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Uncertainty in smoke transport models

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Abstract: Data from full scale experiments are collected and organized in a database. A statistical method is developed to evaluate the uncertainty in predictions of smoke transport models. The method is based on a regression analysis of measured and predicted data. The computer program CFAST is evaluated to exemplify the statistical method. The uncertainty is quantified with a regression coefficient and the residual variance When the model uncertainty is quantified it is possible to adjust the model predictions for the model error. The uncertainty in CFAST's predictions of smoke gas temperature and position of the interface is investigated for a number of different scenarios

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Summary

Today an engineering approach to achieve fire safety often involves the use of calculation models, to predict the course of events when a fire starts in a building. It is important to be able to state with confidence how close the model predictions are to the actual conditions.

The project 'uncertainty in smoke transport models' is a part of the Brandforsk project S.65: "Performance based fire safety design". The work has been carried out at the Department of Fire Safety Engineering at Lund University. The objectives with this project has been to evaluate the uncertainty in model predictions and find a way to adjust the predictions for the model error. The work has been devided into two parts. In the first part data from nineteen full-scale experiments were collected and organized in a database. The database includes measurements of smoke gas temperature and the interface position, i.e. the smoke layer height. Model simulations of the experiments has been carried out with the smoke transport model CFAST. In the second part a statistical method was developed to analyze the differences between the experimental and simulated data.

An analysis of the experiments and simulations showed that the relationship between the two was fairly linear. There can be two different kinds of model error identified. The first one is a bias, i.e. and over- or underprediction of the actual conditions, and the other one is a random error, i.e. a statistical error. The statistical method, used to evaluate the uncertainty, is based on a linear regression. The relationship between measured and predicted data was determined in every scenario tabulated in the database. A scenario is a combination of tests where the geometry and flow pattern is similar.

The results of the uncertainty analysis shows that the magnitude of the uncertainty is varying, depending on the variable evaluated. The mean biases indicates that CFAST is overpredicting the smoke temperature and underpredicting the position of the interface. The mean bias is varying between 0.7-0.8 for the temperature predictions, depending on the scenario. This corresponds to an overprediction by between 25-40 %. The mean bias is varying between 1.1-1.7 in the interface predictions, which corresponds to an underprediction of the measured interface by 10-40%. It is not appropriate to adjust the predictions just by looking on the mean bias. The bias indicates the average over- or underprediction in a scenario. Due to the size of the random error a general conclusion can not be drawn, by just looking at the mean bias. The variance of the bias, i.e. the random error, has to be taken into account.

With knowledge about the uncertainty it is possible to adjust the model predictions for the model error. In risk analysis based on probabilistic calculations, it is possible to include the information about the uncertainties. The uncertainty will be taken into account, by expressing the variable of interest as a stochastic variable, according to the regression analysis. If a prediction is going to be used in a deterministic design equation, adjustment has to be made with a prediction interval, to be sure to end up with a conservative design value.

It must be of interest for all engineers to be aware of the uncertainty in the tools they are using. If a models is overpredicting the hazardous conditions, to conservative values can be the result and the design will be unnecessary expensive. If the model is underpredicting the hazardous conditions, unsafe buildings will be the result.

Sammanfattning (Summary in Swedish)

Vid brandteknisk dimensionering har användningen av datormodeller ökat kraftigt. Med hjälp av dessa kan brandförlopp i olika typer av byggnader simuleras och effekterna av olika dimensionerings alternativ utvärderas. För att beräkningar med datormodeller skall bli trovärdiga krävs att man kan bestämma hur väl simuleringarna stämmer överens med motsvarande verkliga förhållanden.

Det måste ligga i alla ingenjörers intresse att vara medveten om osäkerheterna i de verktyg som används. Om en modell överskattar farliga förhållanden, kommer resultatet av dimensioneringen att bli onödigt dyr. Om modellen underskattar de kritiska förhållandena kommer inte dimensioneringen att vara tillräckligt säker. Har man inte studerat osäkerheten i de verktyg man använder vet man inte vilken sida man befinner sig på. Med kunskap om modellosäkerhet kan korrigering av modellfel göras, så att konservativa dimensionerings-värden erhålls.

Osäkerheten i en modell som beräknar spridning av brandgaser varierar beroende på den geometriska planlösningen och på flödesförhållandena. Det är orealistiskt att försöka bestämma en generell modellosäkerhet för en hel modell, gällande för alla tänkbara scenarier. Osäkerheten i modellfelet skulle bli orimligt stor och ingen praktisk användbar korrektion av simuleringsresultaten skulle vara möjlig. Genom att definiera och beräkna modellosäkerheten för ett begränsat antal vanligt förekommande scenarier, ges möjlighet att korrigera för modellfelen i dessa scenarier.

En analys av experimentellt uppmätta och beräknade data med hjälp av datorprogrammet CFAST visar att förhållandet mellan dessa är relativt linjärt. Två olika typer av modellfel kan identifieras. Den ena är ett sk systematiskt fel som i medeltal beskriver modellens över- eller underskattning av experimentella data. Över- eller underskattningen är inte konstant i ett scenario, dvs det förekommer en viss variation. Denna variation beskrivs med ett sk slumpfel.

Resultatet från den statistiska analysen visar att osäkerheten varierar, dels beroende på vilket scenario som utvärderas och dels beroende på vilken variabel som undersöks. Analysen visar att CFAST i genomsnitt överskattar temperaturen och underskattar höjden från golvet till brandgaslagret. Det är inte tillräckligt att enbart justera modellfelet med avseende på det systematiska felet. Rapporten presenterar metoder för att justera beräkningar så att både det systematiska felet och slumpfelet inkluderas.

Projektet 'Osäkerheter i beräkningsmodeller för spridning av brandgas' är ett delprojekt i Brandforskprojektet S.65 'Funktionsbaserad brandteknisk dimensionering'. I detta delprojekt utarbetas en metodik för att analysera osäkerheterna i resultat från simuleringsmodeller som beräknar spridning av brandgas. Projektet består av två olika huvuddelar. I den första delen organiseras en databas med experimentella mätdata från fullskaleförsök. I den andra delen skapas den statistiska modellen för att bestämma osäkerheten i modeller som simulerar spridning av brandgaser.

Acknowledgments

1   Introduction

Over the last two decades, the development within modern building technology has resulted in an overall increase of fire hazard. The buildings tend to be built towards unconventional sizes and shapes, while material contents and fittings exhibit more hazardous flammability characteristics. At the same time real advances have been made in the understanding of fire phenomena and the interaction of fires with buildings. Advancement has been particularly rapid where analytical fire modeling is concerned.

During the last decades fire protection engineering has developed and is starting to become its own engineering branch. The increasing level of knowledge among fire protection engineers has made it possible to develop performance based building codes. According to performance based codes, the engineer can use alternative solutions instead of the traditional prescriptive ones, as long as the design meets up to the objectives in the code. The designer must use reliable calculations and take uncertainty into account, to verify the alternative solution. Similar analysis is expected when fire risk analysis are carried out. Dealing with uncertainties is an important and extensive part, both in verifying design solutions and in performing fire risk analysis.

According to Magnusson, Frantzich and Harada (1995) uncertainty in engineering calculations can be divided into to two different types: knowledge uncertainty (epistemic), due to lack of fundamental knowledge and variability (randomness) in a population. The knowledge uncertainty represents random error, systematic error, irreducible error, or lack of an empirical basis for making an estimate. Variability represents natural randomness in a variable, for example wind velocity or fire load in a certain building type.

The overall uncertainty in the design process is a combination of uncertainty from a number of different sources. To be able to analyze the total uncertainty involved, the different parts has to be studied separately. This project deals with uncertainty in simulation models, which is a knowledge uncertainty.

Simulation models are used to predict 'real conditions' as accurate as possible. The models are based on the laws of physics and empirical expressions, derived from small and full scale experiments. The real conditions are defined as the measured conditions in a full scale test. By defining experimental measurements as real conditions, measuring errors are ignored. The approximation is acceptable, since measuring errors in most cases are very small compared to the model errors investigated. When a model is constructed it is necessary to make assumptions and approximations to be able to perform the calculations. This results in error in the calculations. If it is possible to adjust the simulation results for the model error, the simulation tools will be more useful in practical design and deliver results that will agree with reality. In engineering calculations the following questions are of interest:

How much does the simulated results differ from the real ones? Which model gives the most accurate results? How can the model errors be taken into account?

To be able to answer the questions, knowledge about the uncertainties in the models is necessary. In the project 'uncertainty in smoke transport models' a methodology to analyze the uncertainty in smoke transport models is presented. In this report CFAST is studied as an

example The project consists of two parts. In the first part, data from nineteen full-scale experiments are collected and organized in a database. Simulations of the experiments with the smoke transport model CFAST are carried out. In the second part, a statistical method is developed to analyze the differences between experimental data and simulations.

The objective with the project is to develop a statistical method that can quantify the uncertainties in smoke transport models. With knowledge about the model uncertainty it is possible to adjust for the model error in simulation results. The results will then be more accurate and closer to actual conditions in case of fire.

The smoke transport models generates a lot of useful information. For example the smoke temperature is often of interest in design situations. High temperature can create untenable conditions for humans and affect load bearing structures so that the strength is reduced. Other variables that can describe hazardous conditions are toxic concentration of species, low visibility, descending smoke layer height (interface), high level of radiation etc. Smoke transport models are used to investigate the conditions in case of a fire. Since the models includes model errors, the calculated conditions will not be the same as when a real fire occurs. If the building is designed according to the simulation results, the design will include an unknown design error.

In this report the uncertainty in predictions by smoke movement models are investigated and quantified by a statistical method. The method compares measured and predicted data to evaluate the uncertainty in the predictions. In the master thesis of Bragason (1994) experimental results are collected, re-evaluated and organized in a database, to allow comparison. In section 2 the different experimental scenarios in the database are described. The re-valuation methods are described in section 3. The statistical method is applied to the well known smoke transport model CFAST, that is described in section 4. The statistical method is described in section 5. Section 6 presents the results and section 7 contains discussion and conclusions.

2 Description of experiments

2.1 Introduction

Five different real-scale fire test series were selected for the current comparisons with CFAST. The test series are all available from published articles. The test were carried out in 1, 2 and 3 room configurations, the rooms were of various shapes and sizes. Different types of fuels were used as a fire source with varied intensity of the fire. The main measurements were of gas temperatures and smoke layer heights.

Here follows description of each scenario from the database, which are named; V1, V2, V3, V4 and V8.

With each description follows a database, given in the Appendix A, containing information about interface, upper layer temperature and rate of heat release.

2.2 Fire tests in a single enclosure [V1]

2.2.1 Introduction

Hägglund, Jansson and Nireus presented in 1985 experimental study of the smoke filling process by a fire in a single enclosure. Fifteen experiments were performed with the fuel size and fuel position varied. Five out of fifteen experimental tests were chosen for the study presented here. The main purpose of the experimental work was to measure the smoke filling times and temperatures of the descending smoke layer. Therefore the tests were stopped shortly after the smoke layer had reached the floor level.
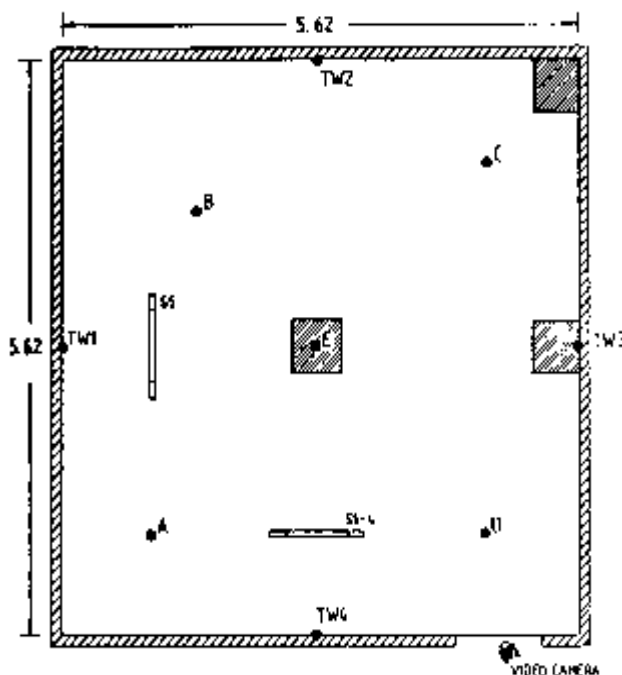
Figure 2.1 Plan view of test room V1 (Hägglund et al. 1985).

2.2.2 Description of experiment

The fires were conducted in a room of floor area 5.62 ∗ 5.62 meter and of height 6.15 meter. The material of floor, ceiling and surrounding walls was concrete. The room was closed except for a 0.25 meter high by 0.35 meter wide opening at the bottom of the room, near the center of one wall. A plan and side view of the room are given in figure 2.1 and 2.2.

The fuel used in all tests was kerosene having a density of 780 kg/m^3 and lower heat of combustion of 43 MJ/kg. The fuel was burnt in open square steel pans with sizes of 0.25 ∗ 0.25, 0.50 ∗ 0.50 and 0.75 ∗ 0.75 meters. The experimental condition for the various tests are displayed in Table 2.1. In all five tests the fire was placed centrally in the room and 20 cm above the floor.

A video camera recorded the smoke layer forming process. Squares of 1 meter were painted in black and white on two walls to make it easier to determine the smoke layer height by visual observations.

Temperature was measured by thermocouples distributed over vertical lines on a 50 cm spacing. Four lines; A, B C and D were placed near each corner of the room.
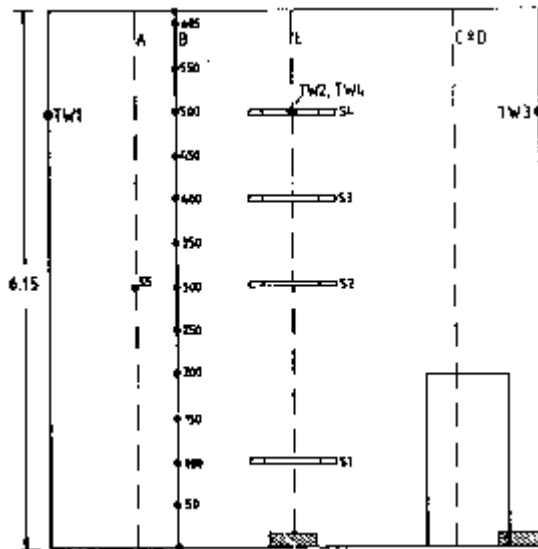
Figure 2.2 Side view of test room V1 (Hägglund et al. 1985).

Mass loss rate was measured during the burning and the fires showed a typical pool fire burning with a build up period of the mass burning rate which lasted for 30 - 60 seconds and a steady state period during which the burning rate maintained at a constant, maximum value.

An effective value of 30 MJ/kg for the heat of combustion of kerosene was used in the calculations. This was determined by oxygen consumption technique. When using this technique the fuel is placed under an open hood. The combustion gases and a certain amount of air are collected in the exhaust duct and by measuring the decrease in oxygen concentration and mass flow of the gases the rate of heat release is calculated. By measuring the weight loss

rate at the same time the effective heat value of the burning material is obtained. The rate of heat release is then found by multiplying mass loss and effective heat value.

Test	Outdoor temp. (°C)	Indoor temp. at start (°C)	Fuel size (m)	Time to steady state (sec)	Mass loss (g)
V1T2	12	15	0.50 ∗ 0.50	60	6.2
V1T3	14	17	0.50 ∗ 0.50	60	6.4
V1T5	17	17	0.25 ∗ 0.25	45	0.95
V1T6	22	18	0.25 ∗ 0.25	30	1.0
V1T7	22	19	0.75 ∗ 0.75	40	13.0

Table 2.1 Experimental condition for test V1.

2.3 Smoke spread from a small to a large room [V2]

2.3.1 Introduction

The spread of fire smoke from a small fire room to an adjacent large room and smoke filling of the latter has been studied by experiments (Hägglund, 1992; Onnermark, Jansson, Hansson, 1992). The test program consisted of a series of separate tests involving varying compartment and ventilation configuration. 20 experiments were carried out in three series. Two tests from series 1 are utilized here.

2.3.2 Description of experiment

The test configuration involved two rooms connected by an open doorway. The fires were conducted in the room of floor area 3 ∗ 4 meters and of height 2.6 meters. The floor area of the adjacent space was 5.6 ∗ 5.6 meters and the ceiling height 6.1 meters. The doorway between the burn room and the adjacent space was 2 meters high and 1 meter wide.

Series 1 involves that the secondary room is closed except for a 0.25 meter high by 0.80 meter wide opening to the outside at the bottom of the room. Table 2.2 displays experimental conditions for the tests. In figure 2.3 a view of the rooms is given. The floor, ceiling and surrounding walls of both rooms, were made out of concrete.
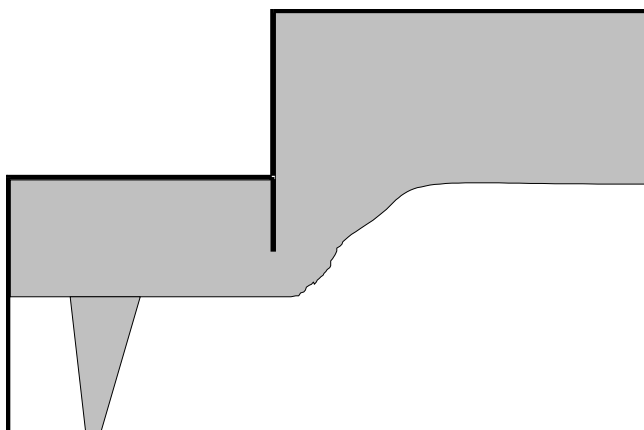
Figure 2.3 Side view of test rooms (Hägglund, 1992).

Test (Series 1)	Outdoor temp. (°C)	Indoor temp. at start (°C)	Fuel size (m)	Time to steady state (sec)	Maximal effect (kW)
V2T1	15	15	0.25 * 0.25	90	330
V2T5	16	16	0.50 * 0.50	90	670

Table 2.2 Test configurations.

The fuel used was kerosene of the density 780 kg/m^3. The fuel was burnt in square steel pans. The size of the pan was 0.25 * 0.25 meters in test 1 and 0.50 * 0.50 in test 5. Mass loss rate was measured during the burning and is used to calculate the combustion. An effective value of 30 MJ/kg was used in calculations which is a value taken from V1, determined by oxygen consumption technique.

Temperature was measured by thermocouples distributed over vertical lines on a 50 cm spacing. Three lines were used to measure the temperature of the burn room and four lines, placed near each corner of the room, were used to measure the temperature of the burn room.

The smoke layer height was not measured in the small burning room. In the secondary room, layer height was derived from video records.

2.4 Three room test including corridor [V3]

2.4.1 Introduction

Peacock, Davis and Lee published in 1988 a report describing a series of tests in a three room configuration with a simple steady-state gas burner (Peacock, Davis, Lee, 1988). The study was conducted as a part of a program to develop a generic methodology for the evaluation and accuracy assessment of fire models. A carefully constructed and well-instrumented large scale fire test facility was developed to provide experimental data for evaluation of fire models (Peacock, Davis, Babrauskas, 1991). Bukowski, Jones and Peacock (1993) used data from these real scale laboratory experiments for comparison with the CFAST model (Jones, Forney, 1992).

2.4.2 Description of experiments

The experimental arrangement is shown in figure 2.4. The compartment included two small rooms and a corridor. The fire was placed in one of the smaller rooms. Table 2.3 summarizes the dimensions of the three rooms and the connecting vents. Table 2.4 shows the construction materials used in this test.
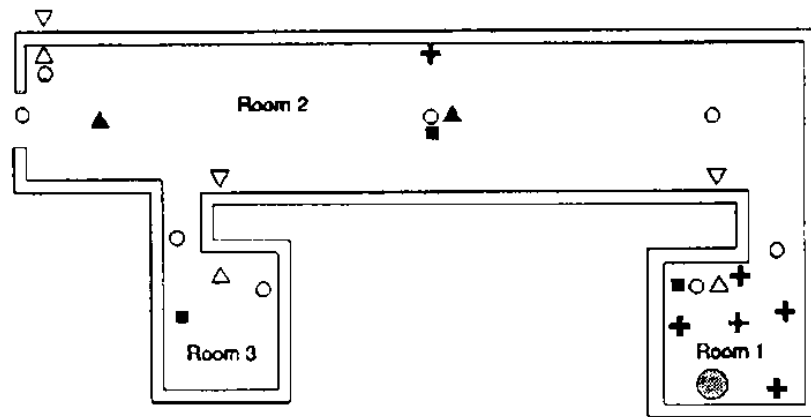
Figure 2.4 Experimental layout for three room test with a corridor (Peacock et al. 1993).

Location	Room	Vent	Width	Length	Height	Sill
Room 1 (burn room)	x		2.34	2.34	2.16	
Room 2 (corridor)	x		2.44	12.19	2.44	
Room 3	x		2.24	0.94	2.43	
Doorway 1; room 1 to room 2		x	0.81		1.6	0
Doorway 3; room 3 to room 2		x	0.79		2.04	0
Doorway 2; room 2 to ambient		x	0.76		2.03	0

Table 2.3 Room and vent sizes for three room test. All values in meters.

Location	Wall	Ceiling	Floor
Room 1	Ceramic fiber	Ceramic fiber	Fire brick
Room 2	Calcium silicate	Calcium silicate	Gypsum board
Room 3	Gypsum board	Gypsum board	Concrete

Table 2.4 Construction materials (Peacock et al. 1991).

The fire source was a diffusion flame burner using natural gas, placed against the middle of the back wall of the burn room. The top of the burner was placed 0.5 m above the floor. The fires with nominal heat release rates of 100, 300 and 500 kW were conducted under the following configurations:

1. Open doorway 2 and closed doorway 3.

2. Closed doorway 2 and closed doorway 3.

3. Open doorway 2 and open doorway 3.

4. Closes doorway 2 and open doorway 3.

A hood was located over doorway 2, collecting the exhaust from the fire tests. Temperatures, velocities and oxygen and carbon dioxide concentrations in the exhaust collection hood were monitored. With these measurements the rate of heat release of each fire was determined. In case 2 and 3 the doorway 2 was closed, hindering the measurement in the collection hood and determination of the heat release. Cases 1 and 3 with doorway 2 open are treated here and were broken down to different categories as follows in Table 2.5. Because of closed doorway 2, sets 2,3 and 6 are not used here.

Set	Nominal fire size	Doorway 2	Doorway 3	Number of tests
1	100 kW	open	closed	11
4	100 kW	open	open	8
5	300 kW	open	closed	2
7	300 kW	open	open	3
8	500 kW	open	closed	6
9	500 kW	open	open	3

Table 2.5 Test categories for three room test.

Temperature was measured by thermocouples distributed over vertical lines on a 15 cm spacing. For the first and third rooms a single tree in each room was used. For the corridor three trees were placed along the length of the room.

Coopers method (Peacock, Babrauskas, 1991) was used for defining the height of the interface. Since the calculation depends upon a continuous temperature profile the 15 cm spacing between measured points should give good resolution. Once the interface position has been determined the upper layer temperature is calculated as an average of the temperature profile in the layer.

2.5 Smoke control experiments in large scale spaces [V4]

2.5.1 Introduction

Toshio Yamana and Takeyoshi Tanaka presented a series of full scale experiments in 1985. They investigated the smoke filling behavior in large scale spaces under various smoke control conditions. These experiments served as the validation study of simple analytical theories presented in the same reference.

2.5.2 Description of experiment

The test configuration involved a large scale space with floor area of 720 m^2 and ceiling height of 26.3 meters. It is not clear which material of floor, ceiling and surrounding walls was used, but is assumed concrete. The plan and the section of the laboratory are shown in figure 2.5.
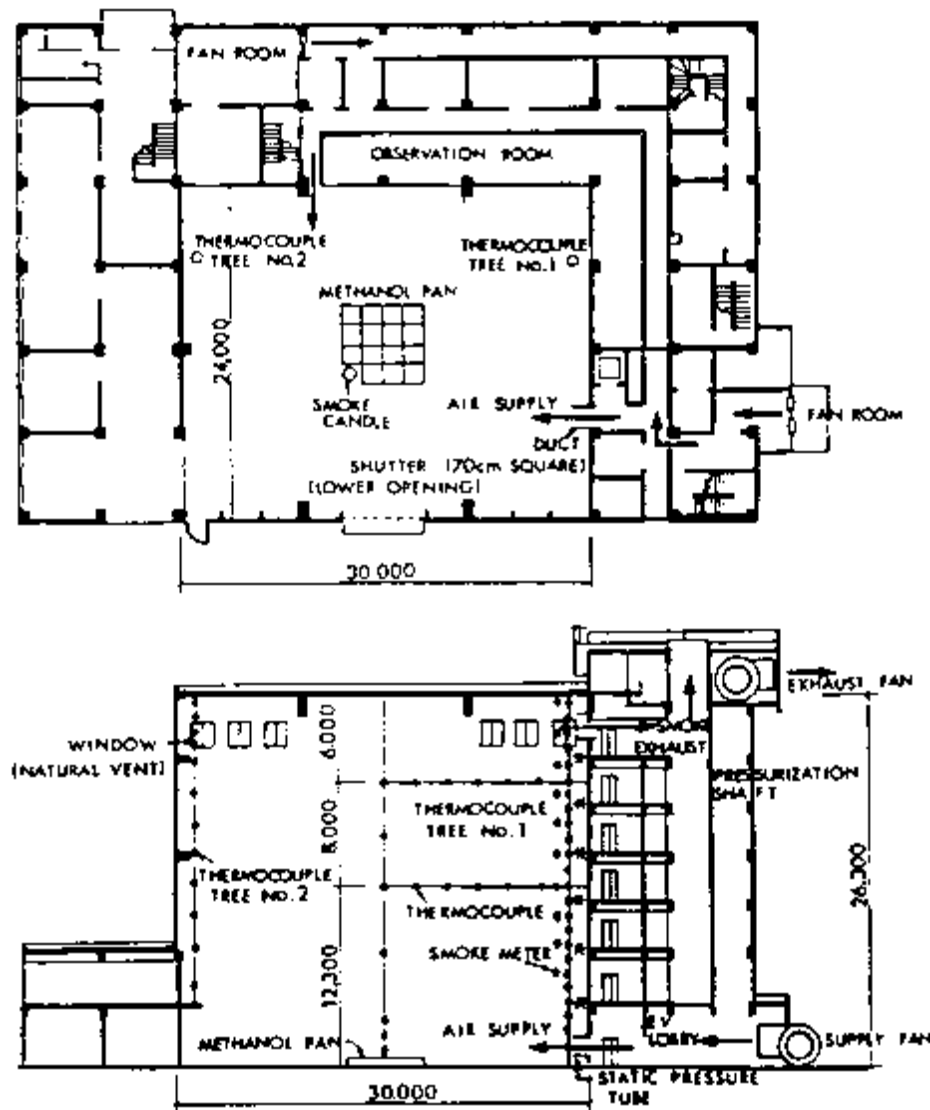
Figure 2.5 Plan and section of the laboratory (Yamana & Tanaka, 1985).

The series of experiments were classified into the following 4 types:

(A) Natural filling: In this system, the smoke layer is just allowed to descent without any smoke venting measurements.

(B) Natural venting: In these experiments four windows, 6.46 m^2, on the upper part of the wall and 3.23 m^2 hole at the bottom of the space were opened. This was to investigate the effectiveness of natural smoke vents.

(C) Mechanical venting: Here the smoke was mechanically exhausted through a duct installed at the height of 7th floor.

(D) Lower part pressurization with vent: In this series, the air was supplied to the lower part of the space to build up internal pressure and at the same time the windows on the upper part of the space were opened.

Test	Initial temp. (°C)	Lower opening (m²)	Upper opening (m²)	Mechanical venting (m³/s)
V4A1	14	0	0	0
V4B1	18	3.23	6.46	0
V4C1	13	3.23	0	6.0
V4C2	12	0	0	4.5

Table 2.6 Test conditions for the four tests chosen for comparison.

The fire source for all the experiments was methanol in 15 square pans of 45 cm side length. The pans formed almost an 180 cm square fire when they were put together on the floor of the space. A smoke candle was placed at a corner of the fire source and the smoke generated was driven by the fire plume.

The burning behavior of the fire source was considered to be essentially the same for all the tests. The burning rate was measured only once where the source demonstrated an almost constant rate. The average mass burning rate was measured 0.0667 kg/s which gives a 1300 kW effect.

For measuring the vertical profile of the smoke layer temperatures two trees of thermocouples were equipped. Tree no 1 was mounted with 1 m spacing from the ceiling and tree no 2 with 2 m spacing except the proximity of the ceiling, where spacing was 1 m.

The smoke layer height was reduced from three sources; temperature profile, the optical smoke density profile and the observation by eye. The former two methods were based on the reading of the time that each sensor started to respond. For the observation method a scale was put on one of the walls from the ceiling to locate the layer boundary.

2.6 An study of upper hot layer stratification [V8]

2.6.1 Introduction

In 1982 Cooper, Harkleroad, Quintiere and Rinkinen (1982) published a paper which describes an experimental study of the dynamics of smoke filling in realistic fire scenarios. The purpose of the study was to create an experimental database for use in the verification of mathematical fire simulation models. In the same paper a method is presented for defining the height of interface between upper hot layer and cooler lower layer depending on a continuous temperature profile. This is described in Section 3.3. The data from the experiment was later used by Rockett, Morita and Cooper (1989) for comparison with NBS/Harvard VI (Gahm, 1988) simulations.

2.6.2 Description of experiment

The test program consisted of a series of separate tests involving a variety of space configuration and fire energy release rates. "Full corridor" is one of four test configurations and was selected for comparison in this report. Plan view of the test is shown in figure 2.6.
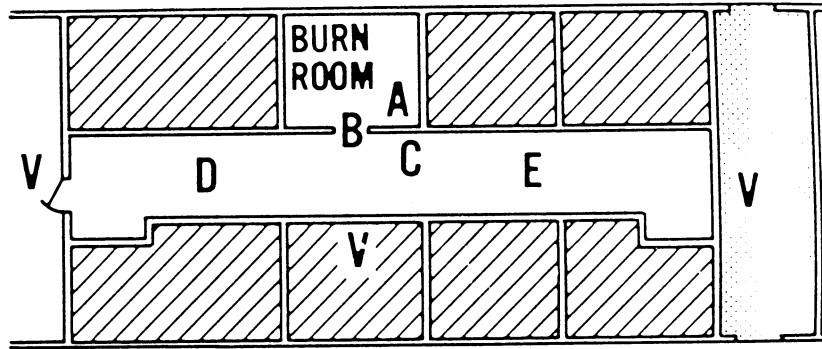
Figure 2.6 Sketch of the test "Full corridor"(Rockett et al. 1989).

Each test used the same burn room with floor area 4.22 * 3.35 meters and of height 2.44 meters. The dimensions of the corridor was 18.97 * 2.41 and of same height 2.44 meters.

The doorway between the burn room and corridor was 2.0 meter high and 1.07 meters wide. A 0.15 * 0.94 meter hole with clear opening to the outside was provided next to the floor in a wall surface of the corridor.

The wall and ceiling surfaces of the burn room and corridor lined with 13 mm thick gypsum board. The floors were of concrete.

The fuel was methane in a 0.30 * 0.30 meters square diffusion burner. It was placed in the center of the room with burning surface 0.24 meter above the floor. The burner was manually controlled from the outside metering system to produce one of four possible energy release rates. In this comparison two of these are applied: a constant rate, Q, of 100 kW and 225 kW. However, the database in the Appendix shows a rate of 65 and 144 kW which is corrected rate because of radiation from the combustion zone.

Temperature was measurement by vertical thermocouples located at position A, B, C, D and E which are identified in figure 2.6. However, only vertically averaged temperature changes, from floor to ceiling, are reported and can therefore not be used for comparison.

Visual evidence of layering was obtained by vertical arrays of photometer and by video records.

2.7 Summary of experiments

Basic facts and names for each test are summarized in Table 2.7. The 'X' in the columns for temperature and interface indicates whether data is available for comparison.

Experiment	Test names	Room no	Length	Width	Height	Temp- erature	Inter- face
V1	T2,T3,T5, T6,T7	1	5.6	5.6	6.15	X	X
V2	T1,T5	1	4	3	2.6		
		2	5.6	5.6	6.1	X	X
V3	S1,S4,S5, S7,S8,S9	1	2.34	2.34	2.16	X	
		2	12.19	2.44	2.44	X	
		3	2.24	0.94	2.44	X[1]	
V4	A1,B1,C1,	1	30	24	26.3	X[2]	X
V8	100, 225 kW	1	4.22	3.35	2.44		
		2	2.41	19	2.44		X

1) For test S4,S7 and S9

Table 2.7 Overview for experiments arranged for comparison.   2) Only for test A1

3   Using experimental results

3.1   Introduction

Temperature in the hot gas layer and smoke layer height are the important parameters to be used in the comparison between theory and experiment. Published reports with experimental results are used to obtain these parameters. Here follows a description of how these results are used and treated to create a database for comparisons.

Furthermore, these parameters can not be used for comparison without knowing necessary input parameters for the computer models. The rate of heat release, room geometry and material in surroundings must be known.

3.2   Layer temperature and interface position

In the experiments, temperature is measured in vertical profiles as is showed in figure 3.1. Thermocouples are distributed over the profile with constant spacing. In small rooms just one profile is used but in large spaces and corridors several thermocouple trees are positioned..
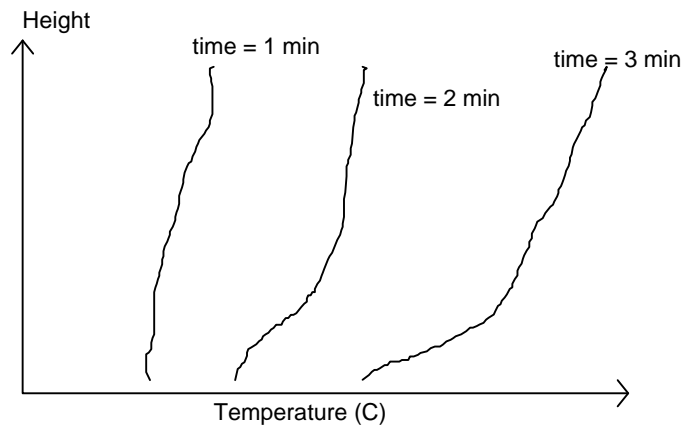
Figure 3.1 Example of temperature profiles for several times.

The computer programs used in the comparison are two-zone models which indicates that the temperature profiles must be used to determine average temperature in hot and cold layer. Here only the temperature in hot layer is used for comparison. The average temperature of the hot layer, T_u , is determined by Peacock and Babrauskas (1991):

$$T_u = \int_{h_N}^{h_t} \frac{T(h)}{h_t - h_n} dh \qquad (3.1)$$

Where h_t is height of the room and h_N is the layer interface height .The layer height, h_N, must be known to calculate the temperature. Several reports present temperature results in the same form as in figure 3.1, or in a time vs temperature curve as in figure 3.2, but no layer interface results are presented. This indicates that the data can not be used unless Coopers method, described in Section 3.3, is used. However, several methods are used in other experiments to determine the layer height, for example video recording, photometer, observation by eye and optical smoke density.
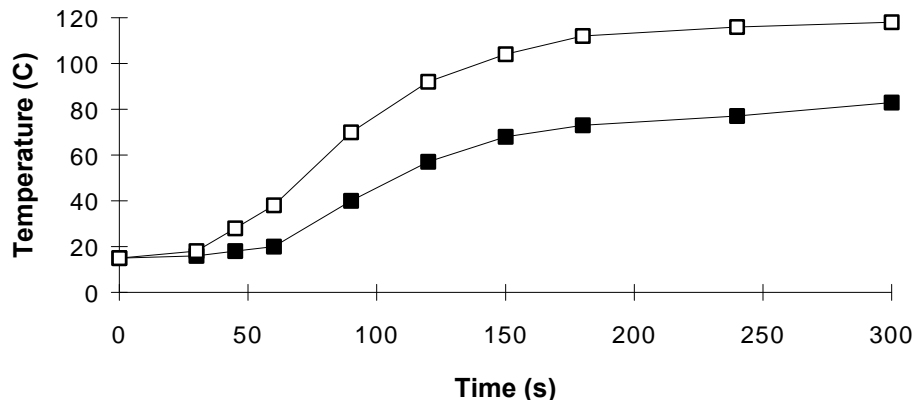
Figure 3.2 Example of time vs. temperature curves.

Once the location of the interface is known, it is a simple matter to determine an average temperature of the hot gas layer using equation (3.1). Linear interpolation is used to determine temperatures between measured points. To show this, one temperature profile is plotted in figure 3.3 with layer interface height and calculated average temperature, T_u.
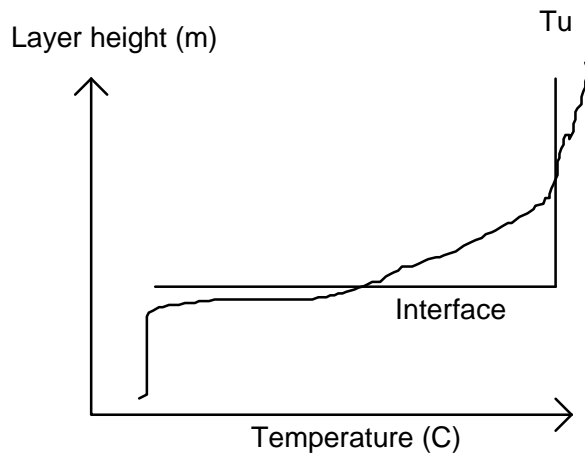
Figure 3.3 Average upper layer temperature and interface position.

3.3 Coopers method

Cooper et al (1982) have presented a method for defining the height of the interface between the relatively hot upper layer and cooler lower layer induced by fire. Peacock and Babrauskas (1991) wrote an report about this method. Quoted from this article; "Since the calculation depends upon a continuous temperature profile, and a limited number of pointwise measurements are practical, linear interpolation is used to determine temperatures between measures points. The equivalent two-zone layer height is the height where the measured air temperature is equal to the temperature T_N, determined by examination of the measured temperature profile from T_b up to T_{max} with the relationship:

$$T_N = C_N \left(T_{max} - T_b \right) + T_b \qquad (3.2)$$

C_N is determined empirically and typically ranges from 0.15 to 0.2."

The accuracy of this type of evaluation is reported to be good, but can not be used for all profiles. It is not possible to get an accurate temperature Tb if the spacing between the couples is large and the lowest one is not at floor level. An example for this is report from Stroup and Madrzykowski (1991) where the lowest thermocouple was at height 0.26 m and the spacing 40 cm. In one of the experimental test series, in this report, Coopers method is used to determine the layer interface height. In this experiment the spacing between the thermocouples was 15 cm.

4   Smoke Transport Models

4.1   Models for calculating smoke movement

During the last decade progress has been made in the understanding of the fire process and its interaction with humans and buildings. Advancement in analytical fire modeling has been particularly rapid. There are three different types of deterministic fire models developed

The most sophisticated of these are the "field models" or "CFD (Computational Fluid Dynamics) models". The enclosure volume is divided into a very large number of sub-volumes and the basic laws of mass, momentum and energy conservation are applied to each of these. Using such models requires a large amount of computational capacity as well as expert knowledge in many areas.

A second type of deterministic fire models are those that divide the room into a limited number of control volumes or zones. The most common type is the "two-zone model" where the room is divided into an upper, hot zone and a lower cold zone. Some of these only simulate a fire in a single compartment, others simulate fires in several compartments, linked by doors, shafts or mechanical ventilation.

A third way of analytically describing some basic fire processes is to use simple hand calculation methods. These are basically a collection of simplified equations, based on empirical data, to calculate flame heights, mass flow rates, temperature and velocities in fire plumes, time to sprinkler activation, room over-pressure etc.

This chapter will only consider two-zone models, since these are commonly used in design practice and used in the evaluation.

4.2   Two-zone models

The most common fire model, known as a "two-zone model", generally uses two control volumes to describe a room, one layer next to the ceiling which contains the hot combustion products and one over the floor which contains fresh air. A steep thermal gradient separates the two layers and is called interface. Figure 4.1 shows the division into the two homogeneous layers. Each layer is assumed be characterized by one temperature, gas concentration and smoke density. For given fire size, specified in terms of heat release rates, the model solves differential equations for mass and energy balance. The set of equations can compute the form of conditions at a given time in a specified volume of air (Peacock, Forney, Reneke, Portier, Jones, 1992; Hägglund, 1996).
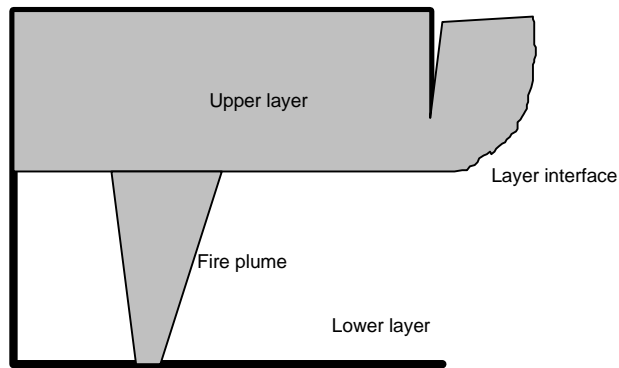
Figure 4.1 Two-zone model terms.

This chapter will describe in some details the two-zone model CFAST 2.0. CFAST solves the complete general heat conduction equations and also takes account of the rate of pressure rise in the energy conservation equations.

4.3 The two-zone model CFAST 2.0

4.3.1 Description of CFAST 2.0

CFAST (Peacock et al. 1992; Portier, Reneke, Jones, Peacock, 1993) is a two-zone model which has been developed at National Institute of Standard and Technology (NIST) in USA. The model calculates the evolving distribution of smoke, fire gases and the temperature throughout a building. It allows input files with up to 15 compartments, 18 ducts and 5 fans. In CFAST, all rooms have two-zone except the fire room, which has an additional zone for the fire plume.

CFAST 2.0 includes the following programs:

- CEdit   interactive input
- CFAST   the model itself
- CPlot   interactive output to display data produced by the model
- Report   produce time history (ASCII) output text
- ReportG   animation of graphics description(s)

4.3.2 Using CEdit

Input to the program is performed under the user friendly program CEdit. The data is entered to the program in the following sections (Portier et al. 1993):

1. Overview   A summary of the CFAST data file is presented here. The   title, simulation time, print interval, and history interval.

2. Ambient Conditions Internal and external ambient temperatures, pressure and station elevation. Wind speed, scale height and power law are used to calculate the wind coefficient.

3. Geometry   Input screen for all the compartments dimensions. The parameters are width, depth, height and floor elevation.

4.	Vents(doors,..)	All horizontal flow connections between compartments and openings are specified here. A open/close position for any vent can be specified.
5.	Vents(ceiling,..)	Vertical flow connections between compartments and opening to the outside are specified here.
6.	Fans, Ducts,...	Mechanical ventilation systems are entered using this screen.
7.	Thermal properties	Material used in the ceiling, floor and walls are picked up for each compartment from a database.
8.	Fire Specification	The combustion properties of the main fire are entered in this section. Rate of heat release is entered against time.
9.	Objects	Objects to be burned in the fire scenario can be specified here.
10.	Files	File names are specified here.

When the input is finished the evaluations are done by the model CFAST and results are treated in the output program Cplot. However, results can not be plotted directly to printer which is disadvantage for this program package.

4.4 Simulations of the experiments

Before the data from the experiments, described in Section 2, were organized into the database, they were re-evaluated. The re-evaluation makes it possible to use the data for comparison with predictions from two-zon models. Information from Section 2 and Appendix A are used for input to simulate the experiments in CFAST. In Appendix B the results from the predictions are plotted with the re-evaluated experimental results.

5   Statistical evaluation

The smoke transport model CFAST consists of a number of sub-models. There are sub-models for calculating the flame height, smoke velocity, entrainment in the plume, the mass flux in openings, the position of the interface, smoke temperature etc. The sub-models are connected to each other in a complex way. Output from one sub-model will be input to another. In all sub-models, approximations and assumptions are made. The approximations are necessary to be able to quantify the problem. When the smoke temperature is calculated, a number of different sub-models are used. An error in a sub-model will propagate through the system of sub-models. The total model error in a prediction is a combination of the model errors in all the sub-models used. Sometimes the errors in the sub-models compensate for each other, sometimes the errors are aggregated. It is not convenient to quantify the model error for the general range of model applications. The evaluation has to be limited to predictions of a specific scenario, where the flow pattern and geometry is similar.

The combination of sub-models in a calculation is depending on the scenario and the variable of interest. In other words, the model error will vary between predictions of the interface and the smoke temperature, for the same scenario will. If the same variable, for example smoke temperature, is studied in two different scenarios the model error will also differ. To evaluate a scenario, the tests in the database are organized in five specific scenarios. Each scenario contains a number of tests, where the combination of sub-models will be the same when they are simulated. The scenarios are presented in Table 5.1. The variables that have been evaluated is smoke temperature and the smoke layer height.

Scenario	Nr of tests
V1, single enclosure	5
V2, smoke spread to large room	2
V3, three room test including corridor	6
V4, smoke control in large scale spaces	4
V8, corridor	2

Table 5.1 Overview of scenarios

The scenarios in Table 5.1 are simulated with CFAST and the uncertainty in the predictions are evaluated. In the presentation of the statistical method, used in the evaluation, the prediction of smoke temperature will be used to illustrate the methodology.

5.1   Background

The objective with this project was to develop a method to quantify the uncertainty in smoke transport models. The data used while deriving the method comes from the database, presented in Appendix A, and simulations by the two-zone model CFAST. The two-zone model is presented in Section 4. CFAST was used to simulate the test, that has been carried out in full scale experiments and organized in the database. As a first step to investigate the differences between the measurements and predictions, the results are compared in graphs for every test. These graphs are presented in Appendix B and indicates that there is a obvious difference between the results. If these differences can be quantified it is possible to take the model error into account and correct future predictions. To be able to find the right method to quantify the differences, a brief analysis is made of the data.

If the measured and the predicted temperatures does not differ at all, the following equation can describe the relationship between the two variables

$$T_m = T_p$$

<div align="right">(5.1)</div>

T_m = measured temperature in full scale experiment
T_p = predicted temperature by smoke transport model

Model uncertainty is not taken into account in equation 5.1. The predicted values are assumed to be exactly the same as the measured one. This approximation is appropriate when the differences between measured and predicted values are close to zero. The graphs in Appendix B show that this assumption is not applicable when T_m and T_p are compared.

When the graphs in Appendix B are studied it seems like the predicted temperature is higher than the measured in almost every test. This indicates that the model is overpredicting the temperature. The differences seems to increase with temperature. A conclusions from the observation of the graphs is that the overprediction might be proportional with the predicted temperature. The evaluation of this kind of model error is illustrated by the following example:

In Table 5.2 a fictive test, with experimental measurements and model predictions, is presented. T_p is overpredicting T_m with a constant, but unknown percentage. The data-pairs will be numbered as: data-pair nr (j) = (T_{mj}, T_{pj})

nr (j)	time [s]	T_{mj} [°C]	T_{pj} [°C]
1	20	25	35
2	40	48	66
3	60	66	91
4	80	79	110
5	100	93	129
6	200	141	196
7	300	161	223
8	400	172	239
9	500	180	251
10	600	187	260
11	700	192	268
12	800	198	276

Table 5.2 Fictive example with constant overestimation by the model.

The data from the example is plotted into two graphs, figure 5.1 and 5.2, to illustrate the linear relation between the variables. Figure 5.2 show that a clear constant linear relationship between measured and predicted temperature can be identified.
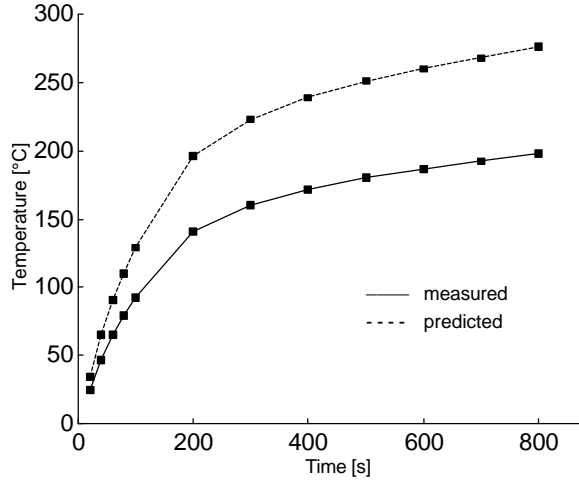
Fig 5.1   Fictive example, T_m and T_p plotted against time
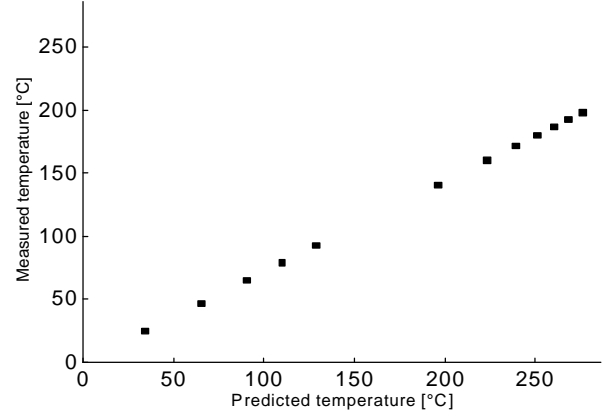
Fig 5.2   Fictive example, T_m plotted against T_p

Assume that the relation is linear through zero and that the bias, i.e. the unknown and overprediction, is expressed with factor γ. This relation can be quantified with a simple linear regression analysis. The relationship is expressed as:

$$T_m = g \cdot T_p \tag{5.2}$$

T_m = measured temperature
T_p = predicted temperature
g = regression coefficient, bias

g is calculated with standard statistical equations (Walpole and Myers, 1993):

$$Q_{mp} = \sum_{j=1}^{n} T_{m_j} T_{p_j} \tag{5.3}$$

$$Q_{pp} = \sum_{j=1}^{n} T_{p_j} T_{p_j} \tag{5.4}$$

$$Q_{mm} = \sum_{j=1}^{n} T_{m_j} T_{m_j} \tag{5.5}$$

$$g* = \frac{Q_{mp}}{Q_{pp}} \tag{5.6}$$

n = the number of data-pairs in the test.
j = the number of the data-pair
T_{mj} = measured temperature
T_{pj} = predicted temperature

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The regression coefficient for the data in Table 5.3 is calculated to 0.72, which corresponds to an overprediction with 40% by the model. The linear relationship is: $T_m = 0.72*T_p$

Is this an appropriate way to describe the model errors in CFAST?

A test from scenario V3 is presented in Table 5.3. This test will be refered to repeatedly when the statistical method is described.

nr (j)	time [s]	T_{mj} [°C]	T_{pj} [°C]
1	20	51	35
2	40	75	66
3	60	90	91
4	80	106	110
5	100	117	129
6	200	142	196
7	300	157	223
8	400	168	239
9	500	174	251
10	600	178	260
11	700	182	268
12	800	186	276

Table 5.3 Test 'V3-set 9 room 2', where temperature has been measured and calculated against time

The data is plotted into graphs in the same way as the fictive example.
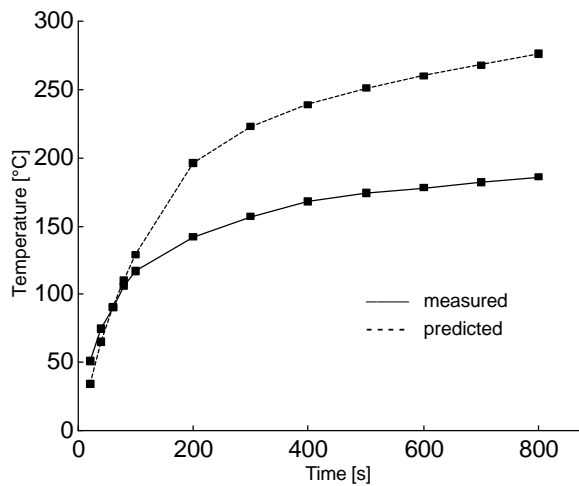
Fig 5.3 'V3-set 9-room 2', T_m and T_p plotted against time
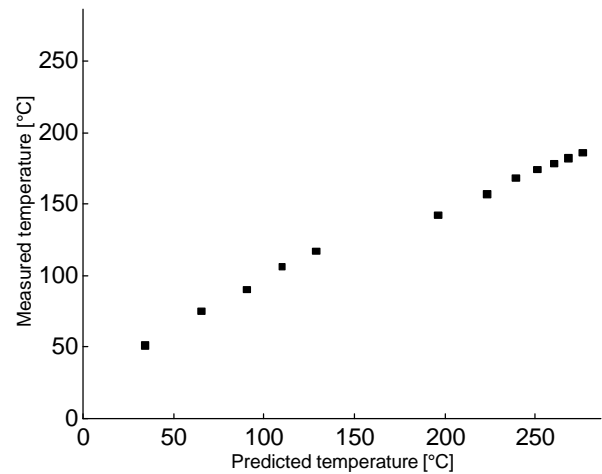
Fig 5.4 'V3-set 9-room 2', T_m plotted against T_p

Figure 5.4 show that relationship between T_m and T_p is fairly linear. The regression coefficient is calculated with the same statistical equations described earlier in this section. The result is $\gamma=0.72$ and the relationship is expressed as $T_m = 0.72\ T_p$.

Even if the linear regression coefficient is equal in the fictive example and the test from the database, figure 5.2 and 5.4 clearly shows that the relationship between T_m and T_p is not the

same. To illustrate this, T_m and the regression curve is plotted against T_p for the two tests. The result is shown in figure. 5.5 and 5.6.

Fig 5.5   Fictive example, T_m and regression line plotted against T_p

Fig 5.6   'V3-set 9-room 2', T_m and regression line plotted against T_p

A clear difference is observed. In figure 5.5 all the datapoints are fitted exactly on the regression curve. In figure 5.6 the datapoints are scattered around the regression line. 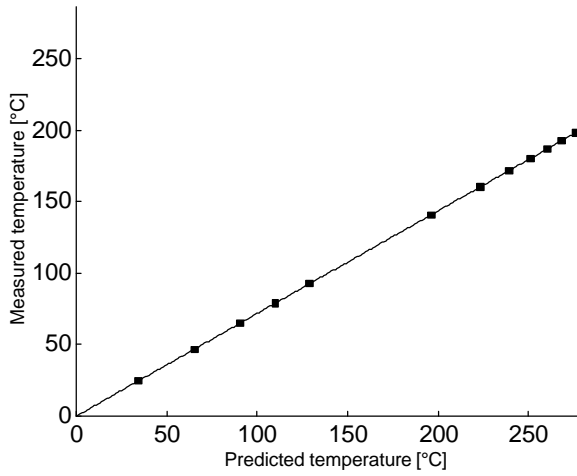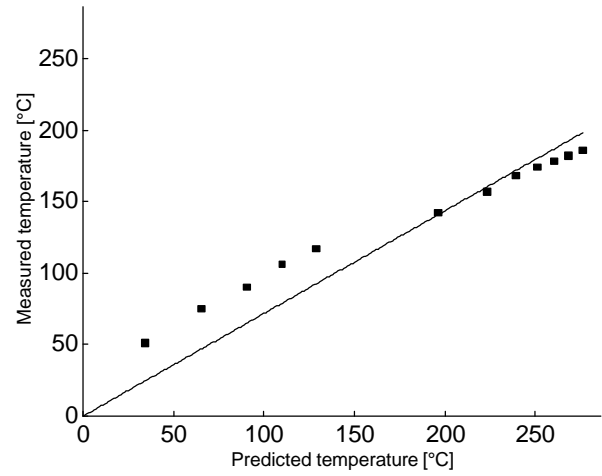The vertical distance between the datapoints and the line is called residual. The variation of the size of the residuals are called residual variance. To take the variance into the relation is expressed as:

$$T_{m_i} = \gamma \cdot T_{p_i} + \varepsilon_i$$

(5.7)

T_{mi} = temperature measured in experiment at a certain time
T_{pi} = simulated temperature with a smoke transport model at the same time
γ = bias, functional dependence between T_{mi} and T_{pi}
ε_i = residual, the random deviation between T_{mi} and the regressions line

The bias, γ, describes the linear relationship between the variables. If the model overpredicts the temperature, γ will be lower than 1 and otherwise, γ will be larger than 1. The residual, ε_i, is called the random error and describes the individual distance between T_{mi} and the regression line. The residuals are assumed to be uncorrelated and belong to a normal distribution, with mean = 0 and standard deviation = s_ε (Walpole & Myers, 1993):

$$\varepsilon \in N(0, s_\varepsilon)$$

(5.8)

The deviation from the regression line at a single data point, (T_{mi}, T_{pi}), is described by this distribution. All the data points, plotted in figure 5.6, can be described by the regression line and the random error, ε. If all data points are described by this relation, the parameters γ and ε can be estimated. This is done in a regression analysis.

The regression analysis is based on the data presented in figure 5.6. All the data points are attached with a random error and could be located with any distance ε from the regression

line. The uncertainty in the datapoints will result in uncertainty in the regression coefficient. The regression coefficient is expressed as a stochastic variable with a mean, $E(\gamma*)$, and a standard deviation, $Std(\gamma*)$. According to the analysis the regression coefficient will be approximately normal distributed. The '*' symbol indicates that the parameter is an estimate of an existing parameter with an unknown value.

The relationship can now be expressed as

$$T = T_m = N(\bar{g}*, s_g^*) \cdot T_p + N(0, s_e) \tag{5.9}$$

T = estimate of measured temperature based on regression analysis

The parameters are calculated with a standard linear regression analysis (Walpole & Myers, 1993):

$$Q_0 = Q_{mm} + \frac{\left(Q_{mp}\right)^2}{Q_{pp}} \tag{5.10}$$

$$\bar{g}* = \frac{Q_{mp}}{Q_{pp}} \tag{5.11}$$

$$\left(s_e^2\right)^* = \frac{Q_0}{(n-1)} \tag{5.12}$$

$$\left(s_g^2\right)^* = \frac{\left(s_e^2\right)^*}{Q_{pp}} \tag{5.13}$$

$\gamma*$ = regression coefficient
s_e* = standard deviation of the residuals
s_g* = standard deviation of the regression coefficient
n = number of datapoints (measuring points) in the test

When the model uncertainty is quantified, it is possible to get a better estimate of the measured temperature, than what the simulation model predicted. The model uncertainty is expressed with one systematic term, the regression coefficient, and one random term, the residual variance. These have been quantified and it is possible to adjust the calculations for the model error. There are three different types of calculations, where the adjustment has to be done in different ways:

1) Probabilistic risk or uncertainty analysis with computer software

The adjustment of T is a function of variables that are defined as distributions. If the analysis is done with numerical calculations tool it is possible to use the equation above. Modern computer programs uses sampling techniques such as Monte Carlo simulation, that can manage calculations with stochastic variables, expressed as functions of more than one distribution.

2) Probabilistic risk or uncertainty analysis with hand calculations

When hand calculations are used, variables are often limited to be described by a single well known distribution. Since T is a function of two stochastic variables, it is hard to identify the distribution for T. How to deal with this problem depends on what kind of calculations are to be performed. In uncertainty analysis with analytical expressions, for example the First Order Second Moment method described in 'Probability Concepts in Engineering Planning and Design' by A. Ang and W. Tang (1984), the variables has to be normal or lognormal distributed. The easiest way to estimate T as a single, well known, distribution is by assuming:

$$T = N(g^*, s_g^*) \cdot T_p + N(0, s_e) \approx N(g^*, s_g^*) \cdot T_p$$

(5.14)

In some cases it is appropriate to use this simplified expression, but the approximation must be carefully investigated when applied.

3) Deterministic design-expressions

In many situations it is not practical to deal with stochastic variables. Calculations of deterministic nature has to be adjusted in a different way, compared to probabilistic calculations. All variables in a deterministic expression are limited to be expressed by a single value. The variables does not contain information about the uncertainty. In design calculations variables with uncertainty are often treated with conservative values. To fulfill the design objectives the conservative design temperature must be higher than the temperature in a real fire. A question the designer will ask is:

I want to be 95% sure that the design value I choose is conservative. How can this be done?

In a design situation the important factor is to obtain the prediction interval corresponding to a given confidence level. In other words, having calculated a gas temperature equal to T_p, which is the value of T to enter into the future design calculations, if we want to be certain to be on the conservative side with a 80% or 95% confidence? This question is answered with standard statistical formulas. Which side of the interval that represents the conservative value, depends on the design problem. The upper limit of the prediction interval for smoke temperature will represent a conservative value if exposure levels are calculated. If sprinkler activation is studied, the lower limit of the prediction interval for the smoke temperature, represents a conservative value in calculation of the activation time.

Since booth the upper and lower limit might be of interest for the same variable, the intervals must be two-sided.

The prediction interval is expressed as(Walpole & Myers, 1993):

$$I = g * \cdot T_{p_0} \pm l_{a/2} \cdot s_e^* \sqrt{1 + \frac{T_{p_0}^2}{\sum_{j=1}^{n} T_{p_j}^2}} \tag{5.15}$$

I = interval for the adjustment of the model error for a given prediction
T_{p0} = the calculated (predicted) temperature that shall be adjusted
$\lambda_{\alpha/2}$ = the quantile at the given confidence level 1- a
a = (1- the confidence level)
n = number of measuring points in the experiment

5.2 Statistical Method

Only the predictions of one single test has been investigated. It is not possible to evaluate every type of situation that can occur in future design and risk analysis work. The regression would just be valid for exactly the evaluated situation. It is obviously more practical to evaluate the model error for a scenario, based on more than one test.

The regression model presented below is based on the same type of regression analysis as described in Section 5.1, but information from all tests in a scenario are used. The reason that it is more complicated is because the model uncertainty for a scenario is a weighted combination of the uncertainty in each test in the scenario.

The measured and predicted data for scenario 3, is used in this analysis The result of the evaluation is presented in Section 6. Analysis result for the other scenarios are also presented in 5.4, but the graphs from the Matlab calculations are presented in Appendix B. The uncertainty of CFAST's smoke-layer height predictions are also analyzed. The data for these analysis are also picked from the database and presented in the same way as the analysis of the temperature.

Let ($T_{p_{ij}}$, $T_{m_{ij}}$), $j = 1, 2, …, n_i$ be n_i 'predictions' and 'measurements' within a test (for example T_p and T_m in temperature-time curves) and $i = 1, 2, …, L$ be L different tests in a scenario. In the earlier equations examples, the number of tests within the scenario has only been one, i.e. $i = 1$ has been used.

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Regression coefficients for each test within a scenario are estimated in the same way as before

$$g_i^* = \frac{Q_{mp}^{(i)}}{Q_{pp}^{(i)}}$$

(5.16)

where e.g.

$$Q_{mp}^{(i)} = \sum_{j=1}^{n_i} T_{m_{ij}} \cdot T_{p_{ij}}$$

(5.17)

and

$$Q_{pp}^{(i)} = \sum_{j=1}^{n_i} T_{p_{ij}}^2$$

(5.18)

This coefficient γ_1^* describes the linear relation (regression coefficient) between measured and predicted temperature in test nr 1 in the scenario.

A weighted combination of these individual estimates gives the regression coefficient for the scenario being analyzed. The expression for the regression coefficient is

$$g^* = \sum_{i=1}^{L} w_i g_i^*$$

(5.19)

where γ^* is the weighted linear relation between the different regression coefficients in the same scenario. γ^* will be the regression coefficient for the whole scenario. The weights are given by:

$$w_i = \frac{\left((s^2)^* + (s_e^2)^* \Big/ \sum_{j=1}^{n_i} T_{p_{ij}}^2 \right)^{-1}}{\sum_{i=1}^{L} \left((s^2)^* + (s_e^2)^* \Big/ \sum_{j=1}^{n_i} T_{p_{ij}}^2 \right)^{-1}}$$

(5.20)

i.e.

$$w_i = \frac{\left((s^2)^* + (s_e^2)^* \Big/ Q_{pp}^{(i)} \right)^{-1}}{\sum_{i=1}^{L} \left((s^2)^* + (s_e^2)^* \Big/ Q_{pp}^{(i)} \right)^{-1}}$$

(5.21)

The weights differ the importance of the different tests by taking the number of measure points (data-pairs) within the different tests and the length of the measuring interval into account. By using these weights the uncertainty through the whole time interval of a test is

merged together. It is possible to adjust model predictions at any part of the interval. In practical application it might be more useful to study a certain part of the time interval. Then the weights have to be determined with another expression. If the interval are decreased, the adjustment of the model error will be less general but on the other hand, the adjustment will be less uncertain. Since this statistical evaluation method is not intended for a specific problem or application, the general approach expressed in equation 5.22 will be used.

Figure 5.8 and 5.9 show two temperature-time curves from two different tests from the same scenario. In booth cases the test represented by the dashed will be more important, i.e. have a higher w_i value, than the other line. If a test has a high wi value it has a high significance on the weighted combination of the uncertainty for the scenario.
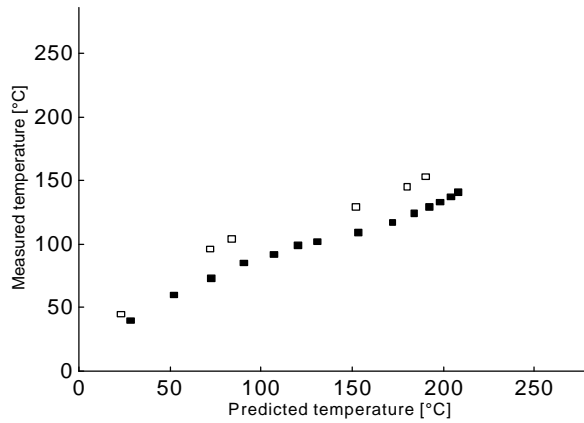

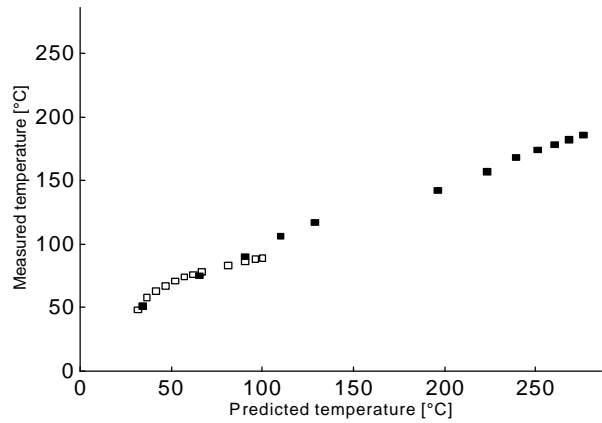Fig 5.8   Two tests with different number of data-points

Fig 5.9   Two tests with different length of measuring interval

The variance $(s_e^2)^*$ of the relations between measured and predicted values (between the data sets) within the different tests is estimated by

$$\left(s_e^2\right)^* = \frac{\sum_{i=1}^{L} Q_0^{(i)}}{\sum_{i=1}^{L}(n_i - 1)}$$

(5.22)

where

$$Q_0^{(i)} = Q_{mm}^{(i)} + \frac{\left(Q_{mp}^{(i)}\right)^2}{Q_{pp}^{(i)}}$$

(5.23)

and the variance of the regression coefficients γ_i between the tests is estimated by

$$\left(s^2\right)^* = \frac{B}{(L-1)} - \left(s_e^2\right)^* \frac{1}{L}\sum_{i=1}^{L}\frac{1}{\sum_{j=1}^{n_i} T_{p_{ij}}^2}$$

(5.24)

where

$$B = \sum_{i=1}^{L} \left(g_i^* - g^* \right)^2 \tag{5.25}$$

is the between tests regressions coefficient sum of squares.

With this model the regression coefficient and the variance for a scenario is created. The total variance for the regression coefficient of a scenario is

$$\left(s_g^2 \right)^* = \sum_{i=1}^{L} w_i^2 \left(\left(s^2 \right)^* + \frac{\left(s_e^2 \right)^*}{Q_{pp}^{(i)}} \right) \tag{5.26}$$

where both the variances within the single tests and the variance between the tests are included.

Finally the model uncertainty for a specific scenario can be expressed as:

$$T = N \left(g^*, s_g^* \right) \cdot T_p + N \left(0, s_e^* \right) \tag{5.27}$$

The parameters in the distributions are weighted between the different tests. The corrections are done in the same way as above, depending on the type of calculations. In the probabilistic hand calculations the simplified expression will be:

$$T = N \left(g^*, s_g^* \right) \cdot T_p \tag{5.28}$$

With statistical knowledge, the prediction interval can be created. The confidence interval describes the variation of the regression coefficient. To make future prediction the residual variance has to be taken account into account again. This is done in the prediction interval.

A confidence interval for an expected measured value at a given predicted value T_{p_0}, is given by:

$$g^* \cdot T_{p_0} \pm 2 \cdot T_{p_0} \sqrt{\sum_{i=1}^{L} w_i^2 \left(\left(s^2 \right)^* + \frac{\left(s_e^2 \right)^*}{Q_{pp}^{(i)}} \right)} = g^* \cdot T_{p_0} \pm 2 \cdot T_{p_0} \cdot \sqrt{\left(s_g^2 \right)^*} \tag{5.29}$$

The confidence level is approximately 0.95.

A prediction interval of an estimated temperature at a given predicted value T_{p0} is given by

$$\bar{g}^{*} \cdot T_{p_0} \pm 2\sqrt{T_{p_0}^2 \left(s^2\right)^{*} + \left(s_e^2\right)^{*} + T_{p_0}^2 \sum_{i=1}^{L} w_i^2 \left(\left(s^2\right)^{*} + \frac{\left(s_e^2\right)^{*}}{Q_{pp}^{(i)}} \right)} =$$

$$\bar{g}^{*} \cdot T_{p_0} \pm 2\sqrt{T_{p_0}^2 \left(s^2\right)^{*} + \left(s_e^2\right)^{*} + T_{p_0}^2 \left(s_g^2\right)^{*}}$$

(5.30)

The confidence level is approximately 0.95

The statistical method described above has been incorporated into a Matlab m-file. In the Section 6 the results from the evaluation of the scenarios are presented.

6 Results

The differences between the CFAST simulations and experiments, presented in graphs Appendix B, has been evaluated and given quantitative measure. The statistic method used in the evaluation is developed by the Department of Mathematical Statistics at Lund University and presented in Section 5.3.

6.1 Evaluation of temperature predictions

The calculation results for scenario V3 - room 2 is shown in figure 6.1 and figure 6.2. The results for the rest of the scenarios are presented in Appendix C.
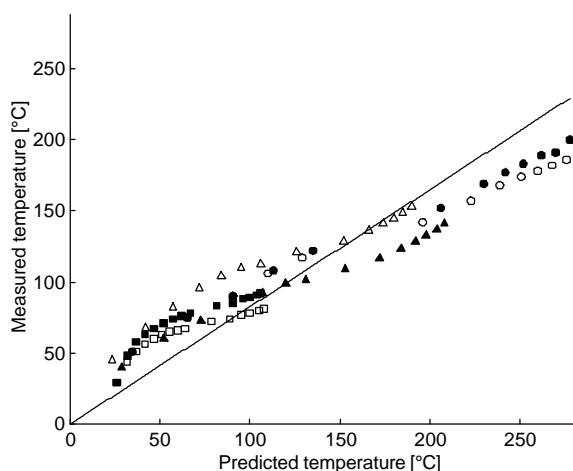

Fig 6.1   Scenario V3 - room 2, the tests and the weighted regression line
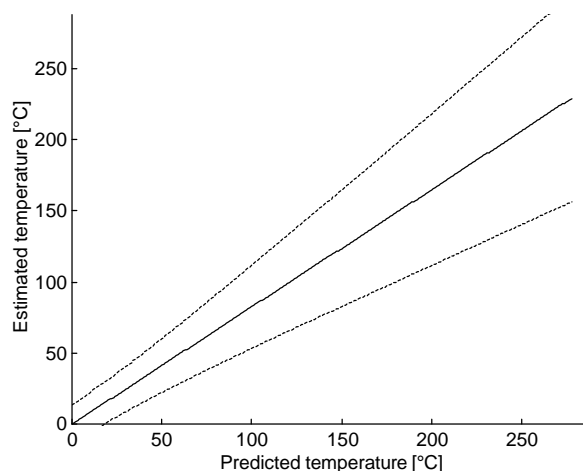
Fig 6.2   Scenario V3-room 2, regression line (——) and 95 % prediction interval (-----)

Scenario V3-room 2 includes six different tests, where the rate of heat release and the openings has been altered between the tests. The scenario consists of three rooms and is described more in detail in Section 2.4.

The results from the Matlab calculation of scenario V3 - room 2 is:

$$g^* = 0.82 \qquad s_g^* = 0.051 \qquad s_e^* = 17$$

The prediction interval is calculated for the temperature interval in the scenario and plotted with dashed lines in figure 6.2. In a deterministic calculations of exposure levels, T is approximated with the upper limit of the 95% prediction interval in figure 6.2. If the temperature is predicted with CFAST, for example $T_{p0} = 150°C$, the 95% interval of the measured temperature will be between 80°C and 170°C. Since the temperature is representing an exposure level, the conservative design value in this example will be 170°C. The regression line corresponds to the average over- or underprediction of the model. In the example above the temperature would be 130°C. This approximation ignores the random errors in the model predictions and should not be used to for adjustment, unless the residual variance is very small. The parameters from all regression analysis of the temperature predictions with the Matlab is presented in Table 6.1.

Scenario	V1	V2	V3		
			room 1	room 2	room 3
$\overline{g}^*$	0.65	0.77	0.82	0.82	0.72
s_g^*	0.052	0.095	0.055	0.051	0.041
s_e	4	6	62	17	6

Table 6.1 Values of regression parameters for the temperature evaluation

6.2 Evaluation of interface predictions

The calculation results for scenario V1 is shown in figure 6.3 and figure 6.4. The results for the rest of the scenarios are presented in Appendix D.
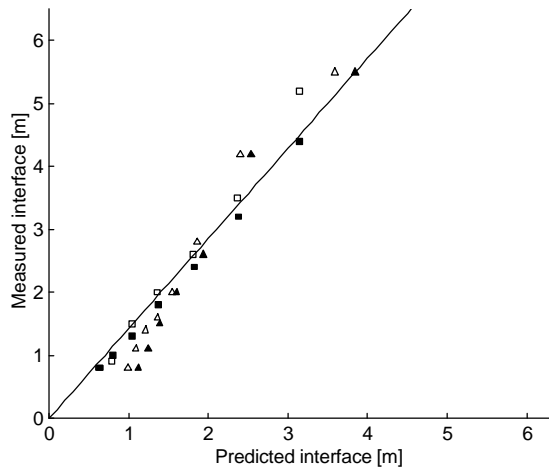

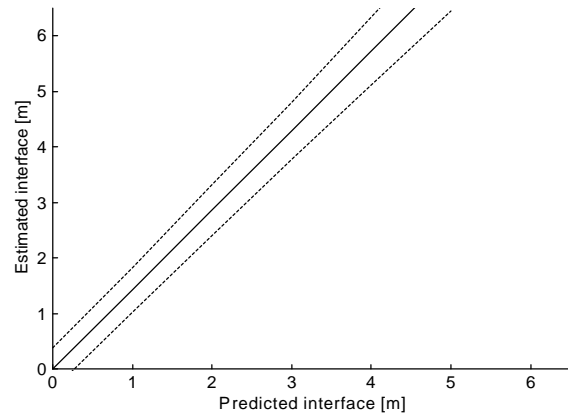Fig 6.3   Scenario V1, the tests and the weighted regression line

Fig 6.4   Scenario V1, regression line (——) and 95 % prediction interval (-----)

The results from the Matlab calculation are:

$$g^* = 1.4 \qquad = \quad s_g^* \ 0.042 \qquad = \quad s_e^* \ 0.38$$

The results from the calculation of the model uncertainty in CFAST's interface predictions is presented in Table 6.2.

Scenario	V1	V2	V4	V8
g^*	1.4	1.4	1.7	1.1
s_g^*	0.042	0.14	0.23	0.10
s_e	0.38	1.5	1.9	0.26

Table 6.2 The model uncertainties for CFAST's smoke layer height simulations in the different scenarios.

7   Discussion

7.1 Comments on the results

With the statistical analysis, described in this paper, it is possible to quantify uncertainties in smoke transport models. In the analysis simulated data is compared with experimental data and the relation between the two is determined with quantitative measures. In the analysis, it is possible to take the uncertainties in the model predictions into account when performing engineering calculations. The comprehensive fire model CFAST was used as an example of model to compare with the experimental data.

The purpose of the comparisons was to quantify the degree of model uncertainty and give numerical values to certain regression parameters. The statistical method that is developed gives the opportunity to:

- describe the model uncertainty with a stochastic expression, which can be used to adjust predictions in risk and uncertainty analysis.

- estimate conservative design values in deterministic design-expressions

- validate different simulation models and compare the uncertainties with quantitative measurements

The analysis of the relation between the predicted data from CFAST and measured data from full scale experiments, shows that there are obvious differences. The predictions from the smoke transport model CFAST includes model errors that have to be taken into account. An engineer does not want to use an unconservative estimate of the real temperature in his calculations. In many cases model predictions are the only cost-effective method to estimate the consequences of a fire in a building. If the differences (model errors) not are taken into account, the building will be more or less safe than the designer intended.

The results of the uncertainty analysis shows that the magnitude of the uncertainty is varying, depending on the variable evaluated. The mean biases indicates that CFAST is overpredicting the smoke temperature and underpredicting the smoke layer height. The mean bias is varying between 0.7-0.8 for the temperature predictions, depending on the scenario. This corresponds to an overprediction by between 25-40 %. The mean bias is varying between 1.1-1.7 in the interface predictions, which corresponds to an underprediction of the measured interface by 10-40%. It is not appropriate to adjust the predictions just by looking on the bias. The mean bias indicates the average over- or underprediction. Due to the size of the random error a general conclusion can not be drawn, by just looking at the bias. In the result section it is shown that a conservative design temperature can actually be higher than the predicted value, even if the bias is indicating a overpredicted temperature.

The random error is very large in some scenarios. In some cases the adjustment of the predictions can result in unrealistic values. The uncertainties are studied during the whole time period of the fire development. The adjustments in the early stage of a test can be so large that it results in negative.

The uncertainties in the adjustments for the model error, i.e. the residual variance, can be reduced. Decreasing the variance in the relation between measured and predicted data will decrease the uncertainty in the adjustments. This can be done by improving the smoke transport model, use a more sophisticated regression model, increasing the number of investigated test in each scenario and increase the number of measuring points in the tests.

Another way is to analyze a specific part of the total time interval. Since the relation between measured and predicted data varies during the time period, uncertainty can be decreased by studying a limited period of the scenario, for example when critical conditions occur.

It must be of interest for all engineers to be aware of the uncertainty in the tools they are using. If a models is overpredicting the hazardous conditions, to conservative values can be the result and the design will be unnecessary expensive. If the model is underpredicting the hazardous conditions, unsafe buildings will be the result.

7.2 Approximations and limitations

The sources to the random error comes from the model itself and from the approximations in the statistical method. The uncertainty in the simulation model can be decreased by further research. In this section the major approximations in the statistical method are discussed.

- The residual analysis quantifies the linear relation within the interval of datapoints measured. Adjustments of the predictions for the model error is not recommended to be done outside this interval. The adjustments are only valid for the temperature range investigated.

- The residual variance in the tests in a specific scenario, is approximated to be of the same magnitude and uncorrelated. This approximations has not been analyzed. A redidual analysis has to be carried out in future work.

- The estimate of the regression parameters are based on a small number of datapoints. The uncertainty in the datapoints are assumed to come from an existing distribution, describing the residual errors. When an estimate of this existing distribution is made from a number of observations, i.e. the datapoints, uncertainty is introduced.

- The regression coefficient is expressed as a normal distributed variable. According to the central limit theoreme (Walpole & Myers, 1993) this is valid when the calculations are based on a large number of observations. If the number of observations are increased, the uncertainty will be reduced.

- In the evaluation predicted data are compared with experimental measured data. Measured data are assumed to represent real conditions. The real conditions are the conditions that the engineer wants the design to meet up to. The uncertainties in the measuring equipment are usually very small, but it is well known that experiments and reality can differ a lot. In experimental situations variables that varies in reality can be held constant and a lot of simplifications can be made. Inspite of this the approximation has to be made to be able to compare the predictions with something. The uncertainties due to this approximation are of the same kind as when a design is based on data from full scale experiments. It is not perfect, but seems to be the best estimate that can be done for now.

- When the predictions are modeled, it is inevitable to avoid a degree of uncertainty caused by the engineer performing the simulations. A Comparison of Fire Simulation Tools (Keski-Rahkonen, 1996) show that engineers modeling the same situation with the same simulation tool will come up with predictions that are not exactly the same. The predictions compared to the measurements in the evaluation are maybe not the ultimate predictions. This uncertainty is hard to totally exclude. The best way is to let a well educated engineer perform the calculations.

- The relation between the measured and predicted values are assumed to be linear. It is obvious that it is no exact linear relation between the data, but for the two different variables studied (temperature and interface), the assumption seems to be valid. The relation between the measured and predicted data for the interface varies in the end and beginning of the time period studied. It is because CFAST assumes that the time for the smoke to reach the ceiling is zero. The model assumes that the smoke layer starts descending towards the floor directly when the fire begins. It is obvious that it takes time for the smoke to reach the ceiling. The regression coefficient, γ^*, will therefore be close zero if only the beginning of the test is studied. It is possible to correct for this assumption in CFAST. To exclude the data sets in the beginning of the test is one approach, but no such work has been carried out within this project.

- There are many ways of quantifying numerical differences between two time dependent data sets. Numerous statistical methodologies, of varying complexities, can be applied to this problem. This study has used a relatively simple methodology to quantify these differences. The regression line is forced through zero and no intercept is allowed. This is a part that can be improved. The graphs presented in Appendix C and D indicates that a regression model where intercept is allowed might decrease the residual variance.

- The database used for comparisons is somewhat limited and should be considerably enhanced for further studies. This work, and the results presented, should therefore be seen as a first, preliminary attempt to quantify the accuracy of fire models. Further studies on this subject

7.3 Future work

The Swedish Fire Research Board has granted funding to continue the work with determining the uncertainty in smoke transport model. The work will be carried out within the project "Quantifying model uncertainty", which is a part of the project "Practical Design Based on Quantitative Risk Assessment".

The objectives with the project 'Quantifying model uncertainty' is to:

- extend the database presented in this report
- improve the statistical method
- evaluate the uncertainty in more simulations models and equations
- investigate uncertainty in model predictions of "time to critical conditions"

This will give a better understanding of the uncertainties involved in predictions with the smoke transport models.

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APPENDIX A

Database with measurements from full scale experiments

Temperature, interface and rate of heat release (RHR) measurements from the fullscale experiments, described in section 2, are presented in tables. The number of measuring points vary between the test and therefor some positions in the tables will be blank, i.e. no data where registered at that time for the specific test. The time is measured in seconds in all the experiments.

Scenario V1

Interface [s]

Time	T2	T3	T5	T6	T7
0	6.15	6.15	6.15	6.15	6.15
30	4.4	5.2	5.5	5.5	3.4
45	3.2	3.5			
60	2.4	2.6	4.2	4.2	0.8
75	1.8	2			
90	1.3	1.5	2.6	2.8	0
105	1	0.9			
120	0.8	0.8	2	2	0
150	0.6	0.6	1.5	1.6	
180	0.5	0.5	1.1	1.4	
210			0.8	1.1	
240			0.5	0.8	
270			0.2	0.5	
300			0	0.3	

Temperature [°C]

Time	T2	T3	T5	T6	T7
0	15	17	17	18	19
30	16	18	18	19	23.5
60	23	24	20	21.5	44
90	33	34	21	22.5	70
120	40	42	23	24	94
150	50	53	24	24.5	
180	57	60	24	25.5	
210			25	26.5	
240			26	27	
270			26	27.5	
300			27	28	

RHR [kW]

Time	T2	T3	T5	T6	T7
0	0	0	0		0
30				30	390
45			28	30	390
60	186	189	28	30	390
120	186	189	28	30	390
180	186	189	28	30	
300			28	30	

Scenario V2

Interface [m]

Time	T1	T5
0	6.1	6.1
15	6.1	6.1
30	6.1	5.5
42		5
48		4
53		3
58	5.3	2
68	2	1
77	4	
85	3	
93	2	
100	1	
107	0	

Temperature [°C]

Time	T1	T5
0	15	16
30	15	22
45	15	29
60	22	32
90	31	59
120	38	75
180	54	92
240	64	97
300	69	101
360	73	101
420	73	98
480	66	93
540	62	87
600	65	76

RHR [kW]

Time	T1	T5
0	0	0
90	330	670
600	255	670

Scenario V3

Temperature [°C]

Time	Set 1 Room 1	Room 2	Set 4 Room 1	Room 2	Room 3
0	20	20	20	20	20
20	130		130		20
40	168	29	158	29	21
60	185	48	173	44	23
80	211	58	198	51	25
100	219	63	206	56	28
120	224	67	211	60	30
140	227	71	214	63	32
160	228	74	215	65	34
180	229	76	216	66	36
200	232	78	218	67	38
300	239	83	224	72	43
400	243	86	225	74	45
500	245	88	226	77	48
600	248	89	228	78	49
700	249	91	231	80	51
800	251	92	234	81	52
820	252	92	235	81	52
840	247	92	231	82	53
860	235	91	218	80	53
880	218	89			

Time	Set 5 Room 1	Room 2	Set7 Room 1	Room 2	Room 3
0	20	20	20	20	20
20	130	40	150	45	20
40	240	60	294	68	25
60	270	73	320	82	31
80	277	85	340	96	37
100	284	92	352	104	43
120	286	99	356	110	48
140	288	102	359	113	53
200	293	109	373	121	61
300	300	117	387	129	68
400	307	124	400	136	73
500	312	129	412	141	77
600	314	133	424	145	80
700	323	137	432	149	83
800	340	141	437	153	86

Time	Set 8		Set 9		
	Room 1	Room 2	Room 1	Room 2	Room 3
0	20	20	20	20	20
20	400	51	245	51	22
40	465	75	310	75	31
60	505	90	336	90	39
80	555	108	391	106	48
100	570	122	397	117	56
200	600	152	407	142	80
300	618	169	444	157	91
400	634	177	468	168	98
500	650	183	486	174	105
600	666	189	515	178	109
700	690	191	515	182	114
800	690	200	530	186	118

RHR [kW]

Time	Set 1	Set 4	Set 5	Set 7	Set 8	Set 9
0	0	0	0	0	0	0
100			200			
130	53	53		175		
145					400	400
175			240			
195	67	67				
220					440	
250						450
305				235		
345			255	235		
360	78	82		235		
405					425	
425						470
840	81	93	255	235	445	465

Scenario V4

Interface [m]

Time	A1	B1	C1	C2
0	26.3	26.3	26.3	26.3
60	22.1	20.3		
80	20.2			
120		14.7	17.25	17.25
130	16.1			
150			14.15	14.15
170	11.2			
180		11	11.6	11.6
210	9		9.85	9.85
240		8.5	8.25	8.25
270	7		7.15	7.15
300	6	6.6	6.25	6.25
330	5.1		5.3	5.3
360		5.2	4.55	4.55
390	3.2		3.95	3.95
420	2.1	4.2	3.55	3.55
480	1	3.5		

RHR [kW]

Time	A1	B1	C1	C2
0	1300	1300	1300	1300
480	1300	1300	1300	1300

Scenario V8

Interface [m]

Time	100 kW	225 kW
0	2.44	2.44
55		2.29
60	2.29	
70	1.98	1.98
80		1.68
85	1.68	
100		1.37
110		1.07
115	1.37	
130		0.76
140		0.46
145	1.07	
165	0.76	
190	0.46	

RHR [kW]

Time	100 kW	225 kW
0	65	144
100	65	144
200	65	144
300	65	144
400	65	144

APPENDIX B

Comparasion of experimenal measurements and model predictions

Upper layer temperature

Figures 1 to 11 show the vertically averaged temperature, in upper hot layer, in comparison with the two models, CFAST and Argos.

Comparison in scenario V1

The temperature rise during the experiments V1 is in all tests overpredicted by the CFAST and Argos simulations. In T5 and T6 the combustion was to small to build a smoke layer in Argos and therefore no results are plotted and comparison is not available.
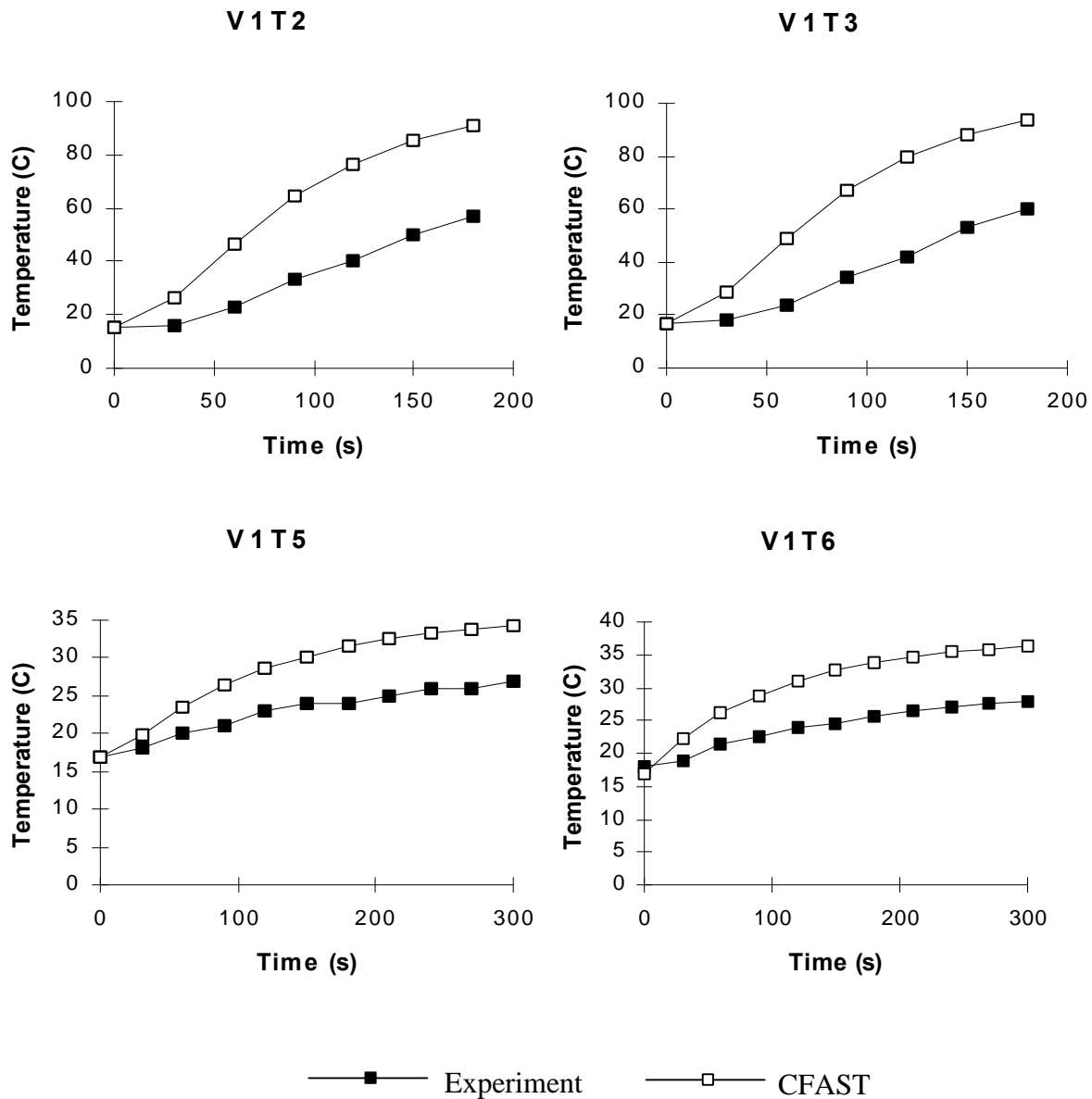
Figure 1   Measured and predicted temperature rises in upper smoke gas layer for the test T2, T3, T5 and T6 from the V1 scenario.

V 1 T 7
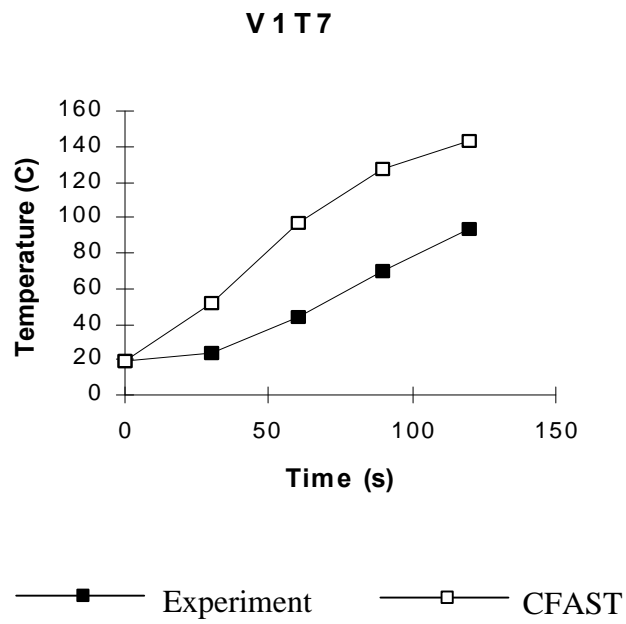
Figure 2 Measured and predicted temperature rises in upper smoke gas layer for the test T7 from the V1 scenario.

Comparison in scenario V2

V 2 T 1   **V 2 T 5**
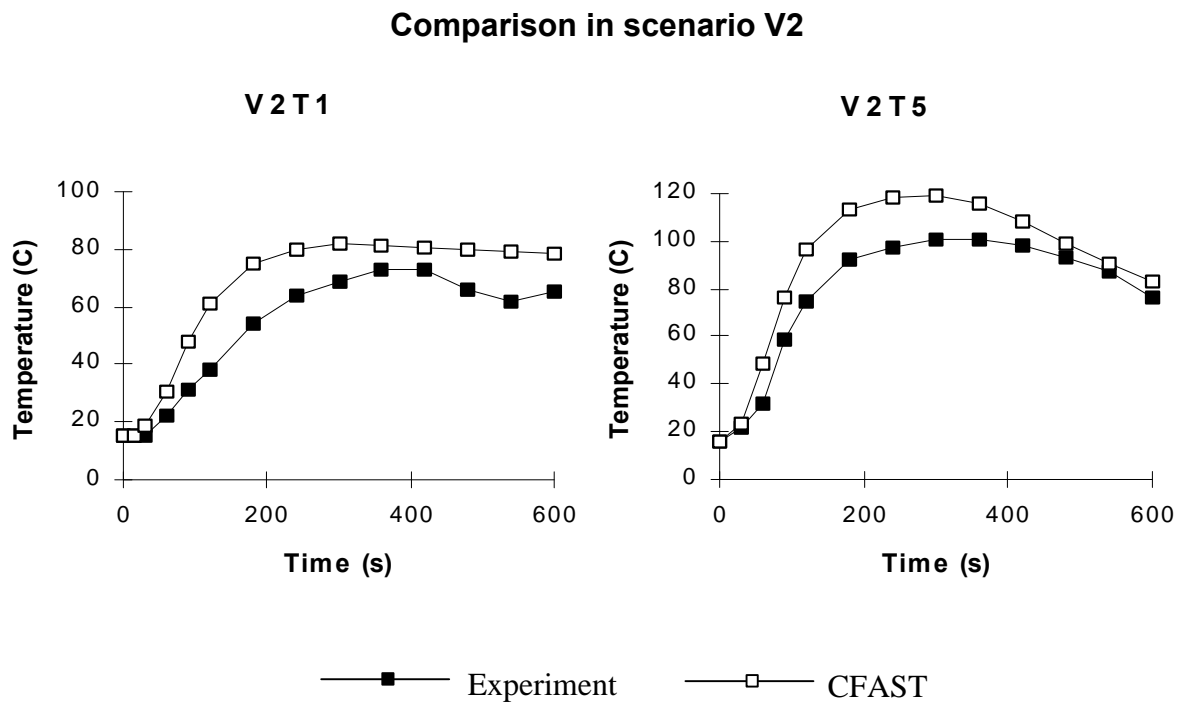
Figure 3 Measured and predicted temperature rises in upper smoke gas layer in room 2 for the V2 scenario, tests T1 and T5.

Comparison with scenario V3

The fire is in all tests placed in room 1. Sets 1 and 4 have an effect under 100 kW, sets 5 and 7 under 300 and finally sets 8 and 9 with maximal effect around 460 kW.

In a number of the cases, the experimental temperature data rises faster at the beginning of the test than the predicted.

Argos seems to underpredict in a number of cases, at least for the burn room.

In sets 8 and 9 the fire results in flashover in the Argos predictions, after a short time and the simulation is terminated. CFAST, however does not terminate the simulation, even though flashover is predicted.
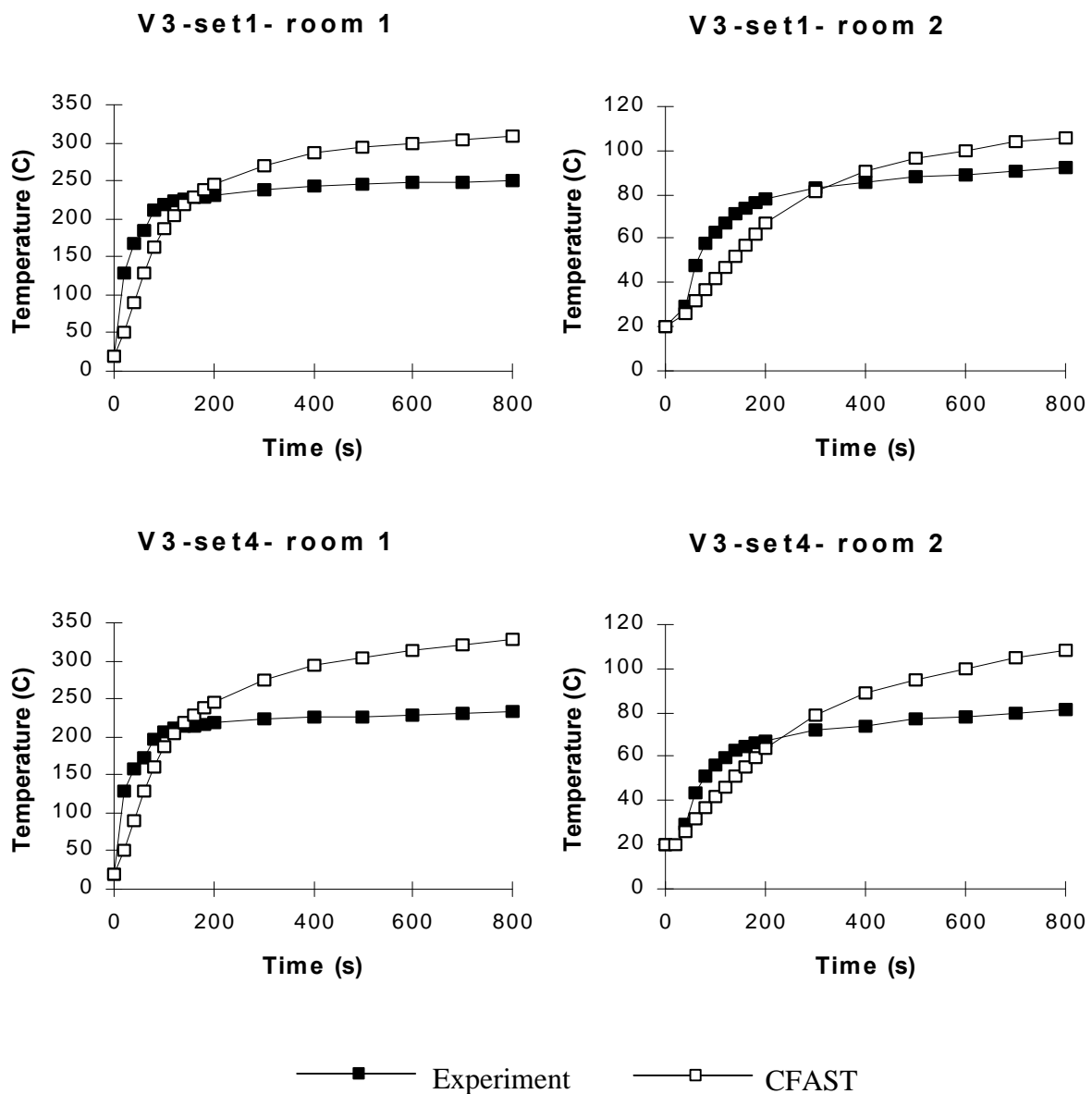
Figure 4   Measured and predicted temperature in upper smoke gas layer for the   V3 scenario, set 1 and set 4.
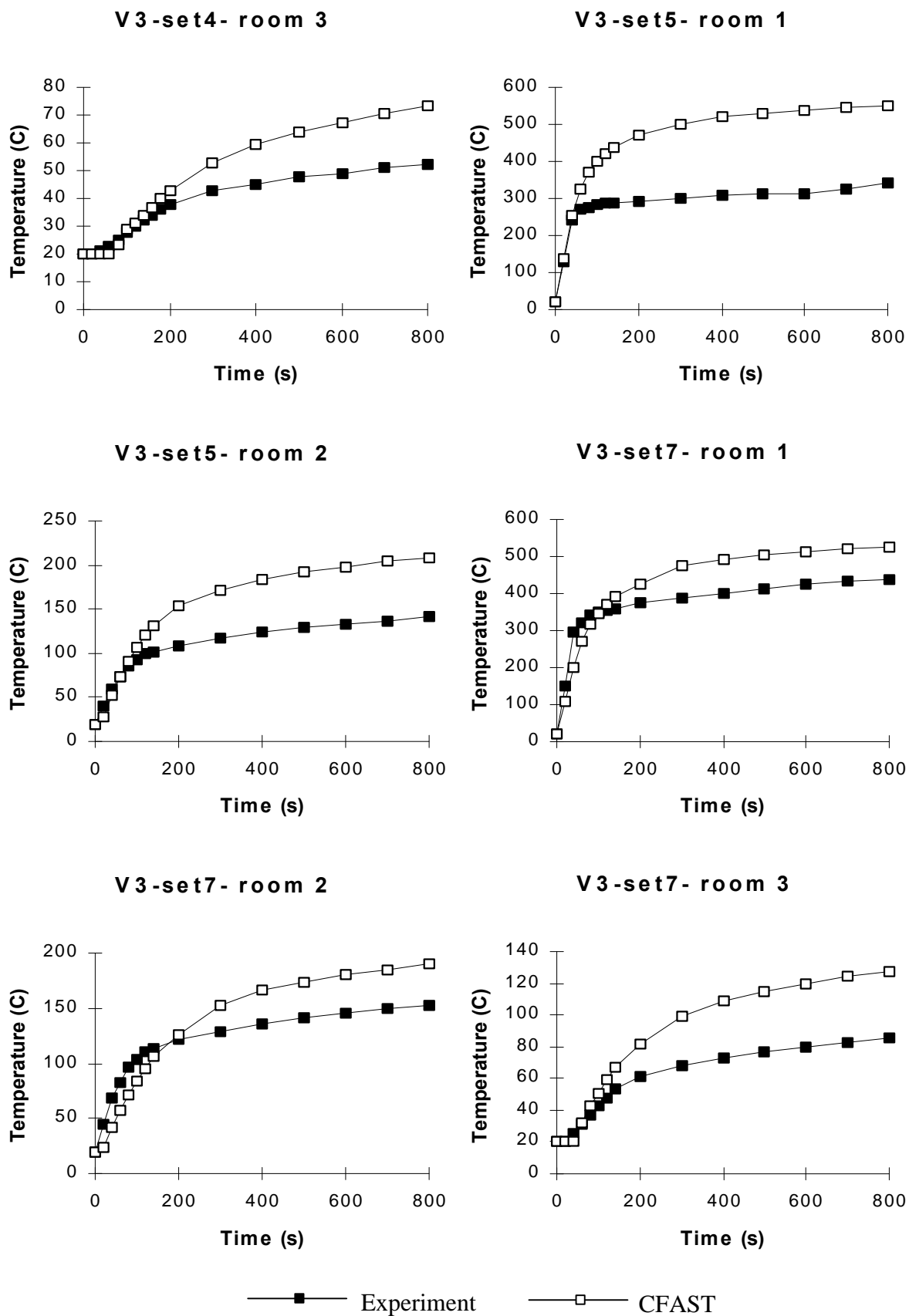
Figure 5   Measured and predicted temperature rises in upper smoke gas layer for   the V3 scenario, set 4, set 5 and set 7.
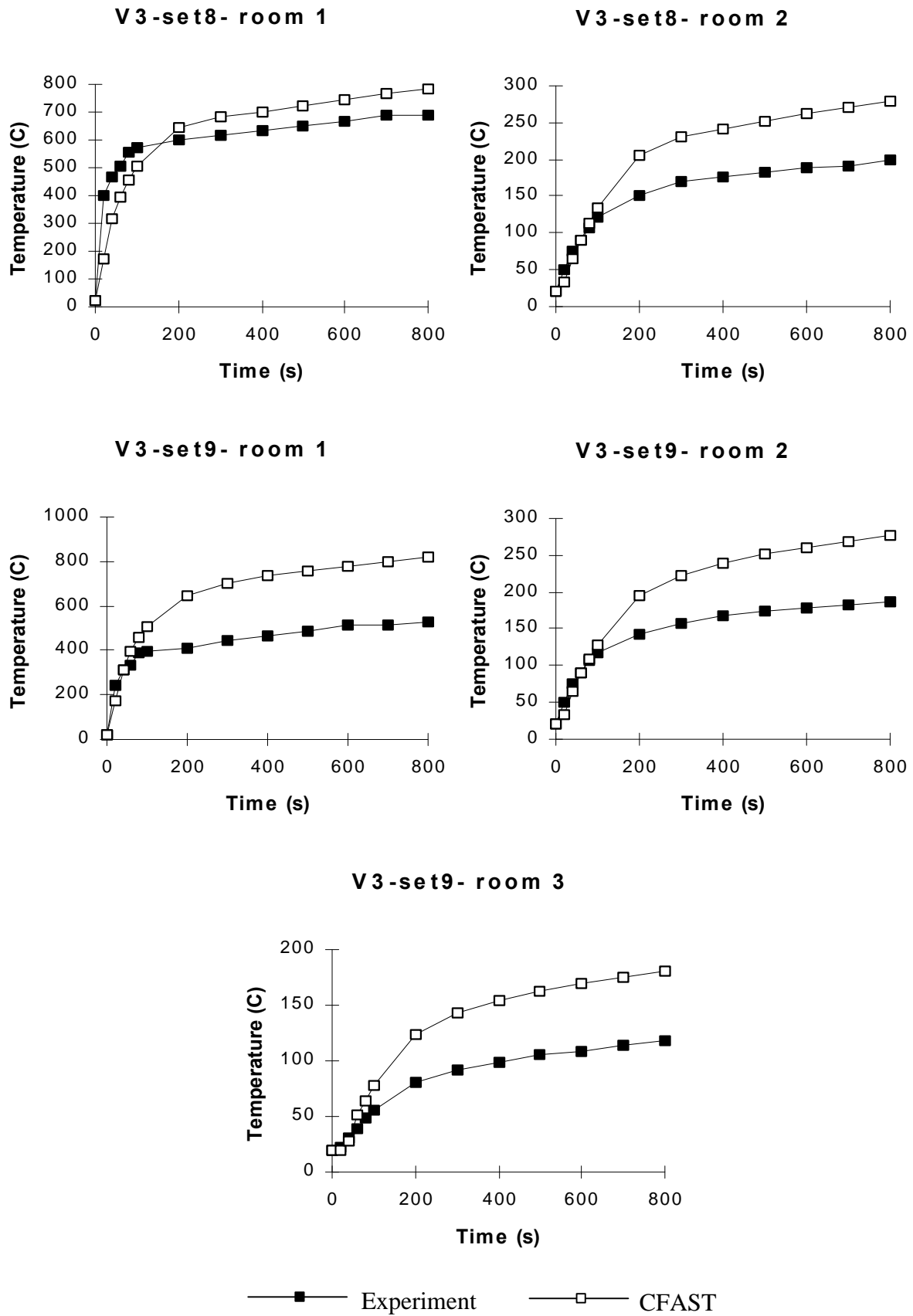
Figure 6 Measured and predicted temperature rises in upper smoke gas layer for the V3 scenario, set 8 and set 9.

Position of the interface

In this section the interface heights for the experiments are compared to the simulation of the two models.

The data series for interface comparisons are fewer than for temperature. The V3 tests, which are dominating the temperature comparison, do not give explicit data for the interface position and are therefore not used here.

Comparison with scenario V1

As was said in Section 5.2.1 no prediction is available from Argos tests T5 and T6. The time interval between data points is 15 sec. but the first result from Argos appear after, 45 sec. in tests T2 and T3. From Fig. 5.12 it may be concluded that the smoke layer height shows fairly good agreement between the measured data and the theoretically predicted values.

V 1 T 2

V 1 T 3

V 1 T 5

V 1 T 6

Experiment   CFAST
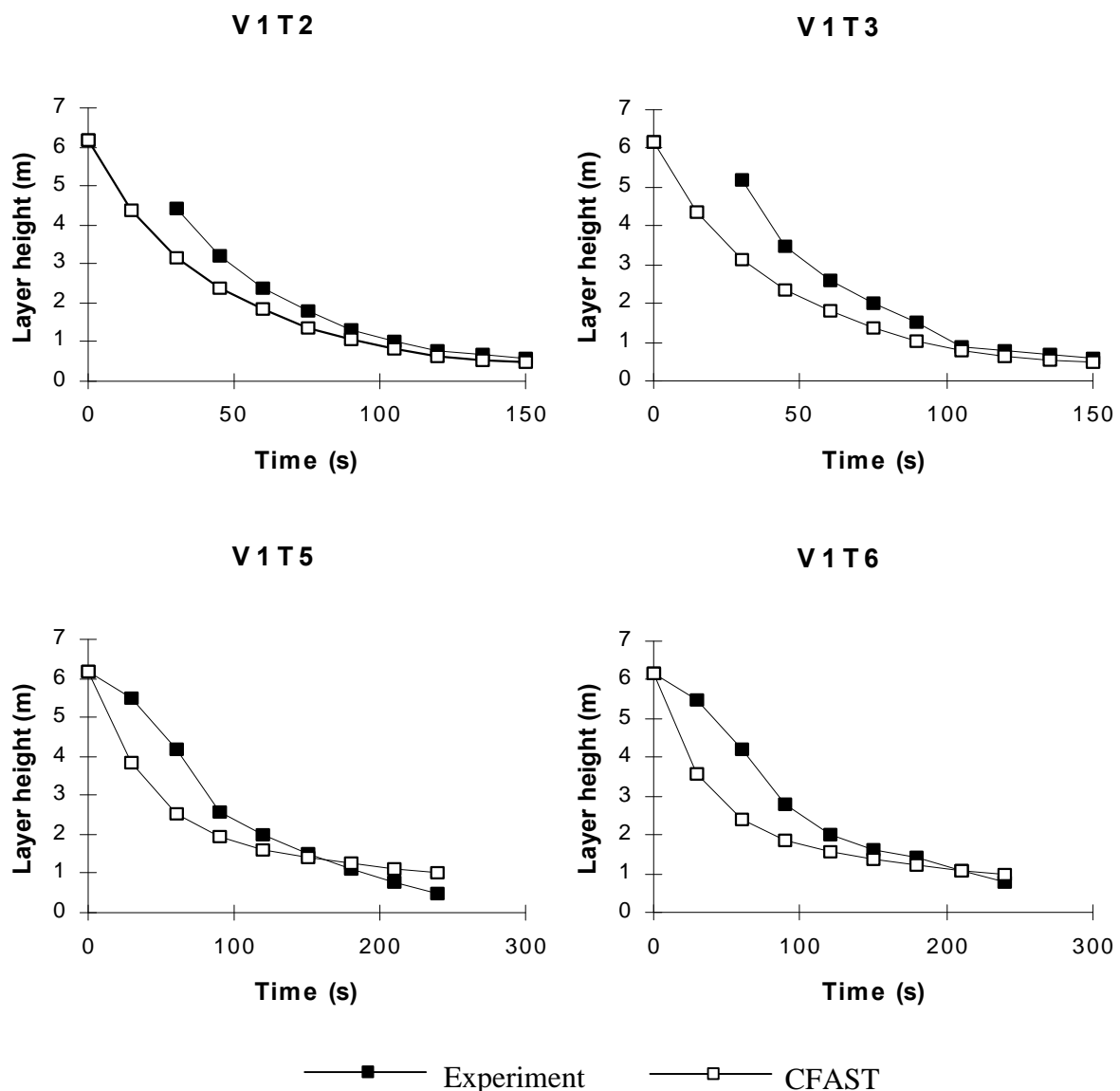
Figure 7   Height of the interface during tests T3, T4, T5 and T6 from scenario   V1.

Comparison with scenario V2

During the experiment the interface sinks slowly at the beginning in room 2 (it takes time for the burn room to be filled with smoke), but after a while it descends quickly to floor level. CFAST predicts under the measured data points but does not reach floor level in such a short time as the experiment. Argos predicts with the criteria of Alperts formula, which is mentioned in Section 2.4.1, and that makes the interface sink much
later than the CFAST predictions.

V 2 T 1

V 2 T 5
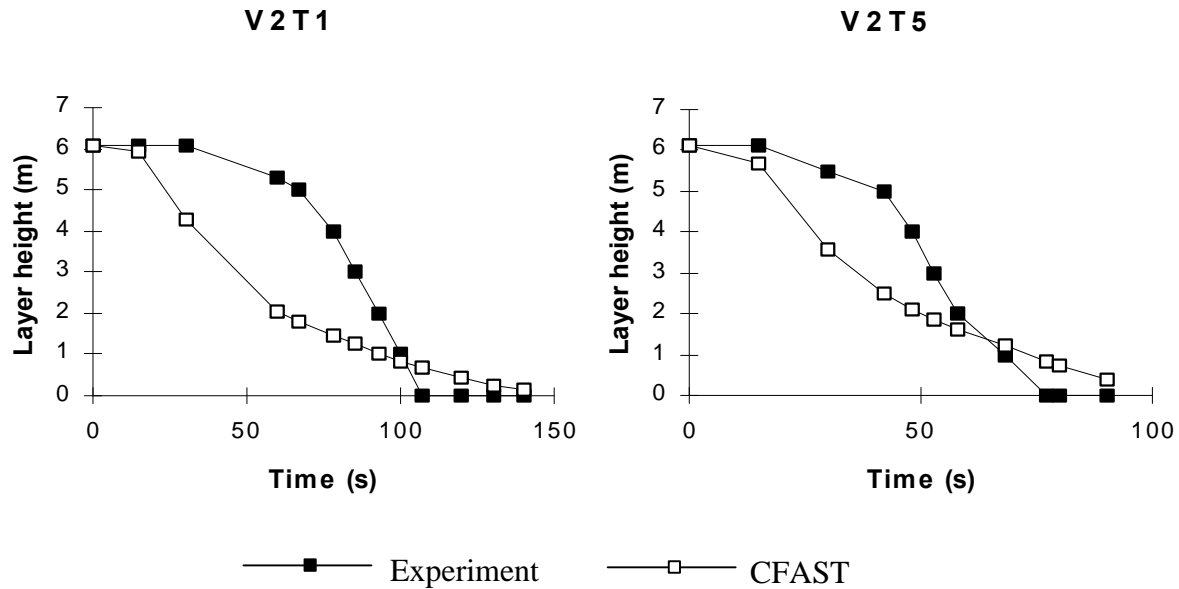
Figure 8   Height the interface during tests T5 and T6 from scenario V2.

Comparison with scenario V4

In tests C1 and C2 the smoke was pulled out mechanically from the upper part of the space. In C1 a 3,23 m^2 opening was at floor level, but no such opening was provided in test C2. Argos does not include mechanical functions and does not predict C1 and C2.

V 4 A 1

V 4 B 1

V 4 C 1

V 4 C 2

■ Experiment   □ CFAST
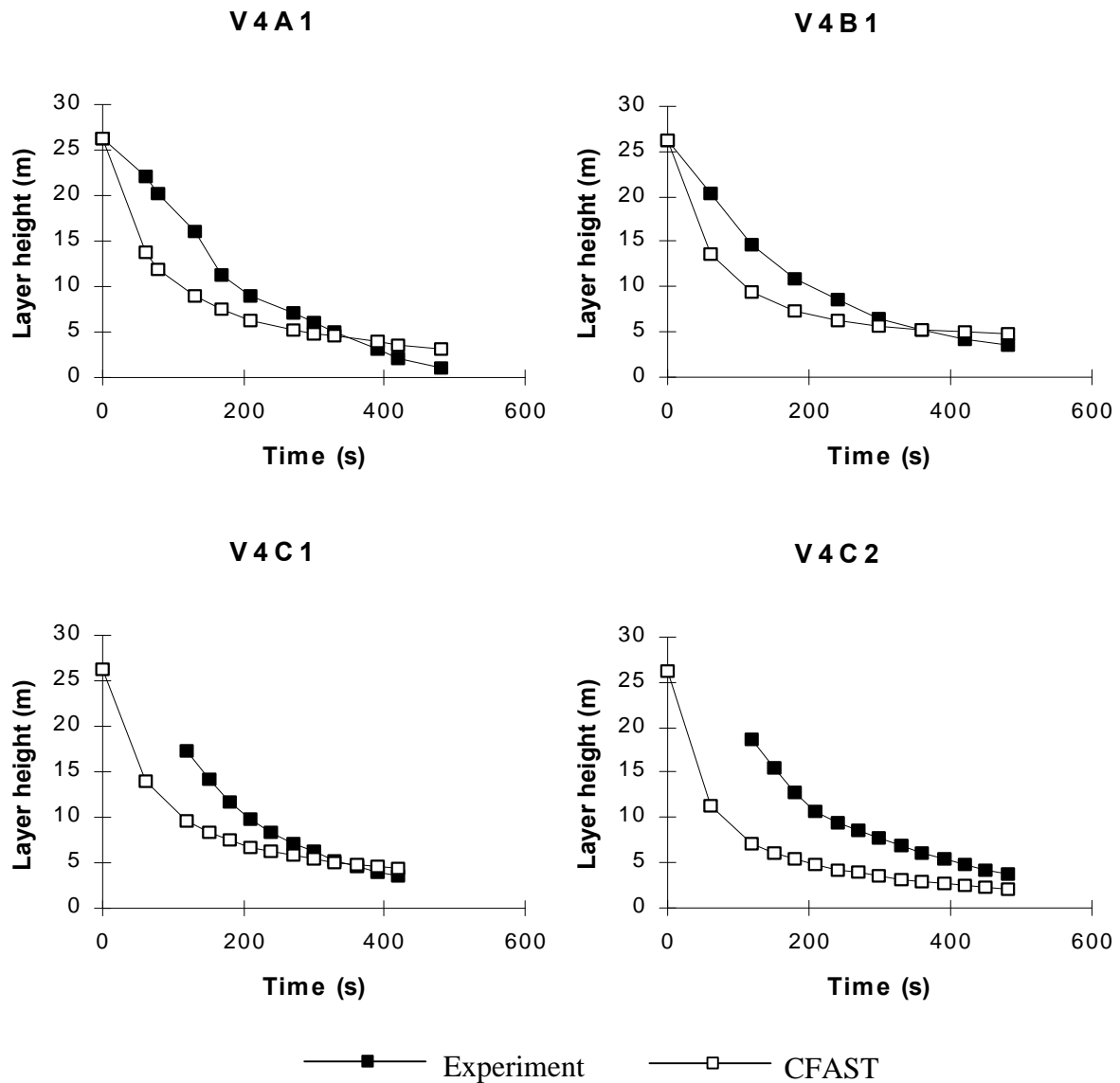
Figure 9 Height of the interface during tests A1, B1, C1 and C2 from the V4 scenario.

Comparison with scenarioV8

This comparison is in room 2 which is a corridor connected to the burn room. The experimental data points are average values from the two data sets, Vc and Vd, showed in the Appendix.
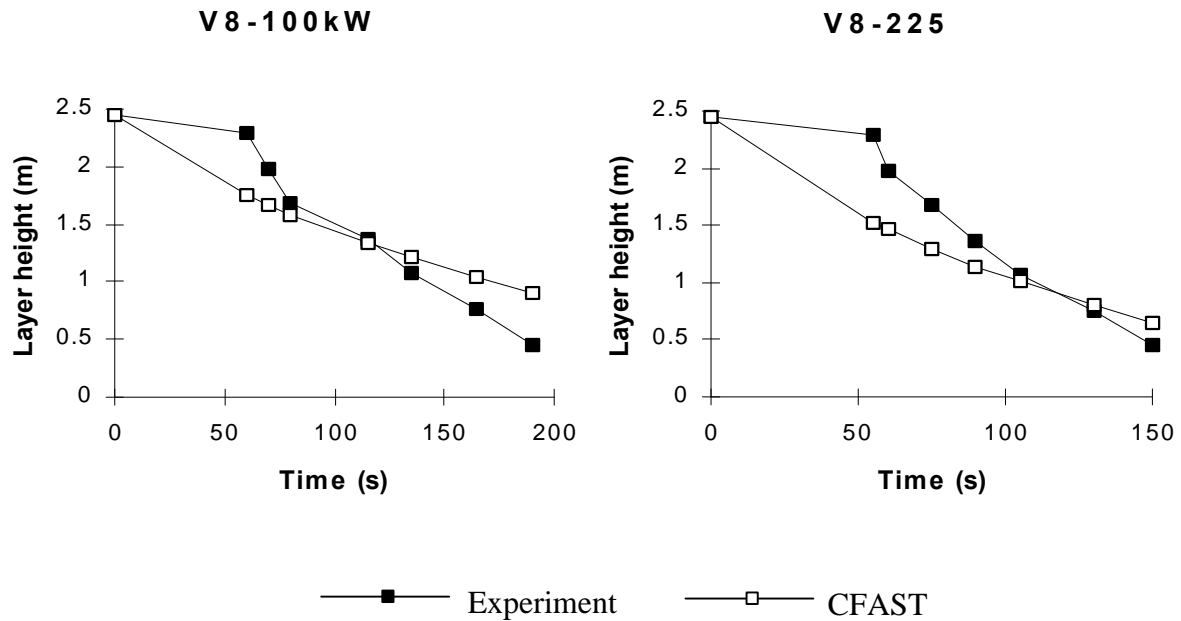
Figure 10   Height of the interface during the 100 and 225 kW tests from the V8 0 scenario.

APPENDIX C

Matlab calculations of uncertainties in temperature predictions

Scenario V1, temperature

Scenario V1 is a fire test in a single room enclosure and is described in detail in Section 2.2.

Series: V1T2, V1T3, V1T5, V1T6, V1T7
Major differences between tests: RHR
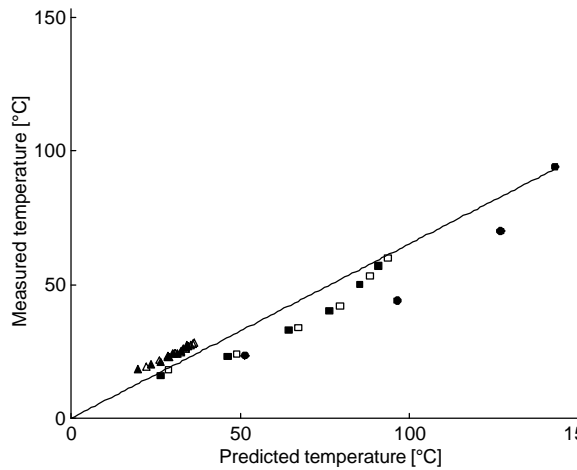
Regression curve $(T_m = \gamma^* \cdot T_p)$ and measured temperature plotted against predicted temperature
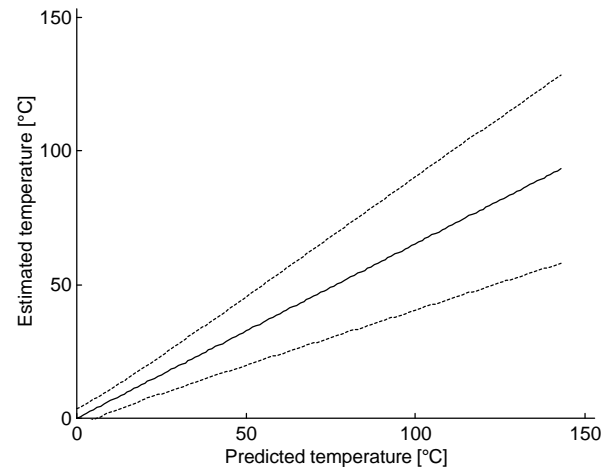
——— Mean estimate of temperature - - - - 95% prediction interval

The results from the Matlab calculation are:

$$g^* = 0.65 \qquad s_g^* = 0.052 \qquad s_e^* = 4$$

Scenario V2, temperature

In this scenario smoke spread from a small to a large room is studied. The scenario is described in detail in Section 2.3.

Series: V2T1, V2T5
Major differences between tests: RHR
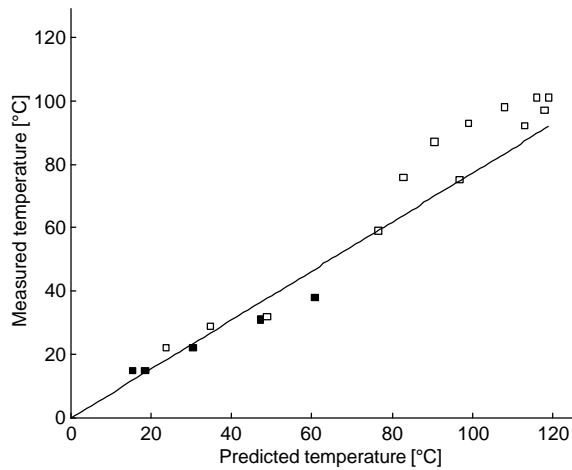
Regression curve $(T_m = \gamma^* \cdot T_p)$ and measured temperature plotted against predicted temperature
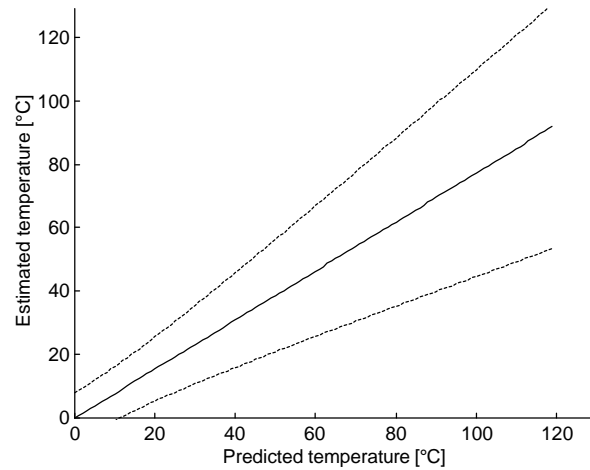
—— Mean estimate of temperature - - - - 95% prediction interval
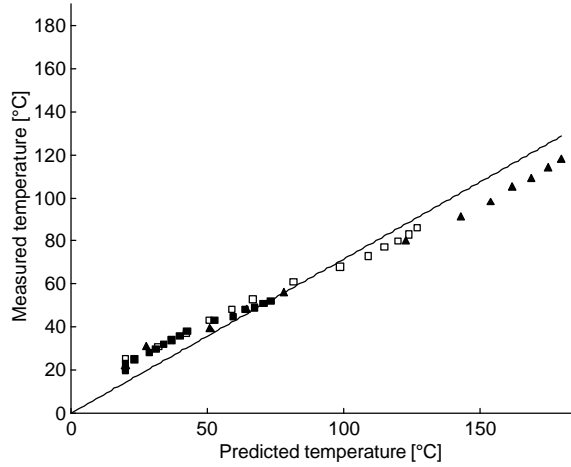
The results from the Matlab calculation are:

$$g^* = 0.77 \qquad s_g^* = 0.095 \qquad s_e^* = 6$$
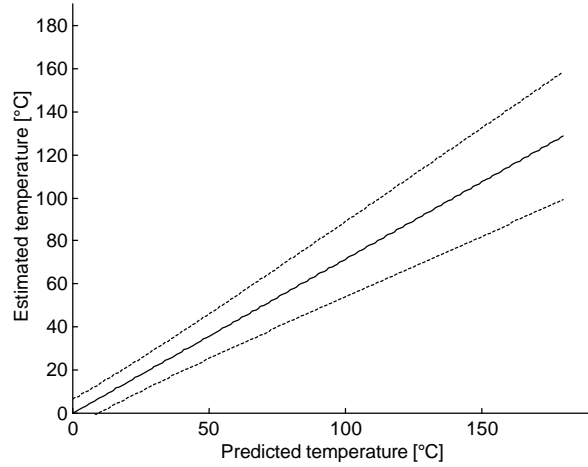
Scenario V3 room 1, temperature

The three room test including corridor is described in detail in Section 2.4.

Series: V3set1, V3set4, V3set5, V3set7, V3set8, V3set9
Major differences between tests: RHR, opened doors

Regression curve $(T_m = \gamma^* \cdot T_p)$ and measured
temperature plotted against predicted temperature

——— Mean estimate of temperature
- - - - 95% prediction interval
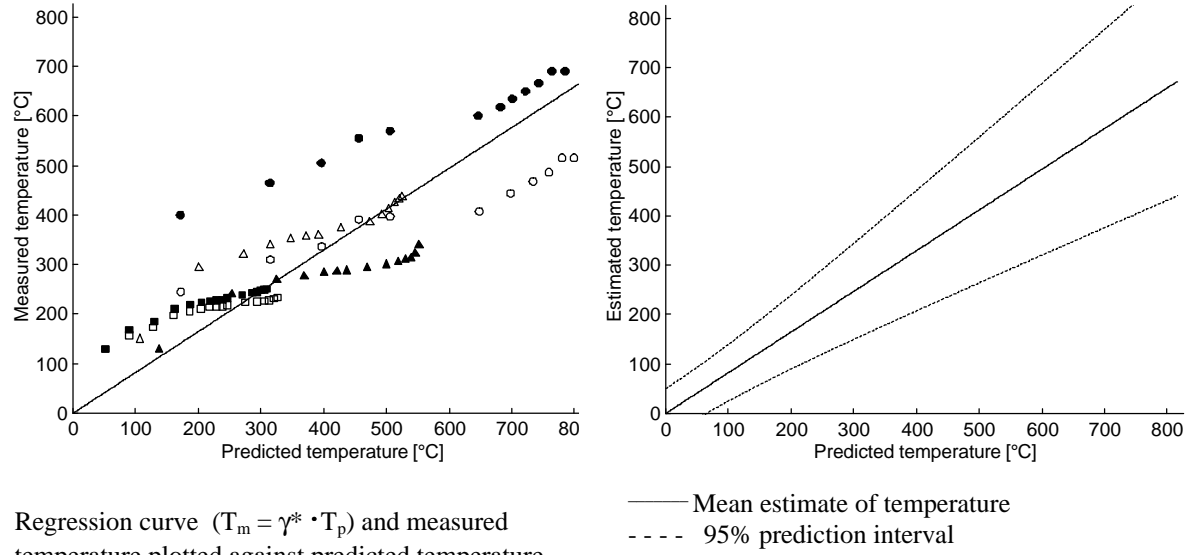
The results from the Matlab calculation are:

$$g^* = 0.82 \qquad s_g^* = 0.055 \qquad s_e^* = 62$$

Scenario V3 room2, temperature

The three room test including corridor is described in detail in Section 2.4.

Series: V3set1, V3set4, V3set5, V3set7, V3set8, V3set9
Major differences between tests: RHR, opened doors
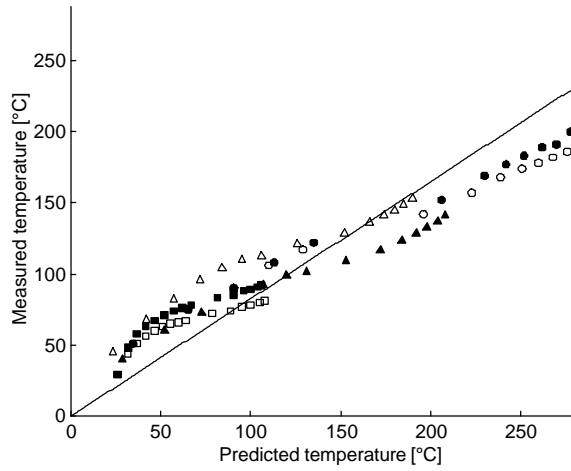
Regression curve $(T_m = \gamma^* \cdot T_p)$ and measured temperature plotted against predicted temperature
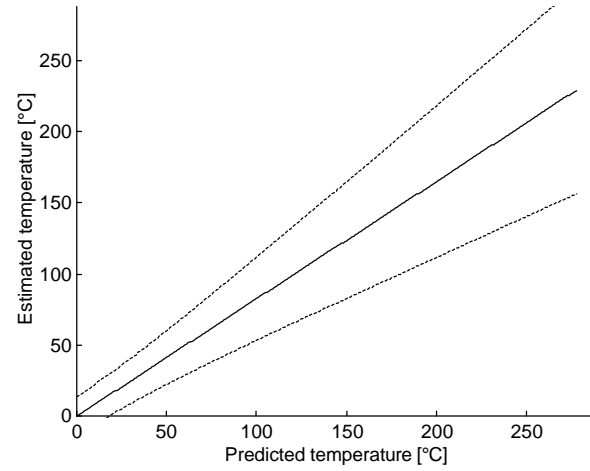
——— Mean estimate of temperature
- - - - 95% prediction interval

The results from the Matlab calculation are:

$$g^* = 0.82 \qquad s_g^* = 0.051 \qquad s_e^* = 17$$

Scenario V3 room3, temperature

The three room test including corridor is described in detail in Section 2.4.

Series: V3set4, V3set7, V3set9
Major differences between tests: RHR

Regression curve $(T_m = \gamma^* \cdot T_p)$ and measured
temperature plotted against predicted temperature

——— Mean estimate of temperature
- - - - 95% prediction interval
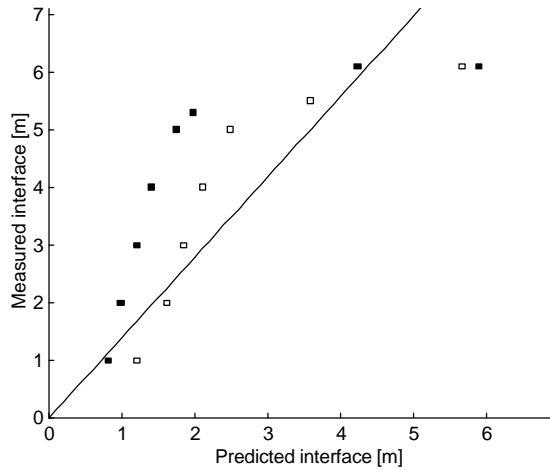
The results from the Matlab calculation are:

$$g^* = 0.72 \qquad s_g^* = 0.041 \qquad s_e^* = 6$$

APPENDIX D

Matlab calculations of uncertainties in interface predictions

Scenario V1, interface

Scenario V1 is a fire test in a single room enclosure and is described in detail in Section 2.2.

Series: V1T2, V1T3, V1T5, V1T6
Major differences between tests: RHR
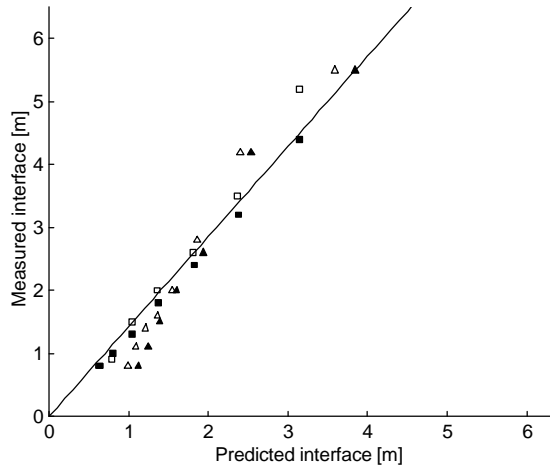
Regression curve $(I_m = \gamma^* \cdot I_p)$ and measured interface plotted against predicted interface
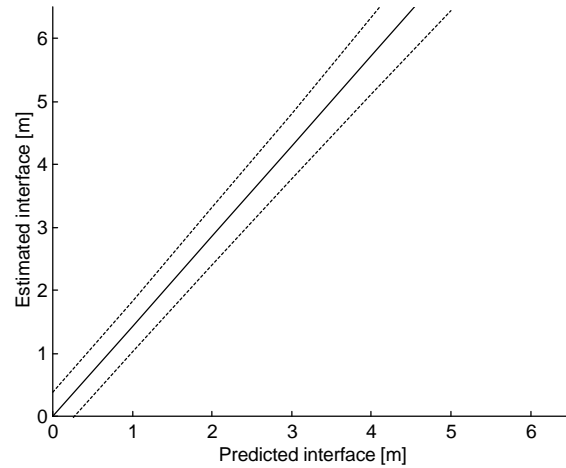
——— Mean estimate of interface
- - - - 95% prediction interval
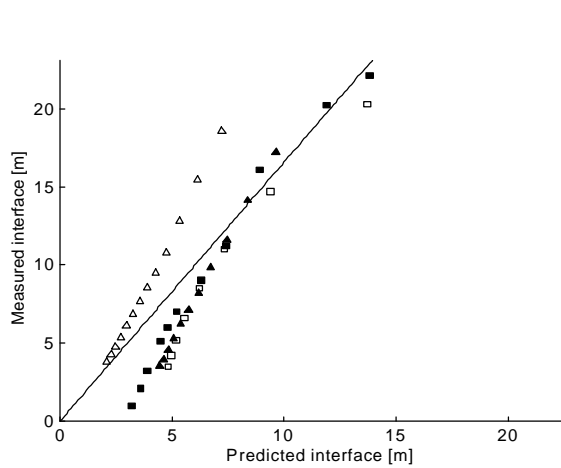
The results from the Matlab calculation are:

$$g^* = 1.4 \qquad\qquad s_g^* = 0.042 \qquad\qquad s_e^* = 0.38$$

Scenario V2, interface

In this scenario smoke spread from a small to a large room is studied. The scenario is described in detail in Section 2.3.

Series: V2T1, V2T5
Major differences between tests: RHR

Regression curve ($I_m = \gamma^* \cdot I_p$) and measured interface plotted against predicted interface
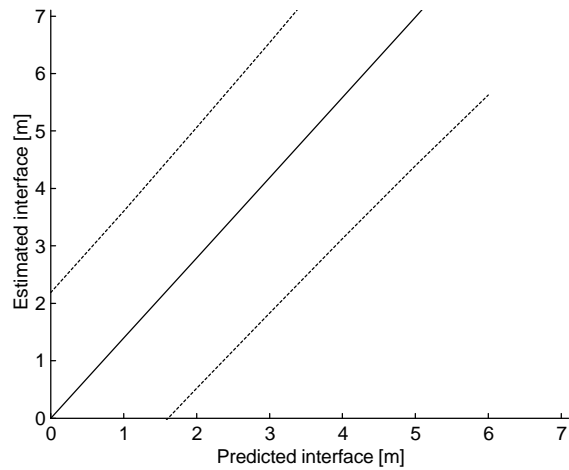
—— Mean estimate of interface
- - - - 95% prediction interval

The results from the Matlab calculation are:

$$g^* = 1.4 \qquad s_g^* = 0.14 \qquad s_e^* = 1.5$$
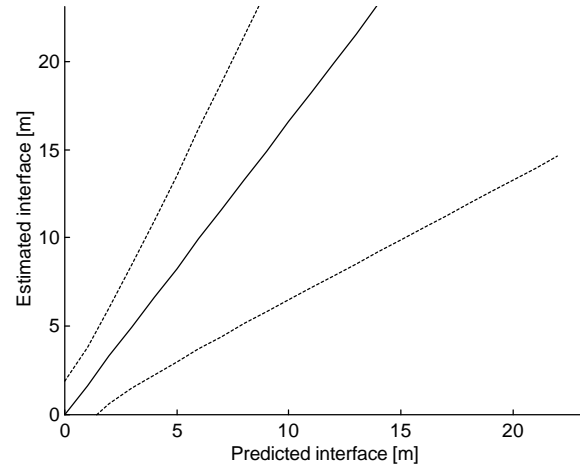
Scenario V4, interface

The scenario covers smoke control in large scale spaces and is described in detail in Section 2.5.

Series: V4A1, V4B1, V4C1, V4C2
Major differences between tests: ventilation conditions (no vent, roof vent, two fan tests)

Regression curve $(I_m = \gamma^* \cdot I_p)$ and measured interface plotted against predicted interface

———— Mean estimate of interface
- - - - 95% prediction interval

The results from the Matlab calculation are:

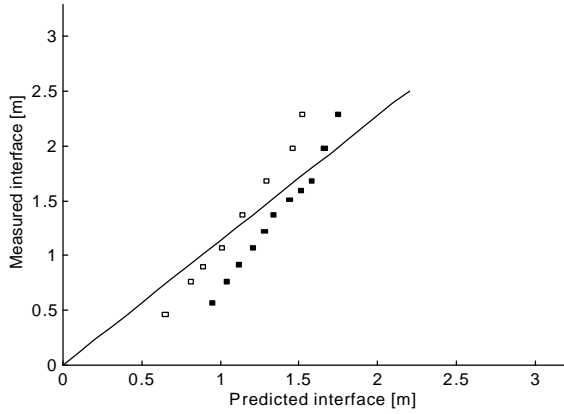$$g^* = 1.7 \qquad s_g^* = 0.23 \qquad s_e^* = 1.9$$
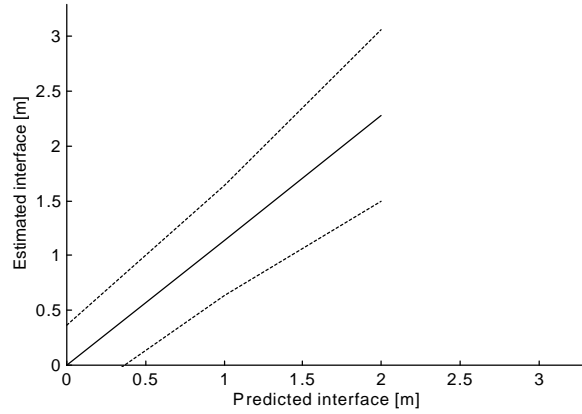
Scenario V8, interface

The scenario is a study of upper hot layer stratification and is described in detail in section 2.6.

Series: V4100, V4225
Major differences between tests: RHR

Regression curve $(I_m = \gamma^* \cdot I_p)$ and measured interface plotted against predicted interface

—— Mean estimate of interface
- - - - 95% prediction interval

The results from the Matlab calculation are:

$$\gamma^* = 1.1 \qquad s_\gamma^* = 0.10 \qquad s_e^* = 0.26$$