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VERIFICATION OF FIRE MODELS FOR FIRE SAFETY SYSTEM DESIGN

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ABSTRACT

Fire modeling is an essential part of risk-cost assessment. Fire models, particularly those of zone type, have flourished in recent years. The selection of a fire model as a sub-model for a fire safety system model needs further verification and review in a number of aspects. In the present study, the performances of two fire models, namely NRCC and CFAST, are evaluated with respect to accuracy, efficiency and simplicity. This study indicates that discrepancies exist between the experimental results and the predictions of both models for one type of fire scenario or another. The merits and weaknesses of the two models are identified in regard to the demands of a risk assessment system model.

INTRODUCTION

The cost-effective risk assessment and engineering performance-based design solutions to achieve an acceptable fire safety record in buildings have long been recognized[1] and the performance-based design approach for fire-safety systems in buildings is gradually being adopted world wide[2]. Research has been in progress for over a decade to develop risk-cost assessment models to estimate the risks to life safety and the economic consequences of the effects of fire in buildings[1,2,3,4,5]. The models evaluate the life risks and fire costs over the lifetime of a building by assessing the interactive characteristics of fire growth, fire and smoke spread, fire detection and suppression systems and human response in the building. The evaluation of the performance of a fire safety system is a complicated and challenging issue. In fire safety assessment, a risk-based approach identifies every possible fire scenario and computes the associated losses. A risk-cost assessment system model consists of a number of sub-models which cover a wide range of phenomena that are the subject of fire research. Because of the comprehensiveness of the system model, efficiency and simplicity become high priority requirements for the development of the sub-models.

For the purpose of engineering performance-based design, a fire safety system model, called CESARE-Risk[6], is being developed at the Victoria University of Technology (VUT), Australia, to integrate several sub-models describing the physical, psychological and sociological processes associated with fire growth and spread, human behavior, communication and the responses of the building fire safety sub-systems and fire brigade to fires and to predict the interaction between fire growth and spread, human behavior and building design.

The fire model is a major component of a risk-cost assessment system model. Adequate prediction of fire development and the fire environment with acceptable efficiency and accuracy is essential for other sub-models. Many fire growth models exist in literature and are available publicly[7]. A two-zone fire model, CFAST[8,9], and a one-zone fire model, NRCC[10], are two among those models. The result of a verification exercise for the former has been presented in a previous publication[11] where the model's prediction was compared with a set of experimental results. However, the selection of either of the above models as a sub-model for the fire safety system model requires further verification against a wider range of experiments and a comparison between the two models. So it is necessary to further investigate their performance under a variety of fire scenarios and to carefully define their merits and limitations.

Design fires have been categorized into three groups in fire research: namely, smoldering fire, flaming fire and flashover fire[10]. A realistic building fire may cover these three design fire scenarios at different stages in its development. A smoldering fire is equivalent to the early stage of a real fire, and a flashover fire is the fully-developed fire stage in a building enclosure. A flaming fire may represent the transition stage between the smoldering and flashover stages.

Air-handling systems are commonly used in modern buildings. There has been a concern within the fire safety research community regarding the hazard of smoke transport via air-conditioning systems[12] and ceiling vents[13]. However, the effects of the air-handling system on fire development in an enclosure of fire origin has not been fully examined systematically. Ventilation conditions are one of the major factors which affects fire development and the fire environment. The operation of the air-handling system can significantly change the ventilation condition of a building.

This paper presents some verification activities and focuses on a comparison of the predicted results from the CFAST (Version 2.01) and NRCC fire models against the results of a series of experiments including smoldering fires, flaming fires and flashover fires under different building configurations and different ventilation conditions (with and without the operation of the air-handling system). The experiments were conducted at the Centre for Environmental Safety and Risk Engineering (CESARE), VUT.

Fire Model

General

Techniques to model the heat and mass transfer processes associated with fires in buildings fall broadly into two categories[7]: namely field models and zone models. Field models (computational fluid dynamics or CFD models) divide an enclosure into a large number of cells and solve the basic laws of physics for the fluid flow. Field models require the incorporation of sub-models of a wide variety of physical phenomena, including convection, conduction, radiation and combustion processes and do not make significant simplifications[14,15]. Accordingly, field models need intensive computational power and CPU time. The field models can provide detailed information on the fluid flows. Hence, they are often used in fundamental research to study some specific aspects of building fires but are unsuitable for a risk-cost assessment system model.

Zone models assume a limited number of zones in an enclosure. Each zone is assumed to have uniform properties such as temperature, gas concentration, etc. Zone models also solve the conservation equations for mass, momentum and energy for the variables of interest (temperature, gas concentration, etc.). However, zone models usually adopt simplifying assumptions to the basic conservation equations to reduce the computational demand for solving the equations. A PC is usually sufficient to carry out the implementation of the model and more phenomena can be included without loss of efficiency. This makes the zone model a powerful tool for the fire safety system model.

CFAST Model

The CFAST model (Consolidated Model of Fire Growth and Smoke Transport)[9] uses a two-zone method to calculate both fire growth and smoke spread in a multi-enclosure and multi-level building. The model divides each enclosure into two zones and solves the conservation equations of mass, energy and momentum at the vent, the plume and the relevant zones for various physical parameters. The CFAST model has the capability to incorporate the mechanical ventilation system during fire. Compared with other zone models, the computation procedure in CFAST is relatively more rigorous. However, the model requires the measured heat release rate as the input data. Also, the ratios of species concentrations and the time of window breaking have to be prescribed in the input data file. Because of the limitations embedded with the simplifying assumption and the empirical correlations that are adopted by the model, the application range of the model is often confined to non-flashover fires. The CFAST model is well documented in the literature and enjoys a wide acceptance in fire research and engineering communities. The CFAST model version 2.01 was used in the present paper.

NRCC Model

The NRCC fire growth model was developed by researchers at the National Research Council of Canada (NRCC)[10]. It is a simplified one-zone model for single room fires. It treats the fire room as a well stirred combustion chamber and assumes uniformly distributed quantities inside the room. The model predicts the condition of the combustion products, hence the results should be equivalent to the upper layer conditions of the CFAST model results. The fuel burning rate in this model is coupled with the conditions in the fire room. The NRCC Fire Growth Model is one of a few models that correlates the burning rate of the fuel with the burn room conditions[10,16]; this capability is a valuable attribute. In calculating heat release rate, the model takes into account the radiation enhancement of flame spread rate over the burning fuel surface and the influence of oxygen concentration in the surrounding environment. The computer program has also been found to be computationally efficient.

The model does not distinguish between flaming and flashover fires. The flashover condition is achieved by specifying a larger amount of fuel load and favorable ventilation conditions. Only the smoldering fire is treated differently.

The NRCC fire growth model has been verified against the identified three types of fire scenarios: namely, smoldering, flaming and flashover under natural ventilation conditions[17,18]. Modifications to the model have been undertaken to achieve closer agreement between the predicted and the measured results and to enable it to handle the mechanical ventilation conditions. The modified model has taken into account the enhancement of radiation by soot[19], the variable equivalent radius and flame spread rate and the effect of the real size of the window breakage. The modified version has been applied in this study.

Experimental Set-up

A series of fire experiments was conducted at the Centre's full-scale compartment building—the Experimental Building-Fire Facility (EBFF). The fire scenarios covered a wide range of variation of ventilation conditions, fuel types, fuel configurations and building configurations. Two different building configurations are presented in this study: that is, a small burn room (2.4 m × 3.6 m × 2.4 m high) and a large burn room (5.4 m × 3.6 m × 2.4 m high). The layouts of the building configurations are illustrated in Figure 1. For the small burn room, the building configuration varied with the status of doors D1 and D2 during experiments. A mass platform was located on the floor of the small burn room to record the fuel mass dynamically during fire experiments. For the large burn, two mass platforms were situated on the floor of the burn room.

The results presented in this paper are applicable to the cases where no flashover fires are pre-

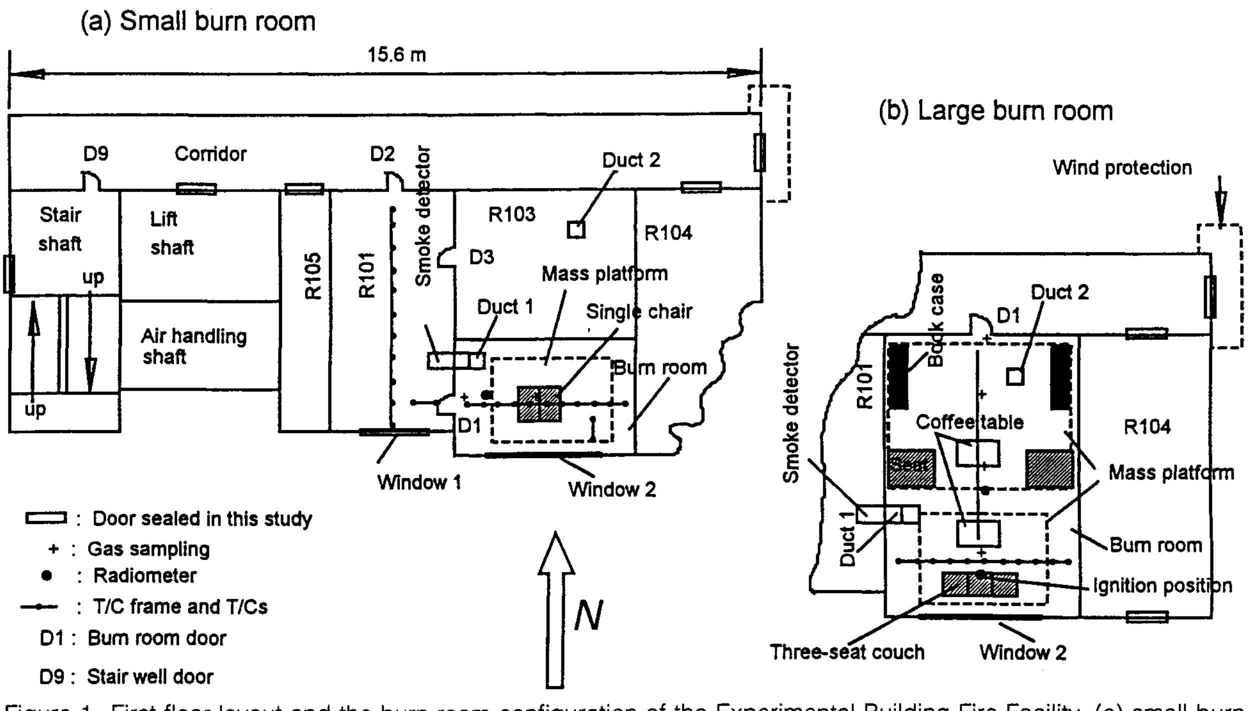

Figure 1. First floor layout and the burn room configuration of the Experimental Building Fire Facility. (a) small burn room; (b) large burn room and fuel configuration for flashover fire tests; for flaming fires, only a three-seat mock-up couch was placed on the small platform.

sented for the configuration of the small burn room and no smoldering fires are presented for the large burn room. Ten representative experiments were chosen for the purpose of comparison of the CFAST model results and the NRCC model results with the experimental results. A summary of the conditions of the ten fire experiments is given in Table 1.

Two experiments were selected from each of three types of fires and each of the building configurations. Tests No. 1 and 2 were designated as smoldering fires in the small burn room where the burn room door D1 was closed. Tests 3, 4, 5 and 6 were flaming fires conducted in the small burn room. In the former pair of experiments (Tests 3 and 4), the burn room door (D1) was closed. In the latter (Tests 5 and 6), doors D1 and D3 were open and door D2 was closed, hence the whole compartment with three rooms was involved in these two experiments. Tests 7 and 8 were flaming fires which were carried out in the large burn room. Tests 9 and 10 were conducted in the large burn room as potential flashover fires. However, Test 10 did not reach the flashover stage because of the forced ventilation (extraction of smoke). Further discussion will be given later. For the large burn room configuration, doors D1 and D9 were open and door D2 was closed during experiments (Tests 7-10); only the burn room and the corridor were involved in the experiments.

For each type of fire and building configuration, one experiment was designated with the operation of the air-handling system and another without. In Tests 1, 3, 5, 7 and 9, the air-handling system was turned off; in the other experimental results presented in this paper, the air-handling system was in operation during the test (Tests 2, 4, 6, 8 and 10).

Fuel configurations (furniture) varied with the fire scenarios. For the experiments conducted in the small burn room, a single mock-up chair was used and placed at the centre of the burn room on the mass platform (see Figure 1(a)). The fuel configuration in the burn room illustrated in Figure 1(b) is designed for the flashover fire tests. The fuel (furniture) consisted of a three-seat couch, two single-seat sofas, two coffee tables, and two book shelves with stacks of phone books. The couch and one coffee table were located on the small mass platform (the couch was close to Window 2), the others were on the large mass platform. For the experiments of the flaming fires in the large burn room, a three-seat mock-up couch was used. The couch was placed on the small mass platform near Window 2. Window 2 was broken and the window glass was dislodged during the flashover fire experiments (Tests 9 and 10). The dislodgement was recorded on video. The results were used for the input of the CFAST model. During the smoldering and flaming fire experiments, Window 2 remained unbroken.

The air handling system in the EBFF can be run under two different modes: (1) normal air supply and return mode, (2) smoke management mode with smoke exhaust and stair pressurization. In the normal air-handling mode (air supply and return), the system is run under a recycle condition with no fresh air. In the smoke management mode, the air-handling fans continue to operate but with 100% fresh air (no return air); the fresh air is supplied to all levels other than the level of fire origin. The exhaust system is applied only to the level of fire origin. In addition, the stairwell is pressurized using separate fans. The design is in accord with the Australian standard for the design of smoke management systems in multistory buildings.

For those experiments conducted with the air-handling system turned on, the smoke management operation of the air-handling system was controlled by a smoke detector which was placed in a duct (see Figure 1) at the ceiling level. The air-handling system was operating at the start of the fire experiments. Two air supply ducts (0.4 m × 0.4 m) were located on the ceiling. For the small burn room, Duct 1 was placed in the burn room and Duct 2 was in another room (Room 103) (see Figure 1(a)). However, for the large burn room, both air-supply ducts were located in the burn room (see Figure 1(b)). The air flow rates through these two ducts were 46 and 50 L/s respectively. The system switched to smoke management mode automatically at about 80 s for all cases when the smoke detector operated; about 800 L/s of air (smoke) was then extracted out from the burn room using smoke spill fans.

The EBFF was equipped with instruments to measure temperature, radiation, gas composition and smoke optical density. The measured

Table 1. Experimental conditions of fire scenarios

Test No	Layout	Air system	Design fire	Door status	Fuel Configuration	Fuel load/ consumed (kg)
1	S[i]	off	Smoldering	D1 closed	Single mock-up chair, 1.88kg P/U[ii] and 0.88kg cover (cotton 40% linen 60%)	2.76 / 0.87
2	S	on	Smoldering	D1 closed	Single mock-up chair, 1.98kg P/U and 0.78kg cover (cotton 40% linen 60%)	2.76 / 0.85
3	S	off	Flaming	D1 closed	Single mock-up chair, 4.12kg P/U and 1.10 cover (cotton 40% linen 60%)	5.22 / 4.51
4	S	on	Flaming	D1 closed	Single mock-up chair, P/U and cover (cotton 40% linen 60%), exactly weight of materials is not available	NA / 5.42
5	S	off	Flaming	D1 and D3 open, D2 closed	Single mock-up chair, 3.88kg P/U and 1.04kg cover (cotton 40% linen 60%)	4.92 / 3.40
6	S	on	Flaming	D1 and D3 open, D2 closed	Single mock-up chair, 3.86kg P/U and 2.06kg cover (cotton 40% linen 60%)	5.92 / 5.50
7	L[iii]	off	Flaming	D1 open, D9 open	Three-seat mock-up couch, 6.84kg P/U and 2.58kg Acrylic	9.42 / 9.30
8	L	on	Flaming	D1 open, D9 open	Three-seat mock-up couch, 6.84kg P/U and 2.58kg Acrylic	9.42 / 9.30
9	L	off	Flashover	D1 open, D9 open	Furniture: 276.9kg (wood, P/U, cover, carpet); phone book: 265.2kg	542.1 / 273.6
10	L	on	Flashover	D1 open, D9 open	Furniture: 274.5 kg (wood, P/U, cover, carpet); phone book: 265.2kg	539.7 / 42.9

[i]S: Small burn room, see Fig. 1.
[ii]P/U: Polyurethane foam (A23-130)
[iii]L: Large burn room, see Fig. 2.

data were collected using a PC-based data logger. The details of the experimental set-up have been described elsewhere[11].

Data Processing

In order to compare the measured results with the zone model predictions, spatially distributed values obtained from experiments need to be averaged. It is essential to determine the interface position between the upper hot and the lower cool zones from the experimental data before the averaging is carried out. An N percent rule[20] has been modified and used in this study to estimate the interface height of each room from the vertical distribution of measured temperature. The method used for temperature averaging has been described in the literature[21].

Vent openings of an enclosure would be more reasonable locations to obtain physical quantities for comparison with model predictions. However, appropriate bulk average parameters of the exhaust and inlet flows at a vent are based on transport terms and require the measurements of flow velocity, as well as the parameter profiles[21]. Not all of the required parameter profiles were measured in the experiments discussed in this paper. In consideration of consistency, the room averaging technique together with the *N* percent rule as mentioned above were chosen. Nevertheless, the species concentrations measured at the doorway of the burn room 1.7 m above the floor were used for comparison with model predictions. It was found in an earlier study that the measured results at this point coincide well with those taken inside the burn room at the same height[11].

For the purpose of comparing with the NRCC model results, the values of the upper and lower layers from the experimental results and the CFAST model results were further averaged over the whole room.

Results and Discussion

Mass Release Rate and Input for Zone Models

The CFAST fire model requires the prescription of the mass or heat release rate. In this study, the total mass of fuel was recorded dynamically against time with a mass platform in the burn room, the mass release rate being deduced from the measurement. The results of the ten selected experiments are plotted in Figure 2. The result of the mass release rate was used as input to the CFAST model for each case. In running the NRCC model, the total fuel load and estimated maximum burning surface area were specified as the input data. The model calculates the flame spread rate, the burning surface area and hence fuel burning rate using the conditions in the burn room[10]. The predicted mass release rate of each case from the NRCC model is also included in Figure 2. Given in Figure 3 are the experimental results and the NRCC model predicted results of the total mass of fuel consumed. It seems that the NRCC model results are in good agreement with the experimental results for all cases except for the smoldering fires (Tests 1 and 2) and Test 3.

As expressed previously, the air-handling system supplied fresh air at the beginning of the experiments; at about 80 s, the air handling system was switched to the smoke management mode

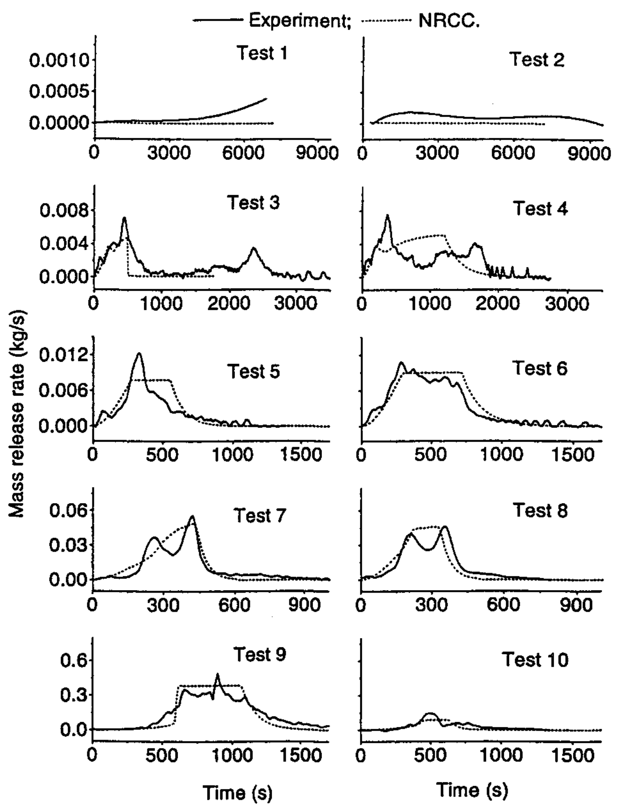

Figure 2. Measured and NRCC model predicted mass release rates.

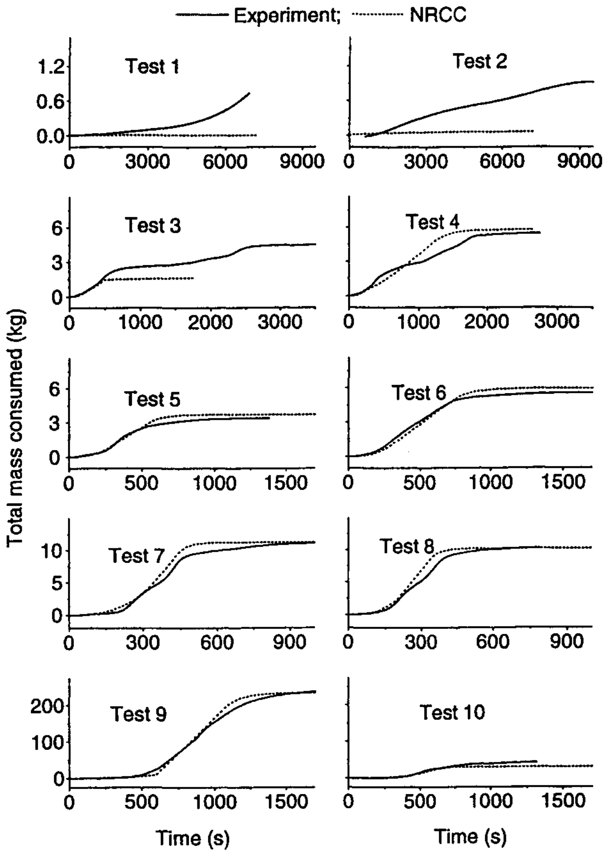

Figure 3. Measured and NRCC model predicted total mass consumed.

automatically for all cases. However, the CFAST model could not simulate the situation exactly. If the model simulated the supply air during the first 80 s, then re-started with the extraction of smoke, the results would suffer from the numerical instability. In order to avoid this difficulty, the situation was simplified in the CFAST model. Since the supply air was relatively small (46 and 96 L/s), and the duration (80 s) was negligible compared with the duration of the total fire period (greater than 800 s), the air-handling system was simplified such that the smoke management system operated (extract smoke) from the time of ignition in the CFAST model. The air-handling system was also simulated in the NRCC model.

Comparison in Burn Room

The verification activities are to choose the fire growth models between the two-zone CFAST model and the one-zone NRCC model for the fire safety system model. The NRCC model is applicable to the room of fire origin only. The predicted results are equivalent to the predicted results of the upper layer from the CFAST two zone model.

The measured temperatures were spatially averaged with two layers based on the *N* percent rule[20,22]. The results of the upper layer were then used for comparison with the NRCC predicted results.

The experimental results, the related CFAST model results and the NRCC model results for the selected ten cases are plotted in Figures 4-8. Column (b) of each figure is associated with the operation of the air-handling system and Column (a) with the air-handling system switched off. Each figure shows temperature, O_2, CO_2 and CO in the burn room (upper layer for the CFAST model results and experimental results).

Generally, the predicted results from the CFAST fire model and the NRCC fire model were similar but deviated from the experimental results to some extent. The CFAST model over-predicted the upper layer temperature in the burn room in flaming and flashover fire experiments. The temperatures obtained from the NRCC model were closer to the measured temperatures than those from the CFAST model. The NRCC model has the tendency to over-estimate carbon monoxide and carbon dioxide concentrations for flaming and flashover fires with forced ventilation and under-estimate these quantities under natural ventilation conditions. CFAST tends to under-predict species concentrations particularly when the burn room door was closed.

It was revealed in a previous study that the layering effect in the room of fire origin could quickly diminish in fast growing flaming fires[11]. Due to turbulent mixing, the condition in the burn room is more likely to be a well mixed one zone rather than two zones. The measured and the CFAST predicted temperatures of the upper and lower layers were further averaged over the whole burn room and plotted in Figure 9. The NRCC model results were also re-plotted. The room averaged temperatures from the CFAST model results closely agreed with the room averaged temperatures from the experimental results for Tests 4, 6, 7 and 8, and significantly improved for the other tests. The results from the NRCC model agreed well with the room averaged CFAST model results and with the experimental results for some cases and deviated from the experimental results for others. For Test 3, the NRCC model results were in good agreement with the experi-

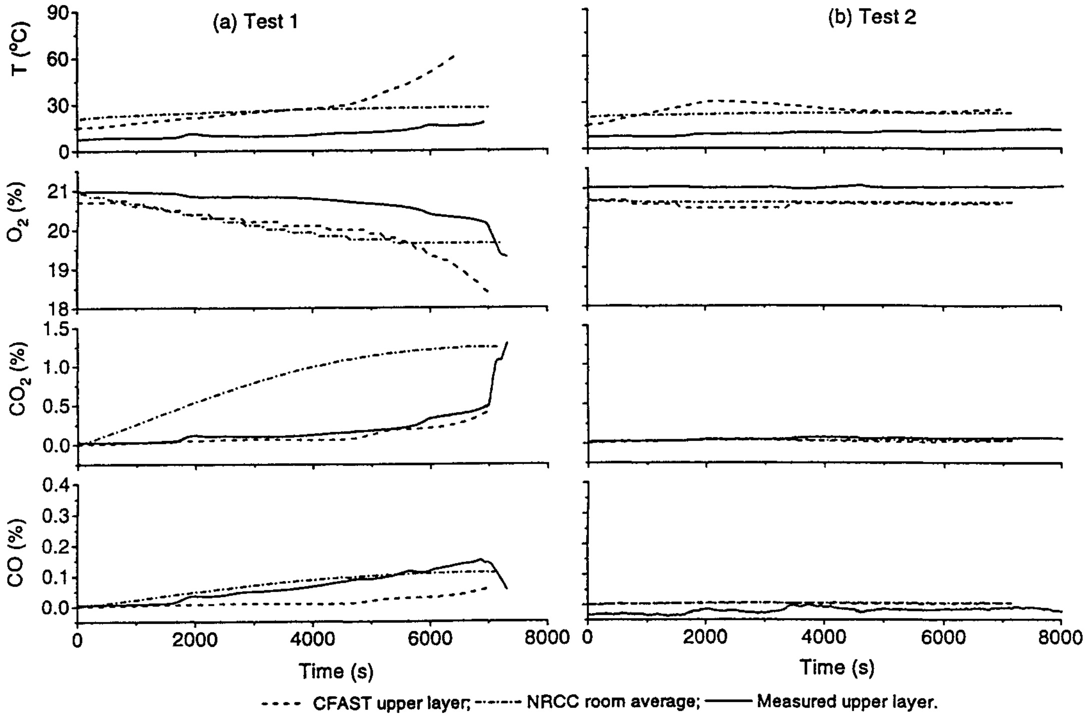

Figure 4. Smoldering fire results of upper layer in small burn room from CFAST model and experiments and results from NRCC model; The burn room door (D1) closed (D3 not applicable); (a) Test 1, air-handling system off; (b) Test 2, air-handling system on.

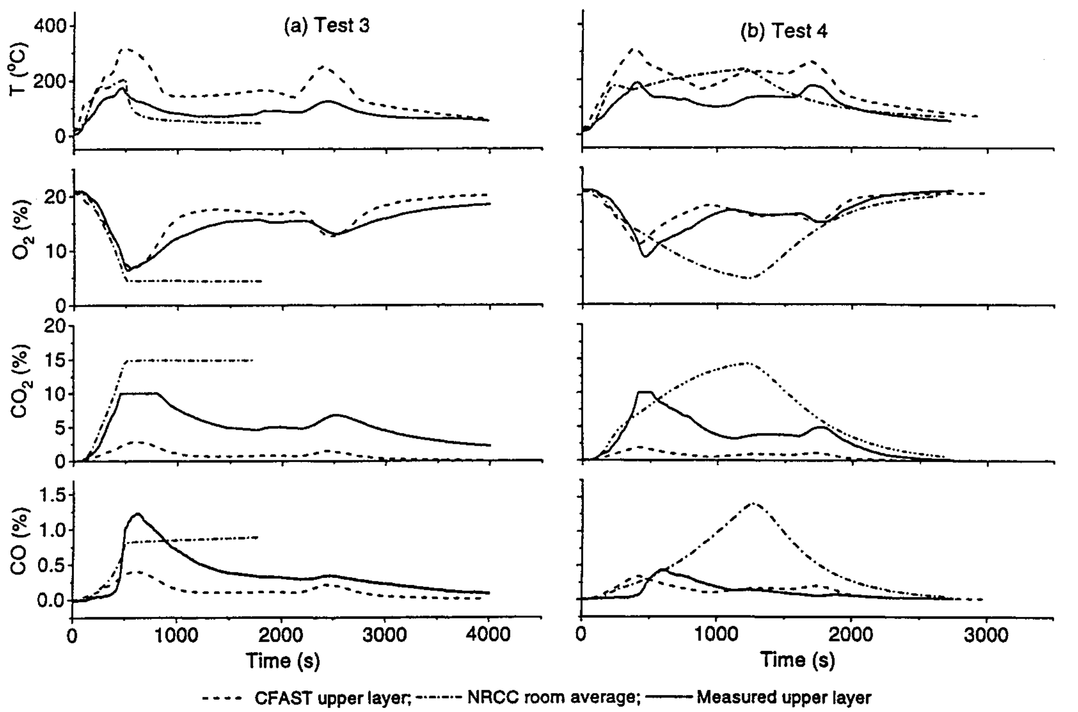

Figure 5. Flaming fire results of upper layer in small burn room from CFAST model and experiments and results from NRCC model; The burn room door (D1) closed (D3 not applicable); (a) Test 3, air-handling system off; (b) Test 4, air-handling system on.

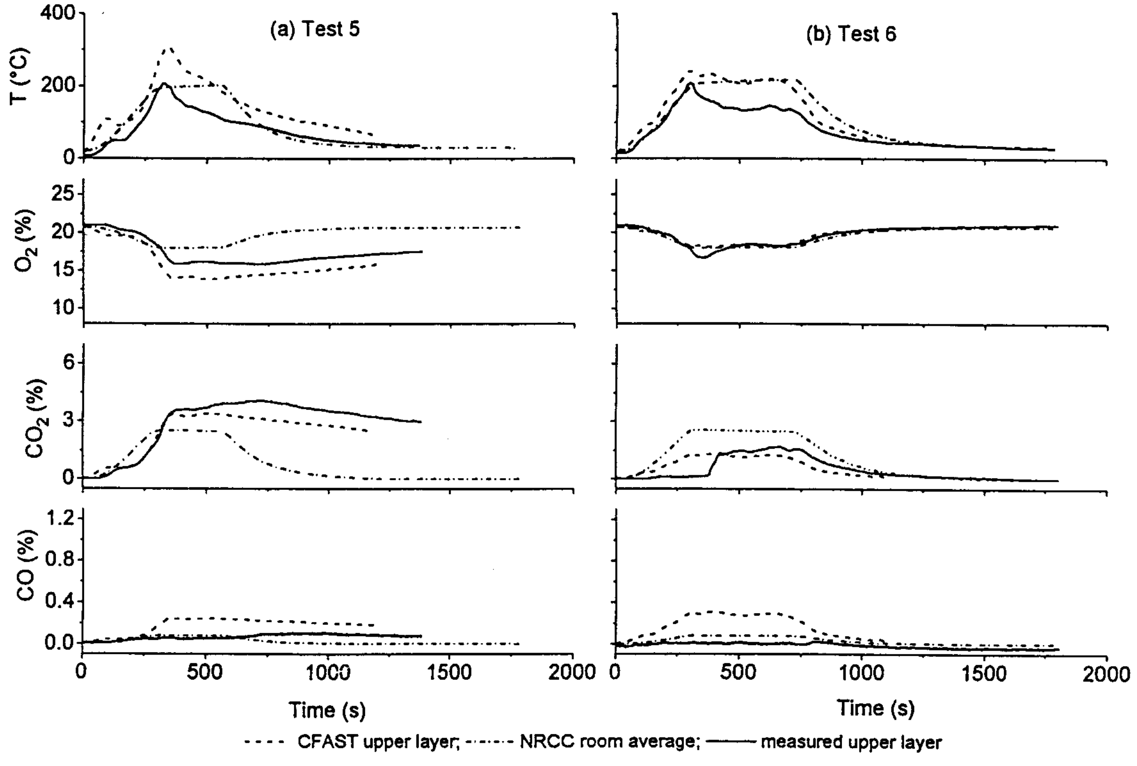

Figure 6. Flaming fire results of upper layer in small burn room from CFAST model and experiments and results from NRCC model; The burn room door (D1) and D3 open; (a) Test 5, air-handling system off; (b) Test 6, air-handling system on.

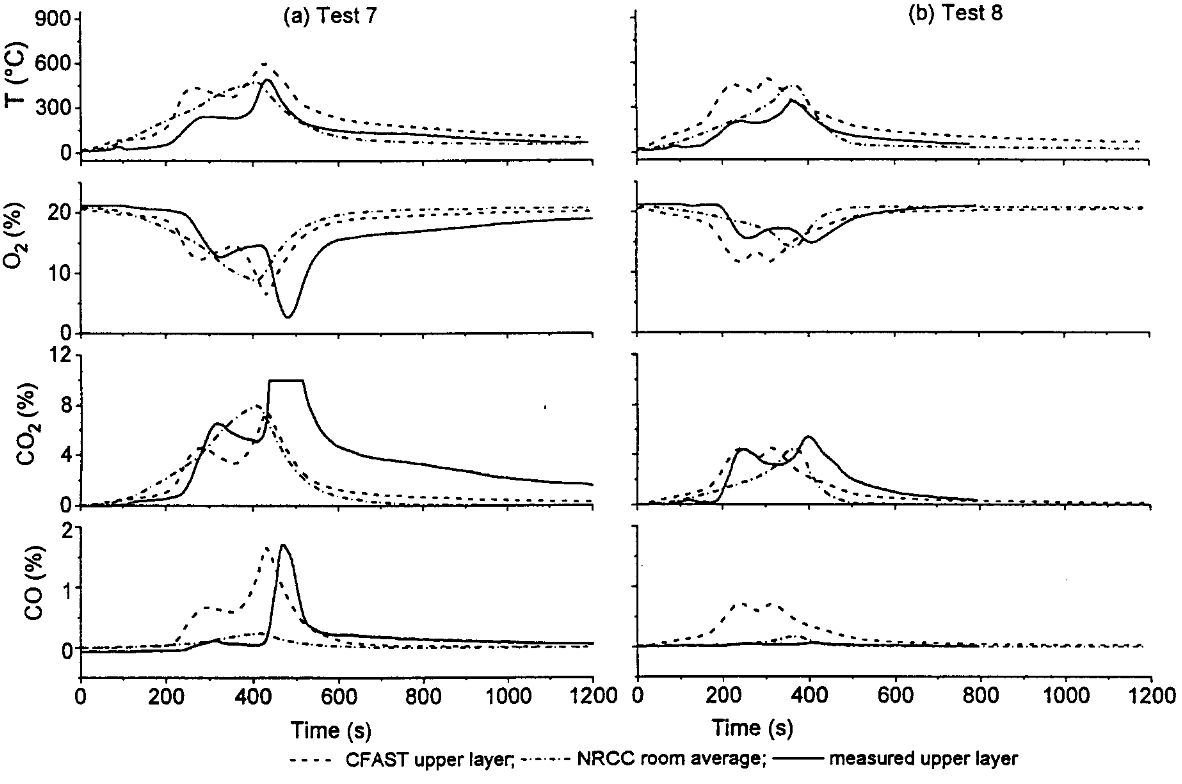

Figure 7. Flaming fire results of upper layer in large burn room from CFAST model and experiments and results from NRCC model; The burn room door (D1) open; (a) Test 7, air-handling system off; (b) Test 8, air-handling system on.

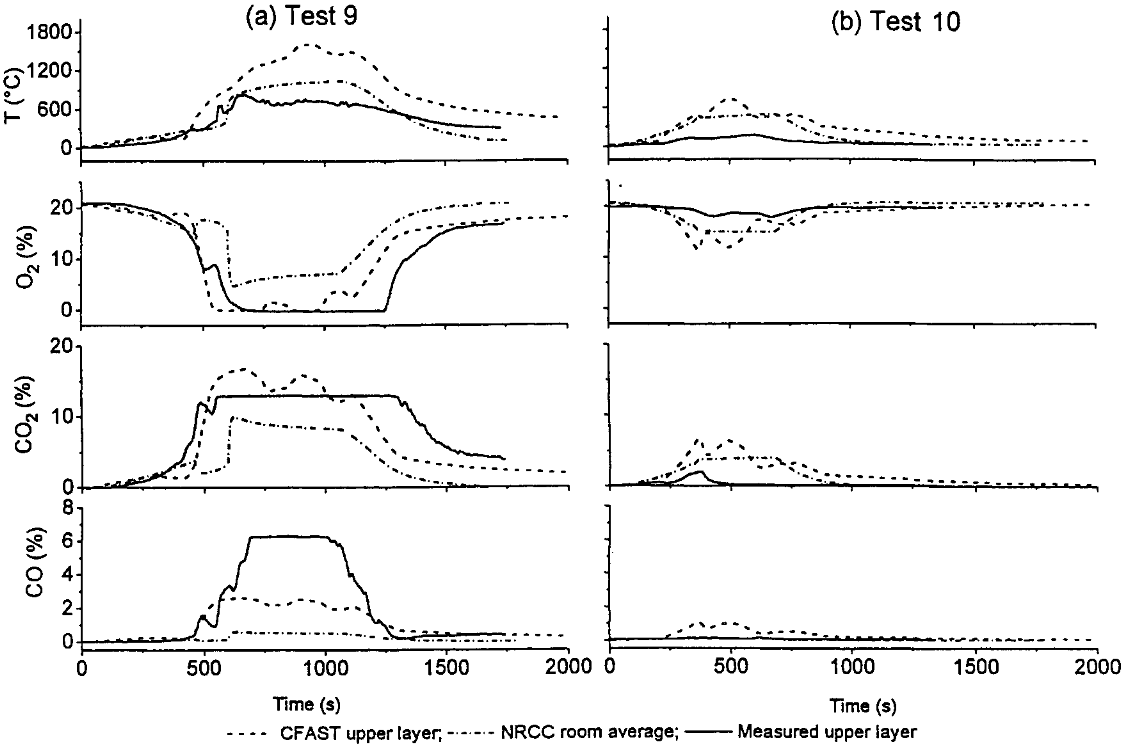

Figure 8. Flashover fire results of upper layer in large burn room from CFAST model and experiments and results from NRCC model; The burn room door (D1) open; (a) Test 9, air-handling system off; (b) Test 10, air-handling system on.

mental results up to the first peak of the mass release rate at about 500 s (Figure 2). The model failed to predict the second peak of the mass release rate. The total mass consumed from the NRCC model prediction was significantly lower than that from the experimental results (Figure 3).

The concentrations of oxygen and carbon dioxide obtained from both the CFAST model and the NRCC model are in a reasonable agreement with the experimental results for all cases but Tests 3 and 4. The NRCC model under-estimated the combustion in the flashover fire case in the large burn room (Test 9), hence gave a higher O_2 and lower CO_2 concentrations than the measured values. Although the NRCC model also under-estimated the combustion in the flaming fire case in the small burn room (Test 3, the burn room door, D1 closed), it predicted lower O_2 and higher CO_2 concentrations than the experimental results. It is plausible that the leakage condition of the closed burn room has not been simulated correctly.

The CFAST results for carbon monoxide are inconsistent with the experimental results. The discrepancies may result from the forced ventilation. When the air-handling system is turned off, the CFAST model tends to under-predict the CO concentration; while if the air-handling system is turned on, the model tends to over-predict the concentration of carbon monoxide. It seems that the NRCC model correctly estimated the CO concentrations when the air-handling system was in operation, but under-estimated the CO concentrations when the air-handling system was turned off except for Tests 3 and 4.

Comparison in Adjacent Enclosures

Two adjacent rooms (Rooms 101 and 103) were involved in Tests 3 and 4 and a corridor was involved in Tests 7-10. The CFAST model is applicable to the adjacent and remote enclosures of fire origin. Figure 10 describes the upper and lower layer temperatures in Rooms 101 and 103 obtained from the CFAST model and the measured results for Tests 3 and 4. Figure 11 depicts the upper and lower layer temperatures in the corridor for Tests 7-10. Both the model results and the experimental results revealed that there existed two distinguishable layers in the adja-

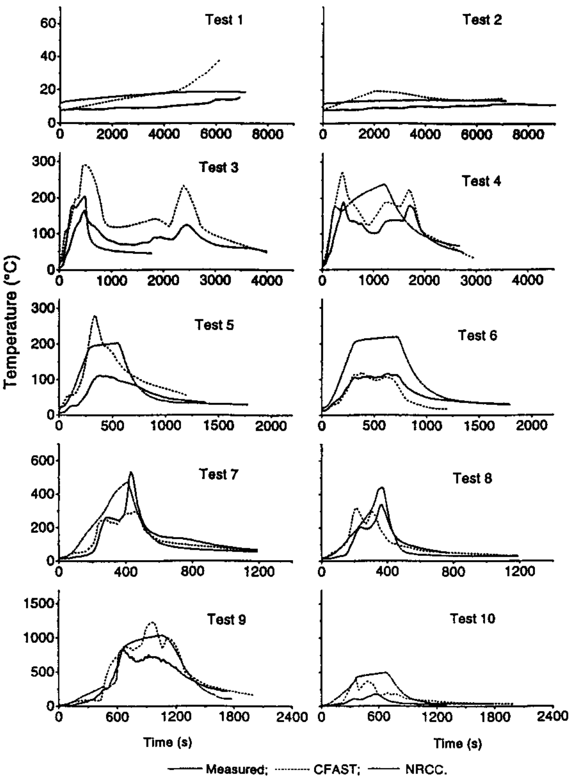

Figure 9. Temperatures from NRCC model and spatial average over the whole burn room for CFAST model and experiments.

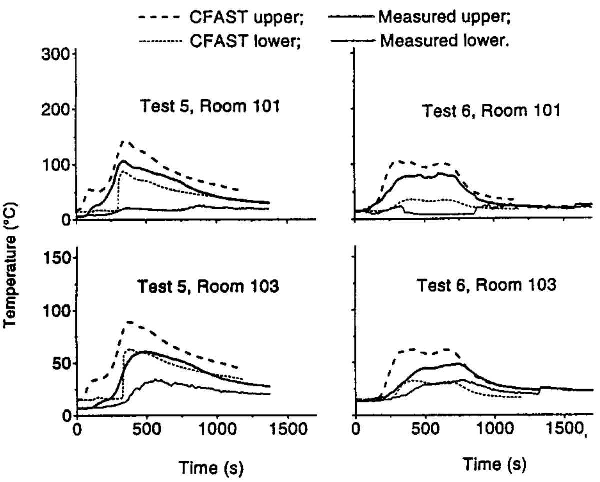

Figure 10. Temperatures in adjacent rooms from CFAST model and experiments (small burn room).

cent enclosures: namely an upper hot layer and a lower cool layer, though the CFAST model over-estimated the upper layer temperatures.

Effects of Air-Handling System

In the flashover (potential) fire tests (Tests 9 and 10), the fuel configuration in the burn room was as depicted in Figure 1(b). The fire was started

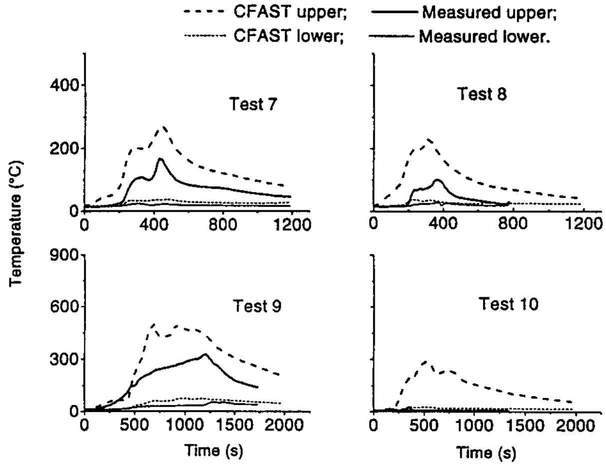

Figure 11. Temperatures in corridor from CFAST model and experiments (large burn room).

at the front of the three-seat couch near Window 2 and then spread to other items. The closest item to the couch was the coffee table which was about 0.5 m away from the couch. In Test 10, the smoke spill fan was in operation during the experiment and the hot air (smoke) was extracted. The maximum temperature in the burn room in the experiment reached only about 300°C. The fire failed to spread to other items in the burn room.

In general, when the air-handling system is in operation, combustion products are exhausted, and more fresh air is entrained into the burn room. Hence, the measured concentration of carbon monoxide in the burn room is significantly lower than that when the air-handling system is turned off. The CFAST model tends to over-estimate the CO concentration when the air-handling system is on. Both the CFAST model and the NRCC model under-estimate the CO concentration when the system is off for most cases.

Simplicity and Efficiency

The NRCC one-zone model is much simpler than the CFAST model, and hence easier to modify for the purpose of the fire system model. A Pentium 90 personal computer was used to simulate the selected fire scenarios. The CPU time of running the CFAST model and the NRCC model for each case is listed in Table 2. The results show that the NRCC model can simulate a case in under 10 s which is 10-20 times faster than the CFAST model. This is very important for the fire safety system model, in which hundreds of thousands of fire scenarios may need to be simulated.

Table 2. CPU time (s) on a Pentium 90 PC

Test	1	2	3	4	5	6	7	8	9	10
NRCC	3	3	3	3	3	3	3	3	7	7
CFAST	14	14	15	17	20	24	27	24	190	29

Conclusions and Recommendations

The CFAST model over-predicted the upper layer temperatures compared with the experimental results in the burn room. However, the spatially averaged temperatures of the upper and lower layers from CFAST were in good agreement with the averaged temperature over the whole room from the experimental results and the NRCC one-zone model results. This indicated that a one-zone assumption represents well the situation in the burn room. The CFAST model tends to over-predict CO concentrations when the air-handling system is turned on; both the NRCC model and the CFAST model tend to under-predict CO when the system is off.

The NRCC model is simple compared with the CFAST model. The NRCC model can simulate a fire scenario in the burn room in under 10 s which is 10-20 times faster than the CFAST model.

It is obvious that two zones exist in the adjacent and remote enclosures. The NRCC model is applicable to the room of fire origin only. The CFAST model has the capability to predict the conditions in the remote areas. For the purpose of the fire safety system model, the major weakness of the CFAST model is the requirement of prescription of the mass or heat release rate, while the system model simulates hundreds or thousands of fire scenarios. Considering the efficiency and simplicity of the fire growth model required for the system model and the accuracy of the prediction, the one-zone NRCC model is recommended for the system model to predict the burn room conditions and a simple two-zone model for the adjacent enclosures.

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