

Analysis of components effecting free convection intensity in steel rectangular sections

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Abstract Free convection is one of the heat transfer modes which occurs within the heat-treated bundles of steel rectangular section. A comprehensive study of this phenomenon is necessary for optimizing the heating process of this type of charge. The free convection intensity is represented by the Rayleigh number Ra . The value of this criterion depends on the following parameters: the mean section temperature, temperature difference within the section, kinematic coefficient of viscosity, volume expansion coefficient and the Prandtl number. The paper presents the analysis of the impact of these factors on free convection in steel rectangular sections. The starting point for this analysis were the results of experimental examinations. It was found that the highest intensity of this process occurs for the temperature of 100 °C. This is mainly caused by changes in the temperature difference observed in the area of sections and changes in kinematic coefficient of viscosity of air. The increase in the value of the Rayleigh number criterion at the initial stage is attributable to changes in the parameter of temperature difference within the section. After exceeding 100 °C, the main effect on convection is from changes in air viscosity. Thus, with further increase in temperature, the Rayleigh number starts to decline rapidly despite further rise in the difference in temperature.

Keywords: Free convection; Rayleigh number; Section bundles; Effective thermal conductivity; Heat treatment

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Nomenclature

A_i	–	coefficients in Eq. (6)
C	–	constant in Eq. (2)
g	–	gravitational acceleration, m/s ²
Gr	–	Grashof number
L_c	–	characteristic length, m
n	–	constant in Eq. (2)
Nu	–	Nusselt number
Pr	–	Prandtl number
R^2	–	coefficient of determination
Ra	–	Rayleigh number
t	–	temperature, °C
T	–	thermodynamic temperature, K

Greek symbols

β	–	volume expansion coefficient, 1/K
Δt	–	temperature difference, K
ν	–	kinematic coefficient of fluid viscosity, m ² /s

Subscripts

a	–	point on the hot surface of the section
b	–	point on the cold surface of the section
c	–	characteristic
Fr	–	furnace
m	–	mean
max	–	maximum
min	–	minimum
rf	–	reference
s	–	surface
∞	–	area of the fluid sufficiently far from the surface

1 Introduction

Free convection is the mode of heat transfer which is connected with the motion of fluid caused by the heterogeneity of its density in a gravitational field [1,2]. The heterogeneity of density in this case is caused by a variation of the temperature field of the fluid. Due to the geometry of the area in which this phenomenon occurs, we distinguish free convection in closed space (internal flow) and free convection in open space (external flow) [3,4]. This division is a very important because influence of the dimensions and geometry of the heat transfer area have essential significance to the free convection process. If this effect does not occur or is negligibly small, the space is considered as open [5].

The above types of free convection differ from each other by specific nature of the occurring phenomena. This differentiation is reflected in the approach to their theoretical analysis. In the case of free convection in open space the fluid motion occurs mainly next to the surface of the solid body in the boundary layer area. Outside the boundary layer, fluid motion is insignificant and essentially does not have any effect on heat transfer. Therefore, it was assumed in theoretical investigations that in this case the fluid outside the boundary layer is stationary and does not affect the flow generation.

In the case of free convection in a confined space, at the edges of the area are formed the boundary layers. These layers reduce the space in which rest of the fluid is closed. This space is called the nucleus. The shape and size of this nucleus depend on the geometry of heat exchange area and geometry of boundary layers. At the same time there is a mutual conditioning of the flows in nucleus and in boundary layers. This conditioning constitutes the essential difficulty for theoretical analysis of this issue.

The phenomena of free convection in the closed space concern, among other things, such problems as: heat exchange in rooms, flows in the channels and ducts in the temperature field, temperature distributions and the fluid motion in the containers, solidification of castings and ingots. A special case of a free convection in the limited area is the convection heat transfer occurred in the inner spaces of the steel rectangular sections which are heat treated [6]. During these operations the sections are usually heated in bundles, examples of which are shown in Fig. 1. Heating of the sections in such a form is caused by the fact that the stock in this form ensures the most efficient utilization of the furnaces workspace. In addition, sections tied as bundles are convenient in transport.

Optimization of heat treatment processes requires the knowledge about thermal properties of heated elements [7]. Section bundle due to the geometrical structure is a two-phase porous medium. For this reason, its basic thermal property is the effective thermal conductivity, k_{ef} [8]. This parameter expresses quantitatively the medium ability to energy transfer by different modes of heat flow and is commonly used in the theory of porous media [9–11]. The value of k_{ef} coefficient of a section bundle depends on the intensity of particular heat transfer modes which occur during heat treatment. One of these modes is a free convection of the gas that occurs in the inner spaces of the individual sections. Hence the knowledge about the course of the free convection phenomenon in the section bundle is necessary

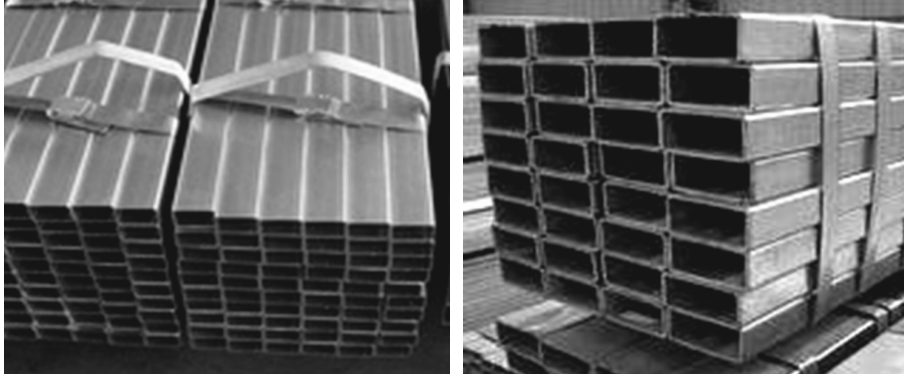


Figure 1: Examples of the bundles of steel rectangular sections.

in analytical determination of the coefficient k_{ef} of such medium.

The article presents the analysis of free convection occurring in the area of rectangular steel sections heated in bundles. For this purpose the Rayleigh number was used, which is a dimensionless criterion of similarity for free convection. The starting point for calculations were the results of experimental tests. These tests were carried out on the section bundle samples heated in a laboratory box-type furnace.

2 Rayleigh number as the free convection parameter

The key problem of the theoretical research related to the heat transfer is the solution of equations representing mathematical model of the considered process. Mathematical description of convection phenomenon includes the continuity, momentum and energy equations [1–4]. These equations must be completed by the uniqueness conditions, which include equations describing dependences of the fluid physical properties on the temperature and the boundary and initial conditions. This makes that at consideration of the convection phenomenon we have to solve a system of coupled nonlinear partial differential equations. Solving this system is possible only through approximation, after making a number of simplifying assumptions [4].

Due to the above difficulties with the analysis of free convection, the theory of similarity is often used [1,2,12]. This method consists in reduction of differential equations that describe the phenomenon analyzed to the

dimensionless form. This approach yields dimensionless parameters termed numbers of similarity. The dimensionless parameter that represents the natural convection effects is the Grashof number [3,12]

$$\text{Gr} = \frac{g\beta(t_s - t_\infty)L_c^3}{\nu^2} . \quad (1)$$

This parameter represents the ratio of the buoyancy force to viscous force acting on the fluid. This means that the role played by Reynolds number in forced convection is played by the Grashof number in natural convection. As such the Grashof number provides the criterion in determining whether the fluid flow is laminar or turbulent in natural convection.

The simple empirical correlations for the average Nusselt number in free convection are of the form [12]

$$\text{Nu} = C(\text{GrPr})^n = C(\text{Ra})^n , \quad (2)$$

where Ra is the Rayleigh number, which is the product of Grashof and Prandtl numbers

$$\text{Ra} = \text{GrPr} = \frac{g\beta(t_s - t_\infty)L_c^3}{\nu^2} \text{Pr} . \quad (3)$$

This means, that the Rayleigh number Ra is the dimensionless parameter for free convection. The Rayleigh number for an enclosure (internal flow) is determined from [12]

$$\text{Ra} = \text{GrPr} = \frac{g\beta(t_a - t_b)L_c^3}{\nu^2} \text{Pr} , \quad (4)$$

where the characteristic length L_c is the distance between the hot and cold surfaces, and t_a and t_b are the temperatures of the hot and cold surfaces, respectively. When for heat transfer in enclosure $\text{Ra} > 1700$, the buoyant forces overcomes the fluid resistance and free convection currents are initiated. For $\text{Ra} > 3 \times 10^5$ the fluid motion in enclosure becomes turbulent [12].

From the geometrical point of view steel section can be treated as the enclosure. Hence Rayleigh number allows for a very simple assessment of the free convection intensity which occurs inside the heated sections.

3 Experimental tests

The problem of free convection in the area of steel sections has been the focus of several previous studies [13–15]. This phenomenon has been analyzed

in both steady and unsteady conditions. It was found that the Rayleigh number for convection inside steel sections obtained for the unsteady conditions is by an order of magnitude greater than the values recorded under steady conditions. Since heating of steel section bundles during heat treatment is an unsteady process, the value of the Rayleigh number obtained for unsteady conditions seems to be interesting from the practical point of view. It was also demonstrated that, regardless of the heat transfer conditions (steady or unsteady), maximal values of Ra parameter are observed over a relatively narrow range of temperatures of about 70–90 °C. Further increase in mean temperature of section, t_m , regardless of the temperature difference in its area, Δt , leads to a rapid decline in the Ra parameter.

Equation (4) shows that Ra number is affected by the four temperature-dependent parameters: volume expansion coefficient, β , temperature difference, Δt , kinematic coefficient of viscosity, ν and the Prandtl number, Pr. Experimental examinations were needed to evaluate the effect of these parameters on free convection that occurs inside heated sections. The experiments involved heating the steel section specimens in a laboratory box-type furnace with internal chamber dimensions of 250 mm \times 300 mm \times 1000 mm (height \times width \times length). The heating elements in the furnace were provided by coils of resistant wire located along side walls of the chamber. The examinations were carried out for the range of temperature of 25–700 °C, which is the range typical to the most of steel products heat treatment operations [7]. Heating was carried out in the air atmosphere.

Two bundles were examined, made of square sections with external dimensions of 60 mm and 80 mm and wall thickness of 3 mm. Section length was 800 mm. The examinations consisted in the measurement of the temperature in the areas of the selected sections. Measurement points were located in the half of the section length on the opposite walls with respect to the heat flow direction. This allowed for obtaining a hot point (denoted as a) and cold point (denoted as b). Measurements for the 60 mm section bundle were carried out in the area of two adjacent sections, denoted as I and II . This bundle was composed of sixteen sections with four layers. Furthermore, in the 80 mm section bundle, measurements were carried out only in the area of a single section of the second layer. This bundle was composed of nine sections with three layers. Small dimensions of the furnace chamber caused that the size of the this bundle was limited to only three sections in the layer. Location of the temperature measurement points in individual bundles is presented in Fig. 2. With heating elements fixed

inside the furnace chamber, it can be adopted that heat transfer in the area of bundles was one-dimensional, which is denoted in Fig. 2 with arrows.

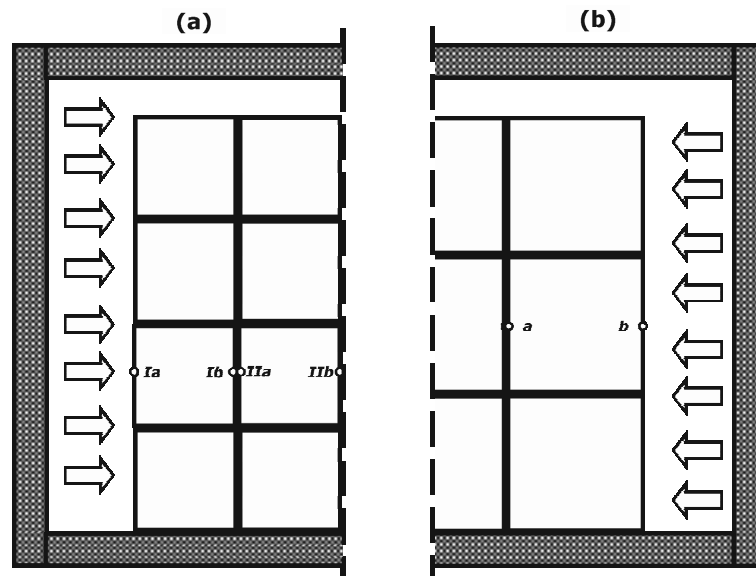


Figure 2: Location of temperature measuring points inside tested samples: a) bundle of the sections 60 mm, b) bundle of the sections 80 mm (arrows indicate the direction of heat flow to the charge).

The temperature measurement system was comprised of a digital micro-processor thermometer (EMT 200), multichannel switch (PMP 201) and jacked-thermocouple (type K) with diameter of 1 mm. The system allowed for temperature measurement with accuracy of $0.5\text{ }^{\circ}\text{C}$ [16]. Measurement tips of thermocouples were fixed in small grooves made on external surfaces of the sections. Heat-resistant silicone was used to fix the tips. Figure 3 presents one of the bundles inside the furnace chamber and fixing of one of the thermocouples to the section surface. Temperatures measured during the heating process were recorded at 5-minute intervals.

Heating was continued until the final temperature, t_{Fr} , was reached (set at $750\text{ }^{\circ}\text{C}$). With the 60 mm sections bundle, this temperature was reached in 50 min. During heating of the 80 mm section bundle due to higher porosity of the charge and, consequently, its lower mass, final temperature was obtained after 25 min. Figure 4 illustrates changes in the temperature in the furnace chamber, t_{Fr} , and temperatures at the measurement points of the bundles studied. As can be seen from the figure, heating of bundles

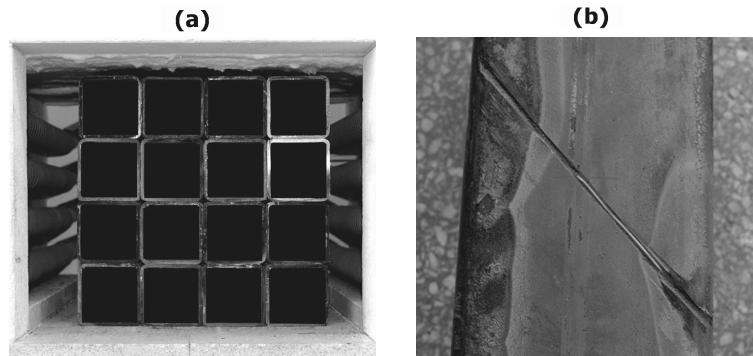


Figure 3: (a) View of the bundle of 60 mm section inside the furnace chamber - on the side walls are visible the heating elements, (b) image illustrating fixing of the thermocouple to the section surface.

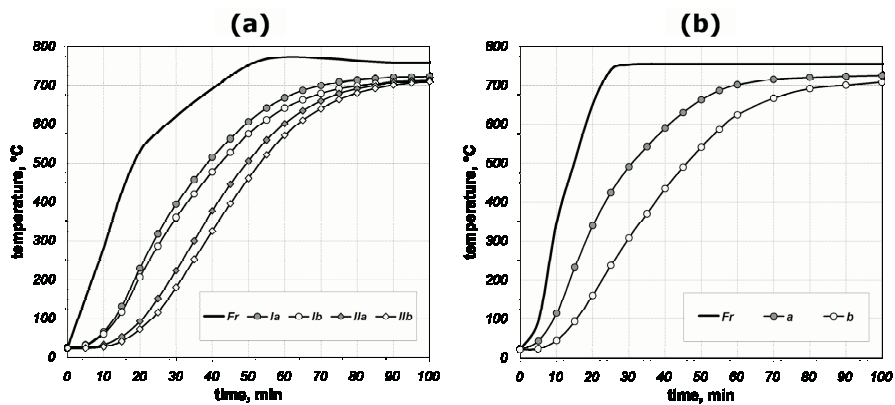


Figure 4: Changes of the furnace chamber temperature t_{Fr} and the temperatures of the measuring points of the samples: (a) results for the 60 mm section bundle, (b) results for the 80 mm section bundle.

to reach the target final temperature (700°C) in both cases took around 100 min.

From the standpoint of the analysis of the Rayleigh number, the temperature difference, Δt , between the hot point and cold point in the heated sections seem to be critical. Changes in the parameter, Δt , obtained for 60 mm sections and 80 mm section are presented in Figs. 5 and 6, respectively. Figures 5(a) and 6(a) illustrate changes in the parameter Δt with time of heating, whereas Figs. 5(b) and 6(b) illustrate these changes with respect to mean section temperature, t_m . The temperature t_m for each

section was calculated as the arithmetic mean of its temperature in points a and b

$$t_m = 0.5 (t_a + t_b) . \quad (5)$$

The maximum value of Δt parameter for the 60 mm section bundle for both sections was observed after 40 min of heating. For the section I , this parameter was 51°C , obtained for the mean temperature of 350°C . For the section II , this value was 37.5°C , reached for the mean temperature of 496°C . A substantially greater temperature difference was found for the 80 mm section. The maximum value of the parameter Δt in this case was 188°C , with mean temperature of 331°C .

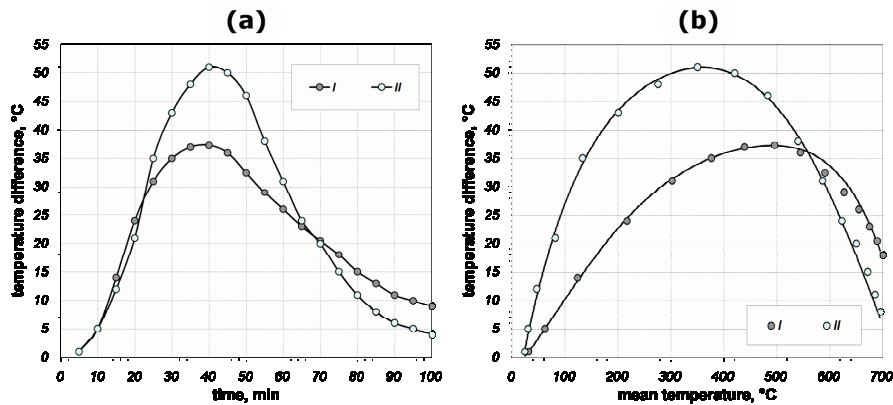


Figure 5: Temperature differences Δt within the 60 mm sections: (a) changes as a function of the heating time, (b) changes as a function of the section mean temperature t_m .

For the purposes of further analysis, changes in the temperature difference of the sections vs. mean temperature (presented in Figs. 5(b) and 6(b)) were approximated with regression equations. The best fit of the approximated values to the measurement data in all the cases were obtained for the equations in the form of the 5th order polynomial

$$\Delta t = A_1 t_m^5 + A_2 t_m^4 + A_3 t_m^3 + A_4 t_m^2 + A_5 t_m + A_6 . \quad (6)$$

Values of coefficients A_1 – A_6 and coefficient of determination R^2 obtained for individual sections are presented in Tab. 1.

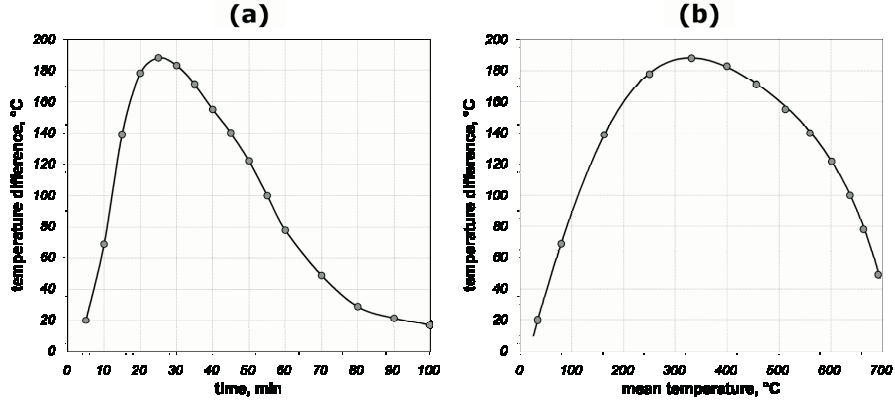


Figure 6: Temperature differences Δt within the 80 mm section: (a) changes as a function of the heating time, (b) changes as a function of the section mean temperature t_m .

Table 1: Values of coefficients A_1 – A_6 from Eq. (7) and coefficient R^2 for analyzed sections.

Section	60 mm I	60 mm II	80 mm
A_1	-2.67×10^{-12}	3.13×10^{-12}	-1.34×10^{-11}
A_2	4.28×10^{-9}	-6.61×10^{-9}	2.11×10^{-8}
A_3	-2.53×10^{-6}	5.17×10^{-6}	-1.04×10^{-5}
A_4	0.00049	-0.00222	-3.44×10^{-5}
A_5	0.0994	0.5568	1.1726
A_6	-2.532	-11.03	-19.472
R^2	0.998	0.999	0.998

4 Analytical calculations

Apart from the temperature difference Δt , the equation that defines the Rayleigh number also contains three temperature-dependent parameters, namely volume expansion coefficient, β , kinematic coefficient of viscosity, ν , and Prandtl number, Pr. Coefficient β of an ideal gas at the thermodynamic temperature, T , is equivalent to the inverse of the temperature [3,12]

$$\beta = \frac{1}{T}. \quad (7)$$

In our case, the coefficient β was calculated from

$$\beta = \frac{1}{T_{rf}} = \frac{1}{t_{rf} + 273}, \quad (8)$$

where the temperature t_{rf} is termed the reference temperature, which is the arithmetic mean temperature of the hot and cold fluid. The temperature t_{rf} used for calculation of other thermal properties of air was adopted as equal t_m .

Changes in kinematic coefficient of viscosity and Prandtl number for air vs. temperature are presented in Fig. 7. The data were found in the literature [12]. The increase in air viscosity with temperature is given by the equation

$$\nu = 6.8 \times 10^{-8} t_m^2 + 9.52 \times 10^{-8} \times t_m + 1.3 \cdot 10^{-5}. \quad (9)$$

Furthermore, changes in Prandtl number for the discussed temperature range is given by a 4th order polynomial

$$\text{Pr} = 3.16 \times 10^{-13} t_m^4 + 8.76 \times 10^{-10} t_m^3 + 8.97 \times 10^{-7} t_m^2 - 0.00032 t_m + 0.738. \quad (10)$$

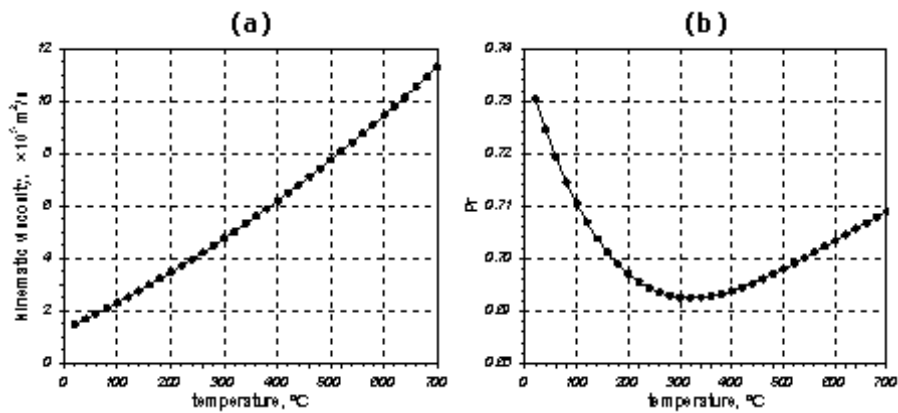


Figure 7: Temperature changes of: a) kinematic coefficient of viscosity, b) Prandtl number, of air.

The results of calculations of the Rayleigh number for the analyzed three sections obtained from the Eqs. (7) and (8)–(10) are presented in Fig. 8. Figure 8(a) illustrates the values concerning the 60 mm sections. Maximal value of Ra parameter for the section *I* was observed for the mean temperature of 110°C and was 5.6×10^4 . For the section *II*, this value was found

for the mean temperature of 80°C and was 15.3×10^4 . Almost three-time greater maximum value of Ra criterion for the section *II* was caused by a higher temperature difference. Furthermore, the parameter Δt for both sections has a different profile in the function of mean temperature. Variation of the results obtained for both sections indicates that the Rayleigh number is affected by both parameter Δt and its changes with respect to mean temperature. Figure 8(b) presents the results of calculations of Ra parameter obtained for the 80 mm section. Maximal value in this case was observed for the mean temperature of 85°C and was 126.8×10^4 . Compared to the result obtained for the section 60 mm *II* (also shown in Fig. 8(b) for comparison), this value is by one order of magnitude greater. Comparison of the results obtained for both sections should also take into consideration their different dimensions. For 80 mm section, characteristic dimension L_c is 0.75 mm, whereas for the 60 mm section, this dimension is 54 mm. As can be seen, the increase in the parameter, L_c , by 27% contributes to a ten-fold increase in the value of the Ra number. This happens because the dimension L_c in the equation of the Rayleigh number occurs with the power of 3. Therefore, the dimensions of the space where free convection occurs are critical for this type of heat transfer. Changes in the parameter Ra shown in Fig. 8 for all three sections have a similar and very characteristic profile. A very dynamic increase is observed from the initial temperature to the value of around $80\text{--}100^{\circ}\text{C}$. After reaching the maximal value, further increase in temperature is followed mainly by a similarly rapid decline. Over the range of temperature of $200\text{--}250^{\circ}\text{C}$ the Rayleigh number values decreases by half. This demonstrates that the intensity of free convection during section heating in this process is varied with time. The highest intensity of this phenomenon is observed at the initial stage of heating, where mean temperature of the sections does not exceed 100°C .

In order to achieve the aim of the study, the attempt was also made to verify the changes of which parameters (termed in the title as components) affect the value of Ra number. A series of calculations were carried out for this purpose. A constant value was adopted for each parameter during the calculations. Calculations were carried out for each parameter and for three values: maximal, mean and minimal. The values adopted for calculations are presented in Tab. 2. The minimal values for the temperature difference for both sections were adopted as equal to mean temperature, t_m , for which the maximum was observed for the parameter Ra.

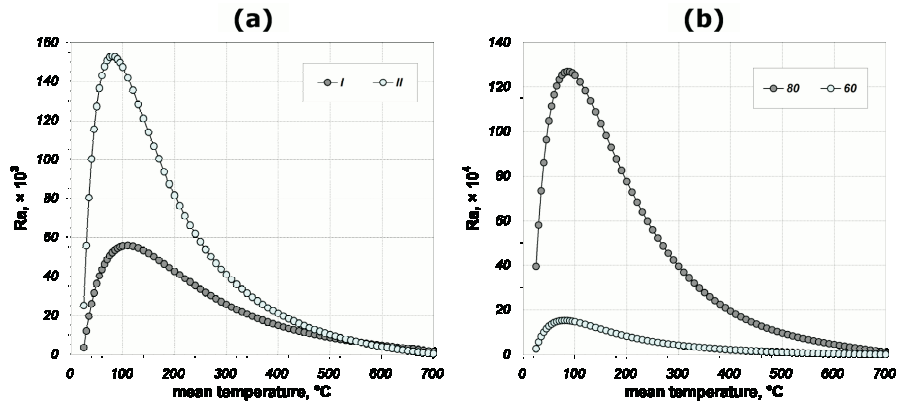


Figure 8: Calculation results of the Rayleigh number: (a) values for the sections 60 mm, (b) values for the section 80 mm and section 60 mm II.

Table 2: Maximal, mean and minimal values of the components used in calculations.

Parameter	Pr	ν , m^2/s	β , $1/K$	Δt_{60} , $^{\circ}C$	Δt_{80} , $^{\circ}C$
maximal	0.729	11.3×10^{-5}	0.0033557	50.9	188.2
mean	0.703	5.52×10^{-5}	0.0018813	34.3	128.2
minimal	0.692	1.54×10^{-5}	0.0010277	21.6	69.6

Figure 9 presents the results of calculations obtained for constant values of the Prandtl number. As can be seen, changes in this parameter affect the Rayleigh number only to an insignificant degree. This is due to the fact that changes in the Pr number for air in the analyzed range of temperature are insignificant. With respect to the maximal value of Pr number, these changes are only 1.4%.

The results of calculations of the Rayleigh number obtained for constant kinematic coefficient of viscosity are presented in Fig. 10. It can be noted that changes in this parameter significantly affect the value of the discussed criterion. The increase in air viscosity substantially reduces the Ra number, thus decreasing the intensity of free convection. This effect is caused by an increase in resistance for fluid flow. Furthermore, curves in these charts have entirely different profiles compared to the curves from Fig. 8. This suggests that the characteristic profile of curves in Fig. 8 can be attributable, among other things, to changes in air viscosity with temperature. Maximal

values of the Ra number in this case occur at the temperature of 210°C , i.e., they are shifted by over 100°C compared to the maximal values from Fig. 8. Since the coefficient ν in the Rayleigh number equation occurs with the power of two, a relatively small decline in this parameter significantly increases the value of Ra.

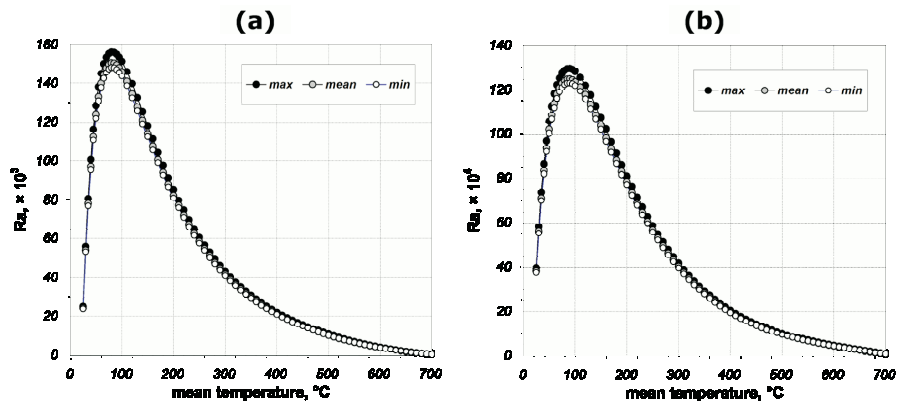


Figure 9: The Rayleigh number obtained for fixed values of the Prandtl number: (a) values for the section 60 mm II, (b) values for the section 80 mm.

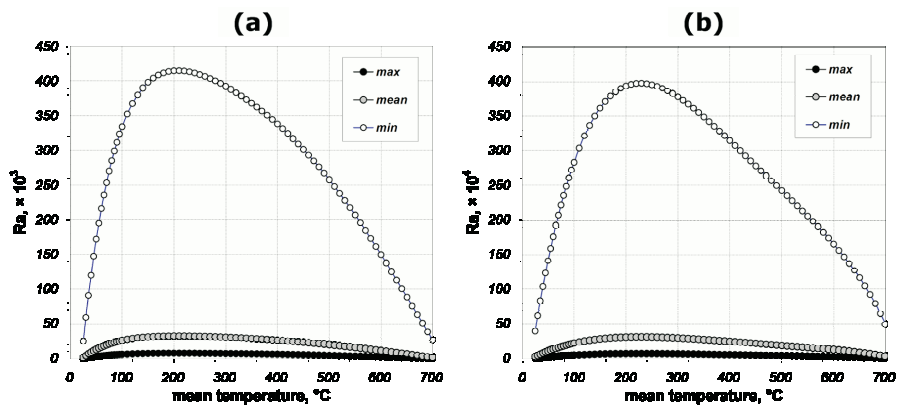


Figure 10: The Rayleigh number obtained for fixed values of the kinematic coefficient of viscosity, ν : (a) values for the section 60 mm II, (b) values for the section 80 mm.

Figure 11 presents the results of calculations obtained for constant volume expansion coefficient, β . Changes in this parameter have a noticeable effect on the Ra number. This effect, however, is not that substantial as

it was the case in kinematic coefficient of viscosity. Importantly, shape of curves in this figure is similar to the curves in Fig. 8. Therefore, changes in the coefficient β do not affect the intensity of convection with respect to temperature.

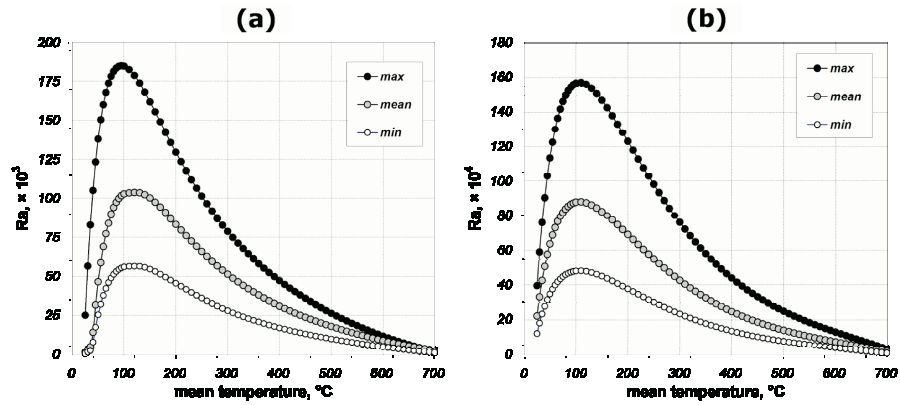


Figure 11: The Rayleigh number obtained for fixed values of the volume expansion coefficient β : (a) values for the section 60 mm *II*, (b) values for the section 80 mm.

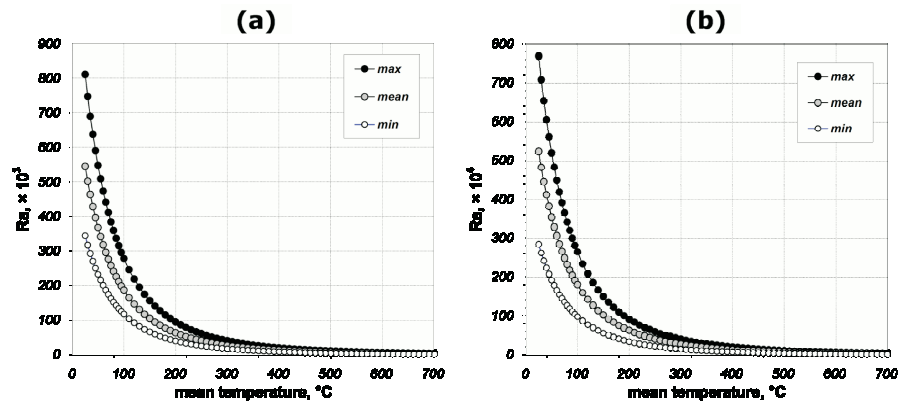


Figure 12: The Rayleigh number obtained for fixed values of the temperature difference Δt : (a) values for the section 60 mm *II*, (b) values for the section 80 mm.

Figure 12 presents the results of calculations obtained for constant values of the temperature difference. In this case, the profile of the curves is the most different compared to those presented in Fig. 8. This means that the

characteristic profile of changes in the Ra number with respect to temperature is mainly attributable to changes in the parameter Δt . Figure 12 shows that, for constant Δt , Ra number decreases over the whole range of temperature. The curves obtained in this case are similar in their shape to equilateral hyperbolas.

5 Summary

The study demonstrated that the phenomenon of free convection in the area of rectangular steel sections is varying in terms of intensity. It was found that the highest intensity of this process occurs for the temperature of 100 °C. This is mainly caused by changes in the temperature difference observed in the area of sections and changes in kinematic coefficient of viscosity of air. The increase in the value of Ra criterion at the initial stage is attributable to changes in the parameter Δt . After exceeding of 100 °C, the main effect on convection is from changes in air viscosity. Thus, with further increase in temperature, the Rayleigh number starts to decline rapidly despite further rise in the difference in temperature. At the same time, it should be aware that the value of parameter Δt depends on the other heat transfer mechanisms that are present in the analyzed system. These mechanisms include conduction in the wall of the section and thermal radiation between its surfaces and free convection. All these mechanisms are interrelated which makes that the course of convection depends on the section geometry and thermal properties of the steel. It should be noted that the share of conduction, radiation and convection in the total heat transfer change with the furnace temperature increase. Accurate evaluation of the quantitative contribution of these modes of heat transfer to the process of heating the section bundles will be the subject of future publications. However, for the temperature ranges used for heat treatment of steel sections, it should be emphasized that convection does not have a substantial effect on intensity of section bundles' heating. Finally it must be emphasized that the presented results refers to a very particular case and therefore, cannot be generalized.

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