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Experimental tests for the occurence of convective heat transfer within the bed of rectangular steel profiles

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Abstract The paper describes tests intended to examine the occurrence of natural convection within the space occupied by 40×20 mm rectangular steel sections. Within these tests the bed of four layers of section was heated by the electric palate heater. Depending on the manner in which the heater was positioned, the tests were divided into two series. In the case of heating from above, the heat flowing through the bed is transferred only by conduction and radiation. When heating the bed from below, in addition to conduction and radiation, also a convective heat transfer will occur. Should this be the case, it will result in the intensification of the heat exchange. The results of measurements carried out have not demonstrated that the occurrence of any possible natural convection would influence the development of a temperature field in this type of charge.

Keywords: Free convection; Rayleigh number; Rectangular sections

Nomenclature

C	–	constant value
d	–	diameter, m
g	–	gravitational acceleration, m/s^2
Gr	–	Grashoff number
Ra	–	Rayleigh number
Pr	–	Prandtl number

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t – temperature, K
T – absolute temperature, K

Greek symbols

ε – intensification
λ – heat conductivity, W/(m K)
ν – kinematic viscosity, m^2/s

Subscripts

A – constant value
cv – convective
h – hydraulic
eq – equivalent
f – fluid
m – mean
tr – actual
rd – radiative
tr – actual

1 Introduction

Heat treatment operations carried out on a large-scale may significantly influence the operation of the whole facility. They determine parameters, such as: productivity, energy consumption, final product quality, or pollutant emissions [1,2]. Therefore, a number of research works and studies are conducted with the aim of optimizing these operations. This task is hindered by the lack of capability to directly control the changes in the microstructure of the charge being treated. So, this is most often done indirectly based on the changes of temperature within the charge. However, such tests, when carried out on an industrial scale, are burdensome and costly, and for that reason rarely undertaken. An attractive alternative to such tests is provided by mathematical modelling, thanks to which it is possible to precisely predict variations in the charge temperature as a function of several variable external parameters, such as, e.g., heat flux intensity and the furnace temperature field. A starting point to this analysis is the differential equation of heat conduction [3,4]. The correct solution of this equation for a given heating case will require precise information about the thermal properties of an element to be treated. For the heating of solid steel elements, the determination of these properties is relatively simple, as it only requires the knowledge of the steel type. On this basis, the thermal conductance of the material in question can be read from relevant tables or calculated [5,6].

Difficulties in determining thermal properties are encountered in the case of heating charges of a porous structure. In industrial practice, such a situation is met in the case of large-scale heat treatment of long elements that are fed into a furnace in the form of bundles. In such a bundle, aside from the solid phase that is made up of individual steel elements, voids filled with gas also occur.

The inhomogeneous internal structure of such charge types causes a complex heat flow to occur within the charge during heating or cooling. As a consequence, their thermal properties are totally different from those of the sole steel. For computation purposes, they are expressed using the effective heat conductivity, λ_{ef}. In a general case, this quantity is represented by the sum of the following [7]:

$$\lambda_{ef} = \lambda_{tr} + \lambda_{rd} + \lambda_{cv} \ . \tag{1}$$

Parameters occur on the right-hand side of the equation of concern in a quantitative manner as conduction, radiation and convection, respectively.

In contrast to conduction and radiation, convective heat transfer, which is associated with the motion of gas, may occur in porous charge in specific cases only. The convective motion of gas, occurring within the voids (pores) of such charge, is a case of natural convection in gaps. Theoretical analyses of these phenomena reveal that the main parameters decisive to the motion of fluid are: surface temperature difference, ΔT; distance between the surfaces; the area height to width proportion; and the value of the Rayleigh number, Ra [8]. Based on those analyses it has been demonstrated that when the value of the Ra number is less than 1700, the heat transfer in the fluid region takes place solely by conduction. The possibility of omitting the convection makes the problem of determining the thermal properties of porous charge much easier, since the λ_{ef} coefficient is in that case the sum of only the first two quantities occurring on the right-hand side of Eq. (1).

2 Description of tests carried out

The paper describes tests intended to examine the occurrence of natural convection within the space occupied by 40×20 mm rectangular steel sections of a wall thickness of 2 mm. Within these tests, a relatively simple experiment was carried out. This involved heating of bed built of four layers of sections with a unidirectional heat flux. For this purpose, an electric plate heater was used, which was placed during the tests in two ways. Depending on the manner in which the heater was positioned, the tests were divided into two series. During the first series, the heater was positioned above the bed. During the second series, the bed was placed on the heater.

In the case of heating from above, heat flowing through the bed is transferred only by conduction and radiation. No gas convection occurs inside the sections. When heating the bed from below, the layers of lower density molecules are below the higher density molecules, so the system becomes unstable. In this situation it can be expected that, in addition to conduction and radiation, also a convective heat transfer will occur. Should this be the case, it will result in an intensification of the heat exchange.

Information about the influence of convection on the intensity of global heat transfer within the bed of sections will be provided by the distribution of temperature. Therefore, temperature measurements were taken at selected bed points during the tests. For this purpose, thin K-type jacket thermocouples were used, whose tips were installed on the outer section surfaces. Profiles on which measurements were taken, were situated in the second and third layers of the bed. The arrangement of measurement points within the bed is shown in Fig. 1.

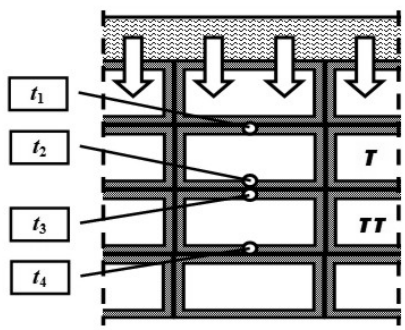

Figure 1. Schematic illustrating the arrangement of temperature measurement points within the bed. The situation shown concerns the case of heating from above.

Viewed from above, the measured temperatures at particular points are denoted with the symbols t_1–t_4. The upper layer section is denoted with the symbol I, while the lower layer section, with the symbol II. From the temperatures t_1–t_4, temperature differences across the section height were calculated:

$$\Delta t_I = t_1 - t_2 \ , \quad \Delta t_{II} = t_3 - t_4 \ . \tag{2}$$

These values were related to the mean temperature, t_m:

$$t_{mI} = \frac{t_1 + t_2}{2}\ , \quad t_{mII} = \frac{t_3 + t_4}{2}\ . \tag{3}$$

During the both test series, four heater power values were used, namely: 200, 300, 400 and 500 W. In order to obtain the most extensive results possible, measurements were taken for both the steady state and the transient state. In the first case, after switching on the heater for a given supply power, temperatures were read out at constant time intervals of 15 min. In the second case, temperature measurements were done on a one-off basis upon reaching a steady state in the system. This state was achieved after a dozen or so hours of heating.

The values of temperature differences within the sections, determined during the tests, provide a measure of heat exchange intensity in the system. If, with heating from below, the share of convection in the overall heat transfer is significant, then the recorded temperature difference should be significantly smaller compared to the results obtained for heating from above (for the same heat flux conditions). If, on the other hand, the values of this parameter computed for the both cases are similar, this indicates that the convection in the gas filling the section interior does not occur or is very small, whereby it does not influence the temperature distribution.

3 Measurement results

First, the results obtained for measurements taken under steady heat exchange conditions will be discussed. These results are presented in the diagrams in Fig. 2, where the temperature differences, as obtained for particular heating directions, are related for the mean temperature. The results for heating from above are denoted by u-h, while the results for heating from below, by d-h. For the heating power values applied (200–500 W), the mean temperatures of sections were contained in the following ranges: for layer I, from about 80 to 170 °C, and for layer II, from about 70 to almost 150 °C. As can be noticed, the temperature differences for the both layers were around a similar level, ranging from 5 to 14 °C, and increased linearly as a function of mean temperature.

The presented data do not reveal any significant differences in the values of the parameter Δt for respective heating variants. The observed deviations are at a level of around 1 °C. They stay within the measuring error range,

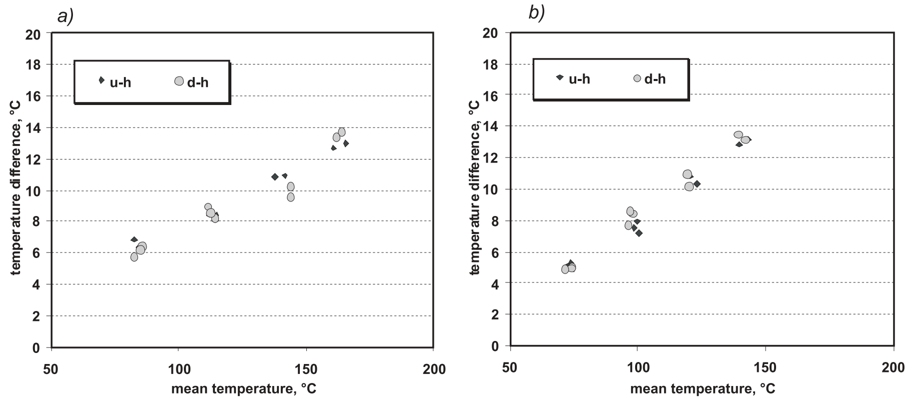

Figure 2. Distribution of temperature differences within sections as a function of mean temperature under the steady conditions of heat flow from above and from below, respectively: a) layer *I*; b) layer *II* u-h – heating from above; d-h – heating from below.

since the apparatus employed in the experiment allowed temperature to be measured with an accuracy of ± 0.5 °C. So, it can be stated on this basis that under the steady heat exchange conditions, no convective gas movements occur within the sections under examination.

Based on the results from Fig. 2 and using the least squares method, regression functions defining the relationship between the temperature difference within a shape and its mean temperature were determined. Then, making use of this relationship, the value of the Ra number in the temperature range of 100–900 °C was computed. This parameter was calculated from the following relationship [9,10]:

$$\mathrm{Ra} = \mathrm{GrPr} = \frac{g d_h^3 \Delta t}{\nu^2 T_m}\mathrm{Pr}\,. \tag{4}$$

Hydraulic diameter for the case of considered shapes was equal to $d_h = 20.57 \times 10^{-3}$ m. The Prandtl number, Pr, of air was taken as 0.7 [11]. The value of kinematic viscosity of air was determined based on literature data [5]. Based on this data following relationship between the viscosity and temperature were determined:

$$\nu = (0.0108 t_m + 13.286)\, 10^{-6}\,. \tag{5}$$

The dependence of the Rayleigh number for the both bed layers as a function of mean temperature is represented in Fig. 3. As can be noticed,

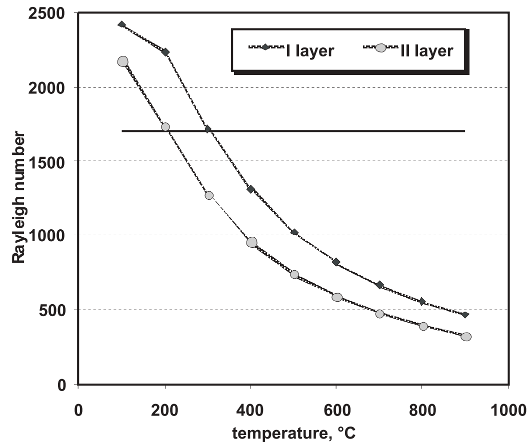

Figure 3. Results of computation of the Ra number as a function of temperature for the steady heat transfer.

the Ra number value rapidly drops as a function of temperature. The critical value (indicated by the solid horizontal line in the diagram) has been exceeded for layer *I* for temperatures up to 300 °C, and for layer *II*, for temperatures up to 200 °C. These results confirm the findings resulting from the analysis of measurement data. For the lower temperature range, where the computation results indicate that the critical value of the Ra parameter has been exceeded, the heat flow can be considered as intensified heat conduction in fluid. The analysis of this problem will be presented in further part of this paper.

Heating of charge during heat treatment is associated with an unsteady heat transfer. Therefore, results of measurements taken for unsteady conditions seem to be more reliable. Figures 4 and 5 represents the variation of the parameter Δt as a function of mean temperature, based on the results obtained for heating the bed with a power of 200 and 300 W, respectively. In turn, Figs. 6–7 gives results obtained for heating power of 400 and 500 W.

The results obtained for all heating power values follow a similar pattern. For the initial values of mean temperature, the values of the parameter Δt rapidly increase, and then stabilize. No significant deviations are observed between the results obtained for heating from above and for heating from below. The scatter of Δt parameter values noted for the both heating modes, depending on the heating power, ranges from 2 to 4 °C. This suggests that also under unsteady heat exchange conditions this phenomenon

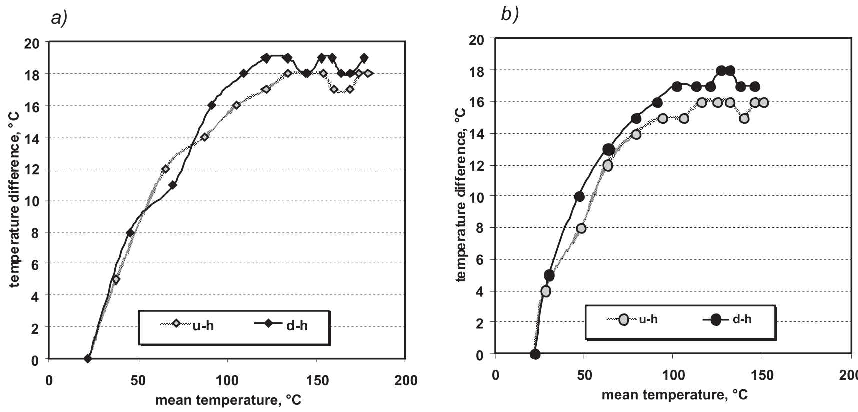

Figure 4. Distribution of temperature differences within the sections for heating with a power of 200 W: a) layer *I*, b) layer *II* (u-h – heating from above, d-h – heating from below).

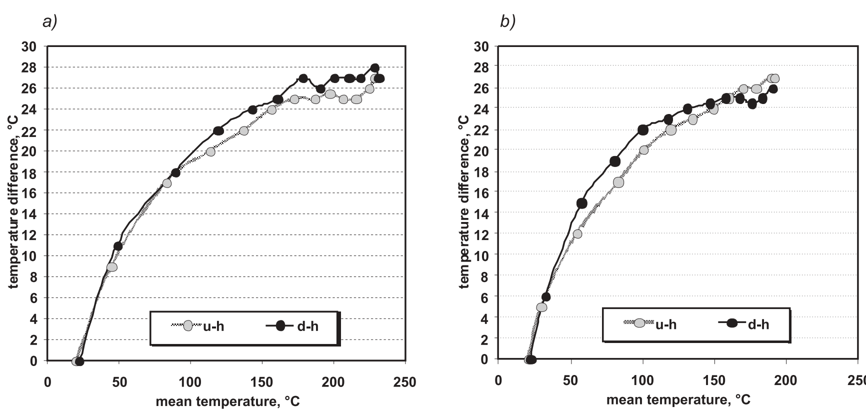

Figure 5. Distribution of temperature differences within the sections for heating with a power of 300 W: a) layer *I*, b) layer *II* (u-h – heating from above, d-h – heating from below).

has no effect, whatsoever, on the heat transfer process in the whole bed, even if convective gas movements do happen within the sections.

In this case, too, the values of the Rayleigh number were computed. The variation of this parameter as a function of temperature is shown in Fig. 8. This indicates that, regardless the heating power, the Ra number increases in the initial period of the process, and then starts decreasing upon reaching a maximum value. In all cases, it comes to exceeding the critical value. Depending on the heating power, the maximum value of the Ra number

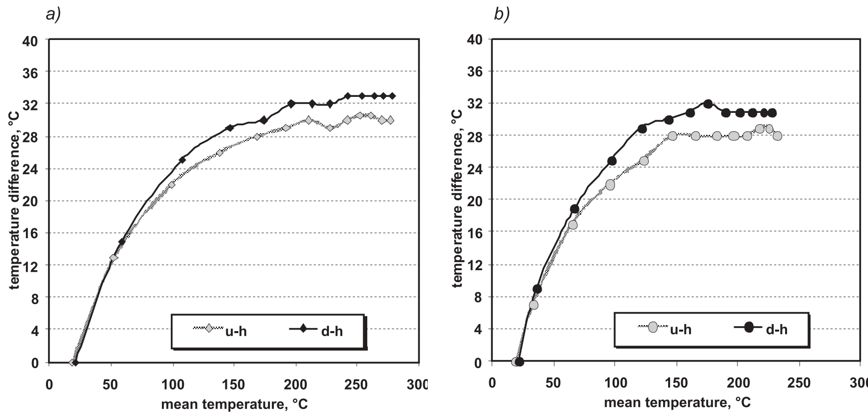

Figure 6. Distribution of temperature differences within the sections for heating with a power of 400 W: a) layer *I*, b) layer *II* (u-h – heating from above, d-h – heating from below).

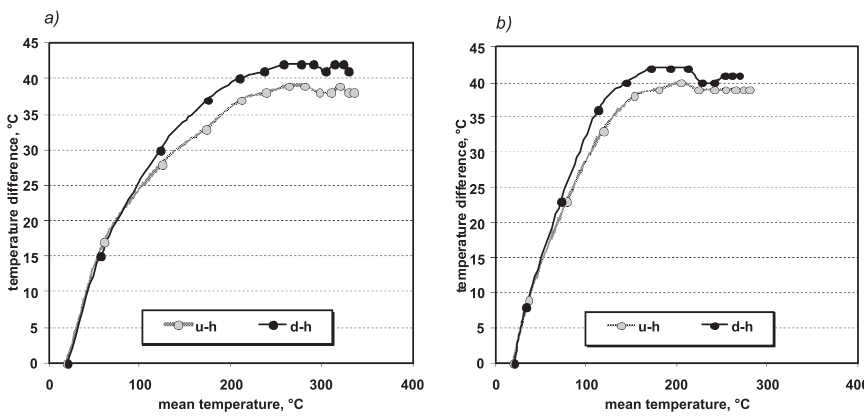

Figure 7. Distribution of temperature differences within the sections for heating with a power of 500 W: a) layer *I*, b) layer *II*(u-h – heating from above, d-h – heating from below).

ranges from nearly 6000 to 9000. The lower range of this parameters ends in a value of approx. 2000. This shows that under unsteady heat exchange conditions convective fluid movements occur within the internal spaces of the sections under analysis. However, the intensity of this phenomenon is small, which manifests itself in the absence of any significant differences in the bed temperature distribution, which could be observed for the respective heating directions.

As has been mentioned earlier, the intensification of heat transfer within

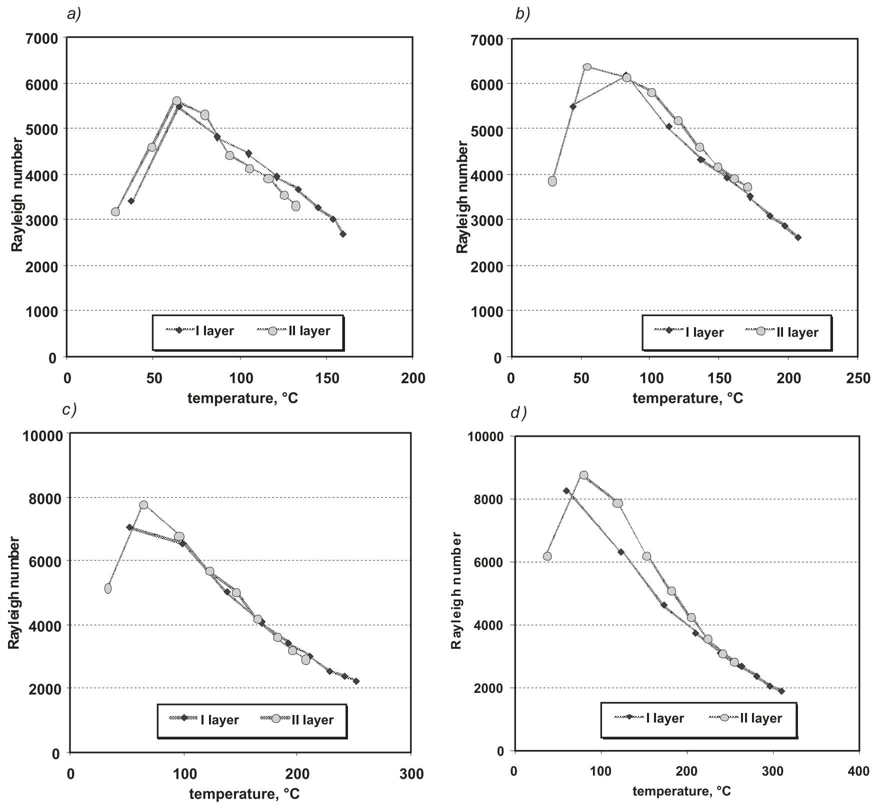

Figure 8. Developing of the Ra number value within the space of rectangular sections under unsteady heat transfer conditions: a) 200 W, b) 300 W, c) 400 W, d) 500 W.

a gas filled gap, caused by the occurrence of natural convection, can be expressed with the equivalent thermal conductivity in fluid [9,10]:

$$\lambda_{eq} = \varepsilon_{eq}\lambda_f \ . \tag{6}$$

The factor ε_{eq} defining the heat transfer intensification against the stationary fluid is determined from empirical relationships. Most commonly, a power relationship is used here:

$$\varepsilon_{eq} = C\mathrm{Ra}^A \ . \tag{7}$$

The values of the constants C and A depend on the Rayleigh number value range [10]. For the Ra numbers that characterize the heat transfer in the gaps of the bed of sections under analysis, the value of the ε_{eq} coefficient, as calculated from Eq. (7), are contained in the range of 1.03–1.61.

During carrying out of the tests, the gaseous phase was atmospheric air. Therefore, after considering the values that the coefficient ε_{eq} assumes, the equivalent thermal conductivity of air for the sections under examination will be contained in the range of 0.021–0.0925 W/(mK). Compared to the thermal conductivity of steel, which is the solid phase of the porous change under consideration, the equivalent thermal conductivity is smaller by three orders of magnitude. On this basis it is arguable that, in the bed of sections under consideration, the thermal phenomena occurring in the gaseous phase space have practically no effect on the overall heat transfer. Mechanisms that play a key role here are conduction in the steel phase space, contact conduction at the sections contact locations and, in a temperature range above 300 °C, radiation occurring between the surfaces of the sections.

4 Summary

An analysis of the occurrence of natural convection of the gaseous phase within the space of rectangular steel sections has been made in the paper based on experimental tests. The results of measurements carried out have not demonstrated that the occurrence of any possible natural convection would influence the developing of a temperature field in this type of charge. The Rayleigh number values, that characterize the convective heat transfer, in this case allow this phenomenon to be regarded as the intensified conduction of heat in fluid.

Resolving the convection problem requires the solution of complex differential equations describing the motion of fluid. The possibility of omitting the convection considerably facilitates the determination of the thermal properties of charge made up of bundles of sections under discussion.

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