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# DETERMINING THE HEAT-TRANSFER COEFFICIENT IN AN ISOTHERMAL MODEL OF A SHAFT FURNACE

## DOLOČITEV KOEFICIENTA PRENOSA TOPLOTE V IZOTERMNEM MODELU JAŠKOVNE PEČI

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The paper addresses an analysis of the influence of the batch grain size and air flow through a shaft furnace on the transfer coefficient from the air to the batch and the time for heating the batch to the required temperature. The stated influence was experimentally investigated on a reduced shaft-furnace model at three air-flow amounts, 48.8 $m^3 h^{-1}$, 56.3 $m^3 h^{-1}$ and 72 $m^3 h^{-1}$, and three varying grain sizes of the used batch: 4–8 mm, 8–10 mm and 10–12 mm. The influence of the stated parameters upon the evenness of the velocity field of the air along the cross-section of the furnace was also monitored in two selected horizontal planes in order to obtain information about the air velocity in the vicinity of the wall of the model furnace and at distances of 1.5 cm, 3.5 cm and 5.0 cm from it.

Keywords: batch grain size, heat-transfer coefficient, velocity field

Članek obravnava analizo vpliva zrnatosti vložka in pretoka zraka skozi jaškasto peč na koeficient prenosa iz zraka na vložek in na čas segrevanja vložka na potrebno temperaturo. Navedeni vpliv je bil eksperimentalno preiskovan na pomanjšanem modelu jaškaste peči, pri treh pretokih zraka 48,8 $m^3 h^{-1}$, 56,3 $m^3 h^{-1}$ in 72 $m^3 h^{-1}$ ter pri treh različnih zrnatostih vložka: med 4–8 mm, med 8–10 mm in med 10-12 mm. Opazovan je bil tudi vpliv omenjenih parametrov na enakomernost hitrostnega polja zraka po preseku peči v dveh izbranih horizontalnih ravninah z namenom, da bi dobili informacijo o hitrosti zraka blizu stene modelne peči in na razdaljah: 1,5 cm, 3,5 cm in 5,0 cm od nje.

Ključne besede: zrnatost vsipa, koeficient prenosa toplote, hitrostno polje

## 1 INTRODUCTION

Using various technical devices, it is necessary to examine the intensity of the heat exchange between two substances – most often between a gas and a solid substance. The heat-exchange intensity is represented by a heat-transfer coefficient and it takes place via conduction, convection, flow and radiation.[1–2]

Metallurgical furnaces currently represent a complicated mechanised and automated equipment and equally complicated procedures taking place within. The thermal regime of such industrial aggregates is very complicated and it therefore requires appropriate attention.

Several authors focus upon the heat transfer in varying metallurgical furnaces and compare their results obtained experimentally with the results from numeric simulations.[3–5]

## 2 EXPERIMENTAL PART

### *2.1 Description of the heat exchange in a layer of a shaft-furnace batch*

The heat exchange in a batch layer of shaft furnaces and similar furnace aggregates is provided by direct contact between the gas medium and the batch. The heat in the batch layer is mainly transferred via radiation and convection.[6–8] The radiation component is present to a lesser extent than the convection component. When heating a batch, gas radiation is influenced by the small dimensions of the channels created between individual grains of the batch material and the low concentration of heteropolar gases. In practice, heat exchange via radiation only takes place at high batch temperatures.

Heat exchange via conduction also takes place between individual pieces of the batch. However, this heat exchange is negligible.

The gas-flow velocity has a decisive effect during the heat exchange between a flowing medium and a batch.[9] An analysis of convection during the heat transfer from the heated air to the batch was carried out on a "cold model". This means that a simulated batch formed of crushed chamotte at an ambient temperature was exposed to a flow of heated air with a known temperature and known volume. The influence of the grain size of the batch and the air flow upon the intensity of the heat exchange between the air and the batch was monitored and represented by the heat-transfer coefficient from the air to the batch.[10]

### *2.2 Experimental model furnace*

An experiment focusing upon obtaining the information necessary to determine the heat-transfer coefficient was carried out on an equipment representing an isothermal model of a shaft furnace. A diagram of the model is on **Figure 1** and an image of the experimental equipment during the measurement is on **Figure 2**. The basic parameters of the model are given in **Table 1**. The model has a double insulation in the lower part consisting of perlite and chamotte flour. The insulation in the upper part of the model consists of just chamotte flour. The brickwork comes into direct contact with the batch and the flowing air. The bottom of the model is formed of a graduated grid, on which the batch is placed. Below the grid, there is pipework, through which the air, heated in a recuperator, is transported to the furnace model.

**Table 1:** Basic parameters of the model
**Tabela 1:** Osnovni parametri modela peči

| | | | |
|---|---|---|---|
| Height of the model furnace (mm) | 856 | | |
| Inner diameter of the model furnace (mm) | 110 | | |
| Height of filling (mm) | 488 | | |
| Gas medium | air | | |
| Batch | crushed chamotte | | |
| Batch density (kg m$^{-3}$) | 1900 | | |
| Batch grain size (mm) | 4–8 | 8–10 | 10–12 |
| Void fraction of the batch (1) | 0.55 | 0.61 | 0.623 |
| Air flow (m$^3$ h$^{-1}$) | 48.8 | 56.3 | 72 |

The air flow was measured using a gas meter and its pressure using a U-tube manometer. The measurement of the temperature of the batch and air was carried out using K-type (NiCr-Ni) contact thermocouples. The thermocouples were led to terminal boards from where an electric signal was transported to the data logger.

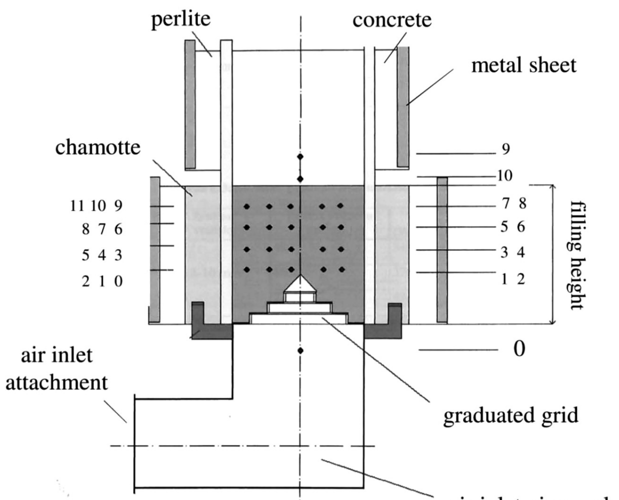


**Figure 1:** Furnace model with the thermocouple distribution
**Slika 1:** Model peči z razporeditvijo termoelementov

**Figure 2:** Image of the experiment equipment during the measurement
**Slika 2:** Pogled na eksperimentalno napravo med merjenjem

Recording and storing the data was provided by computer software.

Before starting the measurement itself, air at an ambient temperature was blown into the furnace using a fan in order to stabilise the temperature in the batch. The air flow and grain size changed during the experiment. The temperature of the batch material and the temperature of the flowing air were measured along the height of the model during the experiment.

A scheme of the furnace model with the appropriate equipment and measurement devices is shown on **Figure 3**.

## 3 DETERMINATION OF THE HEAT-TRANSFER COEFFICIENT

Balance equations were used for determining the heat-transfer coefficient. The amount of delivered heat $Q$ was stated using Equation (1):

$$Q = Q_V \cdot c(t'_{vz} - t''_{vz}) \cdot \tau = m \cdot c_m (t''_m - t'_m) \qquad (1)$$

The heat-transfer coefficient related to the total volume of the model furnace can be determined from Equation (2):

$$Q = \alpha_V \cdot V \cdot \Delta t_{LS} \cdot \tau \qquad (2)$$

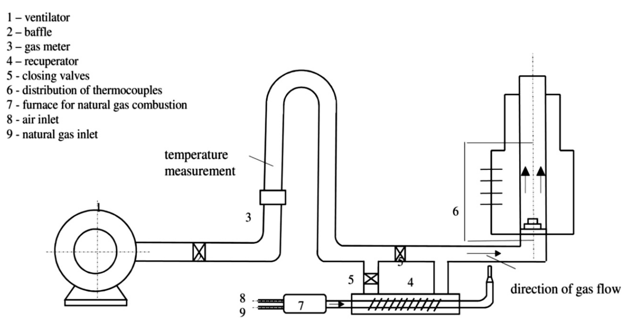


**Figure 3:** Scheme of a model furnace
**Slika 3:** Shema modela peči

For the logarithmic mean temperature difference $\Delta t_{LS}$, Equation (3) is used:

$$\Delta t_{LS} = \frac{\Delta t' - \Delta t''}{\ln \dfrac{\Delta t'}{\Delta t''}} \tag{3}$$

whilst $t'_{vz} - t''_{m} = \Delta t'$ is the temperature difference of the air and the batch at the inlet to the model and $t''_{vz} - t'_{m} = \Delta t''$ is the temperature difference of the air and the batch at the outlet of the model.

By comparing Equations (1) and (2), we obtain the formula for the heat-transfer coefficient related to the volume of the furnace model:

$$\alpha_V = \frac{m \cdot c_m (t''_{m} - t'_{m})}{V \cdot \Delta t_{LS} \cdot \tau} \tag{4}$$

### *3.1 Conditions for calculating the heat-transfer coefficient*

For a batch grain size of 10–12 mm and the lowest air flow of 48.8 m$^3$ h$^{-1}$ logarithmic mean temperature difference $\Delta t_{LS}$ was determined from Equation (3) under the following conditions:

$t'_{vz} = 272.1$ °C  $t''_{m} = 261.5$ °C

$t''_{vz} = 160.9$ °C  $t'_{m} = 101.4$ °C

The volume of the shaft furnace model with a filling height of $h$ = 0.488 m and an area of $S$ = 0.0095 m$^2$ represents value $V$ = 0.0046 m$^3$.

The weight of the batch for the monitored volume was determined using Equation (5)[4]:

$$m = V \cdot \rho \cdot (1-\varepsilon) \tag{5}$$

The calculated weight is 3.32 kg.

The value of the volume heat-transfer coefficient is 38 963 W m$^{-3}$ K$^{-1}$.

**Figures 4** and **5** show the development of the heat-transfer coefficient depending upon the time with three different flows and batch grain sizes of 10–12 mm and 4–8 mm.

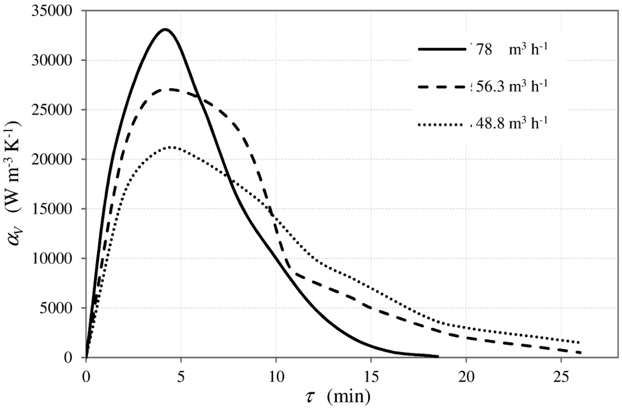


**Figure 5:** Development of the heat-transfer coefficient in relation to time with three varying flows and a grain size of 4–8 mm

**Slika 5:** Spreminjanje koeficienta prenosa toplote glede na čas, pri treh različnih pretokih in zrnatosti 4–8 mm

The air-flow velocity is related to the flow. With three different air flows (48.8 m$^3$ h$^{-1}$, 56.3 m$^3$ h$^{-1}$ and 78 m$^3$ h$^{-1}$), it can be seen that the heat-transfer coefficient $\alpha_V$ grows with the growing flow (**Figure 5**). The higher the air flow, the higher is the value of the heat-transfer coefficient and the time necessary for heating the batch shortens.

**Figure 6** shows the development of the heat-transfer coefficient for the batch grain size of 10–12 mm in relation to time, with the air flow of 48.8 m$^3$ h$^{-1}$ in three places along the horizontal plane of the furnace. The distances of the places from the furnace wall were 1.5 cm, 3.5 cm and 5.5 cm. The horizontal plane was fictitiously placed at a height of 288 mm on the furnace. **Figure 7** shows the development of this coefficient along the same plane and in the same places but with a smaller batch grain size (4–8 mm). The most marked difference in the heat-transfer-coefficient value is at the distance of the measured place of 1.5 cm from the wall where, for

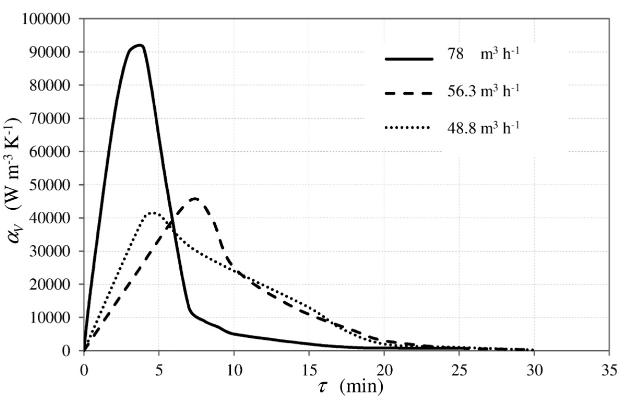


**Figure 4:** Development of the heat-transfer coefficient in relation to time with three varying flows and a grain size of 10–12 mm

**Slika 4:** Spreminjanje koeficienta prenosa toplote glede na čas, pri treh različnih pretokih zraka in zrnatosti 10–12 mm

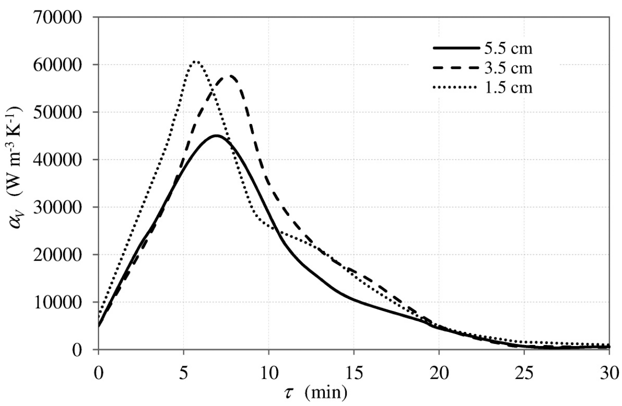


**Figure 6:** Development of the heat-transfer coefficient in relation to time with a grain size of 10–12 mm and air flow of 48.8 m$^3$ h$^{-1}$

**Slika 6:** Spreminjanje koeficienta prenosa toplote glede na čas za zrnatost vsipa 10–12 mm in pri pretoku zraka 48,8 m$^3$ h$^{-1}$

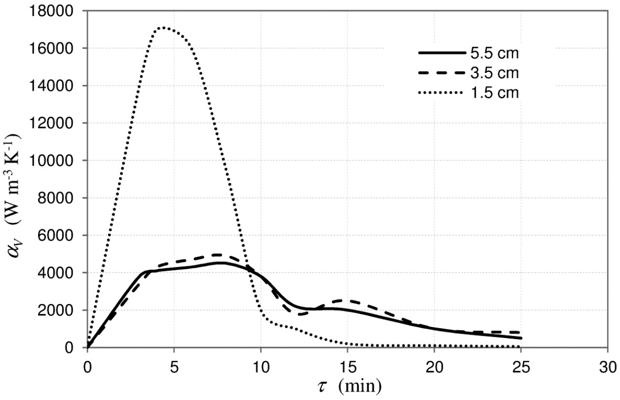


**Figure 7:** Development of the heat-transfer coefficient in relation to time with a grain size of 4–8 mm and air flow of 48.8 m$^3$ h$^{-1$}

**Slika 7:** Spreminjanje koeficienta prenosa toplote glede na čas pri zrnatosti vsipa 4–8 mm in pretoku zraka 48,8 m$^3$ h$^{-1}$

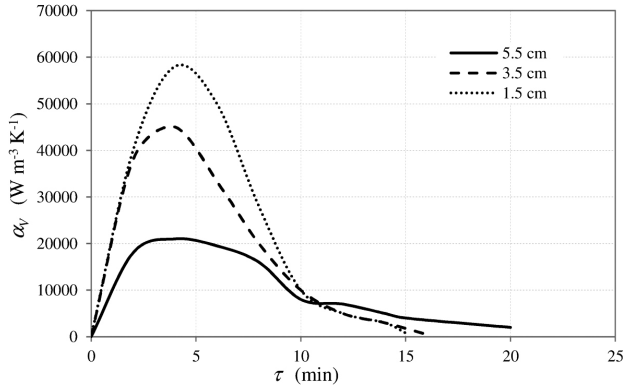


**Figure 9:** Development of the heat-transfer coefficient in relation to time with a grain size of 4–8 mm and air flow of 72 m$^3$ h$^{-1}$

**Slika 9:** Gibanje koeficienta prenosa toplote glede na časa pri zrnatost vsipa 4–8 mm in pretoku zraka 72 m$^3$ h$^{-1}$

example, with the flow of 48.8 m$^3$ h$^{-1}$ and the batch grain size of 4–8 mm (**Figure 7**), the heat-transfer coefficient is 17000 W m$^{-3}$ K$^{-1}$. With the same flow and the same distance from the wall, this coefficient increases with an increase of the batch grain size to 10–12 mm (**Figure 6**), by about 62 %. At the distance of 5.5 cm from the wall and under the same conditions (the grain size of 4–8 mm, the flow of 48.8 m$^3$ h$^{-1}$) the coefficient is 4200 W m$^{-3}$ K$^{-1}$ and with the grain size of 10–12 mm, it is almost 46000 W m$^{-3}$ K$^{-1}$. This represents an approximately 9-fold increase in the value of this coefficient.

It can be seen from **Figures 6** and **7** that the smaller the batch grain size, the greater is the hydraulic resistance of the batch, and the air in the direction of the flow only partially passes through the centre of the model. For this reason, the flow is more intensive in the very close vicinity of the wall of the furnace model. The flowing air therefore delivers less heat to the batch than in the case of a lower hydraulic resistance, where the air passes through the cross-section of the furnace more evenly – this is the case with a larger batch grain size.

With a greater air flow and the largest batch grain size used in the experiment (10–12 mm), there was a more even distribution of the air flow along the cross-section of the model furnace (**Figure 8**). With the grain size of 4–8 mm, the air flow was again more intensive close to the wall (**Figure 9**).

In order to verify the air-flow conditions along the cross-section of the batch in the model furnace, a calculation was carried out using the numeric method in the ANSYS_CFX program. The solution was expected to confirm or deny the nature of the flow and the distribution of the air-velocity field along the cross-section of the furnace. The used edge conditions of the solution were identical to the conditions in the real experiment.

**Figure 10** shows the distribution of the velocity along the cross-section of the model furnace with the air flow of 48.8 m$^3$ h$^{-1}$, grain sizes of 4–8 mm and 10–12 mm, and with the batch height of 280 mm. **Figure 11** shows the distribution of the velocity along the

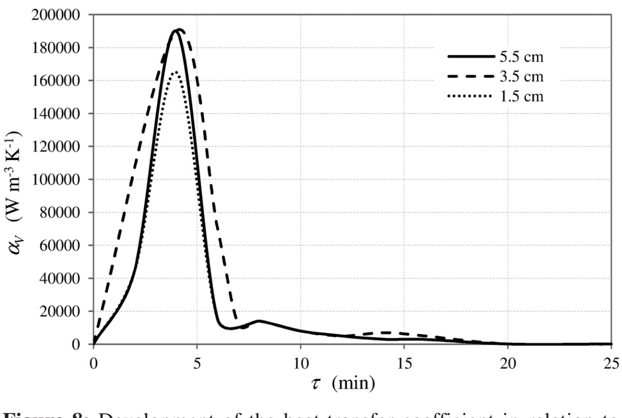


**Figure 8:** Development of the heat-transfer coefficient in relation to time with a grain size of 10–12 mm and air flow of 72 m$^3$ h$^{-1}$

**Slika 8:** Spreminjanje koeficienta prenosa toplote glede na čas pri zrnatosti vsipa 10–12 mm in pretoku zraka 72 m$^3$ h$^{-1}$

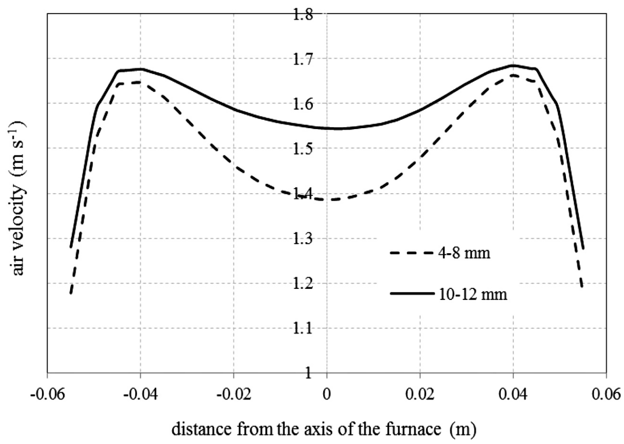


**Figure 10:** Air-velocity profile along the cross-section at a height of batch of 280 mm and air flow of 48.8 m$^3$ h$^{-1}$

**Slika 10:** Hitrostni profil zraka po prečnem prerezu peči, pri višini vsipa 280 mm in pretoku zraka 48,8 m$^3$ h$^{-1}$

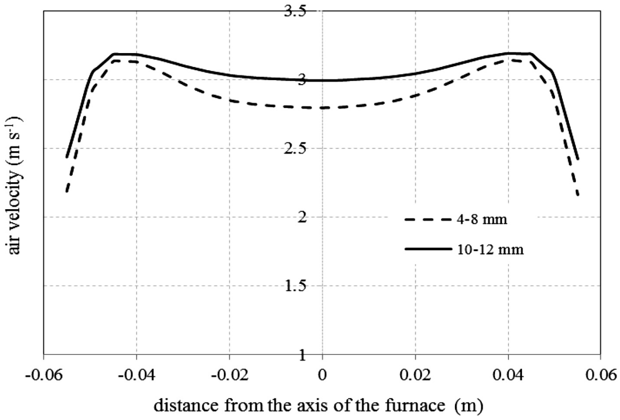


**Figure 11:** Air-velocity profile along the cross-section at a height of batch of 280 mm and air flow of 72 $m^3$ $h^{-1}$

**Slika 11:** Hitrostni profil zraka po prečnem prerezu peči, pri višini vsipa 280 mm in pretoku zraka 72 $m^3$ $h^{-1}$

cross-section of the furnace, at the same batch height, the selected grain sizes and at the higher air flow (78 $m^3$ $h^{-1}$).

At the air flow of 72 m3·h-1 and the batch grain size of 4–8 mm, the air-velocity field is displayed in the vector shape on **Figure 12a**. **Figure 12b** shows the velocity field at the same flow and the grain size of 10–12 mm. **Figure 12b** documents a more even distribution of the air-velocity field than in the case of using a smaller batch grain size.

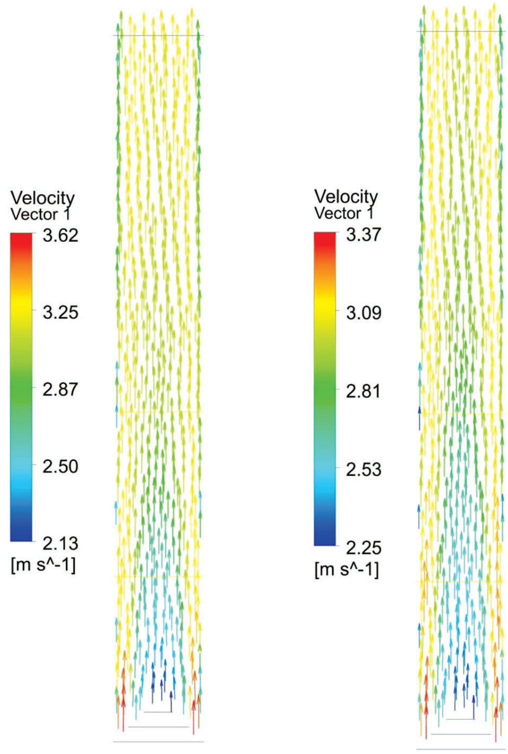


**Figure 12:** Air flow along the whole cross-section of the furnace with an air flow of 72 $m^3$ $h^{-1}$

**Slika 12:** Kroženje zraka po celotnem prečnem prerezu peči, pri pretoku zraka 72 $m^3$ $h^{-1}$

## 4 RESULTS AND DISCUSSION

The influence of the flow upon the heat-exchange intensity is shown on **Figures 4** and **5**. With the grain size of 10–12 mm and air flow of 78 $m^3$ $h^{-1}$, the heat-transfer coefficient was about 50 % higher compared to the flow of 48.8 $m^3$ $h^{-1}$. With the grain size decreased to 4–8 mm and the same flow of 78 $m^3$ $h^{-1}$, this coefficient decreased by about 63 %. The maximum value of the heat-transfer coefficient for both flows was reached in approximately the same time of heating the batch which was about 4 min.

The heat exchange in the batch along the cross-section of the model furnace has a varying intensity. This is related to the structure of the batch and the amount of the air flow. For example, at the distance of 1.5 cm from the wall, the flow of 48.8 $m^3$ $h^{-1}$ and the batch grain size of 4–8 mm (**Figure 7**), the heat-transfer coefficient is about 17000 W $m^{-3}$ $K^{-1}$. At the same flow and the same distance from the wall, this coefficient increases with an increased batch grain size of 10–12 mm (**Figure 6**) to a value of 60000 W $m^{-3}$ $K^{-1}$, i.e., by about 2.5 times.

Higher air flows influence heat exchange more intensively. With the same distance from the wall (1.5 mm), the air flow of 72 $m^3$ $h^{-1}$ and batch grain size of 4–8 cm (**Figure 9**), the heat-transfer coefficient is circa 58000 W $m^{-3}$ $K^{-1}$. With the same air flow and at the same distance from the wall, the heat-transfer coefficient increases more than threefold with the batch grain size increased to 10–12 mm (**Figure 8**), i.e., to a value of 192000 W $m^{-3}$ $K^{-1}$.

The influence of the distance of the investigated location of the batch upon the heat-transfer coefficient is more pronounced with a lower batch grain size. For example, for the air flow of 72 $m^3$ $h^{-1}$ and grain size of 4–8 mm, the heat-transfer coefficient has a value of 21000 W $m^{-3}$ $K^{-1}$ if the distance from the furnace wall is 5.5 cm. At the same distance from the wall and the grain size of 10–12 mm, the value of the coefficient remains the same as for the distance of 1.5 cm, i.e., 192000 W $m^{-3}$ $K^{-1}$. It is clear from the above that the air velocity along the cross-section of the furnace is distributed more evenly with a greater batch grain size. The same result was confirmed by calculating the flow conditions using the numeric simulation.

## 5 CONCLUSION

The value of the coefficient of the heat transferred from the flowing air into a batch depends upon several factors. Important roles are played by the batch grain size, the fact of how evenly it is distributed, the input temperature of the flowing air and the amount of the air flowing through the batch layer. Most of the heat transferred to the batch at a given temperature of the flowing air was reached with the largest grain size. In order to achieve an intensive heat transfer with a lower batch grain size, it is necessary to ensure a higher flow of the heated air and an even distribution of the batch. With a smaller grain size, it is very complicated, or even impossible, to ensure that the hydraulic resistance of the batch does not increase. This always results in the changes in the direction of the input air flow to the batch layer and the flow is directed towards the furnace wall, where it leaves the model furnace without any significant transfer of heat to the batch. This is documented with the outputs of the numeric simulation.

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**Nomenclature**

| | | |
|---|---|---|
| $\alpha_V$ | heat-transfer coefficient related to the volume of the model | W m$^{-3}$ K$^{-1}$ |
| $c$ | specific heat capacity of the air | J m$^{-3}$ K$^{-1}$ |
| $c_m$ | specific heat capacity of the batch | J kg$^{-1}$ K$^{-1}$ |
| $\varepsilon$ | void fraction | 1 |
| $\Delta t_{LS}$ | logarithmic mean temperature difference | °C |
| $m$ | batch weight | kg |
| $Q$ | amount of heat delivered | J |
| $Q_V$ | air flow | m$^3$ s$^{-1}$ |
| $\rho$ | chamotte density | kg m$^{-3}$ |
| $t_{vz}$' | air temperature at the inlet to the furnace | °C |
| $t_{vz}$' | air temperature at the outlet from the furnace | °C |
| $t_m$' | batch temperature at input | °C |
| $t_m$'' | batch temperature at output | °C |
| $\tau$ | time | s |
| $V$ | volume of the model shaft furnace | m$^3$ |

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