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R. WYCZÓŁKOWSKI*,#, C. KOLMASIAK*, D. URBANIAK**, T. WYLECIAŁ*

USE OF THE SCHLIEREN METHOD TO THE CONVECTION ANALYSIS IN THE STEEL CHARGE OF MIXED POROSITY

WYKORZYSTANIE METODY SCHLIERENA DO ANALIZY ZJAWISKA KONWEKCJI W PRZYPADKU WSADU STALOWEGO O POROWATOŚCI MIESZANEJ

The paper presents experimental studies devoted to the convection phenomenon within the steel charge of mixed porosity. Such charges constitute bundles of hollow long elements such as pipes or rectangular sections which are heat treated. A significant portion of the gas phase in the volume of the charge makes that natural convection of the gas occurring within the individual elements may have an effect on the course of heating. To the tests the Schlieren method was used which is one of the optical visualization methods applied to the analysis of the flow phenomena in the transparent and non luminous media such as air or water. The tested samples have the form of porous charge beds made from pipes and rectangular profiles. During the experiments the samples were heating up for the constant heat flux rate. The direction of flux was vertical, from the bottom to the top.

Keywords: porous charge, free convection, Schlieren method, effective thermal conductivity, heat treatment

W artykule przedstawiono badania eksperymentalne poświęcone analizie zjawiska konwekcji w obrębie wsadu stalowego o porowatości mieszanej. Wsad taki stanowią obrabiane cieplnie wiązki pustych elementów długich, takich jak rur czy profili prostokątnych. Znaczny udział fazy gazowej w objętości tego wsadu powoduje, iż na przebieg nagrzewania może wpływać konwekcja swobodna gazu zachodząca wewnątrz poszczególnych elementów. Do badań zastosowano metodę Schlierena, która jest jedną z optycznych metod wizualizacji stosowanych do analizy zjawisk przepływowych w ośrodkach przeźroczystych i nieświecących, takich jak powietrze czy woda. Badanymi próbkami były złoża wsadu porowatego zbudowane z rur oraz profili prostokątnych. Proces obserwowano przy nagrzewaniu próbek, skierowanym pionowo w górę strumieniem ciepła o stałej wartości.

1. Introduction

Steel pipes and rectangular profiles heated during heat treatment in bundles, due to the geometrical structure, constitute a specific group of porous charge [1]. Basic and yet distinctive feature of this type of charge is significant porosity, associated with considerable participation of the gas phase. This is shown in Figure 1, depicting a view of the pipe and rectangular profile bundles. The solid phase occupies only a small part of the volume of the bundles. The total porosity of the charge being discussed can be divided into external and internal. Therefore, it can be seen that it is a charge of mixed porosity. The external porosity is associated with the occurrence of voids between the individual elements forming the bundle. The share of the porosity largely depends on the shape of elements themselves. Moreover, it is dependent on the method of arrangement of the elements in the bundle that determines the degree of its packing. The external porosity of the packed bundles of rectangular profiles is in the range of 1÷2%, and results from the existence of narrow gaps between the adjacent profiles which existence is a consequence of the lack of their straightness. For packed bundles of pipes this parameter is approximately 21%. For bundles of lesser compaction external porosity can exceed 30%. In turn, the internal porosity of those type of bundles of pipes or profiles is constant as it depends only on the ratio of the internal volume of the elements to their total volume. For thin-walled components the value of internal porosity exceeds even 85% [2].

* CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF PRODUCTION ENGINEERING AND MATERIALS TECHNOLOGY, 19 ARMII KRAJOWEJ AV., 42-200 CZESTOCHOWA, POLAND

** CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF MECHANICAL ENGINEERING AND COMPUTER SCIENCE, 21 ARMII KRAJOWEJ AV., 42-200 CZESTOCHOWA, POLAND

Corresponding author: rwyczolkowski@wip.pcz.pl

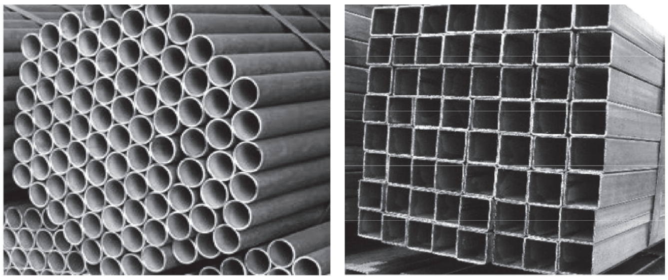

Fig. 1. The bundles of pipes and rectangular profiles as examples of the charge of mixed porosity

A significant share of the gas phase causes so one of the phenomena that affect the intensity of heating of the charge during their heat treatment is natural convection occurring in the gas inside the individual elements. For this reason the knowledge of the course of this phenomenon is significant in the context of design and operation control of heat treatment.

The experimental studies whose aim was to analyze the phenomenon of convection inside the rectangular profiles and pipes are presented in article. The subject of research was a one-dimensional heating process of the charge by heat flux pointing upwards vertically. The Schlieren method was used in the study. It is one of the optical visualization methods of the process consisting in interaction of light emitted from a foreign source to the test medium.

2. General characteristics of the Schlieren method

Despite the intensive development of modern research methods in the field of fluid mechanics and heat transfer such as numerical modeling and thermography, techniques associated with optical visualization are still widely used. This is due to the fact that many studies related to fluid mechanics apply transparent and non luminous media. This means that without the introduction of a proper marker (e.g. a smoke into the air or dye into water), it is not possible to observe directly the flow phenomena at these media. In such cases, however, the optical visualization methods are applicable. These methods make use the effect of changes in the density of overexposed medium on the value of the refractive index. [3, 4]. These methods relatively easily allow to obtain a lot of relevant information on the flow field that can be used to analyze the physics of the phenomenon. There are three basic methods of optical visualization: shadowgraph, Schlieren and interference [5, 6]. The Schlieren method has a special role because it shows a natural, easy to interpret the image of the field of the refractive index gradient. Simultaneously it is more sensitive than the shadow method and at the same it is better to qualitative visualizations than the interference method.

The Schlieren method relies on the angular deflection of light rays passing through the transparent fluid that is characterized by the inhomogeneity of the index of refraction *n*. The gradients of the *n* index are caused by inhomogeneity of temperature, density or concentration of the various components. Devices using above-mentioned phenomenon to the visualization of the inhomogeneity of the medium are called the Schlieren apparatuses. The study of natural convection makes use of the effect of fluid density inhomogeneity caused by varying temperature field on the propagation of light [6]. The changes in light intensity after passing through the test space, as visualized by the Schlieren system, are proportional to the first derivative of the fluid density [7]:

$$\frac{\Delta I}{I} \approx \frac{d\rho}{dx} \tag{1}$$

where: $\Delta I/I$ - the relative change of the light intensity after passing through the apparatus optical system (the light intensity, W/m^2); ρ - the density of the test medium, kg/m^3; x - the direction of the normal to the surface of the equal density, m.

The tracer method was proposed by Foucalt in 1859. Its development was made in 1866 by Toepler who used this technique to study the disorders of the air caused by electric discharges and explosions [5]. Since then the Schlieren method was applied in a vast number of applications in science and technology.

3. Description of test stand

The experimental position, whose schematic diagram is shown in Figure 2, has been used for the research. Its main component was the Schlieren apparatus, consisting of two parts - positioned coaxially horizontally of steel cylinders equipped with appropriate optical components (lenses and mirror). Part of the apparatus numbered *1* generates a parallel beam of light which passes through the testing area *4* where it interacts with the tested medium. Then the light reaches the part *2* in which optical systems are capable of producing an image of the studied phenomenon. This image is displayed on the screen *5*. The digital camera *6* was used to record the generated Schlieren images. The optical cutter is located in the element *7* which directs the light rays at the screen. The light is focused on the edge of the cutter, reproducing the image of the phenomenon. Moving the edge adjusts the contrast and brightness of the image displayed on the screen.

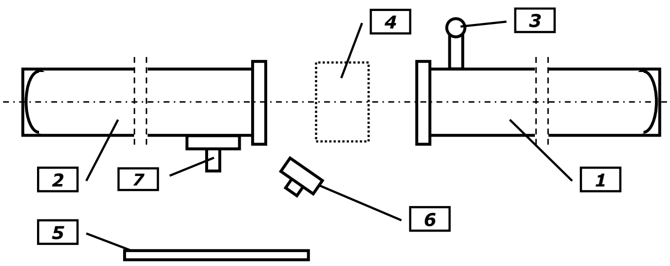

Fig. 2. Scheme of the test stand: (1) part of the apparatus emitting a light beam, (2) part of the apparatus receiving disturbed light beams, (3) spot light source, (4) research area, (5) screen, (6) digital camera, (7) optical cutter

During research in the central part of the tested area of the stand there was an electric heater on which the charge sample are placed. These were the flat beds of rectangular steel profiles and steel pipe clad with steel profiles. The samples were adjusted along the optical axis of the device so that the rays of light passed parallel through the gas spaces of the constituent elements. After starting the heater, heat flux in the test samples was generated directed vertically upward. Due to the structure of the heated components this flux was complex. The heat in the heated samples was transferred by conduction, radiation and convection. The main part of the research was based on the observation of convective air movement occurring on internal areas of the heated components. Examples of tested samples are shown in Figure 3.

The heater which was used in the stand has the form of a flat ceramic plate with transverse dimensions of 300 × 120 mm and the thickness of 40 mm. Resistance spirals were sunk in the plate. The heater was set the shorter side along the axis of the apparatus, so that the tested samples were heating only in the central part on the length of about 150 mm. In this way, the possibility of air movement at the ends of the samples has been eliminated. The presence of these movements would interfere with the image of the observed phenomenon so the results would be worthless. The power of the heater, which was 1000 W, allowed to warm the samples to the temperature above 500°C.

4. Characteristics of the test samples

Due to the geometry of the test samples, convection occurring in the inner area should be considered as a natural one in the horizontal gaps. The results of theoretical analysis [7, 8], experimental studies [9, 10, 11] and numerical calculations [12, 13, 14] of natural convection in this type of systems indicate that the main factors determining the intensity of fluid motion are: the geometry of the area and the temperature distribution on its edges. Therefore, in order to obtain possibly the widest range of the analyzed subject, the samples made of different elements were tested.

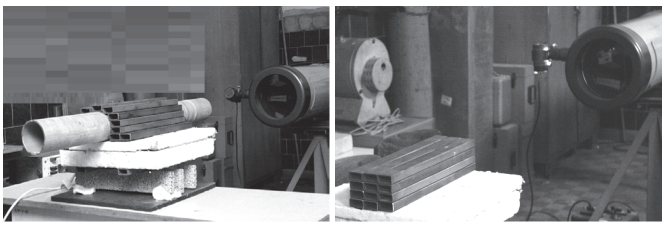

Fig. 3. Photos of the selected samples arranged in the tested space of the experimental stand: a) pipe faced by rectangular sections (sample *A*); b) flat bed of rectangular sections (sample *B*)

The first sample, designated as sample *A*, was a steel pipe of external diameter 81 mm, wall thickness of 4 mm and a length of 1200 mm. In order to eliminate the effect of convective heat fluxes coming from the heater to the outer surface of the pipe, it was covered with the rectangular profiles 20 × 40 mm of the length of 400 mm. The view of this sample is shown in Figure 3a. The second sample (sample *B*) was a flat bed consisting of four layers of the rectangular profiles 20 × 40 mm with the length of 400 mm and the wall thickness of 2 mm. This sample is shown in Figure 3b. The sample designated with the symbol *C* was built of three square sections of 80 mm, wall thickness of 3 mm and the length of 600 mm, arranged in one layer side by side.

5. Analysis of the test results

Implementation of the research consisted of the heating of the described samples by a specific, steady heat flux. In certain time intervals the registration of the images generated by the Schlieren apparatus was made. As a result of heating of the elements that were part of the test samples, the temperature difference along the height of the elements was generated. The result was a temperature variation of air which filled these elements. This, in turn, resulted in differences in its density which meant that the air has also difference in the refractive index. Thanks to this observations of the air movements are possible.

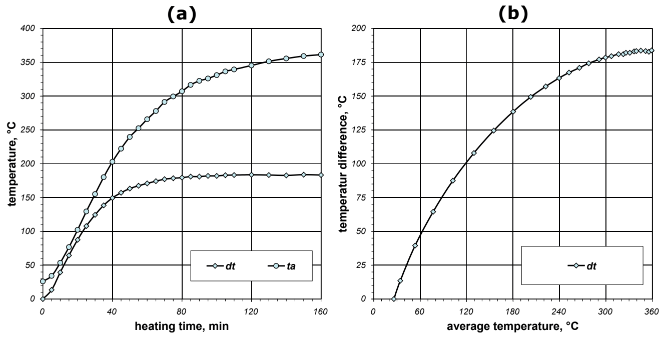

Fig. 4. The temperature difference *dt* obtained at the height of the pipe in the sample A: a) change of the parameter *dt* and the average temperature of the pipe t_a as a function of heating time; b) change of the parameter *dt* as a function of the average temperature of the pipe t_a

First the results obtained for sample *A* are presented. The course of natural convection in confined areas is affected by, among others, the temperature distribution at its edges. Therefore, during testing the sample, the measurements of the pipe surface temperature were made at two opposite points relative to the direction of heat flux. For this purpose the thermocouples of type *K* were used. The changes in the temperature difference at the height of the pipe *dt* as a function of hating time and the average temperature t_s calculated as the average of the temperatures of the lower and upper surfaces are shown in Figure 4. As can be seen the temperature difference within the pipe most intensively grows for the first 40 minutes of the process when it reaches the value of about 150°C. During further heating the increase of this parameter is much smaller, and after 80 minutes it is to stabilize (about 180°C). That does not mean, however, that the temperature of the pipe was also stabilized. This is evidenced by the continuous increase of the average temperature t_a, which at the end of the process (160 min.) was equal 360°C. This means that at the end of the research the difference in temperature within the pipe was exactly half the value of its average temperature.

Because of the relatively large size of the inner space of the analyzed pipe and a significant temperature gradient between its opposing edges, it should be expected that the phenomenon of natural convection is intensive. However, the images generated by the Schlieren system did not confirm this assumption. Intensive air movements were observed only around the outer surface of the test bed. While inside the pipe air movements visible by direct visual observation were not registered. The only apparent effect were the changes of the shape of the space inside the pipe, which illustrate the pictures shown in Figure 5. They present the test bed respectively at 10, 40, 80 and 120 minutes of the process. The visible change of the inside shape of the pipe from round to oval is caused by the formation along the bottom and upper surface of the thermal boundary layers. But these images do not emerge the presence of any air movement in the area outside of these layers, i.e. in so called core. Thus, the convection movements of air in the pipe in this case did not occur or were so weak that it was not possible to observe them.

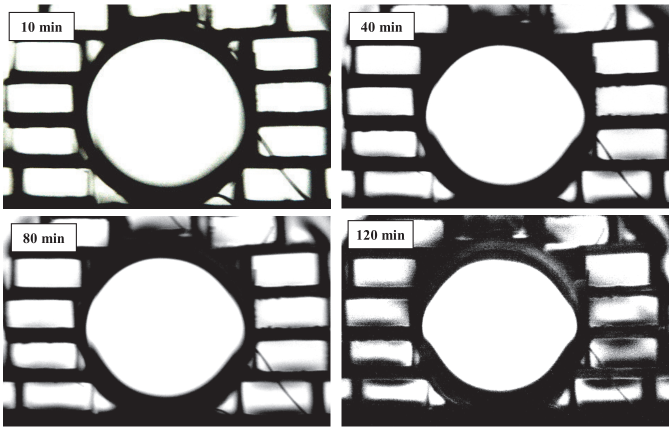

Fig. 5. Schlieren images of the sample *A* recorded in 5, 30, 80 and 120 minutes of heating process

As it was previously mentioned, the image generated by Schlieren system depends on the position of edge of the optical cutter relative to the focused light beam. Moving the cutter within appropriate limits significantly changes the contrast and brightness of the projected image. Thanks to this adjustment much darkened images of the tested pipe, which is shown in Figure 6, were obtained. These images have been registered in the final stage of the process of heating up. They show that, contrary to earlier claims of, there are however very slow air movements inside the heated pipe outside the boundary layers. Based on information obtained from the analysis of the figures 5 and 6 it can be concluded that the convection should not affect the temperature distribution within the tested pipe. This statement is supported by the low intensity of the air movement in the core area and the presence of relatively thick boundary layers. Due to the high thermal conductivity of steel, heat conduction along the circumference of the pipe will have the fundamental importance.

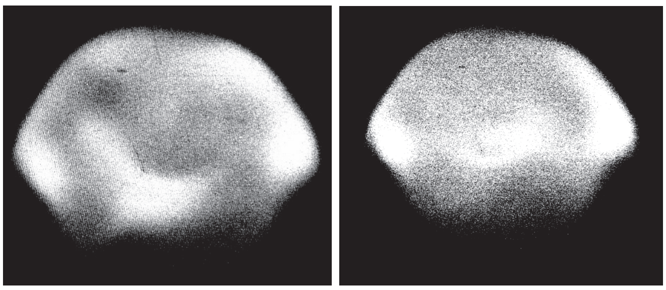

Fig. 6. Schlieren images of the sample *A* recorded in the final stage of the heating obtained after changing the position of optical cutter

The results of the temperature measurements obtained in the test of the sample *B* are shown in Figure 7. This sample consisted of twelve profiles which were arranged in four layers. Presented results were obtained from measurements made within the central profile located at the second layer of the bed. The temperature difference for the tested profile grows to 60 minutes of the process when reaches the value 65°C. In contrast, the average temperature grew for the whole duration of the process, reaching at the end (120 min.) 336°C. The value of this parameter is similar as in the case of sample *A*, for which in the 120 minute was equal to 345°C.

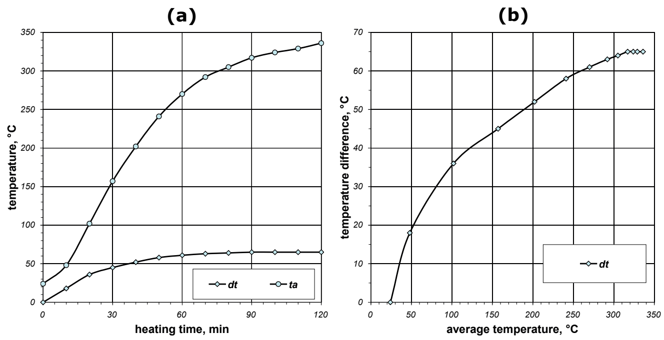

Fig. 7. The temperature difference *dt* obtained for the central profile in the sample *B*: a) changes of the parameter *dt* and the average temperature of the profile t_a as a function of heating time; b) change of the parameter *dt* as a function of the average temperature of the profile t_a

The Schlieren images obtained during research of the sample *B* are shown in Figure 8. Images recorded in the initial heat-up period (10 and 20 min) do not detect any thermal changes of the medium inside the profiles. Convective air movements only along the outer surface of the heated bed are shown here. Isothermal boundary layers along the horizontal walls of the profiles are revealed just in the image obtained in the fortieth minute. However, these layers are stable and do not show any movement. A similar situation occurs in the image registered in the sixtieth minute. A characteristic feature of the two images is extremely intense convection on the outside of the bed. Flow line shapes indicate that in this case there is a fully developed natural turbulent convection.

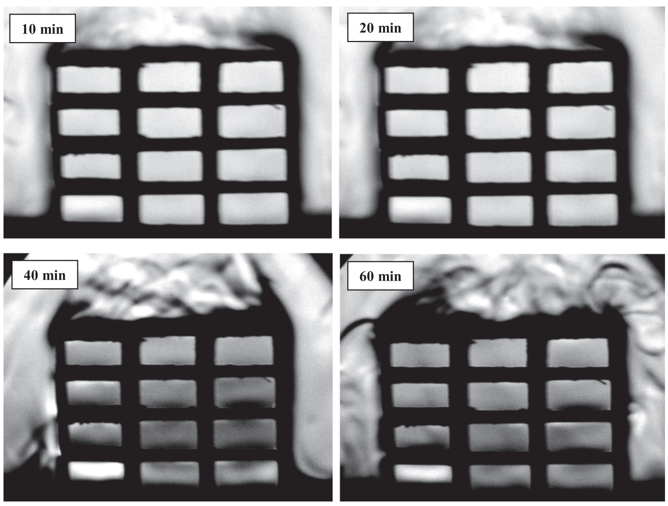

Fig. 8. The Schlieren images of the sample *B* recorded at 10, 20, 40 and 60 minute of the heating process

Results of the temperature measurements carried out at the horizontal walls of the middle profile of the sample *C* are shown Figure 9. The maximum temperature difference *dt* at the height of this element was 220°C, with average temperatures t_a exceeding the value of 420°C. The heating process was realized over a period of 160 minutes. The increase of the parameter *dt* occurred primarily during the first 40 minutes of heating (*dt* = 201°C) while the average temperature of the profile grew for the entire duration of the process.

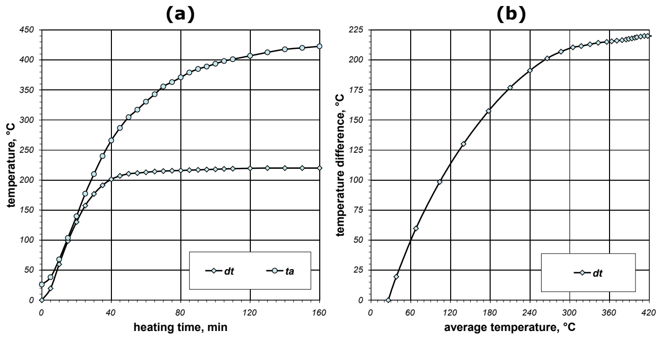

Fig. 9. The temperature difference *dt* obtained for one of the profiles in the sample *C*: a) the changes of the parameter *dt* and the average temperature of the profile t_a as a function of heating time; b) the change of the parameter *dt* as function of average temperature of the profile t_a

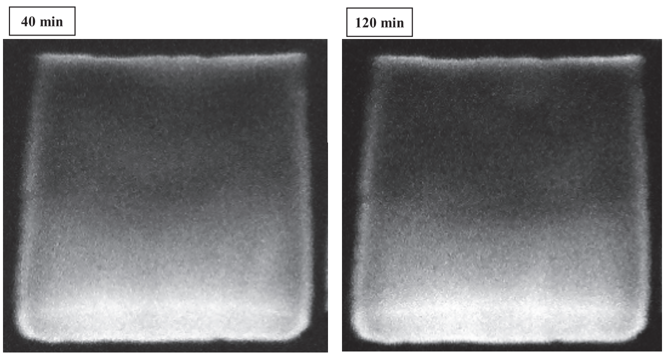

Fig. 10. The Schlieren images of the sample *C* recorded at 40 and 120 minutes of the heating process

The Schlieren images obtained for the central profile of the sample *C* are shown in Figure 10. Images obtained for this sample for the entire heat-up period were very similar to each other. For this reason, only two images, for 40th and 120th minutes of the process, are included in the figure. They highlight the presence of boundary layers along the vertical walls of the profile. The thickness of these layers increases with height, but it is small compared with the total thickness of the air layer in the element. Outside of these layers, air is characterized by a horizontal distribution of isotherms. However, there is no presence of structures that would demonstrate the existence of convective movements inside the profile. Thus it can be concluded that the convective heat transfer in the interior of this profile does not exist. Air movement with a low intensity can occur only in the immediate vicinity of the boundary layers that form along the vertical surfaces.

At the end of the analysis of the results obtained for the samples *B* and *C*, it should be noted that, as for the sample *A*, the observation was made with various settings of the optical cutter. However, in the case of samples made from profiles, change of the contrast and brightness of the images did not reveal the existence of any structures associated with the movement of air (except the presence of boundary layers previously identified). Therefore, the views of those images are not included.

6. Summary

The results of the research presented in this paper show that the method of Schlieren visualization can be used for the analysis of natural convection in the case of the porous charge, having the form of bundles of long empty elements. Simultaneously it should be noted that the information obtained from these experiments are only qualitative. On this basis it can be concluded that the convection in the interior areas of steel elements long which are heat treated in the form of bundles has no significant influence on the heat transfer process. This is due to the low intensity of air movement. As regards the temperature distribution within the particular elements, the heat conduction taking place along the walls is fundamentally important here. At higher temperatures also thermal radiation begins to be significant. While the heat flow in the whole area of the bundles, in addition to the mentioned mechanisms is determined by contact conduction occurring at the contact points of each elements (pipes or profiles).

Obtaining more detailed information about the analyzed problem requires further research. Quantitative data about the air convection in the considered bundles can be obtained through experimental research consisting in the analysis of the temperature field of the porous charge being heated in different directions from the bottom and from the top. Due to its nature, air convection within the charge occurs only in the first case. The comparison of temperature distribution within the examined samples for both variants of heating can answer about the quantitative participation of the convection in the global heat transfer. Such studies of will be the next stage of research.

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