Fire in a naturally ventilated room: a comparison between real-scale tests and FDS simulation

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ABSTRACT

The present paper describes a series of full-scale tests on enclosure fire carried out by authors, and the comparison with FDS simulations of same scenarios.
The case study is a naturally ventilated room, similar to those included in many office buildings and dwellings. The occurrence of a fire in this kind of rooms includes many issues from the point of view of life safeguard: (i) small rooms are usually not equipped with extinguishing systems or smoke / heat control systems; (ii) limited ceiling height leads to quick de-stratification of smoke and therefore deterioration of tenability conditions.
Full-scale experiments were carried out in a masonry building, internally arranged in a corridor and some rooms. The effect of different strategies involving the opening of doors and windows was observed, focusing on how this affects the distribution of smoke and tenability conditions.
Then, FDS simulations were developed in order to compare results with experimental data. The comparison was done taking into account gas temperature, smoke layer height, oxygen concentration and visibility. A sensitivity analysis was carried out on some parameters as HRR curve, material thermal properties, and soot yield.
Results of experiments and FDS simulations are here presented, discussed and compared with similar tests described in technical and scientific literature.

INTRODUCTION

Small rooms (less than 20-30m2) are common in office and dwellings. In Italy, these rooms are usually not provided with mechanical ventilation neither extinguishing system, in particular for what concerns ancient buildings and edifices with historical and artistic value. The small floor area of this kind of room, and the typical low height ceiling makes the smoke de-stratification fast, representing a threat for life safeguard of occupants. Fire models are commonly used by fire engineers to evaluate the risk related to the occurrence of a fire in a confined environment. The most used fire models, as FDS (Fire Dynamic Simulator) are validated taking into account a wide range of well-documented experiments that includes different geometry, fire size and fuel. Regarding fire in a small room, two of the most recent experiments are the 2008 NIST experiments and the 2005 Dalmarnock fire tests. Nist Full Scale Enclosure Experiments (2008) are a series of 30 experiments carried by NIST to study the under-ventilated fire by varying fuel, location of fire and opening dimensions. In the NIST Experiments, the analysis domain was a single room, the ISO 9705 fire compartment, which dimension is 2.4mx3.6mx2.4m, with one door having fixed height and variable width. The fire room was located in a hangar. Instrumentation included 2 thermocouple trees, each with 11 uniformed

spatially thermocouples. Heat Release Rate varies from 190kW to 420 kW. The same scenarios, reproduced with FDS showed a good agreement with experimental results.
Dalmarnock fire tests (2005) are a series of full-scale tests carried out in a multi-storey residential building in Glasgow, Scotland. The analysis domain was an entire building, subject to external variable conditions, with a more complex geometry compared with the NIST single room experiments. During tests, different furniture were burned: an upholstered sofa, two desks with computers, an upholstered office chair, a wooden chair, 3 bookcases, 3 coffee tables and numerous newspapers and magazines, corresponding to the typical furnishings of an office or home. The ignition source was a trash can containing paper impregnated with heptane. The HRR generated by furnishings combustion reached the value of 3MW in about 5 minutes and then it remained constant until the windows broke, when HRR reacheed the peak of 5MW thanks to the new oxygen supply. Instrumentation included thermocouple trees, thermal radiation sensors, obscuration sensors, air velocity meters. The study has involved also two series of numeric simulations developed with FDS: a priori and a posteriori. The a priori simulations, carried out taking into account the available data but not the experimental results, showed a considerable difference between the numerical results and the experimental results. The a posteriori simulations, taking into account empirical data such as the ignition time of the different furnishings and the breaking time of the windows, reproduced the experimental results quite accurately. However, some differences were observed between experimental results and a posteriori simulations, in particular after the breaking of the windows. Numerical simulations over-predicted the temperature increase in the room. Simulations gave a good prediction of temperature in the upper layer (error within 10%), and a worse prediction in the lower layer (error within 80%).

METHOD

Both experimental test and numerical simulations were used to study the fire in a small room without extinguishing system neither mechanical smoke evacuation. A literature review was initially conducted to resume the state of the art about small room experimental tests. A suitable place was found for the experiments, inside the Esseci plant in north-Italy. A preliminary study was made in order to define the fire. It was not possible to burn real furnishing, so a suitable equivalent fire was defined using wood rods and cardboard. Three scenarios were set-up changing the natural ventilation conditions, acting on the opening of door and window in the room. The same scenarios were simulated by means of FDS6 (Fire Dynamic Simulator, NIST) and a comparison was made between empirical and numerical results.

EXPERIMENTS SET-UP AND RESULTS

The experiments took place in the second floor of a brick masonry building built in the early 1900s and recently renovated. The second floor, accessible through a stairwell, consists of an 18m long central corridor and 8 office rooms (each one large17-20 m^2) on both sides. Rooms have aluminum and double-glazed windows, fire doors, floating floor and a vaulted ceiling dating back to the time of construction. At the two ends of the corridor there are two doors connecting to the outside. The room in which the fire was located, called *Fire Room*, is 5.55mx3.90m, with average height 2.95m, has an entrance door of 1.00mx2.05m and a window of 1.00mx1.50m.
Many sensors were positioned in the *Fire Room* and in the corridor: thermocouples at different height, oxygen concentration sensors, opacity sensors, smoke detectors, video-cameras. The main output of the experiments were the smoke layer height, the gas temperature and the oxygen concentration.

Figure 1: The building used for the experiments - photos

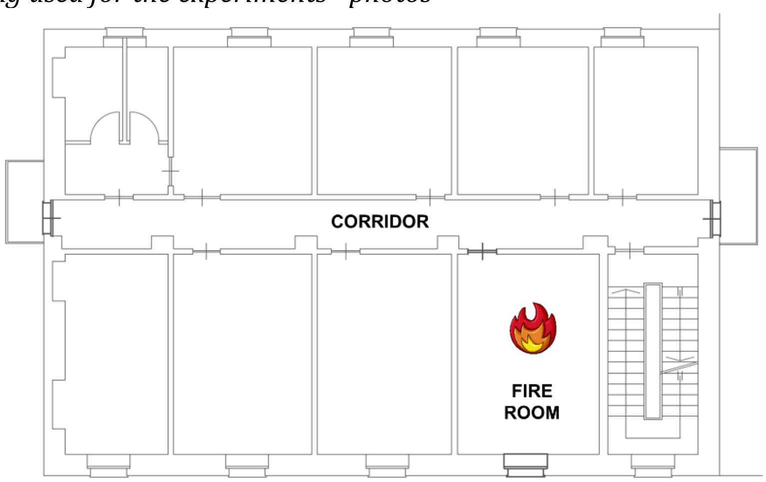

Figure 2: The building used for the experiments - plan

After a series of preliminary tests, varying quantity and geometry of the combustible materials, a 6kg pine wood crib was chosen to reproduce the furnishing fire, with a pan filled of ethyl alcohol as ignition source. The wood crib generated a peak HRR of 100kW, calculated by means of the formula $HRR=\Delta m*H$ with H= heat combustion of wood (17MJ/kg), Δm = variation of mass measured during the test. Crib combustion lasts for 22 minutes. Along with the wood crib, a smoke generator was placed in the room. It was made by a rolled cardboard sheet positioned in a metallic cylinder (diameter 165mm, height 280mm) opened at the both ends. It produced a smoldering fire, producing light gray smoke for 600-800s.

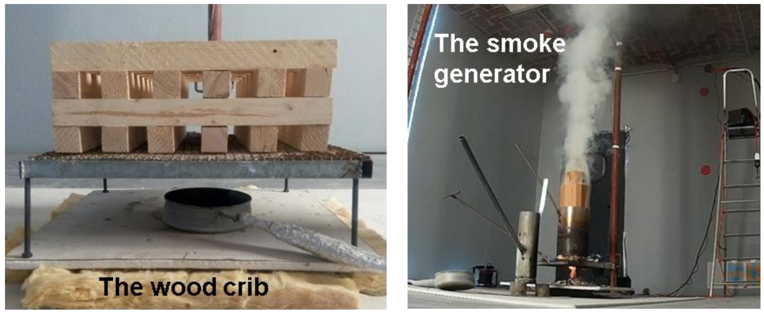

Figure 3: The wood crib and the smoke generator

The HRR produced by the wood crib was estimated measuring the mass variation over time, in three different tests. An average curve was extrapolated to estimate the heat release rate of the wood crib fire.

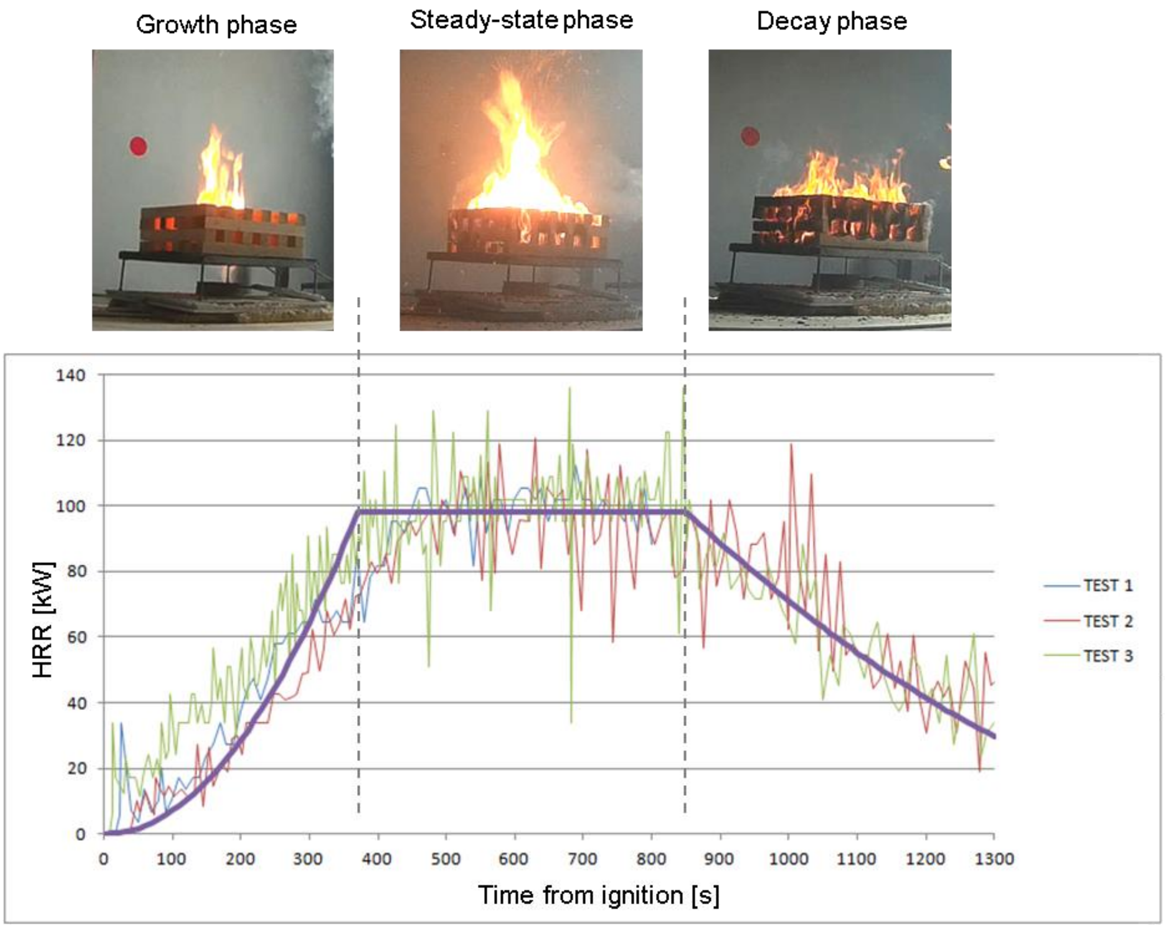

Figure 4: HRR curve

Three different scenarios have been studied, given the same wood crib and smoke generator. Scenarios differed each other for the opening/closing of doors and windows.

Scenario 1: Door and window in *Fire Room* was initially closed. The door was opened after 6 minutes from ignition, and the *Fire Room* windows was opened after 13 minutes from ignition. After 11 minutes, one door at the corridor end was opened. This scenario represented a sudden propagation of smoke in corridor, after an initial accumulation in the *Fire Room*.

Scenario 2: The door of the *Fire Room* was initially opened; the *Fire Room* window was opened after 11 minutes from ignition. After 11 minutes, one door at the corridor end was opened. This scenario represented a slow propagation of smoke in the corridor.
Scenario 3: *Fire Room* door and window were opened after 1.5 minutes from the ignition. A door at the corridor end was opened after 2 minutes from ignition. This scenario represented the presence of automatic natural evacuation system.
Outdoor temperature were equal to 20°C during scenario 1 and 2, and equal to 8°C during scenario 3.
In all scenarios, the gas temperature at 2 meters from floor inside the *Fire Room* exceeded 60°C, which is considered the safety threshold by Italian law and many international regulations. Time needed to reach the threshold depended on the experiment and is included between 8 and 14 minutes. In all scenarios, the opening of the window produced a fresh air flow in the lower part of the room.

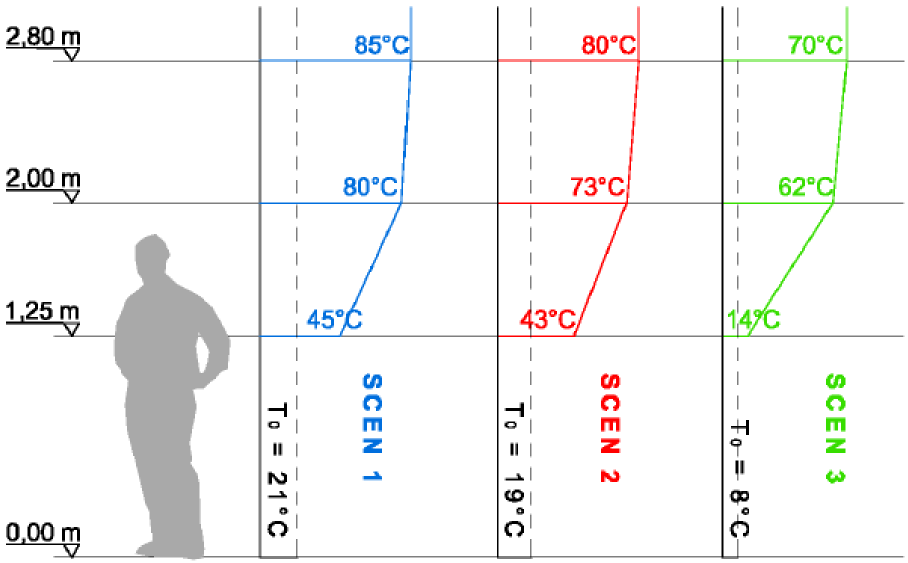

Figure 5: maximum gas temperature at different heights

In all scenarios, the smoke layer height in the corridor decreased under 2 meters after 5 minutes from the ignition. In scenario 3, the smoke layer height was equal to 1.7meters for the whole duration of the experiment, thanks to the fact that the early opening of door and window produced a fresh airflow. In the other scenarios, the smoke layer height in the corridor decreased until zero by the end of the experiment. The *Fire Room* was rapidly filled with smoke during scenario 1 (door and window closed), while in scenario 3 the opening of the window produced a smoke layer higher than in scenario 2, when the window was initially closed.

Figure 6: smoke layer height in the Fire Room

The positive effect of natural ventilation was observed also from oxygen concentration data. In scenario 3 the oxygen concentration remained larger than 19.5% for the whole duration of the experiment. In the other scenarios, the oxygen concentration dropped under 19.5% after 6-9 minutes from the ignition.

COMPARISON WITH FDS SIMULATIONS

The FDS model includes the *Fire Room* and the corridor, together with the openings to the outside zone. A 0.1mx0.1mx0.1m mesh was used and a simple chemistry combustion of $CH_{1.7}O_{0.83}$ with CO yield equal to 0.005. Soot yield, wall properties and thermocouples features were defined by means of a sensitivity analysis, based on the empirical results, in *a posteriori* mode. HRR curve was modeled using a burner surface of 0.5mx0.5m dimensions, HRRPUA 393 kW/m^2 and the power vs time curve obtained from experiments (Figure 4).

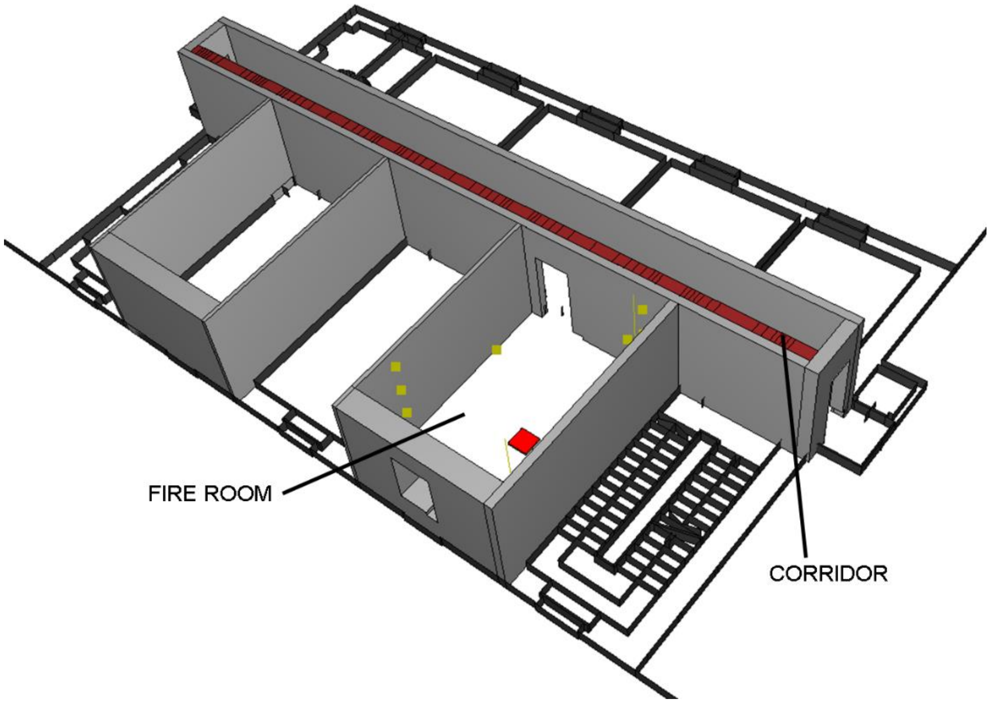

Figure 7: FDS model of Fire Room and corridor

Numerical simulations tended to over-predict the gas temperature. In particular for the lower layer, when difference between experiments and simulations ranged from 20°C to 45°C depending on the scenario (Figure 8). Scenario 3 (high ventilated) is the one in which the simulation prediction of gas temperature was more similar to the empirical values.

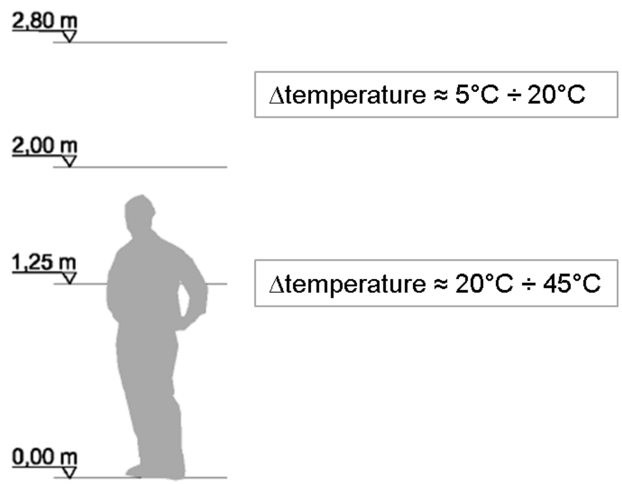

Figure 8: differences in temperature prediction between experiments and simulations

In scenario2, the predicted temperature in the simulation showed higher peaks than the test (Figure 9). In the simulation, the window opening cause a stronger decrease of temperature respect to the test. The difference between simulation and tests was smaller in scenario3, where the fresh airflow was established since the first phase of experiment.

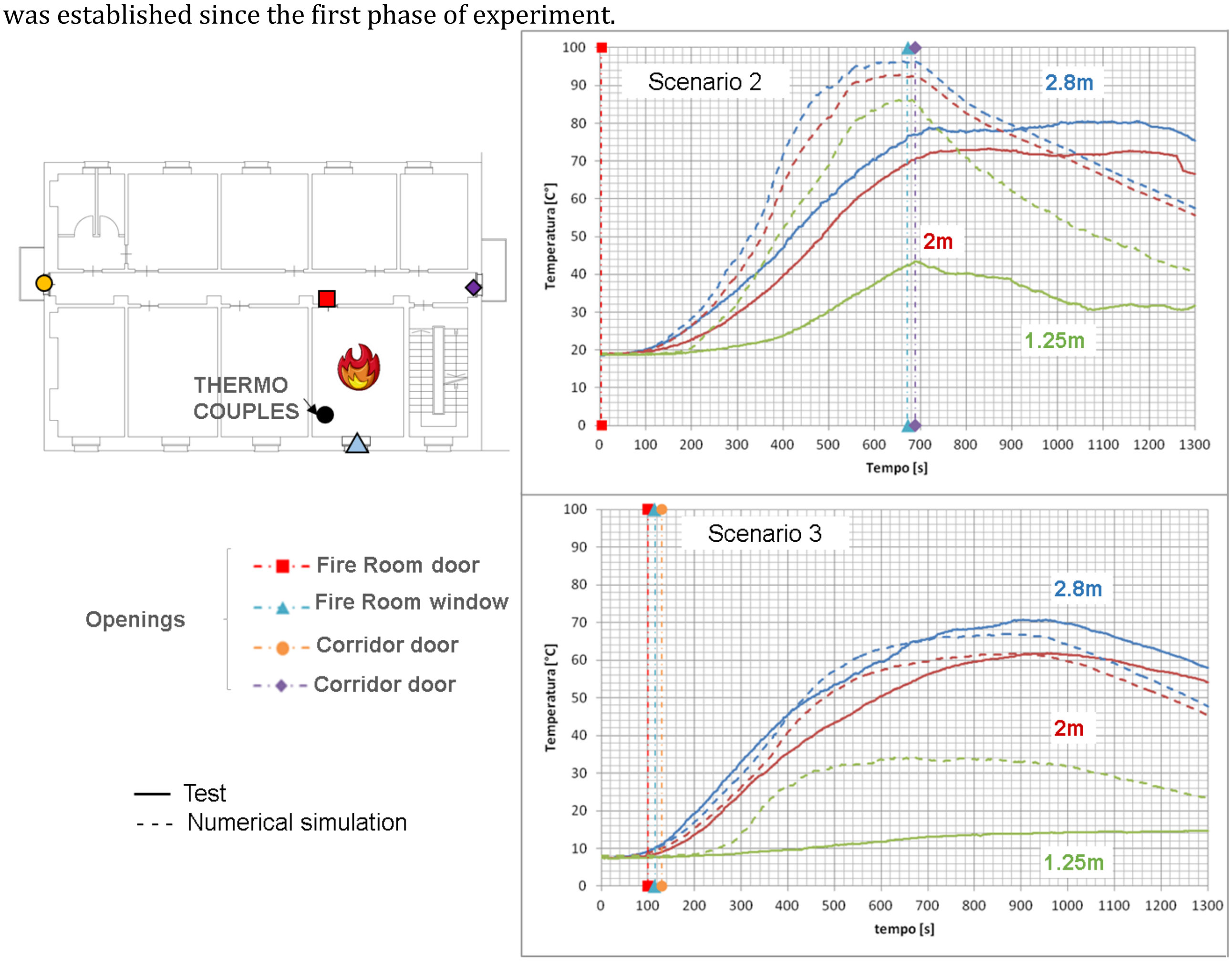

Figure 9: comparison between gas temperatures in experiments and simulations

During tests, the estimation of smoke layer height was based on video recordings and graded rods. This estimation became difficult when fresh air mixed with smoke so the test data are reported only until 700s. Scenario2 showed (Figure 10) a good agreement between test and simulations. In scenario 3, the simulation prediction was worse than empirical observations. In general, there was low correspondence between experimental data and simulation results, related to the difficulties in empirical measurements during the tests.

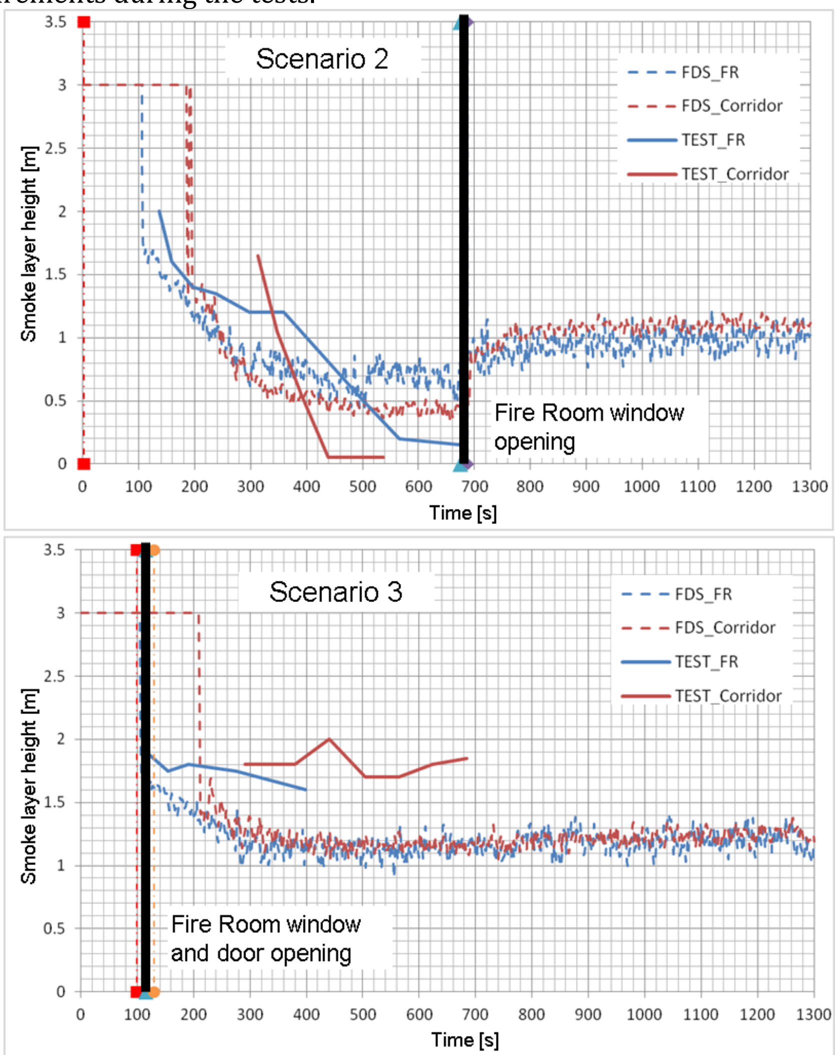

Figure 10: comparison between smoke layer height in experiments and simulations

The oxygen concentration in *Fire Room* predicted by the simulation was similar to test data. In scenario 2, initially under-ventilated, simulation under-estimated oxygen concentration. In scenario 3, highly ventilated, simulation slightly over-estimated the oxygen concentration. In this scenario, test data showed a peak around 400s that is probably due to a sensor malfunctioning.

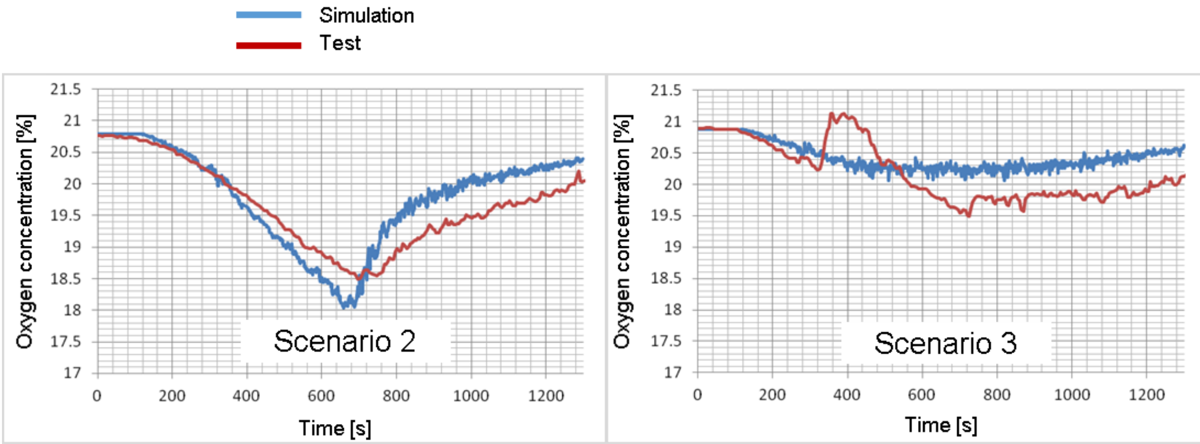

Figure 11: comparison between oxygen concentration in experiments and simulations

CONCLUSION

Due to the fire, tenability conditions in the fire room were quickly compromised. The smoke layer height, and the visibility as a consequence, rapidly deteriorated. Also in the corridor, tenability conditions deteriorated quickly. The lack of fire extinguishing systems and mechanical ventilation systems made the analyzed fire a threat for life safety, despite its relatively low HRR (100 kW max). Nevertheless, the 3rd Scenario has demonstrated the positive effect of natural ventilation, in particular regarding the smoke layer height, that has been keep higher than 1.7m, and the oxygen concentration, that did not fall under 19.5% for the whole duration of the test. This scenario demonstrated that a simple action, as the manual opening of the window in the first moments of fire, could give a positive contribution to the maintenance of tenable conditions.

Regarding the agreement between experiments and numerical simulations, the outcome of the tests showed a good agreement with Dalmarnock Fire Tests results. In particular: (i) a better agreement in gas temperature detected in the hot smoke layer than in the lower layer; (ii) a divergence between experimental and numerical results in correspondence of the window opening instant; (iii) the importance of sensitivity analysis on some parameters, such as soot yield, which are difficult to evaluate during experimental tests. Finally, it was observed that numerical simulations generally gives more conservative outcomes than experimental test.

It is important to notice that the experimental set-up, both in the present analysis and in the Dalmarnock Fire Tests, was quite complex, as it depended on the external environmental conditions (temperature, wind) and many other variables that are difficult to predict and control. This is a significant difference compared to experiments carried out in specially-made rooms inside a shielded environment. Future developments should therefore aim to obtain more experimental data relating to complex experimental setups.

REFERENCES

Aniszewska M., Gendek A., Comparison of heat of combustion and calorific value of the cones and wood of selected forest trees species, in “Forest Research Papers”, Vol. 75 (3), pp 231-236, September 2014, DOI: 10.2478/frp-2014-0022

Beutner H.P., Measurement of Opacity and Particulate Emissions with an On-Stack Transmissometer, in “Journal of the Air Pollution Control Association”, Vol. 24 (9), pp 865-871, 1974, DOI: 10.1080/00022470.1974.10469984

Biteau H., Steinhaus T., Schemel C., Simeoni A., Marlair G., Bal N. and Torero J.L., Calculation Methods for the Heat Release Rate of Materials of Unknown Composition,in “Fire Safety Science”Vol. 9, pp 1165-1176, 2008, DOI:10.3801/IAFSS.FSS.9-1165

Italian regulation - D.M. 3 agosto 2015, Approvazione di norme tecniche di prevenzione incendi

Mulholland G.W., How well are we measuring smoke?, Centre of Fire Research - National Bureau of Standards, June 1982

Mulholland G.W., Smoke Production and Properties, in “SFPE Handbook of Fire Protection Engineering”, 2nd Edition, Chapter 15, Section 2, pp 217-227, 1995

NIST Technical Note 1603. Experimental Study of the Effects of Fuel Type, Fuel Distribution, and Vent Size on Full-Scale Underventilated Compartment Fires in an ISO 9705 Room. 2008.

Oberkampf W.L., Trucano T.G., Verification and validation in computational fluid dynamics, in “Progress in Aerospace Sciences”, Vol. 38 (3), pp 209-272, 2002, DOI: 10.1016/S0376-0421(02)00005-2

Peacock R.D., SanfordD. and Babrauskas V., Data for Room Fire Model Comparisons, in “Journal of Research of the National Institute of Standards and Technology”, Vol. 96 (4), pp 411-462, July-August 1991, DOI: 10.6028/jres.096.022

Rein G., AbecassisEmpis C., Carvel R., *The Dalmarnock Fire Tests: Experiments and Modelling*, Edinburgh, published by the School of Engineering and Electronics - University of Edinburgh, 2007

Staffansson L., Selecting design fires, Department of Fire Safety Engineering and Systems Safety, Lund University, 2010

U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research (RES), Electric Power Research Institute (EPRI), Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications – Volume 2: Experimental Uncertainty, NUREG-1824, May 2007

U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research (RES), Electric Power Research Institute (EPRI), Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications – Volume 7: Fire Dynamics Simulator (FDS), NUREG-1824, May 2007

U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research (RES), Electric Power Research Institute (EPRI), Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications – Supplement 1: Final report, NUREG-1824, November 2016

U.S. Nuclear Regulatory CommissionOffice of Nuclear Regulatory Research (RES), Electric Power Research Institute (EPRI), Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications – Volume 1: Main Report, NUREG-1824, May 2007

Van Hees P., Validation and Verification of fire models for fire safety engineering, in “Procedia Engineering”, Vol. 62, pp 154-168, 2013, DOI: 10.1016/j.proeng.2013.08.052