Fire Technology, 45, 163–177, 2009

DOI: 10.1007/s10694-008-0075-3

Comparison of FDS Prediction of Smoke Movement in a 10-Storey Building with Experimental Data

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Received: 17 December 2008/**Accepted:** 17 December 2008

Abstract. In this study, the Fire Dynamics Simulator (FDS), a computational fluid dynamics (CFD) model developed by National Institute of Standards and Technology (NIST) is used to simulate fire tests conducted at the National Research Council of Canada (CNRC). These tests were conducted in an experimental 10-storey tower to generate realistic smoke movement data. A full size FDS model of the tower was developed to predict smoke movement from fires that originate on the second floor. Three propane fire tests were modelled, and predictions of O_2, CO_2 concentrations and temperature on each floor are compared with the experimental data. This paper provides details of the tests, and the numerical modelling, and discusses the comparisons between the model results and the experiments. The 10-storey experimental tower was designed to simulate the centre core of high-rise buildings. It includes a compartment and corridor on each floor, a stair shaft, elevator shaft and service shafts. Three propane fire tests were conducted in 2006 and 2007 to study smoke movement through the stair shaft to the upper floors of the building. The fire was set in the compartment of the 2nd floor. Thermocouples and gas analyzers were placed on each floor to measure temperature and O_2, CO_2 and CO concentrations. Comparisons in the fire compartment and floor of fire show that the FDS model gives a good prediction of temperature and O_2 and CO_2 concentrations. In the stair shaft and upper floors there are some small differences which are due to the effect of heat transfer to the stairs that was not considered in the model. Overall the study demonstrates that FDS is capable of modelling fire development and smoke movement in a high rise building for well ventilated fires.

Keywords: fire safety, smoke movement, fire dynamics simulator (FDS), fire modelling

1. Introduction

Smoke movement is one of the basic and most important part of a fire risk analysis. There are many fire incidents where occupants have died due to smoke inhalation while attempting to evacuate [1]. It is therefore crucial to accurately predict smoke movement in a multi-storey building with corridors, stair shafts, and compartments, in order to undertake performance-based fire safety design or a fire risk analysis.

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Many computer models have been developed to assist fire safety researchers and engineers to predict fire growth and smoke movement from the fire compartment to other compartments in the building. These models have become important tools for performance-based fire safety design and fire risk analysis. There are mainly three different types of computer models which are used to predict smoke movement in buildings: (1) network models; (2) zone models; and (3) computational fluid dynamic (CFD) models [2].

The Fire Dynamics Simulator (FDS) is a powerful CFD model developed at the National Institute of Standards and Technology (NIST). "The model solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flows with an emphasis on smoke and heat transport from fires" [3].

In this paper, a full size FDS model was developed to predict smoke movement in an experimental 10-storey tower. Three propane fire tests conducted by Yan [4] in this tower are simulated using FDS Version 5. Comparisons of FDS predictions with the data from these tests are presented in this paper.

2. Description of the Facility

The 10-storey experimental facility located at the fire research laboratory of the National Research Council of Canada (CNRC) in Almonte, Ontario was used to conduct the tests that simulate heat and smoke movement in multi-storey buildings. The tower has a number of compartments on each floor. The floor plans of the test facility are shown in Figures 1 and 2. The ceiling height of the 1st and 2nd floors is 3.35 m and the ceiling height of all other floors is 2.4 m.

Three propane fire tests (PP1, PP2, PP3) were conducted study smoke movement through the stair shaft of multi-storey buildings. The open/closed conditions of doors during the tests are shown in Table 1. Fresh air enters from the first

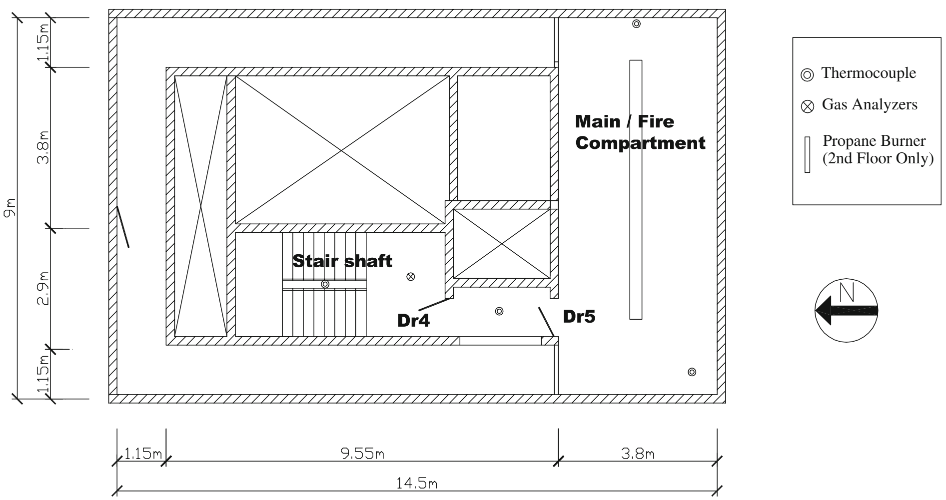

Figure 1. Typical floor plan.

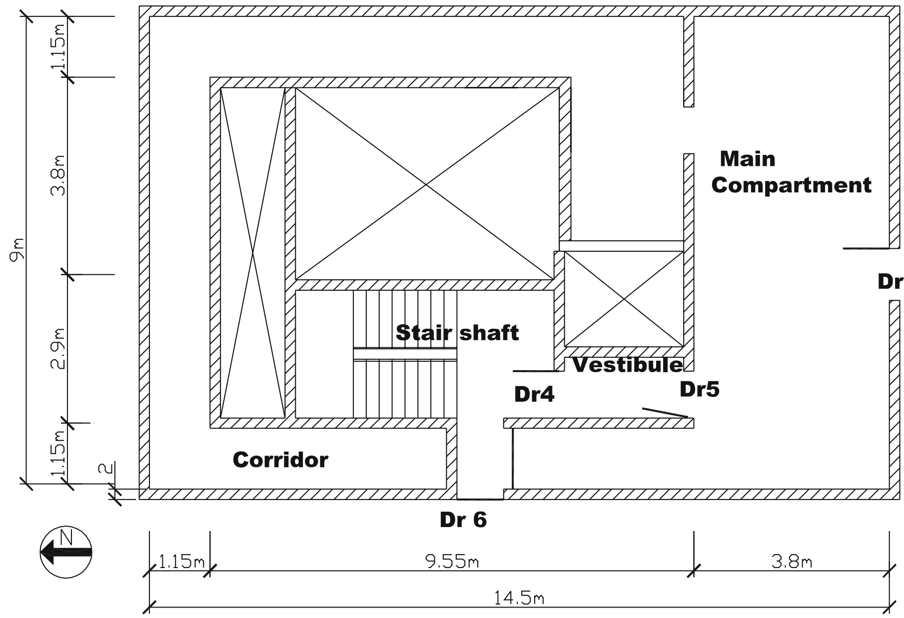

Figure 2. First floor plan.

Table 1
The Open/Closed Condition of Doors

Floor	DR4	DR5	Note
10F	Open	Partly open	–
9F	Closed	Open	–
8F	Open	Partly open	–
7F	Closed	Open	–
6F	Open	Partly open	–
5F	Closed	Open	–
4F	Open	Partly open	–
3F	Closed	Open	–
2F	Open	Open	–
1F (PP1&PP2)	Open	Open	DR2 Open DR6 Closed
1F (Test PP3)	Closed	Closed	DR2 Closed DR6 Open

floor, moves through the stairshaft and reaches the fire compartment. Smoke moves upwards through the stairshaft to the compartments with door open. The expected smoke movement is shown in Figure 3.

The fire was located in the main compartment of the 2nd floor. The fire compartment is $9 \times 3.8 \times 3.35$ m high. The fire was produced using a propane burner. The surfaces of the fire compartment and the 2nd floor vestibule were covered by one-inch thick ceramic fibre insulation. Elsewhere, the walls and floors are exposed concrete surfaces.

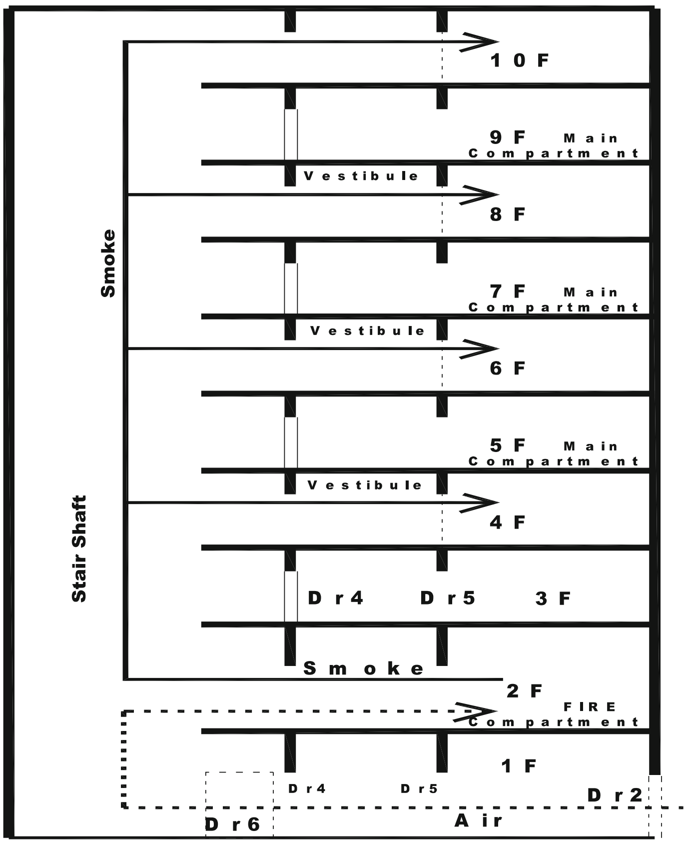

Figure 3. Direction of smoke movement.

Thermocouples and gas analyzers were used to record gas temperatures and concentrations of O_2, CO and CO_2. Two thermocouple trees were placed in the southwest corner and east side of the fire compartment to record the temperature profile of the compartment. Another thermocouple tree was located in the doorway between the vestibule and the stair shaft of the 2nd floor.

A thermocouple was also placed in the middle of the stair shaft and below the ceiling of the vestibule and main compartment of each floor from the 1st to the 10th floor. Gas analyzers were placed in the vestibule and stairshaft of each floor. Details of the test instrument set-up can be found in Yan's thesis [4]. The experimental data obtained from these tests are compared with the predictions of FDS.

3. Description of the FDS Model

The FDS model of the building is enclosed within a 15 m × 9 m × 28.8 m tall rectangular volume. This volume was divided into 486,000, 0.2-m × 0.2-m × 0.2-

m cells. A 5.0 × 0.4-m vent was put in the fire compartment on the second floor to model the fire. The same fuel supply flow rate as in the experiment was modelled by describing the mass flow rate of propane measured by the flow metre during the experiment. The combustion properties of propane are given in Table 2. The heat release rate of the fire is shown in Figure 4.

The size of the walls, doorways, and openings were based on the dimensions of the building rounded to nearest cell size (0.2 m). The walls and floors of the ten-storey tower are made of concrete and the doors are made of wood. The material properties used in the model are shown in Table 3.

Table 2
Combustion Properties of Propane [5]

Fuel	Heat of combustion (kJ/kg/K)	Soot yield factor Y_s (g/g)	CO yield factor Y_{co} (g/g)
Propane	4.37	0.024	0.005

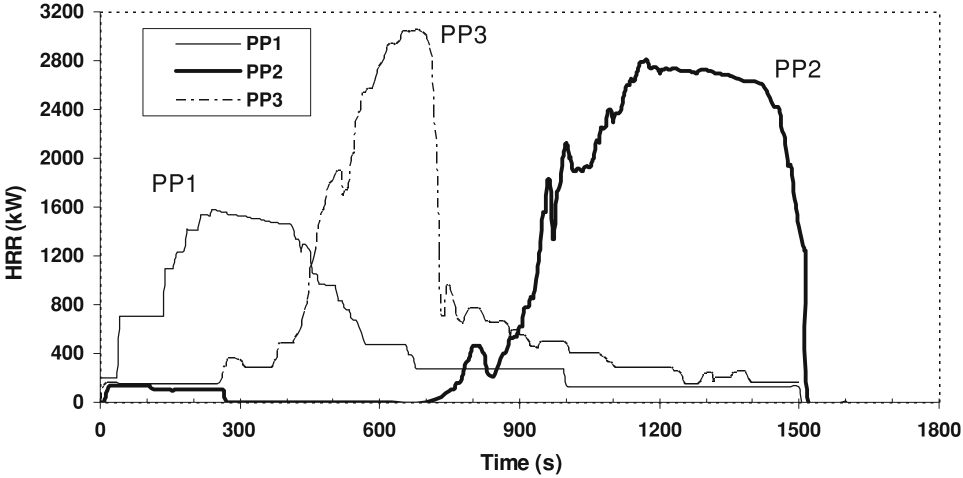

Figure 4. HRR of Propane Test.

Table 3
Material Properties Used in Model

Item	Material In FDS	Thickness (m)	Density [5] (kg/m3)	Specific heat [5] (kJ/kg/K)	Thermal conductivity [5] (W/m/K)
Wall/Floor/Ceiling	Concrete	0.2	2,200	0.88	1.37
Stairs	Steel	0.08	7,830	0.47	43
Doors	Wood	0.1	420	2.70	0.11
Isolation of fire compartment	Adiabatic	–	–	–	0

Thermocouples and gas analyzers were set at the same positions as in the experiment to record gas temperatures and concentrations of O_2, and CO_2. These results are compared with the experiment data.

4. Comparison of Results

The predicted data are compared with the experimental data to determine how well the FDS model can predict smoke movement in a high rise building.

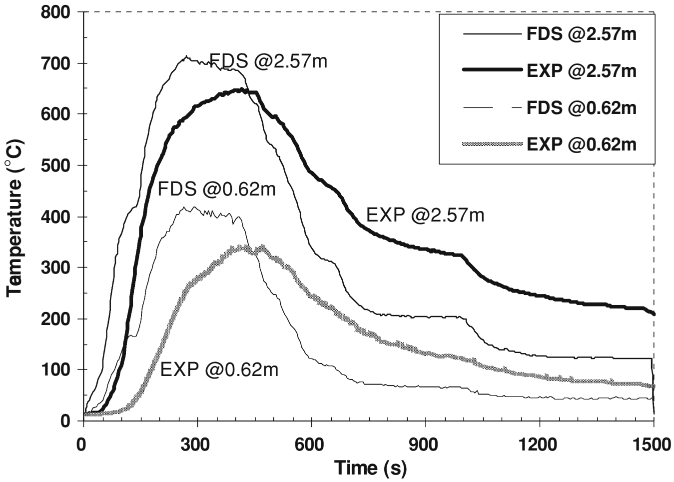

Figure 5. Temperature in fire compartment PP1.

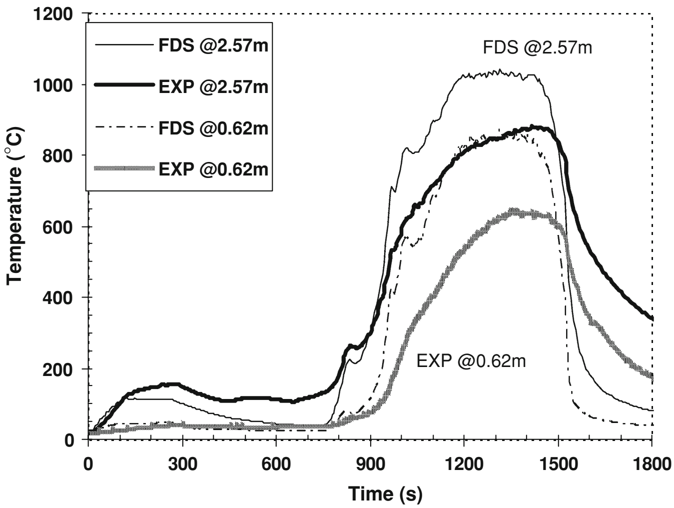

Figure 6. Temperature in fire compartment PP2.

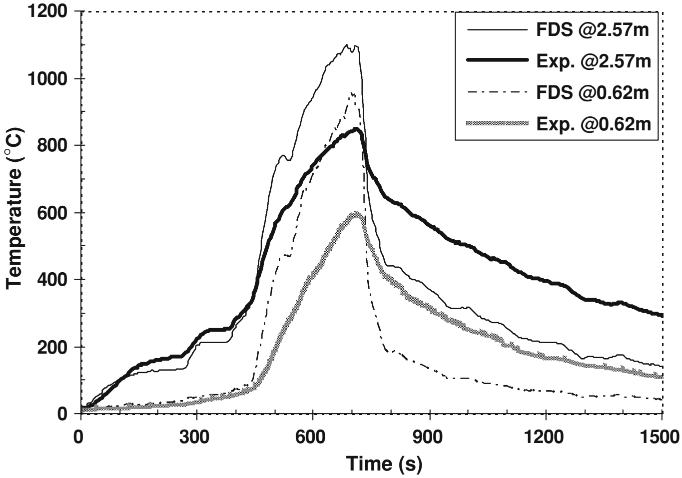

Figure 7. Temperature in fire compartment PP3.

Figures 5–7 compare the predicted and the experimental upper layer temperatures in the fire compartment for the three tests. Theses figures show that the predicted and the experimental results compare very well. The model predicted that temperatures increase faster than the experimental data. One reason for this may be the fact that heat losses through the ceramic fiber, which covered fire compartment walls, were ignored in the model.

The figures also show that the difference between the experimental and predicted temperatures is greater at lower heights. For example in Test PP3 the

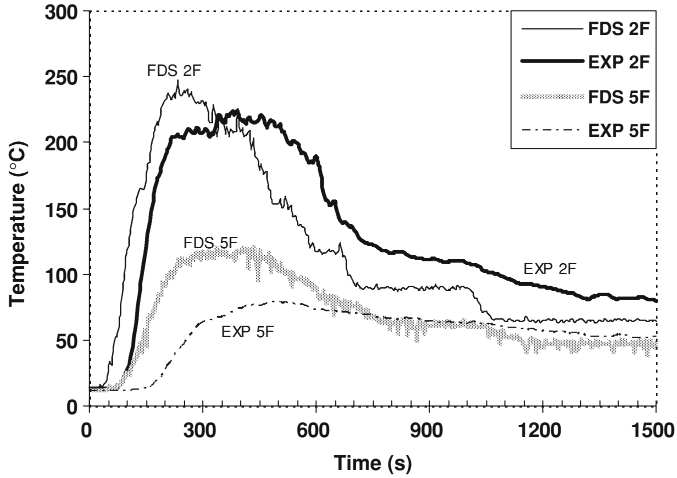

Figure 8. Temperature in stairshaft PP1.

model predicted a peak temperature at 0.62 m of 948°C, and the experimental result is only 592°C.

Comparisons of the predicted and the experimental temperatures in the stairshaft are shown in Figures 8–12 for the three tests respectively. The peak temperatures in the stairshaft predicted by FDS are a little higher than the experimental results. This difference was expected as heat losses through conduction to the stairs were not considered in model. These losses may be significant as the stairs are made of steel.

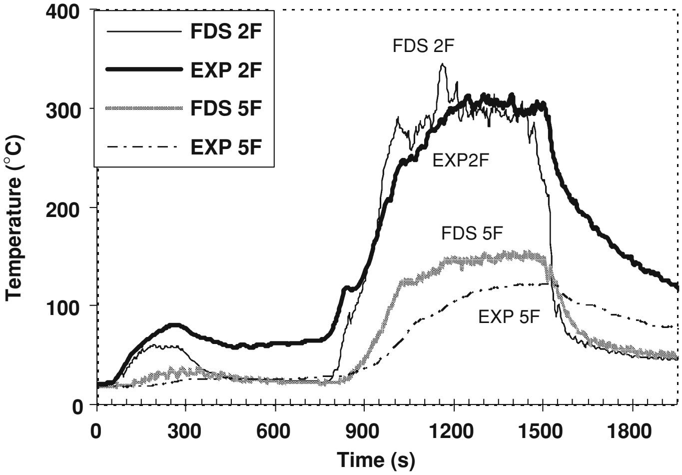

Figure 9. Temperature in stairshaft PP2 (2F&5F).

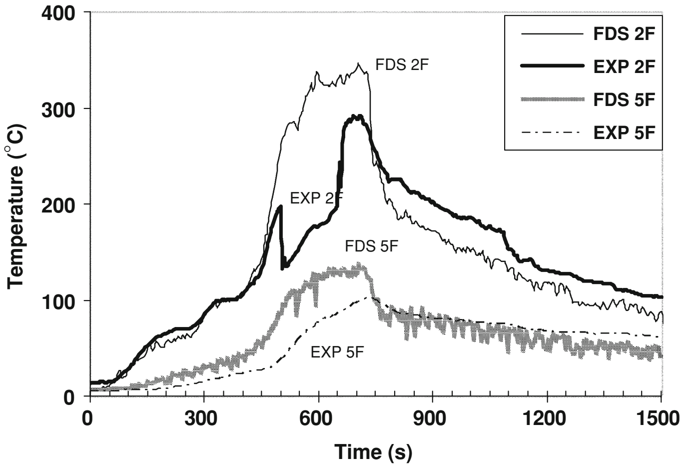

Figure 10. Temperature in stairshaft PP3(2F&5F).

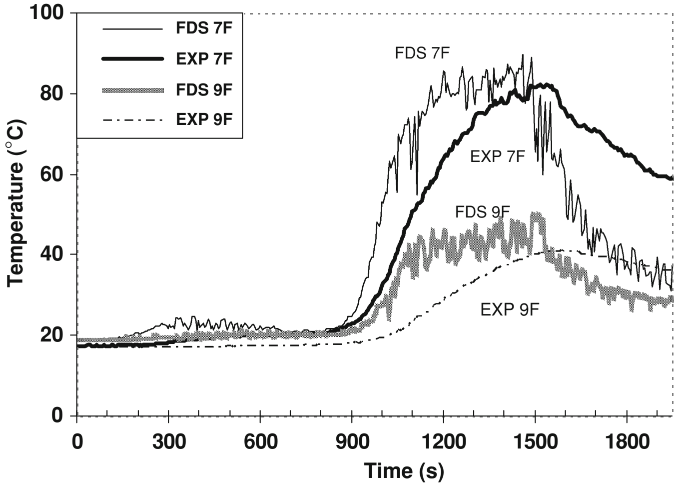

Figure 11. Temperature in stairshaft PP2 (7F&9F).

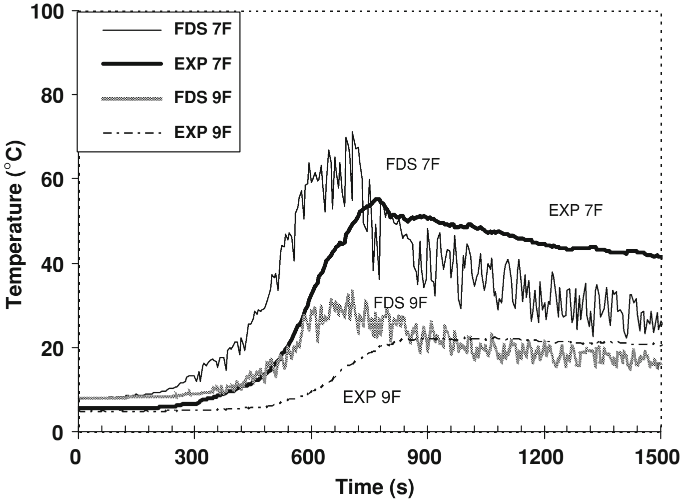

Figure 12. Temperature in stairshaft PP3 (7F&9F).

Table 4 shows temperatures in the stairshaft at different heights and times. The results show that in both the experiments and the model results the temperature in the stairs decrease with height. This trend is seen at even 1,500 s. So, although hot gases move upwards, due to the losses to the stairshaft walls and mixing with air the temperature of the hot gases decreases as the gases move up the stairshaft.

Figure 13 shows smoke distribution in the stair shaft. Smoke slowly moves upwards through the stairshaft and fills the main compartment on each floor one

Table 4
Temperatures in the Stairshaft

Test	Time	Temperature °C									
		St-01	St-02	St-03	St-04	St-05	St-06	St-07	St-08	St-09	St-10
	FDS 300 s	13	231	197	157	116	79	48	30	30	24
PP1	EXP 300 s	–	207	139	95	64	48	30	20	15	14
	FDS 600 s	13	118	138	107	89	70	46	42	28	29
	EXP 600 s	–	189	126	94	74	62	49	37	26	23
	FDS 1200 s	19	309	289	202	145	109	86	59	45	39
PP2	EXP 1200 s	22	299	192	141	103	83	64	43	28	25
	FDS 1500 s	19	226	252	187	142	110	66	67	49	41
	EXP 1500 s	23	305	204	156	122	105	82	58	40	34
	FDS 600 s	8	334	198	182	125	89	60	42	29	21
PP3	EXP 600 s	7	177	164	118	77	57	33	18	9	7
	FDS 900 s	8	172	116	109	80	56	43	34	19	20
	EXP 900 s	7	202	138	108	81	67	51	35	22	17

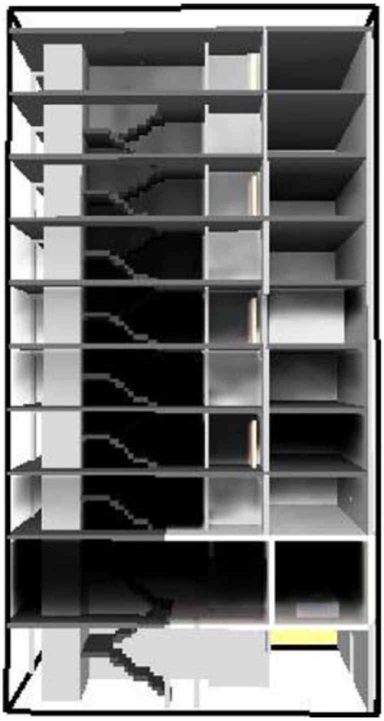

Figure 13. Smoke movement of test PP2.

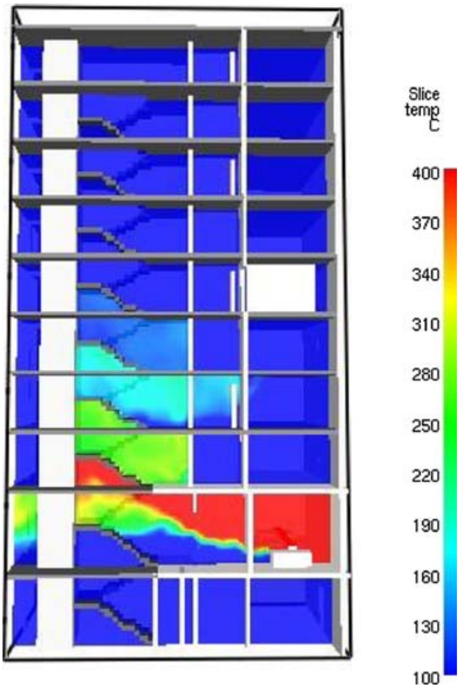

Figure 14. Temperature distribution in the stair shaft PP3.

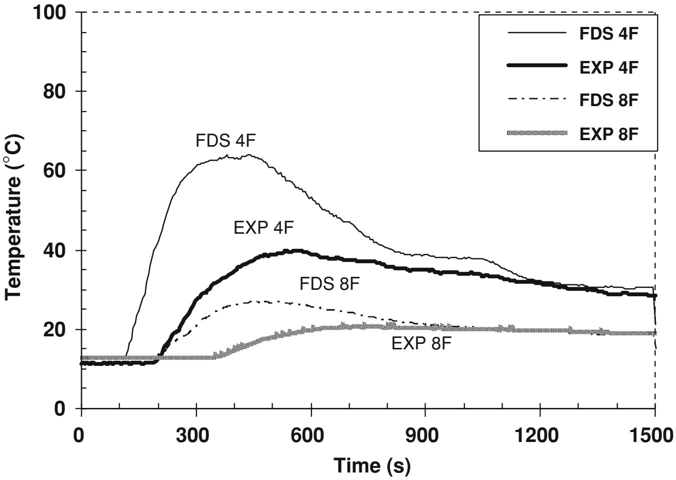

Figure 15. Temperatures in main compartments PP2.

by one from the lower to the upper floors. Some smoke also enters the 3rd and 5th floor compartments through the gap around the stair shaft door.

Figure 14 shows the temperature distribution in the stair shaft. It can be seen that a hot gas layer forms under the stairs at the 2nd floor level. This indicates that the stairs play an important role in the movement of smoke in the stairshaft and cause significant mixing.

Figures 15–17 compare the predicted and the experimental temperatures in the main compartment on floors that had the door partially open. The temperatures predicted by FDS are higher than the experimental results, which is due the higher predicted smoke temperatures of the fire compartment and the stairshaft. It may

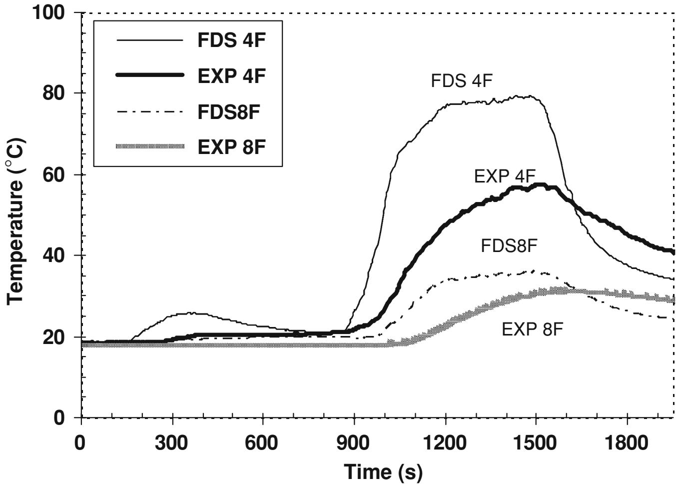

Figure 16. Temperatures in main compartments PP3.

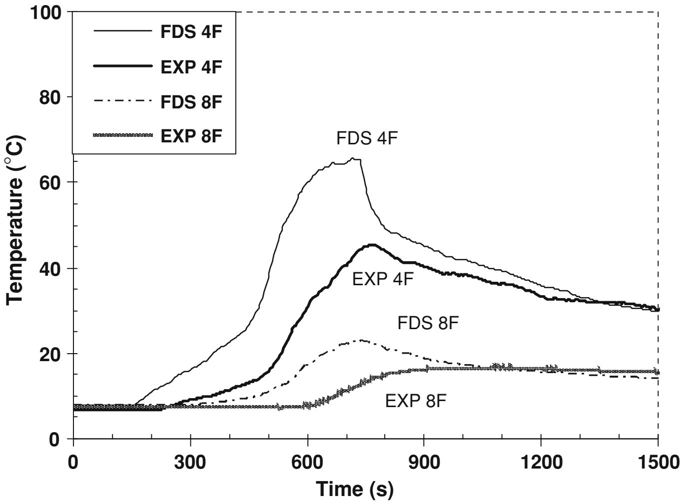

Figure 17. Temperature in main compartments PP3.

also be due to the fact that the opening of Door 5 in the model is a little larger than the actual opening since the opening boundaries are adjusted to fit the grid. This allows more hot gases to enter the compartment causing a higher temperature.

Figures 18–20 compare concentrations of O_2 and CO_2 in the stair shaft at the fire floor for Tests PP1, PP2 and PP3. The comparisons show that FDS provides a good prediction of O_2, and CO_2 concentrations.

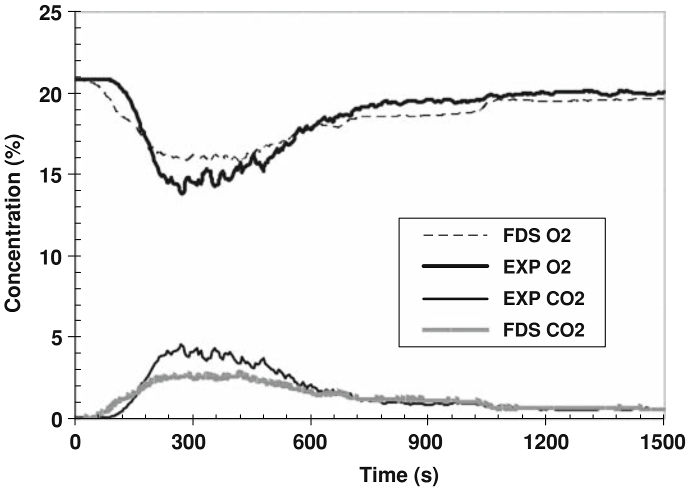

Figure 18. Concentrations of O2 and CO2 in stairshaft PP1.

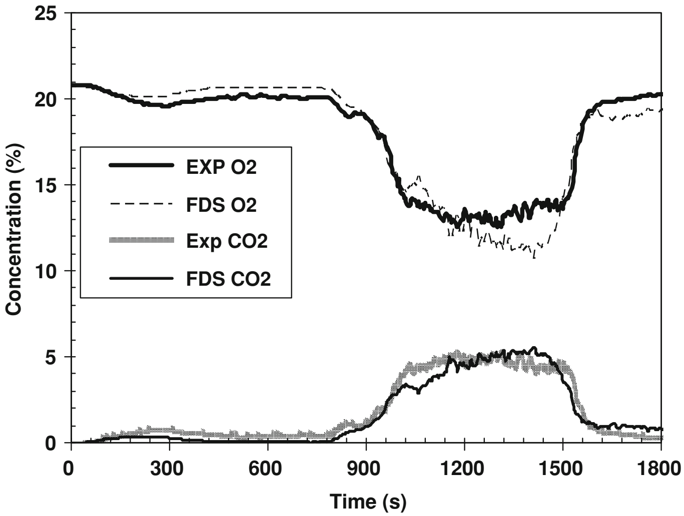

Figure 19. Concentrations of O_2 and CO_2 in stairshaft PP2.

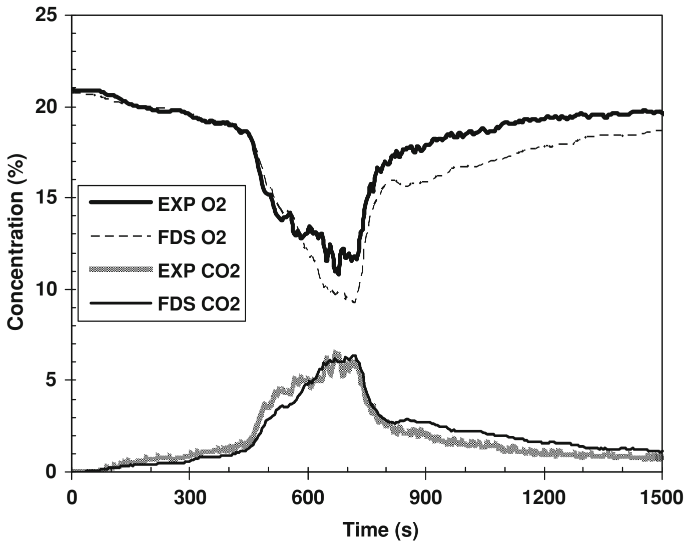

Figure 20. Concentrations of O_2 and CO_2 in stairshaft PP3.

5. Summary

The aim of this study was to demonstrate whether CFDs models can be used to simulate fires in high rise buildings. It is shown that FDS can be used to model fires and smoke movement in these buildings.

The comparisons between the model predictions and experimental data indicate that FDS gives a very good prediction of the conditions on the fire floor. The comparisons in the stairshaft and upper floors are also satisfactory given that the model could not consider heat conduction losses to the metal stairs. As a result, the predicted temperatures in the stairshaft and the compartments of upper floors are higher than the experimental temperatures. The predicted and measured O_2 and CO_2 concentrations are also in good agreement with the experimental data.

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