# ANALYSIS OF THE NUSSELT NUMBER FOR THE NATURAL CONVECTION IN THE PACKAGE OF SQUARE STEEL SECTIONS


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## INTRODUCTION

In industrial heat treatment of steel products, in many situations there is a need to heat a charge of a porous structure. One of the examples of such a charge are the 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. Among other things this time depends 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 the influence of all closing surfaces at the same time. 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). The experimental research conducted by the authors has shown that the Nusselt number changes in a very characteristic manner during heating of the sections. The Nu value depends on the changes in the following parameters: the dimensions of a section, the temperature distribution in a section and the thermo-physical properties of air. The paper analyses the influence of the above mentioned parameters on the values of the Nu.

*Fig. 1. A package of square steel sections*

## ANALYSIS AND MODELLING

The 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 $k_{eg}$:

$$k_{eg} = k_g Nu \qquad (1)$$

where: $k_g$ - thermal conductivity of gas, Nu – Nusselt number.

The notation of equation (1) means that the Nu number is the measure of the intensification of heat transfer caused by the occurrence of natural convection in relation to pure conduction. For natural convection of air in horizontal enclosures the following correlations are recommended:

$$Nu = 0.195\,Ra^{1/4} \quad \text{for } 10^4 < Ra < 4\times10^5 \qquad (2)$$

$$Nu = 0.068\,Ra^{1/3} \quad \text{for } 4\times10^5 < Ra < 10^7 \qquad (3)$$

The Rayleigh Ra number is defined as:

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

where: $g$ – gravitational acceleration, $\beta$ – coefficient of volume expansion, $\Delta t$ – temperature difference between surfaces of the enclosure, $L_c$ – characteristic length of the geometry (for a section this is the distance between the inner surfaces), $\nu$ – kinematic viscosity of the fluid, $Pr$ – Prandtl number, for air $Pr$ = 0.71.

In order to determine the value of the *Nu* number for the heated package according to equation (4) it is necessary to have information about the $\Delta t$ 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. One of the packages inside the furnace is presented in Fig. 2. During this process the temperature within chosen sections was measured with the use of sheathed thermocouples. The values of $\Delta t$ 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 $\Delta t$ obtained for individual sections have been collated in Table 1.

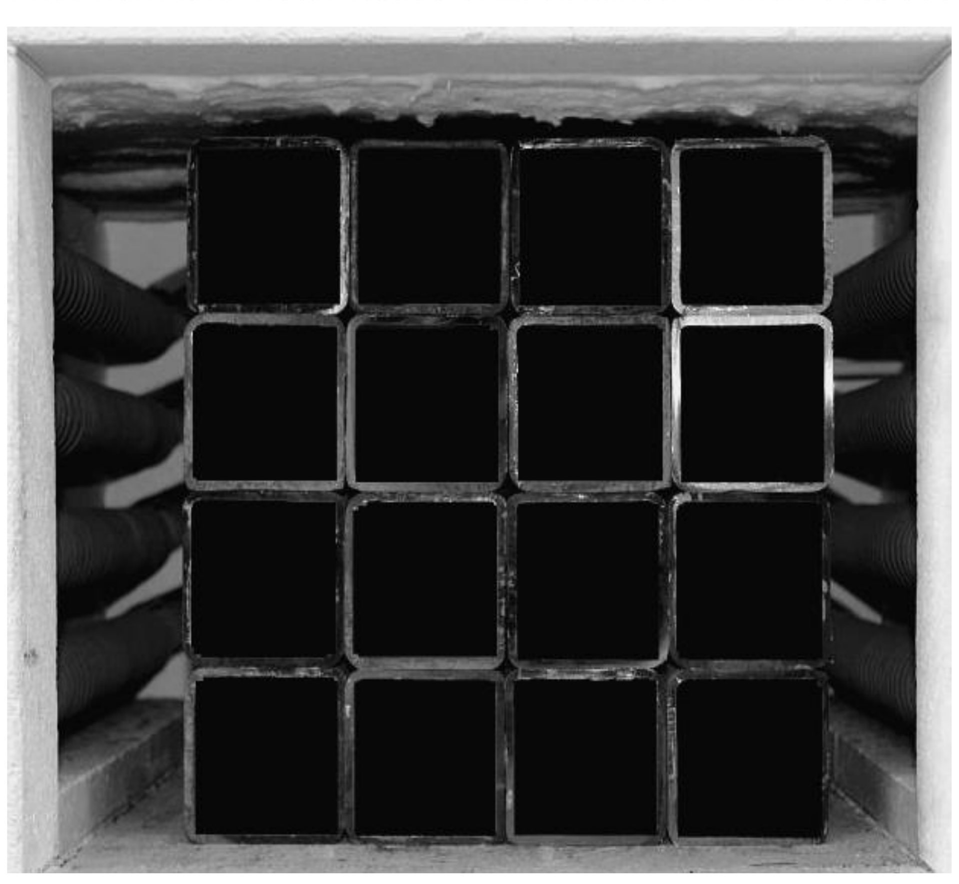

*Fig. 2. A package of 60 mm sections in the furnace chamber.*

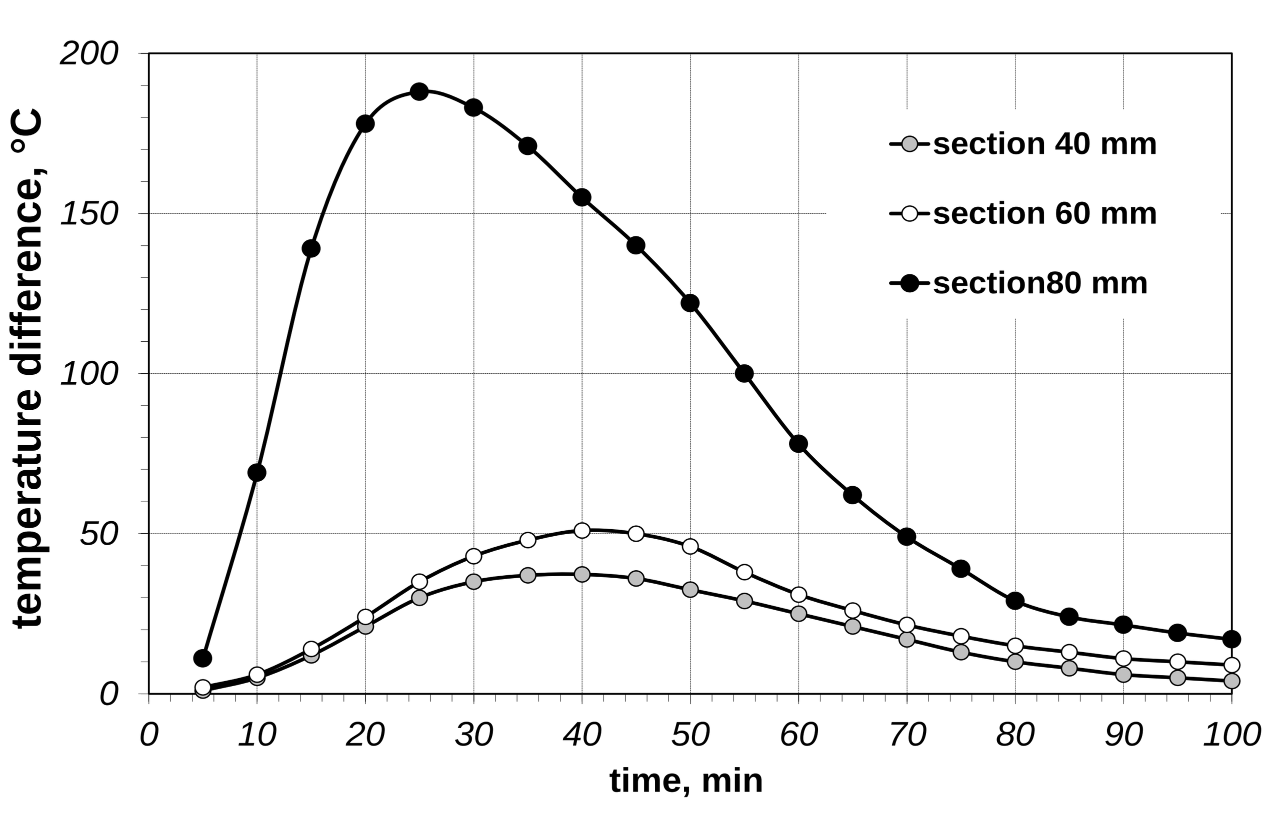


*Fig. 3. The values of $\Delta t$ parameter in the function of heating time.*

*Table 1. Maximum and mean $\Delta t$ values for particular sections.*

| section | $\Delta t_{max}$ | $\Delta t_{mean}$ |
|---|---|---|
| 40 mm | 38 | 25°C |
| 60 mm | 53 | 38°C |
| 80 mm | 186 | 137°C |

Equations describing $\Delta t$ changes in the function of mean temperature of a section have been determined for further analyses:

$$\Delta t_{40} = 3.8\cdot10^{-7}t_m^3 + 1.6\cdot10^{-4}t_m^2 + 0.09t_m - 1.25 \qquad (5)$$

$$\Delta t_{60} = 3.8\cdot10^{-4}t_m^2 + 0.28t_m - 0.04 \qquad (6)$$

$$\Delta t_{80} = 8.4\cdot10^{-7}t_m^3 + 2.3\cdot10^{-3}t_m^2 + 1.3t_m - 15.4 \qquad (7)$$

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. 40 mm – 340°C.

The changes of kinematic viscosity of air in the $t_m$ function have been described by equation:

$$\nu = 6.8\cdot10^{-11}t_m^2 + 9.5\cdot10^{-8}t_m + 1.3\cdot10^{-5} \qquad (8)$$

For the given temperature range, the minimum, mean and maximum value of $\nu$ equal respectively: $1.49\times10^{-5}$ m²/s, $5.73\times10^{-5}$ m²/s and $1.1\times10^{-4}$ 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.

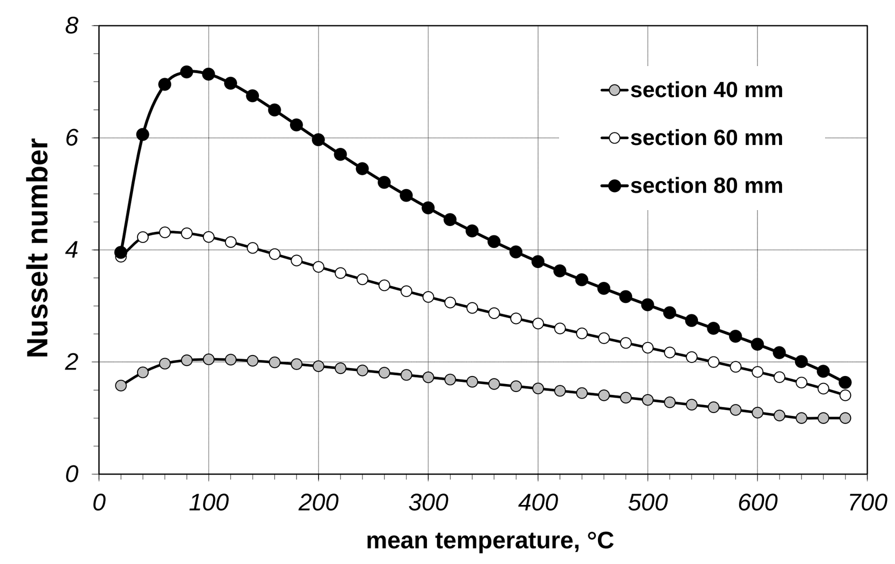


*Fig.4. The results of the Nu number calculation in the temperature function.*

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 70-80°C. Above this temperature a nearly linear decline of the *Nu* is observed. Table 2 collates values of the *Nu* number (maximum and mean for the whole temperature range) for individual sections.

*Table 1. Maximum and mean $\Delta t$ values for particular sections.*

| section | $Nu_{max}$ | $Nu_{mean}$ |
|---|---|---|
| 40 mm (34 mm) | 2.05 | 1.57 |
| 60 mm (54 mm) | 4.32 | 2.95 |
| 80 mm (74 mm) | 7.17 | 4.34 |

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

$$Nu_{max} = 12{,}8\,L_{in} - 2.39 \qquad (9)$$

$$Nu_{mean} = 6.92\,L_{in} - 0.79 \qquad (10)$$

In order to establish which factors determine such characteristic changes in the *Nu* further calculations have been done. First of all calculations for constant values of $\Delta t$, equal to 25°C and 137°C have been done (Figs. 5a and 5b). 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 $\Delta t$ parameter. The following results apply to the 80 mm section and constant values of $\nu$: the minimum, mean and maximum (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 $\nu$ and $\Delta t$ values – they show that the decline in the *Nu* is also attributable to the coefficient of thermal expansion $\beta$.

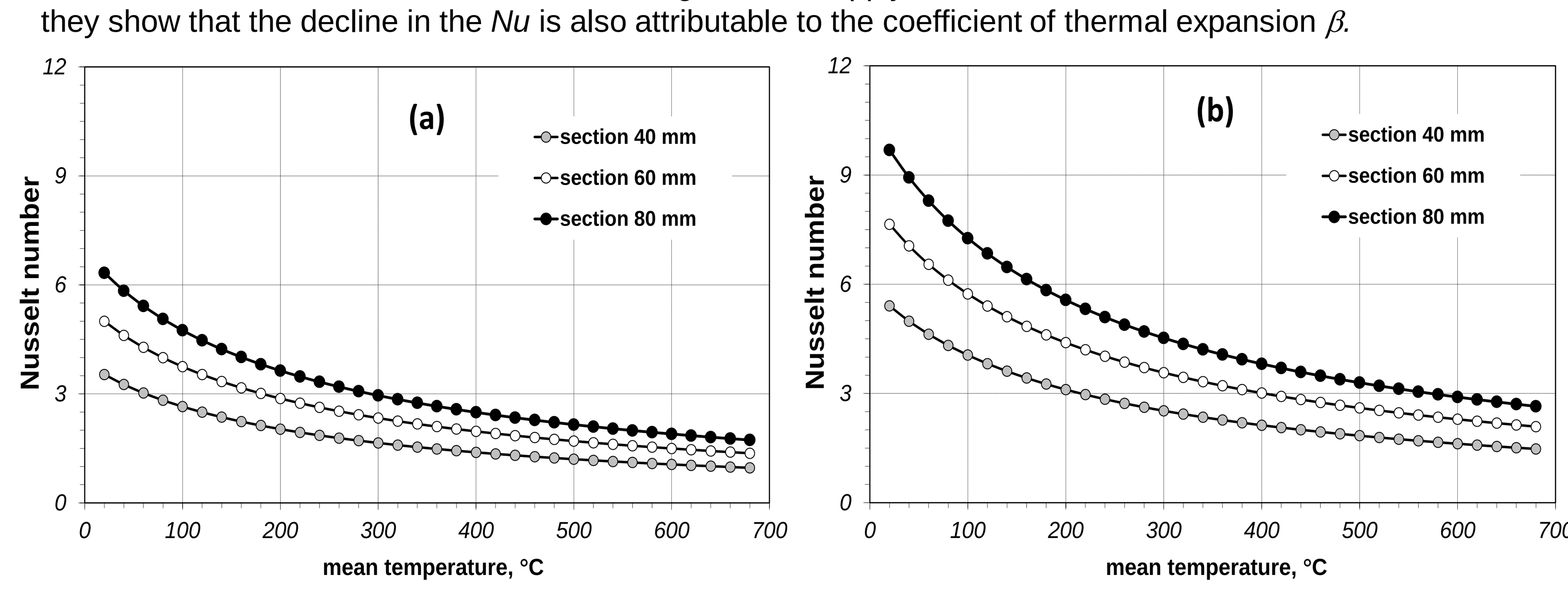


*Fig.5. The values of the Nu number obtained for constant values of the temperature difference: (a) $\Delta t$ = 25°C, (b) $\Delta t$ = 137°C.*

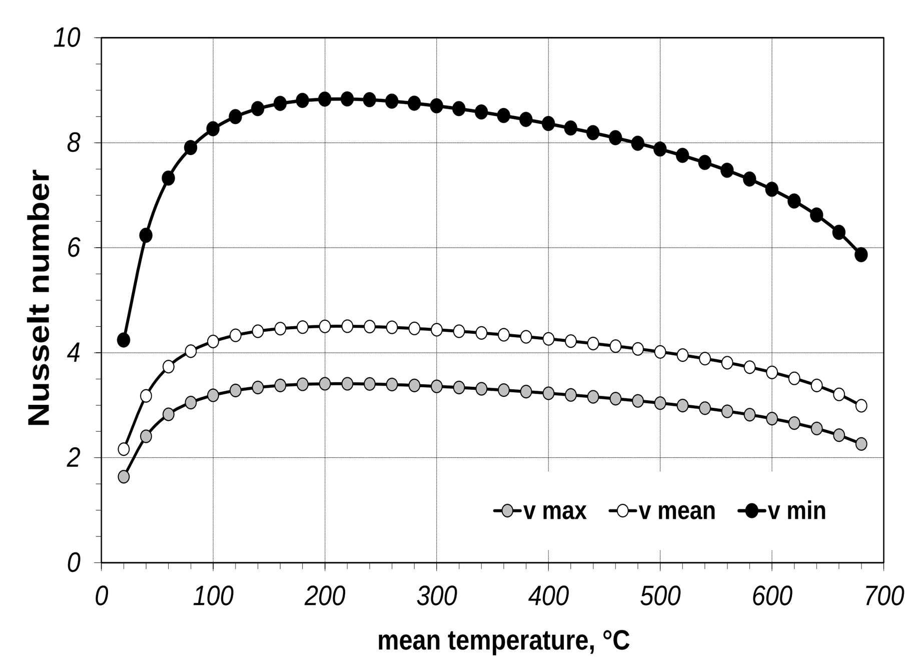


*Fig.6. The Nu number for an 80 mm section obtained at constant kinematic viscosity.*

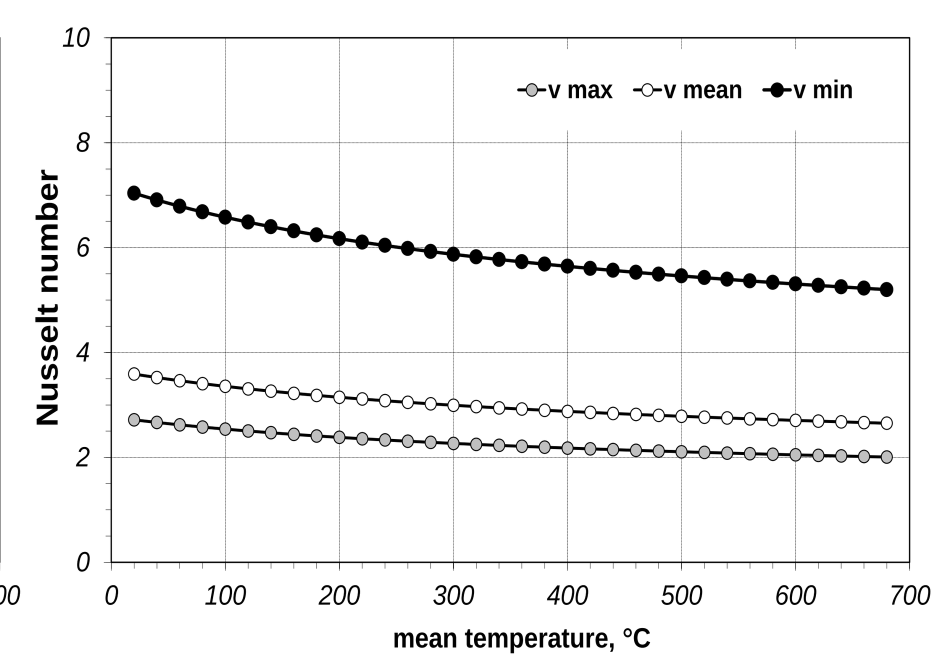


*Fig.7. Nu number for an 80 mm section obtained at constant kinematic viscosity and $\Delta t$ = 38°C.*

## 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 $\Delta t$, the kinematic viscosity coefficient $\nu$ and the coefficient of thermal expansion $\beta$. At the same time the initial increase in the *Nu* is attributable to the $\Delta t$ 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.