AVERAGE HEAT TRANSFER OF TUBES IN DOWNWARD FOAM FLOW

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ABSTRACT

The model of heat exchanger was investigated experimentally. This model consists of three vertical lines of horizontal tubes with five tubes in each. Tubes were arranged in a staggered order. Heat transfer of staggered bundle of tubes to downward static stable foam flow was investigated experimentally. Heat transfer dependence on specific gas and liquid velocity was determined. Dependence of volumetric void fraction of foam on heat transfer was investigated also. Heat transfer rate dependence on tube position in the line of tube bundle was investigated experimentally. It was established that heat transfer rate highly depends on tube position in the line. Influence of tube position on heat transfer from tube bundle in upward foam flow was compared. Heat transfer dependence on tube position in the bundle was investigated experimentally also. Influence of wall of foam generator on heat transfer to sideline of tubes was established. Experimental results of heat transfer of bundle of tubes to downward static stable foam flow were generalized using dependence between Nusselt and Reynolds numbers.

1. INTRODUCTION

Foam is generated during some cases of gas flow and liquid contact. There exists different kind of foam: turbulent-dynamic, structural, fire-fighting and static stable foam flow. If foam is generated in vertical channel, the same foam flow depending on height of channel and foaming zone can change his state and different kinds of flow can be formed: first turbulent-dynamic, structural, and then static stable foam. Dynamically stable foam is very unstable two-phase system. It exists during the gas foaming only. If the delivering of gas stops, the turbulent foam immediately destroys into pure liquid and gas (if a foam is generated from the pure liquid) or in the case of the surfactant solution it turns into the statically stable foam. Statically stable foam flow is generated when gas and liquid solution with surfactants comes into contact. As a result, statically stable foam flow can not be generated from the pure liquid. Statically stable foam (cellular foam) consists of gas bubbles, which have a shape of regular polygons, separated each from other by the thin liquid films. Without gas delivering SSF can live quite a long period of time (from seconds to years).

The apparatus with a foam flow are used in evaporation, concentration, drying, burning processes as well as in a variety of technological systems for waste water treatment or utilization “V. Tichomirov, (1983)”. Due to the relatively small dimensions, low energy and material consumption these apparatus are suitable to use in advanced technologies like nuclear power plant heat exchangers, food industry, chemical and oil processing industry. The heat exchangers in which static stable foam flow is used have a lot of merits, for example, heat transfer rate is relatively high, liquid rate for foam flow is low, energy consumption is low. Moreover, the foam generation can be located in a long distance from the place of heat transfer.

Properties and usage possibilities of dynamic foam flow were widely investigated by Pozin et al.(1955) Pozin, (1959) and other scientists. At the same time properties of the static stable foam (especially from the practical point of view) are poorly investigated. Scientific research in this area of activity mainly include only particular problems like usage of static stable foam flow apparatus Gylys et al., (1989) or investigation of particular foam flow properties Tichomirov (1983). In most cases conclusions and results of these theoretical investigations can be used in steady static stable foam layer and are not suitable in investigation of processes which take part in foam flow. Especially poor investigations are of heat transfer and hydrodynamic processes, which occur when static stable foam flow removes heat from different surfaces. Heat transfer processes from single tube and single line of tubes to static stable foam flow were experimentally investigated by Gylys (1998). It is clear that investigation of heat transfer of tube line can not be completely treated as modeling of processes in real heat transfer apparatus which consists of greater number of heat transfer surfaces. In order to meet these problems experimental investigations of heat transfer from vertical bundle of horizontal tubes to upward static stable foam flow were performed Gylys et al. (2000). In this paper results of experimental investigation of heat transfer of vertical bundle of horizontal tubes to downward static stable foam flow are presented.

2. STRUCTURE OF STATICALLY STABLE FOAM FLOW

The frame of statically stable foam flow consists of liquid films, which are almost flat and which appear at the same time as the walls of foam bubbles. At the place of contact of three films foam bubbles are conjoined at the angle of 120^o (Fig. 1). In the place of conjunction, a so called Plateau channels, liquid has a concave surface, in which liquid pressure is significantly lower than in the flat films. Due to pressure difference liquid flows from the flat walls of foam frame to Plateau channels and foam walls become thicker.

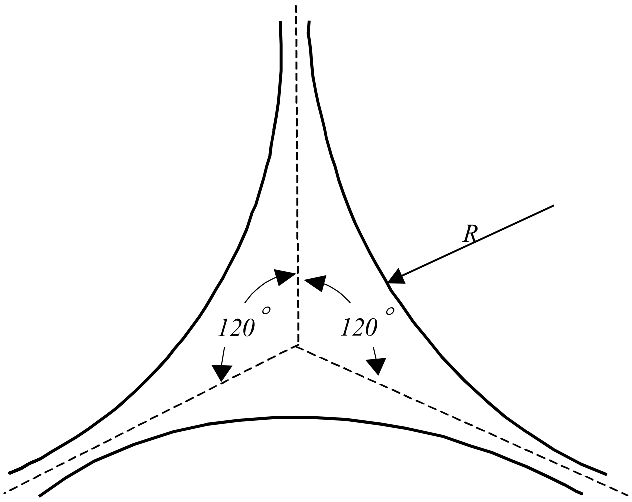

Figure 1. A model of Plateau channel

3. FOAM DRAINAGE PROCESS

There are three major factors of foam destruction: foam drainage, diffusion of gas between foam bubbles and breaking of walls of bubbles inside the foam. Foam drainage is the factor, which has the main influence on hydrodynamics of foam flow, because statically stable foam flow flows in the foam channel for a small period of time. Due to it structure and total volume of foam flow does not changes significantly. Geometrical properties of foam bubbles itself changes during foam drainage process: liquid films (walls) and Plateau channels become thicker, value of void fraction rises (which has direct influence on heat transfer intensity), productivity of foam generation channel changes. Liquid from the bubbles is drained through the Plateau channels under the influence of gravity and capillary forces. In the vertical direction these forces are acting together. In the horizontal direction there are no influence of gravity forces and all processes in the walls of foam bubbles are running under the influence of capillary forces. Electrostatic and molecular forces have influence on foam drainage process also, but this influence is not significant.

Gravity forces make influence on liquid flow in all system of Plateau channels, but their influence on liquid flow from walls of foam bubbles to Plateau channels is not significant. Intensity of liquid flow from walls into channels does not depend on their position in the system but mainly depends on capillary forces.

The relation between gravity and capillary forces defines liquid state inside the foam. Hydrostatic stability of the foam may be defined by the equation

$$\frac{\delta p_k}{\delta h} + \rho g = 0 \qquad (1)$$

$\delta p_k/\delta h$ – pressure gradient of liquid in Plateau channel according to the height.

After generation of the foam flow, liquid begins to flow from the walls of bubbles to Plateau channels, there is no liquid drainage and capillary forces are bigger than Gravity forces ($\rho g < -\ \delta p_k/\delta h$). This period is also called "accumulation" period.

Drainage of the liquid begins when $\rho g > -\delta p_k/\delta h$. This process consists of two parts – accelerated liquid drainage and drainage under the constant flow velocity. During the drainage process geometrical properties of foam cells are changing as it was mentioned above. During liquid flow gradient of capillary pressure rises and this gradient causes further liquid drainage. Due to it velocity of liquid flow drops. When gradient of liquid pressure reaches the maxim value, drainage process continues only due to the liquid from broken walls of foam bubbles. It was noticed that more intensive drainage occurs in the solutions with less concentration of surfactants. Many scientists investigated foam drainage process, but still there is no universal equation for it calculation.

Foam drainage process must be taken into account when analyzing heat transfer from bundle of tubes to static stable foam flow. It is so because after the contact with the tubes of the bundle some cells of the foam are destroyed and additional liquid flows appear. Due to the influence of these flows heat transfer intensity of tubes inside the bundle may increase or decrease (this depends on the tube position in the bundle).

4. EXPERIMENTAL METHOD

4.1. FACILITY

The experimental model consisted of the following main parts: foam generation (experimental) channel, two regulating valves for gas and liquid, two rotameters for gas and liquid respectively, two reservoirs for liquid storage and for liquid constant level keeping, air fan, transformer and stabilizer for electric current. A schematic view of experimental arrangement is shown in Fig. 2.

Experimental channel consisted of the following: riddle at the bottom of the channel and experimental part. The whole experimental channel was made of glass in order to observe optically foam flow regimes and the structure of foam bubbles. The cross section of the channel was equal to (0.14 x 0.14) m^2

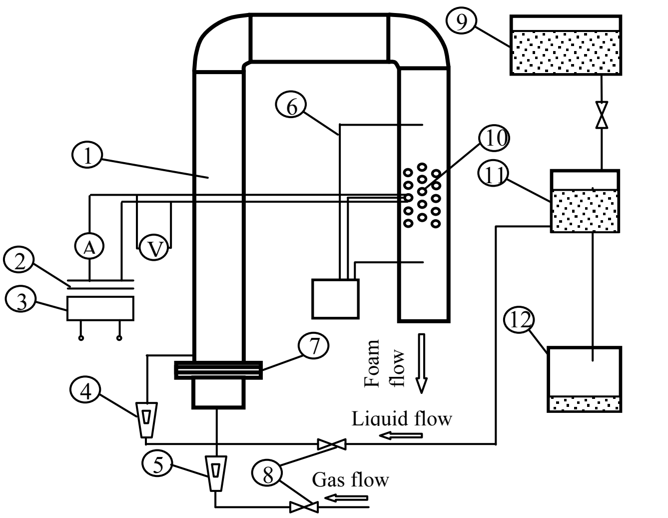

Figure 2. Experimental arrangement.

1–Foam generation channel; 2–Transformer; 3–Stabilizer; 4–Rotameter of liquid; 5–Rotameter of gas; 6–Thermocouple for temperature measuring; 7–Riddle of foam generator; 8–Regulating valves; 9–Tank of liquid solution storage; 10–Tank of liquid solution level keeping; 11–Tank for collecting of liquid solution overflow.

The height of experimental channel was 1.8 m. Foam flow was generated on the riddle. The water solution with surface active admixtures from reservoir was delivered on the riddle, while gas flow was delivered through the riddle. When gas and liquid came into contact, foam flow was created. Liquid in experiment was used only once and was not supplied back to reservoir.

A riddle of the foam generator was made of stainless steel plate with thickness of 2 mm. The diameter of the holes was 1 mm and spacing among centers of holes was 5 mm. Holes were arranged in staggered order.

Schematic view of experimental section can be seen in Fig. 3. The bundle of tubes consisted of three vertical rows with five tubes in each. Spacing among centers of tubes $s_1 = s_2 = 0.035$m. All tubes had an outside diameter of 0.02 m. The heated tube was made of copper and had an outside diameter of 0.02 m also. The endings of the tube were sealed and insulated to prevent heat losses through them. The tube was heated electrically. The electric current value was measured by ammeter and voltage by voltmeter.

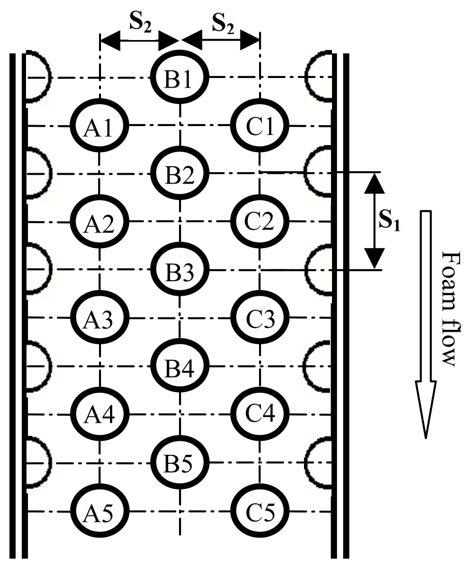

Figure 3. Experimental section of foam channel

The temperature of foam flow was measured by two calibrated thermocouples: one was placed in the foam flow in front of the bundle and one behind. The temperature of heated tube surface was measured by eight calibrated thermocouples. Six of them were placed at an even spacing around central part of heated tube and two of them were placed in both sides of tube at the 50 mm distance from the central part.

The water solution was used in experiments. Concentration of surfactants was kept constant and it was equal 0.5 %.

Measurement accuracies for flows, temperatures and heat fluxes were of range correspondingly 1.5 %, 0.15-0.2 % and 0.6-6.0 %.

4.2. EXPERIMENTAL PROCEDURE

Investigation of tube heat transfer in the bundle consisted of three series of experiments. The experiments were provided for different values of mean volumetric void fractions β = 0.996, 0.997 and 0.998. The volumetric void faction can be expressed by equation

$$\boldsymbol{\beta} = G_g / (G_g + G_l) \tag{2}$$

The foam flow rate can be written as

$$G_f = G_g + G_l \tag{3}$$

where G_g – gas flow rate, m^3/s; G_l – liquid flow rate, m^3/s.

Gas and liquid velocities were changeable by changing gas and liquid flow rates respectively

$$\overline{w}_g = G_g / F \tag{4}$$

$$\overline{w}_l = G_l / F \tag{5}$$

The temperature of the tube surface and the foam flow, electric current and voltage were measured and recorded during the experiments. These values were registered not earlier than 90 s after the latest foam flow rate or electric current change. The investigations showed that the foam flow regime at 35 mm distance from the riddle becomes stable after 90 s. After registration of electric current and voltage the heat flux density on the tube surface q_w was calculated.

After registration of heated tube surface and foam flow temperature by means of thermocouples, the temperature difference $\overline{\Delta T}$ between the mean temperature of the foam flow $\overline{T}_f$ and the mean temperature of the tube surface $\overline{T}_w$ was calculated. The average heat transfer coefficient was calculated as

$$\overline{\boldsymbol{\alpha}} = q_w / \overline{\boldsymbol{\Delta T}} \tag{6}$$

The thermal conductivity of the foam flow was determined as follows

$$\boldsymbol{\lambda}_f = \boldsymbol{\beta}\boldsymbol{\lambda}_g + (1 - \boldsymbol{\beta})\boldsymbol{\lambda}_l \tag{7}$$

In order to avoid possible errors during the work all the experiment series were done and repeated three times.

5. RESULTS

Experimental results of heat transfer for B4 tube in the middle line of tube bundle are presented in Fig. 4. The experimental results have shown that the heat transfer rate depends both on the average gas velocity and on the mean volumetric void fraction β of the foam flow. It was noticed that heat transfer intensity increases with increase of gas velocity and decrease of volumetric void faction. With increase of gas velocity foam flow becomes more turbulent and more intensive destruction of laminar boundary layer on heated tube takes place. Influence of volumetric void fraction reduction on heat transfer intensity is more significant at greater gas velocities. When these two factors (greater gas velocity and reduced void fraction) are combined, effect of foam flow vortex is much greater. The character of dependencies is the same for all tubes of the bundle regardless their position in the middle or the side line. These conclusions coincide with the ones which were obtained during the investigation of heat transfer of tube bundle in upward statically stable foam flow by Gylys et al. (2000).

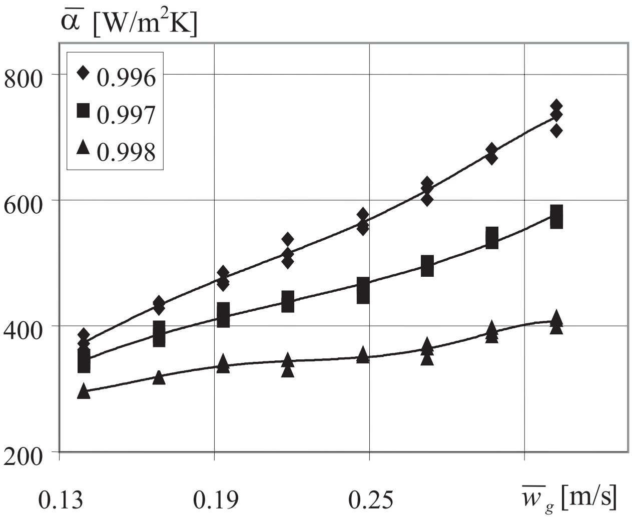

Figure 4. Heat transfer of the fourth tube in the middle line of the bundle (B4)

In Fig. 5 and Fig. 6 experimental results of the heat transfer for the middle line and the side line of the tube bundle are plotted against gas velocity. Fig. 5 and Fig. 6 represents heat transfer results for the middle and the side tube line when volumetric void fraction $\beta = 0.996$.

It was noticed that in the case of the side line of tube bundle (Fig. 6) the highest heat transfer rate can be observed for the first tube (A1 and C1) of the side line for both values of volumetric void fraction. Heat transfer rate decreases when going down by the side line of the bundle and the lowest can be observed in the case of the fifth tube of the bundle (A5 and C5). It can be noticed that experimental section in this case can be divided into three subsections: the first tube of the side line (A1 and C1), last tube of the side line (A5 and C5) and internal tubes (A2, A3, A4 and C2, C3, C4). An influence of tube position in the line on heat transfer intensity is not so clear for the internal tubes, especially in the initial period of gas velocity augmentation. Heat transfer intensity of the first tube of the line is significantly higher then of the internal tubes in all gas velocity diapason. The main reason for this phenomenon is the influence of middle line tubes on hydrodynamics of foam flow. Some bubbles of downward foam flow after contact with the first tube of the middle line are destroyed and liquid, which was"locked" in their walls, intensifies the drainage process as it was discussed in Section 3 of this paper. Drainage solution from the central part of the channel is directed into the side zone under the influence of capillary forces and heat transfer intensity of the first tube of the bundle increases. This phenomenon takes part at all length of tube bundle but influence of it on heat transfer intensity of internal tubes is not so significant.

It should be noted that tube bundle acts as an obstruction in the path of the foam flow and while passing through it foam velocity decreases. Due to it heat transfer intensity of the following tubes becomes lower than of the previous tubes. Influence of the walls of the channel must be taken into account here, also. Foam flow near the walls of the channel of the foam generator is slowed and it acts as an attraction force for liquid solution, which means that foam flow in the space around the tubes is dried more and more, thus decreasing the intensity of heat transfer. For this reason heat transfer rate of the last tube of the side line (A5 and C5) is the lowest of all tubes of the side line.

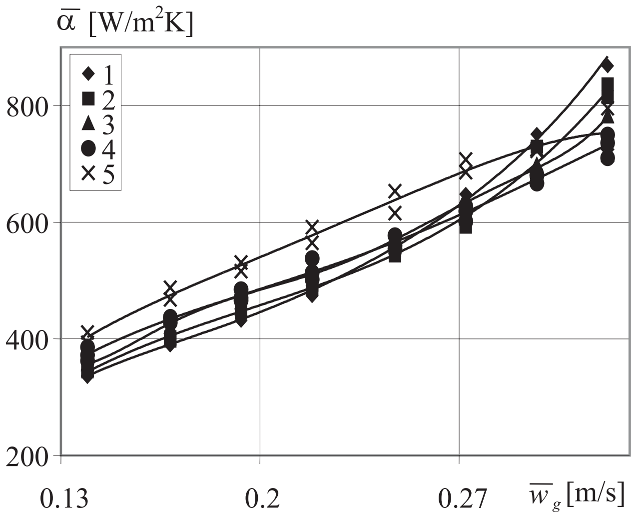

Figure 5. Heat transfer of the middle line of the tube bundle: $\beta = 0.996$;
1, 2, 3, 4, 5–B1, B2, B3, B4, B5 tube correspondingly

It was noticed that for the middle line of the tube bundle (Fig. 5) situation is slightly different. Influence of tube position in the line on heat transfer intensity is insignificant in initial gas velocity augmentation, also. Only the heat transfer rate of the fifth i.e. the last tube of the bundle is significantly higher than of other tubes. When gas velocity is higher (starting at the 0.28 m/s) the influence of tube position can be seen more clearly. At lower foam flow velocity heat transfer intensity for tubes from the first (B1) until the fourth (B4) are similar. Because of low mean gas velocity, foam flow consisting of large size bubbles (d_b = 8–14 mm) is generated on the riddle of experimental channel. Due to it frontal tubes of the bundle are in contact with large size foam bubbles, smaller amount of liquid fraction gets to the heated tube surface and conditions of heat transfer becomes worse.

The large bubbles of foam passing through the bundle of tubes are destroyed into smaller bubbles (d_b = 2–5 mm). It means that the fifth tube is wetted by the foam flow with more homogeneous structure and liquid fractionof foam flow can access surface of heated tube more easily and heat transfer intensity increases.

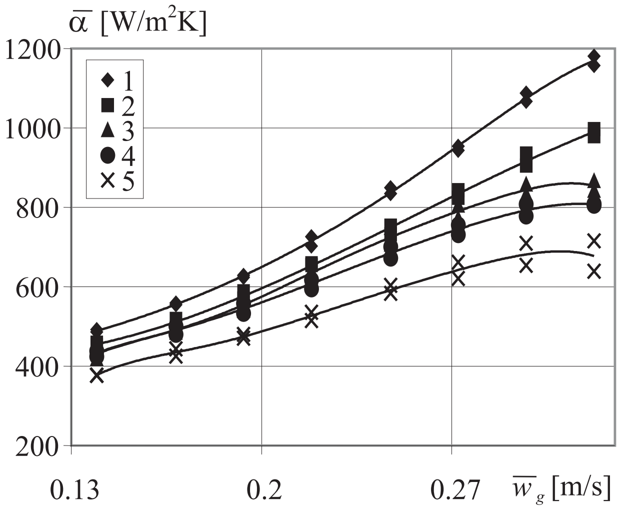

Figure 6. Heat transfer of the side line of the tube bundle: $\beta = 0.996$;
1, 2, 3, 4, 5–A1, A2, A3, A4, A5 tube correspondingly

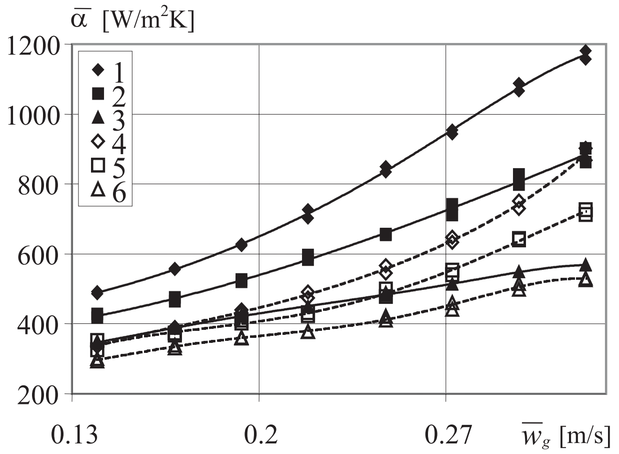

Figure 7. Comparison of heat transfer intensity for the first tube in the middle and the side lines of the bundle
1,2,3–A1 and C1 tubes; 4,5,6–B1 tube; β: 1, 4–0.996; 2, 5–0.997; 3, 6–0.998

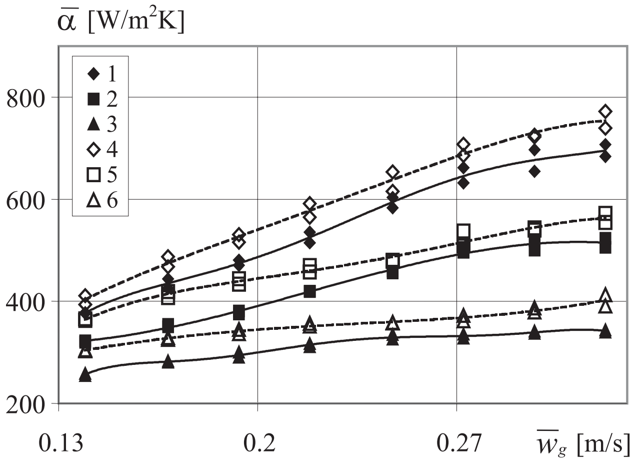

Figure 8. Comparison of heat transfer intensity for the third tube in the middle and the side lines of the bundle
1,2,3–A3 and C3 tubes; 4,5,6–B3 tube; β: 1, 4–0.996; 2, 5–0.997; 3, 6–0.998

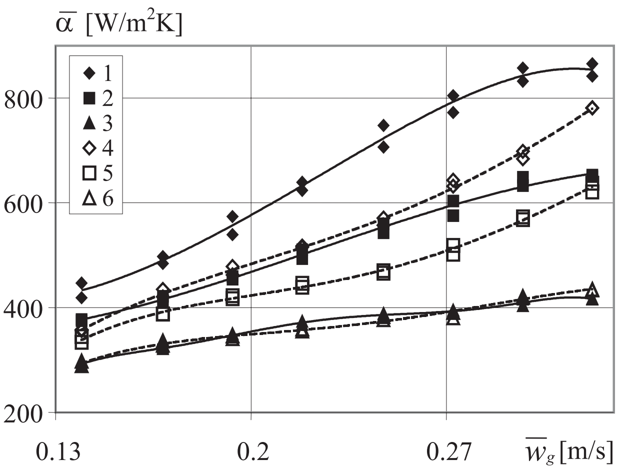

Figure 9. Comparison of heat transfer intensity for the fifth tube in the middle and the side lines of the bundle
1,2,3–A5 and C5 tubes; 4,5,6–B5 tube; β: 1, 4–0.996; 2, 5–0.997; 3, 6 – 0.998

If the gas velocity is higher foam flow becomes more turbulent and laminar boundary layer on the wall of tube is destroyed more effectively. Due to it heat transfer rate of frontal tube increases. At the same time size of the foam bubbles becomes smaller in the initial part of a bundle of tubes. That has influence on intensification of heat transfer of frontal tubes also. Conditions of heat transfer of the fourth and the fifth tubes do not change at the higher gas velocity and heat transfer intensity becomes lower than of the frontal tubes.

In Fig. 7, 8 and 9 experimental results of heat transfer are compared for tubes in the middle and the side lines of the bundle.

Figure 7 represents comparison of heat transfer intensity for the first tube in the middle line (B1) and the first tube in the side line (A1 and C1) of the bundle. Figure 8 represents comparison of heat transfer intensity for the third tube in the middle line (B3) and for the third tube in the side line (A3 and C3) of the bundle. Figure 9 represents comparison of heat transfer intensity for the fifth (the last) tube in the middle line (B5) and the fifth (the last) tube in the side line (A5 and C5) of the bundle.

It can be noticed that in the case of the first tube (Fig. 7) and internal tubes (Fig. 8) the higher heat transfer rate can be observed for the tubes located in the side line of the bundle. In the case of the fifth tube (Fig. 9) the higher heat transfer rate can be observed for the tube, located in the middle line of tube bundle. It can be noticed also that the higher difference in heat transfer rate can be observed for the wetter foam flow, i.e. the lower value of volumetric void fraction. In the case of the third tube of the bundle (Fig. 8) at the volumetric void fraction of $\beta = 0.998$ heat transfer intensity of the tube in the middle and the side line is almost the same. The main reason for this phenomenon may be the influence of middle line tubes on intensification of heat transfer of the tubes in the side line. Some bubbles of statically stable foam flow are destroyed after the contact with the tubes of the bundle, as it was discussed above. Drainage solution from the central part of the channel is directed into the side zone under the influence of capillary forces and heat transfer intensity of the tube in the side line of the bundle increases and becomes higher than of the tube in the middle line. Influence of this phenomenon on heat transfer intensity of internal tubes is not so significant and difference of heat transfer intensity becomes lower as it can be seen by comparing curves in Fig. 7 and Fig. 8. When foam flow is drier, it carries less liquid and influence of drainage on heat transfer conditions and intensity of the tubes in the middle and the side lines becomes insignificant. In such case (curves 3 and 6 in Fig. 8) heat transfer intensity of the tubes in the middle and the side lines is almost the same.

6. HEAT TRANSFER GENERALIZATION

The experimental results of heat transfer were generalized using dependence between Nusselt and Reynolds numbers. This relationship can be written as follows:

$$\overline{Nu}_f = c \cdot \overline{Re}_g^n \qquad (8)$$

Values of coefficients *c* and *n* are presented in Table 1.

Table 1. Values of coefficients *c* and *n* in Eq. (8).

Tube pos.	β = 0.996		β = 0.997		β = 0.998	
	Re_g = 190 ÷ 320					
	c	n	c	n	c	n
A1, C1	2.58	0.93	5.24	0.77	11.73	0.59
A2, C2	2.03	0.96	4.78	0.77	17.89	0.49
A3, C3	3.04	0.88	7.21	0.69	24.68	0.42
A4, C4	4.73	0.79	9.55	0.63	33.25	0.36
A5, C5	4.88	0.76	9.12	0.62	31.99	0.35
B1	2.67	0.86	7.74	0.65	7.07	0.65
B2	3.86	0.79	9.48	0.62	11.37	0.56
B3	4.23	0.78	13.67	0.56	22.41	0.44
B4	6.46	0.71	16.75	0.52	35.38	0.35
B5	5.56	0.75	19.39	0.50	47.24	0.30
	Re_g = 320 ÷ 450					
A1, C1	0.37	1.27	0.58	1.15	11.73	0.59
A2, C2	2.03	0.96	4.78	0.77	17.89	0.49
A3, C3	3.04	0.88	7.21	0.69	24.68	0.42
A4, C4	4.73	0.79	9.55	0.63	33.25	0.36
A5, C5	4.88	0.76	9.12	0.62	31.99	0.35
B1	0.017	1.72	0.1	1.39	7.07	0.65
B2	0.039	1.57	0.14	1.34	11.37	0.56
B3	0.36	1.20	0.45	1.14	22.41	0.44
B4	0.98	1.03	2.30	0.85	35.38	0.35
B5	5.56	0.75	19.39	0.50	47.24	0.30

7. NOMENCLATURE

d_b external diameter of the foam bubble (m)
d_t external diameter of the tube (m)
F cross section area of channel in free part (m^2)
G volumetric flow rate (m^3/s)
$\overline{Nu}$ average Nusselt number [$\overline{\alpha}\, d_t / \lambda_f$]
q heat flux density (W/m^2)
$\overline{Re}$ average Reynolds number [$\overline{w}\, d_t / \nu_f$]
s spacing among tubes (m)
T temperature (K)
$\overline{\Delta T}$ average temperature difference [$(\overline{T}_w - \overline{T}_f)$]
$\overline{w}$ mean velocity (m/s)

Greek Letters

$\overline{\alpha}$ average coefficient of heat transfer (W/K m^2)
β volumetric void fraction
λ thermal conductivity (W/K m)
ν kinematic viscosity (m^2/s)

Subscripts

b value referred to the foam bubble
f value referred to the foam flow
g value referred to the gas
l value referred to the liquid
t value referred to the tube
w value referred to the wall

8. CONCLUSIONS

1. Heat transfer intensity increases with increase of mean gas velocity and with decrease of volumetric volume void fraction.
2. The highest heat transfer rate in the side line of the bundle can be observed for the first tube of the bundle and the lowest – of the fifth tube.
3. The highest heat transfer rate in the middle line of the bundle at the value of volumetric void fraction of 0.996 can be observed for the fifth tube of the line. At the value of volumetric void fraction of 0.998 situation is similar as the one observed in the side line of the bundle.
4. The higher heat transfer rate is of the tubes, located in the side line of the bundle. The lower value of volumetric void fraction, the higher difference in heat transfer intensity can be observed. In the case of the fifth tube of the bundle the higher heat transfer rate can be observed for the tube, located in the middle line.
5. Heat transfer results were generalized by using dependence between Nusselt and Reynolds numbers $\overline{Nu}_f = f(\overline{Re}_g)$.

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