RISK EVALUATION OF CARBON MONOXIDE IN COMPARTMENT FIRE

Kwang Il Kim
Dep't of Health and Safety Engineering, Inje Unversity

ABSTRACT

In order to investigtate the generation of carbon monoxide and heat loss of incomplete combustion in compartment fires, an experiment was conducted in a small scale comartment by using methanol as a fuel. The concentration of carbon monoxide and the toxicity parameter showed high values when the mass air - to - fuel stoichiometric ratio Φ is under 1.0. The constitution of the combustion gas was showed to estimate it from the Φ. The heat loss due to incompleteness of combustion is about one third of heat of combustion in case of Φ under 1.0.

Keyword : Compartment fire, Toxicity parameter, Heat loss, Incomplete combustion.

1. INTRODUCTION

In recent years many of furnitures and fabrics have been made of polymeric material. It is well known that those materials generate various toxic gases when they are under combustion. And in order to prevent the fire from propagating beyond its place of origin a method of compartmentation become popular. As a result the residents of the building today are exposed to the risk of toxic gases more than ever. Thus, a study of toxic gases from combustion of construction & interior materials are absolutely needed. Overall risk out of building fire consists of smoke, toxic gases, heat and lack of oxygen. Recent report showed the priority of major cause to death as the order of toxic gases, heat and lack of oxygen[1,2,3,4]. And among the toxic gases carbon monoxide is believed to be the major harmful gas both in its amount generated from fire and its toxicity[5,6,7].

The generation of toxic gases varies with kinds of combustible materials, amount of combustible materials, ventilation factor and the shape of the compartment. Especially under the same condition of those factors the toxic gases are generated mostly in its quantity per unit time while the combustion is transferred from incomplete combustion to complete combustion[8,9,10]. But, understanding of these phenomena has not been completed.

Risk evaluation about carbon monoxide out of fire was conducted in this paper.

2. GENERATION OF CARBON MONOXIDE AND EVALUATION OF TOXICITY

2.1 Generation of carbon monoxide and the effect of ventilation

Carbon monoxide can be generated both from flame fire and smoldering fire. And its generation ratio is proportional to the rate of incomplete combustion[11,12]. Asumming the yield converted from carbon to carbon monoxide as Y_{CO}, and the yield converted from carbon to carbon dioxide as Y_{CO2}. And the other carbon containing materials could be generated during the combustion are not considered. Therefore the following equation can be assumed; $Y_{CO} + Y_{CO2} = 1$

$$Y_{CO} = \frac{[CO]}{[CO]+[CO_2]} \quad (1)$$

where [CO], [CO_2] is the ratio of volume.

Air to fuel stoichiometric ratio is defined as Φ.

$$\Phi = M_a / G_f K_a \quad (2)$$

where G_f is the egression rate of fuel

K_a is the stoichiometric ratio of fuel to air

M_a is the rate of air entrainment to the compartment[15].

$$M_a = 0.52\, A_o \sqrt{H} \quad (3)$$

where A_o is the sum of opening area in the compartment

H is the height of the opening in the compartment

The generation of carbon monoxide in the compartment fire is controlled by the condition of ventilation. Y_{co} can be obtained from equation (1), and Φ

can be calculated from the equation (2). Calculate Y_{CO} and Φ are plotted in the figure 1. Regardless of A_f, surface area of fuel, carbon monoxide generating during the compartment fire meets its peak rate when the value of Φ varies from 0.62 to 1.0. It was learned that carbon monoxide is generated mostly in its volume during the compartment fire when the burning rate exceeds the air entrainment rate. And also it was found that under 0.62 of Φ the combustion was stopped due to lack of air. This conclusion showed same result from the Tewarson's report[8].

Table 1 shows the generation rate of carbon monoxide and carbon dioxide under well-ventilated fire($\Phi>2.0$) and under-ventilated fire($\Phi<1.0$). This also illustrates the CO generation rate is greatly affected by A_f, the surface area of fuel. The figure 2 shows the correlation of air-to-fuel stoichiometric ratio as a function of ventilation parameter. It indicates that Φ is inverse proportional to Af.

Table 1 Dependences of the generation of CO, CO_2 for well-ventilated and under-ventilated fire on the fuel surface area

Fuel surface area(m^2)	Well-ventilated ($\Phi>2.0$)		Under-ventilated ($\Phi>1.0$)	
	Y_{CO}	Y_{CO_2}	Y_{CO}	Y_{CO_2}
0.0056	0.001	0.999	0.018	0.982
0.0225	0.060	0.940	0.520	0.480
0.0228	0.018	0.982	0.290	0.710
0.0432	0.089	0.911	0.420	0.580
0.0801	0.153	0.847	0.580	0.420

2.2 Evaluation of Toxicity of Fire Generated Gas

The risk and toxicity of fire generated gases was reported in N-Gas Model of NIST[8,12] and Tsuchiya's report[13]. The basic approach of those two reports was to evaluate the total toxicity by summing up each toxic gases generated from fire. Assuming toxic parameter as T_x, it is expressed as following;

$$T_x = \sum_j C_j / (LC_{50})_j \qquad (4)$$

where C_j is the concentration of combustion gas-j[ppm]
$(LC_{50})_j$ fatal concentration of gas-j resulted in 50% of exposed animal during fixed time

The value of Tx for LC_{50} of total fire generated gas is 1. Therefore the toxic parameter for CO and CO_2 can be expressed by following equation(5);

$$T_x = \frac{C_{co}}{(LC_{50})_{co}} + \frac{C_{co2}}{(LC_{50})_{co2}} \qquad (5)$$

LC_{50} of CO is 4600ppm and LC_{50} of CO_2 is 18000ppm based on 30 minutes' exposure[14]. The relation of toxic parameters derived from the equation (5) and Φ are shown in the figure 3. When the generation rate of CO, the toxic parameter increases. And when the value of Φ exceeds 1, the generation rate of CO and the value of toxic parameter grow. This is why the amount of oxygen supplied by air cannot be used for combustion completely.

3. COMPOSITION OF COMBUSTION GAS

The experimental value of the composition of combustion gas was compared by calculated value. Incomplete combustion gas normally contains CO, H_2, HC & etc. Sometimes it contain soots. But, in case of methanol combustion soots are not generated and the amount of HC is very nill. Therefore, only CO and H_2 are studied in this paper.

It is CO mainly produced from incomplete combustion. Weight of carbon in 1 kg of fuel was assumed as ckg, and the generated amounts of CO_2 and CO throughout combustion was assumed as cxkg and c(1-x)kg. In case of excessive air supply hydrogen can be generated during combustion. The amount of hydrogen consumed to form H_2O was assumed as hykg and the amount of hydrogen remain as hydrogen was assumed h(1-y)kg. The volumes of CO_2, CO, H_2O and H_2 generated during the incomplete combustion of 1 kg of fuel are as follow;

$$VCO_2 = \frac{22.4}{12.0} cx \ [m^3/kg], \quad VCO = \frac{22.4}{12.0} C(1-x) \ [m^3/kg] \qquad (6)$$

$$VH_2O = \frac{22.4}{2.0} hy \ [m^3/kg], \quad VH_2 = \frac{22.4}{2.0} h(1-y) \ [m^3/kg] \qquad (7)$$

The amount of oxygen required to the complete combustion, VO2min, is as follow;

$$VO_{2min} = \frac{22.4}{12.0} c + \frac{22.4}{4.0} h - \frac{22.4}{32.0} o \ [m^3/kg \cdot Fuel] \qquad (8)$$

where o is the amount of oxygen required for complete combustion of 1 kg of fuel

Assuming the amount of oxygen contained in the supplied Φ as VO_{2in}, then VO_{2in} can be derived from equation (8) and expressed as;

$$VO_{2\ in} = \Phi\ VO_2\ [m^3/kg] \qquad (9)$$

The composition of combustion gas has relation with Φ, x and y. Thus, the value of x and y can be obtained from Φ.

In order to cx kg of C is converted into CO_2 completely, required amount of O_2 becomes cx/12[kmol].

In order to cx kg of C is converted into CO completely, required amount of O_2 becomes c(1-x)/(12x2)[kmol]

In order to hy kg of H_2 is converted into H_2O completely, required amount of O_2 becomes hy/4[kmol]

The amount of oxygen required to complete combustion is as follow;

$$VO_{2n} = \frac{22.4}{12.0}\left\{\frac{c(1+x)}{2} + 3hy - \frac{3}{8}o\right\} \qquad (10)$$

The volume of oxygen contained in combustion gas is shown in equation (11).

$$VO_2 = VO_{2\ in} - VO_{2\ n}\ [m^3/kg] \qquad (11)$$

The volume of nitrogen contained in combustion gas can be derived from equation (9) and expressed as follow;

$$VN_2 = VO_{2\ in} \times 79/21\ [m^3/kg] \qquad (12)$$

Assuming the concentration of H_2 and H_2O as $[H_2]$ and $[H_2O]$, they can be calculated from equation (13) and (14).

$$[H_2] = VH_2/(VCO_2 + VCO + VH_2 + VH_2O + VO_2 + VN_2) \quad (13)$$

$$[H_2O] = VH_2O/(VCO_2 + VCO + VH_2 + VH_2O + VO_2 + VN_2) \quad (14)$$

The volume of oxygen was measured under the condition of no water vapors. Therefore, the calculated value of oxygen was shown in the following equation.

$$[O_2]_d = \frac{VO_2}{VCO_2 + VCO + VH_2 + VO_2 + VN_2} \quad (15)$$

The value of y can be obtained from the measured value [O2]d to Φ. From this value of y we can calculate $[H_2]$ and $[H_2O]$ by utilizing equation (13),(14). The concentration of O_2, CO, CO_2, H_2, H_2O, and N2 with water vapor can be calculated with the measured concentration data of O_2, CO, CO_2. An example was illustrated in the table 2. The differences between the experimental value and the calculated value come from the existence of water vapor.

Table 2 Comparison of the calculated and experimental value based on the air ratio from combustion gas. (A_f : 0.0432㎡, Φ=1.95)

Species	Experimental value (%)	Calculated value (%)
O_2	9.60	8.95
CO	1.34	1.24
CO_2	5.74	5.35
N_2	-	71.11
H_2	-	0.47
H_2O	-	12.88

4. CONCLUSION

In the compartment fire the rate of CO generation has no close relationship with the size of fire. The generation rate of CO depends strongly on the ventilation condition. It is inverse proportional to the amount of air entrainment. The rate of CO generation under the insufficient ventilated condition(Φ<1.0) is much greater than under the well ventilated condition (Φ>1.0). The total toxic parameter of CO and CO_2 indicated its maximum value when Φ is around 0.62 through 1.0.

The composition of combustion gas could be estimated from the measured value of CO, CO_2, and O_2.

REFERENCE

1. K. I. Nishmaru, : "Toxicity of Smoke". SUT Bulletin Tokyo Science University(1984)

2. Tokio Morikawa and Eiji Yanai : " Toxicity Evaluation of Fire Effluent Gases from Experimental Fires ih a Building". Fire Research Institute of Japan, No. 63(1987)

3. Tokio Morikawa and Eiji Yanai : "Combustion Products of Polymeric Materials in Semi-Full Scale Room Fire Experiments ". Fire Research Institute of Japan, No. 60(1985)

4. Eiji Yanai and Naoshi Saito : "Toxic Gases from Retardant Cellulosic Materials". Report of Fire Research Institute of Japan, No. 50(1980)

5. Harold L. Kapalan, Ph. D and Gordon E. Hartzell, Ph. D.: "Modeling of Toxicological Effects of Fire Gases: I. Incapacitating Effects of Narcotic Fire Gases, "Journal of Fire Sciences, 2, 286~305 (1984)

6. G.E. Hartzell, D.N. Priest and W.G. Switzer; "Modeling of Toxicological Effects of Fire Gasse: II. Mathematical Modeling of Intoxication of Rats by Carbon Monoxide and Hydrogen Cyanide, "Journal of Fire Sciences Vol. 2, p.115~128 (1985)

7. Harrold L. Kaplan, Arthur F. Grand, Gordon E. Hartzell; "Combustion Toxicology: Principles and Test Methods" . Technomic Publishing Co. p.65 ~67 (1983)

8. Archibald Tewarson: "Correlation for the Generation of carbon monoxide in small-and large-scale fires" , Ninth Meeting of the United States/Japan Panel on Fire Research and Safety, May (1987)

9. Robert S. Lerine: Workshop on CO formation in fires - Philadelphia, Pennsylvania November 7 (1985)

10. Beyler, C.L: "Major Species Production by Soils Fuels in a Two-Layer Compartment Fire Environment, "Fire Safety Science, Proceeding of the First International Symposium, Hemisphere Publishing Corporation, New York, NY, p.431 (1986)

11. Lomax, S., and Siommons, R.F.: "The Formation of Carbon Monoxide from Diffusion Flames, "Fire Safety Science, Proceeding of the First International Symposium, Hemisphere Publishing Corporation New Youk, NY, P.441 (1986)

12. Babrauskas, V., Levin, B.C., and Gann, R.G.: "A New Approach to Fire Toxicity Data for Hazard Evaluation, "ASTM Standardization News, September (1986)

13. Y. Tsuchiya and I. Nakaya :"Numerical Analysis of Fire Gas Toxicity : Single and Multiple Component Systems". Bulletin of Japanese Association of Fire Science and Engineering. Vol. 35, No.1(1985)

14. Levin, B.C., Paabo, M., Bailey, C.S, and Harris, S.E.: "Toxicity of the Combustion Products from a Flexible Polyurethane Foam and a Polyester Fabric Evaluated Separately and Together by the NBS Toxicity Test Method, "Fire Safety Science, Proceeding of the First International Symposium, Hemisphere Publishing Corporation, New York, NY, P.1111 (1986)

15. D. Drysdale: An Introduction to Fire Dynamics, John Willy & Sons. p.304 ~310 (1986)

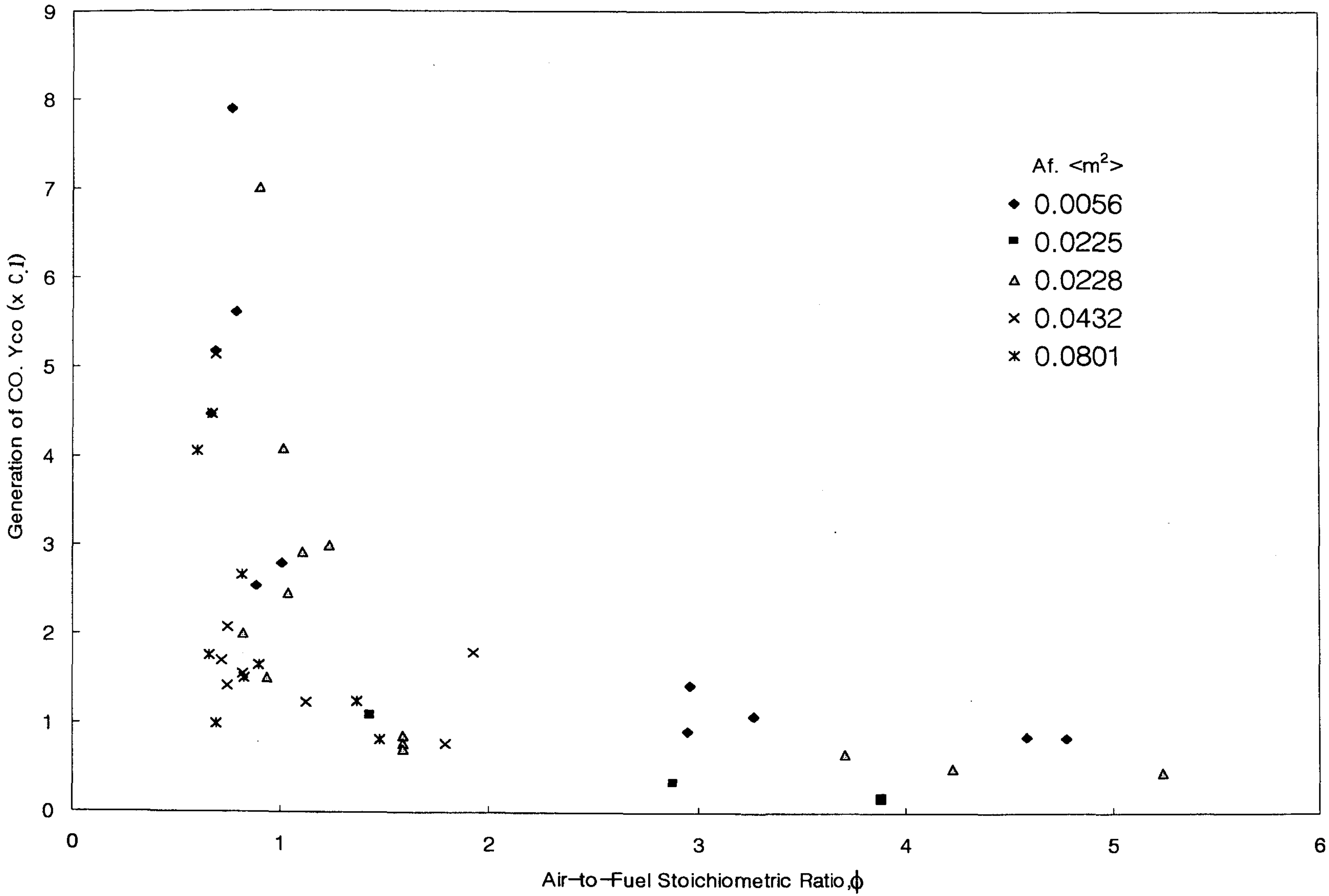

Fig.1 Generation of CO as A Function of Air-to-Fuel Stoichiometric Ratio

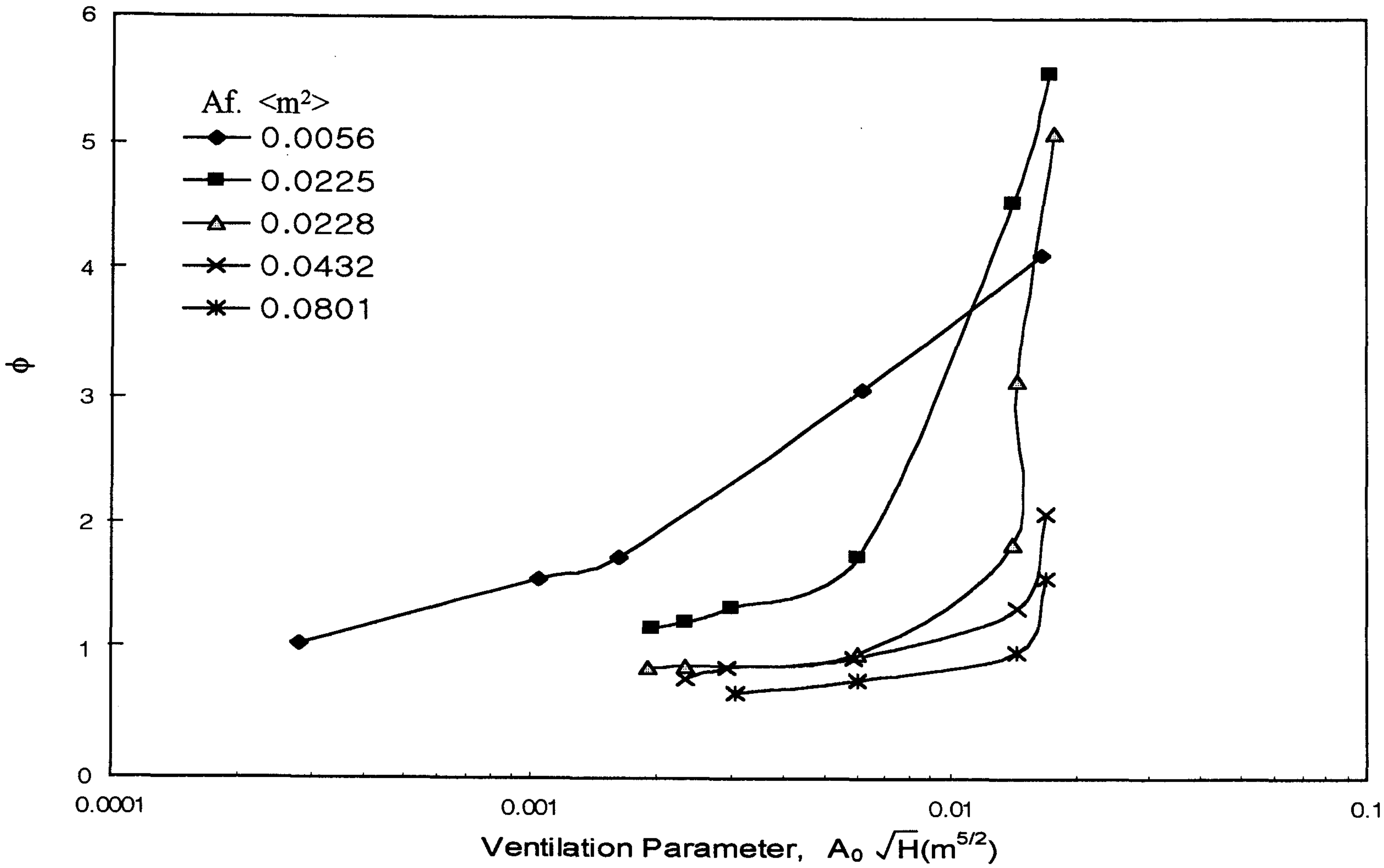

Fig. 2 Correlation of Air-to-Fuel Stoichiometric Ratio as A Function of Ventilation Parameter

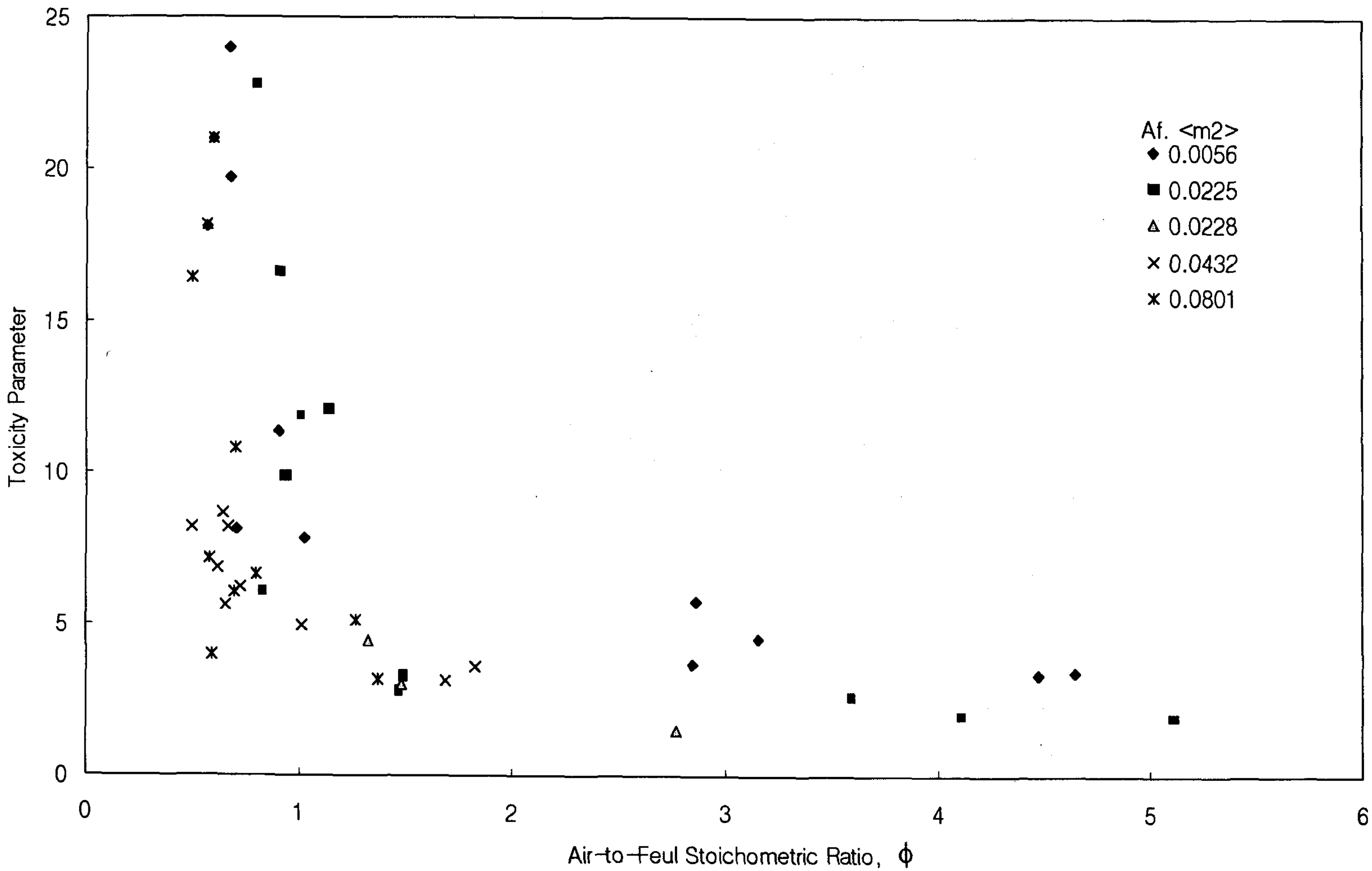

Fig. 3 Toxicity Parameter as A Function of Air-to-Fuel Stoichiometric Ratio.