Predicting Capability of a Multiroom Fire Model

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ABSTRACT

Several refinements were made on the two layers zone model previous-
ly developed by Tanaka in an attempt to provide an engineering means to
predict fire behavior in buildings. One of the refinement is that par-
tial penetration model of upward and downward plumes across layer inter-
faces was introduced. By using this plume partial penetration model, the
predicting capability of the multiroom fire spread model has been signi-
ficantly refined.

Keyword : fire model, opening jet

INTRODUCTION

For a performance based fire safety design method of buildings, user
friendly computer model to predict smoke transport behavior in buildings
is considered to be one of its indispensable elements. As such prediction
models for smoke movement, chiefly two types of zone models have been
developed by now, that is, one based on one layer concept and the other
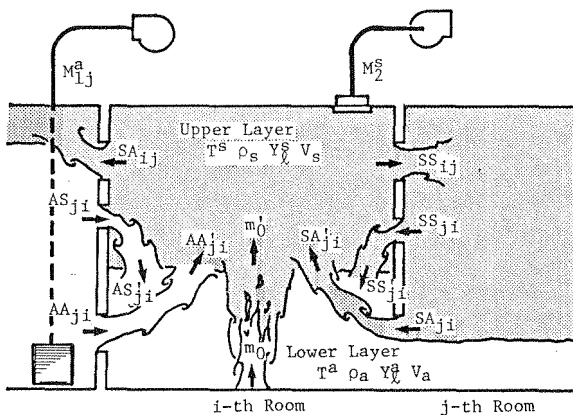based on two layers concept.

Fig.1 Concept of the two layers zone model

However, many of these models, which have been developed primarily for a research purpose, will more or less need to be refined for the convenience of design practice as well as for the improvement in an accuracy to be used for design purposes. A multiroom smoke movement model(Ref.1), which is based on two layers concept, has been refined from this point of view. The points of refinement include, a) the prediction of lower layer properties, by which stack effect due to the temperature difference between inside and outside of building can be treated, b) capability of dealing with mechanical smoke control, c) time scheduled opening and closing of openings, by which the effects of door opening due to evacuation or window breaking due to fire on smoke movement can be assessed, d) capability of dealing with spaces of complex geometry such as a dome, and e) improvement of stability and speed up in numerical calculation.

Since most of the theoretical aspects of the model are given in Ref.2, this paper focuses on the model of the opening jet plume near an opening region.

OPENING JET PLUME NEAR OPENING

In this model, it is assumed that the plumes originated by a fire source and opening jets can penetrate through interfaces of the upper and lower layers, due to which exchanges of mass and heat take place. As a result the method to determine the fraction of mass and heat penetration becomes one of the key points. In the region far away from the source of an opening plume, i.e., opening jet, the fraction can be calculated by modeling opening jet plume as vertically rising plumes and assuming Gaussian profiles on the lateral profile of temperature and vertical velocity in a plume and criterion temperature of penetration (See Appendix).

In the region near an opening, however, simple application of Gaussian profile can cause a problem : i.e. temperature on the axis of modeled plume ΔT_0 can become higher than that of the opening jet ΔT_d. This is illustrated by the example shown in Fig.3. In this example, an opening jet at 300 C enters a lower layer at 20 C and rises through the layer entraining the air and penetrates into an upper layer at 300 C. In this particular case, the excess temperature on the axis of the modeled plume exceeds the temperature difference between the opening jet and the ambient layer ΔT_d(=300-20=280 K) in the region of Z < 0.72 m. So, if the criterion temperature for plume penetration is assumed as

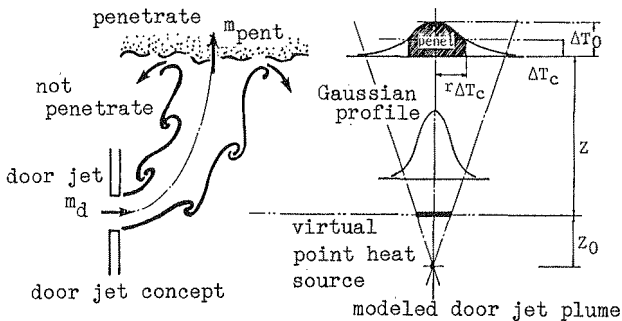$$\Delta T_c = (T_s - T_\infty)/2 = 140 \ (K)$$


Fig.2 Modeling of door jet plume penetration

the net heat gain of the upper layer becomes positive in the region of Z
< 0.25 m as is shown in Fig.3, so that the upper layer is heated while it
has to be cooled in reality. Needless to say, this is attributed to the
sharp peak of Gaussian profile of the temperature near axis, which is
unrealistic in the sense that the plume axis temperature ΔT_0 exceeds the
opening jet temperature ΔT_d.

It will be more reasonable to consider that an opening jet initially
has flat profiles of temperature and velocity, but the profiles collapse
as the distance Z increases and eventually turn into Gaussian profiles.
Here an interim model is proposed as follows to deal with the penetration
in the region near an opening.

Let Z_d be the height where the excess temperature of the axis of a
plume with a Gaussian profile ΔT_0 becomes equal to the temperature diffe-
rence between the opening jet and the ambient layer ΔT_d. The near region
to an opening is defined as the region where $Z < Z_d$. It is assumed that
the temperature profile of the off central part of a plume follows Gaus-
sian profile with axis temperature $\Delta T_0'$, and inner part takes flat tempe-
rature profile. Similar profile is assumed for the velocity profile
being W_0' as the axis velocity of the plume. In other words,

$$\Delta T_d \, / \, \Delta T_0' = \exp(-\beta^2 \, \eta_d^2) \tag{1}$$

$$W_d \, / \, W_0' = \exp(-\eta_d^2) \tag{2}$$
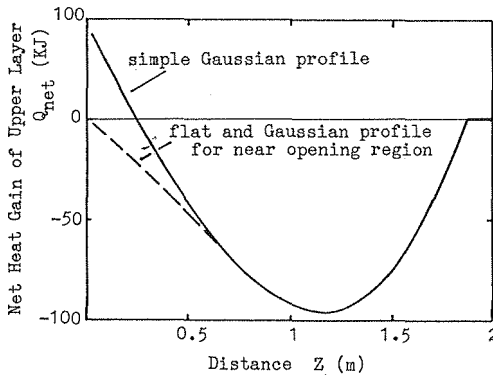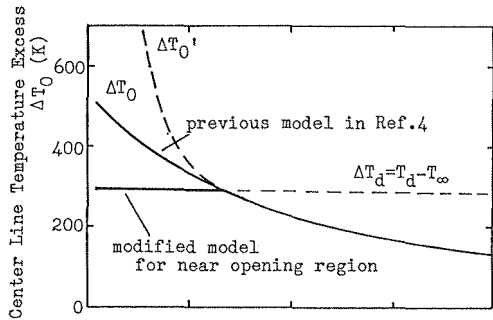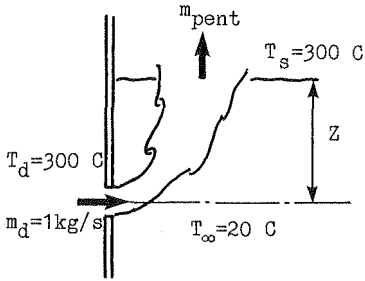
note :

$$Q_{net} = q - C_p T_s m_{pent}$$

$$= C_p(T_\infty - T_s)m_{pent} + kQ$$

Fig.3 Effect of modified temperature and flow profile
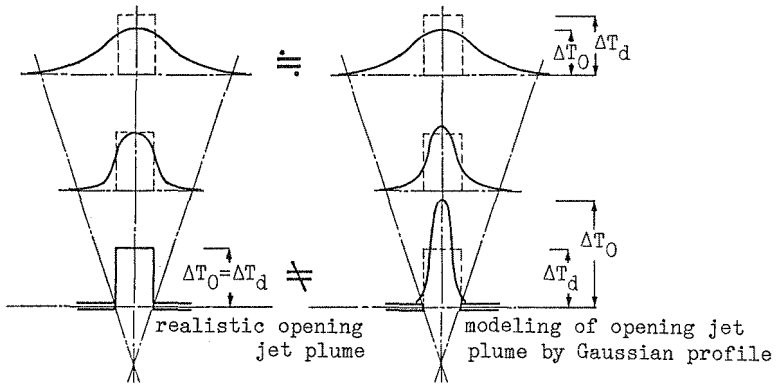near opening region

Fig.4 Limitation of modeling of opening jet plume
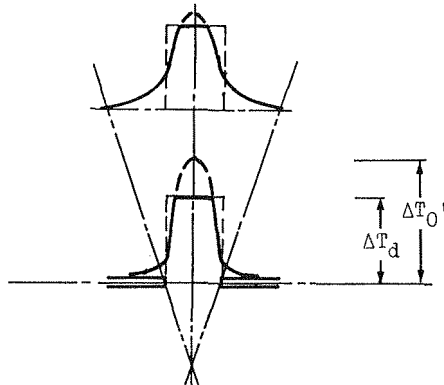   by Gaussian profile

Fig.5 Model of temperature profile near opening region

where η_d is the radius in Howarth transformation which corresponds to ΔT_d on the Gaussian temperature profile.

Now, let m_{z1} be the mass flow rate through near axis area $(0 \leq \eta \leq \eta_d)$, m_{z2} be the rate through off axis area $(\eta_d < \eta)$ and m_z be the total mass flow rate, then

$$m_z = m_{z1} + m_{z2} \tag{3}$$

$$m_{z1} = 2\pi \int_0^{\eta_d} W_0' \exp(-\eta_d^2) \rho_\infty b^2 \eta \, d\eta$$

$$= \pi W_0' \rho_\infty b^2 \exp(-\eta_d^2) \eta_d^2 \tag{4}$$

$$m_{z2} = 2\pi \int_{\eta_d}^{\infty} W_0' \exp(-\eta^2) \rho_\infty b^2 \eta \, d\eta$$

$$= \pi W_0' \rho_\infty b^2 \exp(-\eta_d^2) \tag{5}$$

Similarly, for the rate of heat flow through near and off axis regions, we have

$$Q = Q_1 + Q_2 \tag{6}$$

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$$Q_1 = 2\pi C_p \int_0^{\eta_d} \Delta T_0' \exp(-\beta^2 \eta_d^2) W_0' \exp(-\eta_d^2) \rho_\infty b^2 \eta \, d\eta$$

$$= \pi C_p W_0' \rho_\infty b^2 \Delta T_0' \exp(-(1+\beta^2) \eta_d^2) \eta_d^2 \qquad (7)$$

$$Q_2 = 2\pi C_p \int_{\eta_d}^\infty \Delta T_0' \exp(-\beta^2 \eta^2) W_0' \exp(-\eta^2) \rho_\infty b^2 \eta \, d\eta$$

$$= \frac{\pi C_p W_0' \rho_\infty b^2}{1+\beta^2} \Delta T_0' \exp\{-(1+\beta^2) \eta_d^2\} \qquad (8)$$

From Eqs.(1)-(8) and (A3), η_d can be obtained as follows:

$$\eta_d^2 = \frac{1 - \dfrac{1}{1+2}(\dfrac{Z+Z_0}{Z_0})^{5/3}}{(\dfrac{Z+Z_0}{Z_0})^{5/3}-1} \qquad (9)$$

Using η_d^2, the rate of mass penetrating through a layer interface is given as follows:

$$m_{pent} = m_z - 2\pi \int_{\eta_{\Delta Tc}}^\infty W_0' \exp(-\eta^2) \rho_\infty b^2 \eta \, d\eta$$

$$= m_z \{ 1 - \frac{1}{1+\eta_d^2} \exp(\eta_d^2 - \eta_{\Delta Tc}^2) \} \qquad (10)$$

where $\eta_{\Delta Tc}^2$ is the radius in Howarth transformation which corresponds to threshold temperature of penetration ΔT_c. And the penetration rate of heat is given as

$$Q_p = Q - 2\pi C_p \int_{\eta_{\Delta Tc}}^\infty \Delta T_0' \exp(-\beta^2 \eta^2) W_0' \exp(-\eta^2) \rho_\infty b^2 \eta \, d\eta$$

$$= k Q \qquad (11)$$

where

$$k = 1 - \frac{1}{1+(1+\beta^2)\eta_d^2} \exp\{(1+\beta^2)(\eta_d^2 - \eta_{\Delta Tc}^2)\} \qquad (12)$$

So, it follows that the penetration model near an opening has been obtained.

It should be kept in mind, however, that this theory is not perfect but of a compromised nature since the total mass flow rate have to be calculated using Eqs.(A1),(A2), i.e., the equations for the flow rate for far field region of plume with virtual point heat source as an adjusting parameter.

SAMPLE CALCULATIONS

In the followings, the results of two sample calculations are shown to demonstrate the computation capability of the present model.

Mechanical Smoke Exhaustion at Office Space

A series of field experiments for smoke behavior were conducted

using the pavilions of the international exposition held at Tsukuba, 1985, taking advantage of the time lag between the closing of the fair and the pulling down of the pavilions.

Of the pavilions in which fire experiments were run, IBM pavilion was provided with a mechanical smoke exhaustion system at its office area in compliance with The Building Standard Law. The office area used for the experiments consisted of an office with 51 m^2 and a corridor of 1.75 m wide and 30 m long as is shown in Fig.6. The ceiling height of this area was 2.7 m. One of the mechanical smoke vents was located at a corner of the office and the other at the end of the corridor and could exhaust smoke at the rate of 0.9 m^3/s and 1.3 m^3/s, respectively.

The fire source was placed at the center of floor of the office. The fuel was methanol and the size of the source was 0.9 m x 0.9 m. The heat release rate was estimated as 320 kW.

The predicted and the experimentally observed behavior of the smoke layers are shown in Fig.7 for the case with mechanical exhaustion at the office and the corridor(IB02), and the case without mechanical exhaustion(IB01). The figures schematically illustrates the section of area and the left hand side and the right hand side represents the office and the corridor, respectively. The experimental temperature rise in the smoke layers in Fig.7 were obtained by thermocouple readings and are shown by the shades of different thickness according to the temperature.

In the prediction, the corridor was divided into two parts because it was considerably long and had a turn at the middle.

In the case of no mechanical ventilation, the predicted layer temperatures are somewhat higher than those of measured, but generally speaking, the agreement of the predicted and experimentally obtained layer behavior can be said fair. In the case when the mechanical ventilation operated, both the prediction and the experiment demonstrate that the smoke can be effectively exhausted from the spaces by the smoke control system.
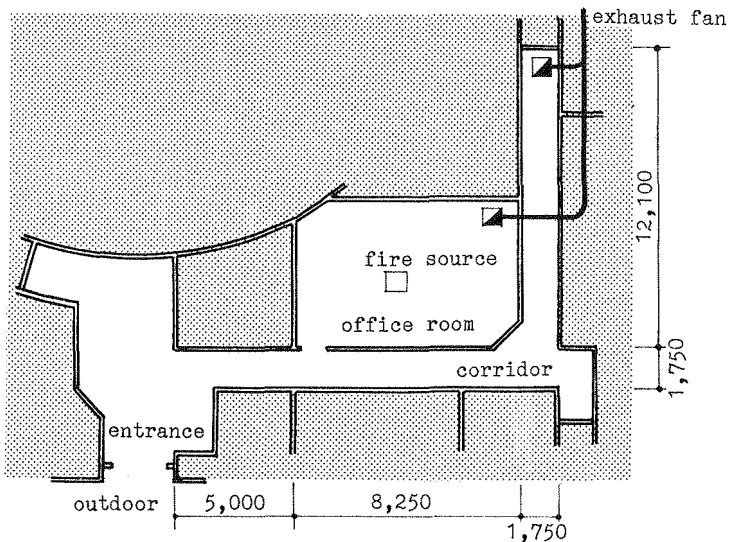

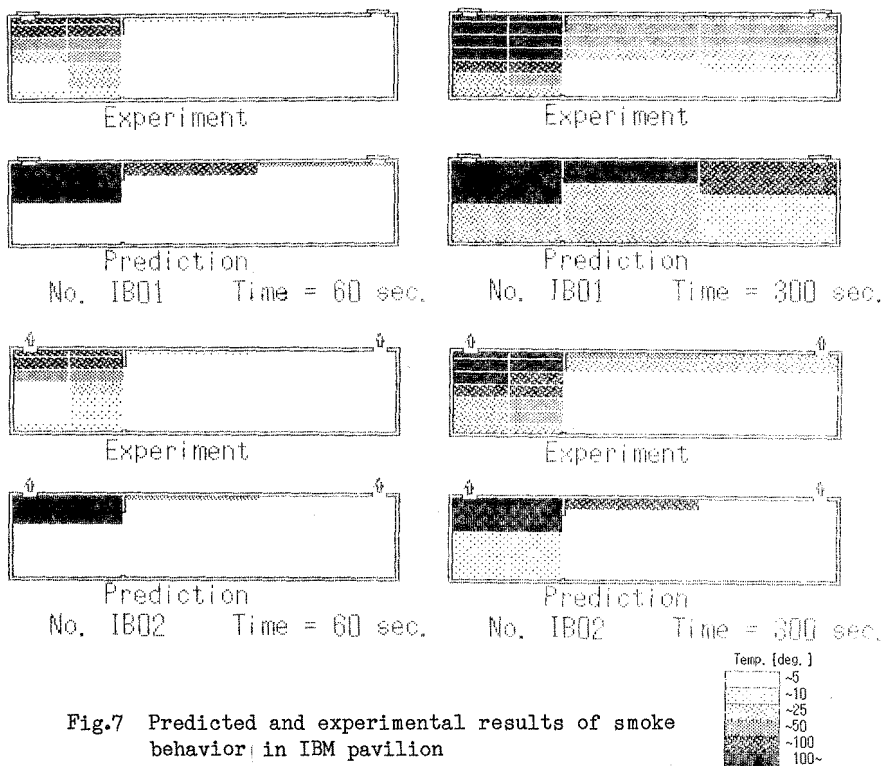Fig.6 Area for the experiments in IBM pavilion

Fig.7   Predicted and experimental results of smoke
        behavior in IBM pavilion

Prediction of Smoke Movement in a Model Building

      Prediction was attempted for the smoke movement for a eight story
model building with an atrium. The building consists of an atrium of
which size is 20 m x 20 m x 32 mH and two rooms of 10 m x 20 m x 3 mH on
each floor. And on 3rd through 8th floor, two fire shutters, 5 m x 3 mH
each, are installed on each opening facing to the atrium. On the top of
the wall of the atrium is a natural smoke vent of 12 m wide and 1 m high,
and on each floor an air supply fan with capacity 4 m³/s is equipped.
The calculation was run under the scenario described as follows:

time	event
before 0 sec.	the outdoor and indoor temperature were 30 C and 20 C respectively
0 sec.	fire breaks out on the floor of the atrium (heat release rate increase linearly from zero to 5 MW in 300 sec and then levels off)
60 sec.	detects fire, evacuation starts throughout the building a window is opened at the office on 7th floor
120 sec.	the fire shutters on each floor close but on 5th and 6th floor one of the two failed to close due to some trouble
125 sec.	mechanical air supply fan switches on at 6th floor
270 sec.	the natural vent opens at the top of the atrium

      The results of the prediction are shown in Fig.9.

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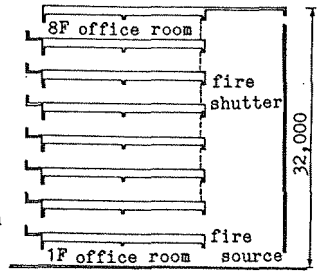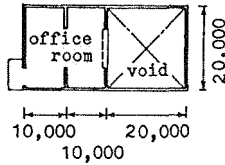
Plan

Fig.8 Outline of 8 story
model building

Section

TEMP. [C]
~30
~40
~50
~60
~70
70~
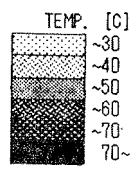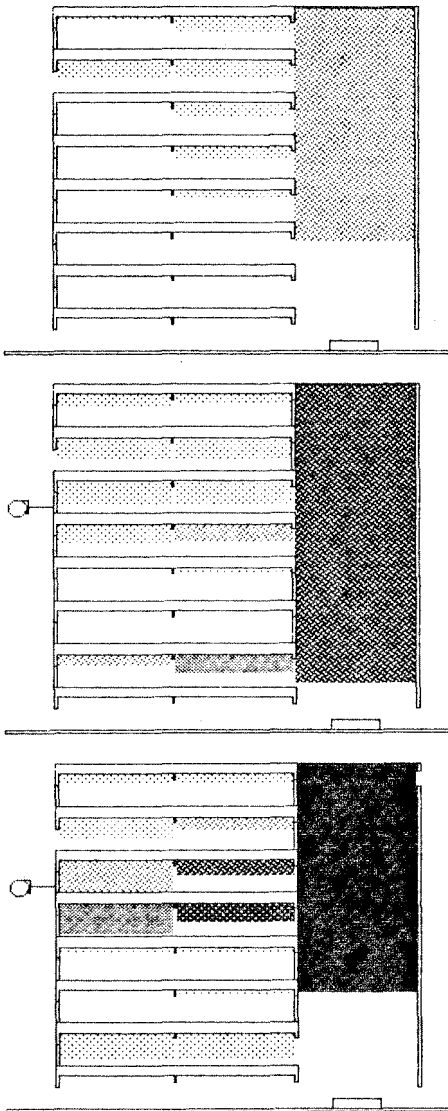
Time = 120 sec.

The temperatures of smoke layers
are not yet very high but smoke
begins to enter the rooms on each
floors. On 7th floor, the smoke
layers expands by mixing with the
air flowing into the building
through the opened window.

Time = 240 sec.

The smoke layer in the atrium
descends to near the bottom and the
layer temperature rises to more
than 50 C. The floors of which
shutters are closed are kept compa-
ratively safe, although some infil-
tration of smoke exists. On the
floors of which fire shutters are
not closed, significant amount of
smoke fills the rooms.

Time = 600 sec.

The smoke is gradually removed
from the atrium through the natural
vent. Hazardous condition develops
on 5th and 6th floors, when the
fire shutters failed to close, but
the temperature of 6th floor is
somewhat lower than that of 5th
floor thanks to the mechanical air
supply.

Fig.9　Smoke behavior in 8 story model building

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CONCLUDING REMARKS

We acknowledge that the models on the entrainment of an opening jet or the penetration of plumes are not based on very solid understanding of the phenomena, so we may have to be careful when we apply the model extensively to various problems.

It is obvious that engineering tools to predict fire behavior can help rationalize fire safety measures of buildings even if they are not perfect. In this sense, many of the existing models can be used in practical issues if sufficient attentions are paid on their limitations.

As for the present model, it is evaluated that with the introduction of partial penetration model of opening jets, the model is refined so that predict smoke movement in building can be predicted reasonably well without giving contradictory results. Also, the model is equipped with several features which are thought to be beneficial for design purposes.

The model still needs improvements on many respects, such as convective heat transfer, lateral smoke propagation along corridors, smoke behavior in narrow vertical shafts and so on, so we would like to continue its refinements absorbing better understandings on these phenomena as they grow.

NOMENCLATURE

Symbols

b transformed plume half width
c_p specific heat of air (kJ/kg/K)
g acceleration of gravity (m/s^2)
k fraction of the heat that penetrates into a layer
m mass flow rate (kg/s)
Q heat (kW)
r plume radius (m)
T temperature (K)
ΔT_c criterion temperature difference for plume penetration (K)
ΔT_0 temperature rise on a plume axis (K)
W plume velocity parallel to plume axis (m/s)
Z_0 distance of virtual point heat source from fire source (m)
β ratio of Gaussian half widths of velocity and temperature profile
η plume radius in Howarth transformation
ρ density (kg/m^3)

Subscript

d denote door jet
$pent$ denote penetration
s,a denote upper layer and lower layer
∞ denote ambient

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APPENDIX   Formation of Plumes (Ref.2)

The flow rate of fire plume is calculated using the formulas
developed by Zukoski et al(Ref.3). Opening jet plumes are modeled as
vertical thermal plumes and to calculate the flow rate of the plumes at
the height of Z, the equation of plume flow rate for far field region by
Zukoski et al(Ref.3) is also applied.

Virtual point heat source is assumed at a certain distance below an
opening jet. The distance is given as

$$Z_0 = [\; m_d \; / \; \{ \; 0.21(\frac{g\rho_\infty^2}{C_p T_\infty})^{1/3} \; Q^{1/3} \} \;]^{3/5} \tag{A1}$$

where

$$Q = C_p \; | T_d - T_\infty | \; m_d \tag{A2}$$

where T_d and T_∞ are the temperature of an opening jet and the ambient
layer, and m_d is the mass flow rate of the opening jet. With the use of
Z_0, m_z is also expressed as

$$m_z = m_d \; \{ (Z + Z_0) \; / \; Z_0 \; \}^{5/3} \tag{A3}$$

Gaussian profile is assumed on the vertical velocity of plume, then
the mass penetration rate through a layer interface is given as

$$m_{pent} = \begin{cases} m_z\{1-\exp(-\eta_{\Delta Tc}^2)\} & (\Delta T_c < \Delta T_0) \\ 0 & (\Delta T_c \geq \Delta T_0) \end{cases} \tag{A4}$$

where η is plume radius in Howarth transformation. With as the critical
temperature for penetration, $\eta_{\Delta Tc}^2$ is defined as

$$\eta_{\Delta Tc}^2 = -(1 \; / \; \beta^2) \; \ln(\Delta T_c/\Delta T_0) \tag{A5}$$

where ΔT_0 and ΔT_c are given as

$$\Delta T_0 = \{ \Delta T_\infty/(g C_p^2 \rho_\infty^2) \}^{1/3} \; Q^{1/3} \; (Z+Z_0)^{-5/3} \tag{A6}$$

$$\Delta T_c = C(T_s - T_a) \tag{A7}$$

In Eq.(A7), C is a constant to be determined empirically.

Similar consideration is applied on the penetration of heat to yield

$$Q_{pent} = \begin{cases} C_p T \; m_{pent} + kQ & (\Delta T_c < \Delta T_0) \\ 0 & (\Delta T_c \geq \Delta T_0) \end{cases} \tag{A8}$$

where

$$k = 1 - \exp\{-(1+ \beta^2)\eta_{\Delta Tc}^2) \tag{A9}$$