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EXPERIMENTAL STUDY OF DIFFERENT IN–LINE TUBE BUNDLES COOLING IN VERTICAL FOAM FLOW

Jonas Gylys, jonas.gylys@ktu.lt
Tadas Zdankus, tadas.zdankus@ktu.lt
Alpas Ingilertas, alpas.ingilertas@stud.ktu.lt
Kaunas University of Technology, Energy Technology Institute, K. Donelaicio 20–212 LK, LT–44239 Kaunas, Lithuania

Stasys Sinkunas, stasin@ktu.lt
Raimondas Maladauskas, R.Maladauskas@elektrine.lt
Kaunas University of Technology, Department of Thermal and Nuclear Energy, K. Donelaicio 20-225, LT-44239 Kaunas, Lithuania

Abstract. *An experimental investigation of two–phase gas–liquid foam flow usage as a coolant was performed. One type of foam – statically stable foam – keeps its initial structure and bubbles' dimension within broad limits of time intervals and demonstrates a perfect availability for cooling of the heated surfaces. Heat transfer of two in–line tube bundles to the vertically downward laminar foam flow was investigated. An experimental setup consisted of foam generator, foam channel, tube bundle, measurement instrumentation and auxiliary equipment. Spacing among the centres of the tubes across and along the in–line tube bundle was equal to 0.03 m in the first case and 0.06 m in the second case. It was determined dependency of heat transfer intensity on flow parameters: flow velocity, direction of flow, volumetric void fraction of foam and liquid drainage from foam. Apart of this, influence of tube position in the bundle to heat transfer was investigated. The results of investigation were generalized by criterion equations, which can be used for the calculation and design of the statically stable foam heat exchangers with in–line tube bundles.*

Keywords*: foam flow, tube bundle, heat transfer, experimental channel.*

1. INTRODUCTION

Single–phase coolants such as water or air usually are used for heat and mass transfer process in heat exchangers. Smaller coolant mass flow rate, relatively large heat transfer rate, low energy consumption required for coolant delivery to heat transfer place may be achieved by usage of two–phase gas–liquid foam flow as a coolant (Gylys, 1998; Gylys et al., 2002). The usage of foam as coolant is restricted by the foam flow capability to keep its structure while it passes different obstacles (turnings, tube bundles and so on), especially during heat transfer process. Characteristics of one gas–liquid foam type – statically stable foam – showed its perfect availability for this purpose (Gylys, 1998). Statically stable foam is such a type of foams, which keeps its initial dimensions of bubbles within broad limits of time intervals, from several seconds to days, even after termination of the foam generation

Number of foam peculiarities: drainage of liquid from foam (Tichomirov, 1983; Fournel at al., 2004), diffusive transfer of gas between bubbles, division and collapse of foam bubbles (Garrett, 1993) complicates an application of the analytical methods for heat transfer investigation. Therefore the most suitable experimental method of investigation was selected in our work.

Heat transfer of different tube bundles to one–phase fluids was investigated enough (Zukauskas, 1982; Hewitt, 2002), but there is no sufficient data concerning heated surfaces heat transfer to the statically stable foam flow yet. Therefore problems arise when foam systems and heat exchangers are designed. In our previous works heat transfer of alone circular surface – tube, and such tubes line to upward statically stable foam flow was investigated (Gylys, 1998). Next experimental series with staggered and in–line tube bundles in upward and downward foam flow were followed (Gylys et al., 2002; 2004; 2006).

Tube bundles of different types and geometry may be used in heat exchangers. The main task of this work was to investigate experimentally heat transfer of two in–line tube bundles with different spacing between tubes to vertical downward foam flow. The results of our experimental investigation are presented and discussed in this paper.

2. EXPERIMENTAL SET–UP AND METHODOLOGY

The experimental set–up consisted of the following main parts (Figure 1): experimental channel, tube bundle, gas and liquid control valves, gas and liquid flow meters, liquid storage reservoir, liquid level control reservoir, air fan, electric current transformer and stabilizer (Gylys et al., 2002; 2004; 2006). The whole experimental channel was made of glass in order to observe foam flow structure and size of foam bubbles visually. Cross section of the experimental channel had dimensions 0.14 x 0.14 m; height of it was 1.8 m. Radius of the channel turning (R) was equal to 0.17 m.

Statically stable foam flow was used for an experimental investigation. This type of gas–liquid foam was generated from water solution of detergents. Concentration of detergents was kept constant and was equal to 0.5%. Foam flow was produced during gas and liquid contact on the riddle, which was installed at the bottom of the experimental channel. Liquid was delivered from the reservoir to the riddle from the upper side; gas was supplied to the riddle from below.

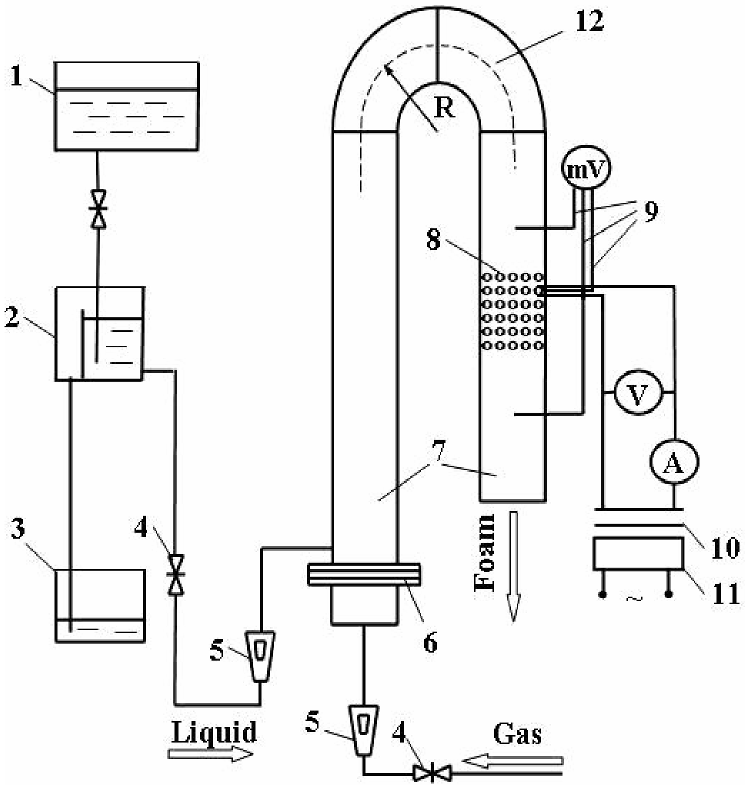

Figure 1. Experimental set–up scheme: 1–liquid reservoir; 2–liquid level control reservoir; 3–liquid receiver; 4–gas and liquid control valves; 5–flow meter; 6–foam generation riddle; 7–experimental channel; 8–tube bundle; 9–thermocouples; 10–transformer; 11–stabiliser; 12–foam flow turn

Two in–line tube bundles with different spacing between tubes centres were used during experimental investigation. A schematic view of the experimental channel with tube bundles is shown in the Figure 2. The in–line tube bundle No. 1 consisted of five vertical rows with six tubes in each. Spacing between centres of the tubes was s_1=s_2=0.03 m. The in–line tube bundle No. 2 consisted of five vertical rows with three tubes in each. Spacing between centres of the tubes across the experimental channel was s_1=0.03 m and spacing along the channel was s_2=0.06 m. External diameter of all the tubes was equal to 0.02 m. An electrically heated tube – calorimeter had an external diameter equal to 0.02 m also. During the experiments calorimeter was placed instead of one tube of the bundle. An electric current value of heated tube was measured by an ammeter and voltage by a voltmeter. Temperature of the calorimeter surface was measured by eight calibrated thermocouples: six of them were placed around the central part of the tube and two of them were placed in both sides of the tube at a distance of 50 mm from the central part. Temperature of the foam flow was measured by two calibrated thermocouples: one in front of the bundle and one behind it.

Measurement accuracies for flows, temperatures and heat fluxes were of range correspondingly 1.5%, 0.15÷0.20% and 0.6÷6.0%.

During the experimental investigation a relationship was obtained between Nusselt number (heat transfer intensity) Nu_f from one side and foam flow volumetric void fraction β and gas flow Reynolds number Re_g from the other side:

$$Nu_f = f\left(\beta, Re_g\right). \tag{1}$$

Nusselt number was computed by formula

$$Nu_f = \frac{hd}{\lambda_f}, \tag{2}$$

where λ_f is the thermal conductivity of the statically stable foams flow, obtained from the equation

$$\lambda_f = \beta\lambda_g + (1-\beta)\lambda_l\,, \tag{3}$$

where λ_g – gas thermal conductivity, W/(m·K); λ_l – liquid thermal conductivity, W/(m·K); h – average coefficient of heat transfer, W/(m^2·K).

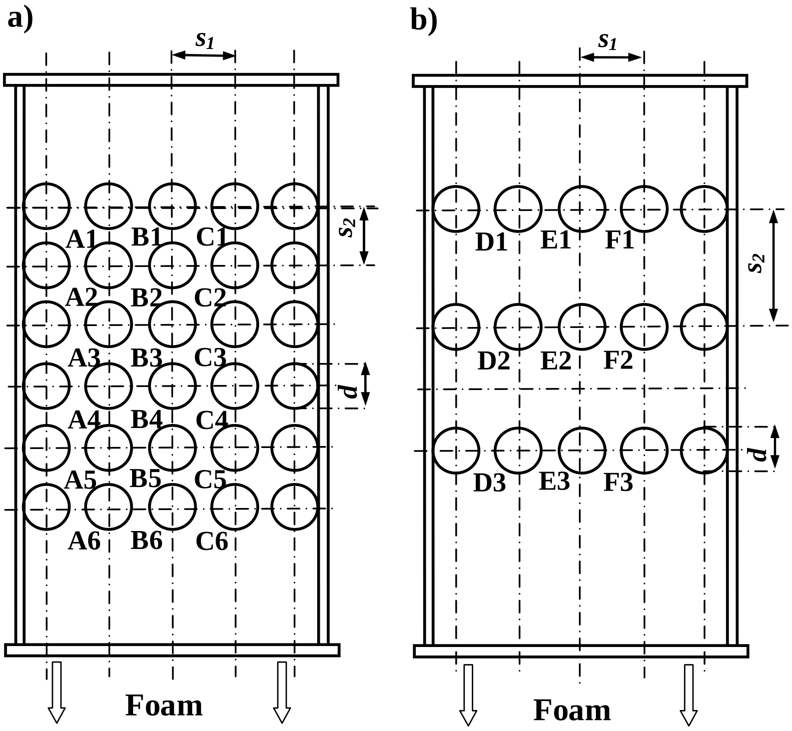

Figure 2. In–line tube bundle No. 1 (a) and No. 2 (b) in downward foam flow

An average heat transfer coefficient was calculated as

$$h = \frac{q_w}{\Delta T}\,, \tag{4}$$

were q – heat flux density on the tube surface, W/m^2; ΔT – difference of temperatures (between the mean temperatures of the foam flow T_f and tube surface T_w).

Foam flow volumetric void fraction β can be expressed by the equation

$$\beta = \frac{G_g}{G_g + G_l}\,, \tag{5}$$

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

Gas Reynolds number Re_g of foam flow was computed by formula

$$Re_g = \frac{G_g d}{A \nu_g}\,, \tag{6}$$

were A – cross section area of experimental channel, m^2; ν_g – gas kinematic viscosity, m^2/s.

It is known (Gylys, 1998) that there are four main regimes of the statically stable foam flow in the vertical channel of rectangular cross section:

– Laminar flow regime Re_g=0÷600;
– Transition flow regime Re_g=600÷1500;
– Turbulent flow regime Re_g=1500÷1900;
– Emulsion flow regime Re_g>1900.

Experiments were performed within Reynolds number diapason for gas (Re_g): 190÷440 (laminar flow regime) and foam volumetric void fraction (β): 0.996÷0.998. Foam flow gas velocity was changed from 0.14 to 0.32 m/s. Heat transfer coefficient (h) varied from 200 to 2200 W/(m^{2}K).

3. RESULTS

During the experiments statically stably foam moved vertically upward, then made 180° degree turning and moved downward crossing tube bundle. Initially an experiments with in–line tube bundle No. 1 were performed; then the tube bundle No. 2 was placed instead of the previous bundle and experiments followed.

The main three parameters of foam flow influence on heat transfer intensity of different tubes of the bundles: foam structure, distribution of local flow velocity and distribution of local foam void fraction across and along the experimental channel. Liquid drainage process influences on the distribution of the foam local void fraction and accordingly on heat transfer intensity of the tubes. Liquid drainage from foam phenomena depends on gravity and capillary (Tichomirov, 1983; Fournel et al., 2004). In a vertical direction these forces are acting together. In a horizontal direction influence of gravity forces is negligible and influence of capillary forces is dominating. Influence of electrostatic and molecular forces on drainage is insignificant (Tichomirov, 1983). Gravity forces act along the upward and downward foam flow. While foam flow makes a turn the gravity forces act across and along the foam flow. Liquid drains down from the upper channel wall and local void fraction increases (foam becomes drier) here as well. After the turn, local void fraction of foam is less (foam is wetter) on the inner – left side of the cross–section (tubes A and D, Figure 2). The flow velocity distribution in cross section of the channel transforms after turn too.

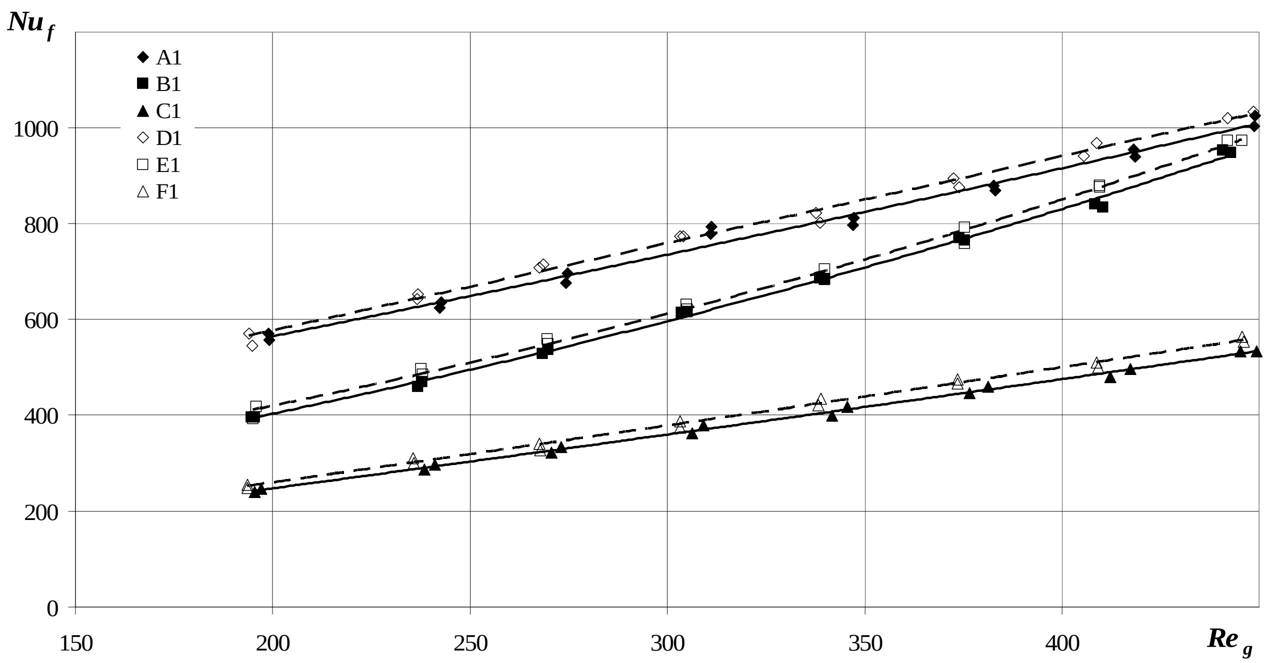

Figure 3. Heat transfer of the tubes A1, B1, C1 and D1, E1, F1 to downward foam flow, β=0.997

Heat transfer intensity of the A1, B1, C1 and D1, E1, F1 tubes of the in–line bundles to downward after turning foam flow at the volumetric void fraction β=0.997 is shown in Figure 3. Increasing foam flow gas Reynolds number (Re_g) from 190 to 440, heat transfer intensity (Nu_f) of the tubes A1 and D1 increases by 1.8 times, by 2.4 times of the tubes B1 and E1, and by 2.2 times of the tubes C1 and D1 for foam volumetric void fraction β=0.997. Heat transfer intensity of the tube D1 is higher than that of the tube A1 on average by 1%, the heat transfer of the tube E1 is higher than that of the tube B1 on average by 2%, and the heat transfer of the tube F1 is higher than that of the tube C1 on average by 3% for β=0.997 and Re_g=190÷440.

Heat transfer intensity of the A3, B3, C3 and D3, E3, F3 tubes of the in–line bundles to downward after turning foam flow at the volumetric void fraction β=0.997 is shown in Figure 4. With increase of Re_g from 190 to 440, heat transfer intensity of the tube A3 increases by 1.9 times, that of the tube B3 increases by 2.1 times, that of the tube C3 increases by 2.1 times, that of the tube D3 increases by 1.8 times, that of the tube E3 increases by 2.2 times, and that of the tube F3 increases by 2.4 for β=0.997. When Re_g=440 heat transfer intensity of the A3 tube is higher than that of the tube C3 and heat transfer intensity of the D3 tube is higher than that of the tube F3 by 1.8 times.

Heat transfer intensity of the tube D3 is higher than that of the tube A3 on average by 26%, the heat transfer of the tube E3 is higher than that of the tube B3 on average by 4%, and the heat transfer of the tube F3 is higher than that of the tube C3 on average by 20% for β=0.997 and Re_g=190÷440.

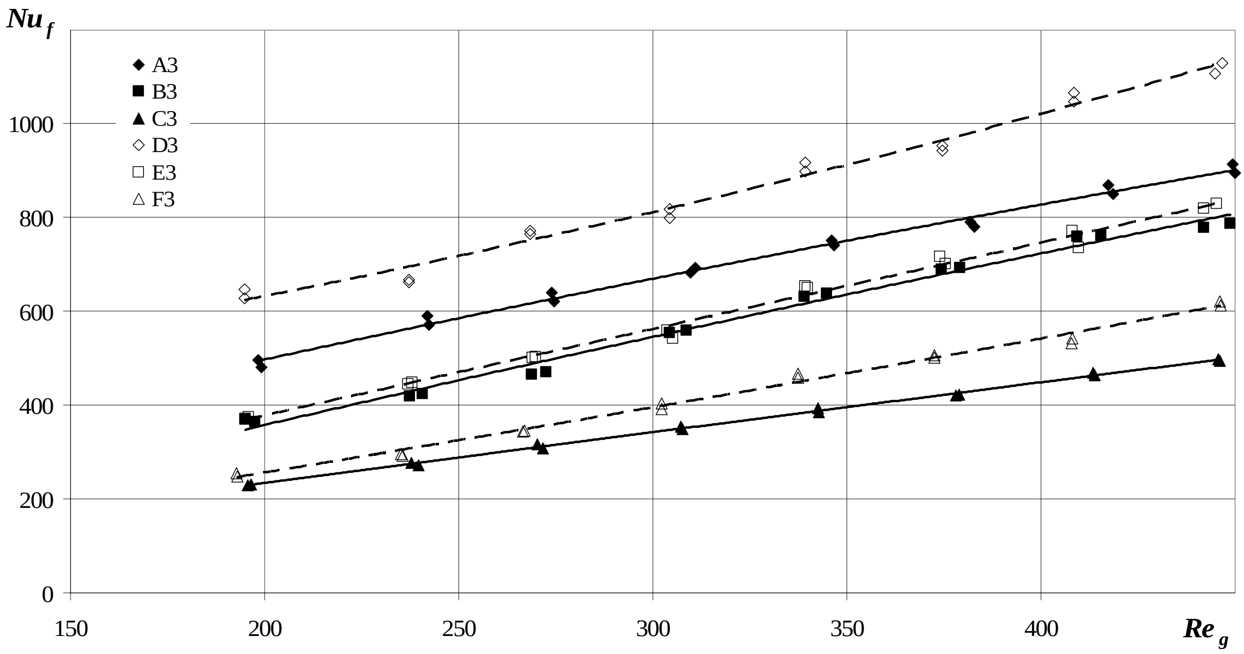

Figure 4. Heat transfer of the tubes A3, B3, C3 and D3, E3, F3 to downward foam flow, β=0.997

An average heat transfer rate was calculated in order to analyze and compare the experimental results of different in–line tube bundles. An average heat transfer intensity of the tubes of the in–line bundle No. 1 and No. 2 to downward after turning foam flow is shown in Figure 5.

The effect of "shadow" takes place in the case of the in–line bundle No. 1 therefore an average heat transfer intensity of the tubes of the in–line bundle No. 2 is higher than that of the tubes of the in–line bundle No. 1 for the whole interval of the Re_g (Re_g=190÷440). Changing Re_g from 190 to 440, an average heat transfer intensity of the tubes of the in–line bundle No. 1 to downward foam flow increases by 2.1 times for β=0.996; twice for β=0.997, and by 1.7 times for β=0.998; and that for the tubes of the in–line bundle No. 2 is by 2.4 times for β=0.996; by 2.1 times for β=0.997, and by 1.8 times for β=0.998.

An average heat transfer intensity of the tubes of in–line bundle No. 2 is higher than that of the tubes of the in–line bundle No. 1 on average by 21% for β=0.996, by 23% for β =0.997 and by 27% for β=0.998 to downward foam flow for whole interval of Re_g (Re_g=190÷440).

Experimental results of investigation of heat transfer of the in–line tube bundles to downward after 180˚ turning statically stable foam flow were generalized by criterion equation using dependence between Nusselt number Nu_f and gas Reynolds Re_g number. This dependence within the interval 190<Re_g<440 for the in–line tube bundle in downward foam flow with the volumetric void fraction β=0.996, 0.997, and 0.998 can be expressed as follows:

$$Nu_f = c\beta^n Re_g^m . \tag{7}$$

On average, for the whole in–line tube bundle No. 1 (s_1=s_2=0.03 m) in the downward foam flow c=12.7, n=334, m=114.6(1.004–β).

On average, for the whole in–line tube bundle No. 2 (s_1=0.03 and s_2=0.06 m) in the downward foam flow c=22.4, n=675, m=167.8(1.002–β).

We are expanding the database of experimental results and investigation of in–line tube bundles with different geometry is processing now. The parameters of bundle geometrical characteristics is planned to be included to the correlation (7) in future.

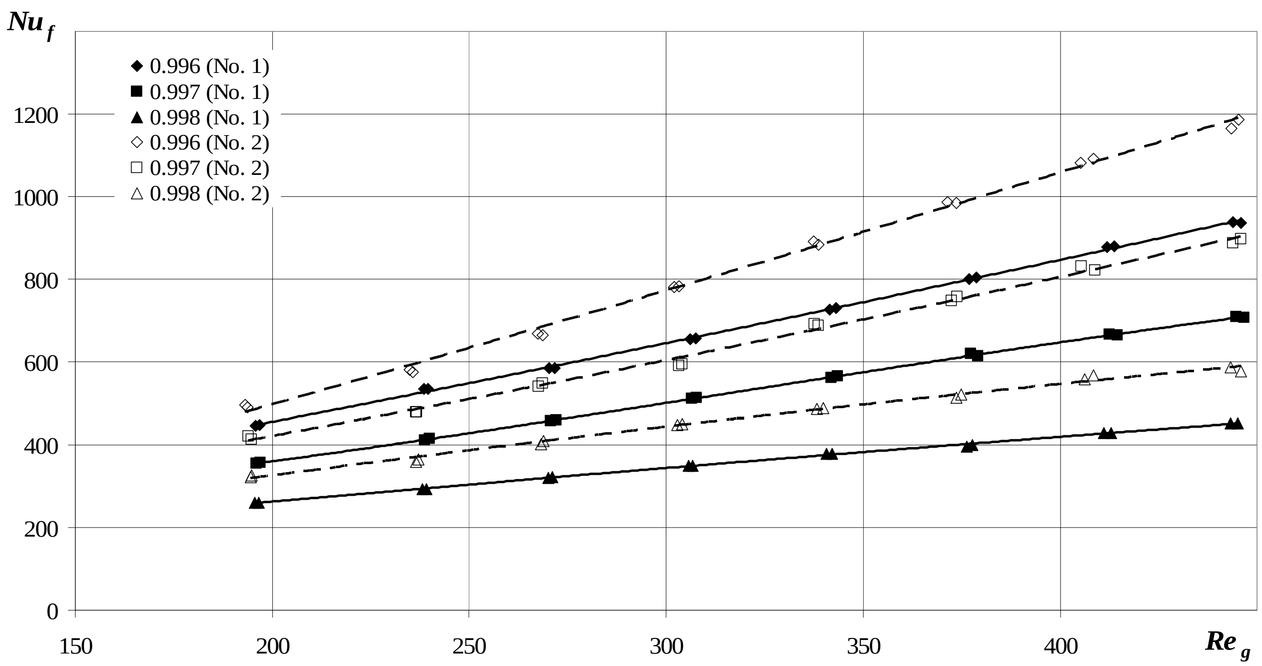

Figure 5. Average heat transfer of the tubes of the in line bundle No. 1 and No. 2 to downward foam flow: β=0.996, 0.997 and 0.998

4. CONCLUSIONS

Heat transfer of two in–line tube bundles with different geometry to vertical laminar downward after 180˚ degree turning foam flow was investigated experimentally.

The heat transfer intensity of both bundles' first tubes to downward foam flow is almost the same.

The heat transfer intensity of the further tubes of the tube bundle No. 2 is better than that of the tube bundle No. 1.

The effect of "shadow" is slight and heat transfer is higher for the tubes of the in–line tube bundle with more spacing between the tube centres along the bundle.

Results of investigation were generalized by criterion equations, which can be used for the calculation and design of the statically stable foam heat exchangers with in–line tube bundles.

5. ACKNOWLEDGEMENTS

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