Reference [3] equations for unconfined ceiling jet temperature, which has been given as

$$\Delta T_{Alp}(H,r) = \begin{cases} 16.9\left(\dfrac{Q^{2/3}}{H^{5/3}}\right) & \left(\dfrac{r}{H} \leq 0.18\right) \\ 5.38\left(\dfrac{Q^{2/3}}{H^{5/3}}\right)\left(\dfrac{r}{H}\right)^{-2/3} & \left(\dfrac{r}{H} > 0.18\right) \end{cases} \tag{6}$$

where Q is the heat release rate of the fire source[3].

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Eq.(5) suggests that the ceiling jet temperature at an arbitrarily stratified configuration, i.e. arbitrary upper layer temperature and layer interface height can be predicted. When there is no upper layer, in which case $Z_a=H$ and also $T_s=T_a$, Eq.(5) is reduced to the Reference [3] equations, and when a room is entirely filled with an upper layer Eq.(5) gives the ceiling jet temperature in the ambient whose temperature is elevated to T_s.
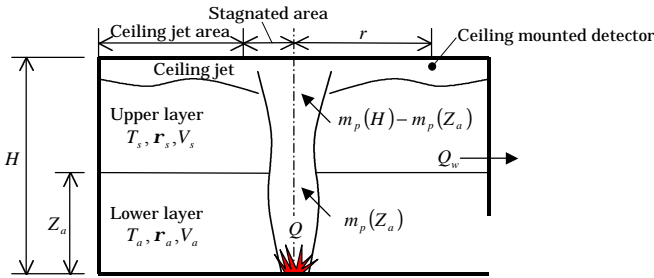

FIGURE 1.　Schematic of ceiling jet in two layer environment

2.2 Two Layer Zone Model

Eq.(5) needs to be further supplemented with the predictions of the upper layer temperature T_s and the layer interface height Z_a to predict the ceiling jet temperature. Obviously, a two layer zone model is appropriate for this purpose. Although a number of two layer zone models are already available, a simple two layer zone model was newly constructed in this study for such existing models are generally so sophisticated that they are not necessarily convenient to apply to such a simple issue as this particular case.

Since the primary interest in this study lies in the relatively early stage of fire, such as smoke filling period, the two layer zone model only addresses the upper layer properties.

(1) Relationship for upper layer
For the upper layer, the following relationships hold:
(a) Mass conservation
Considering no vent flow associated with upper layer, the fire plume is the only mechanism to add mass to the upper layer, hence

$$\frac{d}{dt}\left(\boldsymbol{r}_s V_s\right) = m_p\left(Z_a\right) \tag{7}$$

where $\boldsymbol{r}_s$ and V_s are the density and the volume of the upper layer, respectively. $m_p(Z_a)$ is the plume mass flow rate at the height of the layer interface.
(b) Energy conservation
Although it is said that 30% or so of the heat released by combustion of fire source is lost by flame radiation, it is assumed here that all the heat released is conveyed to the upper layer by the fire plume for the first order approximation since it is considered that a significant portion of the radiated heat is absorbed by the upper layer itself and a part of the rest absorbed by the lower part of the wall is re-radiated to the upper layer. Based on this assumption, the energy conservation of the upper layer can be written as

$$\frac{d}{dt}\left\{c_p T_s\left(\boldsymbol{r}_s V_s\right)\right\} = Q - Q_w + c_p T_a m_p\left(Z_a\right) \tag{8}$$

where Q is the heat release rate of the fire source and Q_w is the heat loss from the layer to the room boundary.

(c) Gas state

The effect of the pressure change induced by fire on air density is normally negligible, so the equation of ideal gas state is reduced to the following equation:

$$r_s T_s = r_a T_a \tag{9}$$

(2) Upper layer temperature and layer interface height

From Eqs.(7), (8) and (9), the coupling ordinary equations for the upper layer temperature and the layer interface height can be derived as follows:

(a) Upper layer temperature

Noting that the left hand side of Eq.(8) can be developed as

$$\frac{d}{dt}\left\{c_p T_s\left(r_s V_s\right)\right\} = c_p r_s V_s \frac{dT_s}{dt} + c_p T_s \frac{d}{dt}\left(r_s V_s\right)$$

and calculating Eq.(8)$-c_p T_s$xEq.(7) yields the ordinary differential equation for the upper layer temperature as follows:

$$\frac{dT_s}{dt} = \frac{Q - Q_w - c_p\left(T_s - T_a\right)m_p\left(Z_a\right)}{c_p r_s V_s} \tag{10}$$

(b) Layer interface height

Eq.(7) can be developed as

$$r_s \frac{dV_s}{dt} + V_s \frac{dr_s}{dt} = m_p\left(Z_a\right) \tag{11}$$

On the other hand, from Eq.(9)

$$\frac{dr_s}{dt} = -\frac{r_s}{T_s}\left(\frac{dT_s}{dt}\right) \tag{12}$$

Using Eqs.(10) and (12) into (11) yields the differential equation for the upper layer volume as follows:

$$\frac{dV_s}{dt} = \frac{Q - Q_w + c_p T_a m_p\left(Z_a\right)}{c_p r_s T_s} \tag{13}$$

In a particular case that the room horizontal section area A_R is constant with height, $V_s = A_R(H - Z_a)$, in other words $dV_s/dt = -A_R(dZ_a/dt)$, Eq.(13) becomes the equation for the layer interface height as follows:

$$\frac{dZ_a}{dt} = -\frac{Q - Q_w + c_p T_a m_p\left(Z_a\right)}{c_p r_s T_s A_R} \tag{14}$$

(2) Component Processes

Although Eqs.(10) and (14) can be said to be the most basic equations in this zone model, sub-models for fire plume and heat transport need to be further incorporated to complete the equations.

(1) Fire plume flow rate

Eq.(4) is used for the mass flow rate of the fire plume, i.e. $m_p(Z_a)$ in Eqs.(10) and (14).

(2) Heat transfer to room walls

The heat transfer from the upper layer to walls consists of the thermal radiation and the convective heat transfer. In this model, the rate of heat transfer from the upper layer to the room boundary is divided into three parts: the heat transfer to the ceiling(w1), to the part of the walls contacting with upper layer(w2) and the floor and the part of wall contacting with lower layer(w3). Schematic of the heat loss rate from the upper layer is shown in Fig.2. The heat flux from the smoke layer to each of the parts are given as

$$
\begin{aligned}
q''_{w1} &= e_w e_s s\left(T_s^4 - T_{w1}^4\right) + h\left(T_s - T_{w1}\right) \\
q''_{w2} &= e_w e_s s\left(T_s^4 - T_{w2}^4\right) + h\left(T_s - T_{w2}\right) \\
q''_{w3} &= e_w e_s s\left(T_s^4 - T_a^4\right)
\end{aligned}
\tag{15}
$$

where h is the convective heat transfer coefficient, of which value $h=0.015\text{kW/m}^2$ was assumed in this model. e_w is the emissivity of the room boundary surface, which is approximated to be $e_w = 1$ at any part. e_s is the emissivity of the upper layer, of which assumed to be $e_s = 1$ since the present model does not predict the concentrations of gaseous nor solid component in the upper layer. T_{w1} and T_{w2} are the surface temperatures of the ceiling and the part of the wall contacting with the upper layer, respectively. The surface temperature of the floor and the lower part is assumed to remain constant at T_a.

Using Eq.(15), the total heat loss rate from the upper layer is calculated as

$$
Q_w = q''_{w1} A_R + q''_{w2} L\left(H - Z_a\right) + q''_{w3} A_R
\tag{16}
$$

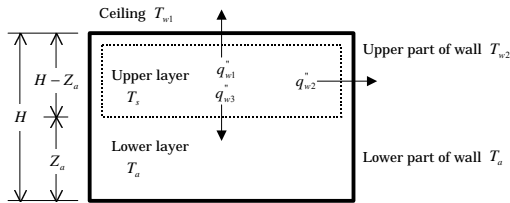where L is the perimeter of the room.

FIGURE 2.   Schematic of the heat loss rate from the upper layer

(3) Wall surface temperature
The surface temperatures T_{w1} and T_{w2} in Eq.(15) are calculated by numerically solving the following one dimensional heat conduction equation by finite difference method.

(a) Heat conduction equation

$$
\frac{\partial T}{\partial t} = \left(\frac{k}{cr}\right)\frac{\partial^2 T}{\partial x^2}
\tag{17}
$$

(b) Boundary condition

$$
-k\frac{\partial T}{\partial x}\bigg|_{x=0} = q''_{in} \qquad \text{and} \quad -k\frac{\partial T}{\partial x}\bigg|_{x=l} = 0
\tag{18}
$$

where k, c and r are conductivity, specific heat and density of wall material, respectively, and x is the distance from the interior surface and l is the thickness of the wall. q''_{in} is the heat flux to the interior surface, which is given as follows

$$q''_{in} = \begin{cases} q''_{w1} & (\text{ceiling}:w1) \\ q''_{w2} & (\text{side wall}:w2) \end{cases} \tag{19}$$

depending on the part being considered.

3. COMPARISON BETWEEN THE PREDICTION AND THE EXPERIMENTS

The ceiling jet temperature predicted using the above two layer zone model and Eq.(5) were compared with the temperature measured in the room fire experiments using the test fires prescribed in the ISO/TC21/SC3 draft standard [2] as the fire source.

3.1 The Experiment

(1) Fire room
The room used for this series of fire experiments is the room constructed for the detector performance tests and complies with the conditions prescribed in the ISO/TC21/SC3 draft standard [2]. The width, the depth and the ceiling height of the room are 10m, 7m and 4m, respectively. The ceiling is made of calcium silicate and the wall is made of normal concrete, with exception of two doors and observation windows. The fire source in the experiment was located on the floor at the center of the room.

(2) Fire sources
Reference [2] prescribes several types of fire sources (TF: = Test Fire) for detector response tests. In this series of experiments, three types of TFs shown in TABLE 1 were employed since the heat release rates of these TFs are relatively large compared with the others, thereby the temperature measurements are easier.

(3) Measurements
(a) Temperature
The array of thermocouples in the experiments is shown in Fig. 3. The thermocouples to measure the ceiling jet temperature were arrayed 0.05m below the ceiling, one in the center and the other 3m from the center. Although the position of the maximum ceiling jet temperature under the ceiling is not clear it is assumed that the temperature at 5cm below the ceiling is not very far from the maximum temperature. Thermocouples were also arrayed vertically at 2.5m and 4.0m from the room center with 0.75m spacing to measure the vertical temperature distribution in the layer.

(b) Heat release rate
The transient heat release rate of each of the fire sources was calculated from the mass burning rate, measured using an electronic balance, and the heat of combustion indicated in TABLE 1. The heat release rates of the three TFs thus obtained are shown in Fig. 4.

3.2 Comparison and Discussion

(1) Calculation conditions
The same conditions as the experiments were used as those of the calculations for predicting the ceiling jet temperatures. The heat release rate of each fire source was the same as that shown in Fig. 4. The data shown in TABLE 2 were used as the thermal properties of the ceiling and the wall.
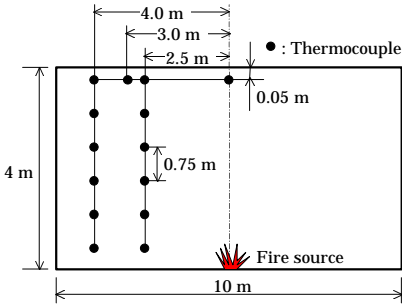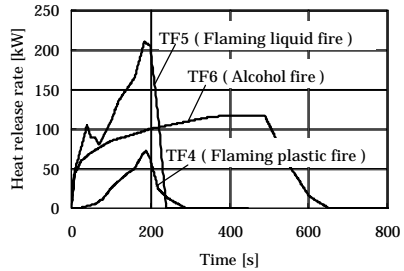
FIGURE 3. Array of thermocouples

FIGURE 4. Heat release rates of the fire sources

TABLE 1. Calorific value of fuels of TFs

Fire type	Fuels	Calorific value [kJ/g]
TF4	Polyurethane	22
TF5	n-heptane	45
TF6	alcohol	26

TABLE 2. Properties of ceiling and wall material

Part	Material	Density [kg/m³]	Specific heat [kJ/kgK]	Thermal Conductivity [kW/mK]	Thickness [m]
Wall	Concrete	2400	0.90	1.2×10^{-3}	0.1
Ceiling	Calcium silicate	622	0.92	0.13×10^{-3}	0.1

(2) The upper layer temperatures measured and predicted by the two layer zone model
An example of the comparison between the upper layer temperatures from the measurement in the experiments and from the prediction using the two layer zone model is shown in Fig. 5. This specific example is the case for TF6(alcohol fire). The thin dashed line indicates the ceiling temperature at the room center, the thin solid lines indicate the temperature recorded by the thermocouples at each height arrayed at 2.5m from the room center, the thick solid line indicates the upper layer average temperature reduced from the measurements by the N% method introduced by Cooper et al (see Note) and the thick gray line indicates the upper layer temperature predicted by the two layer zone model.

As can be seen in Fig. 5, the predicted upper layer temperature and the upper layer average temperature from the measurements generally show good agreement. However, the ceiling jet temperatures are considerably higher than the upper layer average.

(3) The ceiling jet temperature measured and predicted by the Reference [3] equations
An example of the comparison between the ceiling jet temperature measured in the experiments and predicted by the Reference [3] equations is shown in Fig. 6. The example is also the case for TF6(alcohol fire).

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As can be seen in Fig. 6, the measured ceiling temperatures are very far from the prediction by the Reference [3] equations. It is, therefore inappropriate to apply the Reference [3] equations to stratified configuration, which might be easily expected.
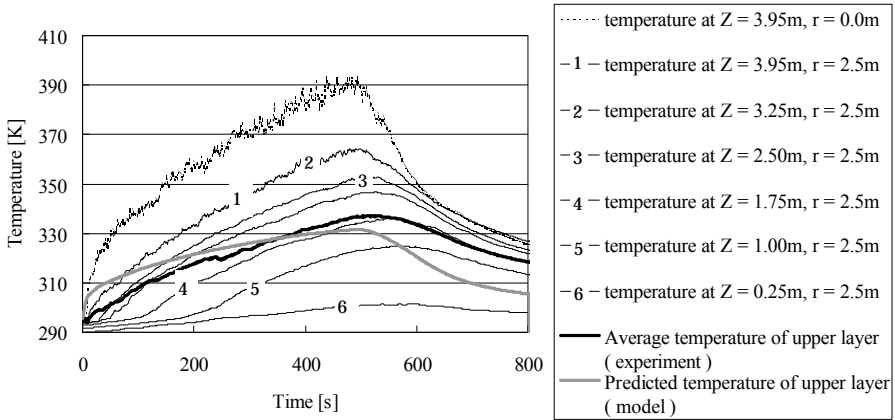

FIGURE 5. Comparison of temperatures between experiment and prediction by the two layer zone model (An example for TF6)
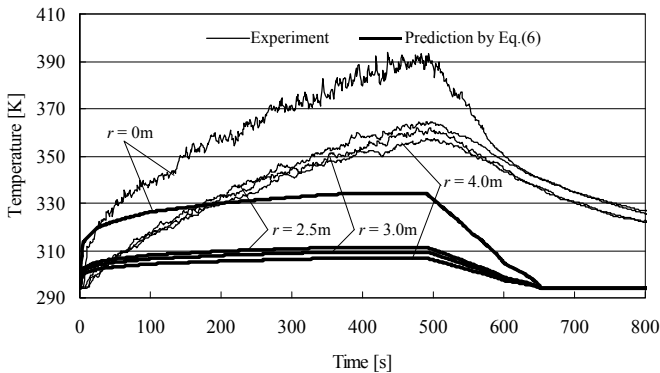

FIGURE 6. Comparison of ceiling jet temperatures between experiment and prediction by the Reference [3] equations (An example for TF6)

(4) The ceiling jet temperature measured and predicted by the present model
The results of comparisons between the ceiling jet temperatures measured in each of the experiments and predicted by Eq.(5) proposed in this study are shown in Figs. 7, 8 and 9, correspondingly to the TF4, 5 and 6.

From these figures, it is shown that the prediction of the ceiling jet temperature is remarkably improved from the predictions shown in Figs. 5 and 6 as long as the growing stage of the fires is concerned, although slight difference which is suspected to be caused by some error involved in the measurements or the zone model is observed. Incidentally, although the results in Fig. 7 through 9 are purely from prediction, the same level of agreement is expected if the measured layer average temperatures are used instead of the

predicted upper layer temperature for both agree well as shown in Fig. 5.

So it may be said the present model, described by Eq.(5) is satisfactory for the purpose of fire detection. However, from the view point of a fire model, the model needs to be further improved since the predicted temperatures gradually part from the measurement and go down to the layer average temperature at the decaying stage of the fire source.
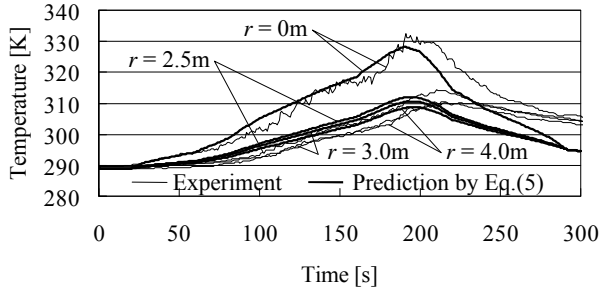

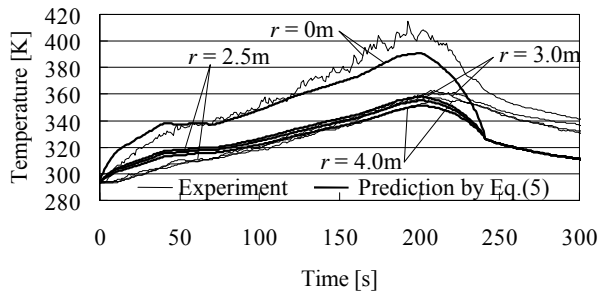**FIGURE 7.**   Comparison of ceiling jet temperatures between experiment and prediction by Eq.(5) for TF4

FIGURE 8.   Comparison of ceiling jet temperatures between experiment and prediction by Eq.(5) for TF5
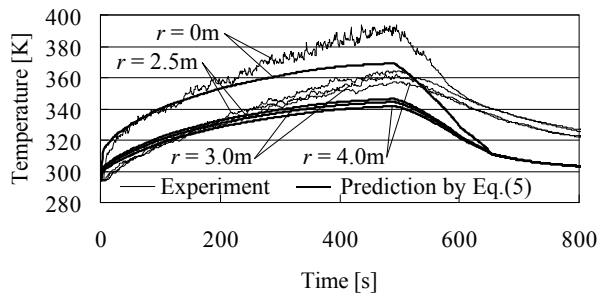

FIGURE 9.   Comparison of ceiling jet temperatures between experiment and prediction by Eq.(5) for TF6

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4. CONCLUSION

A formula for predicting ceiling jet temperature in confined ceiling configuration described by Eq.(5), which was derived by combining the Reference [3] equations, upper layer temperature and layer interface height, exhibits satisfactory agreement with the transient temperatures measured in the experiments conducted in this study. Despite its simple appearance. Eq.(5) is considered to be an effective means to predict ceiling jet temperature in many of the realistic room fire situations.

Note: The upper layer average temperature was reduced by processing the measured temperatures according to the N% method introduced by Cooper et al [13], that is
(1) Determine the layer inter face height using N% method. N=20 in this study.
(2) Average the temperature recordings of the thermocouples within the defined upper layer.

NOMENCLATURE

A_R :Room floor(=ceiling) area[m^2]
c :Specific heat of room boundary material[kJ/kgK]
c_p :Specific heat of air at constant pressure[kJ/kgK]
H :Ceiling height[m]
h :Convective heat transfer coefficient[kW/m^{2}K]
k :Thermal conductivity[kw/mK]
L :Room perimeter[m]
l :Thickness of room boundary material[m]
$m_p(Z)$:Plume mass flow rate at height Z[kg/s]
Q :Heat release rate[kW]
Q_c :Convective portion of heat release rate[kW]
$q_{„w1}$:Heat flux to ceiling per unit area of upper layer surface[kW/m^2]
$q_{„w2}$:Heat flux to wall contacting to upper layer per unit area of upper layer surface[kW/m^2]
$q^{„}_{w3}$:Heat flux to floor and lower part of wall per unit area of upper layer surface[kW/m^2]
$q^{„}_{in}$:Incident heat flux to the interior surface of room boundary material[kW/m^2]
r :Horizontal distance from plume axis[m]
T_a :Lower layer temperature[K]
T_s :Upper layer temperature[K]
$T(Z)$:Plume temperature at height Z[K]
$\Delta T(Z)$:Plume temperature rise at height Z[K]
$\overline{\Delta T(H)}$: Average temperature rise of plume in two layer environment at height H[K]
$\overline{\Delta T_a(H)}$: Average temperature rise of plume in ambient environment at height H[K]
$\Delta T_{Alp}(H,r)$:Ceiling jet temperature as a function of H and r predicted by the Reference [3] equations [K]
$\Delta T(H,r)$: Ceiling jet temperature as a function of H and r [K]
T :Temperature[K]
t :Time[s]
V_s :Upper layer volume[m^3]

x	:Depth from the interior surface of room boundary material[m]
Z	:Height from floor[m]
$\boldsymbol{e}_s$	:Upper layer emissivity[-]
$\boldsymbol{e}_w$	:Room boundary surface emissivity[-]
$\boldsymbol{r}$	:Density of room boundary material[kg/m^3]
$\boldsymbol{r}_a$	:Ambient air density[kg/m^3]
$\boldsymbol{r}_s$	:Upper layer density[kg/m^3]
$\boldsymbol{s}$	:Stefan-Boltsmann constant(=5.67x10^{-11} kW/m^{2}K^4)

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