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COMPARISON OF CFD MODELLING WITH FIRE TESTS
Comparison of CFD Modelling with Results of Full Scale Compartment Fire Tests in a Residential Unit

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Abstract

Two full-scale fire tests were carried out in a derelict apartment block in Bytom (Poland). The primary objective of the tests was to investigate gas temperatures and toxicity conditions during compartment fires in residential units which underwent energy-efficiency improvement works. Such units are typically better sealed and better insulated, in order to reduce heat losses through gaps in the doors, windows and walls. During the tests detailed temperature measurements were collected for both the well-sealed compartment scenario and the benchmark test with included a defined amount of openings in the fire compartment.

As a supplementary activity to the main topic of the research it was decided to carry out a-priori and a-posteriori modelling of the thermal conditions within the compartment, using a CFD software package called Fire Dynamics Simulator (FDS). The main purpose was to validate the software for modelling of under-ventilated fires, as the reliability of CFD models in this application is often questioned. The results of the comparison are herewith discussed.

Keywords: full scale fire tests, compartment fires, CFD modelling, software validation

INTRODUCTION

Due to increasing energy costs and more onerous requirements for thermal efficiency many existing buildings in Poland are currently being improved with respect to insulation properties of the enclosures as well as their air-tightness. This process (often referred to as thermo-modernization) is beneficial in terms of the environmental performance of the residential units. However, it is believed that the reduced ventilation rate within the units can increase the risk of carbon-monoxide poisoning in flats equipped with individual gas boilers or stoves and that it can affect tenability conditions in the event of a fire.

On 20 September 2012 two fire tests were carried out in order to examine fire development in real-life conditions. The first test was conducted inside a residential unit with a high degree of air tightness, the second one in a reference unit with typical leakage-paths and openings. The scope of the tests included the analysis of four parameters of fire development, i.e. temperature, toxicity, visibility and pressure (Sekret and Saleta, 2012).

As an additional element of this research work comparisons are being made between experimental results and numerical predictions, in order to validate selected CFD software packages for modelling of under-ventilated compartment fires.

Analysis of the impact of high temperature and concentration of toxic products of combustion on evacuation conditions for the occupants is also being undertaken however it is outside the scope of this paper.

The tests were organized and carried out by the Department of Heating, Ventilation and Air Protection in the Faculty of Environmental Engineering and Biotechnology at Czestochowa University of Technology and Municipal Headquarters of National Fire Service in Bytom with a cooperation of 17 partners representing various industries, i.e. public administration, rescue services including mining rescue unit, research organisations dealing with fire safety engineering in construction and last but not least the leading fire safety companies in Poland.

1 EXPERIMENTAL SETUP

The tests were conducted in a derelict apartment building, situated in Bytom (Silesian Voivodeship). Characteristics of the apartment building:

- five-storey apartment block built in late seventies, prefabricated reinforced concrete structure (walls and floor slabs) with lightweight concrete infill walls;
- due to structural damage (i.e. wall cracks, expansion joint damage etc.) caused by mining exploitation, the building was vacated and earmarked for demolition;
- the tests were carried out in the gable wall apartment block.

Two fire tests in two residential unit of the same layout were conducted: test number one was a was sealed-room fire on the fourth floor, test number two was a normal (non-sealed) room fire on the second floor. Residential units used for the fire tests were as follows:

- 4th floor flat with total floor area of approx. 37 m^2 and the volume of approx. 91 m^3; the fire test was carried out from in the sitting room of 15,41 m^2.
- 2nd floor flat with total floor area of approx. 38 m^2 and the volume of approx. 94 m^3; the fire test was carried out in the sitting room of 15,41 m^2.

Each residential unit consisted of: a sitting room (15,41 m^2), a bedroom (9,88 m^2), a kitchen (5,07 m^2), a bathroom (3,30 m^2) and an entrance hall (3,93 m^2).

Fig. 1 External view of the building

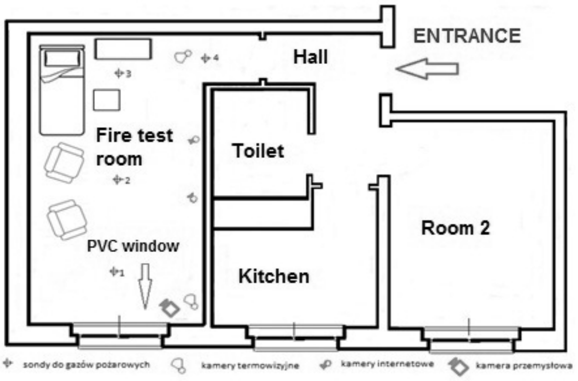

Fig. 2 Geometry of the apartment (test no.1)

During the fire tests temperature inside the compartment was measured using thermocouple trees and infrared cameras. The temperature data was recorded with thermocouples inside the fire room and additional thermocouples positioned outside the building.

- thermocouples t1 and t2 fixed at 200 cm.
- thermocouple t3 fixed at 150 cm.
- thermocouple t4 and thermocouple tree t5 with 3 measurement point – were measuring the parameters of external environment in the vicinity of the window.
- thermocouple trees t6, t7, t8, t9 with 6 measurement points at 110 cm, 150 cm,190 cm, 215 cm, 230 cm, 245 cm.

In the first fire test flat door and entrance door to the staircase were closed, whereas doors in a flat were open. In the second fire test all doors in a flat were open and the window was open 15 cm wide. Data loggers and other recording equipment were located in flats directly below the test location.
Both tests were ignited with a small wood crib (BS 5852, „wood crib 7"), placed on the central arm-chair.

In the first test (sealed room) the fire has quickly involved the entire chair and has then subsided due to lack of oxygen. The chair initially ignited was completely burnt in the test. The bed positioned next to the chair was also ignited and partially burnt during the 30 min duration of the test. Other items placed in the room (i.e. the second chair, the coffee table and the book-case with books / cardboard boxes) were not ignited.

Fig. 3 Experimental set-up for test no.1

Fig. 4 Fire compartment after test no.1

In the second test (room with limited ventilation) the initial fire growth was slightly slower, probably due to a quicker collapse of the source crib. After involving the first char the fire has spread to the adjacent bed which was also totally burned during the 30 minutes of the test. Other items placed in the room were not ignited (except for limited charring at edges).

Fig. 5 Experimental set-up for test no.2

Fig. 6 Fire compartment after test no.2

Both fires were extinguished by the fire brigade personnel after 30 minutes of the test.

2 NUMERICAL MODELLING

Numerical modelling of the fire scenarios corresponding to the two fire tests was carried out using CFD software package called Fire Dynamics Simulator (FDS, version 5). Detailed information about the programme can be found in the User's Manual and the Technical Reference Guide (McGrattan et al., 2010).

The computational domain was set-up to include the geometry of the relevant areas of the fire test apartment. In all simulations a uniform mesh was adopted. Simulations were run using a coarse mesh (10 cm) and a fine mesh (5 cm), resulting in the total number of 147,456 grid cells and 1,179,648 grid cells respectively.

The initial fire was defined as an input, based on the HRR curve obtained from literature. The fire curve selected was a fire test of a single 2-cushion mock-up chair, with peak heat release rate of 260 kW, attained after 5 minutes (Sardqvist, 1993).

Thermal and ignition properties were applied to obstacles defining adjacent objects such as the bed, the second chair and the bookcase so as to allow fire spread from the initial object to the remaining items in the fire room. As the exact properties of the materials used in the tests were not known (i.e. they were not measured), the values used in the simulations were based on the data available in the literature (e.g. Drysdale, 1998).

Combustion was modelled using the default mixture fraction model (a single-step reaction, with local extinction). Default values of the critical flame temperature and lower oxygen limit parameters were used (1427 ^{o}C and 0.15 respectively).

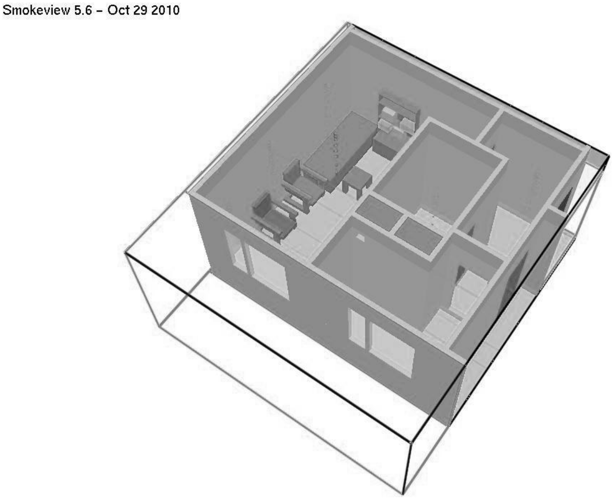

Fig. 7 Geometry of the CFD model

It should be noted that in the post-test simulations the ignition properties of some of the materials were adjusted, in order to achieve better qualitative agreement with fire development observed in the tests. In particular, slightly lower ignition temperatures were adopted compared to the values suggested in the literature.

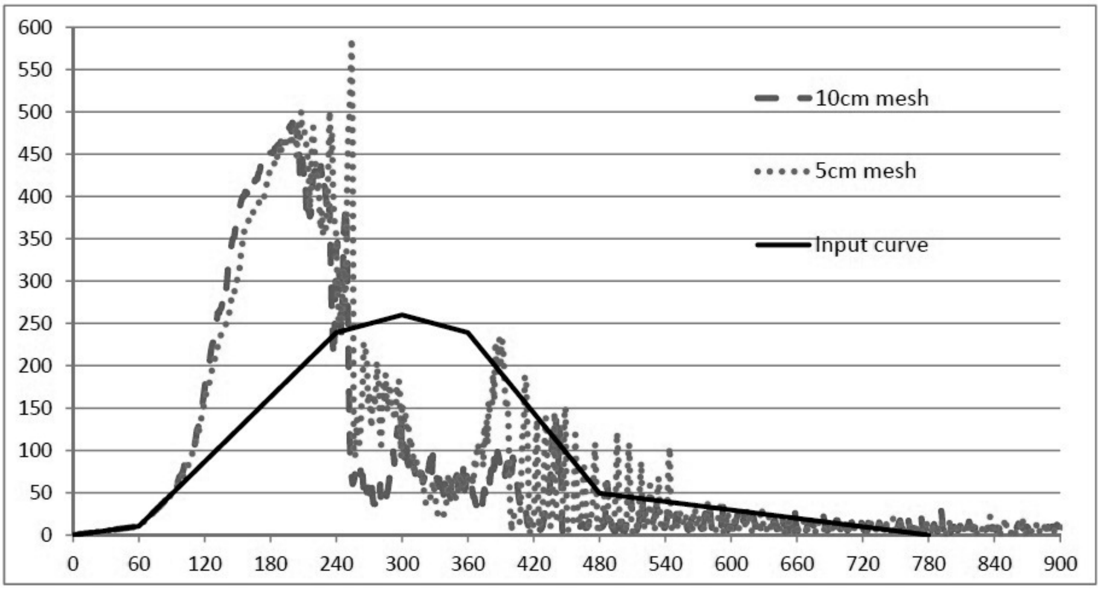

Fig. 8 Comparison of the HRR (in kW) calculated in the simulations for the sealed room scenario with the input curve of a single chair (HRR in kW, time in seconds)

The ventilation conditions in the model were set to replicate the conditions applied in the test. For the fully sealed fire test scenario the only significant opening (leakage path) in the compartment was a ventilation grille in the kitchen.

The rate of hear release computed in the simulation exceeded the growth rate of the initial fire (which was applied as a boundary condition to the top surface of the horizontal cushion of the central chair), which is due to adjacent combustibles being also ignited. After approximately 3.5 minutes the conditions become strongly under-ventilated, which can be seen on the HRR graphs for both 5cm and 10 cm mesh simulations (see Fig. 8).

3 COMPARISON OF CFD PREDICTIONS WITH EXPERIMENTAL RESULTS

Numerical simulations were carried out for both the sealed room scenario and the test with additional ventilation paths introduced (window opening, door gaps etc.). This paper will focus on the comparison of the temperature predictions for the sealed compartment scenario (test no.1) as it better highlights the issues arising with modelling of strongly under-ventilated compartment fires.

Fig. 9 and 10 present comparisons of the hot layer temperatures measured in test no. 1 with the values predicted in the simulations, for 10 cm and 5 cm mesh. The values refer to the thermocouple tree located centrally in the room, approx. 1 m away from the first ignited chair.

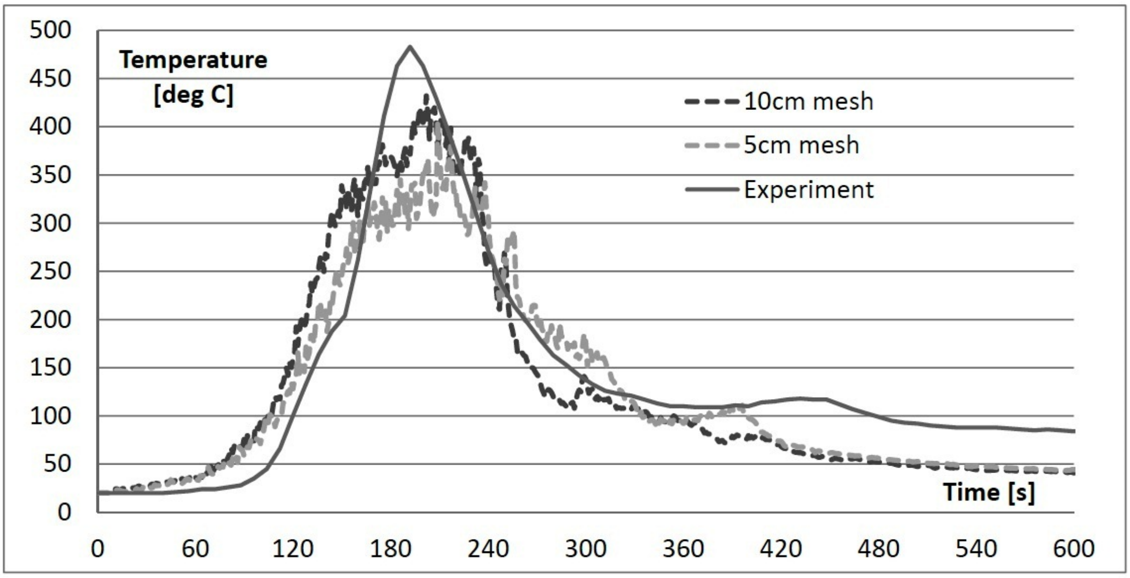

Fig. 9 Temperature 2.40 m above the floor – FDS prediction vs. experimental measurement

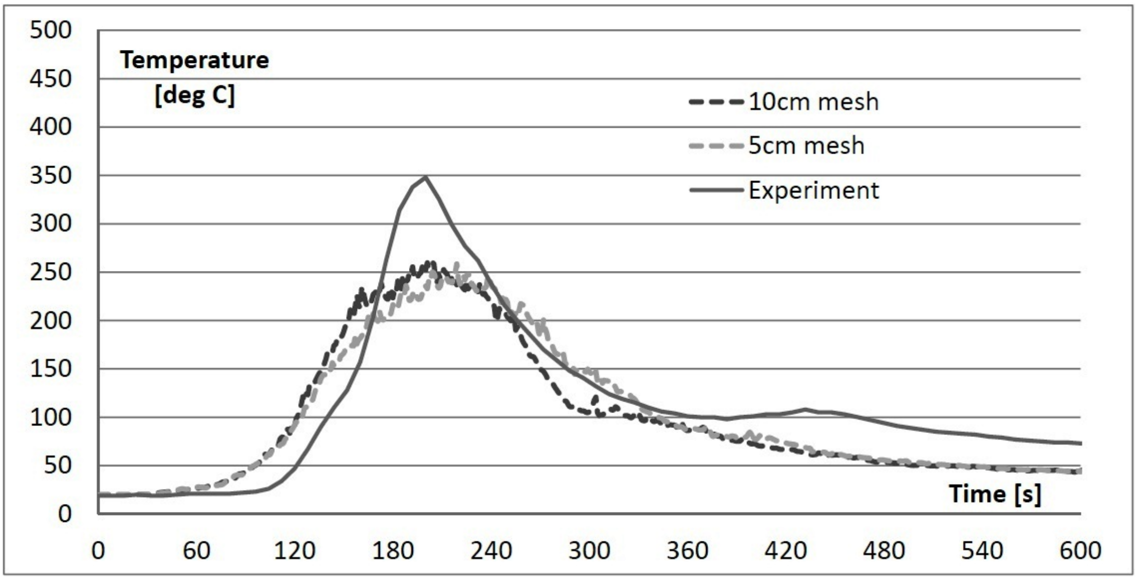

Fig. 10 Temperature 2.00 m above the floor – FDS prediction vs. experimental measurement

Although some allowance should be made for the uncertainties in defining the initial fire and the material properties, it can be generally stated that in the investigated scenario FDS under-predicted the gas temperatures in the hot layer. The peak temperatures in the hot (upper) layer predicted by FDS were 20-25% lower than the measured values.

The relative differences between the numerical end experimental values were even larger for the under-ventilated stage of the fire, when the numerical prediction was 50% lower than the actual temperatures measured in the test. The possible explanation for this may be the following phenomenon observed in the subject simulation undertaken with FDS: in the situation of strong oxygen depletion in the area of fire origin the combustion process (which can be visualized in Smokeview software as the HRR per unit volume) was “shifted” to areas richer in oxygen, even to the room remote from the fire seat and hence much cooler. Such phenomenon was not observed in the experiment. A mixture of air and unburnt fuel gases resulting from an under-ventilated fire can indeed be reignited, however this normally requires high temperature of such gases or an explicit ignition source, neither of which was present in the subject situation.

It is worth to note that the temperature in the cold layer (i.e. 1.00 m above the floor) was generally overpredicted by FDS.

The mesh resolution has a much smaller influence on the predicted temperatures, and no general trend can be identified in this respect. Despite common opinion improved mesh resolution does not seem to lead to higher predicted temperatures for the scenarios investigated.

4 SUMMARY

CFD models such as Fire Dynamics Simulator used in the subject comparison are very useful for fire engineering work, for example as a tool to predict thermal loading on structural elements exposed to a fire. However, particular care must be taken when applying FDS to strongly under-ventilated fire scenarios. Comparison of numerical and experimental values undertaken as part of a larger research programme and described in this paper indicate that FDS may under-predict peak gas temperatures in the hot zone by up to 25%. In the later phase of the fire, when the conditions in the compartment become severely under-ventilated the difference can be even more significant. The possible cause of this is the difficulty of accurately modeling the combustion processes occurring in severely underventilated fires when the simple (default) combustion model is used.

FDS allows more complex approaches to combustion modeling (e.g. two-step reaction or the final-rate, multiple-step combustion model), however these models require more detailed information about the fuel chemistry and much better grid resolutions that would normally be used in practical engineering applications.

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