CI&CEQ
Chemical Industry & Chemical Engineering Quarterly
Available on line at
Association of the Chemical Engineers of Serbia *AChE*
www.ache.org.rs/CICEQ
Chem. Ind. Chem. Eng. Q. 21 (4) 519–526 (2015) CI&CEQ

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SCIENTIFIC PAPER

UDC 66.096.5:536.2:51

DOI 10.2298/CICEQ141022008A

EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN THREE-PHASE FLUIDIZED BED COOLING COLUMN

Article Highlights

- A three-phase fluidized bed was used to study the heat transfer characteristics of the system
- The overall heat transfer in this system was compared to the existing literature correlations
- The smallest error for the case of heat transfer correlation for fluidized beds was obtained
- A new correlation was proposed specifically for the three-phase countercurrent contactor
- Hydrodynamic parameters were calculated according to the available literature correlations

Abstract

A three-phase (gas-liquid-solid) fluidized bed was used to study the heat transfer characteristics of a system consisting of low-density (290 kg/m^3) spherical particles (2 cm diameter) in a 0.25 m cylindrical column with counter-current flow of water and air. The experimental investigation and mathematical modeling of heat transfer between the hot air and the cooling water was carried out. The experiments were conducted for a variety of different fluid flow rates and inlet air temperatures, while the air flow rate was kept constant. Based on the obtained experimental results, a new correlation for heat transfer in a three-phase fluidized system was proposed. The mean percentage error between the experimental and the correlated values of the j_{Hp} obtained was 1.69%. The hydrodynamic parameters of the system were also calculated according to the available literature correlations.

Keywords: turbulent bed contactor, fluidization, heat transfer coefficient, hydrodynamics.

Three-phase fluidized bed systems provide very efficient contact between the present solid, liquid and gaseous phases. They can be applied in various physical, chemical and biochemical processes [1]. Three-phase fluidized bed systems offer considerable advantages over conventional packed-bed columns because they operate at high gas velocities, they have high mass-transfer rates and the mobility of the packing prevents plugging. This makes three-phase systems suitable for handling streams containing particulate matter and precipitates. In addition, there is practically no channeling or bypassing. The high gas and liquid throughputs are made possible by bed expansion by which the flooding is avoided. Some of the disadvantages of three-phase systems include bed pulsations, back mixing in the liquid phase and mechanical erosion of the packing spheres. However, the characteristics of high capacity and high mass transfer and particulate removal rate enabled their successful industrial application. Hydrodynamic properties of three-phase fluidized beds such as bed pressure drop, minimum fluidization velocity, liquid phase holdup, bubble properties, mixing characteristics and bed expansion are very important for analyzing their performance [2-16].

There are several types of three-phase fluidized bed systems [5]. The flow of the liquid and the gase-

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Paper received: 22 October, 2014
Paper revised: 9 February, 2015
Paper accepted: 10 March, 2015

ous phases in three-phase systems can be cocurrent or countercurrent. In the case of cocurrent flow of the liquid and the gas phase, the particles constituting the fluidized bed are usually of high density and of small particle diameter. In the case of countercurrent flow of the fluid phases, the fluidization phase can be either the gas or the liquid phase. Countercurrent fluidized beds in which the gaseous phase is used as fluidizing agent are characterized by the large spherical particles of low density. These types of contactors are often referred to as turbulent bed contactors (TBC). In this work, a countercurrent system was investigated, in which the gaseous phase (air) flows upwards and is used as a fluidizing medium, while the liquid phase (water) flows downwards and is used as a cooling medium.

O'Neill *et al.* [3] classified the operating regimes of the three-phase turbulent bed contactors as type I and type II. In type I regime, fluidization begins before flooding in the column, while for type II regime, fluidization begins after flooding in the column. Vunjak-Novakovic *et al.* [4] developed a chart that can be used for the determination of the type of operating regime in TBC systems.

Packing density contributes significantly to the operating mode. Generally, the packing density of more than 300 kg/m^3 is characteristic of the type II regime, while the packing density of less than 300 kg/m^3 is characteristic of the type I regime. Increasing the flow rate of the liquid phase and the reduction of the particle diameter of the package also changes the mode from type I to type II. Therefore, unlike packed bed towers, TBC systems may operate in flooding conditions (type II) [5].

While the hydrodynamic parameters of the TBCs were investigated by many authors [2-16], to our knowledge there are no available models in the literature describing the heat transfer between the liquid and the gaseous phases in these types of contactors. The main aim of this work was the experimental investigation of the heat transfer between the cold water and the hot air in a countercurrent turbulent bed contactor. Based on the experimental findings, a model for the heat transfer coefficient between the liquid and gas phase in TBC was proposed. The hydrodynamic parameters of the system (the minimum fluidization gas velocity, pressure drop through the bed, liquid hold-up, and bed expansion) were calculated using the available literature models best suited for our experimental system [4]. The countercurrent TBC contactor used in this work consisted of a bed of spherical particles and operated in type I regime.

EXPERIMENTAL SET-UP

The experiments were carried out in three-phase system with fluidized bed, which is used for cooling of the hot air, at different air and water flow rates. The experimental setup is shown in Figure 1. The measured variables included the inlet and the outlet air temperatures (T_{gi} and T_{ge}) as well as inlet and outlet water temperatures (T_{Li} and T_{Le}).

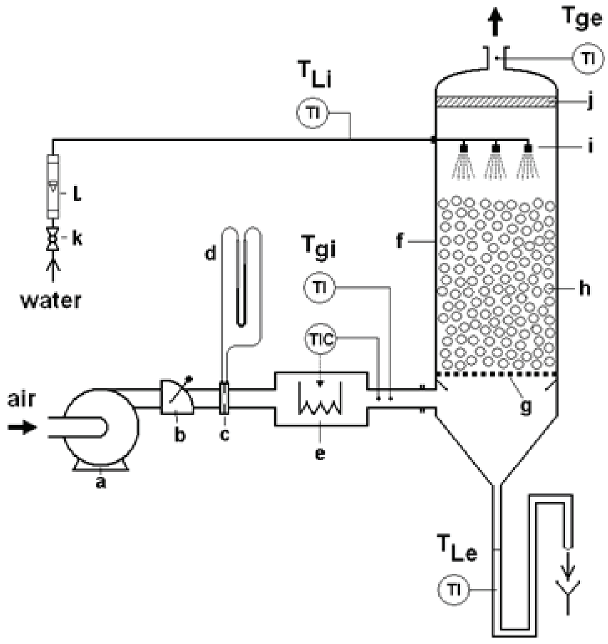

Figure 1. Experimental set-up of the three phase fluidized bed contactor (a - fan, b - butterfly valve for air flow rate regulation, c - throttle plates for air flow rate measurement, d - "U" manometer, e - electric air heater, f - column, g - steel mesh 5mm×5 mm, h - bed of plastic spheres, i - water spraying nozzles, j - drops separator, k - water flow rate control valve, L - rotameter; TIC - temperature indication and control, TI - temperature indicator).

Experimental measurements were performed at constant inlet air volumetric flowrate (V_g) of 275 m^3/h (at 20 °C) and constant inlet water temperature (T_{Li}) of 16 °C. Particle Reynolds number (Re_p) varies from 1795 to 1896 in the experiments because of the change of air velocity (u_g), viscosity (μ) and density (ρ_g) with temperature. A total of 40 experimental points were obtained for different water flowrates and different inlet air temperatures. The parameters of the system and the conditions at which the measurements were made are shown in Table 1.

Based on the water mass flux as well as on the diameter and density of the spheres the operating regime was determined according to the diagram proposed by Vunjak-Novakovic *et al.* [4]. It is clear that

Table 1. Basic parameters of the experimental system

Column diameter	D_c	0.25	m
Column cross-sectional area	A_c	0.04909	m^2
Diameter of light spheres	d_p	0.02	m
Density of light spheres	ρ_p	290	kg/m^3
Density of water	ρ_l	1000	kg/m^3
Static bed height	H_0	0.25	m
Water inlet temperature	T_{Li}	16	ºC
Mass of the particles in the bed	M_{bed}	1.779	kg
Mass of one particle (sphere)	M_1	$1.215 \cdot 10^{-3}$	kg
Number of particles	N_p	1465	pieces
The total external surface of the particles	A_p	1.841	m^2

our experimental system is in the operational mode of type I.

RESULTS AND DISCUSSION

Heat transfer coefficient

The purpose of the TBC used in this work was cooling of the hot air, which was introduced at the bottom of the column. Therefore, the objective was to achieve the gas outlet temperature as low as possible, and to achieve the best possible heat transfer between the cold water and the hot air. The experimental data of the outlet gas temperature as a function of liquid flow rate at constant air flow rate for three inlet air temperatures are shown in Figure 2. Figure 2 shows that with the increase in water flow rate, the outlet air temperature decreases, i.e. the cooling is improved, as expected.

The main objective of this study was the development of the correlation for heat transfer between the hot gas and the cooling water. If it is assumed that the entire amount of water is evenly distributed on the surface of the light solid spheres, the heat transfer actually occurs between the hot gas and the liquid film around the spheres. The overall heat transfer in this system includes the convective, conductive and the radiative heat transfer.

The radiative heat transfer coefficient is very small in temperature ranges lower than 600 °C [17], so it was neglected in this work, as the maximum temperatures in our system are in the range of 110 °C.

The conductive heat transfer between the hot air and the liquid film formed around the solid spheres was also neglected since the thickness of the liquid film around the particles was calculated to be between 0.012 and 0.023 mm (Figure 3). The conduction can be neglected through the hollow plastic sphere, since the air and plastic are substances with small thermal conductivity [18]. Only conduction can occur through the liquid film. The Biot number is defined as the ratio

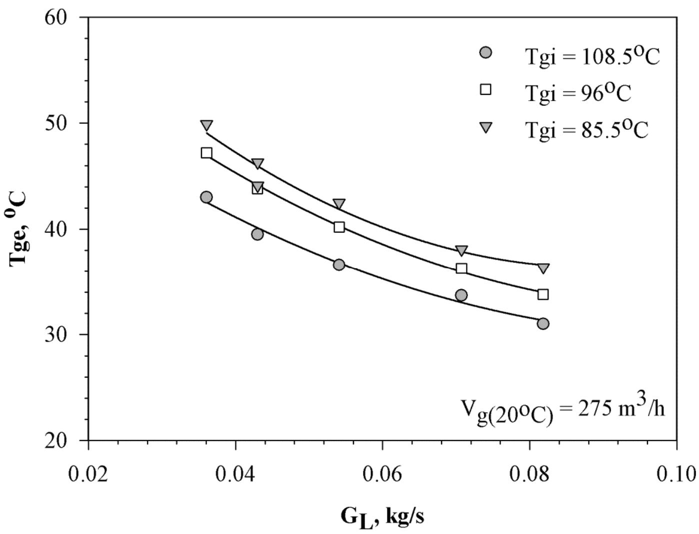

Figure 2. The outlet air temperature as a function of water flow rate at constant air flow rate of $V_{g\,(20\,°C)}$ = 275 m^3/h (G_v = 331 kg/h) for three inlet air temperatures.

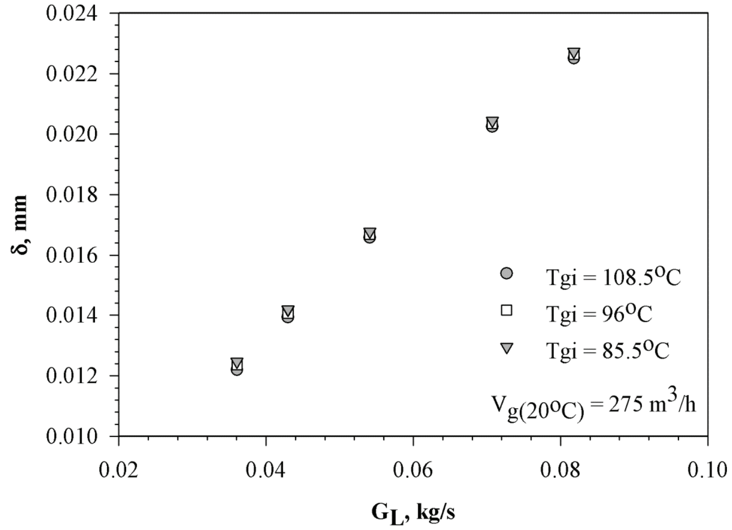

Figure 3. Liquid film thickness in function of water flowrate.

of the convective to the conductive heat transfer, $Bi = (h_p L)/\lambda_{water}$, where the liquid film thickness ($L = \delta$) was taken as a characteristic dimension. As the calculated values of the Bi numbers were much less than 1 ($Bi << 1$), it was concluded that there is negligible resistance to the heat transfer through the liquid film.

The liquid film thickness that is formed around the light spheres in the column was determined from Eq. (1) assuming that the entire amount of liquid present in the column is evenly distributed on the surface of the particles [19]:

$$\delta = 1000 \frac{d_p(\text{mm})}{2} \left[\sqrt[3]{1 + \frac{h(\%)}{100} \frac{\rho_p}{\rho_l}} - 1 \right] \quad (1)$$

The obtained liquid film thickness is presented graphically as a function of the water flowrate for three inlet air temperatures: 108.5, 96 and 85 °C (Figure 3). It can be seen that as the water flowrate increases, the thickness of the film also increases. On the other hand, the inlet air temperatures do not have a significant impact on the film thickness.

According to the above, it was assumed that the overall heat transfer coefficient K is approximately equal to the convective heat transfer coefficient and that all other mechanisms of heat transfer (conduction, radiation) are neglected. Additionally, since the liquid film is very thin, it is appropriate to use the particle diameter for all of the further calculations.

The heat transfer between the hot gas and the liquid film around the particles can be described according to the following equation:

$$Q = K A_p \Delta t_{lm} \quad (2)$$

where $K \approx h_p$, and:

$$\Delta t_{lm} = \frac{(T_{gi} - T_{Le}) - (T_{ge} - T_{Li})}{\ln \frac{T_{gi} - T_{Le}}{T_{ge} - T_{Li}}} \quad (3)$$

The overall heat balance is shown by the following equation:

$$G_v C_{pG}(T_{gi} - T_{ge}) = G_L C_{pL}(T_{Le} - T_{Li}) \quad (4)$$

where G_v and G_L represent mass flow rates of air and water, C_{pL} and C_{pG} specific heat of air and water, T_{gi} and T_{ge} inlet and outlet air temperature, T_{Li} and T_{Le} inlet and outlet water temperatures.

The amount of exchanged heat per unit time, Q, can also be determined from the total heat balance based on gas or on water. In this work, the balance is calculated on the basis of the gas phase, since the gas flowrate was kept constant:

$$Q = G_v C_{pG}(T_{gi} - T_{ge}) \quad (5)$$

In the above heat balances (Eqs. (4) and (5)) heat losses were neglected.

According to Eqs. (2), (3) and (5), h_p was calculated for each experimental run.

The obtained results are shown in Figure 4 as a function of Re_p. It can be seen that with increasing Re_p the heat transfer coefficient slightly decreases (except for the five points that do not follow the trend of other).

Since, to our knowledge, there are no literature correlations describing the heat transfer in turbulent bed contactors, the results obtained were compared to the correlations for heat transfer between the single sphere and the fluid flowing around it [20] as well as

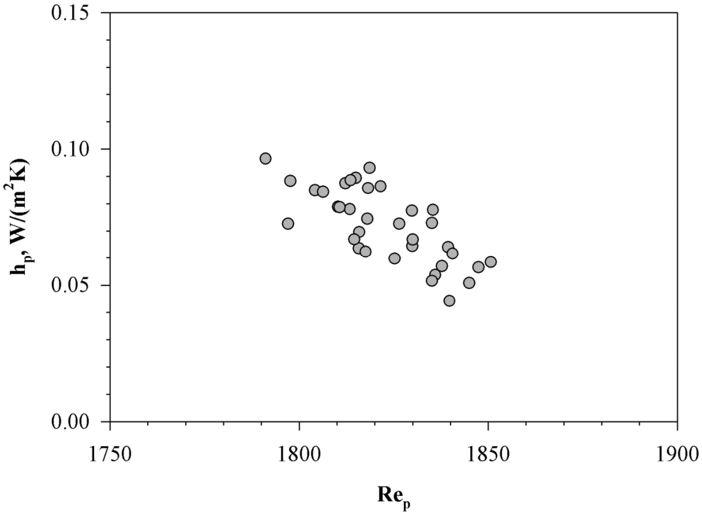

Figure 4. Dependence of heat transfer coefficient of Re_p.

with the correlations for overall heat transfer in packed and fluidized beds [21]. In order to be able to compare the results with the mentioned correlations, Nu_p number was calculated according to the equation:

$$Nu_p = \frac{h_p d_p}{\lambda} \tag{6}$$

Ranz and Marshall [19] correlation for heat transfer from the flowing gas to the single sphere in the form of Nusselt number is:

$$Nu_p = 2 + 0.6 Re_p^{1/2} Pr^{1/3} \tag{7}$$

Kunii and Levenspiel [20] developed correlations for heat transfer in packed beds (Eq. (8)) and in fluidized beds (Eq. (9)) in the same form with different coefficients:

$$Nu_p = 2 + 1.8 Pr^{1/3} Re_p^{1/2} \tag{8}$$

$$Nu_p = 2 + 1.5 Pr^{1/3} \left[(1-\varepsilon) Re_p\right]^{1/2} \tag{9}$$

The results of the comparison of our experimental data with the mentioned correlations are shown in Figure 5. As can be seen from the Figure 5, our experimental values of Nu_p lie mainly between the Nu_p numbers for the packed and fluidized bed systems, closer to the values of the fluidized bed. The mean percentage error of Nu_p in comparison with presented correlations is: for single spheres 49.2%, for packed bed 44.4%, and for fluidized bed 19.6%.

The smallest error obtained for the Nu_p number calculated according to the correlation for the fluidized bed was expected. However, an error of almost 20%

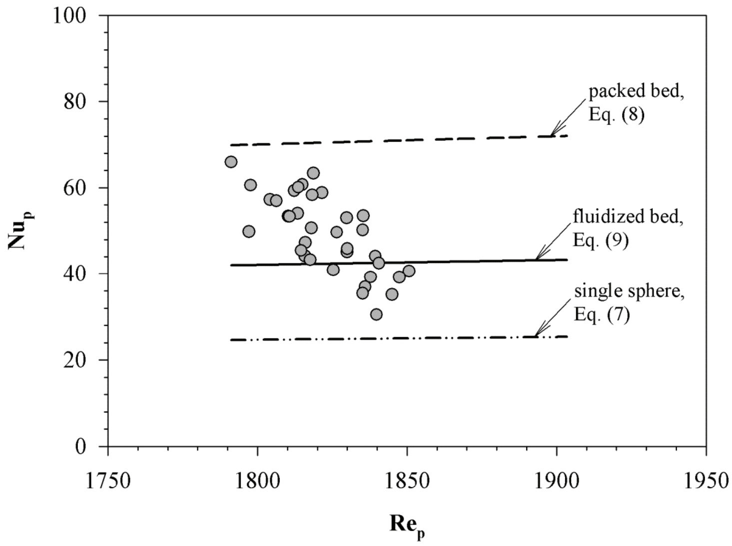

Figure 5. Comparison of the experimental values of Nu_p with literature correlations for single sphere heat transfer, packed and fluidized bed heat transfer.

is significant and that is why a new correlation based on our experimental data was proposed.

In this work, a correlation for heat transfer coefficient calculation was developed in the form of j_{Hp}:

$$j_{Hp} = \frac{Nu_p}{Re_p Pr^{1/3}} \tag{10}$$

The correlation is a function of gas and liquid flow rate and input and output gas temperatures (Eq. (11)):

$$j_{Hp}\left(\frac{L}{G}\right)^{0.1129} = 0.0787\left[\frac{T_{gi}-T_{ge}}{T_{gi}}\right]^{1.7815} \tag{11}$$

Comparison of experimental values of the j_{Hp} and the j_{Hp} values obtained by Eq. (11) is presented in Figure 6. The mean percentage error between the experimental and the calculated values was 1.69%, which represents a very good agreement.

Hydrodynamic parameters of the system

There are a variety of correlations in the literature for the calculation of basic hydrodynamic characteristics of three-phase fluidized bed contactors: liquid hold-up, pressure drop, minimum fluidization velocity and bed expansion [4-16]. However, the problem is that most of these correlations were derived for the specific test system and the range of the experimental data obtained in it. For the calculation of the hydrodynamic characteristics of our experimental system, Vunjak-Novakovic *et al.* [4,6] correlations were chosen, since they were obtained in the systems that are the most similar to our system. The parameters of the system on which the experiments were carried out are given in Table 2. Table 3 shows the corresponding correlations of Vunjak-Novakovic *et al.* [4,6].

The hydrodynamic characteristics of three-phase fluidized bed contactors: liquid hold-up, pressure drop, minimum fluidization velocity and bed expansion were calculated by Vunjak-Novakovic et al. [4,6] correlations given in Table 3. The calculated values of hydrodynamic parameters in our TBC system are given in Table 4.

CONCLUSIONS

The experimentally investigated three-phase system consisted of a fluidized bed of light hollow spheres, with countercurrent flow of hot air and cooling water. The main objective of the study was the development of a correlation for heat transfer coefficient calculation. It was assumed that the total amount of liquid hold-up was evenly distributed on the surface of the solid spheres and that the heat transfer actually occurred between the hot gas and the liquid film around the spheres. The overall heat transfer in this system was compared to existing literature correlations for heat transfer between a single sphere and

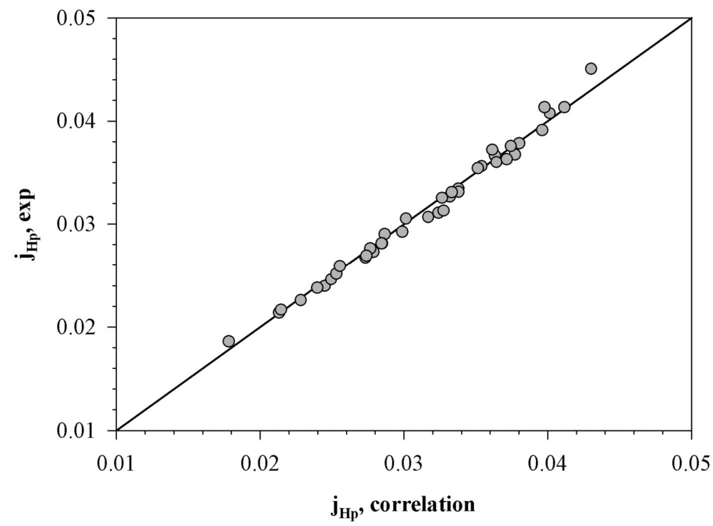

Figure 6. Comparison between the experimental values of j_{Hp} and the values of j_{Hp} calculated from correlation (Eq. (11)).

Table 2. System parameters in Vunjak-Novakovic et al. [4,6] and in our work

Reference	f	H_0 / cm	u_l / m s^{-1}	u_g / m s^{-1}	D_c / cm	d_p / mm	ρ_p / kg m^{-3}
[4,6]	0.36-0.78	10-30	0-0.034	0-4	14-29	10-38	182-980
This work	0.7	25	1.73-1.84	0.001-0.002	25	20	290

Table 3. Used correlations for calculation of the basic hydrodynamic characteristics [4,6]

$$\varepsilon_{l,st} = 6.49 Fr_l^{0.858} Re_l^{-0.139} \left(\frac{H_0}{D_c} \right)^{-0.567}, \text{ Type I operation [4]} \quad (12)$$

$$u_{mF} = k d_p^{1.2} \left\{ (1-\varepsilon_0)(\rho_p - \rho_g) + 2.48\times10^{-3} \rho_l d_p^{-0.568} L^{0.719} 10^{-4.788\times10^{-2} L} \right\}^{0.5}, k = \left(\frac{g}{m\rho_g} \right)^{0.5}, m = 0.064 \text{ [6]} \quad (13)$$

$$\Delta p = \left\{ (1-\varepsilon_0)\rho_p + h_{L0}\rho_l \right\} g H_0 \text{ [6]} \quad (14)$$

$$\frac{H}{H_0} = \frac{\left(1-\varepsilon_0 + 0.00248 \left(\frac{H_0}{D_c} \right)^{-0.567} d_p^{-0.568} L^{0.719} + 0.02 \right)}{\left(1 - 0.62 u_g^{0.237} \right)}, \text{ Type I operation [6]} \quad (15)$$

Table 4. Calculated values of hydrodynamic parameters

$\varepsilon_{l,st}$ / m^3 m^{-3}	Δp / Pa	$u_{mF, avg}$ / m s^{-1}	($H/H_{0, avg}$) / m m^{-1}
0.023-0.013	413.1-386.2	1.43	1.96

the fluid flowing around it, as well as with the correlations for overall heat transfer in packed and fluidized beds. The smallest error for the case of correlation for fluidized beds was obtained.

As the existing literature correlations for heat transfer did not have sufficient accuracy, a new correlation was proposed specifically for the three-phase countercurrent contactor, given in Eq. (11).

The basic hydrodynamic characteristics of the experimental system were also calculated according to the available literature correlations. The most appropriate correlations proposed by Vunjak-Novakovic *et al.* were chosen according to the parameters of the system.

Acknowledgement

Financial support of the Serbian Ministry of Education, Science and Technological Development (Project ON172022) is gratefully acknowledged.

Nomenclature

A_c - cross-sectional area of the column (m^2)
A_p - total particle outer surface area (m^2)
Bi - Biot number
C_{pG} - heat capacity of air (J/kg K)
C_{pL} - heat capacity of water (J/kg K)
D_c - column diameter (m)
d_p - light particle diameter (m)
f - fractional free area of support grid
F_{rl} -Froude number for liquid phase, $u_l/(gd_p)^{1/2}$
g - gravitational acceleration, 9.81 m^2/s
G_L - water mass flowrate (kg/s)
G_v - air mass flowrate (kg/s)
H - height of expanded bed (m)
H_0 - static bed height (m)
h - liquid hold-up (%)
h_{Lo} - operational liquid hold-up (m^3/m^3)
h_p - convective heat transfer coefficient (W/(m^{2}K))
j_{Hp} - heat transfer factor
K - overall heat transfer coefficient (W/(m^{2}K))
L - water mass flux (kg/(m^2 s))
M_1 - weight of single sphere (kg)
M_{bed} - bed weight (kg)
N_p - number of particles
Nu_p - Nuselt number for particle
Pr - Prantl number
Q - exchanged heat per unit time (W)
Re_l - Reynolds number for water, $(D_c u_l \rho_l)/\mu_l$
Re_p - Reynolds number for particle, $(d_p u_g \rho_g)/\mu_g$
T_{ge} - outlet air temperature (°C)
T_{gi} - inlet air temperature (°C)
T_{Le} - outlet water temperature (°C)
T_{Li} - inlet water temperature (°C)
$V_{g\,(20°C)}$ - volumetric air flowrate at 20 °C (m^3/h)
u_g - superficial air velocity (m/s)
u_l - superficial water velocity (m/s)
u_{mf} - minimum fluidization air velocity (m/s)
Δp - pressure drop in the column (Pa)
Δt_{lm} - logaritmic temperature diffference

Greek symbols

λ - air thermal conductivity (W/(m K))
λ_{water} - water thermal conductivity (W/(m K))
ε_0 - bed porosity
$\varepsilon_{l,st}$ - liguid hold-up in stationary regime (m^3/m^3)
μ - air dynamic viscosity (Pa s)
ρ_g - air density (kg/m^3)
ρ_l - water density (kg/m^3)
ρ_p - density of light plastic spheres (kg/m^3)
δ - liquid film thickness (mm)

Abbreviations

TBC – Turbulent Bed Contactor

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NAUČNI RAD

EKSPERIMENTALNA ISPITIVANJA PRENOSA TOPLOTE U KOLONI ZA HLAĐENJE SA TROFAZNO FLUIDIZOVANIM SLOJEM

U okviru ovog rada je proučavan prenos toplote u trofaznom (gas-tečnost-čvrsto) fluidizovanom sloju. Eksperimentalna ispitivanja obavljena su u koloni prečnika 0.25 m sa fluidizovanim slojem sferičnih čestica male gustine (290 kg/m^3) prečnika 2 cm u suprotnostrujnom toku vode i vazduha. Izvršeno je eksperimentalno ispitivanje i matematičko modelovanje prenosa toplote između zagrejanog vazduha i vode za hlađenje. Eksperimenti su izvršeni pri različitim protocima vode za hlađenje i različitim temperaturama zagrejanog vazduha, dok je protok vazduha održavan konstantnim. Na osnovu dobijenih eksperimentalnih rezultata predložena je nova korelacija za prenos toplote u trofaznom fluidizovanom sloju. Srednja procentualna greška između eksperimentalnih i korelisanih vrednosti faktora prenosa toplote, j_{Hp}, je iznosila 1,69%. Hidrodinamički parametri ispitivanog sistema su izračunati na osnovu raspoloživih literaturnih korelacija.

Ključne reči: turbulentni trofazni kontaktor, fluidizacija, koeficijent prenosa toplote, hidrodinamika.