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Enthalpy and Specific Heat as Material Characteristics in Thermal Analysis of Wood Exposed to Fire

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Abstract

Wood burning is among the most dynamic processes which is difficult to simulate using computer software. In modelling process of simulation, it is important to implement the correct material data. In thermal analysis exist two different approaches of implementation the temperature dependent material data properties. First approach is based on specific heat, second is based on enthalpy. The aim of the study was to compare the accuracy of the outputs obtained from the numerical analysis using an approach based on specific heat and enthalpy. The results were compared with small-scale tests of wood samples loaded with a radiant heat source. Numerical analyses were performed by transient thermal analysis in ANSYS software. The results of the comparison of different approaches of implementation the input data into simulations show that both approaches are equivalent and provide sufficiently accurate data compared to real small-scale tests, and the principle based on enthalpy is more suitable in cases where the temperature rises above 100° C, because enthalpy as a material property is easier to determine.

Keywords: Thermal Anylysis; Ansys; Fire; Wood; Enthalpy

1 Introduction

Wood burning is among the most dynamic processes which is difficult to simulate using computer software. When designing a combustion simulation, it is necessary to implement many boundary conditions into the simulations, which creates a difficult problem to solve, in case if necessary to perform a complete combustion simulation. E.g., the finite element analysis (FEA) software ANSYS allows to perform combustion simulations, but from a practical point of view and mainly due to many boundary conditions, it is used mainly for combustion simulations of homogeneous gas. A simpler alternative is thermal analysis where the base element is heat conduction, which Frangi, Erchinger and Fontana [1], Zhang et al. [2], Molina et al. [3], Couto et al. [4], Regueira and Guaita [5], Špilák et al [6], Dúbravská et al. [7] used to examine different types of wooden construction elements loaded by fire.

In the case of the solution of heat conduction in wood, where it is heated above 100 ° C, which is common in fire conditions, a nonlinear problem arises, including phase changes of the water contained in the wood. Wood as a hygroscopic material contains free and bound water. The problem can be solved by setting the input the temperature-dependent properties data of the wood. Zhang et al. [2], Molina et al. [3], Couto et al. [4] Regueira and Guaita [5], Špilák et al [6], Dúbravská et al. [7] used in their numerical analysis studies a combination of three basic material properties, specific heat, density, and thermal conductivity (*specific heat approach*) according to Eurocode 5 [8]. The second possible combination of material properties, which is used minimally in practice, is density, thermal conductivity, and enthalpy (*enthalpy approach*). The use of enthalpy in numerical analysis has some negatives, but it also has advantages, which are showed in case study of Erchiquia et al. [9] and Erchiqui and Annasabi [10]. The gradual use of enthalpy in calculations is also promoted by current ANSYS thermal analysis guides and manuals [11,12].

Enthalpy is the amount of energy needed to change the state of a material at a constant pressure and is defined by a state function, so we cannot determine its value, but only their change. Heating a liquid substance causes its molecules to vibrate more, which increases its temperature (as its specific heat suggests). When the temperature of the liquid substance reaches its boiling point, the adding of more heat does not change the temperature, because all the heat is consumed for the boiling of the liquid substance. The phase change usually occurs at a constant temperature. In the simulations, the definition of enthalpy is adjusted to represent the energy absorbed by the "unit volume" of the body. Enthalpy can be calculated as the product of specific heat, material density and temperature change [9-12].

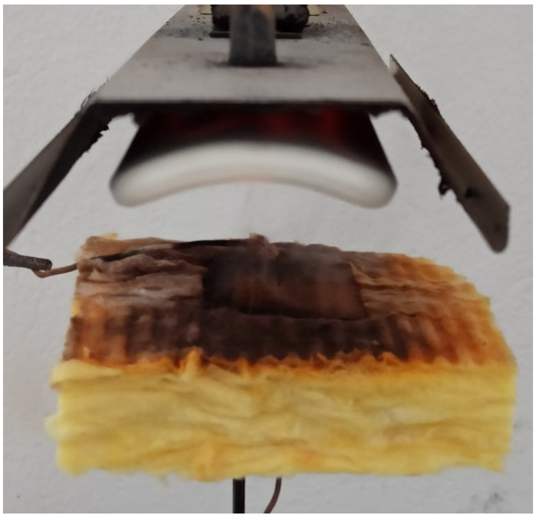
The use of enthalpy and mass heat capacity at the same time is permissible in the simulation, but there may occur collisions in the calculations. Therefore, it is recommended to use only one of the above approaches. The aim of the study was to compare the accuracy of the outputs obtained from the numerical analysis using an approach based on specific heat and enthalpy. The results were compared with small-scale tests of wood samples loaded with a radiant heat source.

2 Material and Methods

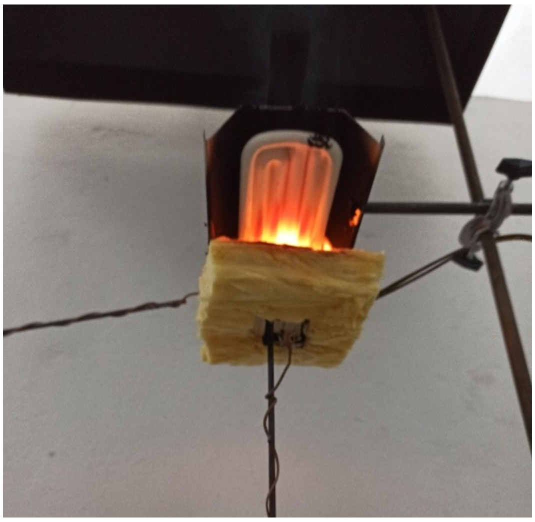
The methodology is divided into two parts. Carrying out small-scale tests of wooden samples to obtain the input information for comparing simulations with real tests and performing different numerical analyzes of heat conduction in samples by ANSYS software.

2.1 Small - scale tests

The principle of the small-scale fire test was to expose samples measuring 5 x 5 x 2 cm to a thermal loading with a radiation panel with a power of 1,000 W (heat flux of 30 $kW \cdot m^{-2}$), placed at distance of 5 cm from the sample for 600 s. The temperature profile of the sample heating was recorded. Temperature profile was measured using NiCr-Ni thermocouples with a measuring range of -40 ° C to +1,200 ° C. Thermocouples were placed on the surface of the thermally loaded and unloaded sides of the test sample (Fig. 1 (a-b)).



(a)



(b)

Fig. 1 Assembly for measuring the temperature profile of samples loaded with radiant heat

AHLBORN ALMEMO 2290-8710 V7 was used to record temperatures. 6 samples were subjected to fire tests, 3 samples were made of Norway spruce and 3 samples were made of Silver fir. All samples were dried in a hot air oven prior to testing and had a moisture content of 10.00 % ± 1.00 %. Each sample was placed in a prepared glass wool frame before being placed in the test set to prevent the flame from passing to the underside of the sample.

2.2 Numerical analysis

Numerical analyses were performed using finite element analysis in ANSYS software by the ANSYS Workbench programming environment. All simulations were performed using transient thermal analysis [13]. Two different combinations of properties were entered. The first combination was density, thermal conductivity, and specific heat [14]. The second was density, thermal conductivity, and enthalpy [14]. The input data about thermal capacity and thermal conductivity of Norway spruce and Silver fir were entered according to Eurocode 5 (Fig. 2 (a,b)) [8]. Thermal conductivity was set as isotropic [15]. The wood density depends on the temperature, so it is necessary to know the initial wood density obtained gravimetrically from prepared samples for small-scale tests. The density of Silver fir wood was 337.58 $kg \cdot m^{-3}$ and the density of Norway spruce wood was 410.70 $kg \cdot m^{-3}$. The graph of wood density versus temperature was created according to Eurocode 5 [8] (Fig. 2 (c)). The enthalpy values for both woods were calculated and entered to the wood properties according to [9,10] (Fig. 2 (d)).

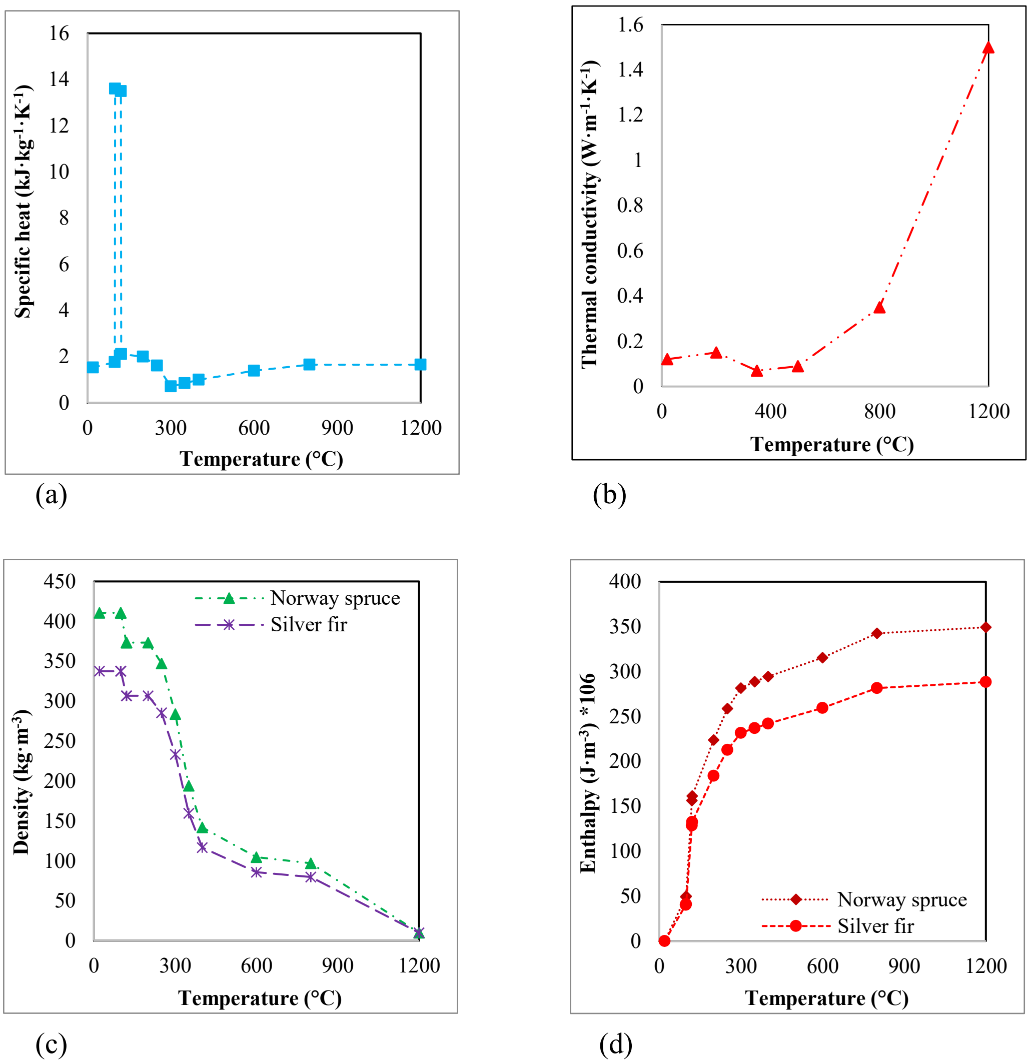


Fig. 2 Material characteristic: (a) Thermal capacity of wood; (b) Thermal conductivity of wood; (c) Density of wood; (d) Enthalpy of wood

The three-dimensional model was created using the SpaceClaim software. The geometry of the three-dimensional model was identical to the small-scale test with significant simplification to the test specimen and the radiation panel. For meshing a regular hex mesh with an element size of 1 mm was used (Fig. 3) [16]. The finite element mesh contained 52,500 elements.

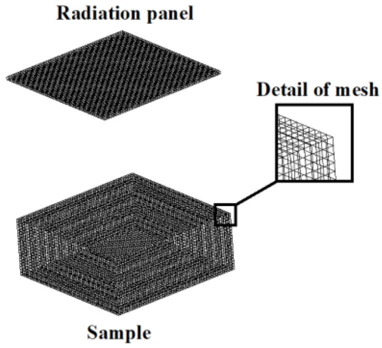


Fig. 3 Simplified finite element model

Thermal loading from the radiation panel was created by manual thermal connection between the radiation panel and the loaded surface of the samples [13]. "Bonded" was selected as the contact type [17]. The "Behavior" link has been reset from the original "Symmetric" setting to "Asymmetric" [17]. As part of the contact formulation, as there is no deformation, the "Pure Penalty" setting has been selected [16]. The "Thermal Conductance Value" was set to 30 $W \cdot m^{-2}$ [13]. In case an error occurs when searching for a contact and to speed up the calculation, a contact region "Pinball Region" with a radius of 60 mm has been entered [17]. The initial temperature was set according to the values found in the small-scale tests. The simulation time 600 s was set according to real fire tests. The duration of one sub-step was of 10 s. The maximum number of iterations has been set to 1,000. For all simulations, the other settings of the calculation mechanism were retained in pre-set values.

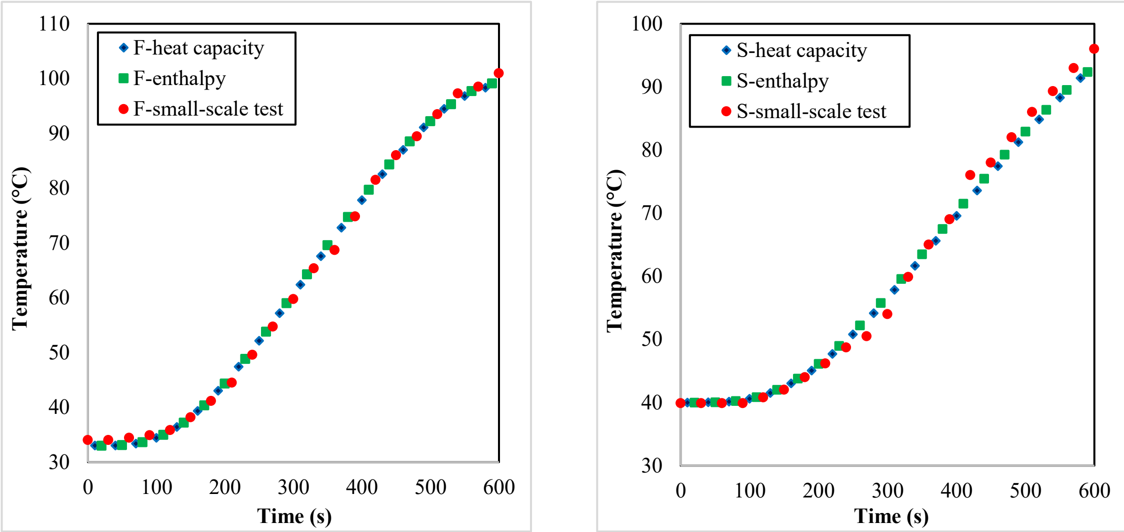
A change was made in the section for nonlinear solution settings, where the original value of thermal convergence was changed from 1.5 % to 10 % [13]. This adjustment was necessary because the convergence criterion was not met in the initial phase of the simulation calculation (the first sub-step of the calculation), which the software evaluated as an error. The problem arose due to an imbalance in the system, where within one sub-step there was a sharp rise in temperature, which the software could calculate only with a certain deviation, exceeding the pre-set criterion.

As the only boundary condition in the simulation, radiation panel temperature of 450 °C was defined for the small-scale test simulations. The values were measured using thermocouples during real fire tests and verified using the documentation for the radiation panel. The temperature was constant throughout the simulation.

3 Result and Discussion

Outputs from small-scale tests were used to determine the appropriate approach in the modelling process. The aim was to determine the appropriate combination of wood properties entered in the simulation. The first combination was density, thermal conductivity, and specific heat. The second was density, thermal conductivity, and enthalpy. From the performed small-scale fire tests, data on the temperature of the sample were obtained and recorded on its thermally unloaded side. The temperature curves from the samples were averaged and compared with the temperature curves obtained from the simulations.

Fig. 4 shows a comparison of temperature profiles obtained from small-scale fire tests and simulations, where 2 different approaches were used: based on either enthalpy or specific heat.



(a) (b)

Fig. 4 Comparison of temperature profiles: (a) Silver fir; (b) Norway spruce

The results of the comparison of the simulation results with small-scale fire tests results of Silver fir wood showed that the temperature profile of the simulation based on heat capacity showed an accuracy of 98.3 %, with an average absolute deviation of 0.85 °C and a percentage deviation of 1.63 %. In the enthalpy-based simulation, the accuracy of the simulation was of 98.3 %, with an absolute deviation of 0.85 °C and a percentage deviation of 1.63 %.

The results of the comparison of the simulation results with small-scale fire tests results of Norway Spruce wood showed that the temperature profile of the simulation based on heat capacity showed an accuracy of 97.8 %, with an average absolute deviation of 1.44 °C and a percentage deviation of 2.21 %. In the enthalpy-based simulation, the accuracy of the simulation was of 97.8 %, with an absolute deviation of 1,36 °C and a percentage deviation of 2,15 %.

The results of the comparison of the individual approaches with the small-scale fire tests results showed that both approaches are equivalent and can provide sufficiently accurate results. In both approaches, it is important to set up the right material data correctly. As the works of various authors have shown [1-5,18], the segment with the constant temperature at 100 °C is problematic, which the simulations only partially or did not imitate at all. All authors used the approach based on specific heat while implemented input data for the simulation according to Eurocode 5 [8]. These data are insufficient because they consider only one specific humidity, which distorts the results. It is therefore worthwhile to use the enthalpy approach because enthalpy can be more accurately determined by calculations as opposed to specific heat [10].

4 Conclusions

The results of the comparison of different approaches of implementation the input data into simulations show the following:

- both approaches provide sufficiently accurate data compared to real small-scale tests with an accuracy of 98%,
- both principles achieve almost identical accuracy of results and are therefore equivalent,
- the principle based on enthalpy is more suitable in cases where the temperature rises above 100 ° C, because enthalpy as a material property is easier to determine.

Acknowledgments

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