

# ANALYSIS OF INPUT PARAMETERS FOR NUMERICAL SIMULATIONS OF FIRE

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## ABSTRAKT

Článek je shrnutím diplomové práce autorky, která se zabývá analýzou vstupních parametrů pro numerické simulace požáru. Pozornost je zaměřena především na určení vlivu ventilace, tedy přísutného kyslíku, na průběh teplot a rychlost, se kterou se uvolňuje energie ve zkoumaném prostoru, ve kterém je modelován požár. Je provedena citlivostní analýza tohoto vlivu ve 3 matematických modelech požáru. Je uvažována parametrická křivka, zónový model a computational fluid dynamics model. Je prezentován popis základních principů modelů, uvážení konkrétního požárního scénáře a vykreslení výstupních hodnot (průběh teploty a vyzářené energie v čase) z jednotlivých modelů. Výsledky jsou porovnány, také v souvislosti s použitím v konstrukčním návrhu za požární situace.

## KLÍČOVÁ SLOVA

Požár v uzavřeném prostoru • Model požáru • Simulace požáru  
• Ventilace • Parametrická křivka • Zónový model • CFD model

## ABSTRACT

This article is a brief summary of author's diploma thesis, which deals with a consideration of input parameters for numerical simulations of fire. An analysis of the extent of ventilation influence to the energy and temperature histories is carried out. A sensitivity analysis is conducted in three different mathematical fire models. Parametric fire curve, Zone model and CFD model are considered in this paper. Description of the basic concepts of each model and consideration of a specific fire scenario is included and the output data (temperature and energy release history) are presented. The results are compared and discussed with respect to structural fire design, for which these outcomes are the key regard.

## KEYWORDS

Enclosure Fire • Fire Model • Fire Simulation • Ventilation • Parametric Fire Curve • Zone Model • CFD Model

## 1. INTRODUCTION

The performance-based fire design is a rapidly developing discipline as the demand for sizes and heights of structures is growing and consequently the standardized approaches can not be implemented. An array of fire models varying in number and details of input data, type of mathematical apparatus used, and the accuracy of output data, is available. Independently of the fire model choice, it is essential to determine the factors that affect the fire and to assess to what extent the ignition and development of fire are affected, more stated in (Šárka Košťálová 2020).

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## 2. MATHEMATICAL MODELS

The analysis is carried out to examine the extent of the influence of ventilation, and thus of the available oxygen, to released energy and temperature histories. Three deterministic fire models, which describe the fire phenomena by mathematical expressions based on physics and chemistry are used for subsequent analysis.

*Parametric fire curve* defined in EC1 part 2 (EN 1991-1-2 2002) is considered. In principle it is one control volume model assuming the whole compartment to be well-stirred reactor. The fundamental concept of parametric fire curve is solution of an equation of heat balance conservation. (Drysdale 2011)

*Zone model* or control volume model divides the compartment horizontally into upper and lower layer. The fire directs the movement of combustion products from the lower to the upper layer via fire plume, which is a buoyant flow of hot gases. The temperature within both upper and lower layer is uniform, and the evolution in time is described by a set of ordinary differential equations derived from the fundamental laws of mass and energy conservation. (CFAST, *Technical Reference Guide, Seventh Edition* 2015)

*CFD model* is the most recent mathematical fire model. The core is a system of coupled partial differential equations. It works on a principle of dividing continuum into definite number of control elements, calculating equations of mass, momentum and energy for each element and each time step. (*Fire Dynamics Simulator, Technical Reference Guide, Sixth Edition* 2013)



Figure 1: Illustration of a difference between fire models used for analysis. It exemplify the assumption of space discretization for parametric fire curve model, zone model and CFD model.

## 3. FIRE SCENARIO

A representative office compartment is assumed. The office's inner dimensions are 6.0 x 4.5 x 3 m. The dimensions correspond to coordinate axis x, y, z and are indicated in Figure 2. The compartment contains an only ventilation opening at the rear size of compartment facing outside. The height of the window remains constant 1.5 m during the simulations to prevent any side-influences

to the heat release rate and temperature histories. Window width is varied and it takes the values from  $w = 0.5$  m with 0.5 m step to  $w = 5.0$  m.

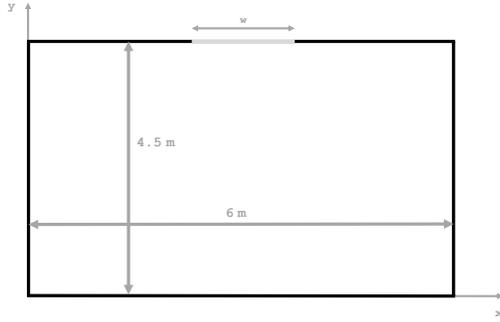


Figure 2: Floor plan of analysed compartment with indicated dimensions.

For all three fire models the fire energy input is taken from EC 1 part 2 (EN 1991-1-2 2002). 80 % fractile of fire load density from Table E.4 for occupancy *office* is considered for the parametric fire curve model. For the zone model and computational fluid dynamics model the fire load density is an insufficient input. A rate, on which the energy is being evolved and maximum rate of heat release must be defined. An analytical expression  $t$ -squared fire is used with input values taken from Table E.5. The  $t^2$  fire curve has been implemented in MATLAB (MATLAB 2010) code and are plotted in Figure 3 for each window width variation. The curves represent the energy input data to the considered numerical fire models.

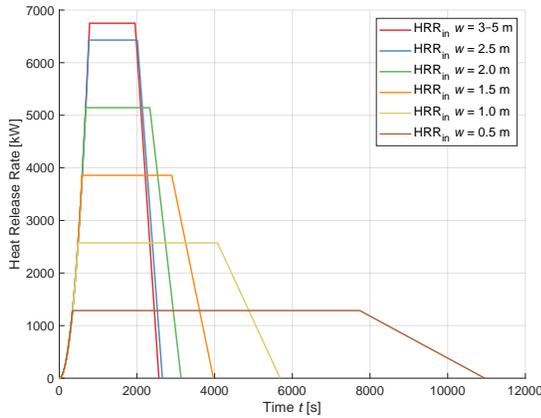


Figure 3: T-squared fire curves used as input rates of heat release.

The assessment of availability of oxygen in compartment is made by using simplified expression:

$$\dot{Q}_{max} = 0.1 \cdot m \cdot H_u \cdot A_v \cdot \sqrt{h_{eq}}, \quad (1)$$

where  $\dot{Q}_{max}$  is maximum level of the rate of heat release [kW],  $m$  is the combustion efficiency [-],  $H_u$  is the net calorific value of wood with  $H_u = 17.5$  [MJ kg<sup>-1</sup>] and  $A_v$  and  $h_{eq}$  is the opening area [m<sup>2</sup>] respectively its mean height [m].

### 3.1. Parametric Fire Curve

For the purposes of the analysis a parametric fire curve is implemented and plotted in mathematical software MATLAB (MATLAB 2010). In principle, parametric fire curve distinguishes between fuel-controlled and ventilation-controlled fire. For each situation a different relation is being used depending on the size of the value  $O$ . Value  $O$  is determined from the size of the opening area and thus is directly influenced by. Thus to determine the point of burning regime switch a calculation of the parametric curve was conducted for different values of the window width and consequently, different opening factors  $O$ . To stay within the limits of opening factor  $O$ , the window widths 0.5 m and 1.0 are not considered.

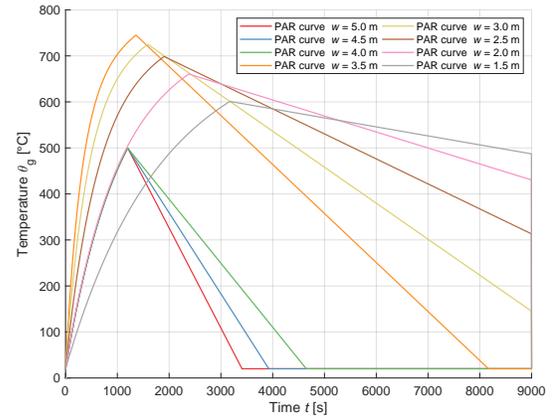


Figure 4: Plot of parametric fire curves for window widths 1.5 m - 5.0 m with 0.5 m step.

Two particular parametric curves located right at the switch of the burning regimes, and thus different analytical prescription, are presented in Figure 5.

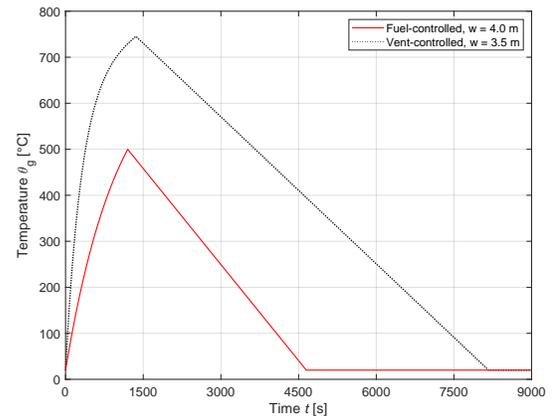


Figure 5: Comparison of parametric fire curves when burning regime switches.

The change of analytical prescription occurs for simulation with window widths 3.5 m and 4.0 m. Thus for a change in window width of 0.5 m, or area of 0.075 m<sup>2</sup>, the parametric curve

model assumes a 250-degree difference in the peak temperature and also variations in the cooling part.

### 3.2. Zone Model

The simulation is conducted in CFAST, developed by National Institute of Standards and Technology of U.S. Department of Commerce. Within consolidated Fire and Smoke Transport (CFAST) the heat release rate is being calculated from equation

$$\dot{Q} = \min(\dot{m}_f \cdot \Delta H_c ; \dot{m}_e \cdot Y_{O_2} \cdot C_{LOL} \cdot \Delta H_{O_2}), \quad (2)$$

where  $\dot{Q}$  is heat release rate [KW],  $\dot{m}_f$  is pyrolysis rate of fuel [ $\text{kg s}^{-1}$ ],  $\Delta H$  is heat of combustion [ $\text{kJ kg}^{-1}$ ],  $\dot{m}_e$  is entrainment rate inside the fire plume [ $\text{kg s}^{-1}$ ],  $C_{LOL}$  is the smoothing function ranging from 0 to 1 [-],  $Y_{O_2}$  is the mass fraction of oxygen in the layer containing the fire [-],  $\Delta H_{O_2}$  is the heat of combustion based on oxygen consumption [ $\text{MJ kg}^{-1}$ ].

The first component of Equation 2 refers to fuel-controlled fire, when the amount oxygen available is sufficient for all the combustibles to take place in the combustion. The second component of Equation 2 stands for rate of heat release within the ventilation-controlled fire, when the oxygen amount is not sufficient and some pyrolysis products leave the compartment without burning away. (CFAST, Technical Reference Guide, Seventh Edition 2015)

As a demonstration of how the reduction assumption in zone model works, a simulation with the maximum value of heat release rate (such for 5-m-wide window) was considered as an input energy of the fire. In the simulation a window width of only 1 m was modelled.

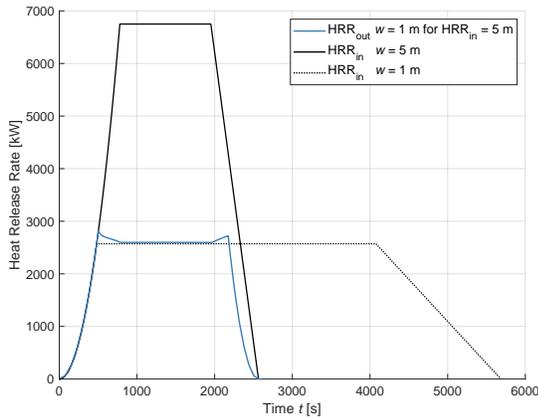


Figure 6: T-squared fire curves denoted as  $HRR_{in}$  for window widths 1 and 5 m are compared to HRR output from zone model based CFAST simulation with 1-m-wide window with energy input for 5 m.

Even though that the reduced value of maximum heat release rate from zone model corresponds to the reduction calculated by Equation 1, it is necessary to account for the conservation of the energy released during a fire which is represented by the area under the curve.

As for the temperature histories, temperature results of the upper layer from CFAST simulations are compared to the parametric fire curves in Figures 7 and 8.

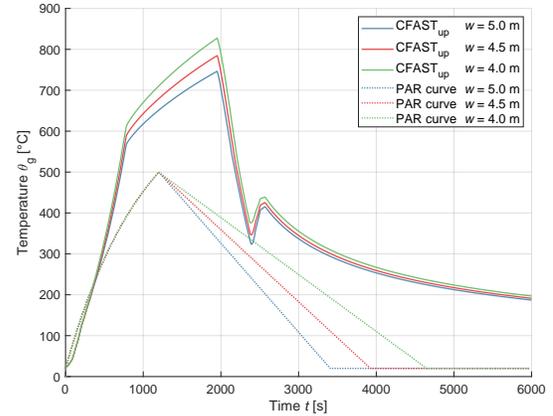


Figure 7: Comparison of upper layer temperature progresses from CFAST and fuel-controlled parametric curves assuming window widths  $\langle 4.0, 4.5, 5.0 \rangle$  m.

The upper layer temperature maximums exceed the parametric fire curves values over 250 °C. The highest temperature is reached for window width 4 m.

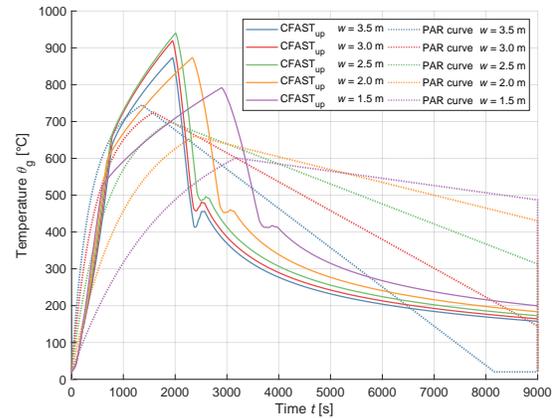


Figure 8: Comparison of temperature progresses from CFAST and ventilation-controlled parametric curves assuming window widths  $\langle 1.5, 2.0, 2.5, 3.0, 3.5 \rangle$  m.

The maximum temperatures increase as the window area is getting smaller. After reaching window width 2.5 m, the maximums start to decay. The deviation from the progress of the cooling part are observed at the times of the considered depletion of fuel by t-squared curve.

### 3.3. CFD Model

An analysis of an influence of ventilation to a prescribed energy release rate is conducted in NIST-developed commercial software FDS. Simulations with window widths  $\langle 0.5 : 0.5 : 5 \rangle$  m and their corresponding energy inputs ( $t^2$  fire curves) are conducted. When using prescribed heat release rate, FDS is using oxygen availability check sub-model to assess if the fire is provided with enough oxygen. If the energy prescribed lacks the oxygen to fulfil the prescribed progress, FDS assumes its restriction. Subsequently the

overall energy assumed is not maintained as the curve is not automatically prolonged by FDS and needs to be done manually or by carrying out more simulations to get the most precise prescription of energy input by the process of iteration.

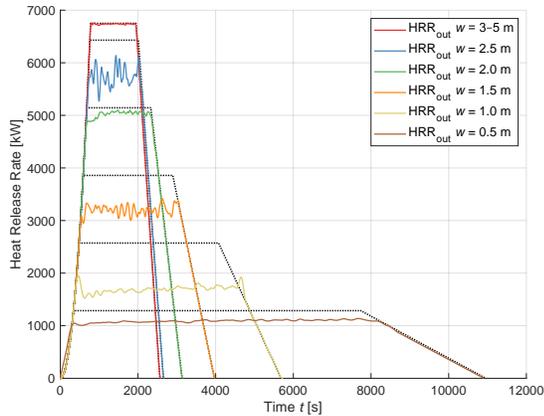


Figure 9: Comparison of HRR inputs ( $t^2$  fire curves) and output HRRs from FDS simulation assuming different opening areas.

For window widths  $\langle 3; 3.5; 4.0; 4.5; 5.0 \rangle$  m the  $t^2$  fire curves have the same prescription among each other, and are not limited.  $T^2$  fire curves of widths  $\langle 0.5; 1.0; 1.5; 2.0; 2.5 \rangle$  m and their maximum rates of energy release are limited according to Equation 1. When comparing the  $t^2$  curves and the output HRR curves, the fuel controlled  $t^2$  corresponds with the outputs (with variations in the horizontal part of the curve). As for  $t^2$  ventilation-controlled curves the extend of limitation of the maximum rate of heat release varies among the simplified expression given in EC1 and FDS's oxygen availability model assumption. The assumption of the point, where the burning regime switches is similar for the  $t^2$  prescription and FDS oxygen availability check sub-model.

An adjustment of  $m$  from Equation 1 can be implemented to a code to preserve the area below the curve which is representing the amount of energy released during the fire.

$$m = \frac{Q_{max}}{0.1 \cdot Hu \cdot A_v \cdot \sqrt{h_{eq}}} \quad (3)$$

Not only is the released energy governed by the available oxygen. It is also influenced by a chemical compound taking place in the combustion. In FDS simulation the so-called surrogate fuel is defined by the user and is to mimic the combustible material present in the given compartment.

#### 4. DISCUSSION

While analysing specific structural element, it is essential to analyse its surrounding ambient and use the temperature or heat flux in the close region depending on the type of analysis and fire model.

A round-robin study (Johansson & Ekholm 2017) was conducted, to assess the variation in results due to user effect in FDS simulation. It shows variations between users - their specification of input data, the way of measuring them and gaining the output values, which are then applied to follow-up structural analysis. However not only relatively large differences within the definition of the issue were observed, some of the participating users also

made mistakes in the definition of fire, mostly by not covering the underlying physics.

To exemplify, a simulation outcome with different surrogate fuels, propane and acetylene, is demonstrated in Figure 10. Heat release rate progresses from simulations with propane and butane are reduced by 800–1000 kW. The influence of a surrogate fuel is a considerable issue when conducting a simulation.

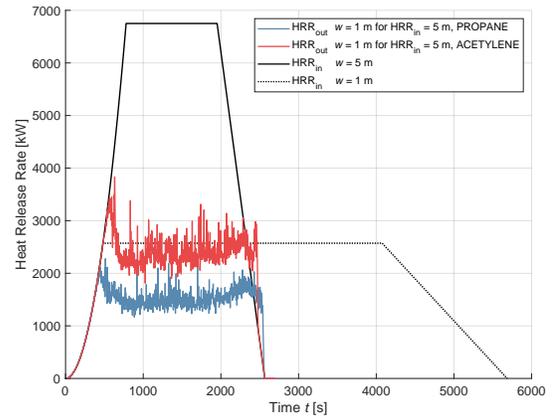


Figure 10:  $T^2$  fire curves denoted as  $HRR_{in}$  for window widths  $w = 1$  and  $w = 5$  m are compared to HRR outcome from FDS simulation with 1-m-wide window with energy input for  $w = 5$  m with propane and acetylene.

The fire models, however, should be thought as of a tool rather than a black box, which miraculously change the input data to desired output data. A thorough assessment of appropriateness of input data and the outcomes from the fire model needs to be conducted. That is connected not only to the validation data and the limitation of the particular model, also to the knowledge of underlying solving apparatus implemented in the particular software, which is being used for the analysis.

#### ACKNOWLEDGEMENTS

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS20/041/OHK1/IT/11.

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