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THERMAL DIFFUSIVITY COEFFICIENTS BY AIR FLUIDIZED BED

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Abstract. *The paper presents experimental research of thermal conductivity and thermal diffusivity coefficients of the siliceous sand bed fluidized by gas. It also provides an outline of research investigations of these coefficients conducted so far by other authors, whose experiments were performed under the conditions similar to those in our own experiments. On the basis of experimental research, the influence of the process's operational parameters upon the obtained values of the bed's thermal conductivity has been analyzed. The results show direct dependence of thermal conductivity on the intensity of mixing, the fluidization rate, and the size of particles. In the axial direction, the coefficients which have been treated have values for one order higher than in the radial direction. Comparison of experimental research results with experimental results of other authors shows good agreement and the same tendency of thermal conductivity change, depending on the size of particles and the intensity of mixing.*

Key words: *Fluidized Bed, Heat Transfer, Experiment, Thermal Diffusivity, Thermal Conductivity.*

INTRODUCTION

Ever since its emergence, the fluidization phenomenon has attracted the attention of numerous researchers. Its appliance in numerous technological operations stems from its excellent properties, which are reflected in: an intensive mixing of solid particles, a high contact-surface between gas and solid particles, an almost constant temperature in the entire bed, as well as simple insertion and removal of the material from the bed. Due to its good characteristics, the fluidized bed has an important application in industrial processes, such as coal carbonization, drying of small-grained materials, calcination of ores and other materials, cracking distillation of oil derivatives, mixing of powders, freezing of food, gasification of coal, etc. In the past several decades, numerous papers and studies of the process of fluidization and its application have been published, most of which are

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based on experimental research. The field of heat conduction has been of high interest to researchers, since the fluidized bed is characterized by high heat conductivity. Yet, despite a large number of papers dealing with this problem, their authors' conclusions are highly disparate, sometimes even contradictory. The reasons for this scattering of results lie in different conditions in which these experiments are performed. These facts have motivated experimental research with the chief goal of determining thermal diffusivity and thermal conductivity coefficients of the fluidized bed for particles of siliceous sand of different fractions. The influence of the most important parameters on the values of thermal diffusivity and conductivity coefficients of the fluidized bed has been analyzed through obtained experimental results; also, certain experimental studies of other authors have been considered.

THERMAL CONDUCTIVITY OF THE FLUIDIZED BED

Since specific thermal capacity of solid particles is volumetrically higher than specific thermal capacity of gas by several orders, moving particles are basic heat holders in the bed. Transfer of heat by the flow of gas is relatively small and, consequently negligible. In this case, Fourier's equation can be used for describing the process of heat transfer in the fluidized bed, where thermal diffusivity coefficient reflects the intensity of the mixing of material in the bed. Its value can be measured by a modified method of the instantaneous heat source, whose essence is as follows: a strong instantaneous thermal impulse is created in the fluidized bed by quickly pouring a small portion of previously heated particles of that same material, and the moment of achieving maximal temperature τ_{max} ($\tau_{max} = r^2 / 2na$) at certain distance from the heat source is registered. The movement of bubbles enables the mixing of particles in the emulsion phase, both in the direction of the bed's height, and in the radial direction, whereby a certain amount of particles passes through any observed intersection of the bed. Since the particles in the non-isothermal bed differ with respect to the value of enthalpy, a resulting flux of warmer particles will appear if their concentration is higher on one side of the observed intersection. Assuming that the concentration of warmer particles per unit of volume changes in the direction of the flow of particles only, their resulting thermal flux per unit of surface can be expressed as:

$$q = -D_s \frac{dH}{dx}. \tag{1}$$

If the following expression of enthalpy is introduced into expression (1):

$$H = \rho_n \cdot h = \rho_p \cdot (1 - \varepsilon_{mf}) \cdot c_p \cdot t, \tag{2}$$

we obtain:

$$q = -D_s \cdot \rho_p \cdot (1 - \varepsilon_{mf}) \cdot c_p \cdot \frac{dt}{dx} = -\lambda \cdot \frac{dt}{dx}, \tag{3}$$

where λ is the thermal conductivity coefficient of the fluidized bed, which is defined as:

$$\lambda = D_s \cdot \rho_p \cdot (1 - \varepsilon_{mf}) \cdot c_p = a \cdot \rho_p \cdot (1 - \varepsilon_{mf}) \cdot c_p = a \cdot \rho_n \cdot c_p. \tag{4}$$

A Review of Research of Thermal Diffusivity and Thermal Conductivity of the Fluidized Bed

For determining the thermal diffusivity coefficient in the axial direction, Borodulja and associates [1] used a glass pipe, length 1m, diameter 80mm. On the upper surface of the bed, an instantaneous surface heat source was created by pouring a small portion (5-7% volumetrically) of particles heated in a furnace up to temperature 100-700°C. The time of particle pouring was less than 0.5s. For measuring the temperature of the bed, two thermo pairs were used; one of them was placed on the distributor, the other at half the height of the bed. Measurements were performed with several mono-dispersion and poly-dispersion fractions of different types of material for different heights of the stagnant bed. The processing of experimental data has shown that the thermal diffusivity coefficient in the axial direction can be described by the following equation:

$$a_a = 0{,}44(N-1)^{0{,}54} Ar^{0{,}144} (1-\varepsilon_f)^{-1} \left(\frac{H_{mf}}{D_t} \right)^{1{,}3} \tag{5}$$

Determination of the thermal diffusivity coefficient in the radial direction is performed in a pipe with diameter 175mm. An instantaneous spot heat source was obtained by quickly pouring a small portion of warm sand particles along the axis of the apparatus through a glass pipe with diameter 25mm. For temperature measurement, a thermocouple was placed at the height of the pouring of particles from the pipe, at the distance of 60-70mm from its axis.

The research has shown that there is a highly intensive mixing of material in the fluidized bed in the axial direction. The axial thermal diffusivity coefficient was within $a_a = (10\text{-}60)$ cm^2/s. On the other hand, the mixing of material in the radial direction was relatively small. The values of radial thermal diffusivity coefficients were: $a_r = (0.4\text{-}1.5)$ cm^2/s.

In Ref. [2], Peters, Orlichek, and Schmidt tried to calculate the thermal conductivity coefficient by determining temperature profile in the fluidized bed. The apparatus was in the shape of a parallelepiped, width 65mm, length 450mm, height 480mm, which was not completely filled with sand (d_{ekv}=0.23mm). As a source of heat, they used an electric heater consisting of a wire spiral, which provided heat evenly along the transverse section of the bed. Thermal insulation of the vessel prevented thermal loss through the wall from being higher than 7%. The calculated numerical values of thermal conductivity in the axial direction were within (1163-1977)W/mK, while in the radial direction, they were of order (1200-2000)W/mK. Zabrodski [1] states that those values are significantly increased, and that they are practically impossible to obtain on the basis of such experimental conditions.

The influence of apparatus geometry can be explained by qualitative conclusions formulated in experimental research by Lewis, Gilliland, and Girouard. The apparatus they used in their experiment consisted of a vertical column, where the glass sample was located between an electric heater and a section cooled by water. Above the reactor, there was a wide precipitation section and a cyclone, which returned particles into the bed. The thermocouples were placed in a column, additionally connected to the potentiometer, which enabled measurement of temperature and temperature variances within the bed, in the axial and radial directions. The column was isolated by two layers of glass wool, and, since it consisted of a number of sectors, the distance between the heater and the cooler was changeable. By using various types of material (micro-spheres of catalysts, glass particles, aluminum powder) as particles for fluidization, the values of thermal diffusivity the authors obtained were within (30-600) cm^2/s. These values are matched by values of thermal conductivity which are much higher in comparison with thermal conductivity of e.g. a copper bar. Lewis and associates also came to the conclusion that thermal conductivity of the fluidized bed is independent of the heater-cooler distance and the height of the stagnant layer, both for the system with bubble and for the system with piston fluidization.

On the basis of the foregoing facts, it can be concluded that research of thermal conductivity of the fluidized bed shows the existence of dispersion of results obtained by various authors, since they show complex dependence of thermal conductivity coefficients on various factors. Therefore, it is very difficult to give any approximation of the obtained results by some global empirical dependence. For practical calculations, it is much more reliable to take absolute values of coefficient λ at a given moment, obtained on the basis of results of experimental research in conditions which are similar to calculative.

EXPERIMENTAL RESEARCH OF THERMAL CONDUCTIVITY IN THE FLUIDIZED BED

The goal of experimental research of the fluidized bed in this paper is the determination of thermal conductivity coefficient and of thermal diffusion in axial and radial directions, depending on operational characteristics of the fluidized bed: velocity, fluidization rate, and the size of particles. Experimental research was conducted on a laboratory apparatus made at Mechanical Engineering Faculty of Nis. The apparatus consists of a measuring part placed under the pipe that supplies heated sand to the bed in addition to a device for the supply of air and another device for measurement, regulation, and registering of the process. Special attention was paid to the construction of the device for the supply of heated sand into the bed. The material, which was previously heated up to temperature 250-350°C, was instantaneously inserted into the fluidized bed by quick surface pouring through the pipe of 45mm into diameter onto bed surface.

A fan from the external environment supplies the air necessary for fluidization. The flow of air is measured by a standard orifice, while the valve enables the desired flow of air. The sections in front of and behind the orifice are long enough to stabilize the flow of air. A chamber isolated by glass wool enables an even distribution of air on the intersection of the operational part of the apparatus. A distributor is placed at the inlet into the operational part of the apparatus, while a tapered extension is placed above, which prevents the removal of minor fractions. Chromel-alumel thermocouples are used for temperature measurement; one of them is placed just above the distributor, while the other is placed at the outlet from the bed.

PRIOR MEASUREMENTS

In order to start experimental determination of the thermal conductivity coefficient, certain measurements were performed prior to it. Siliceous sand with different fractions was used as material for fluidization. It sand was selected because of its favorable application in numerous processes in fluidized beds (for example, carbonization of coal in the fluidized bed). Subsequent to sifting in standard sieves, fractions of siliceous sand with average particle diameter 0.3mm, 0.5mm, and 0.9mm, were separated. Within prior measurements, the following characteristics were determined for each fraction:

- actual sand density $\rho_{\rho,}$
- bulk sand density $\rho_{n,}$
- equivalent particle diameter d_p,
- porosity at minimal fluidization rate $\varepsilon_{mf,}$
- minimal fluidization rate U_{mf}.

Bulk particle density of particles was determined by pouring freely a certain mass of sand into a calibrated vessel, while the actual density was determined by a picnometer. The value of specific thermal capacity was taken from literature [4].

As has been said, for determining the thermal diffusivity coefficient in the axial direction, two thermo pairs are placed in the axis of the stagnant bed, whereby the first was placed at 43.5mm from the distributor, and the second on the surface of the bed. Subsequent to this, the fan is started; by adjusting the flow of air, the desired velocity of air at working temperature is obtained. At this working velocity of air, with known minimal fluidization rate, the fluidization rate was determined. In this established state, an already prepared portion of previously heated sand is instantaneously, very quickly, inserted through the fixed pipe. During the movement of inserted hot sand through the fluidized bed, the thermo pairs measured temperature in the bed, while registration was performed on an acquisition system. For a set fluidization rate, separate bed temperatures were registered at each 0.02s. What can be noticed is that temperature in the bed increases, due to the movement of hot sand particles. At the same time, the time span between two maximal increases in temperature registered by the thermo pairs is read. For known distance between the thermo pairs and read time, the value of the thermal diffusivity coefficient is calculated. Since thermal diffusivity is determined in the axial direction, it is assumed that, in equation $\tau_{\max} = r^2 / 2na$, the value of $n = 1$ [3]. For a certain fluidization rate and the existing conditions, the experiment was repeated several times. The velocity of air was then increased and another experiment was performed, for the same sand fraction, in the way described above. After measuring a certain fraction, the operational part of the apparatus is emptied and another fraction is pouring; the same experiment is repeated on it.

In our own experiment, the values of the thermal diffusivity coefficient in the radial direction were determined by the same procedure as the values of axial diffusivity. As has been described, the difference lay in the positions of thermo pairs, which were, in this case, in the same plane, and in the value of constant n, which was now $n = 3$.

ANALYSIS OF EXPERIMENTAL RESULTS

On the basis of experimental results, diagrams of dependence of change in the thermal diffusivity coefficient on the fluidization rate were made. The coefficient changed as a parameter within anticipated limits, in both axial and radial directions. A comparative review of the dependence of the thermal diffusion coefficient on the fluidization rate for all three sand fractions is given. This dependence is highly complex, so that explanations of the effect of velocity are sometimes contradictory in existing literature.

With the increase of the fluidization rate, the thermal diffusivity coefficient in the axial direction increases for all three cases of the size of sand particles, whereby different increase rates can be noticed. Naturally, it must be remembered that the main reason for the increase of the thermal diffusivity coefficient with the increase of fluidization rate is a more intensive mixing of particles. With particles with average equivalent diameter of 0.3mm, the thermal diffusivity coefficient continually increases up to the value of the fluidization rate $N = 3$, when a sudden increase of its value can be noticed, while the fluidized state becomes similar to one of the 'bad' forms of fluidization. Uniformity of fluidization is not guaranteed for a certain fluidization rate, so that the character of the bed causes the dispersion of results.

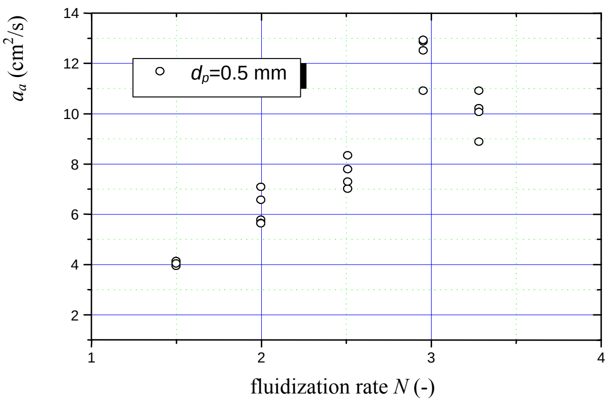

Fig. 1. Dependence $a_a = f(N)$

With particles of average equivalent diameter 0.5mm, a more intense tendency towards the increase of the thermal diffusivity coefficient with the increase of the fluidization rate can be noticed (Fig. 1). The maximum of the thermal diffusivity coefficient at approximate fluidization rate $N = 3$ can appear as a consequence of an increased content of smaller particles in the sand sample. However, it can be confirmed that the main reason for the occurrence of extremes is the maximal intensity of mixing of particles, i.e. transition from one form of fluidization into another. In the case of the largest particles, the experiment showed the biggest increase of the thermal diffusivity coefficient with the change of the fluidization rate.

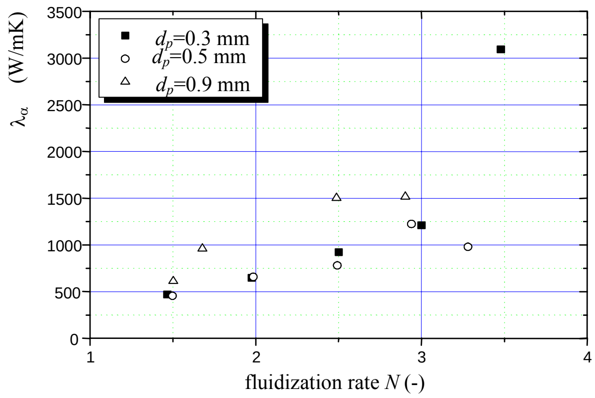

Fig. 2. Dependence $\lambda_\alpha = f(N)$

For assessment of the intensity of mixing in the fluidized bed, the coefficient of effective thermal conductivity is authoritative. In view of the interrelationship between thermal conductivity and thermal diffusivity coefficients, Figure 2 shows the dependence of averaged values of the thermal conductivity coefficient on the velocity of the fluidization agent. Since thermal conductivity and thermal diffusivity are connected through specific thermal capacity of particles and the density of the fluidized bed, which directly depends on the porosity of the bed, the way in which the thermal conductivity coefficient changes with the fluidization rate is similar to the way in which the thermal diffusivity coefficient changes with the fluidization rate. The maximal value of thermal conductivity, which occurs at fluidization rate of approximately $N = 2.5$, once again points to the fact that, at that velocity of the fluidization agent, the mixing of particles brings about more intense contacts and collisions of solid particles. The occurrence of the maximum can also be accounted for by a decrease in the density of the fluidized bed, and an increase in its porosity with the increase of gas velocity, which may cause differing character of the change of the thermal conductivity coefficient.

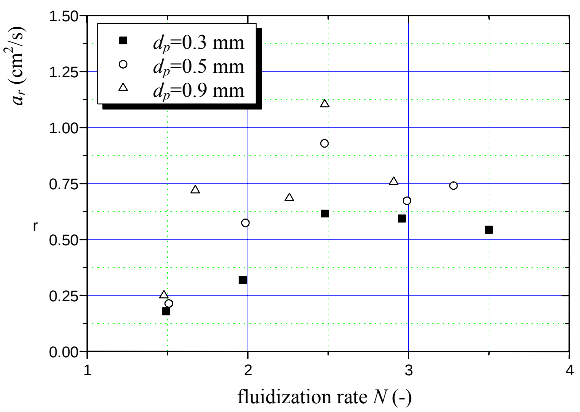

Fig. 3. Dependence $a_r = f(N)$

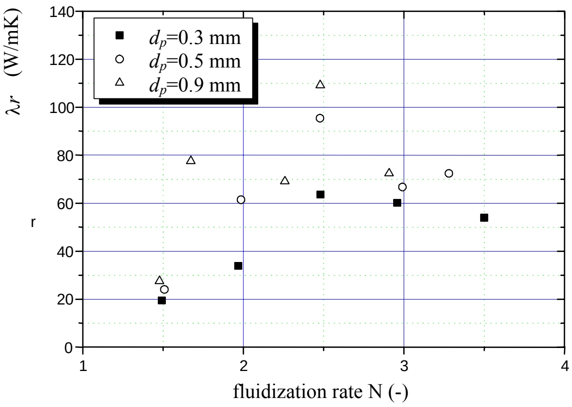

Fig. 4. Dependence $\lambda_r = f(N)$

Generally, the obtained values of the thermal diffusivity coefficient in the radial direction are smaller by an entire order (Figures 3 and 4). In contrast to diffusivity coefficient in the axial direction, in this case, what can be observed with all average equivalent diameters is occurrence of the maximum of the thermal diffusivity coefficient in the radial direction at fluidization rate $N = 2.5$. According to numerous researchers [1, 2], the local concentration of particles influences the passage of heat in the sense of its intensification, when the model of annular distribution of particles on the transverse section of the column, with a solid core in the center, a rarefied bed around the core, and a dense ring next to the wall, is deteriorated. At the same time, the mixing of particles and the frequency of their mutual collisions increases, which enhances a more intensive diffusion of heat. These facts show that it is within this fluidization rate that the most optimal fluidization rate, from the standpoint of the best thermal conductivity, can be found. Certain fluctuations of the values of thermal diffusivity can be observed in the diagrams of dependence of the thermal diffusivity coefficient on the fluidization rate. The cause of these fluctuations may be a successive arrival of differently heated particle packages at observed places, and sometimes bubbles which pass through the bed. When the bubbles go through the bed, at some moment, one of the two thermo pairs may be inside a bubble, thus registering the temperature of air inside the bubble. Since the temperature of air inside a bubble is higher than the temperature of air and of solid particles in the emulsion phase, an increase of temperature will occur at that place at that moment.

By means of their interaction, all treated hydrodynamic parameters influence in a highly complex manner global heat transfer in the fluidized bed, and, consequently, thermal diffusivity and thermal conductivity coefficients. Domination of some of them occurs only in a limited range. The results obtained through the experiment point to the fact that porosity of the bed, i.e. concentration of particles, although a very important factor of heat transfer in the fluidized bed, is not independent from particle flux, relative particle and gas velocity, and reverse mixing.

CONCLUSION

On the basis of the presented results of experimental and theoretical research of thermal diffusivity and thermal conductivity coefficients in the fluidized bed which have been conducted so far, as well as on the basis of the results of our own experimental research, it has been confirmed that the fluidized bed has very good thermal conductivity, which enables its application in numerous industrial processes of heat exchange.

The results obtained in experimental research have shown that thermal diffusivity and thermal conductivity coefficients depend on hydrodynamic structure of the fluidized bed. Although the change in thermal diffusivity and thermal conductivity coefficients differs in axial and radial directions, it generally depends on fluidization rate and the size of particles.

For all treated fractions of the sand, the values of the thermal conductivity coefficient of the fluidized bed in the axial direction were within 450-3100 W/mK, which also represents maximal reached value in all measurements. The obtained values of those same coefficients in the radial direction are within 19-110 W/mK, which provides a satisfactory level of agreement with the results of other authors.

Despite the complexity of the analysis of thermal conductivity through the fluidized bed and existing constraints of the used laboratory apparatuses, the obtained results provide a realistic review of thermal conductivity in the fluidized bed [3], so that they can be used with actual industrial plants, whereby all future theoretical and experimental research of the process of heat conduction in the fluidized bed should be directed towards the creation of a unique physical and mathematical model for the thermal conductivity coefficient.

NOTATION

a – the thermal diffusivity coefficient (m^2/s)
Ar – Archimedes number
c_p – specific thermal capacity of solids (J/kgK)
D_s – solid diffusivity (m^2/s)
H – enthalpy (kJ/kg)
N – the fluidization rate
ε – porosity of fluidized bed
ρ_p – solid density (kg/m^3)

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KOEFICIJENTI TOPLOTNE DIFUZIVNOSTI GASOM FLUIDIZOVANOG SLOJA

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U ovom radu izvršeno je eksperimentalno istraživanje koeficijenata toplotne provodnosti i toplotne difizovnosti gasom fluidizovanog sloja kvarcnog peska. Takođe je dat kratak osvrt na dosadašnja istraživanja ovih koeficijenata od strane drugih autora čiji su se eksperimenti odvijali u uslovima sličnim sopstvenom eksperimentu. Na bazi eksperimentalnih istraživanja izvršena je analiza uticaja radnih parametara procesa na dobijene vrednosti toplotne provodnosti sloja. Rezultati pokazuju direktnu zavisnost toplotne provodnosti od intenziteta mešanja-stepena fluidizacije i od veličine čestica. U aksijalnom pravcu tretirani koeficijenti imaju za čitav red veličine više vrednosti od istih u radijalnom pravcu. Upoređenje rezultata eksperimentalnog istraživanja sa eksperimentalnim rezultatima drugih autora pokazuje dobro slaganje i istu tendenciju promene toplotne provodnosti u zavisnosti od veličine čestica i intenziteta mešanja.

Ključne reči: *fluidizovani sloj, razmena toplote, eksperiment, toplotna difuzivnost, toplotna provodnost*