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THE EXPERIMENTAL STUDY OF THE EFFECTIVE THERMAL CONDUCTIVITY OF BUNDLES OF RECTANGULAR STEEL SECTIONS

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Abstract

Bundles of rectangular steel sections are examples of the porous charge. Due to the voids within the sections, this type of charge is characterized by porosity even exceeding 85%. This makes the thermal properties of these elements, expressed by the effective thermal conductivity k_{ef}, totally different from the thermal conductivity of steel. The value of the k_{ef} coefficient depends on many factors such as: the ratio of the thermal conductivity of steel to that of gas, the structure of the solid matrix and its porosity and the lack of the continuity of the steel phase. The paper describes experimental investigations concerning the measurements of the effective thermal conductivity of a steel sections bundles.

Keywords: effective thermal conductivity, steel sections bundles, heat treatment, guarded hot plate apparatus

1. INTRODUCTION

Steel continues to be the basic construction material, whereby it plays a key role for the growth of the world's economy. More than 80% of its production is processed by plastic working methods, as a result of which sheets and various types of long elements are obtained [5]. Rolled products are required to have high dimensional accuracy, appropriate surface roughness and specified microstructure and mechanical properties. The purchasers of rolled products are

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actually from all sectors of the economy and these products are mostly used for further processing.

In many cases the purchasers require the products supplied to them to have specific mechanical properties. This requires to provide an appropriate microstructure which is achieved by means of the heat treatment [10]. On a mass production scale the heat treatment of long elements is carried out in continuous furnaces on modern technological lines. In view of the optimal use of the heating space of those furnaces and transfer-related considerations, elements to be heated are introduced to the furnace in the form of bundles [8]. A special type of porous charge in the form of bundles is found in the heat treatment of rectangular sections. Examples of such bundles are shown in Fig. 1. Empty spaces which occur inside individual sections that form the bundle, can be treated as the pores. While heated in the furnace they are filled with gas that forms a furnace atmosphere. Therefore, this type of charge can be treated as a diphase porous medium.

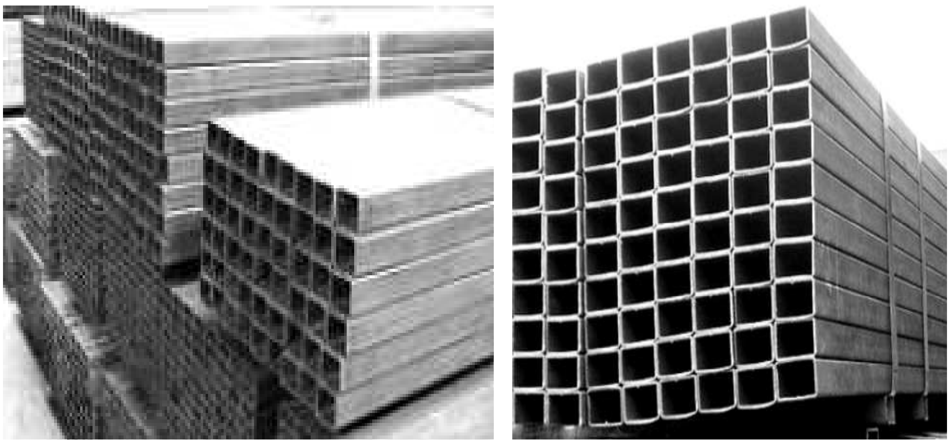

Fig. 1. Examples of bundles formed from rectangular sections

Operations needed for heating metal during the heat treatment can significantly affect variety of factors related to the entire production cycle. The most important among these factors are: production efficiency, energy consumption, pollutant emission and the quality of the final products. For these reasons it is important to achieve precise and continuous monitoring of process parameters related to the course of charge heating processes. Determination of the heating curve and the heating time of the charge allows to acquire a desirable quality of the final product at the same time minimizing the cost of its production. For this purpose, to control above parameters on the modern production lines there are used numerical algorithms which model the complex phenomena occurring in the system furnace-charge-time [4, 7]. One of the conditions which make such algorithms unique are thermal properties of heated elements [11]. For the selection of the optimal parameters for heating, the knowledge of the thermal properties of the heat treated components is needed. Incorrect selection of these parameters can lead to improper charge heating, disturb operation of the furnace and unnecessarily increase the heating time.

2. THERMAL PROPERIIES OF SECTIONS BUNDLES

The basic thermal properties of the heated elements include: thermal conductivity k, specific heat c_p and the density ρ [11]. The most important of these three values is the thermal conductivity. Due to anisotropy of geometrical structure this quantity in different directions obtain very different values.
Heat treated bundles of rectangular sections usually have a length of 3÷6 m, and the transverse dimensions do not exceed 1 m. The ratio of these dimensions causes that the process of the charge heating is determined by heat flow phenomena occurring in the transverse direction of the bundle. Due to the lack of continuity in the metallic phase, the bundles in this direction should be treated as a porous medium with a granular structure. The ability of the heat transfer by such mediums is expressed by the effective thermal conductivity k_{ef} [6, 1]. In contrast to the thermal conductivity of solid materials k_s, the value of k_{ef} parameter is not a material quantity. It only quantitatively defines the ability of the bundles to transfer heat. The k_{ef} coefficient is a function of complex heat transfer mechanisms related to conduction, convection and radiation, which occur within the space of bundles in transverse direction.
The most reliable information about the value of the coefficient k_{ef} provides measurements realized on an adequate sample of the test medium. This article presents the results of measurements of the effective thermal conductivity of flat beds made for different types of flat rectangular steel sections. From the point of view of the geometrical structure, such beds correspond to the sections bundles.

3. METHODOLOGY OF MEASUREMENTS

For the measurements performed in accordance with standard steady state methods in plate apparatus, the effective thermal conductivity is defined as follows [2]:

$$k_{ef} = \frac{q \cdot h}{\Delta t} \qquad (3.1)$$

where: q - heat flux flowing through a sample of the test material, W/m^2; h - dimension of the sample in the direction of heat flow, m; Δt - temperature difference of the outside sample surfaces, perpendicular to the heat flow, K.

The idea of the effective thermal conductivity measurement by the aforementioned method in relation to the flat bed of rectangular sections is shown in fig. 2. According to equation (3.1), the measurement procedure involves forcing an unidirectional steady heat flow, which is expressed quantitatively by heat flux q, in the tested sample. The direction of this flow should be perpendicular to the main surfaces of the bed - the bottom surface (hot surface) which has temperature t_B and the upper surface (cold surface) which has temperature t_U. In order to minimize the heat flow in the side directions, the lateral dimensions of the sample should be many times bigger than its height. After having obtained a steady state in the system, the temperature measurements are made. The value of Δt parameter is calculated as the difference in the temperature of hot surface t_B and the temperature of cold surfaces t_U.

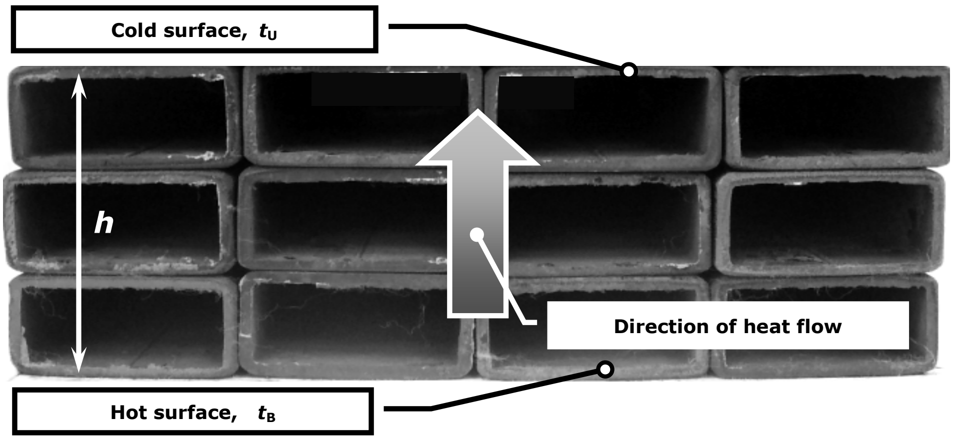

Fig. 2. The idea of the effective thermal conductivity measurement in relation to the flat bed formed from rectangular sections

4. EXPERIMENTAL SET-UP

Measurements of the effective thermal conductivity were performed on a laboratory stand, which had been specially constructed for this purpose. This stand operates on the guarded hot plate apparatus principle [2], and consists of the following components: a heating chamber, autotransformer, the sample temperature measurement system and the control system. A general view of the stand is illustrated in Fig. 3.

The heating chamber (1), which is the main component of the stand is the electric furnace. Its functioning provides required boundary conditions in the test samples. It consists of the following components: steel retort, cover plate, a set of the electric heaters, insulation and steel supporting structure. The retort of the heating chamber is a steel rectangular box with internal dimensions of the base 400×400 mm and a height of 200 mm. It is made from steel sheets with a thickness of 10 mm. The interior of the retort forms a measuring space inside which the test specimens are placed.

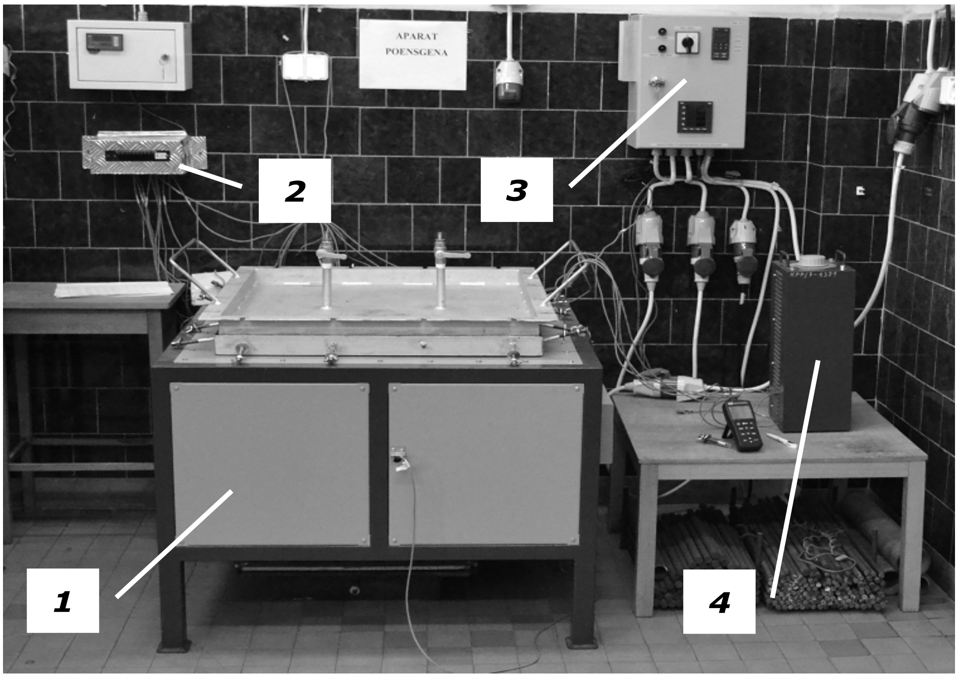

Fig. 3. General view of the measuring stand: 1 - heating chamber, 2 - autotransformer, 3 - sample temperature measurement system, 4 - control system

Under the bottom of the retort there are placed two electric heaters (main heater and the guarded heater). Nominal power of each heater is 4 kW. Construction and mutual positioning of both heaters causes that in the area of the tested samples one-dimensional temperature field is obtained. To the minimization of the unwanted heat losses from the side surfaces of the heaters and the retort, the furnace walls are insulated with a heat-resistant fabric.

To measure the temperature on the surfaces of the samples a separate measuring system (2) was used. It consisted of a K - type jacket thermocouples with an

outer diameter of 0,5 mm, electronic switch of measuring points and microprocessor thermometer EMT-200 [12]. The described system allowed to carry out simultaneous measurements of temperatures in ten points, with a resolution of 0,1°C. Temperatures on the surface of each sample was measured at five mutually opposite points. On the bottom surface there are the points *B1-B5* in which the temperatures t_{B1}-t_{B5} have been measured. On the upper surface there are the points *U1-U5* which correspond the temperatures t_{U1}-t_{U5}.
Heat flux which flows through the sample q was determined by measuring the power received by the main heater. It was possible because this heater is a resistive device. This type of heaters are characterized by 100% efficiency, which means that the whole electricity supplied to them is converted into heat [3]. In addition, it is required that all the heat generated by the main heater must flow toward the sample placed on them. Achieving this effect would provide a guarded heater. Both heaters were separated from each other by a 30 mm-thick ceramic plate. During the operation of the stand the temperatures were measured on the opposite surfaces of the heaters. The control system (3) controled the power of the guarded heater, so that for constant value of the power supplied to the main heater N the temperatures on the surfaces of both heaters were the same. When this condition is obtained, between the heaters the heat does not flow. This means that the whole heat emitted by the main heater flows in the direction of the tested sample. Thus, the heat flux q in the sample can be calculated by dividing the power of the main heater and its surface area A:

$$q = \frac{N}{A} = \frac{N}{0{,}36} \tag{4.1}$$

From the point of view of the heat treatment, it is needed to know the k_{ef} coefficient of the bundles throughout the whole range of temperatures of the process. This is the range from ambient temperature up to about 700°C. Described stand allowed conducting the test in the temperature range between 50° and 600°C. The measurements were performed for ten different values of the average temperature of samples t_m. This value was determined as the average with temperatures of hot and cold surfaces. Changes in temperature t_m were realized by adjusting the current supplied to the main heater. This was allowed by the autotransformer (4), which was plugged into the supply system of the main heater. Setting values of power supply used in the tests and the corresponding values of the heat flux q and average samples temperatures t_m are summarized in Table 1.

Table 1. Process parameters used during the tests

Power of main heater *N*, W	Heat flux *q*, W/m^2	Sample average temperature t_m, °C
200	555	70
400	1111	130
600	1667	190
800	2222	230
1000	2778	280
1300	3611	340
1600	4444	400
2000	5555	470
2400	6667	540
2800	7778	590

5. RESULTS OF MEASUREMENTS

During the tests 9 different samples were investigated. They were made of four different types of sections which have following dimensions: 20×40 mm (3 samples), 40×40 mm (2 samples), 60×60 mm (2 samples) and 80×80 mm (2 samples). Sections 40×20 mm had 2 mm-thick walls while for the rest of the sections the thickness of the walls made 3 mm.

After placing the sample in the heating chamber and attaching thermocouples to its surface a heating chamber was closed with the top cover. Then the heating system was started by adjusting the position of the initial power output of the main heater to 200 v. The measurements of temperature on the surface of the sample were made after a steady state in the system had been reached. Because of the large mass of the heating chamber as well as the test samples this state was reached after 24 hours of heating. After reaching the temperature t_{B1}- t_{B5} and t_{U1}-t_{U5}, the heating power was increased to the next value (Table 1) and the whole procedure was repeated. This means that the full series of the measurements for each sample, in which the stand was continuously operating, lasted for ten days.

The measurement results are shown in graphs (Fig. 4÷7). Each graph is made for the samples with different kinds of sections. Samples on the graphs were denoted by roman numerals indicating the order of the sample and Arabic numerals indicating the kind of sections. As it can be seen, the results of measurements depend on the types of the sections. This means that the size of the section determines the change in the intensity of various types of heat transfer occurring within the inner area of the individual section. This is primarily a gas free convection and radiation. Internal dimensions of the section affect the intensity of these phenomena.

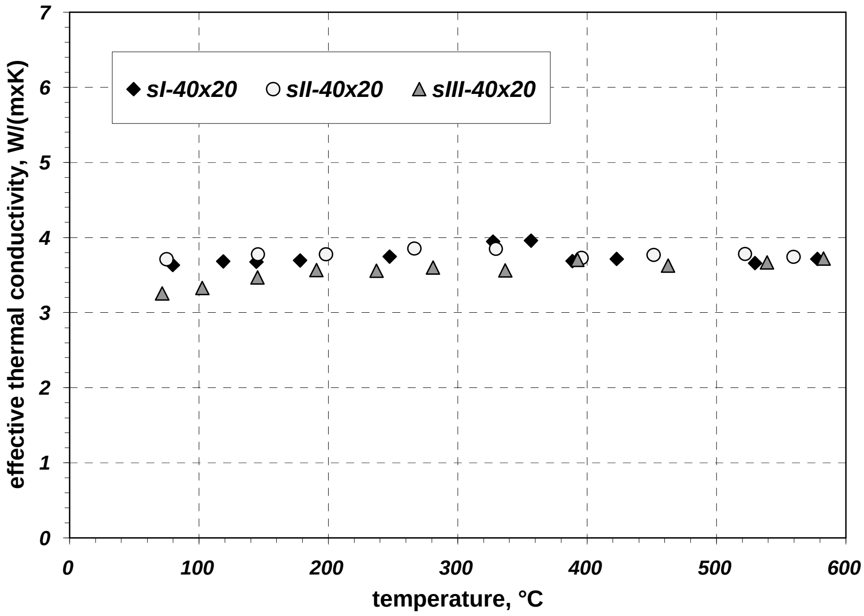

Fig. 4. The effective thermal conductivity of the 20×40 mm sections beds

For a more detailed analysis, regression functions were determined for each sample These functions, which are listed in Table 2, describe the value of the k_{ef} coefficient depending on the temperature. For the most samples this are linear functions. For the three samples, one of the 60×60 mm sections and both of the 80×80 mm sections, this are the polynomials of the second degree. However, the dependence of the temperature coefficient k_{ef} of these samples were described additionally by linear functions.

As it can be seen from the analysis of the graphs, the effective conductivity of the samples increases with increasing the transverse dimensions of the section. This mainly affects the height of the sections. The higher is a particular section the less is the interface between the successive layers of the sections on the length of the bed. On these surfaces there occurs the greatest resistance to the heat transfer in the section bed or bundle. The effective thermal conductivity, because of its unit (W/(m·K)) is referred to the length on which the heat flow occurs. Thus, the less interfaces are on this length greater is the thermal conductivity of the medium.

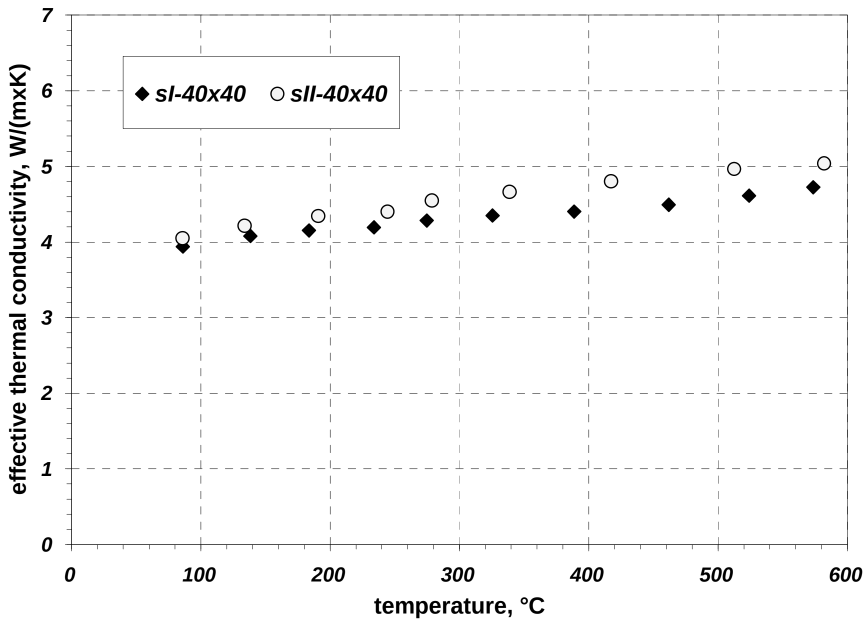

Fig. 5. The effective thermal conductivity of the 40×40 mm sections beds

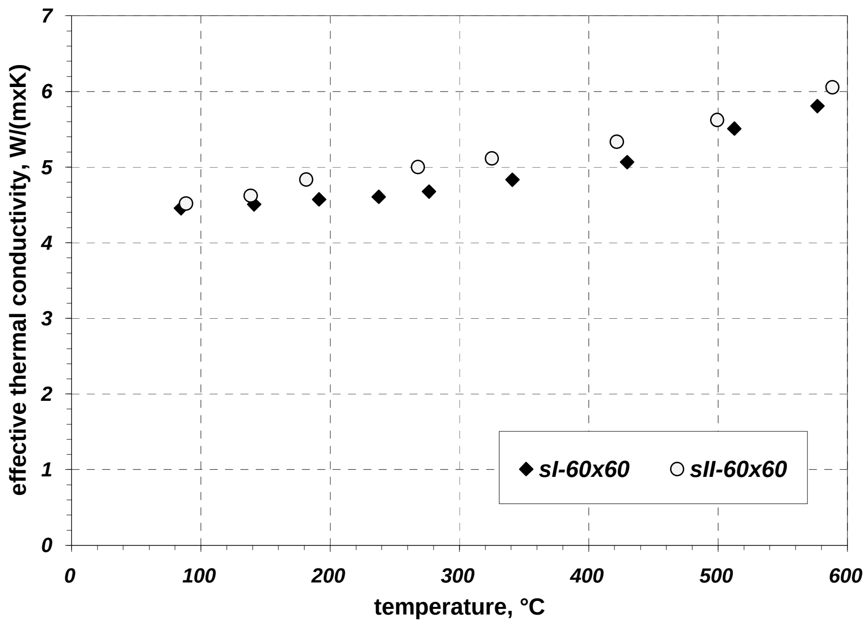

Fig. 6. The effective thermal conductivity of the 60×60 mm sections beds

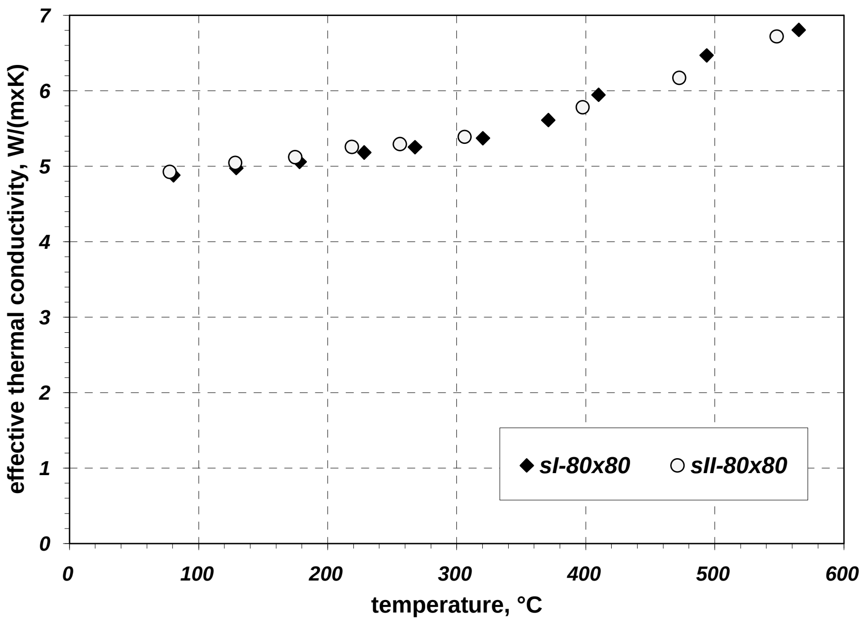

Fig. 7. The effective thermal conductivity of the 80×80 mm sections beds

In the lower temperature range (approximately 50°C), the effective thermal conductivity of the samples were as follows:

- section 40×20 mm - 3,2÷3,7 W/(m·K);
- section 40×40 mm - 3,9÷4,1 W/(m·K);
- section 60×60 mm - about 4,5 W/(m·K);
- section 80×80 mm - about 4,9 W/(m·K).

The growth dynamics of k_{ef} values as a function of temperature for the particular samples indicate the inclination of the graph and the corresponding slope coefficient of the linear equation. The larger dimension of the section of the test sample, the greater is the value of this coefficient (Table 2). As it has been already mentioned, the increase in the effective thermal conductivity of the tested beds correspond to the phenomenon of natural convection and thermal radiation occurring in the internal areas of the sections. However, the mentioned problem is not the topic of this article.

Table 2. Regression functions of coefficient k_{ef} for tested samples

Profiles	Sample	Function
40 × 20	sI-40×20	$k_{ef} = 0{,}0001 \cdot t + 3{,}699$
	sII-40×20	$k_{ef} = 3{,}775$
	sIII-40×20	$k_{ef} = 0{,}0007 \cdot t + 3{,}362$
40 × 40	sI-40×40	$k_{ef} = 0{,}0015 \cdot t + 3{,}856$
	sII-40×40	$k_{ef} = 0{,}0020 \cdot t + 3{,}944$
60 × 60	sI-60×60	$k_{ef} = 6 \cdot 10^{-6} \cdot t^2 - 0{,}001 \cdot t + 4{,}530$
		$k_{ef} = 0{,}0027 \cdot t + 4{,}049$
	sII-60×60	$k_{ef} = 0{,}0029 \cdot t + 4{,}236$
80 × 80	sI-80×80	$k_{ef} = 7 \cdot 10^{-6} \cdot t^2 - 0{,}0006 \cdot t + 4{,}904$
		$k_{ef} = 0{,}004 \cdot t + 4{,}335$
	sII-80×80	$k_{ef} = 7 \cdot 10^{-6} \cdot t^2 - 0{,}0005 \cdot t + 4{,}986$
		$k_{ef} = 0{,}0036 \cdot t + 4{,}488$

On the other hand, in the upper temperature range (600 °C), the effective thermal conductivity of the test samples were as follows:

- sections 40×20 mm - około 3,7 W/(m·K);
- sections 40×40 mm - 4,6÷5,1 W/(m·K);
- sections 60×60 mm - 5,7÷6,1 W/(m·K);
- sections 80×80 mm - about 6,7 W/(m·K).

For the samples of the 40×20 mm sections, the effective thermal conductivity practically does not change with temperature. The observed fluctuations of the coefficient k_{ef} for each samples are less than 0,5 W/(m·K). At this level for the modelling of sections bundles heating variations of the coefficient k_{ef} do not have a major impact on the final calculation results. In the case of modeling of the bundle heating, which are made from larger sections, the changes of the effective thermal conductivity with temperature should be taken into account.

In the conducted analysis, it is important to know to what degree the effective thermal conductivity of the samples differs from the thermal conductivity of the steel from which the sections are made. This discrepancy can be expressed by the reduced conductivity K_r, which is the quotient of the effective thermal conductivity of the sample k_{ef} and the thermal conductivity of the steel k_s:

$$K_r = \frac{k_{ef}}{k_s} \tag{5.1}$$

The tested beds were made from sections of low-carbon steel with a carbon content of 0,2%. Based on the literature data for this kind of steel there was determined a regression function which describes the temperature dependence of the thermal conductivity [9]. This function was assigned for the temperature range of 0÷700°C [9], and has the following form:

$$k_s = -0{,}0229 \cdot t + 50{,}92 \tag{5.2}$$

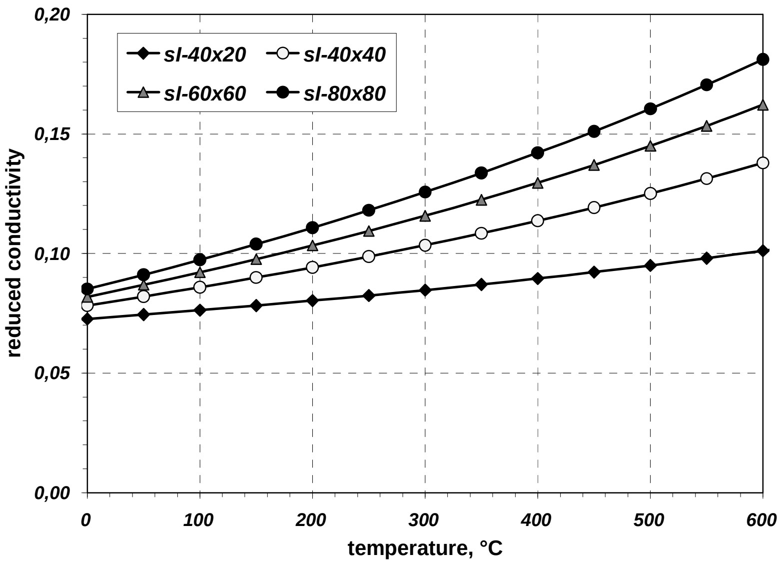

Fig. 8. Reduced conductivity of the selected samples

Changes in the values of the reduced conductivity in the temperature range of 0÷600°C for the selected samples are shown in Fig. 8. Reduced conductivity for the analyzed samples in the lower temperature range are from 0,07 to 0,085. However, in the upper temperature range the value of this parameter varies from 0,1 to 0,18. This means that for the considered range of temperatures the effective thermal conductivity of the test beds does not exceed 0,2 of the thermal conductivity of the steel from which these sections are made.

6. SUMMARY

This paper presents experimental studies devoted to the measurements of the effective thermal conductivity of the bundles formed from rectangular steel sections. It has been shown that the thermal properties of these elements, expressed by the effective thermal conductivity are completely different from the thermal properties of steel. Furthermore, the effective thermal conductivity of the samples increases with temperature, while the thermal conductivity of steel in this situation is reduced.

Obtained results will be used for quantitative and qualitative analysis of the phenomenon of transient heat transfer which occurs during heating of this type of charge. This analysis will be the basis to develop a mathematical model of this phenomenon. This model will be used for the analytical determination of the effective thermal conductivity of the sections bundles of any size.

REFERENCES

1. Cheng P., Hsu C. T.: *Heat conduction, in: Ingham D. B., Pop I.: Transport Phenomena in Porous Media*, Oxford, Pergamon Press, Elsevier Science 1998.
2. Furmański P., Wiśniewski T. S., Banaszek J.: *Izolacje cieplne - mechanizmy wymiany ciepła, własności cieplne i ich pomiary*, Warszawa, Wydawnictwo Politechniki Warszawskiej 2006.
3. Hering M.: *Podstawy elektrotermii*, Warszawa, WNT 1992.
4. Jaluria Y.: *Numerical simulation of the transport process in a heat treatment furnace*. International Journal for Numerical Methods in Engineering, 25 (1988) 387-399.
5. Kajzer S., Kozik R., Wusatowski R.: *Walcowanie wyrobów długich, technologie walcownicze*. Gliwice, Wydawnictwo Politechniki Śląskiej 2004.
6. Kaviany, M.: *Principles of Heat Transfer in Porous Media*, 2nd edition, New York, Springer 1995.
7. Rao T. R., Barth G. J., Miller J. R.: *Computer model prediction of heating, soaking and cooking times in batch coil annealing*. Iron and Steel Engineering, **60**, 9 (1983) 22-33.
8. Sahay S. S., Krishman K.: *Model based optimisation of continuous annealing operation for bundle of packed rods*, Iron and Steelmaking, **34**, 1, (2007) 89-94.
9. Senkara T.: *Obliczenia cieplne pieców grzewczych w hutnictwie*, Katowice, Wyd. Śląsk 1981.

10. *Steel Heat Treatment Handbook. Metallurgy and Technologies*. Edited by Totten G.E., CRS Taylor & Francis Group, 2006.
11. Wiśniewski S., Wiśniewski S. T.: *Wymiana ciepła*. Warszawa, WNT 2012.
12. www.czaki.pl.

BADANIA EKSPERYMENTALNE EFEKTYWNEJ PRZEWODNOŚCI CIEPLNEJ WIĄZEK STALOWYCH PROFILI PROSTOKĄTNYCH

S t r e s z c z e n i e

Stalowe wyroby długie takie jak pręty, rury, profile czy różnego typu kształtowniki, podczas obróbki cieplnej nagrzewa się w postaci wiązek. Z punktu widzenia struktury wewnętrznej wsady tego typu, są niejednorodnym ośrodkiem porowatym. Cecha ta sprawia, że własności cieplne tych wsadów, wyrażane za pomocą efektywnej przewodności cieplnej k_{ef} są zupełnie odmienne od własności cieplnych samej stali. Wiedza na temat kształtowania się wartości współczynnika kef obrabianych cieplnie wiązek, jest istotna z punktu widzenia doboru optymalnych parametrów nagrzewania. W artykule przedstawiono wyniki pomiarów współczynnika k_{ef} wykonane dla próbek w postaci płaskich złóż stalowych profili prostokątnych. Badane złoża wykonano z czterech typów profili: 40×20 mm, 40×40 mm, 60×60 mm i 80×80 mm. Pomiary przeprowadzono według metody stanu ustalonego na stanowisku laboratoryjnym działającym na zasadzie jednopłytowego aparatu Poensgena. Wykazano iż badany parametr (oprócz próbek wykonanych z profili 40×20 mm) rośnie w funkcji temperatury. Ponadto jego wartość jest tym większa im większy jest rozmiar profilu tworzącego daną próbkę. Wartości bezwzględne efektywnej przewodności cieplnej badanych próbek, w zależności od temperatury i rodzaju profili, wynosiły od 3,2 do 6,8 W/(m·K). Wartości te stanowią od 0,8 do 0,18 przewodności cieplnej stali z których wykonano profile. Zaprezentowane badania, stanowią jeden z elementów prac prowadzonych przez autorów nad optymalizacją parametrów technologicznych procesów nagrzewania wiązek różnego typu elementów długich, związanych z ich obróbką cieplną.

Słowa kluczowe: efektywna przewodność cieplna, stalowe profile prostokatne, obróbka cieplna, aparat płytowy

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