

Analysis of Nusselt Number for Natural Convection in Package of Square Steel Sections

R. WYCZÓŁKOWSKI^{a,*}, J. SZMIDLA^a,
M. GAŁA^a AND V. BAGDASARYAN^b

^a Czestochowa University of Technology, 42-201 Czestochowa, Poland

^b Warsaw University of Life Sciences — SGGW, 02-787 Warsaw, Poland

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*e-mail: rafal.wyczolkowski@pcz.pl

The paper analyses the Nusselt number for natural convection in the inner area of square 40, 60 and 80 mm sections in the temperature range 20–700 °C. The obtained values of the Nu number are in the range 1.5–7.2. For each section the maximum value of the Nu occurs at a temperature amounting to approximately 60–90 °C. This is the effect of the simultaneous influence of the temperature difference within the section Δt , the kinematic viscosity and the coefficient of thermal expansion of air. The natural convection depending on the section size increases the heat transfer within gas from 1.5 to 4.3 times upon averaging for the whole temperature range.

topics: natural convection, steel section, heat treatment, Nusselt number

1. Introduction

In industrial heat treatment of steel products, in many situations there is a need to heat a charge of a porous structure [1, 2]. One of the examples of such a charge are packages of square steel sections (Fig. 1). The porosity of such packages can even exceed 0.9.

The heating time of such a charge, which is one of the basic technological parameters, depends on many factors. This time depends, among other things, on the natural convection of gas within individual sections. This is a case of convection in a horizontal enclosure. A full description of this phenomenon requires taking into account the fluid motion within the section while considering



Fig. 1. A package of square steel sections.

the influence of all closing surfaces at the same time [3]. Therefore, simplified solutions are being sought. One of the methods applied in this regard consists in expressing the convection phenomenon in a quantitative manner with the use of the Nusselt number (Nu) [4]. The experimental research conducted by the authors has shown that the Nusselt number changes in a very characteristic manner during heating of the sections [5].

The aim of the present work is to determine: (i) the value of the Nusselt number for the analyzed square profiles (40, 60 and 80 mm) in the temperature range 200–700 °C, (ii) the influence of the dimensions of a section, the temperature distribution in a section and the thermo-physical properties of air on the value of the Nu number.

2. Analysis and modeling

Natural convection within the section is always connected with conduction in gas. Both phenomena can be treated jointly as intensified heat conduction expressed quantitatively by equivalent gas thermal conductivity k_{eg} [6]:

$$k_{eg} = k_g \text{Nu}, \quad (1)$$

where k_g is the thermal conductivity of gas, Nu — the Nusselt number.

The notation of (1) means that the Nu number is the measure of the intensification of heat transfer caused by the occurrence of natural convection in

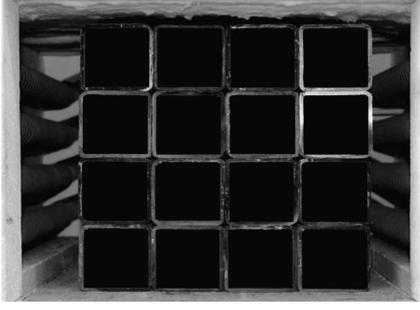


Fig. 2. A package of 60 mm sections in the chamber of the electric furnace.

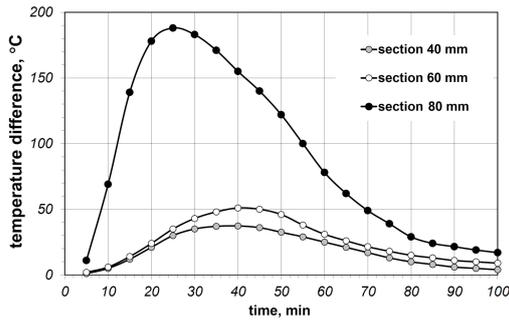


Fig. 3. The values of Δt parameter in the function of heating time.

relation to pure conduction. For natural convection of air in horizontal enclosures the following correlations are recommended [6]:

- for $10^4 < Ra < 4 \times 10^5$

$$Nu = 0.195 Ra^{1/4} \quad (2)$$

- for $4 \times 10^5 < Ra < 10^7$

$$Nu = 0.068 Ra^{1/3}. \quad (3)$$

The Rayleigh Ra number is defined as:

$$Ra = \frac{g\beta\Delta t L_c^3}{\nu^2 Pr}, \quad (4)$$

where g is the gravitational acceleration, β — the coefficient of volume expansion, Δt — the temperature difference between surfaces of the enclosure, L_c — the characteristic length of the geometry (for a section this is the distance between the inner surfaces), ν — the kinematic viscosity of the fluid, Pr — the Prandtl number, for air regardless of temperature $Pr = 0.71$ [6].

In order to determine the value of the Nu number for the heated package according to (4), it is necessary to have information about the Δt parameter. This knowledge has been obtained thanks to experimental research that consisted in heating packages of square 40, 60 and 80 mm sections to 700 °C in a laboratory electric chamber furnace [7]. One of the packages inside the furnace is presented in Fig. 2. During this process the temperature within chosen sections was measured with the

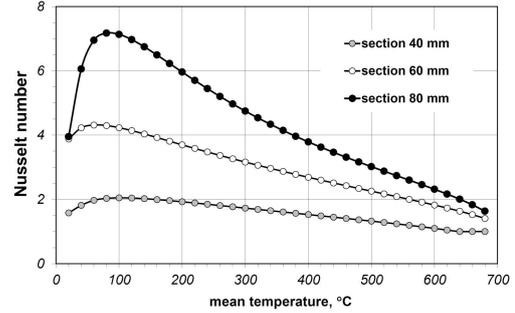


Fig. 4. The results of the Nu number calculation in the temperature function.

TABLE I

Maximum and mean Δt values for particular sections.

Section [mm]	Δt_{\max} [°C]	Δt_{mean} [°C]
40	38	25
60	53	38
80	186	137

use of sheathed thermocouples. The values of Δt have been calculated on the basis of measurement data — the changes of this parameter in the heating time function are presented in Fig. 3. As can be seen, this parameter depends fundamentally on the dimensions of a section, taking the highest values between the 20th and the 50th minute of heating. The maximum and mean values of Δt obtained for individual sections have been collated in Table I.

A description of Δt changes in the function of mean temperature of a section can be provided in further analysis using

$$\Delta t_{40} = 3.8 \times 10^{-7} t_m^3 + 1.6 \times 10^{-4} t_m^2 + 0.09 t_m - 1.25, \quad (5)$$

$$\Delta t_{60} = 3.8 \times 10^{-4} t_m^2 + 0.28 t_m - 0.04, \quad (6)$$

$$\Delta t_{80} = 8.4 \times 10^{-7} t_m^3 + 2.3 \times 10^{-3} t_m^2 + 1.3 t_m - 15.4. \quad (7)$$

Maximum temperature differences for individual sections have been noted at the following t_m values: sect. 40 mm — 460 °C, sect. 60 mm — 360 °C, sect. 80 mm — 340 °C.

The changes of kinematic viscosity of air in the t_m function have been described by [8]:

$$\nu = 6.8 \times 10^{-11} t_m^2 + 9.5 \times 10^{-8} t_m + 1.3 \times 10^{-5}. \quad (8)$$

For the given temperature range, the minimum, mean and maximum values of ν equal, respectively, 1.49×10^{-5} m²/s, 5.73×10^{-5} m²/s and 1.1×10^{-4} m²/s.

Based on the relationships (2)–(8), the calculations of the Nu number have been done. The obtained results in the t_m function are presented in Fig. 4.

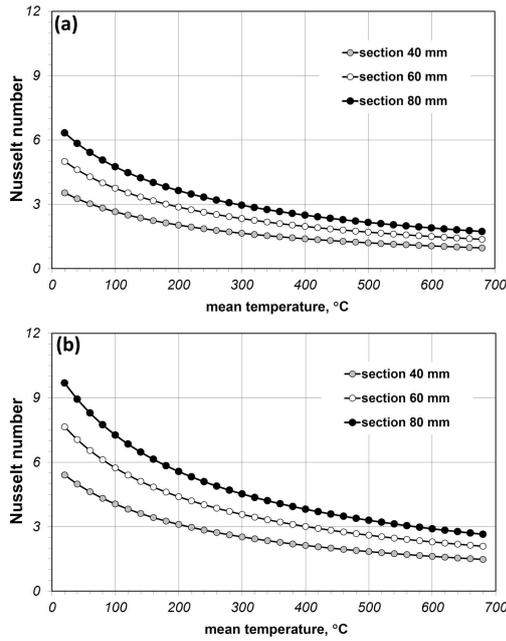


Fig. 5. The values of the Nu number obtained for constant values of the temperature difference: (a) $\Delta t = 25^\circ\text{C}$, (b) $\Delta t = 137^\circ\text{C}$.

TABLE II

Maximum and mean Nu values depending on the section inner size L_{in} .

Section [mm]	L_{in} [mm]	Nu_{max}	Nu_{mean}
40	34	2.05	1.57
60	54	4.32	2.95
80	74	7.17	4.34

As can be seen for each section the changes in the Nu number are of a very similar nature — the maximum value in each case occurs at the temperature of approximately 60–90 °C. Above this temperature a nearly linear decline of the Nu is observed. Table II collates values of the Nu number (maximum and mean for the whole temperature range) for individual sections.

The values of Nu_{max} and Nu_{mean} in the L_{in} function change linearly which can be noted in the form of

$$Nu_{max} = 12.8 L_{in} - 2.39, \quad (9)$$

$$Nu_{mean} = 6.92 L_{in} - 0.79. \quad (10)$$

In order to establish which factors determine such characteristic changes in the Nu number, further calculations have been done. First of all, calculations for constant values of Δt , equal to 25 °C and 137 °C have been done (Fig. 5a and b). In this situation the decline in the Nu value is observed within the whole temperature range. This result indicates that the initial increase of the Nu is attributable to the increase in the Δt parameter.

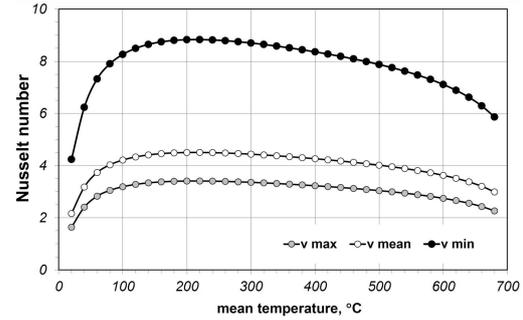


Fig. 6. The values of the Nu number for an 80 mm section obtained at constant values of the kinematic viscosity.

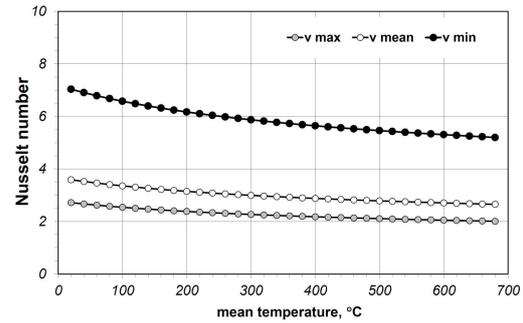


Fig. 7. The values of the Nu number for an 80 mm section obtained at constant values of the kinematic viscosity and $\Delta t = 38^\circ\text{C}$.

The following results apply to the 80 mm section and constant values of ν : the minimum, mean and maximum ones (Fig. 6). The diagram shows that viscosity changes in the temperature function are responsible for the decline of Nu which can be observed above 80 °C. The results in Fig. 7, in turn, apply to the calculations for constant ν and Δt values — they show that the decline in the Nu number is also attributable to the coefficient of thermal expansion β .

4. Conclusions

It has been established that the Nusselt number, which expresses the natural convection in the inner area of square steel sections, changes linearly in the function of the inner dimension of the section. This number reaches the maximum value at mean section temperature amounting to approximately 60–90 °C. This result is the effect of the simultaneous influence of the changes in values of the following parameters: the temperature difference within the section Δt , the kinematic viscosity ν and the coefficient of thermal expansion β . At the same time, the initial increase in the Nu is attributable to the Δt parameter. It has been established that the occurrence of natural convection depending on the size of a section increases the heat transfer within gas from 1.5 to 4.3 times upon averaging for the whole temperature range.

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