Fire Growth and Smoke Spread Model for Fire Safety System Design : Experimental Verification

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ABSTRACT

A one-zone model (NRCC) and a two-zone model (CFAST) have been tested against experiments and used in the fire research community. However, the selection of either of them as a sub-model for a fire safety system model needs further verification against the experimental results under a variety of fire scenarios. In the present study, the performance of the above two models is evaluated with respect to accuracy, efficiency and simplicity.

This study indicates that significant discrepancies exist between the experimental results and the results from both the CFAST model and the NRCC model. The CFAST model generally over-predicts the upper layer temperatures in the burn room but provides reasonable predictions in the adjacent enclosures. The CFAST model over-predicts CO concentrations when the air-handling system is turned on; the model under-predicts CO when the system is off. The NRCC model correlates the burning characteristics of the fuel with the burn room conditions. The results give a good agreement with the experimental results in the burn room for some fire scenarios but discrepancies exist for others. However, the NRCC fire model is applicable to the burn room only.

It was found that the room-averaged temperatures for the burn room obtained from the CFAST model were in a good agreement with the experimental results and the NRCC model results. 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.

KEYWORDS: Zone model, fire growth and smoke spread, experiment, fire safety system model

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INTRODUCTION

The need to identify cost-effective design solutions to achieve an acceptable fire safety record in buildings has long been recognised [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]. For this purpose, a fire safety system model, called CESARE-Risk[6], is being developed at 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 behaviour, 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 behaviour and building design. Because of the comprehensiveness of the system model, efficiency and simplicity become high priority requirements for the development of the sub-models.

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. However, a selection of either of them as a sub-model for the fire safety system model needs further verification against experiments. So it is valuable to further investigate the performance of these two models under a variety of fire scenarios and to carefully define their limitations.

Design fires have been categorised into three groups in fire research: namely, smouldering fire, flaming fire and flashover fire[10]. A realistic building fire may cover these three design fire scenarios at different stages of fire development. A smouldering fire is equivalent to the early stage of 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 smouldering 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[11] and ceiling vents[12]. 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 focusing on comparison of the predicted results from CFAST (Version 2.01) and NRCC fire models against the results of a series of experiments including smouldering 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 have been conducted at the Centre for Environmental Safety and Risk Engineering (CESARE), VUT.

RE MODEL

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chniques to model the heat and mass transfer processes associated with fires in buildings l broadly into two categories[7]: namely field models and zone models. Field models mputational fluid dynamics or CFD models) divide an enclosure into a large number of ls and solve the basic laws of physics for the fluid flow. Field models require the orporation of sub-models of a wide variety of physical phenomena, including convection, nduction, radiation, and combustion processes and do not make significant mplifications[13,14]. Accordingly, field models need intensive computational power and CPU me. The field models can provide detailed information on the fluid flows. Hence, they are en used in fundamental research to study some specific aspect of building fires but are suitable for a system model.

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

FAST Model

e CFAST model (Consolidated Model of Fire Growth and Smoke Transport)[9] uses a two-ne method to calculate both fire growth and smoke spread in a multi-enclosure and multi-el building. The model divides each enclosure into two zones and solves the conservation uations of mass, energy and momentum at the vent, the plume and the relevant zones for rious physical parameters. The CFAST model has the capability to incorporate the echanical ventilation system during fire. Compared with other zone models, the mputation procedure in CFAST is relatively more rigorous. However, the model requires e measured heat release rate as the input data. Also, the ratios of species concentrations and e time of window breaking have to be prescribed in the input data file. The use of the model often limited to non-flashover fires. The CFAST model is widely used in the fire research mmunity. The model is well documented in the literature and readily available. The CFAST odel version 2.01 was used in the present paper.

RCC Model

he NRCC fire growth model was developed by researchers at the National Research Council Canada (NRCC)[10]. It is a simplified one-zone model for single room fires. It treats the fire om as a well stirred combustion chamber and assumes uniformly distributed quantities side the room. The model predicts the condition of the combustion products, hence the sults 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 correlate the burning rate of the fuel with the burn room conditions[10,15]; this capability is a valuable attribute. The computer program has also been found to be computationally very 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 favourable ventilation conditions. Only the smouldering fire is treated differently.

The NRCC fire growth model has been verified against the identified three types of fire scenarios: namely, smouldering, flaming and flashover under natural ventilation conditions[16]. 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 version[16] has been applied in this study.

FIRE EXPERIMENT

Experimental Set-Up

A series of fire experiments has been conducted at the Centre's full-scale prototype 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 (2.4m×3.6m×2.4m high) and a large burn room (5.4m×3.6m×2.4m high). The layouts of the building configurations are illustrated in Fig. 1. For the small burn room configuration, one mass platform was located on the floor; for the large burn, two mass platforms were situated on the floor of the burn room to record the fuel mass dynamically during fire experiments.

The results presented in this paper are applicable to the cases where smouldering fires are confined to the small burn room and flaming and flashover fires to the large burn room. Six representative experiments were chosen for the purpose of comparison of the results of two zone models. Tests No. 1 and 2 were designated as smouldering fires in the small burn room. Tests 3 and 4 were flaming fires in the large burn room. Tests No. 5 and 6 were carried out in the large burn room as potential flashover fires. However, Test 6 did not reach the flashover stage because of the forced ventilation (extraction of smoke).

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 No. 1, 3 and 5, 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 and 6). Table 1 lists summary information for the six fire experiments.

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 Fig. 1a). The fuel configuration in the burn room illustrated in Fig. 1b 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 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 platform. For the experiments of the flaming fires

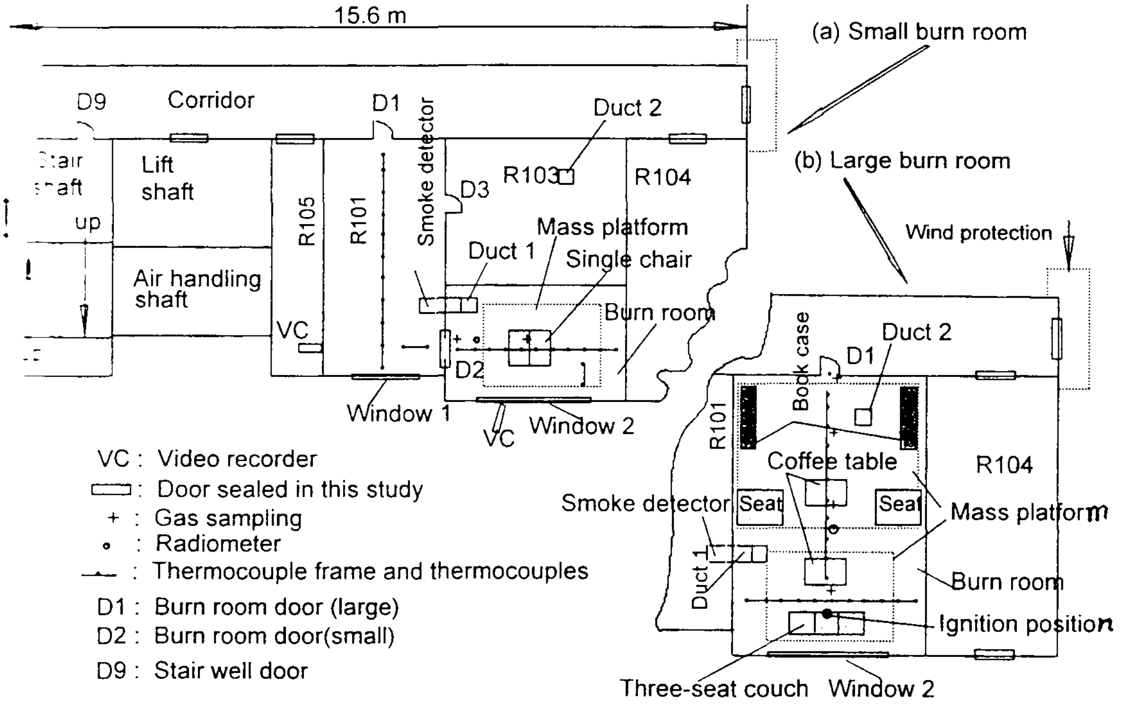


Figure 1 Layout of the first level of the Experimental Building-Fire Facility; (a) Small burn room configuration, the setting-up for smouldering fire tests; (b) Large burn room configuration, the setting-up of fuel configuration for flashover fire tests; for flaming fires, only a three-seat mock-up couch placed on the small platform

In the large burn room, a three-seat mock-up couch was applied; the couch was placed on the small mass platform near Window 2. Window 2 was broken and the window glass was

Table 1 Experimental conditions of fire scenarios

Test No	Layout / air system	Design fire	Door status	Fuel Configuration	Fuel load / consumed (kg)
1	S[†] / off	Smouldering fire	D2 closed	Single mock-up chair, 1.88kg P/U[‡] and 0.88kg cover (cotton 40% linen 60%)	2.76 / 0.87
2	S / on	Smouldering fire	D2 closed	Single mock-up chair, 1.98kg P/U and 0.78kg cover (cotton 40% linen 60%)	2.76 / 0.85
3	L[§] / off	Flaming fire	D1 open, D9 open	Three-seat mock-up couch, 6.84kg P/U and 2.58kg Acrylic	9.42 / 9.30
4	L / on	Flaming fire	D1 open, D9 open	Three-seat mock-up couch, 6.84kg P/U and 2.58kg Acrylic	9.42 / 9.30
5	L / off	Flashover fire	D1 open, D9 open	Furniture: 276.9kg (wood, P/U, cover, carpet); phone book: 265.2kg	542.1 / 273.6
6	L / on	Flashover fire	D1 open, D9 open	Furniture: 274.5 kg (wood, P/U, cover, carpet); phone book: 265.2kg	539.7 / 42.9

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

dislodged during the flashover fire experiments (Tests 5 and 6). The dislodgement was recorded on video. The results were used for the input of the CFAST model. During the smouldering 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 pressurisation. 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 pressurised using separate fans. The design accords with the Australian standard for the design of smoke management systems in multi-storey 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 Fig. 1) at the ceiling level. The air-handling system was operating at the start of the fire experiments. Two air supply ducts (0.4m×0.4m) 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 Fig. 1a). However, for the large burn room, both air-supply ducts were located in the burn room (see Fig. 1b). The air flow rates of these two inlets were 46 and 50 l/s respectively. The system switched to smoke management mode automatically at about 80 seconds 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 data were collected using a PC-based data logger. The details of the experimental set-up have been described elsewhere[17].

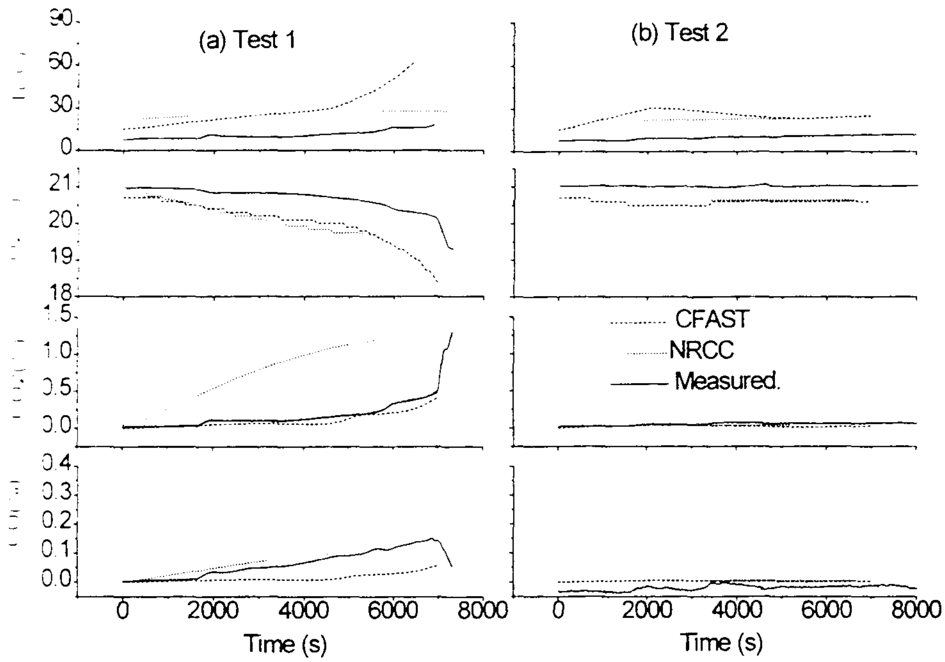
Experimental Data Reduction

In order to compare the measured results with the zone model predictions, spatially distributed values obtained from experiments need to be spatially 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[18] has been modified and used in this study to estimate the interface height of each room from the measured temperatures. The method used for averaging temperatures in a particular volume has been described in the literature[19].

RESULTS AND DISCUSSION

Comparison in Burn Room

To carry out the verification activities, it is necessary to choose the fire growth models between the two-zone CFAST model and the one-zone NRCC model. The latter is applicable to the room of fire origin only. Hence, the comparison of the experimental results with the CFAST results is related to the burn room. The NRCC model results are equivalent to the



gure 2 Smouldering fire results of upper layer in small burn room from CFAST model and experiments and results from NRCC model; (a) Test 1, air-handling system off; (b) Test 2, air-handling system on.

redicted results of the upper layer from the CFAST two zone model. The mass release rate of uel from the experimental results was reported previously[17] and applied to the CFAST mulation. For the NRCC model, the total fuel consumed in each of the experiments was pecified in the input file. All ventilation conditions in the real fire scenarios were carefully mulated in the models. The measured temperatures were spatially averaged with two layers ased on the *N* percent rule[18,20]. The results of the upper layer were then used for omparison with the NRCC predicted results. The measured points of species concentrations n the burn room were limited. It was found that the measured results in the doorway at about 7 m above the floor coincide with the averaged results of the upper zone[17].

The experimental results, the related CFAST model results and NRCC model results for the elected six cases are plotted in Figs 2, 3 and 4. Column (b) of each figure is associated with he operation of the air-handling system and (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 most of the six fire experiments. The temperatures obtained from the NRCC model were closer to the measured temperatures than those from the CFAST model.

It was found that the two-zone concept is likely to break down in the room of fire origin[17]. 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 Fig. 5. The NRCC model results were also re-plotted. The room averaged temperatures from the CFAST model results

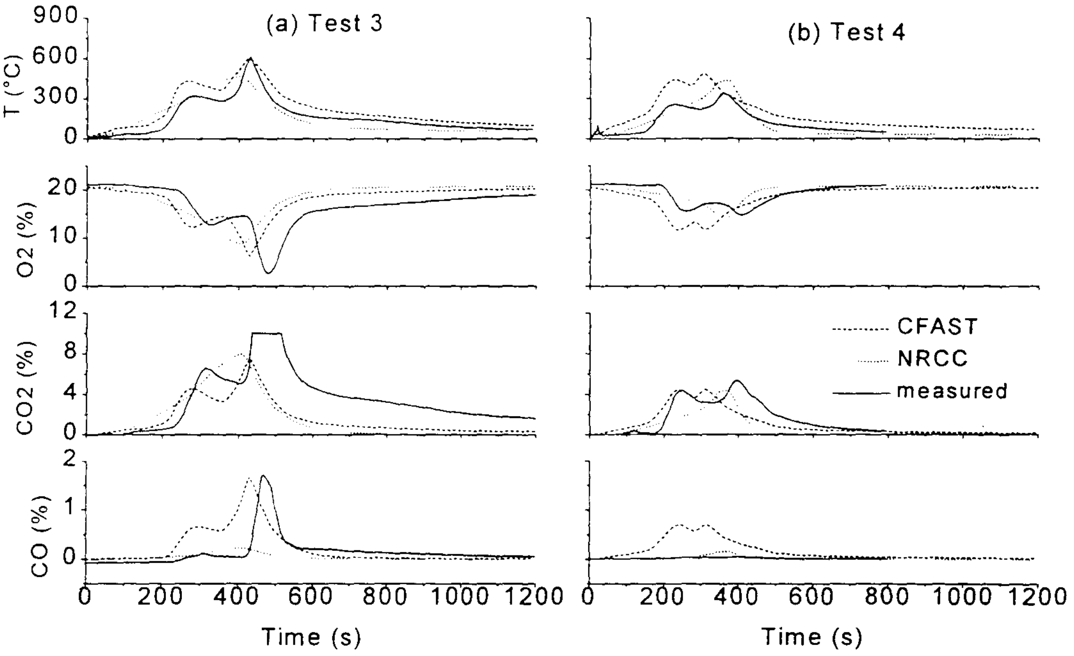


Figure 3 Flaming fire results of upper layer in large burn room from CFAST model and experiments and results from NRCC model; (a) Test 3, air-handling system off; (b) Test 4, air-handling system on.

closely agreed with the room averaged temperatures from the experimental results for Test 3, 4 and 5, and significantly improved for the other 3 tests. The results from the NRCC model agreed well with the room averaged CFAST model results and with the experimental results.

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. The NRCC model under-estimated the combustion in the flashover fire case (Test 5), hence gave a higher O_2 and lower CO_2 concentrations than the measured values. 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 under-predicts the CO concentration; while if the air-handling system is turned on, the model over-predicts the concentration of carbon monoxide (Test 3 is an exception). It seems that the NRCC model correctly estimated the CO concentrations when the air-handling system was in operation, but significantly under-estimated the CO concentrations in the cases of flaming and flashover fires when the air-handling system was turned off.

Comparison in Corridor

A corridor was involved in Test 3, 4, 5 and 6. The CFAST model is applicable to the adjacent and remote enclosures of fire origin. Figure 6 describes the upper and lower layer temperatures in the corridor obtained from the CFAST model and the measured results for Tests 3-6. Both the model results and the experimental results identified that there existed two distinguishable layers in the corridor: namely an upper hot layer and a lower cool layer, even though the CFAST model over-estimated the upper layer temperatures.

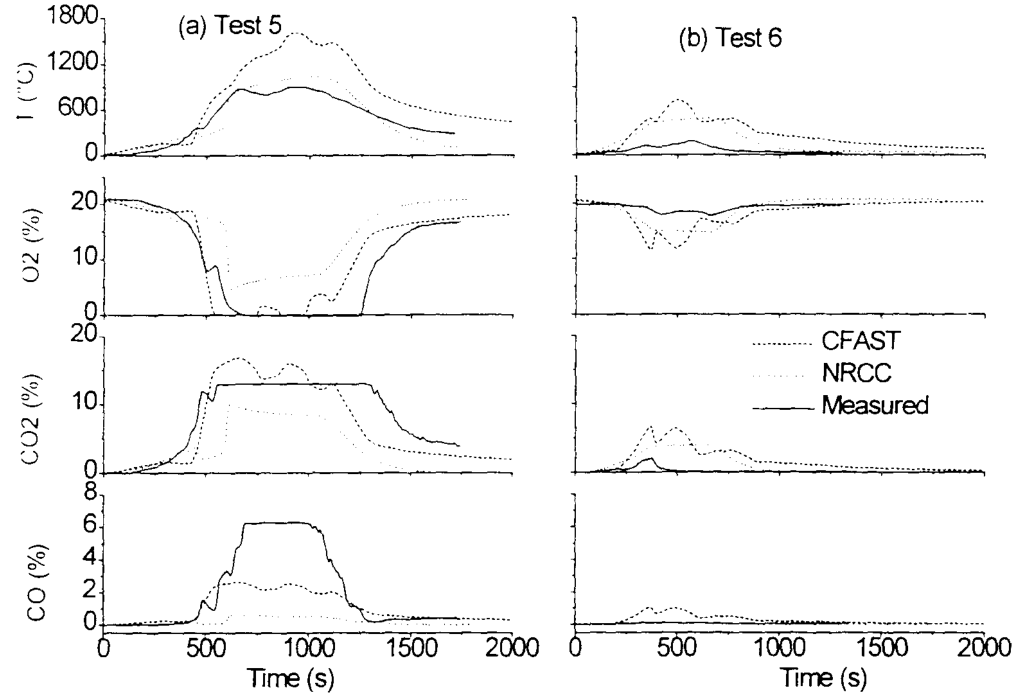


Figure 4 Flashover fire results of upper layer in large burn room from CFAST model and experiments and results from NRCC model; (a) Test 5, air-handling system off; (b) Test 6, air-handling system on.

Effects of Air-Handling System

For the cases (Tests 5 and 6), the operation of the air-handling system caused the fire test to fail to reach flashover (Test 6). In the flashover fire tests, the fuel configuration in the burn room was as depicted in Fig. 1b. The fire was started 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 6, 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.

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

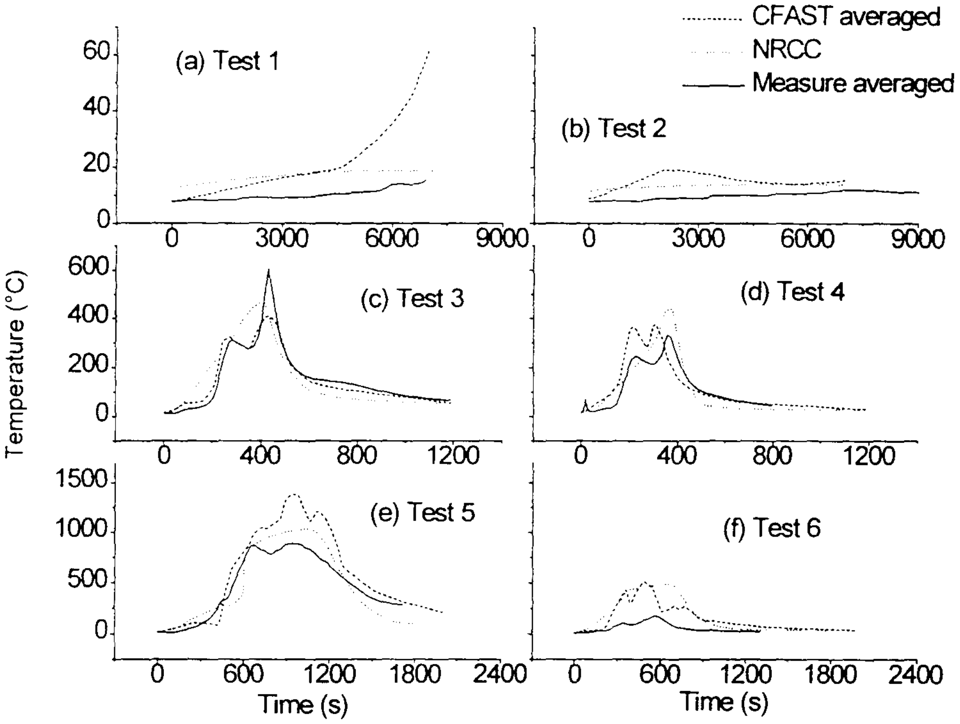


Figure 5 Temperatures from NRCC model and spatial average over the whole burn room for CFAST model and experiments.

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 hundred of thousands of fire scenarios may need to be simulated.

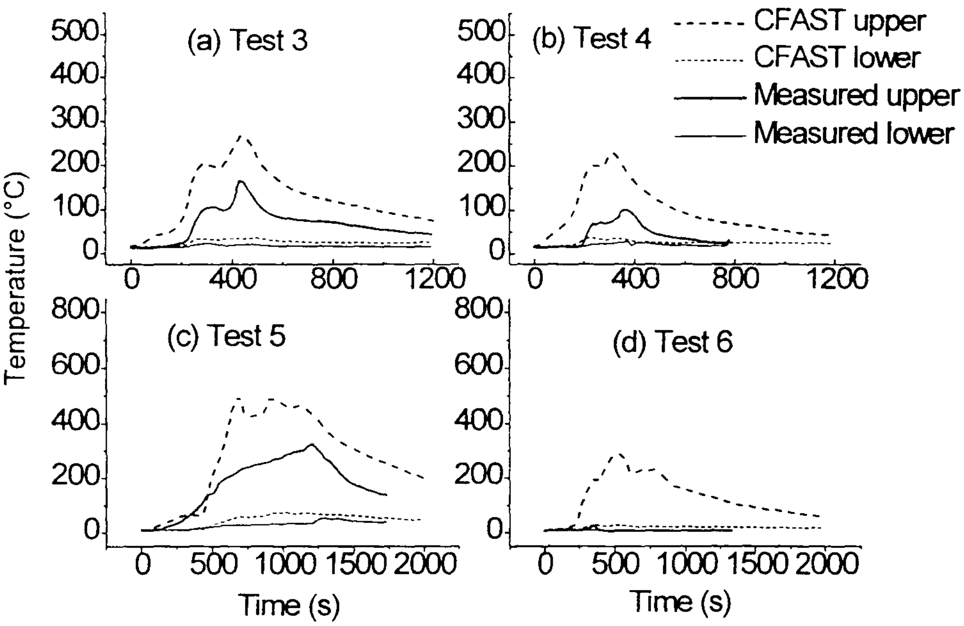


Figure 6 Temperatures in corridor from CFAST model experiments

e 2 CPU time (s) on a Pentium 90 PC

	1	2	3	4	5	6
C	3	3	3	3	7	7
ST	14	14	27	24	190	29

NCLUSIONS AND RECOMMENDATIONS

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

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

obvious that two zones exist in the adjacent and remote enclosures. The NRCC model is licable to the room of fire origin only. The CFAST model has the capability to predict the ditions in the remote areas. For the purpose of the fire safety system model, CESARE-k model, the NRCC model was recommended for the prediction of fire development in the m of fire origin. For sake of the simplicity and efficiency, a simple two-zone model, SARE-Smoke is being developed and will be incorporated into the CESARE-Risk model.

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