The influence of combustion properties of fuel materials upon human evacuation in case of fire

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Abstract. The purpose of this article is to analyze the variation of the tenability criteria (convected heat, radiant heat, toxic gases and smoke visibility) on the main evacuation paths inside of an educational building, in case of fire. The analysis is performed by numerical simulation for three different fire scenarios. The fire load density of fire space (an office type room) is the same, but the main combustible material is changed: wood, plastic and polyurethane foam. The analyzed building can house a great number of people (over 600) and its inner atrium could facilitate the spread of smoke and hot gases in case of a real fire. According to the numerical analysis, it has been concluded that the convected heat variation is not a significant one (within the engineering limits), but the radiant heat, toxic gases and smoke visibility are highly dependent on the type of considered combustible materials.

1. Introduction
The case study consists in the numerical simulation of the development of a fire in an enclosed space – educational building, considering three different fire scenarios. The fire load density is kept the same, but the main combustible materials are changed: wood, plastic and polyurethane foam. The study also aims to monitor the parameters considered relevant in influencing the tenability criteria for human evacuation in the event of a fire.

The applicable part of this paper consists of:
- identification of a building that houses a large number of people, the architecture of the building favouring the spread of smoke and hot gases;
- identification of a rational design fire scenario;
- establishing the design fire corresponding to the fire scenario variants;
- establishing the relevant parameters for the evacuation of persons in the fire situation, in order to monitor: air temperature, gas toxicity, visibility through the smoke layer, thermal radiation on the escape routes, at a height of 2.00 m above the floor level [1], [2], [3];
- construction of the discrete virtual model with finite volumes for the analyzed space, in the FDS software;
- performing the comparative analysis based on monitoring the relevant parameters in the sections of interest and presenting the conclusion.

CFD (Computational Fluid Dynamics) simulation of fire development used in the case of human evacuation is the current design procedure for complex buildings housing large crowded spaces (like airports, shopping mall, subway stations or skyscrapers) or buildings housing people which cannot evacuate themselves (like hospitals, nurseries or retirement homes).
Simulating the real tenability criteria on evacuation paths is essential for the assessment of occupant safety in a building under fire conditions. When hazardous conditions set in before human evacuation, then different measures must be considered for increasing the available safe egress time (ASET), like: replacing the combustible finishes and furniture inside the building, shortening the length of the escape paths, using a automatic fire extinguishing system or using a smoke and heat exhaust system.

2. The model
2.1. The analyzed space
The analysed space is an educational building which belongs to the Faculty of Civil Engineering and Building Services, from “Gheorge Asachi” Technical University of Iași, Romania (Figure 1).

The building, intended for higher education, has the following height regime:
- semi-basement: it houses technical spaces;
- ground floor: it houses an exhibition space and the two entrances of the building;
- mezzanine: it houses the hall of the Romanian Academy of Scientists, it is not intended for educational activities;
- 1st ÷ 4th floor: it houses spaces for educational activities;
- 5th floor: it houses technical spaces.

2.2. The design fire scenario
Studying the characteristics of the building, it was identified as a reasonable (unfavourable) scenario the initiation of a fire in a meeting room located at the mezzanine of the building.

This space houses combustible materials with high thermal loads, which, by releasing a large amount of toxic gases and smoke, can endanger the safety of building users in a probable evacuation process.

An important aspect in establishing this fire scenarios is that the location of this room facilitates the rapid movement of smoke into the atrium.

The design fire scenarios assume that all the doors of the analysed building are closed, except for the access doors of the buildings, the door of the burned space and the doors to the stairwells located on each floor (the self-closing mechanisms of the doors are supposed to be faulty).

All windows of the building are closed, except for the windows of the burning space (the self-closing mechanisms of the doors are supposed to be faulty). The walls are made of bricks with mortar plaster and the slabs are made of reinforced concrete with mortar plaster, materials with common thermal properties [4] [5].

2.3. Variants of fire scenarios and design fires
The combustible materials existing in the analyzed meeting room are presented in table 1.
Table 1. Thermal load corresponding to the combustible materials in the analyzed space

| Object      | No. | Combustible material | Total mass [kg] | $H_u$ [MJ/kg] | Thermal load [MJ] |
|-------------|-----|----------------------|-----------------|--------------|-------------------|
| Desk        | 1   | Wood                 | 36              | 17.5         | 630               |
|             |     | Coton                | 4               | 20           | 80                |
| Chair       | 36  | Plastic              | 90              | 40           | 3600              |
|             |     | Polyurethane         | 7               | 25           | 175               |
| Drapes      | 1   | Polyester            | 5               | 30           | 150               |
| Carpet      | 1   | Polypropylene        | 45              | 40           | 1801              |
| Hanger      | 1   | Wood                 | 55              | 17.5         | 963               |
| Smart board | 1   | PVC                  | 30              | 20           | 600               |
| Carpentry   | 1   | PVC                  | 70              | 20           | 1400              |
| Door        | 1   | Wood                 | 30              | 17.5         | 525               |

Note: Quantities were calculated by estimating the volume and mass of each object.

Based on the thermal loads (fuel energy transformed into heat), table 1, the design value of the thermal load density is determined: 254 [MJ/m$^2$]; the value is much lower than the statistical value for office space (it can be deduced that the design values specified in the European regulations [6] are coverage in most cases).

The percentage in the thermal load of the types of combustible materials inside the burned space are presented in table 2. It can be seen that the predominant group of combustible materials is pure plastic hydrocarbons (PE-polyester, PS-polystyrene, PP-polypropylene), followed by the group of wood and PVC.

Table 2 Percentage in thermal load of each type of combustible material

| Combustible material                      | $H_u$ [MJ/kg] | Characteristic thermal load [MJ] | Percentage [%] |
|------------------------------------------|---------------|----------------------------------|----------------|
| Pure plastic hydrocarbons (PE, PS, PP)   | 40            | 5401                             | 54             |
| Celulozic (wood+coton)                   | 17.5          | 2198                             | 22             |
| PVC                                      | 20            | 2000                             | 20             |
| Polyurethane foam                        | 25            | 175                              | 2              |
| Polyester                                | 30            | 150                              | 2              |

Within the numerical simulations, three variants were assumed for the design fire scenario, $V_i$, generated by the predominant types of combustible materials:
- for $V_1$: cellulose (wood), with the generic name *Wood*, the most common combustible material in office spaces;
- for $V_2$: pure plastic hydrocarbons (PE, PS, PP), with the generic name *Plastic*, predominant for the situation of the analyzed space;
- for $V_3$: polyurethane, generic name *Polyurethane foam*, large generator of smoke and toxic gases.

The design fires corresponding to the variants of the design fire scenario were established, based on the procedures [6], considering that each of them is produced, in turn, by one of the three types of combustible materials: wood, plastic and polyurethane foam. The parameters of each design fire are presented for comparison in table 3.
### Table 3: Design fire parameters corresponding to fire scenario variants

| Parameter                                                                 | $V_1$ Wood | $V_2$ Plastic | $V_3$ Polyurethane foam |
|---------------------------------------------------------------------------|------------|---------------|-------------------------|
| Characteristic thermal load density [MJ/m$^2$]                            | 420        | 420           | 420                     |
| $q_{f,k}$                                                                 |            |               |                         |
| Burning coefficient [-]                                                   | 0.74       | 0.82          | 0.72                    |
| $m$                                                                      |            |               |                         |
| Risk of fire due to compartment size [-]                                  | 1.125      | 1.125         | 1.125                   |
| $\delta_q$                                                               |            |               |                         |
| Risk of fire due to compartment destination [-]                           | 1          | 1             | 1                       |
| $\delta_q$                                                               |            |               |                         |
| Active protection measures [-]                                            | 1          | 1             | 1                       |
| $\delta_a$                                                               |            |               |                         |
| Design thermal load density [MJ/m$^2$]                                    | 350        | 387           | 340                     |
| $q_{f,d} = m \cdot q_{f,k} \cdot \delta_q \cdot \delta_q \cdot \delta_{a}$|            |               |                         |
| Reference space area [m$^2$]                                              | 39.15      | 39.15         | 39.15                   |
| $A$                                                                      |            |               |                         |
| Total energy [MJ]                                                         | 13690      | 15170         | 13320                   |
| $E_t = q_{f,d} \cdot A$                                                   |            |               |                         |
| Fuel-air ratio [-]                                                        | 4.95       | 14.22         | 9.54                    |
| $1/r$                                                                    |            |               |                         |
| Lower calorific value of the combustible material [MJ/kg]                 | 17.50      | 40.00         | 25.00                   |
| $H_u$                                                                    |            |               |                         |
| The area of the surface through which the ventilation of the burned space occurs [m$^2$] | 10.89      | 10.89         | 10.89                   |
| $A_v$                                                                    |            |               |                         |
| The average height of openings throught with the ventilation of the burned space occurs [m] | 1.36       | 1.36          | 1.36                    |
| $h_{eq}$                                                                 |            |               |                         |
| Peak heat release rate [MW]                                               | 17.28      | 15.23         | 12.46                   |
| $Q_{\text{max}} = 0.52 \cdot \frac{1}{r} \cdot m \cdot H_u \cdot A_v \cdot \sqrt{h_{eq}}$ |            |               |                         |
| The development speed of the fire correlated with the destination of the analyzed space [s] | 300        | 300           | 300                     |
| $t_a$                                                                    |            |               |                         |
| Duration of the fire growth phase [s]                                    | 1247       | 1171          | 1059                    |
| $t_g = t_1 = t_a \cdot \sqrt{Q_{\text{max}}}$                           |            |               |                         |
| Parameter | Combustible material |
|-----------|----------------------|
|           | V1 Wood  | V2 Plastic | V3 Polyurethane foam |
| Energy released during the growth phase of the fire [MJ] | $E_g = \frac{t_1 \cdot Q_{\text{max}}}{3}$ | 7181 | 5945 | 4398 |
| Energy released during the fully developed phase of the fire [MJ] | $E_{fd} = 0.7 \cdot E_t - E_g$ | 2401 | 4673 | 4925 |
| Duration of the fully developed phase of the fire [s] | $t_{fd} = \frac{E_{fd}}{Q_{\text{max}}}$ | 139 | 307 | 395 |
| The time measured at the end of the fully developed phase of the fire [s] | $t_2 = t_g + t_{fd}$ | 1386 | 1478 | 1454 |
| Energy released during the decay phase of the fire [MJ] | $E_d = 0.3 \cdot E_t$ | 4107 | 4551 | 3996 |
| Duration of the decay phase [s] | $t_d = \frac{2 \cdot E_d}{Q_{\text{max}}}$ | 475 | 597 | |
| Time measured at the end of the decay phase [s] | $t_3 = t_g + t_{fd} + t_d$ | 1861 | 2075 | 2096 |

The variation of the heat release rate over time for each variant of the design fire scenario is shown in Figure 2. The flashover occurs within about 15-20 minutes from the fire initiation.
Table 4 specifies the values of the parameters that describes each fuel (declared as input data in FDS software), for the case of simple combustion model [7].

**Table 4 Parameters that describes each fuel (declared as input data in FDS software)**

| Parameters                              | Fuel          |
|-----------------------------------------|---------------|
|                                        | $V_1$-Wood    | $V_2$-Plastic | $V_3$-Polyurethane foam |
| C atoms                                 | 1             | 1             | 1                        |
| H atoms                                 | 3.584         | 1             | 1.7400                   |
| O atoms                                 | 1.550         | 0             | 0.3230                   |
| N atoms                                 | 0             | 0             | 0.0698                   |
| Lower calorific value [kJ/kg]           | 17500         | 40000         | 20000                    |
| CO released by fuel after combustion [g/g] | 0.004         | 0.024         | 0.02775                  |
| Soot released by fuel after combustion [g/g] | 0.015         | 0.059         | 0.1875                   |
| H released by fuel after combustion [g/g] | 0.1           | 0.1           | 0.1                      |

### 2.4. Fire safety relevant parameters

In order to monitor the effects of combustion on the human evacuation in case of fire, the following parameters were considered relevant: *air temperature*, *visibility through the smoke layer*, *gas toxicity*, *thermal radiation*; these parameters are correlated with the tenability criteria imposed by the fire safety engineering regarding the evacuation of people from buildings [1], [2], [3].

The parameters were monitored with virtual devices, defined in the FDS software (MS for the Main Staircase and SS for the Secondary Staircase), located in the entrance of each staircase – considered a point of interest – at 2.00 m above the floor.

The critical value of each monitored parameter at a height of 2.00 m above the floor is [1], [2], [3]:
- -100[°C] for the maximum air temperature;
- -10 [m], for the minimum visibility through the smoke layer, the case of large rooms;
- -1.0 [-] for maximum FED toxicity (*Fractional Effective Dose*), in the case of adults;
- -2.5 [kW/m²] for the maximum radiant heat flux.

### 2.5. Discretization of the computational domain

The FDS software user manual [8] recommends that a cell size / discretization volume be in the range $[D^*/16; D^*/4]$, where $D^*$ is the characteristic diameter of the fire. Applying the user manual [8] recommendation for the design fires, corresponding to the three variants of fire scenario it was decided to use a medium-coarse discretization cell of $0.5 \times 0.5 \times 0.5$ m, with which the geometry of the building can be easily described and reduces the running time or hardware resources required for numerical simulations.

The discrete virtual model with finite volumes is the one in Figure 3.

![Figure 3 Discreet virtual model with finite volumes - main facade and perspective view](image)
3. Analysis of results

Next, the comparative graphs are presented (in green for V1-Wood, in red for V2-Plastic and in blue for V3-Polyurethane foam; the horizontal red line mark the critical value), on each monitored parameter at the ground floor of the building (where each person must pass) for the MS – main staircase exit and SS – secondary staircase exit.

**Figure 4.1** Air temperature MS [°C]

**Figure 4.2** Air temperature SS [°C]

**Figure 4.3** Visibility MS [m]

**Figure 4.4** Visibility SS [m]

**Figure 4.5** FED MS [-]

**Figure 4.6** FED MS [–]
4. Conclusions
Based on the present study, the following conclusions could be drawn:
1. The variation in time of the analyzed parameters presents different values for each type of fuel, but these variations have a similar development.
2. The variation of heat release rate in time is different for each type of fuel, but the parameter values are of the same order of magnitude.
3. The air temperature and visibility through the smoke layer, measured at a height of 2.00 m above floor level for each level at the entrance to the stairwells, shows similar values.
4. Gas toxicity, measured at a height of 2.00 m above the floor level, for each level at the entrance to the stairwells, presents different values.
5. The level of thermal radiation of the air, measured at a height of 2.00 m above the floor level, for each level at the entrance to the stairwells, has different values. The highest radiation level is provided by Polyurethane Foam fuel and the lowest radiation level is provided by wood type fuel.
6. The temperature on the surface of the burned elements has different values. The highest temperatures have been obtained by using wood fuel and the lowest values have been by using Polyurethane Foam fuel. The type of combustible material significantly influences the evolution of a fire developed indoors. The accuracy in defining the calculation fire by choosing the correct fuel material is very important, because it ensures a rational and close to reality fire scenario for the numerical simulations.

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