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MODELING SMOKE CONDITIONS IN LARGE COMPARTMENTS EQUIPPED WITH MECHANICAL SMOKE EXHAUST USING A TWO-ZONE MODEL

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ABSTRACT

This paper presents a two zone model for calculating smoke movement in multi-compartment multi-level buildings (FIERAsmoke) that has been developed at the Fire Risk Management (FRM) program of the Institute for Research in Construction. This model will become a sub-model of the FRM's risk-analysis model FIERAsystem, which is a model that evaluates the life risks and property losses from fires in buildings. The paper also presents and discusses a comparison of the results of the model to experimental data. The experimental data were obtained from tests performed at NRC to investigate the effectiveness of atrium smoke exhaust systems. The comparisons indicate that the model can predict well hot layer temperatures, CO_2 concentrations and interface heights.

1. INTRODUCTION

An atrium within a building is a large undivided space, designed for creating a visual and spatial appeal. When a fire occurs in an atrium or an adjacent space, smoke can fill the atrium and the connected floors, and endanger the lives of building occupants. Fire risks of an atrium building are different from those of traditional buildings, and smoke management in an atrium is very important [1,2].

Smoke management systems are used to limit smoke spread from the atrium space to the connected area and escape routes. They achieve this by confining spread of smoke to a limited region, limiting toxic gas concentration, maintaining the clear height at a certain level for a definite time, and limiting the smoke layer temperature to avoid flashover [1, 3]. Thus the prediction of the hazard parameters, including smoke layer depth, toxic species concentration, and temperature rise in the smoke layer, is necessary to design an effective smoke management system [4].

There are three types of applicable analytical approaches to formulating smoke control system design: algebraic equations, computer-based comprehensive zone models and field models. A first-order analysis can be conducted using algebraic equations such as those developed by Klote, Cooper and Tanaka [5-8]. These equations use the zone model concept. In order to get these algebraic equations, many other presumptions are needed, such as using a constant heat-loss factor, neglecting environmental effects, assuming constant density to separately solve the mass and energy conservation equations, and assuming power law heat release rate. A major drawback of these equations is the inability to dynamically simulate the interaction of different smoke management systems [4].

The other two types of analytical approaches are computer-based zone modeling and field modeling. Due to the fewer simplifications and assumptions made in these models, computer-based approaches increase the accuracy and flexibility of the models. In field models, a compartment is divided into a number of small cells, over which the basic mass, momentum and energy conservation is applied. Thus, they can provide more detailed information on the hazard parameters in simulating smoke movement. However, until now they have not been widely applied to practical cases because of their high computation cost, and their difficulties in modeling turbulent combustion and coupling thermal fields to solid phase pyrolysis [9].

Current comprehensive two-zone modeling may be considered a compromise between the field models and algebraic equations. In two-zone models, the gas in each compartment is assumed to be composed of two layers: a relatively hot upper smoke layer and a relatively cool contaminated or not contaminated lower air layer. Within each zone the properties are assumed to be uniform. The basic mass and energy conservation is applied to each layer. The source terms of the basic conservation equations, i.e., mass and energy exchange rates between neighboring zones, are obtained by modeling relevant fire processes, such as plume entrainment, vent flow and heat transfer. A comprehensive computer-based two-zone model

can eliminate the presumptions existing in algebraic equations mentioned above except the two-zone assumption. It can dynamically predict most of the required parameters used in engineering design, such as smoke layer temperature, wall surface temperature, smoke layer thickness and toxic species concentration in each compartment at any time. Details on current zone models can be found in literature [10-12].

FIERAsmoke is a two-zone model developed at NRC for calculating smoke movement in buildings. To determine whether the model is capable of predicting the condition in an atrium with smoke exhaust system, the model is used to simulate tests performed at NRC. These experiments have been conducted at NRC to investigate the effectiveness of smoke management system in an atrium. Three sets of data are presented in this paper.

2. DESCRIPTION OF THE EXPERIMENTS

The detailed description of the experimental facilities can be found in G.D. Lougheed and G.V. Hadjisophocleous [2]. In this paper, only the part related to this study is presented.

The schematic of the experimental facility used in this study is shown in Fig. 1. The facility is a large compartment with dimensions of 9 m × 6 m × 5.5 m height. The interior wall surface of the compartment was insulated using 25mm thick rock fiber insulation.

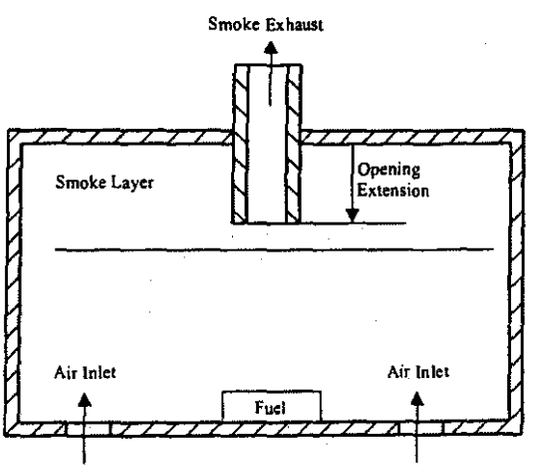

Fig. 1: Schematic of the test facility

A fan was used to supply fresh air into the compartment through openings in the floor around the walls. These openings had a width of 0.1m, and a total length of 22.8 m. Inlet air was supplied to the four sides of the room through a duct system in the under-floor space.

Thirty-two exhaust inlets with a diameter of 150 mm were located in the ceiling of the compartment. These inlets were used to extract the hot gases from the compartment during the tests. All exhaust ducts were connected to a central plenum. A 0.6 m diameter duct was used between the plenum and an exhaust fan.

A square propane sand burner was used as the fire source. The burner was capable of simulating fires ranging from 15 kW to 1,000 kW. The heat release rate of the fire was determined using two methods. One was based on the volume flow rate of propane supplied to the burner. The other was based on the oxygen depletion method.

Twelve CO_2 inlets and fifteen thermocouples (TCs) were located at one of the room quarter points at various heights. The TCs, together with the CO_2 measurements, were used to determine the depth of the hot layer in the compartment.

The volume flow rate, temperature, CO_2 and oxygen concentrations were measured in the main exhaust duct. These measurements were used to determine the heat release rate of the fire, as well as to calculate the exhaust rate of the ventilation system. A pitot tube and TC, located at the center of the duct, were used to determine the volumetric flow rate in the duct.

3. DESCRIPTION OF THE TWO-ZONE MODEL

A two-zone smoke movement model has been developed and coded using MS Visual Basic. The default independent variables of each compartment are pressure, smoke layer enthalpy, smoke layer mass, and lower layer mass, respectively. Various fire sub-models have been implemented in this model, which are briefly described below. For more details of the model refer to Z. Fu and G.V. Hadjisophocleous [13].

3.1 Combustion and Chemistry

Combustion is calculated based on the calculation of fuel and oxygen mass in the fire plume. It is assumed that if the fuel to oxygen ratio in the fire plume is less than the stoichiometric ratio, then combustion behaves like in open air. If not, combustion will be constrained by the available oxygen based on the oxygen consumption principle. A specification chemistry model is implemented. The mass ratios of C, H and O with respect to fuel are specified as input data, so are the mass ratios of CO and soot with respect to the mass

of carbon related products (CO_2 + CO + soot). Also the mass ratio of any toxic to fuel is specified.

3.2 Smoke Flow

In this zone model, two plume models are implemented. One is McCaffrey's model [14], and the other is Heskestad's model with constant coefficients and ignoring virtual origin correction [15].

As shown in Fig. 1, a specification mechanical ventilation model is implemented. Through the opening, smoke can be extracted, or air can be supplied. Two parameters can be specified, i.e., the vertical extension of the opening, and the mechanical volume or mass ventilation rate.

Mass flow through a vertical vent can be calculated by integrating Bernoulli's equation along the vertical direction of the vent. Mass flow through a horizontal-vent is calculated using Cooper's model for shallow, horizontal, circular vents under high-Grashof-number conditions, which is the case encountered in a building fire. If the high-Grashof-number condition is not met, then Bernoulli's equation can be directly used for calculation.

3.3 Heat Transfer

To calculate conduction heat transfer through the compartment boundaries, a one-dimensional transient conduction model is used.

In a fire room, heat loss at the ceiling surface and the upper wall due to a ceiling jet can be calculated using the correlation given by Cooper and Motevalli et al [16, 17]. In this model, the ceiling surface is converted into an equivalent circular surface with the same surface area, and the plume impingement point is assumed to be at the center of the surface. Convection heat transfer for other surfaces is considered to be natural convection, and empirical equations for turbulent convection heat transfer are used.

For radiation, a two-surface model is applied. The flame is assumed to be a sphere with its center located at the position of half flame height above the fuel bed, and the radiation flux of the sphere to any direction is assumed to be uniform. The smoke layer is considered to be an absorptive medium, and the lower layer is considered to be transparent.

4. RESULTS AND COMPARISON

The basic input data used in the model are shown in Table 1. It includes fuel properties, thermal properties of the compartment boundaries, and the compartment dimensions.

Totally forty tests were conducted at NRC, from which three sets of test data are presented in this paper for analysis and comparison with the model results.

Experimental data and predicted results for the three tests are shown in Tables 2 to 4. Some points should be noted. Heat release rates and exhaust rates in the tables are obtained from the experimental data. As shown in Tables 2 to 4, the first three parts of data, i.e., basic settings, heat release rates and exhaust rates are taken as input data of the zone model together with the data of Table 1. The data of heat release rates and exhaust rates are both time-dependent and piece-wise linear.

Table 1: Basic input data of the test facility

Fuel Properties (Propane)					
Mass fraction of hydrogen in the fuel	0.18	Heat of Combustion (MJ/kg)			44
Mass fraction of carbon in the fuel	0.82	Radiation Fraction			0.27
Thermal Properties of Compartment Boundaries		**Dimensions (m)**			
Thickness (m)	0.025		Length	Width	Height
Density (kgm^{-3})	130	Compartment	9	6	5.5
Conductivity ($Wm^{-1}K^{-1}$)	0.08	Floor Vent	22.8	0.1	N/A
Specific heat ($Jkg^{-1}K^{-1}$)	900	Burner's location	4.5	3.0	0.2
Surface Emissivity	0.9				

Table 2: Experimental and simulation results of Test 1

Basic Settings						Exhaust Rate					
Initial Temperature (°C)					24	Time (min.)	0	3	31	36	45
Extension of Ports (m)					0	Rate (kg/s)	4.79	4.79	4.39	3.88	3.88
Heat Release Rate (150-250-600)											
Time (min.)	0	2	15	16	30	31	45				
HRR (kW)	0	150	150	250	250	600	600				

Experimental Results (Maximum Temperature Gradient)					Experimental Results (Maximum Concentration Gradient)				
Time (min.)	15	30	42		Time (min.)	15	30	42	
Z_i (m)	3.38	3.38	2.62		Z_i (m)	3.88	3.38	2.88	
T_U (°C)	46	70	143		T_U (°C)	48	70	145	
C_{CO_2} (m^3/m^3%)	0.15	0.25	0.60		C_{CO_2} (m^3/m^3%)	0.16	0.25	0.64	
Simulation Results (McCaffrey's Plume)					**Simulation Results (Heskestad's Plume)**				
Time (min.)	15	30	42		Time (min.)	15	30	42	
Z_i (m)	3.90	3.58	3.03		Z_i (m)	4.87	4.22	3.05	
T_U (°C)	50	70	149		T_U (°C)	50	70	149	
C_{CO_2} (m^3/m^3%)	0.15	0.26	0.69		C_{CO_2} (m^3/m^3%)	0.15	0.25	0.69	

Z_i --- Interface height, T_U --- Smoke layer temperature, C_{CO_2} --- Smoke layer CO_2 concentration

Table 3: Experimental and simulation results of Test 2

Basic Settings						Exhaust Rate					
Initial Temperature (°C)					26	Time (min.)	0	40	45	52.5	
Extension of Ports (m)					1	Rate (kg/s)	4.79	4.22	3.76	3.76	
Heat Release Rate (25-150-250-600)											
Time (min.)	0	2.5	15	16	27.5	28.5	40	41	52.5		
HRR (kW)	0	25	25	150	150	250	250	600	600		

Experimental Results (Maximum Temperature Gradient)					Experimental Results (Maximum Concentration Gradient)				
Time (min.)	15	27.5	40	52.5	Time (min.)	15	27.5	40	52.5
Z_i (m)	4.25	3.88	3.38	2.25	Z_i (m)	3.62	3.88	3.12	2.88
T_U (°C)	33	53	76	150	T_U (°C)	32	53	72	155
C_{CO_2} (m^3/m^3%)	0.07	0.18	0.27	0.55	C_{CO_2} (m^3/m^3%)	0.08	0.18	0.27	0.66
Simulation Results (McCaffrey's Plume)					**Simulation Results (Heskestad's Plume)**				
Time (min.)	15	27.5	40	52.5	Time (min.)	15	27.5	40	52.5
Z_i (m)	4.30	3.82	3.51	2.98	Z_i (m)	4.30	4.30	4.10	2.99
T_U (°C)	31	53	73	154	T_U (°C)	35	57	74	155
C_{CO_2} (m^3/m^3%)	0.03	0.15	0.27	0.71	C_{CO_2} (m^3/m^3%)	0.06	0.18	0.27	0.71

Z_i --- Interface height, T_U --- Smoke layer temperature, C_{CO_2} --- Smoke layer CO_2 concentration

Table 4: Experimental and simulation results of Test 3

Basic Settings						Exhaust Rate						
Initial Temperature (°C)					7	Time (min.)	0	48	54	60		
Extension of Ports (m)					2	Rate (kg/s)	5.13	4.56	3.99	3.99		
Heat Release Rate (25-150-250-600)												
Time (min.)	0	5	20	21	32.5	33.5	45	46	60			
HRR (kW)	0	25	25	150	150	250	250	600	600			
Experimental Results (Maximum Temperature Gradient)						Experimental Results (Maximum Concentration Gradient)						
Time (min.)	20	32.5	45	60		Time (min.)	20	32.5	45	60		
Z_i (m)	3.62	3.38	3.12	2.12		Z_i (m)	3.12	2.88	3.38	2.88		
T_U (°C)	17	37	62	131		T_U (°C)	16	35	64	137		
C_{CO_2} (m^3/m^3%)	0.10	0.2	0.30	0.55		C_{CO_2} (m^3/m^3%)	0.10	0.20	0.32	0.66		
Simulation Results (McCaffrey's Plume)						Simulation Results (Heskestad's Plume)						
Time (min.)	20	32.5	45	60		Time (min.)	20	32.5	45	60		
Z_i (m)	3.30	3.30	3.30	3.07		Z_i (m)	3.30	3.30	3.30	3.12		
T_U (°C)	15	42	59	129		T_U (°C)	20	52	71	129		
C_{CO_2} (m^3/m^3%)	0.05	0.20	0.30	0.67		C_{CO_2} (m^3/m^3%)	0.09	0.28	0.38	0.67		

Z_i --- Interface height, T_U --- Smoke layer temperature, C_{CO_2} --- Smoke layer CO_2 concentration

The experimental results, shown in these tables, are the interface heights, hot layer temperatures, and hot layer CO_2 concentrations. The interface height is obtained both from the temperature and CO_2 concentration profiles based on their maximum gradient. The smoke layer temperature and CO_2 concentration are then calculated by averaging the measured data within the smoke layer.

The last two parts of the Tables 2 to 4 are the predicted results using both McCaffrey's and Heskestad's plume models.

With the lower heat release rate, less than 250 kW, the interface height determined based on the temperature profiles has no significant difference from that using CO_2 concentration profiles, and neither do the smoke layer temperature and CO_2 concentration. When the heat release rate is high (600 kW in this case), the concentration profile gives considerable higher interface height, and thus higher smoke layer temperature and CO_2 concentration.

With the exhaust duct located below the ceiling, hot layer temperature increases, and for most cases, the interface height decreases. Except for the 600 kW case, longer duct extension results in higher smoke CO_2 concentration.

In general, the predicted results using the two-zone model are in good agreement with the experimental results, especially the hot layer temperature.

In Test 3, McCaffrey and Heskestad's models give agreeable interface heights. For Tests 2 and 3, McCaffrey's model predicts an interface height which compares better with the experiment than the interface height obtained using Heskestad's model.

When the heat release rate is less than 50 kW, the predicted CO_2 concentration of the smoke layer is always much less than the measured value. This may be due to the higher experimental error due to the small values. For 150 to 250 kW, the model's prediction is in good agreement with the experimental data.

When, heat release rate is 600kW, the predicted concentration is considerably higher than the measured data based on the temperature profiles. However, for this case, if we use the CO_2 concentration profile to determine the interface height, then much better agreement can be obtained because the CO_2 concentration profile gives higher experimental interface height, and higher hot layer CO_2 concentration and temperature.

As expected, the higher the concentration is, the higher the temperature rise is. However, temperature is the parameter with the best agreement with the experimental data in this study. Even for the cases where interface heights and CO_2 concentrations are not predicted well, the model still predicts very good results for the hot layer temperature.

5. SUMMARY

This paper presents a comparison between experimental data obtained from tests performed at NRCC to investigate the effectiveness of atrium smoke exhaust system and predicted results of a two-zone model. It is shown that, for the cases investigated in this study, the results of the zone model compare well with the experimental data.

For small to medium heat release rates, the interface heights determined using the temperature profiles have no significant difference from those using the concentration profiles. For the larger HRR, the CO_2 concentration profiles give considerable higher interface heights. Longer duct extension into the room results in higher hot layer temperature rise, and for most cases, higher hot layer CO_2 concentration and lower interface height.

For the larger heat release rates, the predicted concentration is considerably higher than the experimental data if the temperature profile is used to determine the interface height. But if the CO_2 concentration profile is used, then much better agreement is obtained.

Temperature was found to be the parameter with the best agreement to the experimental data.

REFERENCES

1. W.K. Chow and K.W. Lau, "Field tests on atrium smoke control systems", ASHRAE Transactions, Vol. 101, pp. 461-469 (1995).
2. G. Lougheed and G. Hadjisophocleous, Investigation of atrium smoke exhaust effectiveness, ASHRAE Annual meeting, Boston (1997).
3. J.A. Milke, "Smoke management for covered malls and atria", Fire Technology, August (1990).
4. J.A. Milke and F.W. Mowrer, "Computer-aided design for smoke management in atria and covered malls", ASHRAE Transactions, Vol. 100, pp. 448-456 (1994).
5. J.H. Klote and J.A. Milke, "Design of smoke management systems", American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc., Atlanta (1992).
6. L.Y. Cooper, Compartment fire-generated environment and smoke filling, SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, pp. 2-116 to 2-138 (1998).
7. T. Tanaka and T. Yamada, "Smoke control in large scale spaces" (Part 1: Analytic theories for simple smoke control problems), Fire Science and Technology, Vol. 5, pp. 31-40 (1985).
8. T. Yamada and T. Tanaka, "Smoke control in large scale spaces" (Part 2: Smoke control experiments in a large scale space), Fire Science and Technology, Vol. 5, pp. 41-54 (1985).
9. G. Cox, "The challenge of fire modeling", Fire Safety Journal, Vol. 23, pp. 123 (1994).
10. Z. Fu and W. Fan, "A zone-type model for a building fire and its sensitivity analysis", Fire and Materials, Vol. 20, pp. 215 (1996).
11. W.W. Jones and G.P. Forney, "Improvement in predicting smoke movement in compartmented structures", Fire Safety Journal, Vol. 21, pp. 269 (1993).
12. R. Friedman, "An international survey of computer models for fire and smoke", Journal of Fire Protection Engineering, Vol. 4, pp. 81, (1992).
13. Z. Fu and G. Hadjisophocleous, "A two-zone fire growth and smoke movement model for multi-compartment buildings", Submitted to FSJ (1998).
14. B.J. McCaffrey, "Momentum implications for buoyant diffusion flames", Combustion and Flame, Vol. 52, pp. 149 (1983).
15. G. Heskestad, Fire plumes, SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, Mass, pp. 2-9 to 2-19 (1995).
16. L.Y. Cooper, "Heat transfer from a buoyant plume to an unconfined ceiling", ASME Journal of Heat Transfer, Vol. 104, pp. 446 (1982).
17. Y. Motevalli and C. Ricciuti, Characterization of the confined ceiling jet in the presence of an upper layer in transient and steady-state conditions, NIST-GCR-92-613 (1992).