NISTIR 6030

THIRTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY, MARCH 13-20, 1996

VOLUME 2

Kellie Ann Beall, Editor

June 1997
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary R. Buchula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Robert E. Hebner, *Acting Director*

Modeling on Temperature and Ventilation induced by a Model Fire in a Tall and Narrow Atrium Space

by

H. Satoh*, O. Sugawa** and H. Kurioka*

*Kajima Technical Research Institute, Kajima Corp.
2-19-1 Tobitakyu, Chofu-shi, Tokyo 182, Japan
**Center for Science and Technology, Science University of Tokyo,
2641 Yamasaki, Noda, Chiba 278, Japan

ABSTRACT

Temperature rise and ventilation caused by a fire in a tall and narrow atrium are successfully estimated by an engineering model considering the atrium configuration (floor area, height, opening arrangements), dimensionless heat release rate, and Froude number. These two dimensionless numbers are estimated based on inlet-opening width, heat loss to walls, and inlet-to-outlet opening ratio. Measurements of temperature and upward velocity in a flame, plume and atrium space, and velocity of flow induced at openings were carried out. Experiments were done in a reduced-scale model and three different full scale buildings. Comparison of the estimated values of temperature rise, ΔT, and ventilation rate using the model proposed with the results of experiments indicated that the model can be used for the estimation of these values as a simple tool. The model helps to evaluate the fire safety design of a tall and narrow atrium.

Key Words: Atrium, temperature rise, Froude Number, Dimensionless heat release rate,

Nomenclature

A	floor area (m^2)
A_T	total surface area (m^2)
Ad	inlet area (m^2)
Ae	outlet area (m^2)
C	space factor (as defined in this paper) (-)
C_D	orifice constriction coefficient (-) (=0.7)
Cp	specific heat of gas (kJ/kg·K)
Dd	characteristic door length (=$Ad^{1/2}$) (m)
Do	characteristic floor length (=$A^{1/2}$) (m)
Fr_d	Froude number = $\mathbf{Fr_d = Vd^2/g \cdot D_d}$
g	gravitational acceleration (9.8 m/s^2)
H	height of ceiling above source (m)
*h*e	overall heat transfer coefficient ($kW/m^2 \cdot K$)
K^2	$=(Ta/Ts)(Ae/Ad)^2$ (-)
Md	inlet mass flow rate (kg/s)
Me	outlet mass flow rate (kg/s)
Mair	inlet mass flow rate during forced ventilation (kg/s)
Ms	outlet mass flow during forced ventilation (kg/s)
m	= Dd/Do (-)
Q_f	heat release rate (kW)
Qloss	rate of heat loss through walls (kW)
Q_{fd}*	non-dimensional, Froude like door source characterization: $= Q_f/Cp\rho_a T_a g^{1/2} Dd^{5/2}$ (-)
Ta	ambient temperature (K)
Ts	room temperature (K)
ΔT	rise of room temperature above ambient temperature (K)
Vd	inletvelocity of air (m/sec)

Y*	non-dimensional room heat loss	ρ_s	room gas density (kg/m^3
ρ_a	ambient air density (kg/m^3)		

1. Introduction

Buildings having atrium of various scales, forms and uses increased in Japan. Figure 1 gives the space volume and the aspect ratio, H^2/A, [1] for the eighteen buildings [2]. This figure indicates that the atrium spaces fall roughly into three groups: the shopping-mall type, approximately cubic type, and tall-and-narrow type. The ASHRAE Design Guide, based on the study of Heskestad [3], gives appropriate guidelines on fire safety for the first two groups. However, no firm guidelines for the tall and narrow atrium building is given. Several fire tests have been conducted, using reduced model [3~9] and full-scale models [10,11] of compartments. Many researchers [13~15] have proposed models to estimate temperature rise, ΔT, in a compartment while accounting for heat loss through the surrounding walls covering a wide range of temperature up to 600°C. However, most cases dealt with a compartment fire and of which have approximately cubic configuration with an opening and which did not deal with an enclosure of a tall and narrow atrium which is the main subject of this study. We pursued to establish a simple method to evaluate temperature rise in a tall and narrow atrium and the inlet-air velocity at openings during the early stage of a fire for natural and/or forced ventilation of the atrium space revealing the relationships among a number of factors; space factor, dimensionless heat release rate, Froude number, and temperature rise in the space. A simplified model which can be used for evaluating the fire prevention measures and smoke management performance of an atrium, given the form and dimensions of the space and a standard fire source, appears the most likely candidate for supplying answers to the questions confronting both designers and regulators.

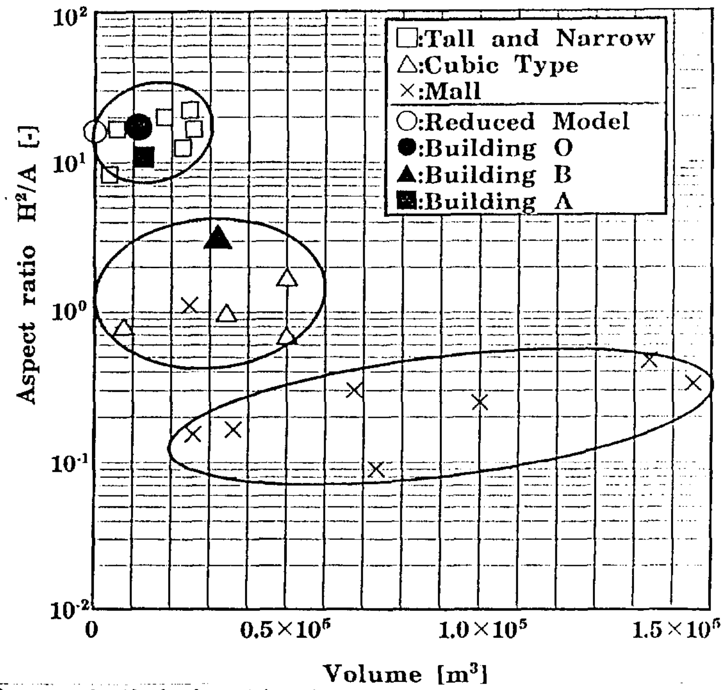


Figure 1 Relationship between the aspect ratio and volume atrium space. Three atrium space used for the experiments and (●,▲,■) reduced model (○) are illustrated.

2. Simplified Model

2.1 Basic Expressions

We firstly attempted to define the equations of conservations of mass, energy, and momentum considering the architectural characteristics of an atrium such as floor area, A, height of ceiling, H, and fixed arrangement of openings.

2.2 Proposal of simplified model

1) Formula to predict temperature rise, ΔT

A formula for predicting temperature rise in a naturally ventilated space can be obtained based on the previous paper. [10, 11],

$$\Delta T / Ta = \left(Q_{fd}^{*}/Y^{*}\right) / \left(C_{D} \cdot C^{1/2}\right), \qquad (1)$$

where the space factor **C** is defined as $C = (j/C_D m)^{2/3}(2K^2/1+K^2)^{2/3}(H^2/A)^{1/3}$ and this includes $K^2=(Ta/Ts)(Ae/Ad)^2$, $Y^{*} = 1 + h_e A_T / (M_d C_p)$, and $Q_{fd}^{*} = Q_f / Cp\rho_a T_a g^{1/2} Dd^{5/2})$.

A prediction of ΔT in a mechanically ventilated space can be made directly from $Q_f = C_p C_D A_d V_d \rho_a (T_s - T_a) + h_e A_T (T_s - T_a) = \{M_d C_p + h_e A_T\} \Delta T$ if h_e is known, but the following formula is more commonly used.

$$\Delta T / Ta = Q_{fd}^{*} / \left(Y^{*} \cdot Fr_d^{\ 1/2}\right) \text{ with } Fr_d = C\left(Q_{fd}^{*}/Y^{*}\right)^{2/3}. \qquad (2)$$

Formulas for predicting the velocity of air flow at openings and also temperature rise in a naturally ventilated space can be induced from the dimensionless heat release rate as defined with the openings in the space, and the space factor. However, eqs. (1) and (2) contain **Y*** so that temperature rise can not be calculated directly using these formulae except when heat loss through the walls is negligible small. These equations must be evaluated from the results of tests. Therefore eq.(2) is transformed into eq.(3) so that Y* may be conveniently obtained from test data. When the value of Fr_d fluctuates by 20% to 30%, the value of **Y*** fluctuates by the third power. This leads to large error and thus **Y*** cannot be used for design purposes.

$$Y^{*} = C^{3/2} Q_{fd}^{*} / Fr_d^{\ 3/2} \qquad (3)$$

Also, the following formula is obtained by rewriting eq. (2).

$$Y^{*} = Q_{fd}^{*} / \left\{C_D C^{1/2} (\Delta T / T_a)\right\}^{2/3} \qquad (4)$$

In eqs.(3) and (4) Q_{fd}^{*} is a given condition, while Fr_d and $\Delta T/Ta$ are measured values, indicating that **Y*** can be predicted in the case of natural ventilation. For the case of forced ventilation, a formula for **Y*** is induced from eq.(2).

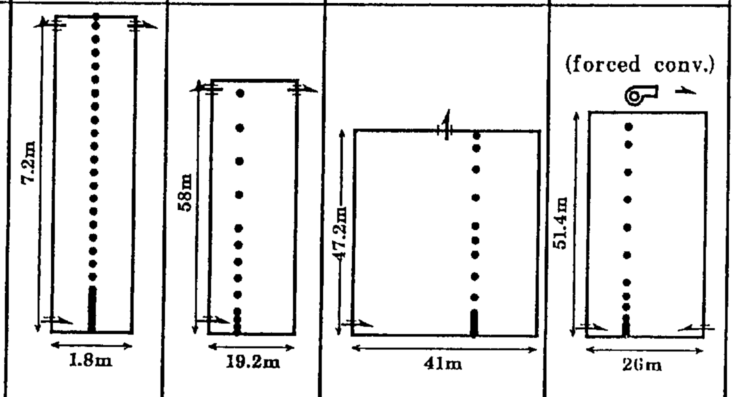
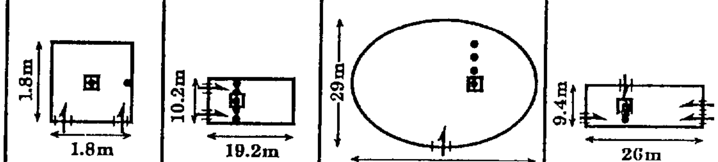
3 Verification of the Model

3.1 Verification by new laboratory tests on scale model

1) Full Scale Atrium

The outline of the full scale models of which size, configuration, and ventilation method are shown in Table 1. Two tests were carried out in tall and narrow atrium of buildings O and A under natural and forced convection condition, respectively. The other test was done in cubic-type atrium of building B under natural convection condition. Measurements of temperature and upward velocity were carried out along the center line and also off-center of ascending flow from a model fire source which composed of methanol pools fire. And also upward velocity was measured along the center line in flame zone. Balloon was released near fire source and was traced by video recording system to visualize the convection and the bottom of the hot layer in the atrium space.

Table 1. Experiment Condition

	Reduced Model	Full-Scale Model		
		Bld. O	Bld. B	Bld. A
Section → Opening • Thermo Couple	 7.2m, 1.8m 1/100	58m, 19.2m 1/1000	47.2m, 41m 1/1000	(forced conv.) 51.4m, 26m 1/1000
Plan → Opening • Thermo Couple	 1.8m, 1.8m 1/100	10.2m, 19.2m 1/1000	29m, 41m 1/1000	9.4m, 26m 1/1000
Inlet Area [m²]	0.0675	26.1 33.9 38.8 46.2	0 4 8	2 5.6
Outlet Area [m²]	0.0675	0 2 4 6 12.1	0 3 8.5 17 34	0 6.3
HRR [kW]	1.5 3 6 12 24	83 351 748 1684	76.5 171 402 1206 1608	76.5 171 402 804

2) Reduced Atrium

Tests were conducted using the reduced model, 1.8m x 1.8m and 7.2m high, of approximately 1/10 scale as reported [10, 11]. The value for h_e of the surrounding walls of the model was ca. 0.0594 kW/m^2·K. The openings for air inlets and outlets were 22.5 cm high and were fitted with sliding doors made of 6-mm wired glass, allowing width of the openings to be adjusted. The width of these openings was set at a standard 30 cm, making the area of each opening 1/50 the floor area obeying the Japanese Construction Act. The fire source, a propane gas diffusion burner of 20cm x 20cm, was set at the center of the floor.

3) Methods of measuring temperature and air flow velocity

Temperatures in the space were measured simultaneously by thermocouples. Velocity of air flow at the air inlets was measured by anemometers. Representative temperature and air flow velocity are also shown in Table 1.

3.2 Observation and Validity of the Proposal Model

(a) Excess temperature and upward velocity

Figure 2 shows the excess temperatures along the ascending trajectory or along almost the center line of the flow normalized by $Q^{2/5}$ which were obtained both in the full and reduced scale tests. Excess temperatures in the full scale and reduced atrium models showed lower than those of open filed, and which may be resulted from the direct striking or active air entrainment into flame zone which was induced through the inlet opening(s). The temperature decreasing modes for vertical direction is similar to those expected from a free flame/plume produced from a diffusion burner.

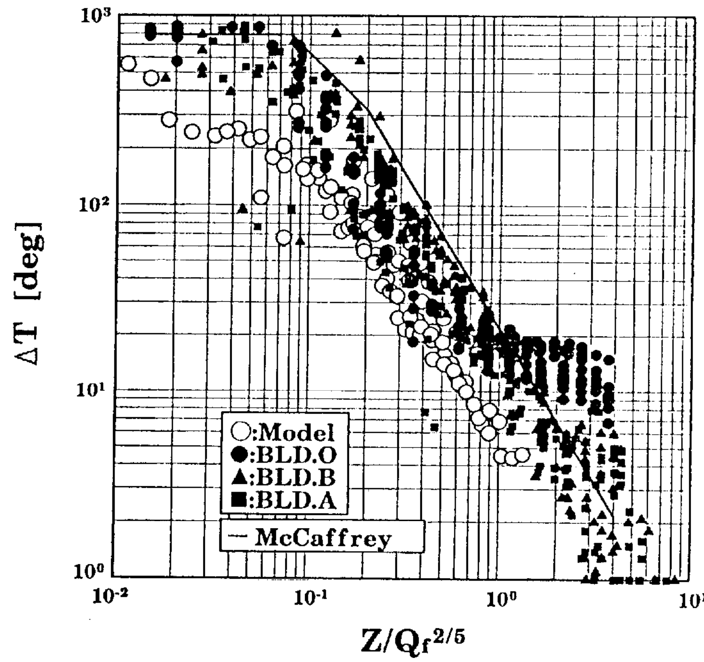


Figure 2 Excess temperature distribution for vertical direction along the ascending trajectory (almost the center line). Verical height is normalized by $Q^{2/5}$.

Figure 3 indicates the representative upward velocity normalized by $Q^{1/5}$ against height corrected by $Q^{2/5}$. Upward velocity in flame and intermittent flame zones showed great fluctuations but lower than ones expected for a free plume. In the upper part of the plume, we could get the apparent upward velocity in the main trajectory from the trace of a balloon and which showed

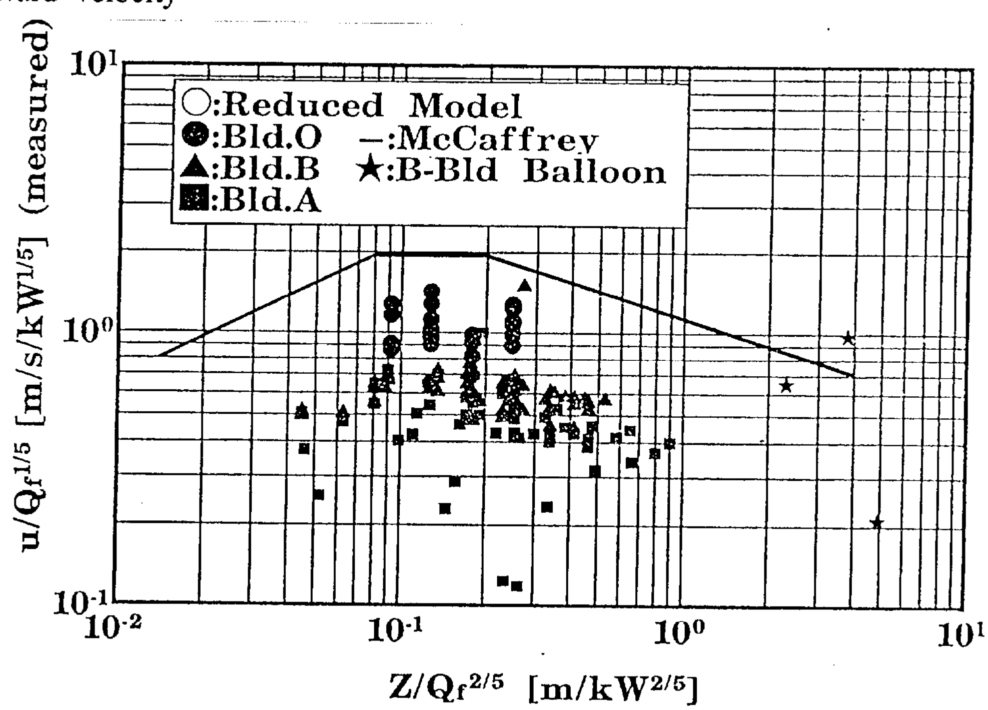


Figure 3 Upward velocity normalized by $Q^{1/5}$ are plotted against the verical height is normalized by $Q^{2/5}$.

almost on a line estimated by McCaffrey's paper. [12] It is not so clearly obtained from our data that the decreasing modes of upward velocity for vertical direction shows the same mode as McCaffrey reported [12].

(b) Comparison between Measured and Estimated Values

Figure 4 indicates the relationship between $Fr_d^{1/2}$ determined from the measured air flow velocity and $C^{1/2}Q_{fd}^{*1/3}$ designed from a fire size and space factor of the atrium. Figure 5 illustrates the relationship between measured temperature rise ΔT/Ta and $Q_{fd}^{*2/3}/C_DC^{1/2}$ under naturally and forced ventilation conditions. The results are arranged in line with the description of the model proposed here. These figures show that all values gained by actual measurement are smaller than theoretical values calculated on the assumption of the adiabatic condition of Y*=1. The curves of measured values are clustered on the same line and which is parallel to those of theoretical values.

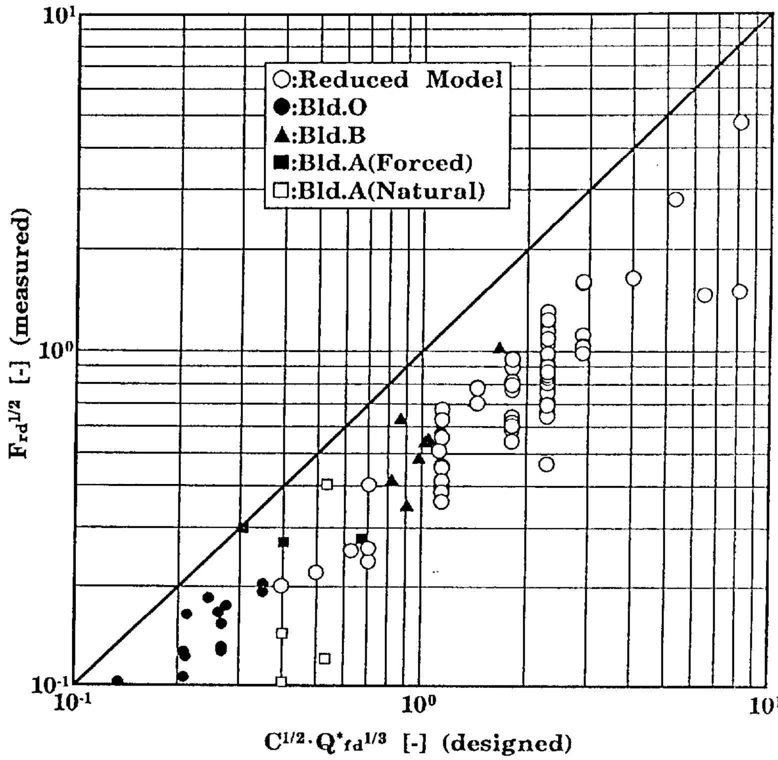


Figure 4 Relationship between Froude number measured as a function of dimensionless heat release rate, Q_{fd}^*, corrected by space factor C.

Figure 5 illustrates also the relationship between measured and predicted values of ΔT/Ta conducted in mechanically ventilated full scale atrium space. This figure indicates that, as was found for naturally ventilated space, measured values are consistently smaller than values produced by the model proposed here because of heat loss through the surrounding walls. The results obtained from the tests, shown in Figures 4 and 5, are smaller than those generated by the model under an assumed condition of thermal insulation that the difference between them cannot be neglected. It is observed, however, that the results of each test reveal regular behavior according to the heat loss characteristic of the atrium used in the test. Therefore it can reasonably be said that when the model is provided with heat loss based on the material used for walls, it can be effectively used to predict with practical accuracy the temperature rise in a space and air flow velocity at inlets, if the space is naturally ventilated. As for application of the model to a mechanically ventilated space, the prediction formula induced by the same theoretical steps as were used to create the prediction formula for a naturally ventilated space.

5. Conclusion

The major points of interest in this study are summarized below.

a) The model presented in this report, which consists of a formula made up of dimensionless heat release rate and the Froude number of the openings, both of which use the openings in the space as their reference point, is able to represent the smoke management performance of an atrium space in the stationary state with heat loss through surrounding walls taken into account, regardless of ventilation system. A distinguishing feature of this all-inclusive model is that it evaluates the performance of the space not just with the conventional dimensionless heat release rate or other terms which take the fire source as their reference point, but with terms which take openings in the space as their reference points and, therefore, represent well the characteristics of the space as a whole.

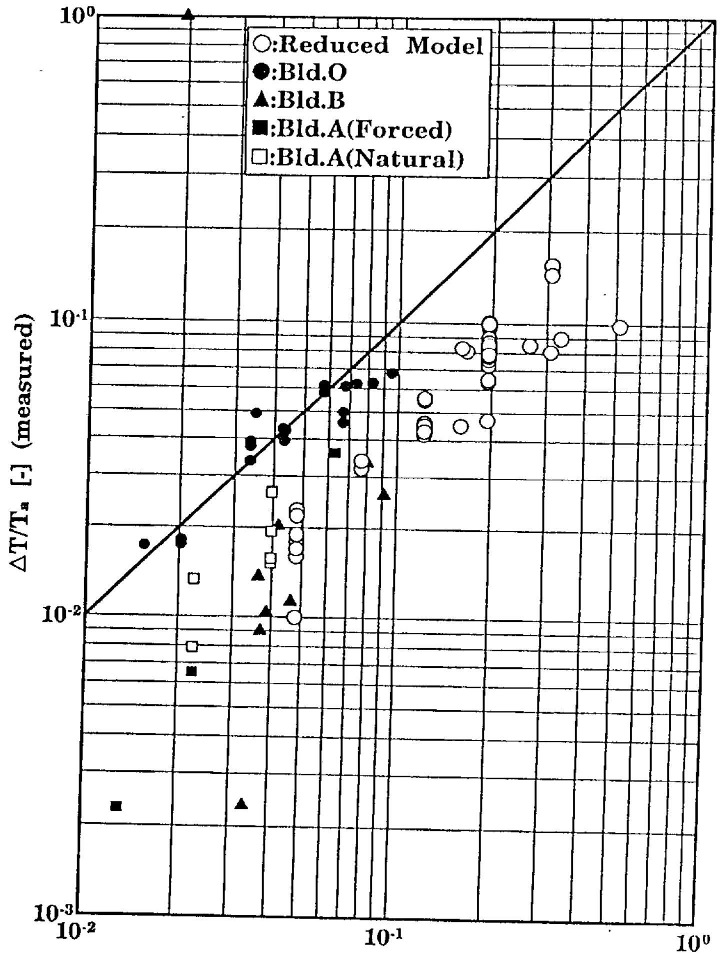


Figure 5 Comparison of measured values of $\Delta T/Ta$ and predicted values as Q^*_{fd} corrected with space factor and drag coeeficient at the opening for naturally and forced convection condition which are estimated from the designed fire size and space configuration.

b) This study verified the validity of the model presented here by comparing values produced by the formula to the results of laboratory tests using a tall and narrow full scale and reduced scale atrium. No inconsistencies between the results produced using the formula and knowledge previously reported or newly discovered were revealed.

c) Heat loss through surrounding walls cannot be neglected when predicting temperature rise in an atrium space for purposes of evaluating evacuation safety, which is the object of this study.

References

1) J. H. Klote, and J. A. Milke; "Design of smoke management systems", ASHRAE, 1992, pp. 107-108.

2) T. Naruse, and S. Sugahara; "Some investigations on fire safety design atriums", Journal of Structural and Construction Engineering (Transactions of AIJ), No. 443, 1993. 1, pp. 147-148.
3) G. Heskestad; see [1].
4) T. Tanaka, M. Yoshida, O. Ishino, K. Kojima, and Y. Kanaya; "Smoke control in atrium space", Japan Association for Fire Science and Engineering Annual Meeting Report, 1991.5, pp. 41-60
5) J. G. Quintiere, W. J. Rinkinen, and W. W. Jones; "The effect of room openings on fire plume entrainment", Combustion and technology, Vol. 26, 19831, pp. 193-201.
6) T. Z. Harmathy; "Ventilation of fully-developed compartment fire", Combustion and flame, 37, 1980, pp. 25-39.
7) K. L. Foote; "Data report of the 1986 LLNL enclosure fire tests", UCID-21236, Lawrence Livermore National Laboratory, 1987
8) K. Kojima, S. Hashimoto, and K. Okajima; "Study on smoke control method (Influence of opening condition for smoke movement)", Japan Association for Fire Science and Engineering Annual Meeting Report, 1993.5, pp. 90-93.
9) E. Yanai, T. Yamada, A. Sekizawa, Y. Watanabe, S. Miyazaki, and N. Saito; "Experimental study on tunnel fire behavior using reduced scale mode", Japan Association for Fire Science and Engineering Annual Meeting Report, 1993. 5, pp. 66-69.
10) H. Satoh, O. Sugawa, and H.Kurioka, "Modeling on Temperature and Ventilation for Fire in a Tall and Narrow Atrium", J. Archit., Plann. Envirn. Eng., AIJ, No.463, 1-10 , 1994,(in Japanease)
11) H. Satoh, O. Sugawa, and H.Kurioka, "Plume Behavior in a Confined Tall and Narrow Space - as One of Sub-Models of Plume for an Atrium -", Proc. 4th Int. Symp. on Fire Safety Science, pp.551-562, Ottawa, (1994)
12) R. J. McCaffrey, and J. G. Quintiere, and M. F. Harkleroad; "Estimating room temperatures and the likelihood of flashover using fire data correlation's", Fire Technology, 17, 2, 1981.
13) K. L. Foote, P. J. Pagni, and N. J. Alvares; "Temperature correlations for force-ventilated compartment fires", Fire Safety Science, Proceedings of the First International Symposium, 1985. 11, pp. 139-148.
14) S. Deal, C. Beyler; "Correlation preflashover room fire temperatures", J. of Fire Prot. Engr. 2 (2), 1990, pp. 33-48.
15) A. Tewarson; "Generation of heat and chemical compounds in fires", The SFPE Handbook of Fire Protection Engineering, SFPE, 1988, 1-179-1-200.

Discussion

Edward Zukoski: I have two questions. First, when the fire plume first starts, it won't reach the walls until it goes up a very long way, even with a 10 to 1 diameter to height ratio. Did you take that into account at all?

Osami Sugawa: The ratio is different from a open area plume. It is wider plume in the enclosed space.

Edward Zukoski: When air comes in at the bottom of the atrium, it might introduce some swirl. Did you see any effect of that?

Osami Sugawa: It does not appear as a swirl.