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REDUCED SCALE EXPERIMENTS FOR CONVECTIVE HEAT TRANSFER IN THE EARLY STAGE OF FIRES

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ABSTRACT

The goal of this study is to develop a simple and practical model for predicting an overall convective heat transfer coefficient in compartment fires. Experiments using a small scale (500 mm cube) and a medium scale (1,500 mm cube) compartments were conducted under different fire sizes to investigate the convective heat transfer coefficient. The method for estimating the mass flow rate through opening using air temperature in compartment in case of uni-direction flow was considered. The rate of convective heat transfer was obtained by subtracting heat loss rate through the opening of compartment from the heat release rate of fire source. The convective heat transfer coefficient was calculated from thus calculated rate of heat transfer and average temperature difference between hot gas and wall surface and surface area of compartment. It is found that non-dimensional heat release rate Q* which is defined using heat release rate of fire source and height of compartment as characteristic length can provide a fair scaling parameter for convective heat transfer coefficient with different heat release rates and scales of compartments in the early stage of fires, in which the flow induced by fire source is considered to be dominant in the flow field in the compartments.

1. INTRODUCTION

The purpose of this study is to develop a means for estimating an overall convective heat transfer coefficient in fire compartments, in order to contribute to improve the accuracy of zone fire models. The convective heat transfer coefficient to be addressed in this study, therefore, should be assessed without the help of local information of the fire field in a fire compartment.

In general, convective heat transfer to a surface is governed by conditions of is adjacent flow, i.e. velocity and temperature. In compartment fires, the principal driving forces of flow field in a compartment can be somewhat different between the following two stages: In the early stage of fire, the flow field is induced dominantly by fire plumes; on the other hand in more developed stage, ventilation through openings induced by the temperature rise of a compartment may become to affect on the flow field.

This paper particularly focuses on the convective heat transfer in the early stage. Reduced scale experiments were conducted under different heat release rates, sizes of compartments and openings to explore the scaling relationship of convective heat transfer in compartment fire.

2. METHODOLOGY

Usually, a convective heat transfer coefficient is obtained based on the measurements of the heat flux to a wall using a heat flux gauge and the temperature measured using a thermocouple located near the gauge. However, this method is not practical for the purpose of estimating the overall convective heat transfer coefficient because a number of heat flux gauges are need to be distributed over the interior surface of the compartment walls, while the number of heat flux gauges is usually limited. Hence a new methodology to measure the overall heat transfer was devised in this paper.

We pay attention to the situation in which the flow through the opening of a fire compartment is uni-directional. Such a situation can be possible in compartments having relatively small opening; when the compartment gas temperature is rising the expansion of gases induces outward only flow through the opening. On the other hand, when the temperature is falling the shrinkage of the gases induces the opposite flow. The experimental setup for this study is illustrated in Fig. 1.

When the opening flow is uni-directional, assuming that every physical value in the compartment is uniform, the following relationships hold for the conservation of energy and mass and the gas state:

Energy Conservation

$$\frac{d}{dt}\left(C_P \rho T V\right) = Q - C_P T_d m - Q_C \quad (1)$$

Mass Conservation

$$\frac{d}{dt}\left(\rho V\right) = -m \quad (2)$$

Ideal Gas Law

$$P = \frac{\rho}{M} RT \quad (3)$$

Noting that V is constant, ρT and C_P can be deemed virtually constant, Eqn. (1) becomes as follows:

$$Qc = Q - C_P T_d m \quad (4)$$

that is, the rate of heat transfer can be calculated from heat release rate of fire source, mass flow rate and temperature of the flow through opening.

For estimating the mass flow rate m in Eqn.(4), the following two methods are considered : One is to calculate the flow rate using measured pressure difference across the opening by:

$$m = \alpha A r \left(2 \rho \Delta P\right)^{1/2} \quad (5)$$

The other method is to use measured air temperature in the compartment : From Eqn.(3), we have:

$$\frac{d\rho}{dt} = \left(\frac{PM}{R}\right)\left(-\frac{1}{T^2}\right)\frac{dT}{dt} \quad (6)$$

Since V in Eqn. (2) is constant, substituting Eqn.(6) into Eqn.(2) yields:

$$m = \left(\frac{PM}{R}\right)\frac{V}{T^2}\frac{dT}{dt} \quad (7)$$

The rate of heat transfer Qc can be calculated by substituting m given either by Eqn.(5) or Eqn.(7) into Eqn.(4).

Finally, letting A and ΔT be heat transfer area and average temperature difference between the fire gases and the compartment walls, respectively, the heat transfer coefficient is calculated by:

$$h = \frac{Q_C}{\Delta T \cdot A} \quad (8)$$

Note that we should use average temperatures for fire gases and wall surfaces since local temperatures are not available in zone fire models.

As will be mentioned later in section 4(2), the radiative part of the total heat transfer is sufficiently small in the experimental conditions in this study, so the heat transfer coefficient thus calculated can be regarded as the convective heat transfer coefficient provided that a small error is allowed.

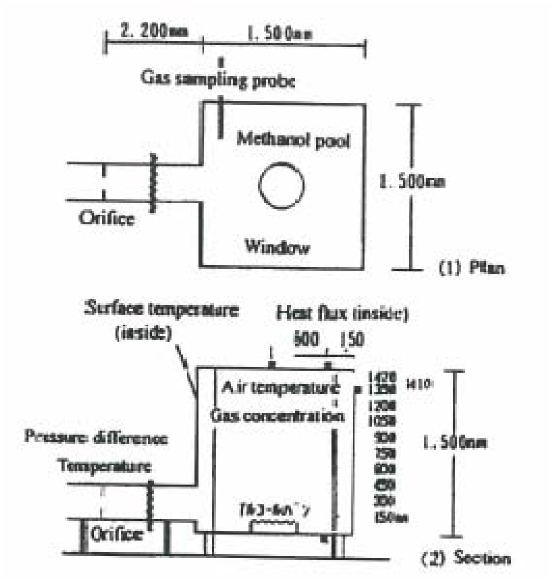
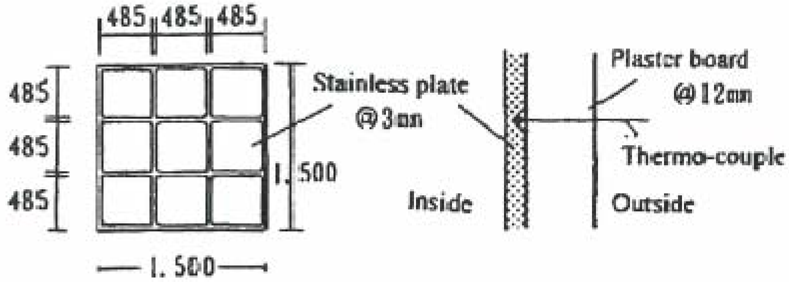


Fig. 1: Schematic of apparatus (medium compartment)

3. REDUCED SCALE EXPERIMENTS

3.1 Compartments

Experiments were conducted using a small scale (500 mm cube) and a medium scale (1,500 mm cube) compartments to which a straight duct of 20 cm in diameter and 2.5 m in length was installed to regulate the flow from the opening as shown in Fig. 1. An orifice plate was installed in the duct to measure the mass flow rate through the opening. The interior surface of the compartment was lined with 3 mm thick stainless steel plates on the walls made of 12 mm thick plaster boards as shown in Fig. 2.



(1) Inside view of wall (2) Section of wall

Fig. 2: Stainless plate and thermocouple

3.2 Measurement Items

Compartment gas temperature (11 vertical points × 2 horizontal points), heat flux to the wall (center and corner of the ceiling, upper part of the wall and the floor), gas concentration (O_2, CO_2 and CO), surface temperature of the wall (8 or 9 points at each of the wall, the ceiling and floor surface), pressure difference across the orifice and temperature in the duct and ambient air temperature were measured. The thermocouples for measuring the wall surface temperatures were welded in the small holes made in the unexposed surfaces of the stainless steel plates. The data acquisition intervals were at every 50ms for the pressure and at every one second for the other measurements.

3.3 Fuel and Heat Release

The fire source was a methanol pool fire in a circular steel pan, whose heat release rate was changed by using the pans with different diameters. The heat release rates of the fire sources were measured in free space prior to the compartment fire tests. It was regarded that the heat release rates in the compartment were not different from those measured in free space because the duration of each test in this series of experiments was short so the effects of temperature rise of compartment gases and walls on the burning rate can be ignored.

3.4 Diameters of Methanol Pool and Orifice

The diameters of methanol pool and orifice, and the heat release rates estimated based on the burn tests in open space are shown in Table 1. It had been known from the previous experiments that the orifice diameters do not affect on the heat transfer in compartment, but they were changed because pressure measurement data were needed for the study on pressure build up behavior in compartment fires.

4. RESULTS OF EXPERIMENTS

4.1 Outline

Fig. 3 shows an example of the pressure differences across the orifice, the average temperatures of the compartment gases and the interior surfaces of the walls. The pressure rose up very quickly after ignition, then fell quickly and became almost zero with elapse of time. After that, the fire went out due to depletion of oxygen. The temperature also rose up quickly after ignition, and stayed at almost constant value during the same time as the pressure difference stayed almost at zero. If the time that pressure difference is zero, the flow rate through opening can be considered zero, therefore it follows that the rate of heat transfer must be the same as the heat release rate during this stage.

Table 1: Diameters of methanol pool and orifice

Diameter of pan (mm)	150	200	250	300	350	200	250	300	350	400	450	500	550	600	700
Heat lerease rate (kW)	4.0	6.6	10.6	15.9	22.2	6.6	10.6	15.9	22.2	29.2	38.0	48.3	52.9	63.6	88.6
Orifice diameter (mm) / area (ﾃ10^{-3}m^2)															
40 / 1.26	2	2	2	2	2	1	1	2	1	2					
50 / 1.96	2	2	2	2	2	1	1	2	2	2	1				
60 / 2.83		2	2	2	2		1	2	1	2	1	2	2		
70 / 3.85			2	2	2			2	2	2	1	2	1	1	
80 / 5.03				2	2				1	2	1	2	1	1	1
100 / 7.85					2					2	2	2	1	1	1
Frame height (calculated)	0.25	0.29	0.34	0.39	0.44	0.29	0.34	0.39	0.44	0.48	0.53	0.57	0.56	0.6	0.67

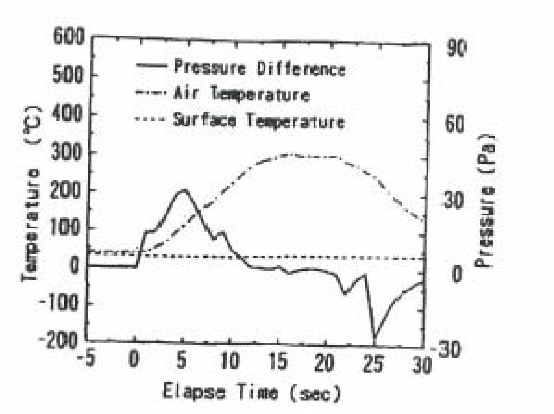


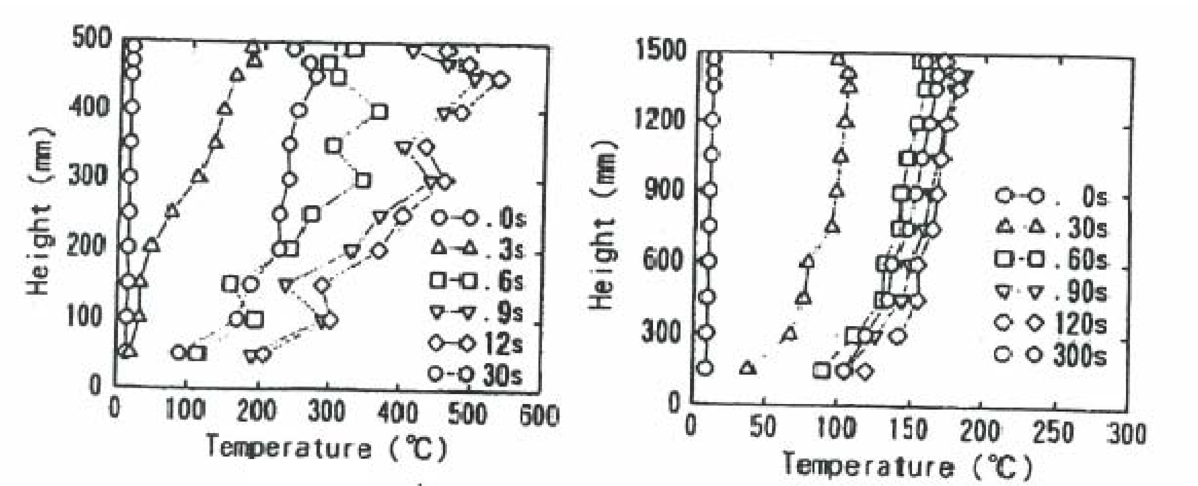
Fig. 3: Temperature and pressure with elapse time

4.2 Radiative Heat Transfer

The rate of radiative heat transfer to wall in each experiment was assessed based on the measurements of the gas concentrations and temperatures. The portion of radiative heat transfer thus estimated falls in about 5-15% of the overall heat transfer as mention below. In addition, the radiative heat transfer from methanol flames was considered to be negligible. So was the radiative heat exchange between the walls because the temperature differences were smaller than 15K. Hence, the rate of the heat transferred measured in this series of experiments were considered to be almost the same as the rate of convective heat transfer.

4.3 Assumption for Estimating Overall Convective Heat Transfer Coefficient

The vertical temperature profiles with elapse of time are shown in Fig. 4. Although a certain extent of difference is observed in the vertical temperatures measurements, it is considered that the whole compartment was filled with high temperature gases in the early stage of fire. Therefore, the average of all the gas temperature measurements was used as the reference gas temperature and the average of the measured wall temperatures was used as the reference wall temperature for estimating the convective heat transfer coefficient. Whole interior wall surface except the floor surface was taken as the heat transfer area. The combustion of the fuel was regarded as complete since the generation of carbon monoxide was not probed in any experiment.



(1) 500 mm cube (2) 1,500 mm cube

Fig. 4: Vertical profile of temperature

4.4 Estimation of Flow Rate through Opening

Fig. 5 shows results of the comparison between the mass flow rates calculated by Eqn.(5) and (7). Although time lag of one second or so, which is attributed to the difference in the response time between the pressure gauge and thermocouples, is observed the both values can be said remarkably close. In this study, it seemed more appropriate to use temperature measurements than to use pressure measurements to calculate the mass flow rate, since the accuracy of pressure measurement becomes uncertain when that value is small. In the following discussions, the mass flow rates estimated based on temperature measurements were used.

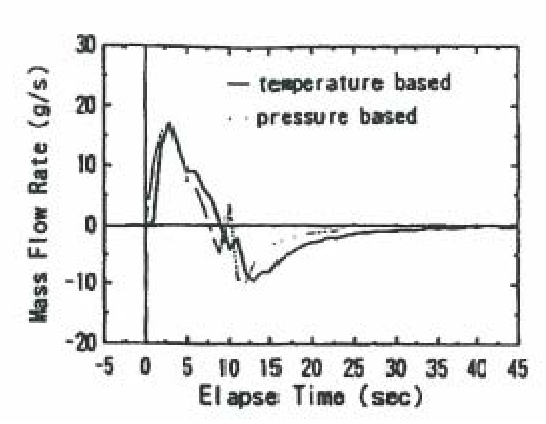
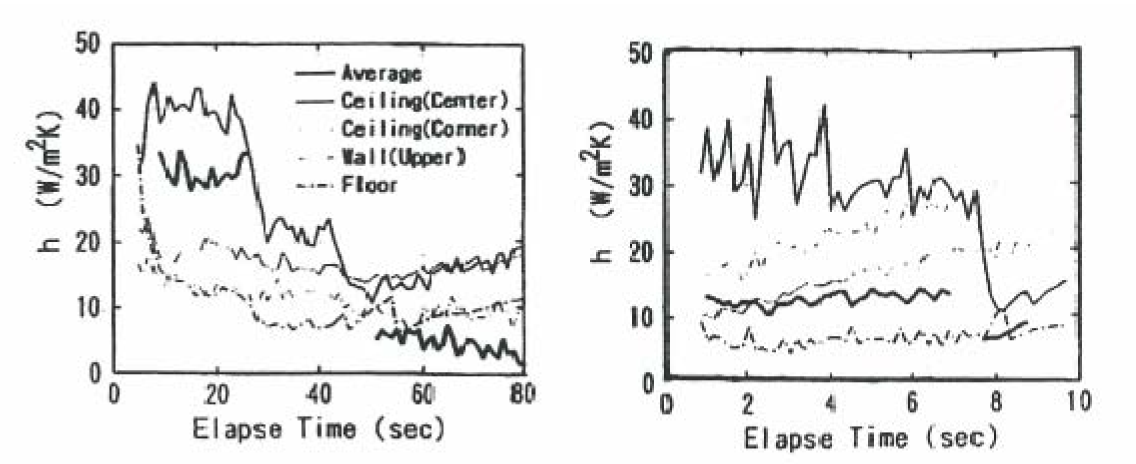


Fig. 5: Estimated mass flow rates based on temperature measurement and pressure measurement

4.5 Convective Heat Transfer Coefficient of Overall and Each Point

Fig. 6 shows the overall convective heat transfer coefficient obtained by the above described method and the local convective heat transfer coefficients obtained from the heat flux measured at several points using the heat flux gauges. The reason that the convective heat transfer coefficients was large while the fire source was releasing heat is considered to be because the walls were exposed to the flows induced by the heat release of the source. On the other hand, the convective heat transfer coefficients became small after the extinction of the fire. This is thought to be because the flows driven by the source had disappeared so the dominant mechanism of the heat transfer was only natural convection due to the temperature difference between the gases and the wall surfaces.

The local convective heat transfer coefficients vary depending on the position on the compartment walls. The dependence of the convective heat transfer to the ceiling on the distance from the plume axis was similar with the existing experimental studies [1-5].



(1) 500 mm cube (2) 1,500 mm cube

Fig. 6: Convective heat transfer coefficient of overall and each point

5. ANALYSES AND DISCUSSIONS

5.1 Additional Data from a Similar Series of Experiments

A similar series of experiments were conducted some years ago, using a 860 mm cube compartment with an opening and methanol used as the fuel. The series of the tests were conducted for 8 sizes of the opening (25 $\times$ 50~100 $\times$ 150 mm) and 5 diameters of the pan (200~400 mm). These data are also used in the following discussion.

5.2 Relationship between Heat Transfer Coefficient, Heat Release Rate and Scale of Compartment

5.2.1 Heat transfer coefficient and heat release rate

The heat transfer coefficient obtained from all the experimental results using 500 mm, 1,500 mm and 860 mm cubes are plotted versus the heat release rate of fire source in Fig. 7. The tendency is that the convective heat transfer coefficient increases as the heat release rate increase or size of the compartment decreases.

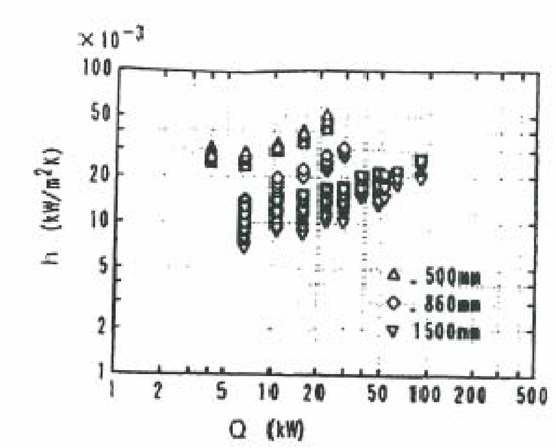


Fig. 7: Heat release rate and convective heat transfer coefficient

5.2.2 Non-dimensional heat transfer coefficient and heat release rate

For fire plumes, it is well known that the non-dimensional excess temperature $\Delta T_0 / T_\infty$ and non-dimensional flow velocity $u_0 / (gZ)^{1/2}$ can be described as a function of non-dimensional heat release rate which is defined using the distance from the fire source as characteristic length [6]. Generally, heat transfer coefficient basically depend on velocity field and to some extent on temperature difference, so it may be reasonable to presume that the convective heat transfer coefficient can be described as a function of non-dimensional heat release rate if a fire plume is the dominant mechanism for generating the flow and the temperature fields in a compartment.

Hence, the non-dimensional heat release rate is defined using the height of the cubic compartment H as the characteristic length as follows

$$Q^* = Q \Big/ (\rho_\infty T_\infty g^{1/2} H^{5/2}) \qquad (9)$$

As for convective heat transfer coefficient, a non-dimensional form is introduced as

$$h^* = h \Big/ (C_P \rho_\infty g^{1/2} H^{1/2}) \qquad (10)$$

which is similar with that introduced by Zukoski et.al [3,4].

5.2.2.1 During heat releasing

Fig. 8 shows the correlation between the non-dimensional heat release rates and the heat transfer coefficients. The fact that all the data tend to converge imply that the non-dimensional heat release rate Q^* is a fairly good scaling parameter of the heat transfer coefficient. A regression formula for the correlation in Fig. 8 may be:

$$h = 0.1(Q^*)^{2/5} \qquad (11)$$

although some deviation from the formula may be seen in the region where $Q^* = 5 \sim 10 \times 10^{-3}$.

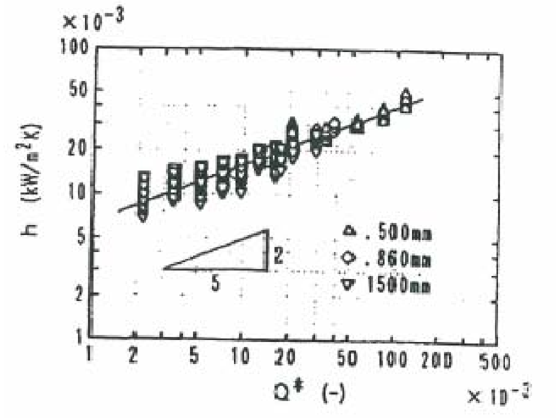


Fig. 8: Relationship between non-dimensional heat release rate and convective heat transfer coefficient

The constant in Eqn.(11) is dimensional. Further generalization can be attained by replacing the dimensional heat transfer coefficient with the non-dimensional coefficient defined by Eqn.(10). Fig. 9 shows the correlation between the non-dimensional heat release rate and the non-dimensional heat transfer coefficient. All the data show a fairly good convergence although there are a few data which do not sufficiently fit.

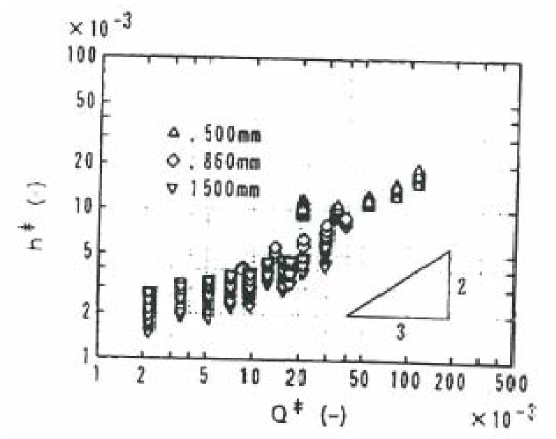


Fig. 9: Relationship between non-dimensional heat release rate and non-dimensional convective heat transfer coefficient (during heat releasing)

5.2.2.2 After extinction

Fig. 10 shows the correlation between the temperature difference and the convective heat transfer coefficient obtained for the stage after extinction. The convective heat transfer coefficient at this stage is presumed to be a function of Grashof number *Gr* because there is no driving force of flow other than the temperature difference between the gases and the wall surface. This presumption will lead to the expectation that the convective heat transfer coefficient is indifferent with compartment scale but is proportional to 1/3 to the temperature difference. According to Fig. 10, the convective heat transfer coefficient seem to depend on the temperature difference in the 500 mm cubic compartment, but the dependence is not clear in the 1,500 mm compartment and, in addition, the difference in the heat transfer coefficients are also observed between the compartment with different scale. But, in terms of non-dimensional heat transfer coefficient, dependence on the scale as well as on temperature difference seem to disappear as shown in Fig. 11.

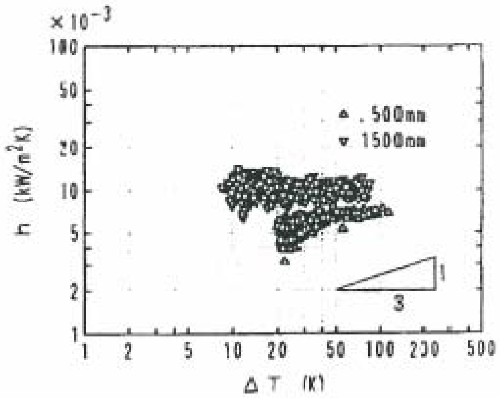


Fig. 10: Relationship between temperature difference and convective heat transfer coefficient (after extinction)

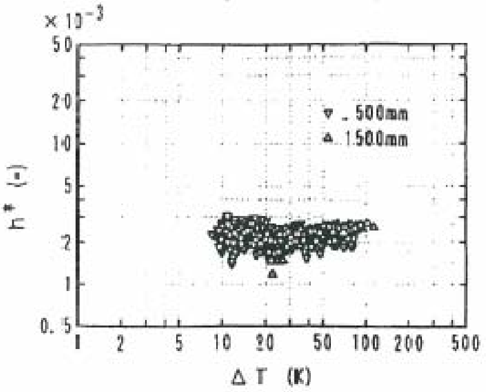


Fig. 11: Relationship between temperature difference and convective heat transfer coefficient (after extinction)

5.2.3 Non-dimensional heat release rate and non-dimensional heat transfer coefficient

Fig. 12 shows the correlation between non-dimensional heat release rate and non-dimensional heat transfer coefficients obtained both for during fire and after extinction periods. Here, the data after extinction are plotted at $Q^* = 0$ because it is regarded as special case of Q^*. Even for the period during heat releasing, non-dimensional heat transfer coefficients is similar to those after extinction when non-dimensional heat release rate is small. In such a case, it is thought that the flow induced by fire plume is so weak that the natural convective heat transfer becomes dominant.

The values of non-dimensional heat transfer coefficient h^* may be correlated into the following formulas.

$$h^* = \begin{cases} 2.0 \times 10^{-3} & (Q^* \le 4 \times 10^{-3}) \\ 0.08(Q^*)^{2/3} & (Q^* > 4 \times 10^{-3}) \end{cases} \qquad (12)$$

6. CONCLUDING REMARKS

The convective heat transfer coefficients in the early stage of the compartment fire experiments in this study were well scaled in terms of non-dimensional heat transfer coefficient and non-dimensional heat release rate, regardless the heat release rate and the scale of the compartments.

Further study will be necessary to elucidate the effect of geometry of compartments on the convective heat transfer.

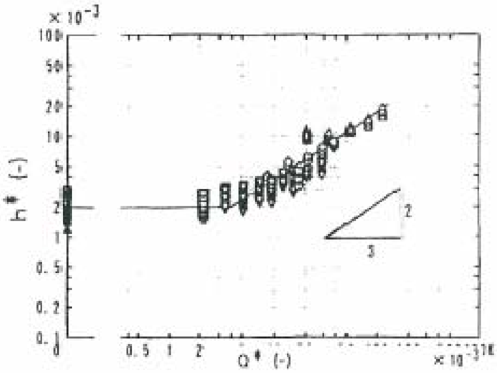


Fig.12: Relationship between non-dimensional heat release rate and non-dimensional convective heat transfer coefficient

NOMENCLATURE

A area of heat transfer (m^2)
Ar area of orifice or opening (m^2)
Cp specific heat capacity (kJ/kg K)
g acceleration of gravity (m/s^2)
H height of ceiling (m)
h convective heat transfer coefficient ($kW/m^2/K$)
h* non-dimensional convective heat transfer coefficient (-)
M molecular weight (kg/mol)
m mass flow rate through opening (kg/s)
P pressure (kPa)
ΔP pressure difference (Pa)
Q heat release rate (kW)
Qc convective heat transfer rate (kW)
Q* non-dimensional heat release rate (-)
R ideal gas constant ($=8.314\times10^{-3}$kJ/mol K)
T air temperature (K)
T_d air temperature of flow through opening (K)
T_∞ ambient air temperature (K)
ΔT temperature difference between air and surface (K)
t time (sec)
u velocity (m/s)
V volume of compartment (m^3)
Z distance from fire source (m)
α flow coefficient (-)
ρ air density (kg/ m^3)
ρ_∞ ambient air density (kg/ m^3)
Φ diameter of orifice (mm)

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