Experimental Measurement and Numerical Simulations of Heat Transfer

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Abstract: Industrial furnaces belong to the most common types of equipment used for heating or controlled cooling in all sectors of industry. Typically, heating takes place in a closed furnace chamber where the chamber temperature is regulated by controllers in response to information from thermocouples installed at defined points in the furnace interior. If the temperature of the charge needs to be determined, one can rely on either experimental measurement or numerical simulations. The optimal approach is to combine both. In the first case, thermocouples are attached to the charge at defined points or, sometimes, other measuring devices are provided. Temperatures at the defined measuring locations are then logged by means of a data logger or card. By contrast, numerical simulations provide information on the temperature distribution throughout the charge. The absolute values of temperature depend on the boundary conditions used, most notably on heat transfer coefficients.

Authors of this article decided to combine both approaches to tackle a simply formulated problem where a thick-walled tube was placed into a laboratory furnace and the temperatures of the chamber and charge were measured at defined points during heating. The temperature-time histories obtained were used as input into numerical simulations of the temperature field within the charge. The purpose of the measurement was to determine the temperature dependence of the heat transfer coefficient and emissivity by experiment. The calibration of heat transfer coefficient values for the simulation was based on the experimental data obtained for the defined locations. The input data for the simulations also included the dimensions of the furnace, positions of heating coils, the temperature sequence, and others. The temperature dependence of thermophysical properties of materials was determined using the JMatPro software based on chemical compositions.

The above-described experimental procedure can be used for calibrating numerical calculations of real-world heat-treatment processes.

Keywords: radiation, thermal process, finite element method

1 Introduction

In this investigation, experimental measurement involving heat transfer and subsequent evaluation using numerical simulations were carried out under the project no. LO1412 Development of the West-Bohemian Centre of Materials and Metallurgy. The objective was to determine heat transfer coefficients for a thick-walled tube using a reverse problem solved by numerical simulation.

2 Experimental measurement

The measurement was carried out in a KM30-13 electrical laboratory furnace which offers a working area of 300×300×300 mm. The furnace is fitted with 12 heating coils which provide the maximum furnace temperature of 1300 °C. A schematic description of the experiment is given in Fig. 1. The diameter and wall thickness of the tube placed in the furnace were 168 mm and 25 mm, respectively. Since the length of the tube of 320 mm was close to the furnace interior depth, which was 330 mm, the simulation could be approached as a plane problem in FEM analysis. The ends of the tube were secured against rotation. Before the tube was placed into the furnace, 6 thermocouples had been attached at defined points. Four thermocouples were on the inner surface of the tube (Fig. 1). Another two thermocouples were used for measuring the instantaneous temperature of the furnace chamber which was affected by the door being opened for placing the tube inside. The values were recorded using a logging card and an in-house script written in the Labview program. The thermocouples were welded onto the surface of the tube. The inner and outer surfaces of the tube were smooth from the tube rolling process.

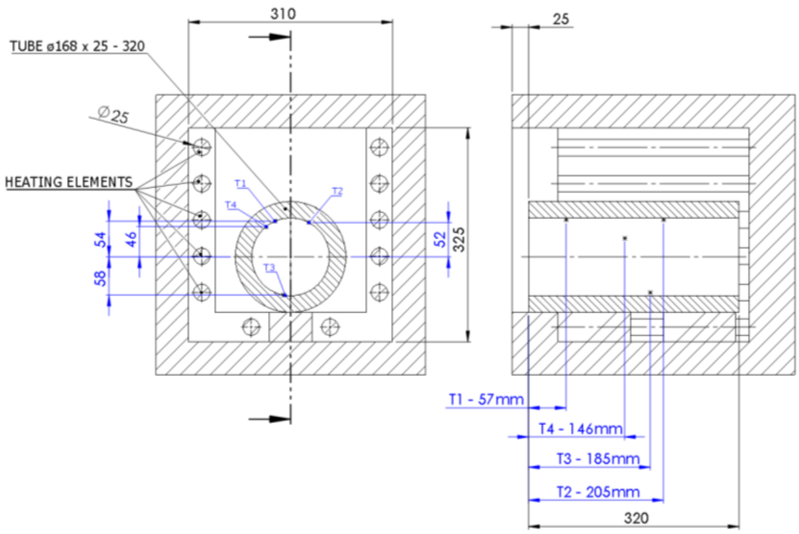


Fig. 1: Sectional view of the furnace

In the experiment, the tube was manually placed into a heated furnace. The end of the heating sequence was defined as the moment the inner diameter of the tube reached the specified temperature of 900 °C. Throughout the heating sequence, temperature was measured by means of thermocouples attached by welding. Subsequently, the tube was left to cool in the furnace. At some point during the experiment, the thermocouple no. 2 failed for unknown reasons. Figure 2 shows temperatures measured on the controller of the furnace, and the calculated input power of the furnace. The input power values were calculated from the furnace's energy consumption measured on its input terminals. The amount of energy was measured using an electric power meter. The calculation of the input power was motivated by the need for finding the energy balance of the furnace-charge thermodynamic system.

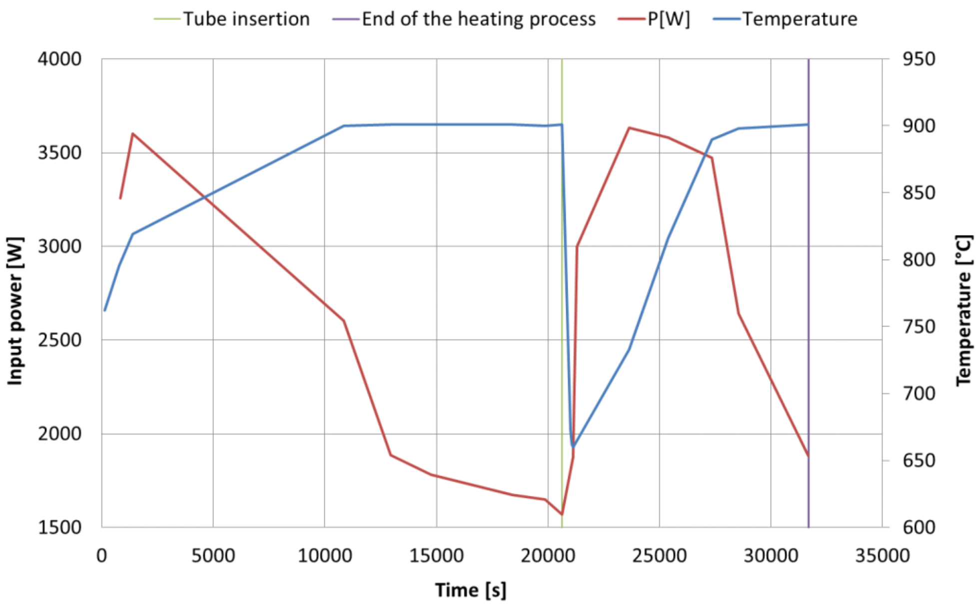


Fig. 2: Temperatures on the controller of the furnace, and the calculated input power

Temperature readings obtained from thermocouples attached at pre-defined points are plotted in Figure 3. After the charge was placed into the furnace, the air temperature dropped all the way to 228 °C. Due to the heat accumulated in the furnace, the furnace atmosphere immediately reached 320 °C and then continued to rise to the required temperature of 900 °C.

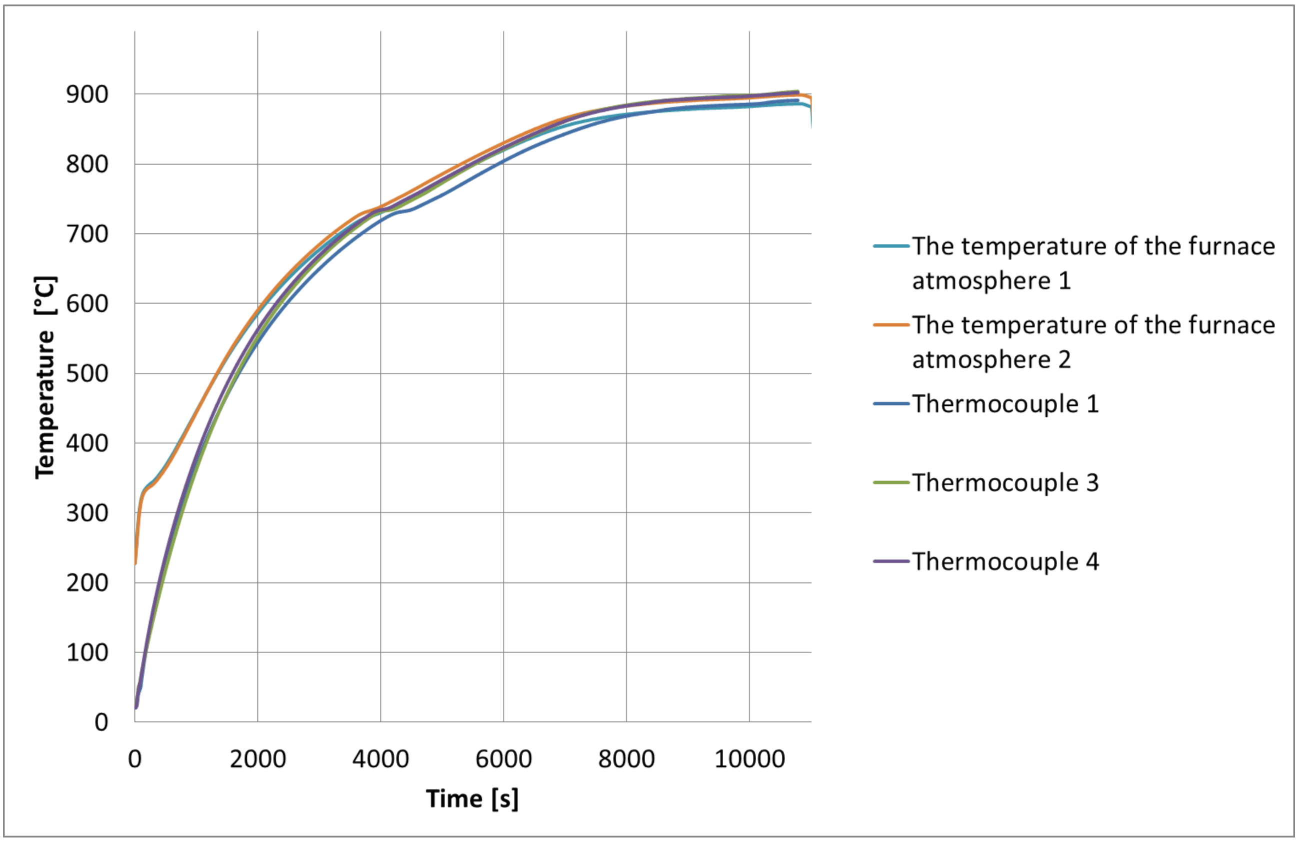


Fig. 3: Experimental results

3 Evaluation by means of FEM software

3.1 Material properties

The purpose of the laboratory furnace experiment was to measure temperatures at the defined points. Based on their values, heat transfer coefficient α [$Wm^{-2}K^{-1}$] was determined by numerical simulation. The parameters of the simulation matched the conditions of the experiment. The chemical composition of the tube material was measured with a Bruker Q4 TASMAN optical emission spectrometer.

Tab. 1: Chemical composition of ČSN 11 353.1 steel

C	Si	Mn	P	S	Cr	Co	Ni	Cu	W
0.158	0.244	0.571	0.012	0.002	0.038	0.002	0.020	0.016	<0.005

Czech Standard class 11 steels are plain structural steels with prescribed mechanical properties (yield strength R_e = 235 MPa, ultimate strength R_m = 340–440 MPa, and elongation A = 25 %). Using the JMatPro program and the measured composition as input data, temperature-dependent thermal conductivity and specific heat values were calculated. Their temperature dependence became part of the material model for numerical simulations.

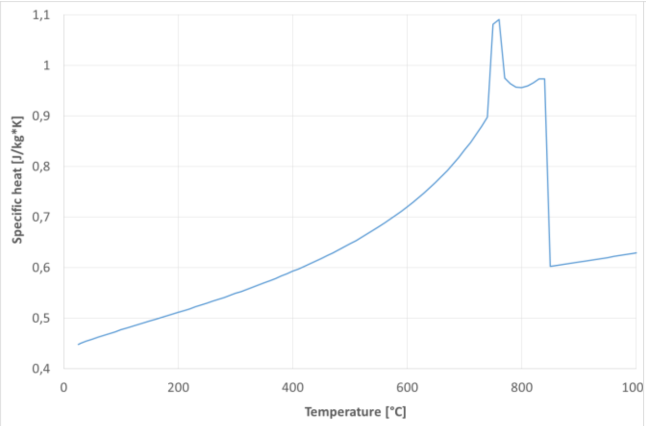


Fig. 4: Specific heat [J/kg K]

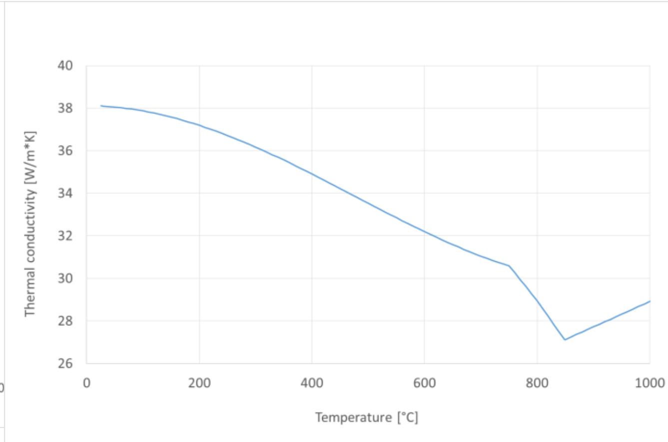
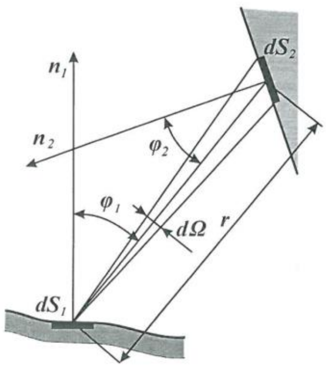


Fig. 5: Thermal conductivity [W/m K]

3.2 FEM simulation

Owing to the favourable geometry of the furnace and the tube, the simulation was first carried out as a plane problem and subsequently as a 3D problem. Using numerical modelling, the temperature field within the thick-walled tube was characterized, and absolute values of temperature were calibrated against the data measured with thermocouples at the defined points.

Generally, the crucial parameters in thermal problems include not only material properties but also heat transfer coefficients α, the subject of the present work. One can approach thermal problems in various ways: considering the heat transfer coefficient α as a parameter that accounts for radiation or by combining natural convection and radiation. The authors had already dealt with the effects of radiation on the heating of a charge, considering the relative positions of the charge and heating elements. In numerical simulations, the relative position is expressed in terms of the view factor which is based on Lambert's law and accounts for the distance and relative angle between two surfaces of an element (Fig 6.).



$$d^2Q_{1\to2} = A_2d^2Q_1 = \frac{1}{\pi}A_2E_1\frac{cos\varphi_1 cos\varphi_2}{r^2}dS_1S_1, \text{ where } d^2Q_{1\to2} = A_2d^2Q_1 = \frac{1}{\pi}A_2E_1\frac{cos\varphi_1 cos\varphi_2}{r^2}dS_1S_1, \text{ where } E_1 = \varepsilon_1C_0\left(\frac{T_1}{100}\right)^4$$

$$d^2Q_{2\to1} = A_1d^2Q_2 = \frac{1}{\pi}A_1E_2\frac{cos\varphi_1 cos\varphi_2}{r^2}dS_1S_1, \text{ where } d^2Q_{2\to1} = A_1d^2Q_2 = \frac{1}{\pi}A_1E_2\frac{cos\varphi_1 cos\varphi_2}{r^2}dS_1S_1, \quad \text{ where } E_2 = \varepsilon_2C_0\left(\frac{T_2}{100}\right)^4$$

(1)

Fig. 6: Heat exchange between surfaces in a general relative position

3.2.1 Plane problem

For the first simulation run to determine the heat transfer coefficients, a simple model with fewer than 5000 elements was constructed. The idea was to use a "small-size" problem to refine the heat transfer coefficient values because a model with fewer elements responds very quickly to changes made to the coefficient. The model was based on certain simplifying assumptions:

- the plane problem approach was used,
- the tube model was placed in the centre of the furnace model, which was not the case in reality,
- the pads on which the tube was resting were omitted from the model,
- identical temperature profiles were used for the furnace and the heating elements.

There were two initial temperatures in the model: 25 °C for the tube, and 228 °C for other components of the model (the furnace and the heating elements). The latter is based on the previous measurement and is the initial temperature of the furnace atmosphere. Boundary conditions were set in terms of heat transfer coefficients. Two spaces were defined for the simulation. In the first one, the heat transfer between the outer surface of the tube, the furnace, and the heating elements was described. The second one described the heat transfer within the tube. In the model, these two spaces were dealt with separately. However, both used an identical temperature profile of the furnace lining (Fig. 3 – The temperature of the furnace atmosphere 1). In both spaces, heat transfer occurred by free convection and by radiation.

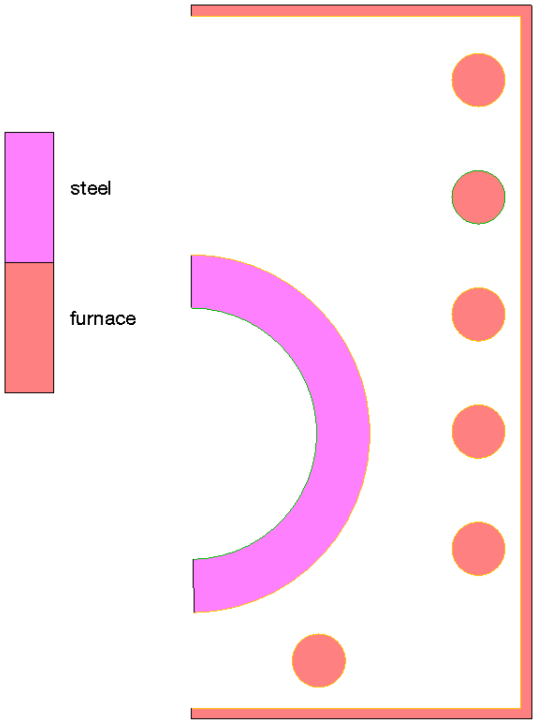


Fig. 7: Material

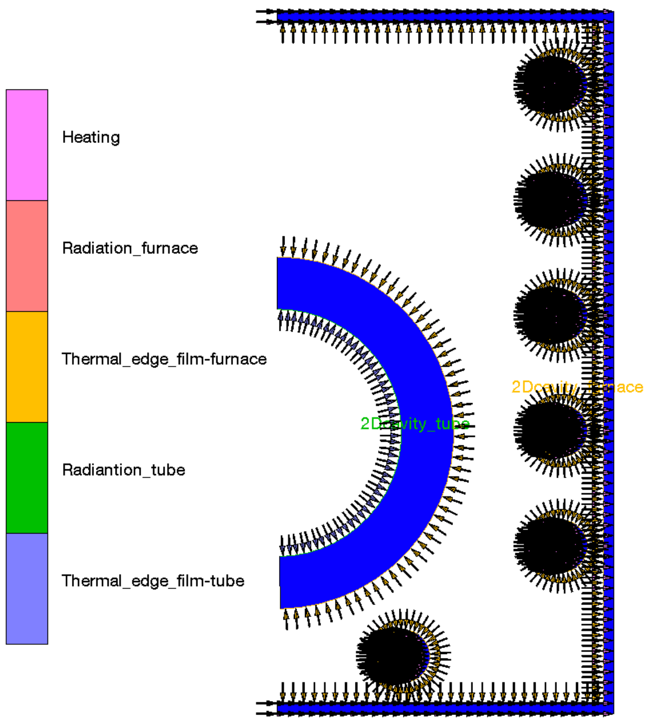


Fig. 8: Boundary conditions

Table 2 lists material properties used for characterizing parts of the furnace (Fig. 7). Table 3 gives element sizes for separate parts of the model. Using the calculated view factor (Fig. 6.) for both spaces, and the refined heat transfer coefficients for free convection given in Table 4, the temperature field at the end of the heating sequence was obtained (Fig. 9). The concrete boundary conditions are shown in Figure 8. Figure 11, which is more informative, illustrates the agreement between experimental data and simulations. The heat transfer coefficients were determined by trial and error in order to achieve the desired agreement between the measurement and the simulation.

Tab. 2: Material properties

Material properties	Units	Tube	Furnace
Specific heat	J/kg*K	graph (Fig. 4)	400
Density	kg/m^3	7850	5000
Thermal conductivity	W/m*K	graph (Fig. 5)	1
Emissivity	-----	0.97	0.97

Tab. 3: Element sizes

Geometry	Tube	Heating element	Furnace
Size of elements	variable size, outer surface: 0.13 mm inner surface: 4 mm	constant size: 1.5 mm	constant size: 5 mm

Tab. 4: Heat transfer coefficients determined

Space	Units	Furnace	Inside the tube
Heat transfer coefficient	W/m^2K	180	5
Ambient temperature	°C	defined by the furnace atmosphere temperature in fig. 3	
Radiation	J/kg	separate space	separate space

3.2.2 3D problem

Once the heat transfer coefficients were determined using the plane problem, they were employed in a 3D model. The model of the furnace was constructed on the basis of its drawings using the SolidWorks software. The 3D calculation reflected the actual position of the tube, the positions of thermocouples on the inner diameter of the tube, and those of the pads used for setting the tube's position inside the furnace. All settings of the 3D model were identical to those employed in the plane problem. In addition, the contact between the pads and the tube was defined, using a heat transfer coefficient of 100 W/m^2K.

3.3 Evaluation of results and discussion

The set-ups for the plane and three-dimensional simulations were identical. Thanks to the thorough mapping of the experiment, the results are identical as well. Heat transfer coefficients were found using 2D simulation, and then applied to the 3D problem. The out-of-centre position of the tube in the furnace had no effect on the experimental results.

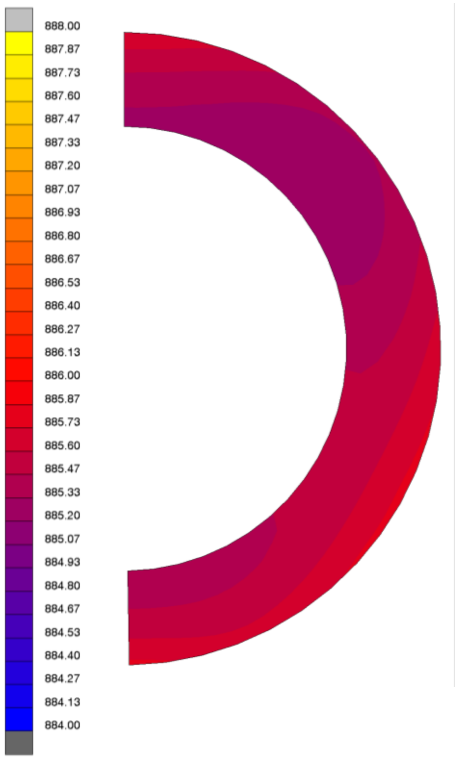


Fig. 9: Distribution of temperature – plane problem

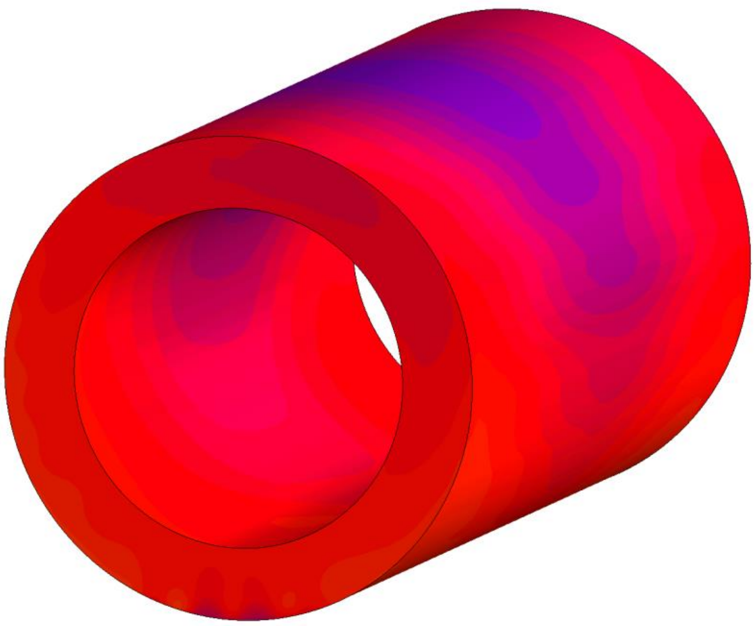


Fig. 10: Distribution of temperature – 3D problem

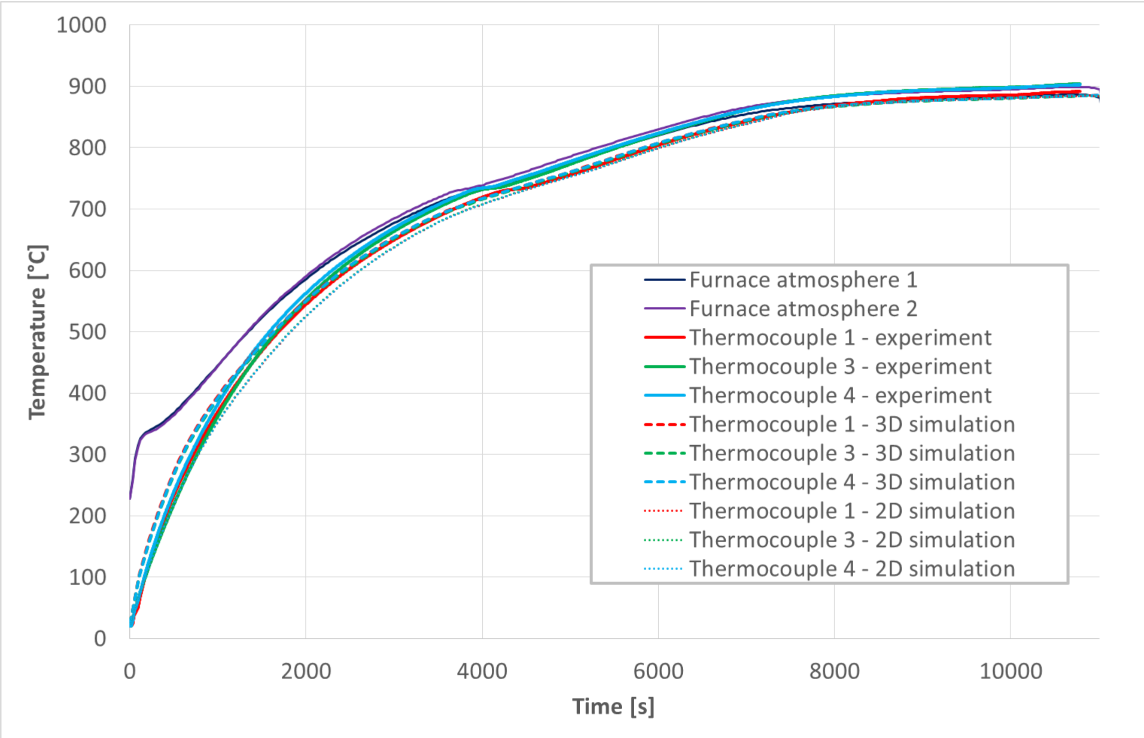


Fig. 11: Comparison of results

In the course of the experiment, a phase transformation at 727 °C was noted, which is highlighted in the graph inset (Fig. 12.). During the near-thermal arrest period, energy is consumed in austenite formation, as indicated by the Fe-Fe_3C equilibrium diagram (Fig. 12.).

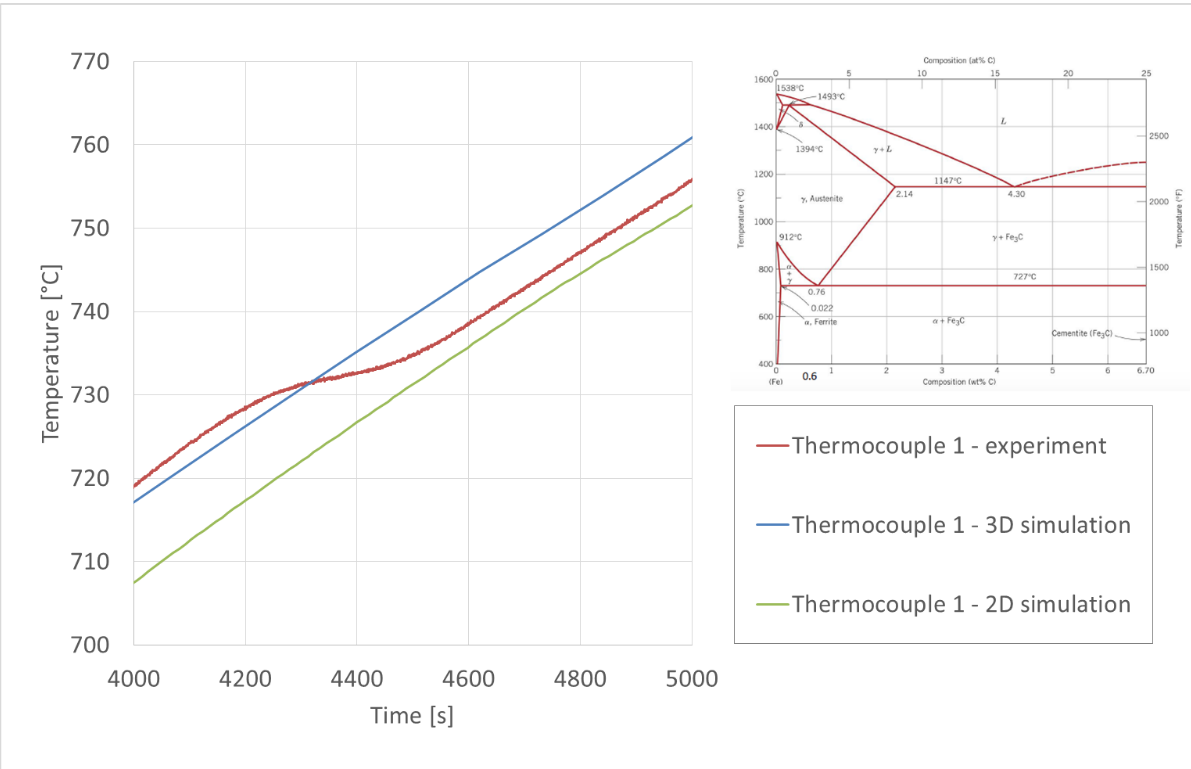


Fig. 12: Plots of experimental T1 readings and simulation results for 2D (one half) and 3D

4 Conclusion

By means of the above-described method, one can experimentally determine heat transfer coefficients in this particular case. Generally, heat transfer coefficients depend on more aspects that described here. There is no single value which could be applied in all cases. However, literature offers recommended values for specific conditions. The coefficients outlined here give a hint of the behaviour of a thick-walled tube during heating. Previously, COMTES FHT completed a range of experiments focused on determining the heat transfer coefficient α under various conditions.

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