

INPUT DATA OF BURNING WOOD FOR CFD MODELLING USING SMALL-SCALE EXPERIMENTS

Petr Hejtmánek¹, Libor Ševčík² and Kamila Cábová³

1. *Czech Technical University, Faculty of Civil Engineering, Department of Building Structures, Thákurova 2077/7, Prague, Czech Republic; hejtmpet@fsv.cvut.cz*
2. *Technical Institute of Fire Protection in Prague. Písková 42, Prague 4 – Modřany, Czech Republic; libor.sevcik@tupo.izscr.cz*
3. *Czech Technical University, Faculty of Civil Engineering, Department of Steel and Timber Structures, Thákurova 2077/7, Prague, Czech Republic; kamila.cabova@fsv.cvut.cz*

ABSTRACT

The paper presents an option how to acquire simplified input data for modelling of burning wood in CFD programmes. The option lies in combination of data from small- and molecular-scale experiments in order to describe the material as a one-reaction material property. Such virtual material would spread fire, develop the fire according to surrounding environment and it could be extinguished without using complex reaction molecular description. Series of experiments including elemental analysis, thermogravimetric analysis and difference thermal analysis, and combustion analysis were performed. Then the FDS model of burning pine wood in a cone calorimeter was built. In the model where those values were used. The model was validated to HRR (Heat Release Rate) from the real cone calorimeter experiment. The results show that for the purpose of CFD modelling the effective heat of combustion, which is one of the basic material property for fire modelling affecting the total intensity of burning, should be used. Using the net heat of combustion in the model leads to higher values of HRR in comparison to the real experiment data. Considering all the results shown in this paper, it was shown that it is possible to simulate burning of wood using the extrapolated data obtained in small-size experiments.

KEYWORDS

Combustion of wood, Pine, FDS, Cone calorimeter, FTCH, Small-size experiment

INTRODUCTION

Computer based modelling of a fire is the one of the progressive methods in fire safety engineering. This approach, used in performance-based design, brings new possibilities to fire safety design of the buildings, which would not be allowed to build according current prescriptive approach or they would require many fire safety appliances and the costs would be inadequate. Computer modelling is a powerful tool, however, it is still a tool only and it comes with several problems or disadvantages. Except others, the method needs a detailed and precise description of input parameters. The numerical solution also takes a lot of time and it demands a lot of computing power.

For pyrolysis and combustion modelling, fire-technical characteristics (FTCH) are the most important input parameters and its obtaining is not an easy task. This task has been a subject of research for many years. Input data for numerical modelling in terms of material pyrolysis properties are introduced in [1]. If we want to model the real-size environment, there are several attitudes, how FTCH can be obtained:

- The most precise values can be acquired from **large-scale experiments**. There is no problem with power and dimensions scaling during a full-scale experiment, on the other hand, it is time and money consuming and it might not match every model application. General characteristic (the “final” characteristics respectively) can be obtained.
- **Intermediate- or small-scale experiments** are much cheaper and it is possible to run series of them to obtain mean values. But there is a question, whether the values are size independent or whether the FTCH must be modified when used on a bigger model object. Again, the “final” characteristics can be obtained.
- Completely different attitude is used with **molecular-scale experiments**. Such experiments give very good knowledge about decay and pyrolysis and those values are size-independent. On the other hand, it is not the final FTCH and the modelling software has to compute the reaction with given data in every cell in every time step and it protracts the computation. This method, as it will be mentioned lower, is almost impossible to run in real-scale building applications.

This paper deals with an optimizing the input phase of fire modelling and it analyses the possibility of using combination of small- and molecular-scale experiments to obtain the “final” characteristics. The goal of the research is to acquire data that can be simplified to a CFD code as a one-reaction material property: so it would be able to simulate heat effect of the wood without direct description of HRR and without need of combustion parameters and setting the reaction, so it can be extinguished, for example.

Series of experiments were performed and then the FDS model of cone calorimeter was built where those values were used. The model was verified comparing the model HRR with the data from the real cone calorimeter experiment. All the experiments were performed with pine wood.

METHODS

For the numerical modelling purpose, the Fire Dynamics Simulator (FDS) was chosen. It is a solver based on finite volume calculation methods called Computational Fluid Dynamics (CFD). This open source software was first released in 2000. The solver itself does not have any user interface. The creation of a model required a knowledge of special FDS language code. For the purpose of preparation of the FDS model the commercial software (e.g. Pyrosim) can also be used. In this paper the basic FDS version 6.1.2 was used.

As well as there are several methods of obtaining FTCH, there are two methods, how to describe the pyrolysis and combustion in modelling software, namely FDS: Firstly, it is possible to use the “final” characteristics, such as HRR, on the object. This method does not require any additional computational time, on the other hand, directly entered HRR cannot react on the environmental changes (for example extinguishing effect of sprinklers). And secondly, it is possible to enter the complex pyrolysis data from molecular-scale experiments and model the pyrolysis and combustion. Because the combustion conditions are revised and computed in every cell and in every time step, it respects the environment, but it is vastly time-consuming. The FDS model, which is described in this paper, covers a relatively small computational space. In the space there are applied as many of elementary attributes as possible in order to calculate temperature analysis of pine wood with high level of accuracy. First of all, the geometry of the model was built. After that heating conditions of the model as well as the material properties were determined.

COMPOSITION OF WOOD AND BURNING OF WOOD

The main goal of conducted small-scale experiments was to determine as many elementary attributes as possible. For the simulation purpose it is necessary to define a proper pyrolysis model which contains the material properties and the reaction of combustion solids. Both of these attributes contribute to burning process of solids in the FDS.

Material properties define the speed and intensity of reaction which the material undergoes during the heating. After building up a geometry and defining the heating condition of the model it is necessary to determine composition of the materials. Wood is highly complex biopolymer material. Biopolymer substances, often in literature described as the main building elements of the wood, cover 90–97 %. Cellulose and hemicellulose stands for approximately 70 % of this main substance. Approximately 30 % of total mass consists of substance called lignin. The other substances are described as accompanying substances, e.g. waxes, tannins, minerals etc. [2]. For modelling purposes, it is ideal to define as many substances as possible in one material.

Every substance in wood has its own function and exhibits unique behaviour during the heating. In a microscopic level the wood is created by the cell walls. Function of the main elements can be likened to concrete. Basic structural component which creates a frame of the cell is cellulose. In concrete analogy it can be compared to aggregates. Hemicelluloses is often likened to a cementing material, which holds the frames together. There are many different types of hemicelluloses. Some of them are very flammable and some of them are not. In general, it can be said that hemicelluloses are greatly contributing to fire development. The last major substance is lignin. It can be likened to an accompanying substance in concrete analogy which is surrounding and strengthening the cells [3]. Lignin consists of mutually connected benzene rings. In other words, it is created mostly from incombustible carbon. From the fire engineering point of view, the very interesting fact is that lignin contributes to the creation of protecting char layer greatly during the heating process.

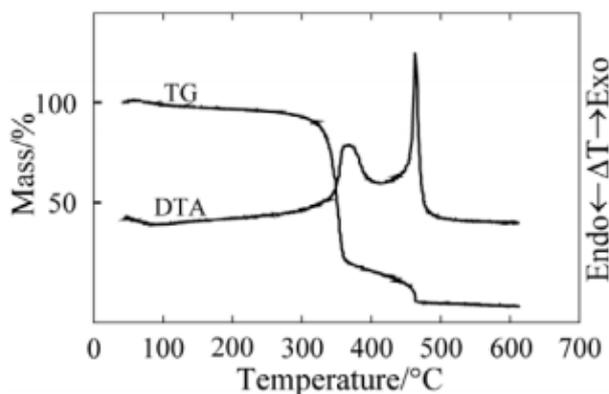


Fig. 1 - Thermal analysis of cellulose in air [4]

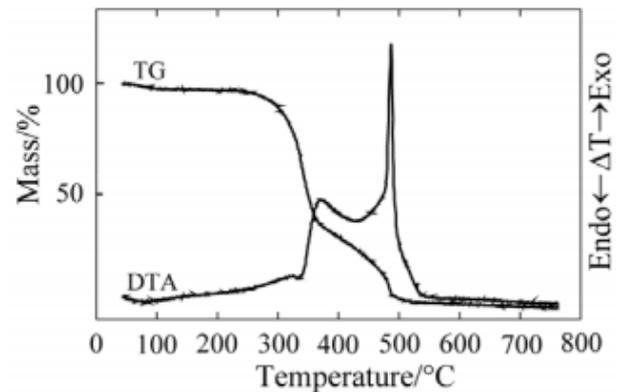


Fig. 2 - Thermal analysis of wood in air [4]

Despite of “inflammable” lignin the wood is still considered as combustible material because it contains high amount of extremely flammable cellulose. Figures 1 and 2 describe the data from thermogravimetric analysis (TGA). The TG curve shows the function of mass loss of cellulose and wood exposed to elevated temperature. As shown, fire behaviour of the cellulose in TGA is very similar to the wood behaviour. The differential thermal analysis (DTA) curve is the first derivation of the TG curve. It describes the momentary speed of mass loss reaction with elevated temperature.

When cellulose was tested (Figure 1), the first mass loss is found around 100 °C and it can be connected with evaporation of bound water, where about 10 % of original mass was lost. First

exothermic peak is found at temperature around 350 °C (around 70 % of mass loss). This thermal degradation is associated to oxidation of cellulose into laevoglucosan, water carbon monoxide and carbon dioxide. The last peak around 450 °C (around 10 % of mass loss) represents breaking carbon-carbon bonds [5, 6]. Although the wood contains many different kinds of substances, it depends mostly on the combustion of cellulose and the main mass loss and energy release is found around 350 °C, when cellulose is decomposed. This finding is used further in FDS modelling, where the wood is viewed as single-component single-reaction material with water in the form of moisture.

MATERIAL PROPERTIES BASED ON EXPERIMENTS

It is necessary to assign detailed material properties to all obstacles in the FDS model. Required data were obtained by performing an elemental analysis of pine wood. The sample material was grinded to a very fine powder in a laboratory of fuel analysis at University of Chemistry and Technology in Prague (UCT). The sample used for an experiment was thoroughly chosen as it was required not to have any defects such as knags etc.

After grinding the sample, the humidity test was performed. The result was 7,76 % of the mass. The heat of combustion test was the next small-scale experiment performed in the laboratory. Data obtained from this experiment belong to the main FTCH which affects the total burning intensity in the model. Performed experiment provided the heat of combustion value of 16,94 MJ·kg⁻¹. This value is very similar to the one specified in the Czech technical standard ČSN 73 0824 [7]. The value of the heat of combustion of the pine wood equals here to 17,00 MJ·kg⁻¹. However, this value cannot be used for model purposes as it does not correspond to a real situation. The measured value is so called “net heat of combustion” and can be achieved only in laboratory conditions when all the sample materials including the carbon rests and other products of burning are burned down. In real situation as well as during the cone calorimetry test a great amount of energy stays unused. This type of heat reaction is called “effective heat of combustion”. This value depends on the process of heating of the material and it can be obtained by performing cone calorimetry experiment. The effective heat of combustion value obtained from cone calorimeter was 11,41 MJ·kg⁻¹. Heat flow used in this experiment was 35 kW·m⁻². The model simulation was performed twice – using net heat of combustion value and value of effective heat of combustion.

Tab. 1 - Entered heat of combustion to the model

Heat of combustion			
Type of experiment	TÚPO Cone Calorimeter 35 kW·m ⁻²	UCT Prague Bomb Calorimeter IKA C200	ČSN Standard value [7]
Value [MJ·kg ⁻¹]	11,41	16,94	17,00

The other part of the grinded sample was conserved and sent to the laboratory for performing elemental analysis. This experiment covers all the combustible sulphur – both organic and inorganic – as well as organic and inorganic carbon. Analysis is performed with a very small amount of the sample. Maximum weighted amount for the Elementar Vario apparatus is 5 mg. The results of this analysis are shown in the Table 2.

Tab. 2 - Results of elemental analysis

Sample	Amount (mg)	% N	% C	% S	% H
E 1 - CVUT	3,114	-	47,400	-	6,477
E 2 - CVUT	4,047	-	47,340	-	6,508
E 3 - CVUT	4,149	-	47,250	-	6,551

Results show that there is neither nitrogen nor sulphur in any form in the sample material. Content of hydrogen is variable depending on the humidity of sample material. The average value of hydrogen is 6,512 %. Carbon is highly represented in the wood as it is the main unit of all wood components (e.g. cellulose). Average carbon content is 47,330 %. The rest is oxygen. Content of this element is 46,158 %. Data obtained during elemental analysis were used for checking the chemical formula of pine wood which can be found in literature. Chemical formula of pine wood is $\text{CH}_{1,7}\text{O}_{0,83}$ [8]. Ratio between the pine wood mass and water moisture was specified to 92,2:7,8. Specific heat capacity, conductivity and density were specified for both of them [8].

Tab. 3 - Material properties

	Density [$\text{kg}\cdot\text{m}^{-3}$]	Specific heat capacity [$\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$]	Thermal conductivity [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$]
Water	1000	4,18	0,6
Pine wood	520	2,5	0,2
Char layer	200	1,6	1

Determination of the appropriate thermal response was essential for creating the pyrolysis model. FDS solver is sufficient with the final products of combustion in material section, resp. in this section the percentage of material that is transformed to both non-combustible rest and to gas is specified.

In the model as well as in the real situation the solid material is not burnt. After heating above certain temperature, the material is degraded with heat without the access of oxygen (pyrolysis). Material structure is changed in this process. The carbon bonds in main material component are disrupted. Cellulose macromolecules are shortened and during this process flammable substance are produced. A good example is an unstable compound of laevoglucosan. Gas and solid ratio is essential for model situation as it determines the amount of fuel which is then changed to thermal energy and therefore to HRR. The gas and solid ratio was found by simple experiment which was performed in the Technical Institute of Fire Protection in Prague (TÚPO). The sample was weighted, completely burnt down and then weighted again. There were two samples examined in the test. Results are shown in the following Table 4.

Tab. 4 - Weight of samples before and after burning

	Unit	Experiment nr. 1	Experiment nr. 2
Weight of sample	g	21,7	18,92
Weight of residue	g	3,32	2,71
Weight difference	g	18,38	16,21

Weight difference was 84,7 %. This measurement was also a part of experiment called Analysis of Combustion Products which is described in the other part of this article.

Thermogravimetric analysis

Except the final products of pyrolysis, it is necessary to define the process of the reaction. In other words, to define the temperature and reaction rate when the material is transformed. These variables can be defined with coefficient based on Arrhenius equation. This equation describes the relationship between the reaction temperature and the reaction rate. Generally, the higher the temperature is, the higher the reaction rate is. These variables can be used in FDS code in two ways.

The first way covers the direct use of both variables in the code. They can be calculated from the following formulas [8]:

$$E_{i,1} = \frac{e r_{p,i}}{Y_{s,i}(0)} \frac{R T_{p,i}^2}{\dot{T}} \quad ; \quad A_{i,1} = \frac{e r_{p,i}}{Y_{s,i}(0)} e^{E/RT_{p,i}} \quad (1); (2)$$

where $r_{p,i}/Y_{s,i}(0)$ is the reference rate of reaction, the R factor expresses the molar gas constant and $T_{p,i}$ stands for the reference temperature of chemical reaction.

All the unknown variables can be found out during the thermogravimetric analysis (TGA) experiment. Parameter \dot{T} describes the rising rate of temperature in the furnace.

Another way of defining the kinetic parameters is a straight assigning of the above mentioned parameters from TGA. FDS solver is able to calculate these kinetic parameters. This data should be given for each pyrolysis reaction. Each material in FDS can undergo only one reaction. If there are two materials defined (pine wood and water), two pairs of kinetic parameters have to be defined in FDS. Results of thermogravimetric analysis, which was carried out with TG-DTA thermal analyser Setaram Setsys Evolution in Laboratory of Thermal-Gravimetric Analysis (TGA), UCT Prague, are shown in the following graph.

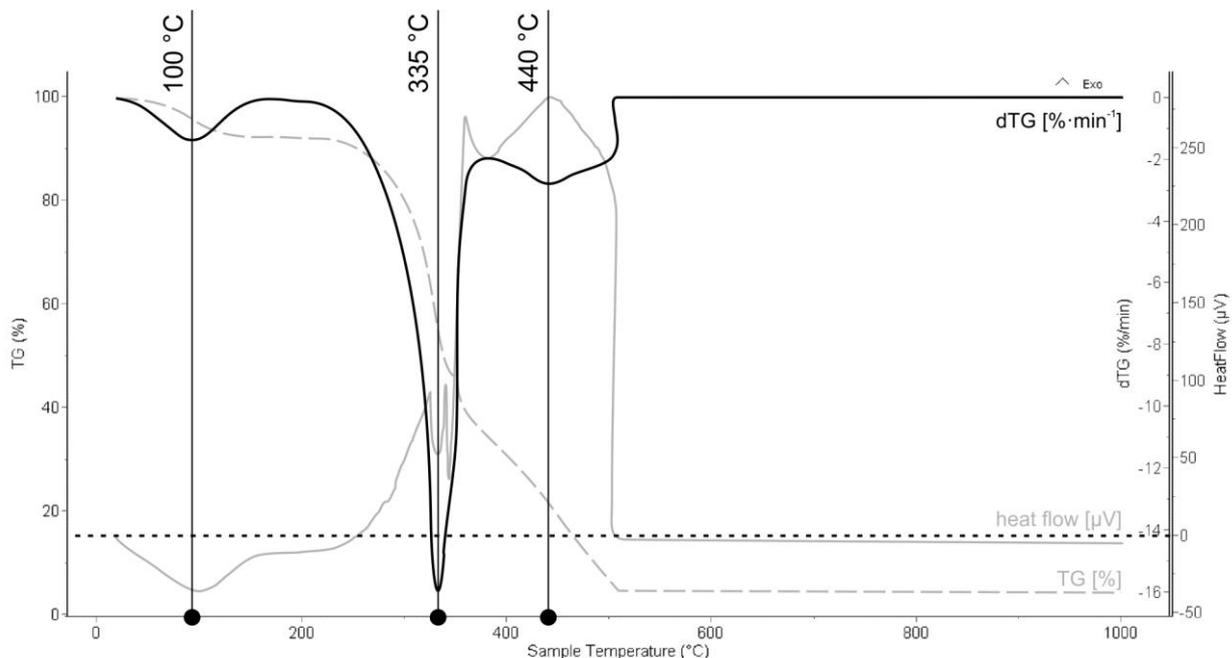


Fig. 3 - TGA data of pine wood

The dashed curve represents the decrease of weight of the tested sample. The decrease of weight depends on the temperature rise. The rise was $5 \text{ K} \cdot \text{min}^{-1}$ (\dot{T}). The black full curve represents the rate of weight decrease depending on the temperature. The grey full curve represents the heat flow produced by the material during the experiment. From the results of thermogravimetric analysis it is possible to identify how many reactions the material undergoes during heating. The decrease of curve means a reaction. When the temperature reaches $100 \text{ }^\circ\text{C}$, the material undergoes the first reaction dehydration – evaporation of unbound water. Another reaction comes at $335 \text{ }^\circ\text{C}$ (another curve decrease), which represents the cellulose and other wood components degradation. The third decrease comes at $440 \text{ }^\circ\text{C}$ and this is the final degradation of lignin. Reference temperatures ($T_{p,i}$) used in FDS model are $100 \text{ }^\circ\text{C}$ for water and $335 \text{ }^\circ\text{C}$ for pine wood. Material consists of two components and so the temperature $442 \text{ }^\circ\text{C}$ was not used in the FDS model. Also the intensity of

reaction is very important. This can also be read from the graph. This value can be found at the top of the curve. Water reaction intensity is $0,00033 \text{ s}^{-1}$, pine wood reaction intensity $0,00267 \text{ s}^{-1}$ and charring reaction intensity is $0,00036 \text{ s}^{-1}$.

REACTION OF COMBUSTION BASED ON EXPERIMENTS

Although wood combustion might look like one complex process in the real life situation, it is actually a mixture of two processes: pyrolysis and combustion. Pyrolysis is the process of solid state decomposition to various gases; combustion, on the other hand, is burning of those flammable gases. In the FDS, those two processes must be distinguished and separately entered. In presented proposal, the pyrolysis is described with stoichiometric equation with values of both reactants and products. To get this equation, it is necessary to explicitly define the chemical reaction of combustion. This equation determines the combustion intensity of the elements that has been created during the combustion process.

Analysis of combustion products

The chemical reaction of combustion which is essential for accurate modelling cannot be made without the knowledge of stoichiometry ratios of combustion products. The analysis to determine the stoichiometry ratio was held in TÚPO.

For the experiment, the smoke chamber which corresponds to the requirements of ISO 5659-2 [10] was used. There were two test samples of pine wood. The smoke chamber is completely airtight and its total volume is 509 litres of air. The cone calorimeter is placed inside this chamber. Its total possible heat flux output is 50 kWm^{-2} . Principle of the experiment is following: the heat flux from the cone emitter falls on the surface of the sample. Due to high amount of thermal radiation the sample completely burns out. The products of combustion are caught in the smoke chamber. After creating the maximum concentration of combustion products, the analysis is performed. Results of the analysis of combustion products are shown in the Table 5.

Tab. 5 - Results of analysis of combustion products

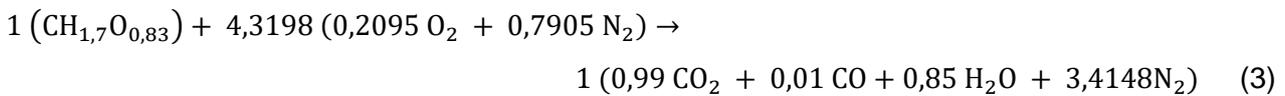
Compound	$\text{mg} \cdot \text{g}_{\text{sample}}^{-1}$	Percentage [%]
CO	12,3	0,8706
NO	0,2	0,0142
CO ₂	1400	99,0898
NO ₂	0,02	0,0014
SO ₂	0,1	0,0071
VOC*	0,24	0,0170

* VOC (Volatile Organic Compounds).

The carbon dioxide (CO₂) was the most produced compound. Other compounds are represented in a small amount of the whole combustion products. The second most represented compound was carbon monoxide (CO). Other inorganics components in fumes are insignificant. In spite of elemental analysis, there were also detected products based on sulphur in the sample in smoke chamber. However, the amount of sulphur dioxide is minimal and it does not have to be included in the CFD code. Moreover, this difference, or error respectively, may be probably at the side of the elemental analysis due to used procedure and measurement errors.

Equation of burning

Chemical equation can be divided into three parts. Firstly, it is the reactants (pine) itself. Chemical equation of the pine wood is $CH_{1,7}O_{0,83}$ [8]. Burning is the reaction of reactant with air. There is roughly 79,05 % of nitrogen (N_2) and 20,95 % of oxygen (O_2). Other components of air can be neglected. The last part of the equation is the product of combustion. Due to the ratio known from the Analysis of combustion products it was further worked with only two most represented compounds carbon dioxide and carbon monoxide (CO_2 , CO). During combustion there is also the leakage of water vapour. It is necessary to enter the stoichiometry of combustion products as well as quantification of chemical equation into FDS. The balance equation of combustion which is used in the FDS is following:



Heat of reaction, heat of combustion

Together with the balance equation which defines the process of combustion, it is necessary to determine an amount of heat released during the exothermic reaction. This parameter is defined by the heat of combustion. The total amount of heat that needs to be added to the system in order to cause exothermic reaction has to be defined as well. This parameter directly influences the time of ignition in the model and it is called the heat of reaction. It is possible to calculate the heat of reaction from the following picture.

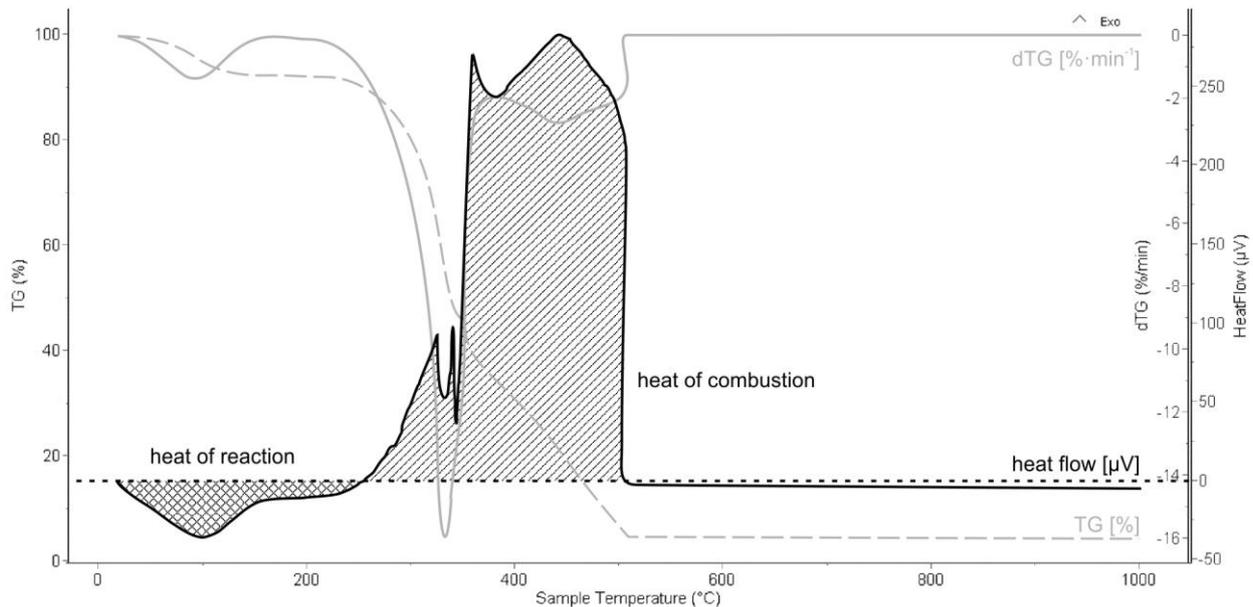


Fig. 4 - Graphical difference between the heat of reaction and the heat of combustion (pine)

From the ratio of areas below and above the curve of heat flow, the heat of reaction has been calculated. Boundary conditions were determined by interface between endothermic reaction and the exothermic one. The reaction is exothermic if the curve is rising.

FDS MODELLING AND COMPARISON OF RESULTS

From all performed experiments, simplified burning of wood setup for FDS was prepared [9]. As mentioned before, both processes (pyrolysis and combustion) and other related entities had to be entered.

Firstly, a material properties of sample were defined. The pine SURF line of the FDS code was due to moisture composed from pine and water in ratio 93:7. Water MATL line was copied from validated examples and it was used only to remove heat as it would be in the real situation. Pine MATL line is a little bit more complicated and used material properties such as density, specific heat or conductivity either from analyses or from literature.

Then, on the same line, the pyrolysis was described forcing the pine to decompose in one reaction into one solid product, char, and one gaseous product, namely pyrolyzate. Char residue covers 15,3 % of the material corresponding results from analysis of combustion products. The reaction is started at reference temperature of 355 °C (main peak of DTA). Other values describing TGA-DTA experiment, reference rate (0,00267 s⁻¹) and heating rate (5 K·min⁻¹) were also entered. Last input in the pine MATL line was heat of reaction (1047 J·g⁻¹), which was computed from the ratio between assumed heat of reaction and heat of combustion acquired from TGA-DTA (see Figure 4) and from the value of effective heat of combustion.

The gaseous pyrolyzate then undergoes the combustion reaction defined in the REAC line and the stoichiometric equation set from combustion analysis (described in the previous chapter) was used. The agents of reaction were PYROLYZATE, AIR and PRODUCTS only, and compositions of those agents were defined in particular SPEC lines as lumped components. In the AIR, only oxygen (0,2095) and nitrogen (0,7905) were defined. Volume fractions of PRODUCTS correspond the chemical combustion analysis results (see Table 5).

For the purpose of numerical modelling a simplified model of cone calorimeter was created. Only parts that were necessary for measuring of HRR were modelled – the conical emitter and the tested item. For both parts a very fine mesh is used. Dimensions of one cell are 10 mm x 10 mm x 10 mm. Coarser part of the model has dimensions of cells of 20 mm x 20 mm x 40 mm. In the coarser mesh there is a part of hood used for catching the combustion products. Total number of cells does not exceed 4 736. The model simulates thermal conditions in real cone calorimeter, heat flux of 35 kW·m⁻² hits the element of size 10 cm x 10 cm x 1 cm. All boundaries of the model space were defined as OPEN, except the exhausting hood in the upper part. The surface of the hood was modelled as a thin steel plate.

The cone of the calorimeter was entered as a set of obstructions that create a pyramidal object. It was made of solid obstructions representing both the steel hood and the source of radiation. The radiation was entered as VENTs with TMP_FRONT = 1553 °C. This temperature is slightly higher than in the real cone calorimeter at TÚPO (around 1400 °C), because VENTs were put only on the bottom surface in the simplified model. The temperature was therefore raised to ensure the required heat flux on the sample surface.

The calculation was performed twice, each with a different heat of combustion (see Table). The Model 1 uses the net heat of combustion (16,94 MJ·kg⁻¹) and the Model 2 includes a value of the effective heat of combustion (11,41 MJ·kg⁻¹). Both models are compared and validated to the experimental measurements.

Values of the heat of combustion are very different. The heat of combustion together with the heat of reaction are the most important FTCH. Both values have significant effect on final HRR process of the material for their indication of the energy amount used in endothermic reaction and produced in exothermic reaction.

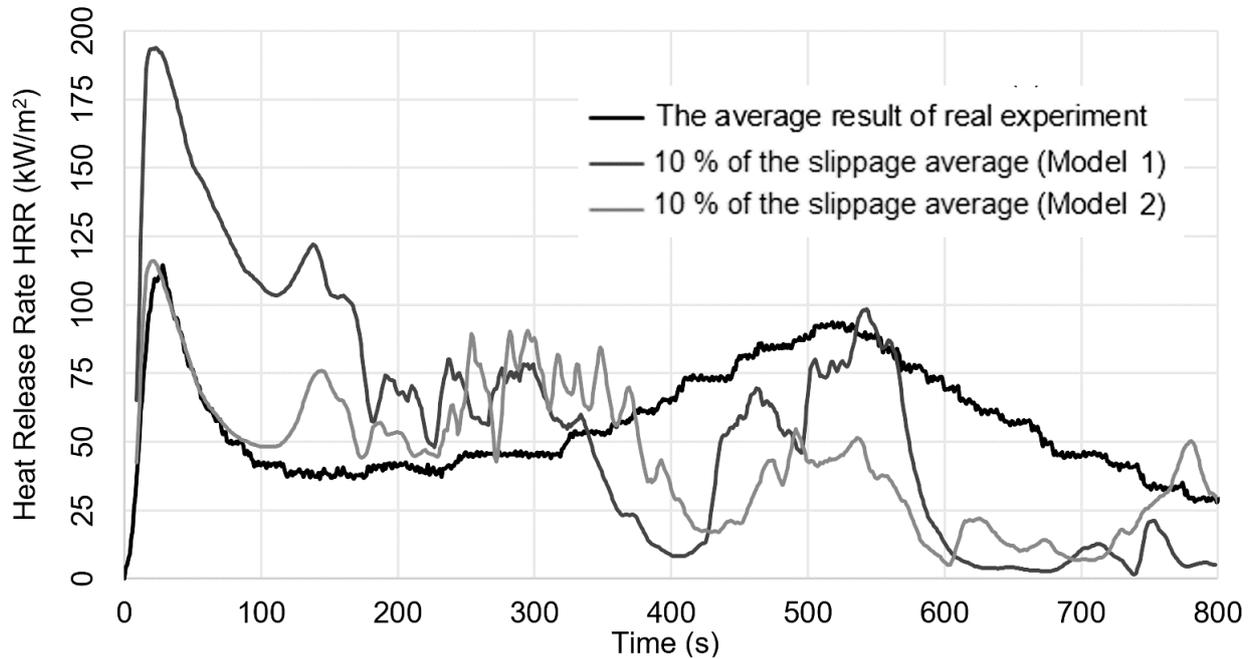


Fig. 5 - Comparison of results

The graph shows the development of HRR in time. The black curve represents the real experiment. There are two peaks. Following Table 6 shows a comparison of real experiment data and data from the model.

Tab. 6 - Comparison of the experimental results and results from the model

		Experiment 35 kWm ⁻²	Model 1	Model 2
Ignition	[s]	90	170	180
	[°C]	440	408	402
1. peak HRR	[s]	28	22	24
	[kW·m ⁻²]	114,59	195,44	120,00
2. peak HRR	[s]	518	Not observed	295
	[kW·m ⁻²]	89,0	Not observed	93,7

The Model 2, which uses effective heat of combustion, is closer to the real experimental data. In both cases the ignition comes at the third minute of the simulation. The difference between this and a real cone calorimeter experiment (90 seconds) is due to the fact of using a spark for easier ignition of the element. In the real experiment, the time of ignition was measured while in the model situation the time of auto ignition was observed. The final peak of HRR in the Model 2 corresponds quite accurately to the real experiment data. In contrast, the Model 1, which uses the net heat of combustion, shows higher values in comparison to the real cone calorimeter experiment.

The difference between these two curves is mainly due to the different ways of burning off the model and the real situation. The first peak, which was very accurately simulated, occurs during the thermal decomposition of the central part of the element. After burning out of the middle section flame moves to the outer parts where the pyrolysis was already held before. Burning off all the outer parts at once creates the second peak.

There is a significant charred part in the middle of the sample. This already degraded part is surrounded by flames burning the outer parts of this sample. As explained above, this is the situation when model does not correspond to the real experiment. There is no gradual expansion of the flame on the element surface. The flame moves randomly on the model – at the first one corner burns and then the other. Fluctuations in HRR values are therefore caused by an incorrect flame spread on the surface of the sample.

CONCLUSION

The goal was to create very simple model of wood burning using results from cheap and fast small-scale experiments that could be used in the CFD modelling programmes such as FDS. Purpose of research is to obtain a virtual material that would spread fire, develop the fire according to surrounding environment and that could be extinguished without using complex reaction molecular description. Small-scale experiments that were conducted were: elemental analysis, thermogravimetric analysis and difference thermal analysis, and combustion analysis.

In this paper, pine wood was used as the tested sample. The aim of the model was to compare HRR values to the real standard fire-technical experiment in the cone calorimeter. In the model the first peak of burning was achieved very accurately. Further development of HRR is different than HRR from the real experiment because of the difference in fire spread on the element's surface. Though, maximum HRR values are similar to the real ones.

It was verified that for the purpose of modelling the effective heat of combustion, which is one of the basic FTCH affecting the total intensity of burning, should be used. Using the net heat of combustion in the model leads to higher values of HRR in comparison to the real experiment data.

There are several things that can be improved in this model. Primarily it is necessary to work on flame spread on the surface of the material. It is also possible to upgrade the description of reaction in the pyrolysis model using coefficient from Arrhenius equation. More wood components can also be defined. The sample element would not consist only of water (as moisture) and pine wood mass but also of lignin, cellulose, hemicellulose and water. For definition of the chemical reaction of burning for all these substances, it would be necessary to perform a number of other small-size experiments (thermogravimetric analysis) that should provide more information about their behaviour during heating.

Considering all the results shown in this paper, it was shown that when adjusting the model as mentioned above, it can be possible to simulate burning of wood using the extrapolated data obtained in small-size experiments.

An adjusting of the model can be a further option in continuing in this work thus appear. Another very important thing is also using the effective heat of combustion in fire engineering practice. This could be certainly used in determining the standoff distances from the buildings, especially from wooden structures and wooden facades. These types of buildings are significantly disadvantaged because of the use of the net heat of combustion.

ACKNOWLEDGEMENTS

The work was supported by project n. 16-18448S, Grant Agency of the Czech Republic. Special acknowledgements go to Ing. Milan Růžička from TÚPO, Ing. David Bouška and Ing. Jakub Havlín, both from UCT.

REFERENCES

- [1] KIM, Mihyun Esther, Dembsey Nicholas. Engineering guide for estimating material pyrolysis for fire modelling. Worcester Polytechnic Institute, 2012.
- [2] GANDELOVÁ, Libuše, Petr HORÁČEK a Jarmila ŠLEZINGEROVÁ. Nauka o dřevě. Vyd. 2. Brno: Mendelova zemědělská a lesnická univerzita, 2002. ISBN 8071575771.
- [3] HIGUCHI, Takayoshi. Biosynthesis and biodegradation of wood components. Orlando: Academic Press, 1985. ISBN 0123478804.
- [4] GAO, Ming, Caiyun SUN and Kai ZHU. Thermal degradation of wood treated with guanidine compounds in air: Flammability study. Journal of Thermal Analysis and Calorimetry [online]. 2004, vol. 75, no. 1, s. 221-232. ISSN 1388-6150.
- [5] AGGARWALL, P. and D. DOLLIMORE. A thermal analysis investigation of partially hydrolyzed starch. Thermochemica Acta, 319, 17-25, 1998.
- [6] SHEN, Dekui, Xiao RUI, Gu SAI and Huiyan ZHANG. The Overview of Thermal Decomposition of Cellulose in Lignocellulosic Biomass. Cellulose-Biomass Conversion. InTech. 2013. ISBN 978-953-51-1172-6
- [7] ČSN 73 0824. *Požární bezpečnost staveb - Výchřevnost hořlavých látek*. Praha: Úřad pro technickou normalizaci, metrologii a státní zkušebnictví, 1992.
- [8] BABRAUSKAS, Vytenis. *SFPE handbook of fire protection engineering* [online]. Sage Publications, Inc, 2016. 164 s. ISBN 0734-9041.
- [9] MCGRATTAN, K. et al. Fire Dynamics Simulator User's Guide. Sixth Edition. NIST - National Institute of Standards and Technology, VTT - Technical Research Centre of Finland. Also available: <http://firemodels.github.io/fds-smv/>
- [10] ISO 5659-2. *Plastics -- Smoke generation -- Part 2: Determination of optical density by a single-chamber test*. Geneva: International Organization for Standardization. 2017.