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IMPACT OF SELECTED FIRE-MODELLING INPUT PARAMETERS ON THE SAFE AVAILABLE EVACUATION TIME

VPLYV VYBRANÝCH VSTUPNÝCH PARAMETROV POŽIARNEHO MODELU NA DOSTUPNÝ BEZPEČNÝ ČAS EVAKUÁCIE

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SUMMARY:

This article deals with the selected parameters affecting results of CFD computer fire models, namely the Fire Dynamics Simulator. The motivation for this analysis comes from the increasing use of the computer fire models and associated potential for error due to not-so-obvious importance of many input parameters. This paper is focused on the grid resolution, compartment geometry and fire specification in relation to the available safe evacuation time. It has been found that it is not possible to predict the effect of these parameters accurately by estimation only. This may affect design assumptions, e.g. increasing the area of smoke reservoir may not sufficiently increase the available safe evacuation time. It is therefore necessary to conduct a sensitivity analysis to establish the importance of all relevant input parameters.

KEYWORDS: *Fire dynamics simulator, enclosure fire, variability, area fixed fire, radially-spreading fire, evacuation*

INTRODUCTION

Fire modelling tools have gained significant popularity, which may be attributed to the steep increase of computational power in the last decade. Computer fire models have come a long way from specialist and difficult-to-use tools to user-friendly packages, which are available to the professionals, often at no charge. Computational fluid dynamics fire models offer the highest degree of precision, assuming that the user uses them correctly and can provide input data of an adequate quality. There is a number of variables which may affect the simulation and its results significantly, without the user realising it.

The purpose of this paper is to analyse the impact of selected input parameters on the available evacuation time. These parameters include mesh geometry, the way fire growth is prescribed and the geometry of the simulated space. The Fire Dynamics Simulator, a free and widely used CFD fire-modelling package was used.

1. IMPORTANT FIRE MODELLING PARAMETERS

This section presents theoretical background to input parameters such as the size of compartment, mesh density and fire spread that cause variability in outputs.

1.1. Geometry of compartment

To build a model of an enclosure in a Fire Dynamics Simulator (FDS), it is important to specify the geometry of whole space. At the beginning, the size of compartment needs to be set. Different sizes of compartment could lead to significant change in outputs. There are also three types of geometry that can be created in FDS:

- obstructions,
- holes,
- vents.

The geometry is described in terms of rectangular (axis-aligned) obstructions that can heat up, conduct heat or simply burn. Surface properties are assigned to each face of obstruction. By default, all sides of an

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obstruction use so called “INERT” surface that represents a smooth wall with fixed ambient temperature. Holes are similar to obstructions - they are defined as axis-aligned blocks but they are just negative regions out of obstructions. Finally, the geometry is made of vents from which air or fuel can be either injected into, or drawn from, the flow computational domain [1].

1.2. Mesh Density

All FDS calculations are performed within a computational domain that is made up of rectilinear volumes called meshes. Each mesh is divided into smaller blocks (cells), the number of which depends on the required resolution of flow dynamics [1].

To achieve optimal accuracy of simulation, it is important to use cells that are the same size in all three directions (xyz). For buoyant plumes the cell sizes are determined using the characteristic fire diameter D^* that is given by the following equation (1) [1]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}}, \quad (1)$$

Where: $\dot{Q}$ - total heat release rate of fire,

ρ_∞ - ambient density,
c_p - ambient specific heat,
T_∞ - ambient temperature,
g - gravity.

The smaller the characteristic fire diameter is, the smaller the cell size (δx) should be. According to [1], the non-dimensional ratio $D^*/\delta x$ is a measure of how well the flow field is resolved. It was also found that $D^*/\delta x$ ratio between 4 -16 adequately resolves plume dynamics. For small fires, a rough rule of thumb $D^*/\delta x \approx 10$ has been considered as an appropriate mesh resolution according to **Chyba! Nenašiel sa žiaden zdroj odkazov.**.

1.3. Fire in an enclosure

Enclosure fires can develop in different ways, mostly depending on the enclosure geometry, ventilation, fuel type, amount of fuel and surface area. A fire in enclosure goes through a series of stages (Figure 1.) [2, 3]:

- Ignition,
- Growth,
- Flashover,
- Fully developed fire,
- Decay.

Source: (Karlsson, 2000)

Figure 1. **Description of the temperature variation with time in an enclosure fire**

As shown in Figure 1, the initial growth period of enclosure fire is accelerating. A simple way to describe the accelerating growth is to assume that the heat release rate increases as the square of time. By multiplying time squared by a factor α, various growth velocities can be simulated and the heat release rate could be expressed as (2) [4]:

$$\dot{Q} = \alpha t^2, \qquad (2)$$

Where: $\dot{Q}$ - heat release rate of fire,
α - growth factor,
t - the time from established ignition.

In FDS, there are three ways prescribing fire development in an enclosure (figure 2.) [2]:

a) Fixed heat release rate per unit area (HRRPUA).
b) Heat release rate per unit area which is time-dependent through a RAMP function.
c) Fire spread from the center point with a defined spread rate.

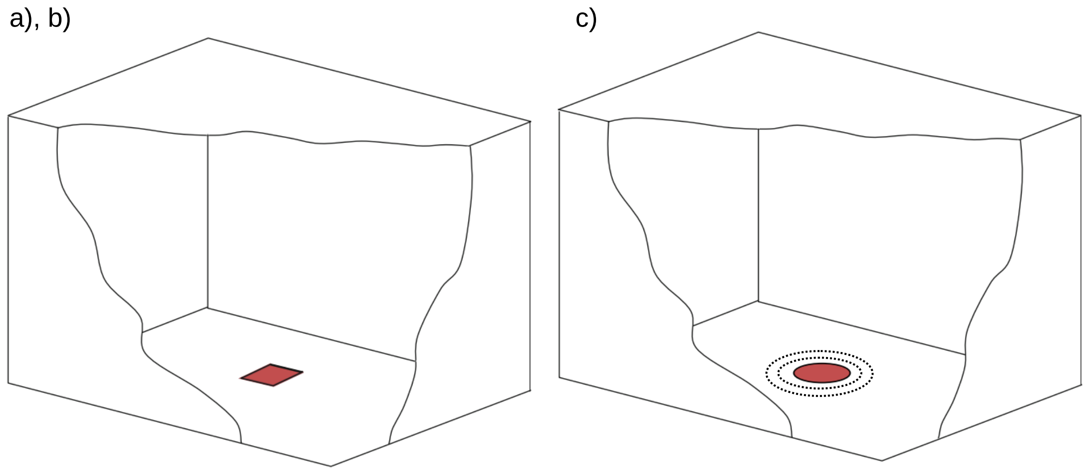

Figure 2. **a), b) Fixed heat release rate per unit area, c) fire spreading from center point**

For the first two alternatives, the heat output of the fire is either fixed or changes with time, however, the burning area remains fixed throughout the simulation. The third alternative represent a fire with a growing heat output as well as growing burning area.

With enclosure fire, there is a limit to how much heat can be released by combustion within a closed room because the heat release is coupled with consumption of oxygen from the air in the enclosure enviroment. It is assumed that oxygen does not enter from outside due to higher pressure in the room, so the fire is extinct due to oxygen exhaustion [5].

2. MODEL SCENARIOS

The computer program "Fire Dynamics Simulator" (FDS) was selected for modelling all enclosure scenarios. FDS is a powerful, open-source, computational fire dynamics simulator developed at the National Institute of Standards and Technology (NIST). The program simulates fire by solving Navier-stokes equations with an emphasis on smoke and heat transport from fire area [6]. Numerical outputs generated by FDS can be visualized by tool "Smokeview".

2.1. Description of geometry

The main goal in geometry was to set inert surface conditions for every scenario. Modelled geometry represents room without vents because in pre-flashover stage of fire, the temperature inside the compartment is too low to break windows. For examinations of variability in size of room, following dimensions (xyz) [m] were set (**Chyba! Nenašiel sa žiaden zdroj odkazov.**Figure 3).

2.2. Mesh specifications

Based on the characteristic fire diameter described in the first chapter, various mesh sizes were set (Table 1).

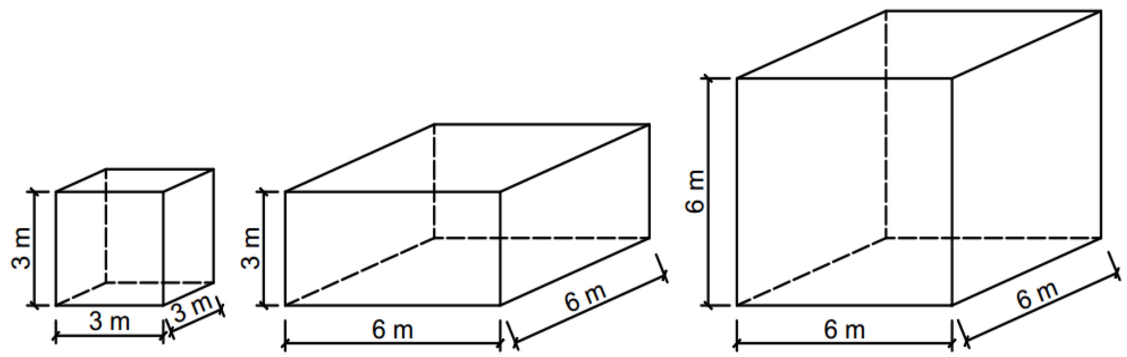

Figure 3. **Input sizes of room**

Table 1

Various mesh sizes based on the characteristic fire diameter

Fire diameter D* [m]	Cell size δx [m]	D*/ δx ratio
0,505	0.125	4
	0.05	10
	0.032	16

With decreasing cell size from 0.125 to 0.032, the total number of cells in mesh (mesh density) grows. To provide better accuracy, it is necessary to choose smaller cell size. But then, there is an issue with numbers of cells in mesh. In the first case, the overall number of cells rises from 13 824 (δx = 0.125) to 884 736 (δx = 0.032). The variability of this parameter has a significant impact on the overall length of simulation.

2.3. Fire specifications

With regards to the compartment conditions, the fire of 500 kW heat release rate was chosen. A mixture of pine wood (70 %) and plastic (30 %) has served as a fuel. Based on equation (1), the growth factor α was set to 0,012 $kW.s^{-2}$ for time interval of 400 s. According to NFPA 204 M, the growth factor corresponds to medium growth rate what allows to observe a gradual decline of smoke layer [7]. Fire development will be prescribed as:

No ventilation to the exterior was assumed to represent a fire in the phase of growth, in which the openings, primarily windows, would still be intact.

a) Fixed heat release rate per unit area. At the beginning of the simulation, this area will not be burning at all but the heat from growing fire will sequentially ramps up to the peak value of 500 kW.
b) Fire spread from the center point with constant spread rate of 0,00279 $m.s^{-1}$.

Both fires are different in terms of spreading but their heat release is approximately equal.

3. RESULTS

Due to variability of inputs parameters, 14 different scenarios were simulated. Results are summarized in this section.

3.1. Geometry impact

The first observed parameter, the size of compartment, was examined on outputs from fire spread scenarios with the cell size of 0,05 m. Figure 4 and Table 2 show the effect of the increasing size of compartment.

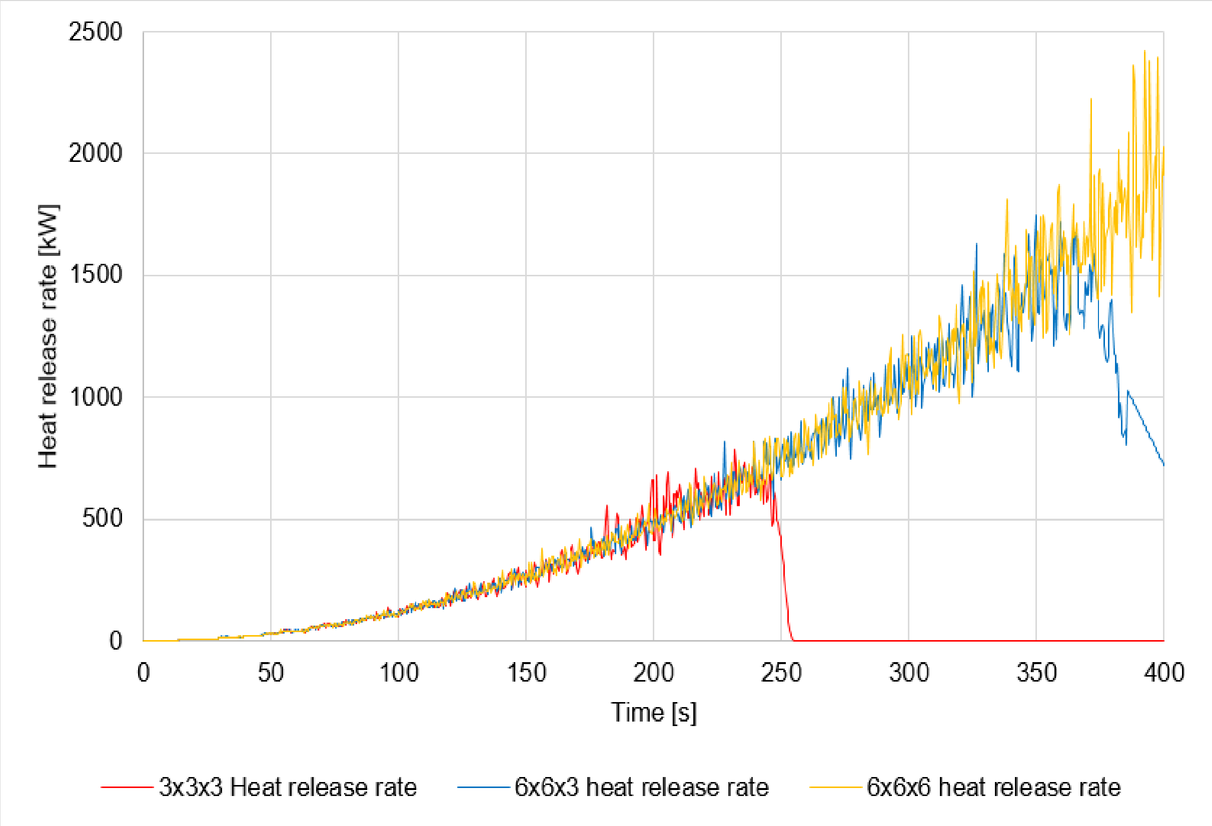

Figure 4. **A diagram showing the relation between the increasing size of compartment and heat release rate for radially-spreading fire**

Table 2

The effect of increasing the size of compartment for radially-spreading fire

Dimension [m]	The volume of room [m^3]	Change in volume [%]	Peak heat release rate [kW]	Change in peak heat release rate [%]	Termination of fire
3x3x3	27	0	783	0	yes
6x6x3	108	300	1749	123	no
6x6x6	216	700	2420	209	no

In the smallest case (3x3x3), there was not enough oxygen to support fire growth, so the fire terminated after 207 s from the beginning. Table 2 also points to the fact that if we scale the dimensions of the compartment up 2 times, volume changes 7 times and total heat release rate goes up by 209 %. The overall size of compartment also affects the height of smoke layer. Changes in smoke layer height by increasing the size of compartment between scenarios with 0,125 m and 0,05 m cell sizes can be viewed in Figure 5 and Table 3.

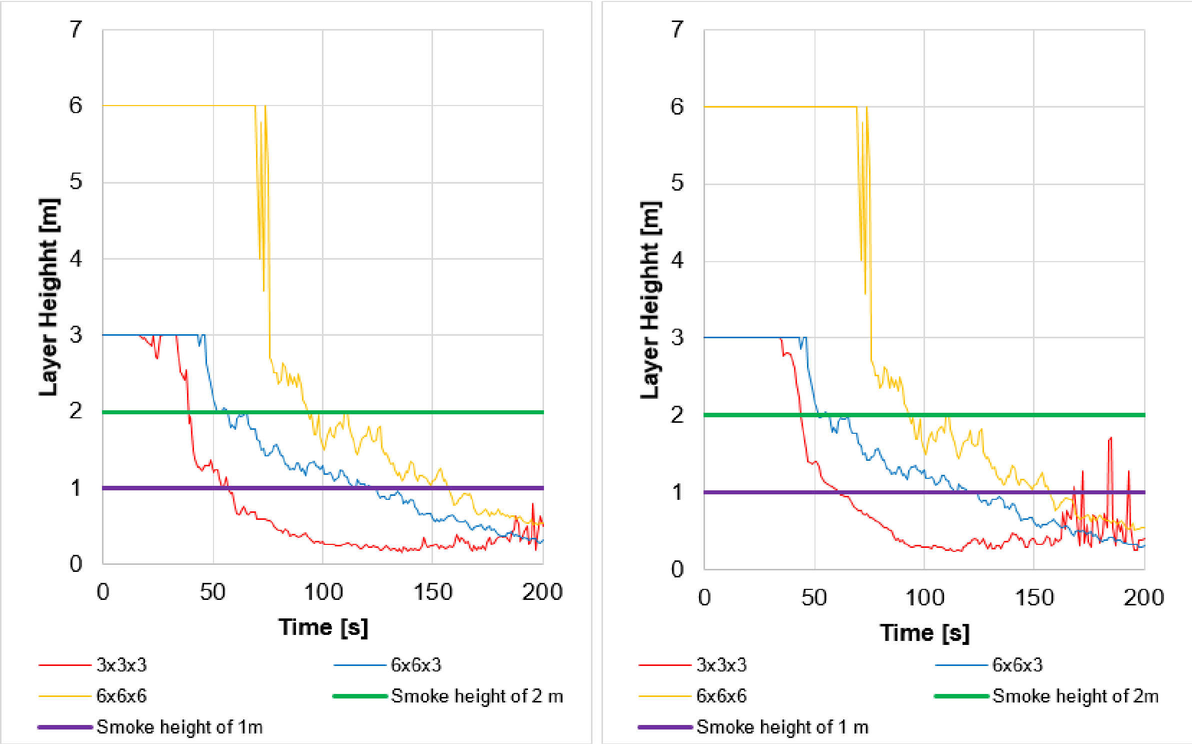

Figure 5. **Diagrams showing the relation between the increasing size of compartment and the height of the smoke layer for the cell size of 0,05 m (left) and 0,125 m (right) for radially-spreading fire**

Table 3

Changes in smoke layer height by the increasing size of compartment between scenarios with 0,125 m and 0,05 m cell sizes for radially-spreading and area fixed fires

	Decrease to 2 m [s]		**Decrease to 1 m [s]**	
Dimensions [m]	**0.125 m cell size**	**0.05 m cell size**	**0.125 m cell size**	**0.05 m cell size**
Radially-spreading fire				
3x3x3	44	39	62	58
6x6x3	57	58	117	124
6x6x6	116	93	164	157
Area fixed fire				
3x3x3	42	39	51	49
6x6x3	53	55	102	106
6x6x6	112	98	153	154

As it is obvious from Figure 5 and Table 3, the critical smoke height of 2 m for evacuees was not exceeded during evacuation, assuming a population density of 1 m^2 per person and calculated as per [STN 92 0201-3], but it is clear that increase in height of space doubles time for safe evacuation. Increasing the size of the smoke reservoir – the floor area of the room – with retaining the height of the room at 3 m did not yield a significant increase in safe available evacuation time, on average only 13,8 s. The outputs from Table 3 for cell size of 0,125 m shows overprediction in time for 3x3x3 room compared to 0,05 m cell size. It is necessary to further investigate which cell size shows more accurate outputs.

3.2. Grid resolution impact

The cell sizes are determined using the characteristic fire diameter D* and cell size ratio δx that should accurately resolve modelling situation. The Figure 6 illustrates impact to heat release rate by decreasing the cell size for the smallest room (3x3x3).

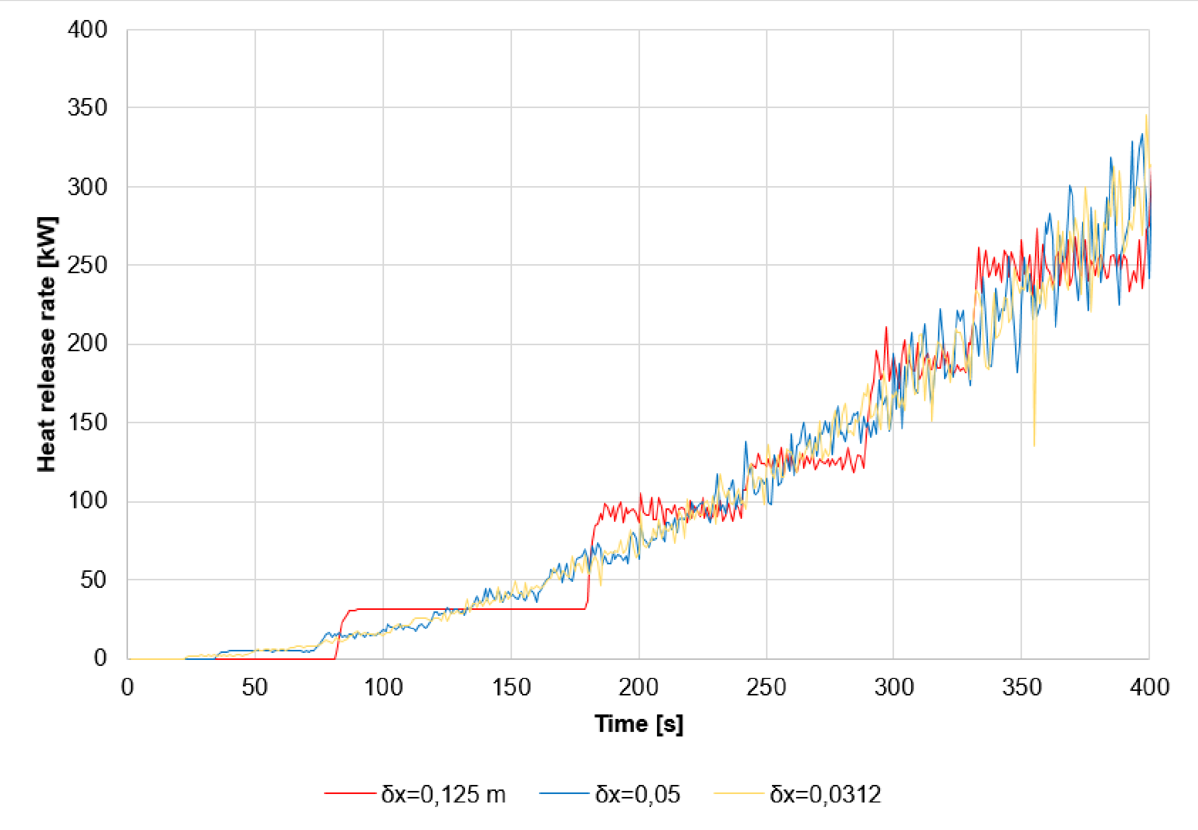

Figure 6. **A diagram showing the impact to heat release rate by decreasing the cell size for 3x3x3 room (radially-spreading fire)**

As can be seen in Figure 6, there is an error in the largest cell size compared to others. The error is caused by the steady value of heat release rate during certain intervals representing the time in which the growing fire reaches the closest bounding cells; the coarser the grid resolution the longer is the interval the fire heat release rate remains fixed.

The Table 4 presents outputs from a grid sensitivity analysis for the smallest room. The decreasing cell size to 0,0312 m results in heat release rate stabilization. We found out that the cell size of 0,05 m provided adequate accuracy and therefore no other simulations for 0,0312 cell size would be necessary.

Table 4

Result of decreasing the cell size for the smallest room (radially-spreading fire)

Cell size [m]	Total number of cells	Total increase of cells (multiple of 0,125)	Heat release rate in 100 s[kW]	Difference in heat release rate [%]
0,125	13824	1	103,87	25
0,05	216000	16	129,97	0
0,0312	884736	64	129,36	0,47

3.3. Fire spread impact

The differences between the spreading fire and the area-fixed fire for the biggest room are displayed in Figure 7. At the beginning, the heat release rate in both cases copies the predicted curve by equation **Chyba! Nenašiel sa žiaden zdroj odkazov.**. After approximately 100 s of fire growth, output values start to fluctuate around the predicted curve with an average difference of 8,34 kW throughout the test, which given the size of fire in the latter stages may be considered negligible. It is worth noting that the fluctuation grows proportionally with time, i.e. the relative difference remains fixed.

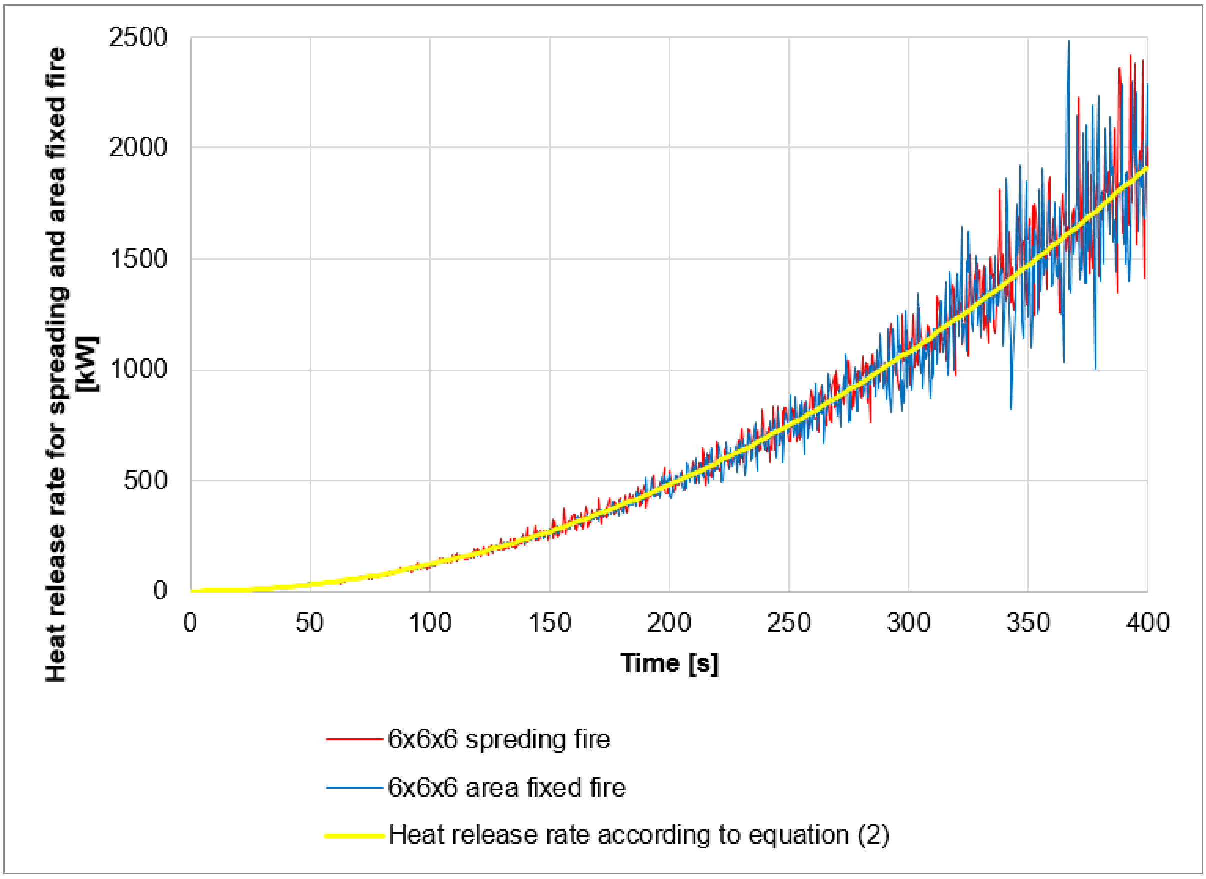

Figure 7. **Spreading fire HRR and area fixed fire HRR in comparison with HRR according to equation (2) for both area fixed and radially-spreading fires**

CONCLUSION

The purpose of this paper was to draw attention to selected parameters that affect the available safe evacuation time with the use of the Fire Dynamics Simulator.

The compartment geometry analysis showed strong influence on the safe available evacuation time, as it affects the size of the smoke reservoir. Interestingly, it was found that the effect of increasing the area of the compartment did not increase as significantly as expected despite the fact that the volume of smoke reservoir grew by 300 %. Only when the area and height increased, a more significant available safe evacuation time was achieved. Hence, it is not possible to make simple assumptions about evacuation time based on geometry changes.

The grid resolution is a very important parameter and a great care must be paid when selecting it. A grid that is too coarse affects the results precision negatively, however, if the grid has a very fine resolution the case becomes computationaly very expensive. Coarser grid resolution also causes overprediction, in general.

With regard to the radially spreading fire, it was found that the fire growth is adversely affected and becomes a series of plateau steps when the grid resolution is overly coarse. The way the fire is prescribed (fixed area vs. radially-spreading fire) also affected the available safe evacuation time. Due to the growing perimeter of the radially-spreading fire and its plume, more surface is available for air entrainment. This effect becomes more pronounced at greater compartment heights, where the plume is longer.

To conclude our paper, the most important findings are:

- The available safe evacuation time does not grow linearly with the volume of the smoke reservoir (room area and height).
- The grid resolution does not only affect the accuracy of simulation results but also the fire behaviour that has spatial dependencies; this was found to be very significant for the scenarios with a radially-spreading fire.

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