

Full Scale Compartment Fire Test with Lubricant Oil (Lubricant Oil Fire Test: Part 2)

M. FUJIZUKA

Mitsubishi Heavy Industries, Ltd.
(Mitsubishi Atomic Power Industries, Inc.)
4-1, Shibakouen 2-chome, Minato-ku, Tokyo, Japan

Y. KABASAWA

Chubu Electric Power Company, Inc.
1, Toushincho, Higashi-ku, Nagoya, Japan

Y. SOUTOME

Hitachi Works of Hitachi, Ltd.
3-1-1, Saiwaicho, Hitachi, Ibaraki-Pref., Japan

J. MORITA

Toshiba Corporation
8, Shinsugita, Isogo-ku, Yokohama, Japan

ABSTRACT

The objective of the tests was to provide the data for use in evaluating the environmental effects of lubricant oil fires in the compartment. Fifty-one tests were conducted to research the environmental effects (atmospheric temperature, radiation heat flux and so forth) on the surroundings with the various size fuel pans and compartments and the various air exchange rates. The concentration of the smoke and CO were also measured in the tests. Test results showed that the radiation heat flux from the high temperature gas and soots was greater than that from the flame because the later was interrupted by the smoke. The gradients of atmospheric temperature were hardly observed in the horizontal temperature distribution but were observed in the vertical temperature distribution in the compartment. It appeared that the concentrations of smoke and CO were able to be estimated from the ratio of burning rate and air supply rate. From the test results, we have developed a conventional and conservative method to evaluate the environmental effects of lubricant oil fire in the compartment.

INTRODUCTION

It seems that the lubricant oil fires may at times occur in an industrial plant facilities. Therefore, fire protection on lubricant oil fire shall be taken into consideration in planning the fire protection program of the industrial plant. In this consideration, we conducted the full scale compartment fire tests with turbine oil. The objective of the tests was to research the thermal influences (ex; radiation heat flux, atmospheric temperature and so forth) to the surroundings and the atmospheric condition (ex; smoke and CO concentration) in the compartment. Preliminary fire tests preceding this test were conducted to get the fundamental data on lubricant oil fire and to obtain necessary data to decide the test condition. (See Reference 1.)

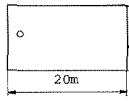
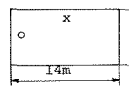
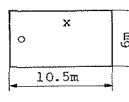
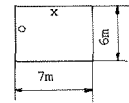
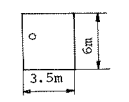
TEST METHOD

Test Condition

Fuel Source Fuel sources was lubricant oil (Turbine oil VG32) contained in circular pans. The size of the fuel pans were 0.1m^2 , 0.3m^2 , 0.5m^2 , 1.0m^2 and 2.0m^2 .

Test Models Rectangular parallel-piped compartment were used in these tests. The internal dimensions of the compartment were 6.0m width, 5.0m height. The length was variable to 3.5m, 7.0m, 10.5m and 14.0m. For the additional case, the compartment with the internal dimensions 20m length, 8.0m width and 5.0m height was also used. The walls of the compartment were constructed with fire resistant insulation board (calcium silicate plate) of 25mm thickness. Test models are shown in Table-1.

Table-1 List of the test models Total: 51 models.

Pattern No.	Compartment size & Fire location	Opening	Air exchange rate (h ⁻¹)	Fuel pan size					Remarks	
				0.1m ²	0.3m ²	0.5m ²	1.0m ²	2.0m ²		
1		None	0	-	-	-	-	○	Duration of the instrumentation ○: 20 min. △: 30 min. □: 40 min.	
			2	-	-	△	○	○		
			10	-	-	△	○	○		
			0	-	-	-	-	○		
			2m ²	2	-	-	-	-		○
10	-	-	-	-	○					
2		None	0	□	△	○	-	-	Fire location ○ x	
			2	-	-	○	△	○		-
			5	□	△	△	○	-		-
			10	-	-	△	○	-		-
3		None	0	□	△	○	-	-		
			2	-	-	○	△	-		
			5	□	△	△	○	-	-	
			10	-	-	△	○	-	-	
4		None	0	○	△	○	-	-		
			2	□	-	○	△	-		
			5	□	□	△	-	-	-	
			10	-	-	△	○	-	-	
5		None	0	□	△	-	-	-		
			2	□	-	-	-	-	-	
			5	□	△	○	-	-	-	
			10	□	-	-	-	-	-	

Ventilation Forced ventilation system (push-pull type) was provided to the compartment as shown in Fig. -1.

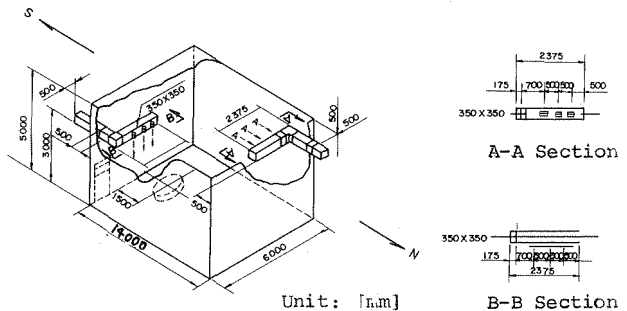


Fig. -1 Configuration of the Compartment model

Fire location The center of the oil pan was located on the north-south center-line of the room and 1.5m away from the south wall.

Location of the instrumentation The location of the instrumentation are shown in Fig. -2.

o T.C 11	o T.C 25	o T.C 19	o T.C 19	o T.C 15	o T.C 15	Exhaust
o V 2	o V 2	o V 3	o V 3	o V 0	o V 2	Dust
	△ Rb 1	△ Ra 0	△ Ra 3	△ Ra 3	△ Ra 3	T.C 2
				□ CO 2	□ Cs 1	V 1
						Cs 1

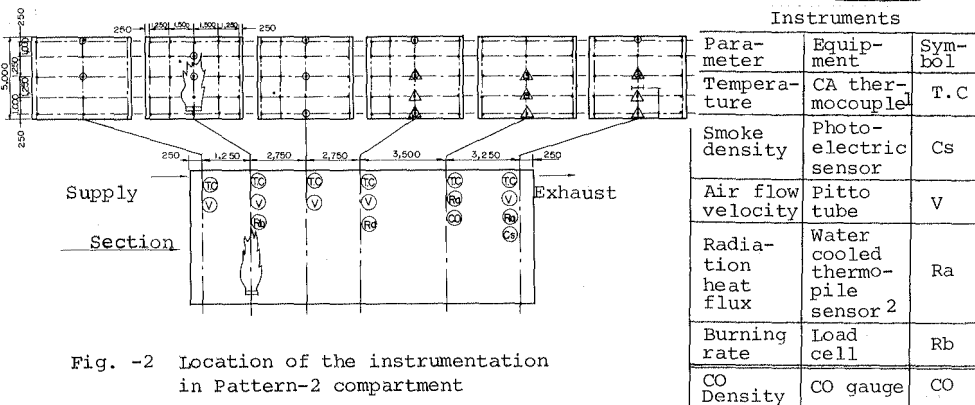


Fig. -2 Location of the instrumentation in Pattern-2 compartment

Test Procedure

Pan was filled with turbine oil to the adequate depth according to the duration of an experiment and the gasoline was floated on the surface. It was set on fire by a little gun powder. After ignited, atmospheric temperature, smoke density, air flow velocity, radiant heat flux, CO density and so forth were measured.

TEST RESULTS AND CONSIDERATIONS

Burning Rate

As shown in Fig. -3, lubrication oil burning rate in the compartment fire was nearly constant not relating to the values of parameter " β "³ derived from the compartment volume and air exchange rates. Fig. -4 is the comparison of the burning rates of closed space fires with that of free burning fires (open space fires). (See Reference 1.) It appears that the variability of the burning rates of the compartment fire is similar to that of the open space fires and the burning rates is correlative to the diameter of fuel pan. Considering the above, we reached to the conclusion that we could estimate the burning rates of the compartment fire based on those of open space fire.

¹Fine thermocouples were used to restrict the ratio of the radiation heat flux in the measurement to a low degree

²Sensors with water jacket were used to restrict the ratio of the convective heat flux in the measurement to a low degree.

³ $\beta = V(n+1)$ β : Air supply rate (m^3/h)
 V : Compartment volume (m^3)
 n : Air exchange rate (h^{-1})

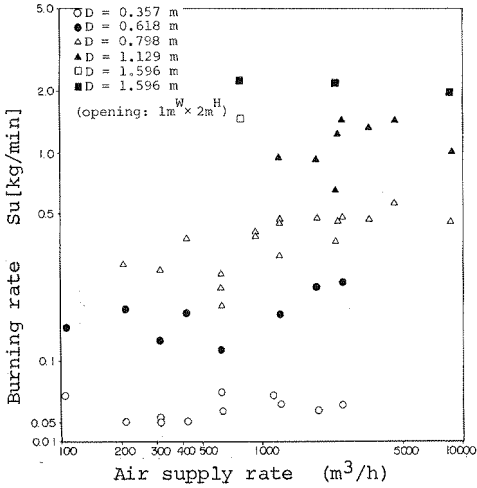


Fig. -3 Dependence of burning rate on air volume

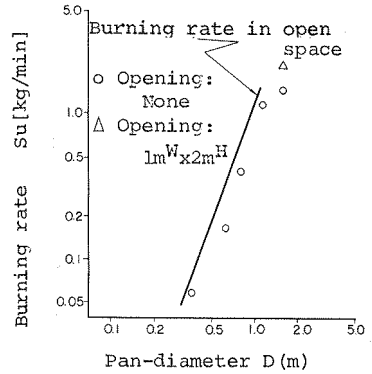


Fig. -4 Dependence of burning rate on pan-diameter

Radiation Heat Flux

As shown in Fig. -5, received radiation heat flux in the compartment fire was greater than that in the open space fire represented by theory locus curves and the decrease of the received radiation heat flux on the distance was not observed except in the proximity of the fuel pan. This might be because the radiation heat flux from the flame was interrupted by the smoke (gas & soots) and that from the gas was rather greater than that from the flame.

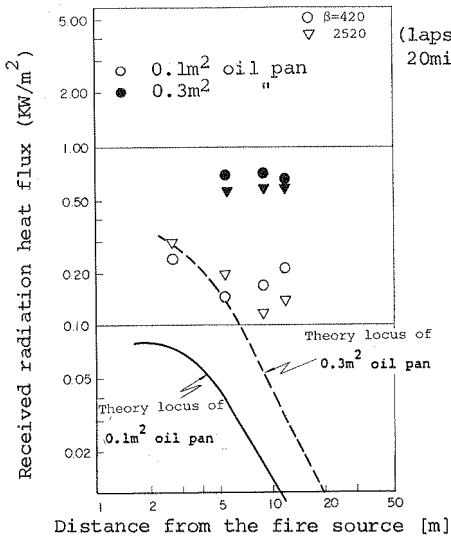


Fig. -5-1 Experimental and predicted received radiation heat flux (Compartment pattern-2 0.1m² & 0.3m² oil pan)

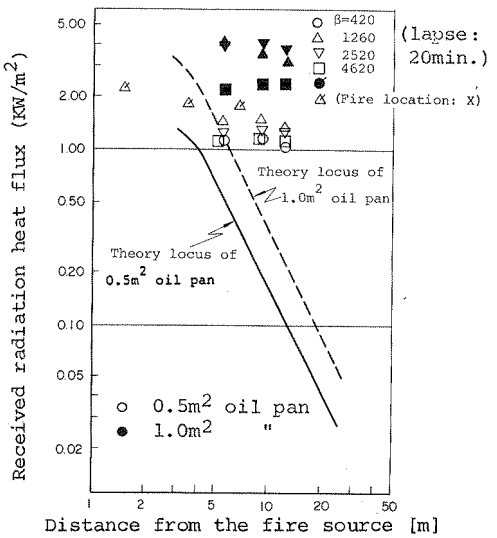


Fig. -5-2 Experimental and predicted received radiation heat flux (Compartment pattern-2, 0.5m² & 1.0m² oil pan)

Fig. -6 shows that the radiation heat flux increases with the increase of gas layer thickness (distance from south wall to receiver) and gas temperature which rises with the lapse of time. In case of small fuel pan, however, radiation heat flux from the flame was greater than the others. This might be because the smoke concentration and gas temperature was low. Considering the above, we studied the radiation heat flux as a function of the gas temperature. The correlation of radiation heat flux and gas temperature is shown in Fig. -7 and -8.

Experimental estimation formulas were developed from the test data as shown in Table-2. In this table, constant "A" means the product of gas emissivity and Stefan-Boltzmann Constant as follows:

$$A = \sigma(1 - e^{-K \cdot L})$$

σ : Stefan-Boltzmann Constant

K : Gas absorption factor

L : Gas layer thickness

R: Coefficient of correlation

In spite of the formulas being developed, we reached to the conclusion that the radiation heat flux from gas might be estimated from the following formula because of three reasons that follows:

1. The difference of the radiation heat flux due to the distance was small.
2. The measured values were the limited one because radiation heat flux sensor could not catch the heat flux beyond the angle of elevation (=2/3 radian).
3. We estimated gas emissivity to the maximum (=1.0). For, we could not estimate the actual gas emissivity because we had not analyzed gas composition in tests.

Distance from south wall (m)	$A_x(10^{-11})$	Remarks
1	2.50	3.670 R= 0.116
2	3.375	4.310 R= -0.756
3	3.50	3.310 R= 0.988
4	4.25	4.017 R= -0.655
5	5.25	3.313 R= 0.976
6	5.75	3.083 R= 0.991
7	6.75	2.894 R= 0.950
8	7.00	3.509 R= 0.981
9	7.875	3.710 R= 0.987
10	10.0	2.807 R= 0.973
11	10.25	3.395 R= 0.983
12	10.4	3.455 R= 0.984
13	13.75	3.514 R= 0.990
14	15.0	2.663 R= 0.967
15	19.75	2.858 R= 0.980

$$Q_r = A(T^4 - T_0^4)$$

Table-2 Experimental estimation formulas on received radiation heat flux

$$Q_r = \sigma(T^4 - T_0^4) \text{ (KW/m}^2\text{)}$$

$$\sigma = 5.67 \times 10^{-11} \text{ (KW/}^\circ\text{K}^4 \cdot \text{m}^2\text{)} \text{ (Stefan-Boltzmann Constant)}$$

Q_r : Received gas radiation heat flux (KW/m²)

T : Atmospheric temperature (°K)

T_0 : Receiver temperature (°K)

In the end, we reached to the conclusion that the radiation heat flux in the compartment fire could be estimated conservatively by summing the heat flux values of gas radiation and flame radiation.

Atmospheric Temperature

As shown in Fig. -9, the gradients of atmospheric temperature were observed in the vertical temperature distribution and were on the increase depending on the increase of fuel pan diameter or the decrease of the air exchange rate.

Oil pan size
 ○ 0.1 m²
 ● 0.3 m²
 △ 0.5 m²
 ▲ 1.0 m²

Air exchange rate
 ○ n=0
 ○ n=2
 ○ n=5
 ○ n=10

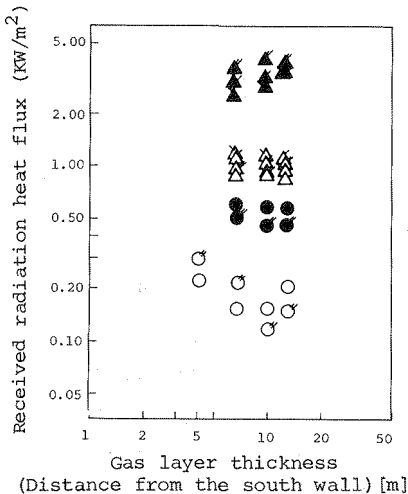


Fig. -6-1 Dependence of received radiation heat flux on gas layer thickness (lapse: 10min.)

Oil pan size
 ○ 0.1 m²
 ● 0.3 m²
 △ 0.5 m²
 ▲ 1.0 m²

Air exchange rate
 ○ n=0
 ○ n=2
 ○ n=5
 ○ n=10

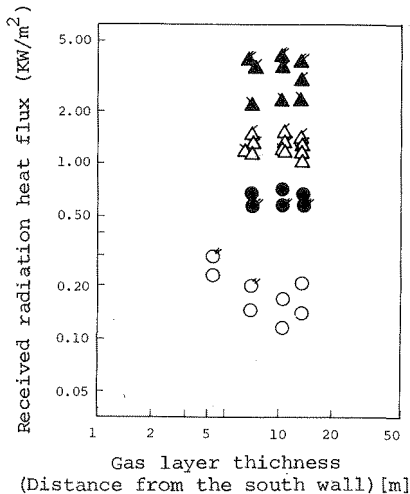


Fig. -6-2 Dependence of received radiation heat flux on gas layer thickness (lapse: 20min.)

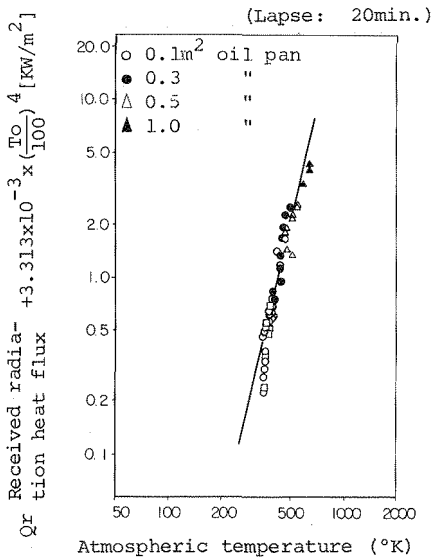


Fig. -7 Radiation heat flux vs. gas temperature (at 6.75m against south wall)

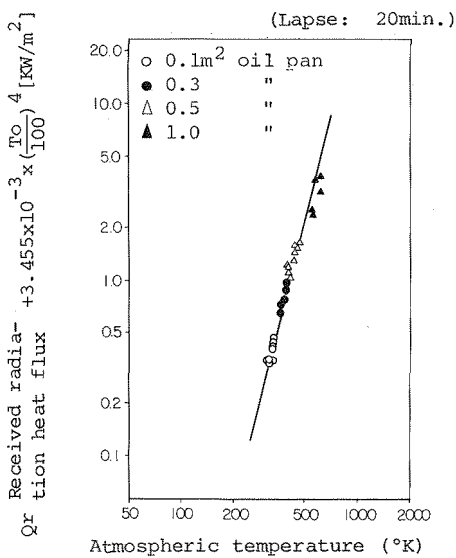


Fig. -8 Radiation heat flux vs. gas temperature (at 13.75m against south wall)

And the difference due to the fire location was not observed. The gradients of atmospheric temperature were also not observed in the horizontal distribution except just above the fuel pan. That is to say, atmospheric temperature was constant everywhere at the same elevation in the compartment. The correlation of the maximum atmospheric temperature at the same elevation and the parameter " α "¹ is shown in Fig. -10.

$$l_{\alpha} = \frac{V(1+nt)}{S}$$

- α : Ratio of burning fuel weight to total air supply
- V: compartment volume (m³)
- n: Air exchange rate (h⁻¹)
- t: lapse (h)
- S: burning fuel weight (kg)

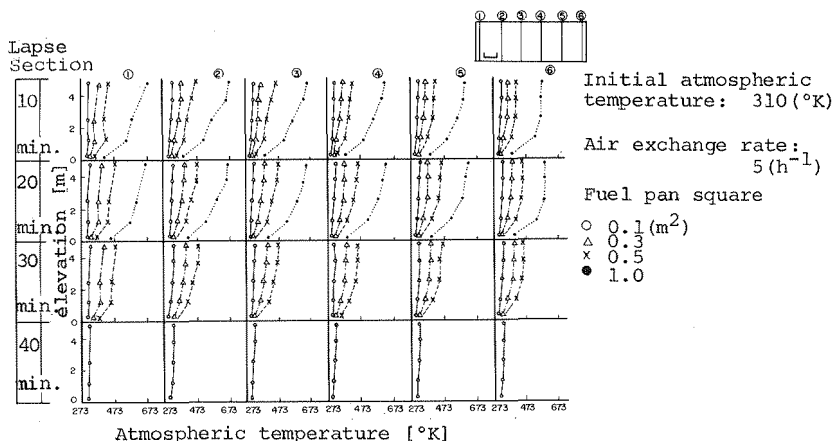


Fig. -9-1 Atmospheric temperature distribution in pattern-2 compartment (Effects of fuel pan size)

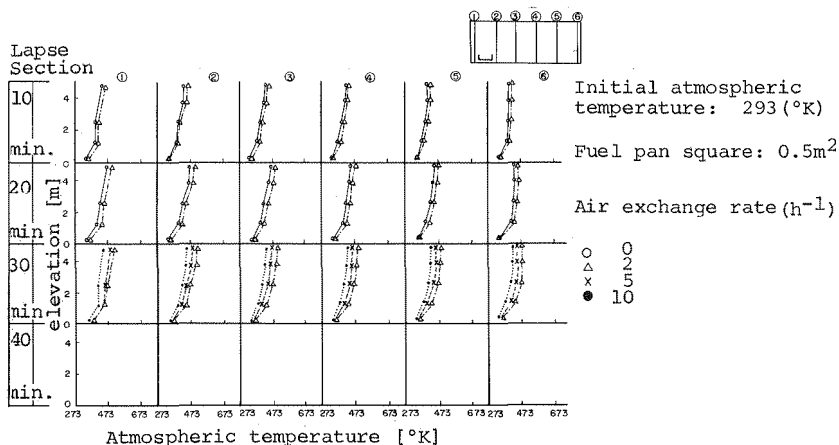


Fig. -9-2 Atmospheric temperature distribution in pattern-2 compartment (Effects of air exchange rate)

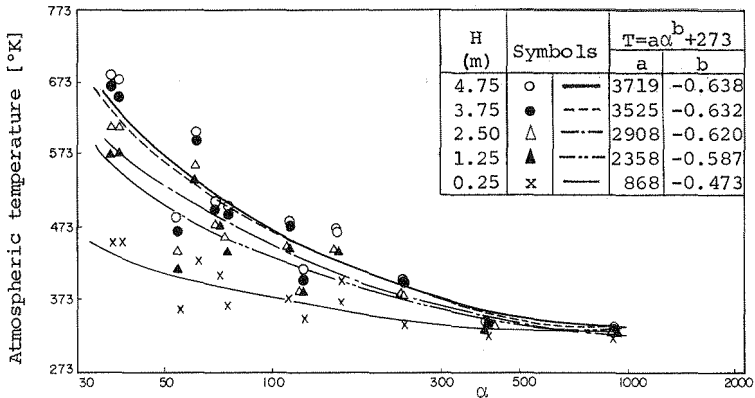


Fig. -10 Correlation of atmospheric temperature (Lapse: 20min.)

In the end, we developed the following formula to estimate the atmospheric temperature of free elevation.

$$T = a\alpha^b + 273$$

$$a = 1344 \cdot h^{0.354}$$

$$b = -0.494 \cdot h^{0.0745}$$

T: Atmospheric temperature (°K)

h: Elevation (m)

NOTE: This formula is available in case of initial atmospheric temperature being about 293°K (=test condition). Difference in initial atmospheric temperature should be taken into consideration in case of estimating the atmospheric temperature in other initial condition.

Smoke

As shown in Fig. -11, the concentration of the smoke became beyond the measuring limit (Cs=5) of the instrument by about 5 minutes. It was observed that the speed of smoke accumulation was very high in the compartment fire. We developed the following experimental formula to estimate the smoke concentration.

$$Cs = 40.57 \cdot \alpha^{-0.485}$$

Extinct coefficient: Cs (1/m)

$$I = I_0 \cdot e^{-Cs \cdot \ell}$$

I₀: Source illuminance (Lux)

I: Receiver illuminance (Lux)

ℓ: Distance from the source to receiver (m)

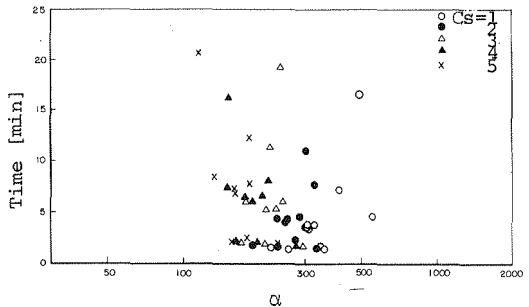


Fig. -11 Dependence of smoke concentration on alpha

CO Concentration

As shown in Fig. -12, the values of CO concentration were on the decrease with the increase of parameter "α". It became to the dangerous concentration for long stay (approximately, 1000 - 3000ppm) in case of parameter "α" being under 100.

We developed the following experimental formula to estimate the CO concentration.

EL: 1.25M CO = 3.33 x 10⁵ · α^{-1.282}

EL: 2.50M CO = 7.16 x 10⁵ · α^{-1.482}

CO: CO concentration (ppm)

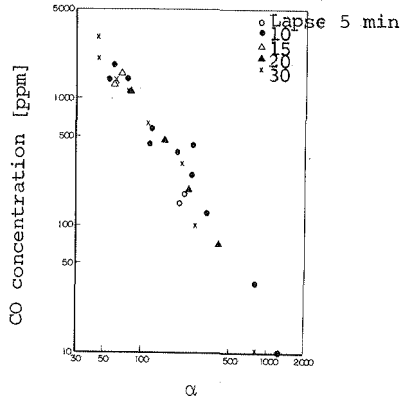


Fig. -12 Dependence of CO concentration on α (H=1.25m)

Air Flow Velocity

As shown in Fig. -13, the values of air flow velocity were on the decrease with the increase of convection distance.

We developed the following experimental formula to estimate the air flow velocity.

V = a · x^{-b}

a = 6.73 · Su^{0.164}

b = 0.880 · Su^{-0.0607}

V: Air flow velocity (m/S)

Su: Burning rate (kg/min.)

x: Convection distance (m)

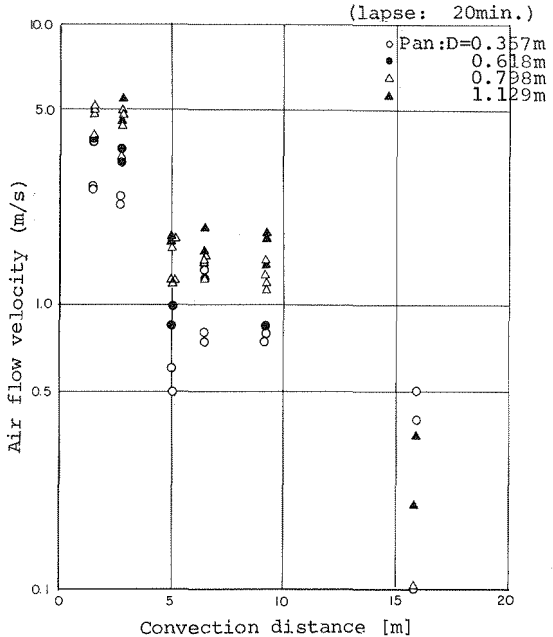


Fig. -13 Dependence of air flow velocity on convection distance

CONCLUSION

We developed the method to estimate the compartment fire behavior conservatively as follows.

- (1) The burning rate in the compartment fire can be estimated at that in the open space fire.
- (2) The radiation heat flux can be estimated at the sum of heat flux values of gas radiation and flame radiation.
- (3) Atmospheric temperature can be estimated depending on the following formula.

$$T = a \cdot \alpha^b + 273 \text{ (}^\circ\text{K)} \quad \begin{aligned} a &= 1344 \cdot h^{0.354} \\ b &= -0.494 \cdot h^{0.0745} \end{aligned}$$

- (4) Concentration of the smoke can be estimated depending on the following formula

$$Cs = 40.47 \cdot \alpha^{-0.485} \text{ (l/m)}$$

- (5) Concentration of the CO can be estimated depending on the following formula.

$$CO = 3.33 \times 10^5 \cdot \alpha^{-1.282} \text{ (ppm) (EL: 1.25M)}$$

$$CO = 7.16 \times 10^5 \cdot \alpha^{1.482} \text{ (ppm) (EL: 2.50M)}$$

- (6) Air velocity of convection flow can be estimated depending on the following formula.

$$V = a \cdot X^{-b} \text{ (m/s)} \quad \begin{aligned} a &= 6.73 \cdot Su^{0.164} \\ b &= 0.88 \cdot Su^{-0.0607} \end{aligned}$$

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REFERENCE

1. T. Tanaka, Y. Kobasawa, Y. Soutome and M. Fujizuka: "Preliminary Test for Full Scale Compartment Fire Test (Lubricant Oil Fire Test; Part-1)," First International Symposium on Fire Safety Science, 1985