ZONE MODEL VERIFICATION BY ELECTRIC HEATER

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ABSTRACT

Selecting a suitable design tool is essential for estimating the fire environment and implementing engineering performance-based fire code. Computer zone model is one of the choices for estimating the buoyancy-driven flow. This paper presents the evaluation and verification of computer zone models by full-scale test and a 24 kW electric heater. A full-scale zone model fire test was conducted in a 2.3 m by 4 m by 2.6 m high fire chamber. Ventilation was provided through a single open doorway 0.9 m wide and 2 m high. The results of upper layer temperature and interface height are presented. Predictions for these parameters were also developed by computer models, Available Safe Egress Time (ASET) and CFAST. These predictions are compared with experimental data obtained from the fire test for validation. In order to minimize the measuring errors of the experimental results, an electric heater will be adopted for verification of the room fire test.

1. INTRODUCTION

The buoyancy-driven flow within an enclosure is predicted by a zone model by solving the conservation of mass, momentum, and energy equations for a small number of zones [1]. The enclosure is usually divided into two distinct zones: an upper hot gas layer and a lower cool gas layer.

However, there are many factors affecting the accuracy of zone models [2]. For example, in reality, there is no clear and sharp change to distinguish the lower and upper layer. Moreover, mathematical models are usually expressed in the form of differential or integral equations. They are very complex and unable to obtain an analytical solution. Therefore, numerical techniques are needed for finding approximate solutions [2].

Practically, there are many methods to overcome the above problems. In this paper, the interface height and the upper layer temperature will be used for comparing with the result of computer software. Thus, model uncertainty and experimental uncertainty will be the main parameters that affect the accuracy of zone model. Model uncertainty is primarily due to the uncertainty of model inputs. It can be eliminated by the sensitivity analysis in order to identify the critical input parameters. It is used to study how changes in model parameters affect the results generated by the model and determine the dominant variables in the models. However, experimental uncertainty is mainly caused by measuring errors. Therefore, by ASTM Standards suggestions, model verification should be used to eliminate these errors. It is the process to determine the correctness of the solution of a system of governing equations in a model. In this research, an electric heater will be adopted to eliminate measuring errors to overcome the problem of unsteady heat release rate of real fires. The model should be validated properly. It is the process of determining the correctness of the assumptions and governing equations implemented in a model when applied to the entire class of problems addressed by the model.

2. ROOM FIRE TEST

Room fire experiments are a means of generating input data for computer models. Also, it can provide some useful output data to compare modeling results for validation. Standard fire test methods can be used to perform full-scale room fires to learn about the room fire build-up process [3].

ASTM E603, Standard Guide for Room Fire Experiments, was used as a reference to assist planning to conduct full-scale compartment fire experiments. It suggests a minimum level of instrumentation for measuring the heat release rate, temperature, interface height, etc. However, the plan of the room fire test cannot follow the recommendation entirely. The main differences between the ASTM Standards and room fire test are shown in Table 1.

It is recommended in the ASTM Standards that the heat release rate of the ignition source should be less than 15% of that estimated to produce flashover in the burn room. The maximum heat release rate of heater is only 24 kW. It is smaller than 15% of the flashover criterion (600 ^oC of gas temperature at ceiling level) for the fire laboratory (around 60 kW) in The Hong Kong Polytechnic University (PolyU). Therefore, rated power of heater is adopted in the preliminary test.

Table 1: Comparison between ASTM Standards and room fire test

	ASTM Standards	Room Fire Test
Objective	Evaluate the role of material or product in fire growth within compartment	Evaluate the computer zone model (ASET & Hazard I)
Compartment design	With ventilation opening	Without ventilation opening
Compartment size	2.4 m × 3.7 m × 2.4 m high	2.3 m × 4 m × 2.6 m high
Ignition source	Gas burner or fuels (wood)	Electric heater

Besides, it is also suggested that thermocouples should be placed at vertical intervals of 76 mm to 152 mm. This arrangement is still suitable for evaluating the zone model. However, the thermocouples should be more concentrated to locate at the upper level of the chamber for determining the interface height with high accuracy. Therefore, the thermocouples would not be located with the same interval.

3. EXPERIMENTAL ARRANGEMENTS

3.1 Experimental Test

The room fire test was conducted in the PolyU laboratory and its schematic is shown in Fig. 1.

Calibration instrument – thermocouples (type K and type T) were carefully calibrated with two standard sources (i.e. boiling water and ice), and then comparing the reading of thermocouple with thermometer. From the result of Fig. 2, it is shown clearly that the error of thermocouple type K is around 2.5 ºC and this value is quite acceptable.

Heat release rate measurement – One clamp-on leak Hi Tester was used to measure the actual current passing through five-core cables connected to the heaters. The heat release rate of these heaters can then be calculated by:

$$\text{Power} = \sqrt{3} \times 380\ \text{V} \times \text{I} \times 2$$

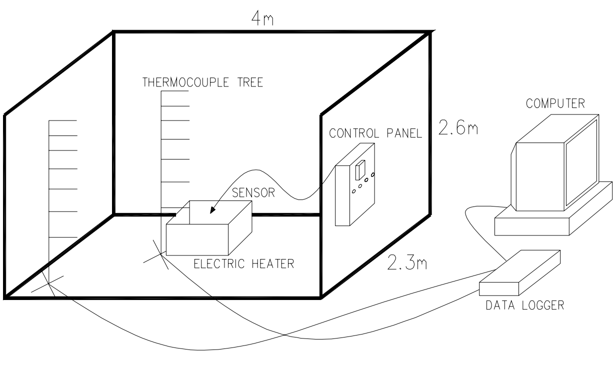

Fig. 1: Schematic diagram of experimental setup

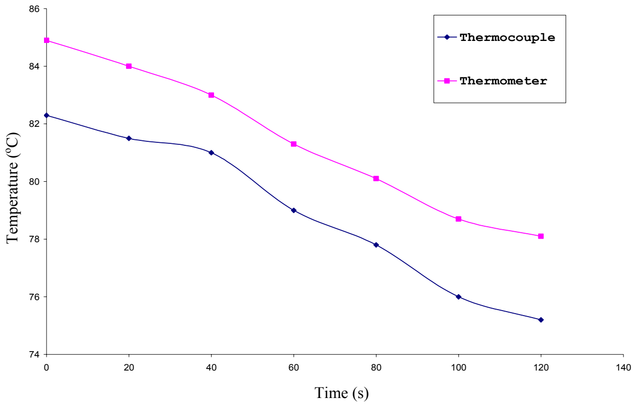

Fig. 2: Calibration of thermocouple K

In this calculation, exactly the same values of heat release rate provided by the two heaters are assumed. When the heaters were not operated in the full-load conditions, a thermal controller is used to control their powers. This controller can be on/off control (proportional mode is set to zero) or PID control.

Temperature measurement – Two thermocouple trees with vertical array of a total of 14 measurement points with Type K thermocouple were set up to measure the temperature distribution inside the chamber. One of them stood at the centre (near the heater) and another one stood at the corner of the chamber. Thermocouples were placed at vertical intervals of 200 mm for the top four from the ceiling. The others were separated at 350 mm. Also, the temperatures were recorded every second. It satisfied the recommendation by ASTM Standards (at least 15 s per data). Lastly, the data were recorded by a data logger connected to the computer.

3.2 Development of Electric Heater and Control Panel

A 24 kW heater (12 units of 2 kW heater) as shown in Fig. 3 is placed inside the fire chamber and used to simulate the fire scenario. The dimensions of 500 mm width, 500 mm length, 400 mm height and 100 mm feet were made. Its power density is 96 kWm^{-2} or 192 wm^{-3}, and the current capacity is 10 A/heater and 40 A/phase. In this research, the heater will be located in different locations inside the laboratory for evaluating the computer models and finding their limitations.

There are two reasons for using a heater instead of a pool fire. The first reason is that it can provide repeatable, predictable and steady heat release rate. It is useful to eliminate the measuring errors by verification. Another reason is that the upper layer gas is usually assumed as 'heated air'. Since air entrained into the flame is typically 10 to 20 times that required for complete combustion [1], molecular radiation contribution from N_2, CO_2, CO and unburnt hydrocarbons can be ignored. This assumption quite matches the scenario provided by an electric heater.

For controlling the output of the electric heaters and safety reason, one thermal controller (Fig. 4) is selected. This controller is connected to two contactors with 5 A rating through an on/off switch. It means that two groups of heater will be switched on and off simultaneously. There are four indicating lamps, two for 'supply healthy' and the rest for 'heater on'. If 12 kW heat release rate is used, it is quite simple that one electrical supply would be removed from one contactor. Besides, all the electrical cables (Fig. 5) connecting to the heater are fire-resistant cables. Moreover, for double protection, one more 6 A MCB is connected between the main supply and the controller.

Fig. 3: Electric heater

Fig. 4: Thermal controller

Fig. 5: Wiring inside the controller

4. COMPUTER SIMULATION

Computer simulation is a very useful and time-saving design tool for predicting the fire situation in enclosure. However, all models have assumptions and limitations (Table 2). If they are known and understood already, then these models can be very powerful and helpful tools. In this research, Available Safe Egress Time – Visual Basic (ASET-VB) and CFAST were studied and evaluated.

4.1 ASET-VB

It is a simple, user-friendly, one room smoke-filling model computer program which simulates the smoke layer thickness, temperature, and concentrations of products of combustion due to a fire of time-dependent, user-specified, energy and product release-rate. In this computer model, the location of the interface height can be predicted by an equation describing the conservation of mass for the lower or upper layer (Fig. 6), i.e.

$$\frac{dZ_i}{dt} = -\frac{T_u \dot{M}_e}{\rho_a T_a A} - \frac{H - Z_i}{Tu}\frac{dT_u}{dt} \qquad (1)$$

And heat release rate, i.e.

$$\dot{Q} \equiv \frac{(1 - L_r)\dot{Q}}{\rho_a c_a T_a (g\Delta Z_i)^{1/2}\Delta Zi^2} \qquad (2)$$

In this model, heat release rate cannot be used from default value by software. Since the heat release rate of the heater is nearly constant all the time and it is different from a fuel fire. Therefore, custom fire is adopted.

Table 2: Major assumptions and limitations used in ASET-VB and CFAST

ASET- VB	CFAST
The pressure within the compartment is constant and equal to atmospheric pressure	The pressure within the upper layer and lower layer are identical, and it will change with time
Temperature of the lower gas layer is constant and equal to ambient temperature	It has been limited to one- and two- family residential structures, and all rooms are rectangular in shape
Venting occurs only through a crack-like vent located at floor level	Condition within a room only varies from floor to ceiling, not horizontally
Radiative fraction is set equal to 35 %	Zones and surfaces radiate and absorb like grey bodies

Also, this program assumes that low layer temperature is the same as the ambient temperature. By conservation of upper layer energy, the hot-layer temperature is:

$$\frac{dT_u}{dt} = \frac{(1-L_c)Q - \dot{M}_e c_p (T_u - T_a)}{\dot{M}_u c_p} \quad (3)$$

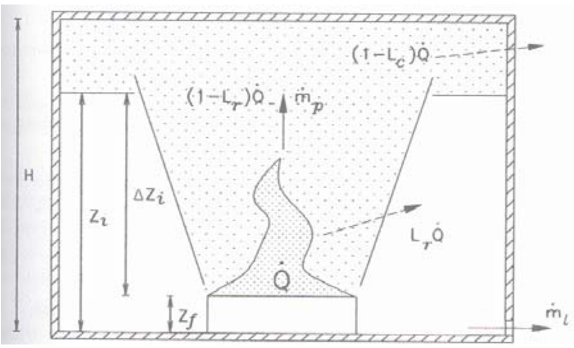

Fig. 6: Schematic diagram of ASET-VB

4.2 CFAST

It consists of a collection of data, procedures, and computer programs that are used to simulate the important time-dependent phenomena involved in residential fires [4]. The major functions provided include calculation of production of energy and mass, the resulting temperatures, smoke optical densities and gas concentrations. The upper layer temperature is defined as:

$$\frac{dT_u}{dt} = \frac{1}{\beta}\left(\frac{T_u}{PV_u}\right)\left(\dot{E}_u + \frac{V_u}{(\beta-1)V}\dot{S}\right) \quad (4)$$

4.3 Sensitivity Analysis

Sensitivity analyses have been done before using ASET-VB (Figs. 7 and 8). It has been shown that there are no sudden changes for input of various heat release rates from 6 kW to 24 kW (rated power of heater). Also, the trend of upper layer temperature and interface height produced by these heat release rates is nearly the same. Thus, the model uncertainties are not significant.

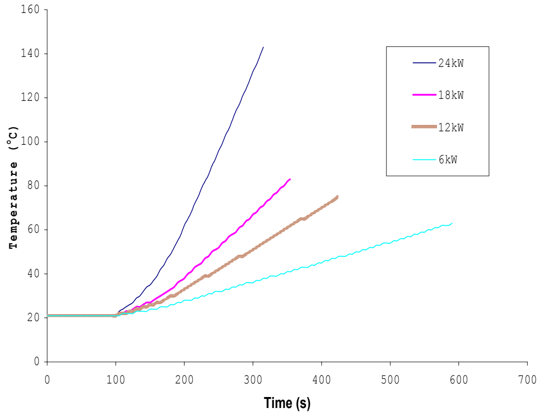

Fig. 7: Sensitive analysis of ASET (Temperature)

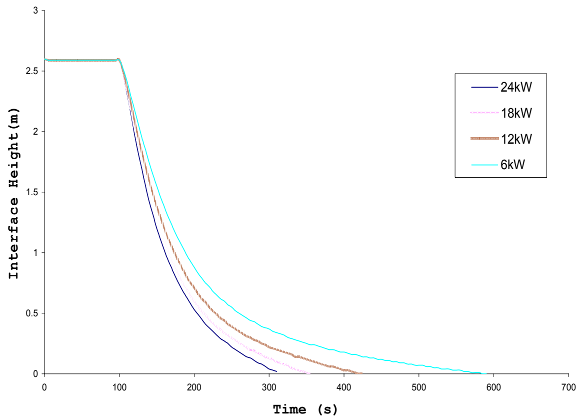

Fig. 8: Sensitive analysis of ASET (Interface height)

5. RESULTS AND COMPARISON

- Interface height

  There was a thermocouple located just below the ceiling. The interface height was derived by estimating the temperature at the interface at 15 % of the temperature rise on the top of temperature. The vertical temperature distribution will be obtained by the linear interpolation between thermocouples. This is the only one and most suitable method for measuring interface height in this heater simulation. It is because there is no smoke generation by the heater and thus no visual observations of the smoke layer.

- Upper layer temperature

  After determining the interface height, the upper layer gas temperature was defined from the average reading of the thermocouples located above interface height.

- Comparison between computer model and experimental data

  Comparison of the heat release rate, upper layer temperature and interface height measured from the room fire test and predicted from computer models are shown in Table 3.

6. DISCUSSION

Before comparing the results between room fire test and ASET-VB, the heat release rate of the heater should be ensured that it was large enough to create a plume by buoyancy effect. If the heater cannot make the hot gas rise to the ceiling due to the decrease of plume gas temperature by the entrained air, the rated power of the heater must be enlarged. As shown in Fig. 9, the highest thermocouple (near the ceiling) has the highest temperature. Thus, a 24 kW heater is acceptable.

From the findings in Table 3, it is shown clearly that the heat release rates come from the heater rose steadily at the early stage (Fig. 10). After around 100 s, the maximum point was reached. In order to obtain better prediction results from computer program, these heat release rates had also used to create a specific fire file for simulation. However, it was found that the predictions from the ASET-VB have large deviations compared with the experimental data, especially in the interface height.

From the experimental result, it is shown that the heater needed a longer time for the hot layer temperature to reach a certain level compared with the computer model. This is mainly due to errors from assumption of the software. It is because gases of lower layer and upper layer are assumed to be separated in ASET. However, it is different from the real case and these two layers would be mixed together. Therefore, the upper layer temperature must be lower than the predicted value. This deviation will be very significant when the fire chamber is larger.

It can be seen from the results in Fig. 11 that the speed of decreasing of the hot layer is slower when the heater was located at the centre of the chamber. It can be predicted because the room corner usually represents the worst fire scenario, since the air entrainment is restricted into the corner plume by two adjacent walls. Thus, the flame spread rate is much higher when the walls and ceiling of a building corner are combustible.

Besides, the 12 kW heater cannot increase the upper layer temperature very much, even when it is located at the corner. However, the interface height has the opposite result. It can make the lower layer gas decrease from the ceiling more quickly. This result may reflect that this heat release rate cannot provide sufficient buoyancy. It causes the hot gas to be cooled already by the entrained air before reaching the ceiling. Therefore, this upper layer temperature and interface height may fail.

Table 3: Comparison between room fire test and ASET-VB

	I (A)	T_d (s)	Q (kW)	T_u (°C)	Z_i (m)
24 kW Heater (Centre)	38.4	60	25.3	27.3	2.30
	44.8	600	29.5	61.3	1.65
	44.8	1200	29.5	66.9	1.61
12 kW Heater (Corner)	19.2	60	12.7	26.2	2.03
	22.4	600	14.75	41.4	1.63
	22.4	1200	14.75	44.8	1.62
ASET-VB	--	60	25.3	39	1.22
		150	29.5	72	0.22
		315	29.5	143	0

From all the results shown, the ASET is not suitable for simulating fire scenarios produced by a heater, since the heat release rate of a heater (steady) is not equal to a fuel fire (unsteady). Besides, there are some vents (air diffuser and leakage of door) at the upper part of the chamber. They will also affect the experimental results and not be supported by the ASET program.

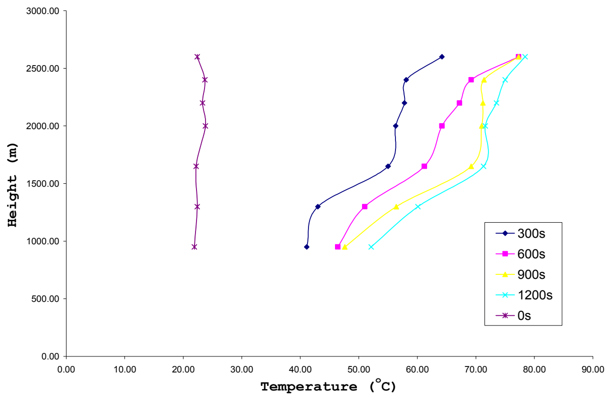

Fig. 9: Temperature profile of the fire chamber

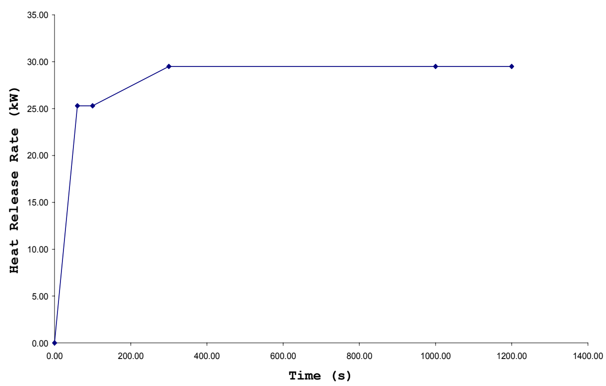

Fig. 10: Heat release rate of the 24 kW heater against time

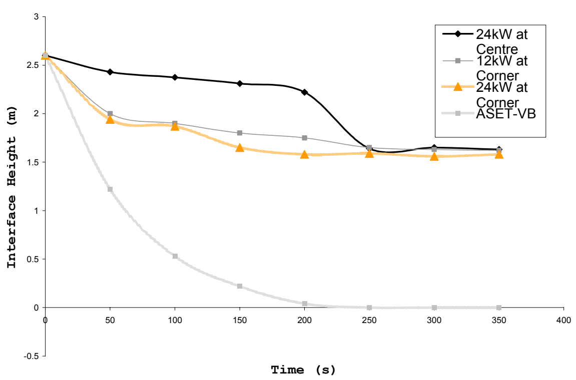

Fig. 11: Comparison of interface height between the 24 kW and 12 kW heater and ASET

7. CONCLUSION

After comparing the results of computer models and preliminary full-scale test, the agreement between their outputs is not very good. This may be due to wrong data input to the computer models, or measuring errors in the fire test. Therefore, the research must be further improved to find out the main factors causing these errors. In fact, the ASET model is not suitable for estimating the fire scenario if high accuracy is required. It is because its assumptions are quite different from the real situation.

In short, there are many parameters affecting the heat release rates, such as the location of the heater, the geometry of the fire chamber, etc. They are very useful for evaluating the computer models and thus will be studied in the next semester. Also, CFAST or other software will be used for comparison.

NOTATIONS

T_d	duration of burning, s
T_u	upper layer gas temperature, °C
Q	heat release rate, kW
Z_i	distance between floor and bottom of smoke layer, m
L_c	conductive fraction
L_r	radiative fraction
I	measured current through heater rate, kW
Δt	time interval, 15 s
ρ_a	density of ambient air, kgm^{-3}
M_e	air mass flow entrained in the flame and plume, kgs^{-1}

ACKNOWLEDGMENT

The author would like to thank Dr. N.K. Fong for his valuable advice. Help from laboratory staff, especially Angus Cheng, was also greatly appreciated.

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Q & A

Q1: Have you repeated the experiment with different conditions, for example, using the warm or cold boundary?

Chan: I will repeat and try to do the room fire test using other method, for example, such as changing the ceiling height, opening the door or window.

Q2: ASET will not concern the thermal radiation, it may cause error. How can you eliminate this error?

Chan: ASET will have its default value of thermal radiation. It is recognized that when the temperature increases, thermal radiation will become the more important part of the heat transfer. Thermal radiation may be the main part because there is difference between the experimental result and the predicted result. So, in my future study, I will try to use the CFAST model, as the default value can be changed much more easily.

Q3: How do you distinguish the interface height temperature in your experiment?

Chan: From the diagram, firstly, I will try to determine what is the upper temperature first. The ASTM standard of the room fire test suggested that the upper layer temperature can be assumed as the average of the upper four thermocouples. Then, take this average, and times 0.85, this is the temperature of the interface height level.