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THE INFLUENCE OF THE BED VOIDAGE ON HEAT TRANSFER BETWEEN IMMERSED HEAT TRANSFER SURFACES AND CIRCULATING FLUIDIZED BED

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Abstract. *The paper presents theoretical knowledge and practical experiences from the experiment on heat transfer between immersed heat transfer surfaces and circulating fluidized bed (CFB). Both theory and experiments agree that heat transfer coefficient is strongly dependent on hydrodynamics of the bed, i.e. on the bed voidage, which is the most important hydrodynamic factor.*

1. HYDRODYNAMIC MODELS OF CFB

Circulating fluidized bed is one of recently developed regimes of fluidization, which belongs to the group of so called transport regimes. The main characteristic of CFB is continual entrainment of solids out of the bed. The solids circulate along the circulation loop, which connects all parts of the CFB. The condition of CFB is marked by relatively high solids concentration, agglomeration of solids into clusters and strands which are destroyed quickly and formed again by intensive backmixing of particles.

Radial nonuniformity of bed voidage, at least for smaller bed cross-sections is widely accepted. There are some doubts about voidage distribution in large industrial units, due to lack of data for large diameter beds. There is general consensus about the existence of a denser bed in the lower part and relatively dilute regions in the upper part of the reactor. Relative position of those phases in a system depends on gas velocity, particle circulation and pressure drop. The solids from group A of Geldart's classification (ρ_p<1400kg/m^3, d_p=0.020÷0.100mm) are usually used in CFB.

Fundamental investigations of the CFB are behind it's practical application in industry. It is obvious, especially in the field of CFB hydrodynamics, because there is no unique model of hydrodynamics. Empiric nature of the published models limits their

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application on experimental conditions from which they are derived. The majority of hydrodynamic models of CFB consider axial profile of particle or gas phase concentration. Some models follow the investigations of bubbling fluidized beds and use some expressions from bubbling beds for some regions of CFB.

The model of *Kwauk* et al. *(1985)* is one of the mostly accepted hydrodynamic models. They considered that the CFB consists of dilute continuum of separately distributed particles and relatively dense strands or clusters, dispersed in it. Clusters or strands are formed quickly and then broken, making new agglomerations of particles. *Kwauk* derived the equation for bed voidage ε along the bed height z:

$$\ln\frac{\varepsilon-\varepsilon_b}{\varepsilon-\varepsilon_t}=-\frac{1}{z_0}=(z-z_i) \tag{1}$$

Equation (1) plotted ε vs. z gives an S - shaped curve (Fig. 1.). The point of inflection z_i on the curve marks the transition from the bottom region of the dense phase to the top region of the dilute phase. Characteristic length z_o represents the length of transition region from dense to dilute phase. At the bottom of the bed voidage tends to ε_b as $z\rightarrow+\infty$, and at the top of the bed voidage tends to ε_t as $z\rightarrow-\infty$.

The deficiency of the model of *Kwauk et al.* is that it considers the average bed voidage ε in the cross-section of the CFB. The investigations have proved radial nonuniformity of CFB. In the axis of the bed there is dense core, surrounded by dilute annular region. Near the bed wall there is dense layer where particles move up and down.

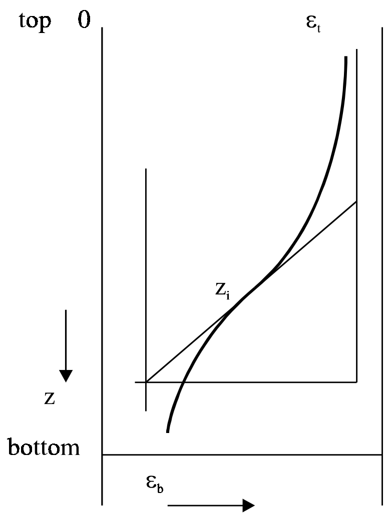

Fig.1. S-curve of voidage distribution

2. Heat transfer models of circulating fluidized bed

Three main heat transfer processes in CFB, as well as in bubbling beds occur, the most important of which is heat transfer between CFB and heat exchange surfaces. Other two processes, between particles and gas and heat transfer from one part of the bed to the other, are less important for investigation, because active zone of heat transfer at the entrance of the bed is so short, that the bed is considered isothermal throughout the volume. High heat transfer coefficients between heat exchange surfaces and a bed enable heat transfer and temperature drop to occur just near heat exchange surface, while the rest of the bed remains isothermal. Experimental investigations are conducted only on laboratory scale apparatusses. There are still not published results about experiments on large industrial units, and it is a good reason to suppose that such results can somewhat change existing understanding of heat transfer in CFB.

Heat transfer between suspension and heat exchange surface is the most important heat transfer process in CFB. Overall heat transfer coefficient suspension-surface can be divided into three separate components: h_{gc}- gas phase convection, h_{pc}- particle phase convection and h_r- radiation.

$$h = h_{gc} + h_{pc} + h_r \ . \tag{2}$$

Models of heat transfer between suspension and heat exchange surfaces in the circulating fluidized bed are based on the models of heat transfer in conventional fluidized beds. The base of those models is the "packet model" of *Mickley* and *Fairbanks* and the modifications of *Baskakov*, who introduced additional thermal resistance of the gas film on the heat transfer surface. In these models heat transfer by the particle convection is modeled as the process of unstationary conduction of the particle clusters which are in contact with heat exchange surface for a definite period of time, nearby the heat exchange surface there is a gas film which transfers heat by gas conduction. Particle convection heat transfer coefficient is defined as:

$$h_{pc} = \frac{1}{\dfrac{1}{h_w} + \dfrac{1}{h_s}} \ . \tag{3}$$

Heat transfer coefficient of the gas conduction through the gas boundary layer on the heat exchange surface depends on gas film thickness:

$$h_w = \frac{\lambda_g}{\delta} \ . \tag{4}$$

The thickness of gas film has the values of (0,1 -0,4)d_p. The component of particle convection h_s, which comes from suspension or clusters is modeled depending on suspension hydrodynamics on heat exchange surface.

Although there is great variety of heat transfer models, the majority of them consider particle concentration, or the bed voidage as the most significant hydrodynamic factor in heat transfer between the bed and heat exchange surfaces.

Basu et al. (1988) proposed a model of heat transfer in circulating bed, based on the theory of clusters, where total heat transfer coefficient (including radiation) is defined as

$$h = h_{cl}\delta_{cl} + (1-\delta_{cl})h_d + h_r \ , \tag{5}$$

where δ_{cl} is the part of the heat exchange surface covered by clusters:

$$\delta_{cl} = \frac{x(1-\varepsilon_{cl})-y}{1-\varepsilon_{cl}-y} \quad . \tag{6}$$

In the equation (6) y is the volume fraction of solids in the dilute phase (out of clusters) and x is the ratio of volume concentration of solids on the wall to that averaged over the cross-section of the bed. Particle convective component from clusters of voidage ε_{cl}, which are in contact with heat exchange surface during the period of time t_{cl} is:

$$h_{cl} = \frac{1}{\dfrac{d_p}{10\lambda_g} + \sqrt{\dfrac{t_{cl}}{4\lambda_{cl}\rho_p(1-\varepsilon_{cl})}}} \quad . \tag{7}$$

Particle convective component from clusters is directly proportional to the concentration of solids in the clusters $C_{cl} = (1 - \varepsilon_{cl})$. Since the component h_{cl} is dominant in the great part of the CFB operating range, the influence of particle concentration is very significant to heat transfer between immersed heat transfer surfaces and the circulating fluidized bed. It means that particle concentration increase directly increases total heat transfer coefficient.

The model of *Martin* (1984), primary developed for conventional fluidized beds, can be applied on circulating fluidized bed, since it is valid in the wide range of concentrations from C_{mf} to $C \to 0$ and high fluidization velocities, that cover circulating fluidized beds. *Martin'*s model predicts strong dependence of heat transfer on average solid concentration, which is in agreement with experimental results.

$$\frac{h_{pc}d_p}{\lambda_g} = CZ\left[1-\exp(Nu_{pc}/kZ)\right] \tag{8}$$

The lack of this model is that it takes into account the average concentration of the bed cross-section, and not the one around the heat transfer surfaces.

The model that underlines the influence of the particle concentration the heat transfer in the circulating fluidized bed most of all is the model of *Fraley* et al. (1983). It expresses the heat transfer coefficient as the dependence on the suspension density only. Two equations are given - for the axis of the bed (9) and for the bed wall (10):

$$h = 10.2\rho_s^{0.656} \tag{9}$$

$$h = 2.87\rho_s^{0.902} , \tag{10}$$

where suspension density is

$$\rho_s = C\rho_p + (1-C)\rho_g \; . \tag{11}$$

3. Experimental investigations

An experimental investigation of heat transfer in CFB was conducted on laboratory scaled apparatusses made of plexiglas. Column or a riser is 120mm in inner diameter and 5m in height. On the outlet of the column, there is a cyclone, 200mm in diameter and 600mm in height, which effects the recovery of the solids through the recirculation column, or return-leg and through the flow-valve back to the circulating bed. Flow valve is a non-mechanical V-valve, or loop seal, designed as a double chamber. Solids from the return-leg come to the first chamber and flow over to the second, where bubbling fluidization is affected by the fluidization air. Fluidized solids are risen to the top of the chamber and returned to the column through the connecting pipe. Heat exchange surface is a copper tube with an electric heater (100W) inside, and thermocouples on outer surface. Fluidization air is divided on main stream for circulating fluidized bed and secondary air for bubbling fluidized bed in the flow-valve. By secondary air quantity the dosing of solids into the bed is regulated. The power of electric heater is regulated by voltage variation with a variable transformer. Air temperature is measured by thermocouples. Inlet air temperature is measured in front of the orifice plate, and bed air temperature at the height of 2.1m above the distributor plate.

Heat transfer coefficient between heat exchange surface and the CFB is estimated as:

$$h = \frac{VI}{F(t_W - t_b)} \tag{12}$$

Quartz sand, which was used in the experiment has the following properties:

- mean particle diameter d_p= 0,150 mm
- density ρ_p= 2669 kg/m^3
- bulk density ρ_ε=1340 kg/m^3
- Geldart's classification group B

In axial direction heat transfer coefficient varied from the bottom to the top of the bed in the following range:

H (mm)	h (W/m^{2}K)
800	120.46-321.54
1700	72.49-220.31
2550	72.88-197.43
3550	62.06-233.27

Fig.2. shows heat transfer coefficient distribution along the bed height in characteristic radial ratios and at different fluidization velocities. Comparison of the values of heat transfer coefficients for four different heights shows that the highest values are obtained in the lower part of the bed. The values decrease along the bed height from the bottom to the top of the bed. This is direct consequence of suspension density, i.e. voidage distribution according to the S - curve (*Kwauk* et al. 1985).

Decreasing of the value of heat transfer coefficient is obvious along the bed height, but it is the most extending after the first measuring height, after which decreasing is much slower. It shows that somewhere about the first measuring height could be placed inflection point on the curve of axial voidage distribution. Similarity of the shapes of experimental curves of heat transfer coefficient distribution and the curve of bed voidage distribution confirms direct dependence of the heat transfer coefficient on concentration.

Experimental investigations of both hydrodynamics and heat transfer in CFB show a strong dependence on particle concentration in CFB. Particle concentration is the key factor of the hydrodynamics of CFB. The dependence of heat transfer between immersed

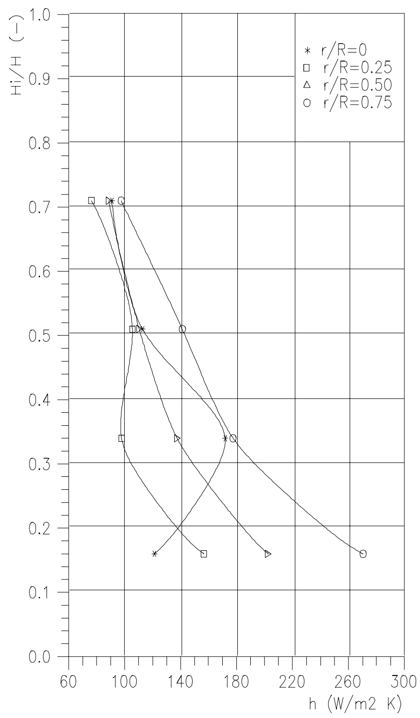

Fig.2. Axial distribution of heat transfer coefficient at fluidization velocity of *U*=3.33m/s in four radial positions.

heat transfer surfaces and CFB comes from dominant contribution of particles convection to the overall heat transfer, and the importance of particle concentration on it. Experimental investigations of axial profile of heat transfer show that it varied from the bottom to the top in the same way as the particle concentration of the bed, i.e. inversely from the voidage.

4. Conclusions

The results of experimental investigations confirmed the existence of direct dependence of heat transfer coefficient between immersed heat transfer surfaces and CFB on hydrodynamic structure of CFB. The changes of heat transfer coefficient in axial direction follows the changes of local bed voidage. Heat transfer coefficient decreases from the bottom to the top, with the curve which corresponds to the S-curve of bed voidage, but for the heat transfer coefficient such curve is not yet defined. Inflection point on S-curve of bed voidage represents the boundary between lower dense bed and the top dilute phase. The results of the experiments show that this boundary is not only the transitions between the regions with different bed voidage, but also the transitions between the regions with different intensity of heat transfer in axial direction.

Notation

C	- volumetric concentration (-)
d_p	- mean particle diameter (mm)
H	- height (m)
h	- heat transfer coefficient (W/m^2K)
F	- electric heater outer surface (m^2)
I	- electric current (A)
k	- constant
Nu	- Nusselt number (-)
r/R	- radial ratio (-)
t	- time (s)
t	- temperature (^oC)
V	- voltage (V)
z	- coordinate (m)
Z	- dimensionless coefficient (-)
z_o	- characteristic length (-)
δ	- gas film thickness (m)
ε	- voidage (-)
λ	- thermal conductivity (W/mK)

Subscripts

b	- bottom
cl	- cluster
g	- gas
i	- inflection point
p	- particle
pc	- particle convection
r	- radiation
s	- suspension
t	- top
w	- wall

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UTICAJ POROZNOSTI SLOJA NA RAZMENU TOPLOTE IZMEĐU URONJENIH IZMENJIVAČKIH POVRŠINA I CIRKULACIONOG FLUIDIZOVANOG SLOJA

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U radu su prikazana teorijska saznanja i rezultati realnog eksperimenta o razmeni toplote između uronjenih izmenjivačkih površina i cirkulacionog fluidizovanog sloja (CFB).