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FIRE RESISTANCE ASSESSMENT ACCORDING TO THE THERMAL INSULATION CRITERION – AN ENGINEERING APPROACH

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Abstract: *The paper presents the numerical simulation of a fire in a conference hall and the analysis of temperatures on opposite sides of the walls and slab of the fire space. The purpose of this case study is to establish if a fire can develop in the adjacent rooms of the conference hall due to the heat transfer (verifying fire resistance of the enclosure elements for the thermal insulation criterion). Using CFD (Computational Fluid Dynamics) simulations it was concluded that for the considered fire scenario the materials in contact with the enclosing elements of the fire space cannot ignite.*

Key words: *CFD, FDS, HRR, fire safety engineering, heat transfer.*

1. Introduction

Numerical simulations of the various phenomena in different fields has become and essential part of science and engineering. Due to high cost of real scale fire experiments the CFD analyzes are often used both by fire protection engineers and fire researchers to help predict and optimize product behaviour and validate designs.

This case study is based on the assumption of starting a fire in a conference hall of a building intended for teaching activities for higher education.

The analyzed building (Figure 1) is the main house of the Faculty of Civil Engineering and Building Services from Jassy, Romania, and the main futures of the building are presented in Table 1.

Fig. 1. *Analyzed building*

The ground floor plan of the building is presented in Figure 2.

The main futures of the building Table 1

Floor	Description
G	3 lecture halls + 1 conference hall
$1^{st} – 3^{rd}$	3 lecture halls + 1 laboratory
4^{th}	1 lecture hall

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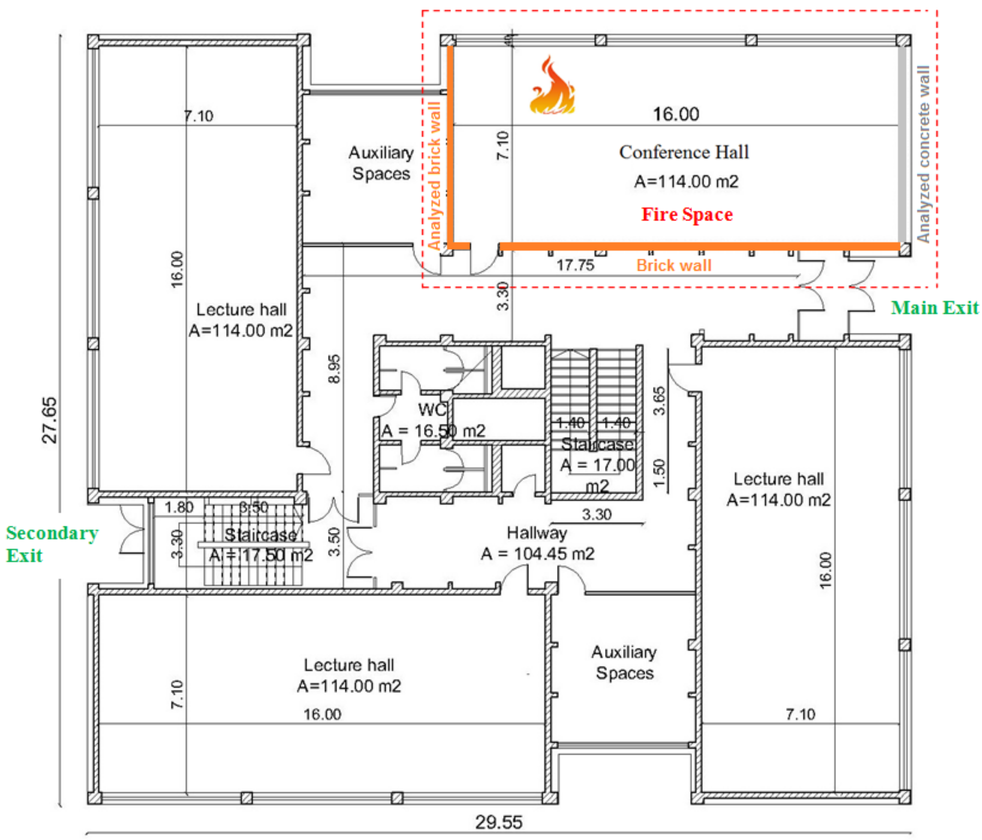

Fig. 2. *Ground floor plan of the building*

The furniture from the conference hall (Figure 3) is specific to the office type spaces and the combustible materials are mainly wood.

The dimensions of conference hall are 7.10 x 16.00 m and 3.80 m height.

Fig. 3. Conference hall

The conference hall has a 1.20 x 2.10 m door and 3 windows of 5.00 x 3.00 m.

2. Objectives

The objectives of this paper are:

- defining the HRR (Heat Release Rate) according to the European legislation;
- numerical simulation of the fire using a CFD software;
- temperature analysis on the walls and slab which separates the fire space from the rest of the building;
- establishing if the combustible materials from the adjacent rooms can ignite due to heat transfer (radiation and convection through the fired environment, conduction through the walls and slab).

3. Material and Methods

The research instruments used in this case study are special software used both by fire protection engineers and fire researchers.

The development of fire from the conference hall is described using a wood fuel and the heat release rate according to the European legislation.

3.1. FDS 6.1.1

FDS (Fire Dynamics Simulator) is a CFD model of fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed (Ma < 0,3), thermally-driven flow with an emphasis on smoke and heat transport from fires [1]. The partial derivatives of the conservation equations of mass, momentum and energy are approximated as finite differences, and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver [2].

FDS was subjected to verification [3] (the equations are being solved correctly) and validation [4] (comparing model results with experimental measurement).

Heat Conduction for Solids

FDS assumes that solid surfaces consist of multiple layers (each layer composed of different materials), with each layer having its own thermal properties and thermal degradation reactions (each reaction can produce multiple gas and solid species) [2].

Heat conduction for a solid is assumed only in the direction normal to the surface (direction x pointing into the solid, $x = 0$ represents the surface). The temperature value of the surface at the “x” depth and at the “t” time is presented in [2]:

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k_s \frac{\partial T_s}{\partial t} \right) + \dot{q}_s^{'''}. \qquad (1)$$

where:

$\rho_s c_s$ - average volumetric heat capacity value of the layered surface;

k_s - average conductivity value of the layered surface;

$\dot{q}_s^{'''}$ - volumetric heat flux consisting of the chemical reactions following the pyrolysis process, $\dot{q}_{s,c}^{'''}$, and radiative absorption and emission in depth, $\dot{q}_{s,r}^{'''}$, is [2]:

$$\dot{q}_s^{'''} = \dot{q}_{s,c}^{'''} + \dot{q}_{s,r}^{'''}. \qquad (2)$$

In case of the present paper the component due to pyrolysis is not considered (no combustible materials are used) only the radiative absorption component is considered.

The boundary condition on the surface in contact with the fire is [2]:

$$-k_s \frac{\partial T_s}{\partial t} = \dot{q}_c^{''} + \dot{q}_r^{''}. \qquad (3)$$

where:

$\dot{q}_c^{''}$ - convective heat flux;

$\dot{q}_r^{''}$ - radiative heat flux;

On the opposite surface, two possible boundary conditions may be declared:

- if the surface is open either to the computation domain (Equation 3);
- if the surface is perfectly insulated [2]:

$$-k_s \frac{\partial T_s}{\partial t} = 0. \qquad (4)$$

Radiation Heat Transfer to Solids

If it is assumed that the thermal

radiation from the gaseous environment is absorbed within an infinitely thin layer at the surface of the analyzed element, then the radiative heat flux, $\dot{q}_r''$, is [2]:

$$\dot{q}_r'' = \dot{q}_{r,in}'' - \dot{q}_{r,out}''. \tag{5}$$

where:
$\dot{q}_{r,in}''$ - incoming radiative heat flux;
$\dot{q}_{r,out}''$ - outgoing radiative heat flux (the case of transparent materials).

Convective Heat Transfer to Solids

In FDS the convective heat flux can be computed in two different ways:

- DNS (Direct Numerical Simulation);
- LES (Large Eddy Simulation);

For the current study a LES was used to significantly reduce the simulation running time.

For LES the Empirical Natural/Forced Convection Model is also available. The convective heat transfer coefficient, h, is based on a combination of natural and forced convection correlations [2]:

$$\dot{q}_c'' = h(T_g - T_w). \tag{6}$$

$$h = \max\left[C\left|T_g - T_w\right|^{\frac{1}{3}},\ \frac{k}{L}Nu \right]. \tag{7}$$

where:
$\dot{q}_c''$ - convective heat flux;
h - convective heat transfer coefficient;
T_g - gas temperature in the center of the first gas phase cell;
T_w - wall surface temperature;
k - thermal conductivity of the gas;
L - characteristic length related to the size of the physical obstruction;
C - coefficient for natural convection (1.52 for horizontal plane and 1.31 for vertical plane);
Nu - Nusselt number.

For the present case (planar surfaces) the Nusselt number is [2]:

$$Nu = C_1 + C_2 \operatorname{Re}^n \operatorname{Pr}^m. \tag{8}$$

where:
Re - Reynolds number;
Pr - Prandtl number;
$C_1 = 0,\ C_2 = 0.037,\ n = 0.8,\ m = 0.33.$

3.2. PyroSim 2014.2.0807 and Smokeview 6.1.11

FDS don't have a user interface; all input data is entered using command lines. PyroSim is a graphical user interface for FDS that helps to quickly create and manage the details of complex fire models [5].

Smokeview is a software tool designed to visualize numerical calculations generated by FDS. It can display contours of temperature, velocity and gas concentration in planar slices [6].

Smokeview was also subjected to verification [7] (verifying the various visualization capabilities).

3.3. Combustion using the Heat Release Rate

The fire load density was considered according to the European legislation [8], 420 MJ/m^2, corresponding to office occupancy (common objects can be found in the conference hall).

For this case study the design value of the fire load density was 951 MJ/m^2 [9].

The total energy released by the combustible materials from the storage room is 108400 MJ and the maximum heat release rate is 80,159 MW. According to [9] the heat release rate of the design fire considered in this fire scenario is presented

in Figure 4. For this analysis a user-defined fuel was used. It is assumed that the burning objects from the storage room are predominantly cellulosic/wood.
According to [10] a wood fuel has the proprieties presented in Table 2.

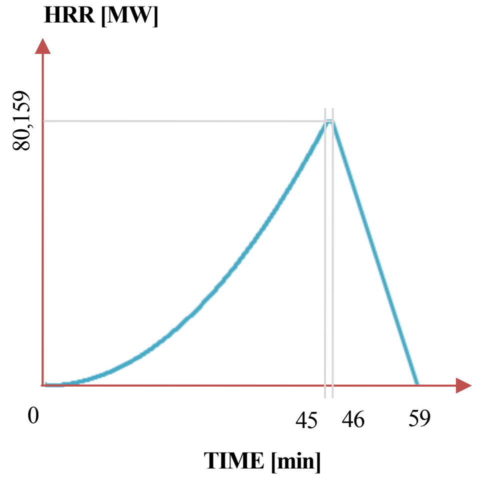

Fig. 4. Heat Release Rate

Fuel properties Table 2

User input data	Value
Carbon atoms	3,4
Hydrogen atoms	6,2
Oxygen atoms	2,5
Critical Flame Temperature	1427,0 °C
Heat of combustion	17500 kJ/kg
Soot Yield	0,015 kg/kg
Hydrogen Fraction	0,1

3.4. Grid cell size and boundary conditions

For the fire simulation that involves buoyant plumes, a measure of how well the flow field is resolved is given by the non-dimensional expression D*/δx, where D* is a characteristic fire diameter and δx is the nominal size of a mesh cell [1].

Generally the D*/δx values ranged from 4 to 16 [11].

In this analysis it was considered a 0,30 x 0,30 x 0,30 m cell size corresponding to a fine grid size:

$$\frac{Q^*}{\delta x} = \frac{5,538}{0,30} = 18,461 . \tag{9}$$

The fire mesh is extended with 0,90 m from conference hall (the red dashed rectangle from Figure 2) and its boundaries were declared "open" to better capture the spread of smoke through the windows.

3.5. Thermal properties

FDS can solve heat conduction in solids only if the wall/slab is less than or equal to one mesh cell thick and if there is a non-zero volume of computation domain on the other side of the wall [1].

The component layers of the analyzed elements are presented in Table 3 and the thermal properties of the used materials are presented in Table 4 [12, 13].

Enclosure elements properties Table 3

Enclosure elements	Layer thickness		
	Plaster	Concrete/ Brick	Plaster
Concrete slab	2.5 cm	15 cm	2.5 cm
Concrete wall	2.5 cm	20 cm	2.5 cm
Brick wall	2.5 cm	20 cm	2.5

Thermal properties of materials considered in the analysis are [12, 13]:

Materials thermal properties Table 4

Properties	Materials		
	Plaster	Concrete	Brick
Density [kg/m^3]	1800	2500	2000
Specific Heat [kJ/(kg·K)]	0.84	0.84	0.87
Conductivity [W/(m·K)]	0.93	1.74	1.16
Emissivity [-]	0.88	0.95	0.94

The ignition temperatures [14, 15] of materials that can be in contact with the opposite surfaces of the walls and slab of the conference hall are presented in Table 5:

Ignition temperature Table 5

Material	Ignition temperature [ºC]
Cardboard	300 ... 360
Celluloid	125 ... 190
Cellulose	160 ... 170
Paper	165 ... 363
Leather	400 ... 450
Polystyrene	340 ... 345
Polyurethane foam	310
Polyvinyl chloride	455
Wood	> 250

4. Results and Discussions

The CFD analysis supports that the spread of smoke on conference hall facade is free (without accumulation in the computational domain) and the back wall temperature map support the fact that the temperature not evenly distributed on the analyzed elements (Figure 5).

Following the numerical analysis the maximum temperatures of the analysed elements are presented in Table 6.

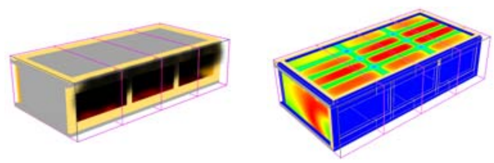

Fig. 5. The spread of smoke and the back wall temperature

Maximum temperatures Table 6

Enclosure element	Maximum temperature [°C]	
	Interior surface	Exterior surface
Concrete slab	707	22
Concrete wall	661	21
Brick wall	771	21

It can been seen that the exterior surface temperature is well below the ignition temperatures from Table 5 and there is no danger for the fire to propagate to the adjacent rooms due to heat transfer.

Following the numerical analysis the temperature profiles in the thickness of the analysed elements (concrete wall, brick wall and concrete slab) are presented in Figure 6, 7 and 8.

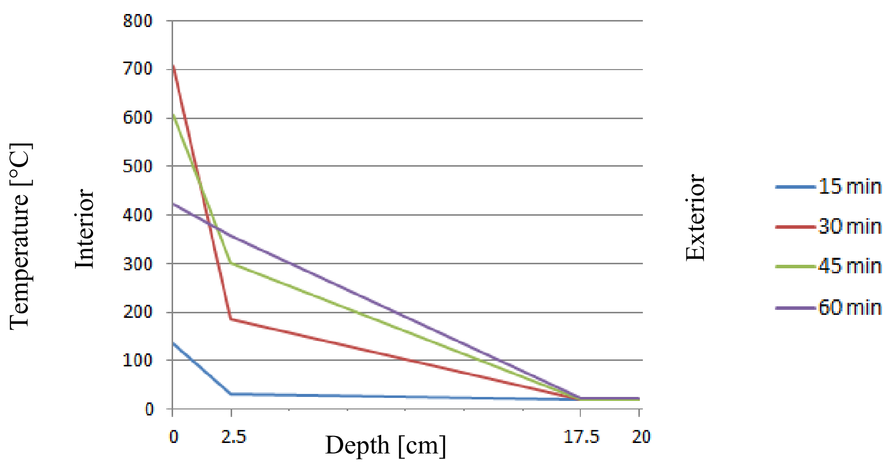

Fig. 6. Temperature profile in the concrete slab

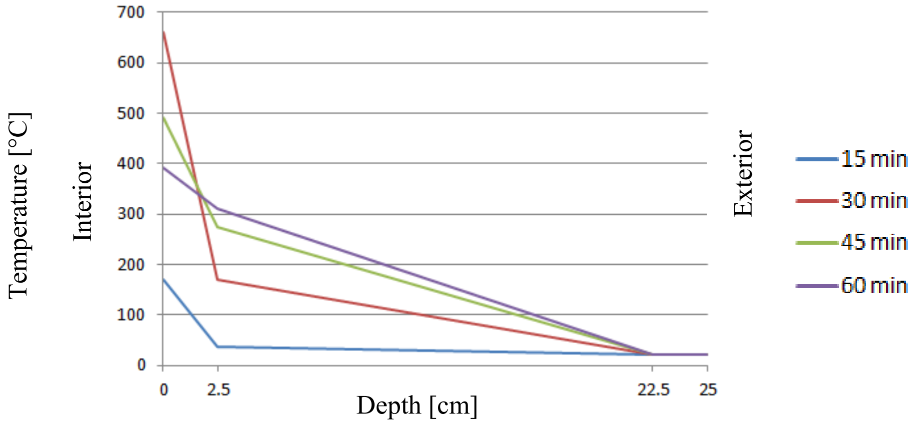

Fig. 6. Temperature profile in the concrete wall

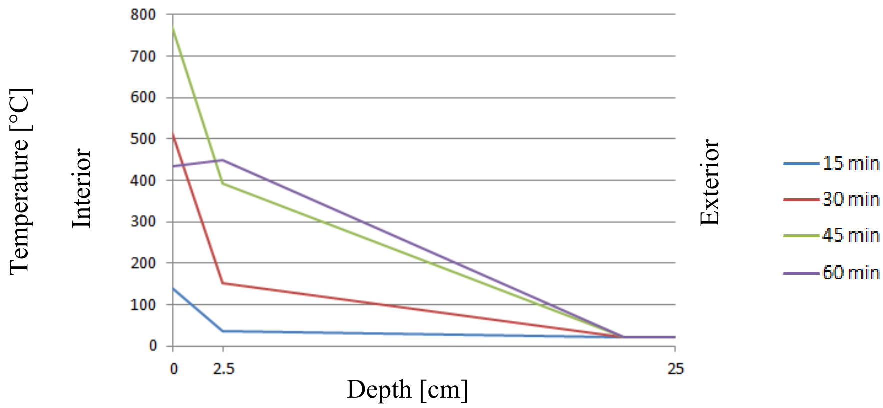

Fig. 7. Temperature profile in the brick wall

5. Conclusions

The paper presented a case study about verifying the thermal insulation criterion using a CFD software.

The results obtained from the numerical simulation show that common combustible materials, in contact with the exterior surface of the conference hall, can not ignite.

For the considered fire scenario there is no danger for the fire to propagate due to heat transfer through the fire environment (due to radiation and convection) and through the walls and slab (due to conduction).

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References

1. McGrattan, K., Hostikka, S., McDermott, R., et al.: *Fire Dynamics Simulator – Use's Guide*, NIST Special Publication 1019 Sixth Edition, USA, 2013.
2. McGrattan, K., Hostikka, S., McDermott, R., et al.: *Fire Dynamics Simulator – Technical Reference Guide – Volume 1: Mathematical Model*, NIST Special Publication 1018 Sixth Edition, USA, 2013.
3. McGrattan, K., Hostikka, S., McDermott, R., et al.: *Fire Dynamics Simulator – Technical Reference Guide – Volume 2: Verification*, NIST Special Publication 1018 Sixth Edition, USA, 2013.
4. McGrattan, K., Hostikka, S., McDermott, R., et al.: *Fire Dynamics Simulator – Technical Reference Guide – Volume 3: Validation*, NIST Special Publication 1018 Sixth Edition, USA, 2013.
5. *** *PyroSim 2014 User Manual*, Avaible at: http://www.thunderheadeng.com/pyrosim/pyrosim-resources/ . Accessed: 11-08-2014.
6. Forney, G. P.: *Smokeview (Version 6) – Atool for Visualizing Fire Dynamics Simaltion Data – Volume II: Technical Reference Guide,* NIST Special Publication 1017-2, USA, 2013.
7. Forney, G. P.: *Smokeview (Version 6) – Atool for Visualizing Fire Dynamics Simaltion Data – Volume III: Verification Guide,* NIST Special Publication 1017-3, USA, 2013.
8. *** SR EN 1991-1-2: *Eurocode 1 – Actions on Structures, Part 1-2: General Actions – Actions on structures exposed to fire, Annex E – Fire load densities.* Accessed: 11.08.2014.
9. Grigoraş, Z.C., Diaconu-Şotropa, D.: *Defining the design fire according to SR EN 1991-1-1-2 Annex E.* In AICPS Review (2014), No. 1-2, p. 150-156.
10. Rinne, T., Hietaniemi, J., Hostikka, S.: *Experimental Validation of the FDS Simulations of Smoke and Toxic Gas Concentrations,* VTT Technical Research Centre of Finland, 2007.
11. Stroup, D., Lindeman, A.: *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*. NUREG-1824, supplement 1, United States Nuclear Regulatory Commission, Washington, DC, 2013.
12. *** C107/1–2005: *Normativ privind calculul coeficienților globali de izolare termică la clădiri de locuit.* Accessed: 24.09.2014.
13. *** *Emissivity Values for Common Materials.* Available at: www.infrared-thermography.com/material-1.htm Accessed: 24-09-2014.
14. *Diaconu-Şotropa, D: Bazele securității la incendiu în construcții (Fundamentals of Fire Safety for Buildings).* Iaşi. Politehnium Publishing House, "Gheorghe Asachi" Tehnical University of Iaşi, 2014.
15. *** *PVC's Physical Properties.* Available at: www.pvc.org/en/p/pvc-physical-properties Accessed: 25-09-2014.