Analysis of Tube Bank Heat Transfer In Downward Directed Foam Flow

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ABSTRACT

Apparatus with the foam flow are suitable to use in different technologies like heat exchangers, food industry, chemical and oil processing industry. Statically stable liquid foam until now is used in technologic systems rather seldom. Although a usage of this type of foam as heat transfer agent in foam equipment has a number of advantages in comparison with one phase liquid equipment: small quantity of liquid is required, heat transfer rate is rather high, mass of equipment is much smaller, energy consumption for foam delivery into heat transfer zone is lower.

The paper analyzes the peculiarities of heat transfer from distributed in staggered order and perpendicular to foam flow in channel of rectangular cross section tube bundle to the foam flow. It was estimated the dependence of mean gas velocity and volumetric void fraction of foam flow to heat transfer in downward foam flow. Significant difference of heat transfer intensity from front and back tubes of tube row in laminar foam flow was noticed. Dependence of heat transfer on flow velocity and volumetric void fraction of foam was confirmed and estimated by criterion equations.

Keywords: Foam Flow, Gas Velocity, Void Fraction, Heat Transfer, Tube Bundle, Downward Flow.

1. INTRODUCTION

Two–phase substances such as gas–liquid, liquid and solid particles, or gas and solid particles are often used in many technological processes, during which heat and mass exchanges take place. Two–phase flows of water and water vapor (liquid and gas) are very frequent in thermal energy systems where evaporation processes take place in boilers or nuclear reactors, or vapor condenses in condensers. They are also widely spread in chemical industry at rectification columns where they appear during evaporation or condensation processes.

The intensity of evaporation, condensation, absorption, desorption, burning and other technological processes depend on the inter–contact surface size of both phases (liquid and gas). In contemporary heat and mass exchange apparatuses large inter–phasic surfaces are created in two main ways: by diffusing liquid within gas (in scrubber type equipment) or diffusing gas within liquid (in barbotage type equipment). Foam equipment, different in its design, foam structure and regimes, belong to barbotage equipment group.

In recent years, foams equipment operating with steady foam regimes found increasingly wider application. Equipment of this type is used for drainage treatment, solution burning [1], solution concentration, evaporation, cooling, and foam inhibition.

Foam is distinguished by especially large inter–phasic contact surface and can be applied for the conduction of different purpose heat and mass exchanges. The efficiency of mentioned processes depends on the capacity "to control" foam. Presently, the most widely researched processes include hydrodynamic, heat and mass exchangers taking place in the flows of dynamic and fire-fighting foam [2]. However, these processes are investigated insufficiently especially in the regime of statically stable foam.

The application of statically stable foam flow in heat exchangers is perspective in both economic and engineering aspects. Studies [1] showed that heat exchangers with statically stable foam as an agent of heat transfer have many advantages:

small quantities of consumed liquid, conditionally large heat transfer rate, low energy consumption required for foam delivery to heat exchange space and etc.

Nomenclature

$\overline{w}$ – velocity, m/s; $\overline{Re}$ – Reynolds number; $\overline{Nu}$ – Nusselt number; ν – kinematic viscosity, m^2/s; β – volumetric void fraction; G – volumetric flow rate, m^3/s; A – cross section area of experimental channel, m^2; d – outside diameter of tube, m; q – heat flux density, W/m^2; $\overline{T}$ – average temperature, K; $\overline{\alpha}$ – average coefficient of heat transfer, $W/(m^2 \cdot K)$; λ – thermal conductivity, $W/(m \cdot K)$; d_b – diameter of foam bubble, m; *k, m, n* –coefficients

Indexes

f – value referred to foam flow;
g – value referred to gas;
l – value referred to liquid;
w – value referred to wall of heated tube.

2. REGIME OF STATICALLY STABLE FOAM FLOW

Excess pressure in the liquid forms up inside a bubble and is counterbalanced by surface tensile forces when gas is bubbled via liquid. Bubble formed up in pure liquid is destroyed before reaching the surface of the liquid. High surface tension and high excess pressure inside a bubble distinguish pure liquid, but the thickness of bubble's walls is insufficient. Owing to this reason, statically stable foam is formed up only of strong detergent solutions having less surface tension. When surface tension is small and, at the same time, excess pressure inside the bubble is small, strength bubble walls is strong enough to keep it undestroyed inside the liquid for some time. Bubble in statically stable foam keeps initial dimensions within broad limits of time interval from several seconds to days even after termination of gas supply. In practice, heavy statically stable foams are formed during various hydrodynamic, heat and mass exchange processes in food treatment (starch, milk powder, gelatine manufacturing) and other systems.

Statically stable foam may be formed from solutions of small compared with pure water surface tension. Even small concentration of detergents may be the reason of intensive generation of statically stable foam due to bubbling of gas. There exists minimum concentration of detergents for different kinds of detergents and different liquids, at the presence of which a certain liquid volume can be transformed into a flow of statically stable foam [3]. However, the concentration of detergents in solution predetermines the gas content of generated foam. Larger detergents' concentration allows generating foam of smaller gas content. For experimental foam production concentration of detergents must ensure required stability of foam and satisfy defined requirements to volumetric void fraction. Liquid drainage by Plateau channels is a comparatively slow process [4, 5]. Foam flow of larger velocity may have much more liquid content than the slow one being under greater influence of drainage.

It is known [6] that there are four main regimes of the statically stable foam flow in the vertical channel of rectangular cross section:

- Laminar flow regime $\overline{Re}_g$ =0 ÷ 600;
- Transition flow regime $\overline{Re}_g$ = 600 ÷ 1500;
- Turbulent flow regime $\overline{Re}_g$ = 1500 ÷ 1900;
- Emulsion flow regime $\overline{Re}_g$ > 1900.

Where

$$\overline{Re}_g = \frac{G_g \cdot d}{A \cdot \nu_g}. \qquad (1)$$

3. EXPERIMENTAL SETUP

The experimental model consisted of the following main parts: foam generation channel, gas and liquid control valves, gas and liquid rotameters, liquid storage reservoir, liquid level control reservoir, air fan, electric current transformer and stabilizer (Fig.1).

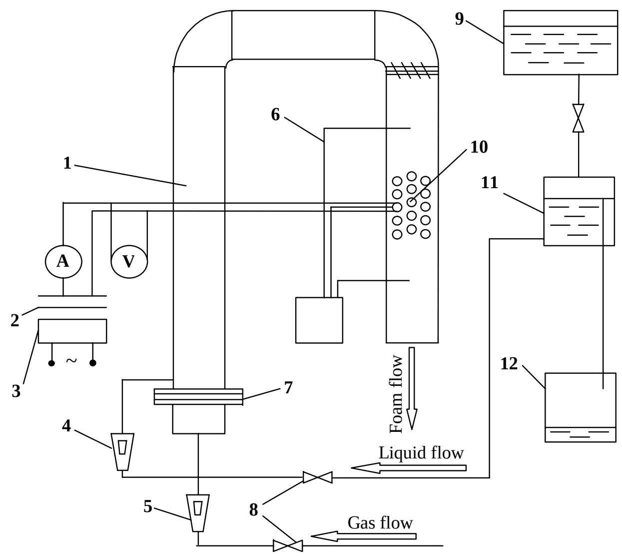

Fig.1: Experimental equipment scheme:
1 - foam channel; 2 - transformer; 3 - stabilizer; 4 - liquid rotameter; 5 - gas rotameter; 6 - thermocouples; 7 - foam generation riddle; 8 - gas and liquid control valves; 9 - liquid reservoir; 10 – channel with bundle; 11- liquid level control reservoir; 12 - liquid receiver

Experimental channel has a riddle at the bottom of experimental part. The whole experimental channel was made of glass in order to observe visually foam flow structure and the size of foam bubbles. The cross section of the channel has dimensions 0.14 x 0.14 m. The height of experimental channel was 1.8 m. Foam flow was generated on the riddle. The water solution with detergents was delivered from reservoir to the riddle from sides; gas was supplied to the riddle from below. When gas and liquid contacted, foam flow was produced. Liquid in experiment was used only once and was not returned 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, spacing among centers of holes was 5 mm. Holes were located in staggered order.

Schematic view of experimental section of the channel with tube bundle can be seen in Fig. 2.

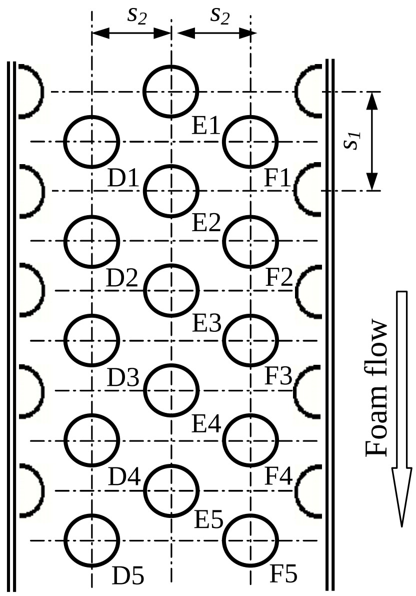

Fig. 2: Tube bundle in downward foam flow

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. The temperature of foam flow was measured by two calibrated thermocouples: one 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 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 detergents was kept constant and it was equal 0.5 %.

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 fraction can be expressed by equation:

$$\beta = \frac{G_g}{G_g + G_l}. \qquad (2)$$

The foam flow rate can be written as:

$$G_f = G_g + G_l. \qquad (3)$$

Gas velocity was changeable by changing gas flow rate and can be expressed by equation:

$$\overline{w}_g = \frac{G_g}{A}. \qquad (4)$$

The temperature of the tube surface and the foam flow, electric current and voltage were measured and recorded during the experiments. Our preliminary investigations showed that hydraulic and thermal regime stabilizes completely within 90 s after change of experiment conditions. Therefore measurements were started not earlier than 90 s after adjustment of foam flow parameters. After registration of electric current and voltage the heat flux density on the tube surface q_w was calculated.

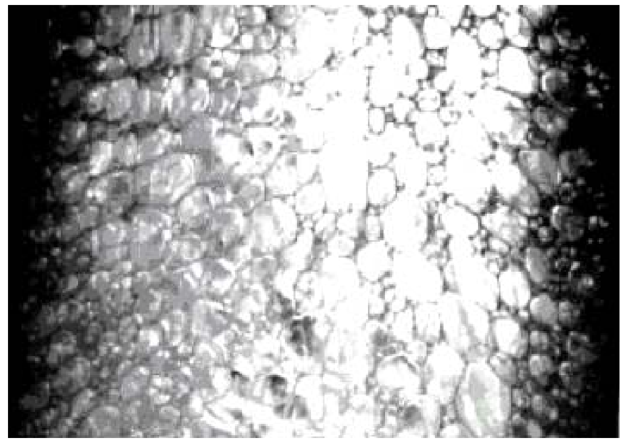

Fig. 3: Statically stable foam flow in the experimental channel

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

$$\overline{\alpha} = \frac{q_w}{\overline{\Delta T}}. \qquad (5)$$

The Nusselt number was determined as follows:

$$\overline{Nu}_f = \frac{\overline{\alpha} \cdot d}{\lambda_f}. \qquad (6)$$

Here λ_f - the thermal conductivity of the statically stable foams flow, W/(m·K):

$$\lambda_f = \beta\lambda_g + (1-\beta)\lambda_l. \qquad (7)$$

In order to avoid measurement errors and to increase reliability of investigation results all experiments and measurements were repeated three times.

During experiments foam flow was observed visually (Fig. 3).

4. RESULTS

The experimental results showed the great dependency of heat transfer intensity on mean gas velocity $\overline{w}_g$ and volumetric void fraction β. With an increase of $\overline{w}_g$ and decrease of β, heat transfer intensity increases. Heat exchange intensity between middle line of the first tube in the bundle and downward directed statically stable foam flow is shown in Fig.4.

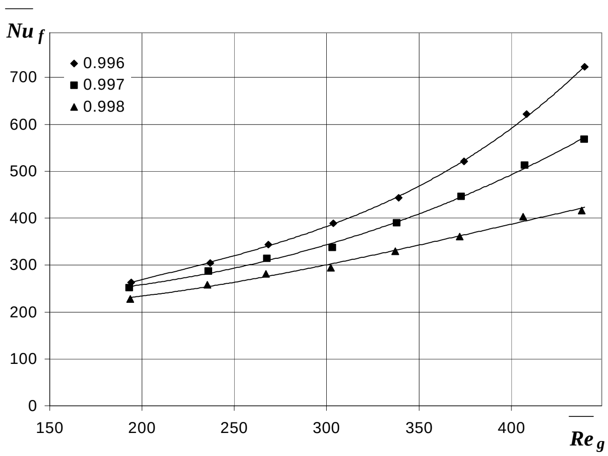

Fig. 4: Heat transfer of the first tube (E1) in the middle line of the bundle

When gas Reynolds number $\overline{Re}_g$ changes within the limits 190÷430, $\overline{Nu}_f$ of the first tube in the middle line tube bank (E1) (when β=0.996) increases from 260 to 720 W/(m^2·K) (Fig. 4).

In the meanwhile, mean $\overline{Nu}_f$ values of other tubes in the middle line increase less. The reason of these phenomena can be explained by the fact that the first tube in the bundle is being directly influenced by the foam flow, which reduces thickness of boundary layer on the tube and, at the same time, intensifies heat exchange. Further tubes of the bundle are allocated within internal space restricted by the tube bundle, where the foam flow is being obstructed and tube surface washing conditions become worse since the foam flow flows by way of smallest resistance–along space among the tube lines.

The impact of volumetric void fraction β on the intensity of heat exchange is high for all middle-line tubes of the bundle. It was noticed that upon decrease of volumetric void fraction (foam is getting wetter) the values of heat transfer intensity increase. When volumetric void fraction is reduced from 0.998 to 0.996, the intensity of heat exchange can be augmented even two times at the same mean gas velocity. This means that upon decrease of volumetric void fraction more liquid transferred with the foam flow. Apart from that, it was noticed that changes in foam volumetric void fraction influences not only on magnitude of mean heat transfer intensity but also on the character of relationship.

The comparison of heat transfer intensity of the bundle's middle line tubes in downward directed flow of statically stable foam at void volumetric fraction β=0.996 and β=0.998 is shown in the Fig.5.

When gas Reynolds number $\overline{Re}_g$ changes within the limits 190÷375 and void volumetric fraction is β=0.996, the fifth tube is distinguished by the best heat transfer rate to statically stable foam flow. This happens due to the fact that when gas velocity is small, foam flow consists of large size bubbles (d_b = 8÷14 mm). Passing through the bundle of tubes large bubbles of foam are destroyed into smaller bubbles. The drainage process between heated surface and statically stable foam becomes more intensive. This also increases heat transfer intensity of that tube.

When mean gas velocity increases, the foam of smaller bubbles starts forming up in the foam-generating channel. Smaller foam bubbles, greater number and more dense distribution of them make foam flow more homogenous and better washing heated surfaces. Besides of that, owing to thicker Plateau channel network, more intensive liquid drainage from foam bubbles takes place, which additionally intensifies heat transfer rate of the frontal tubes in the bundle.

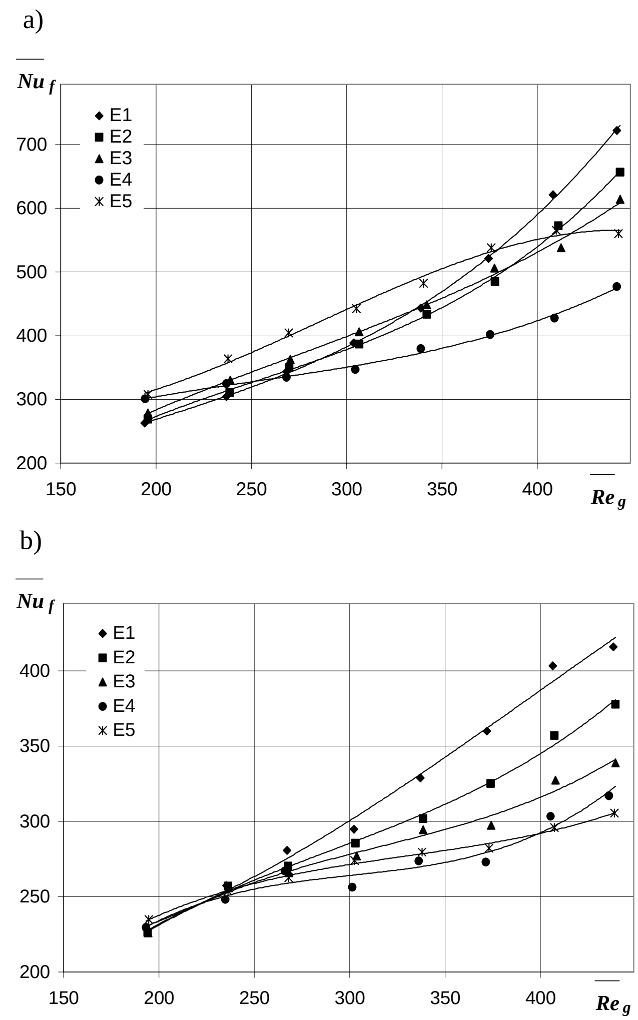

Fig. 5: Heat transfer of the tubes in the middle line of the bundle in foam flow: a) β= 0.996, b) β= 0.998

In the same manner was investigated heat transfer rate of side tubes in the bundle in cross-downward statically stable foam flow. It was noticed that the first sideline tube most sensitively reacts to the changes in mean flow velocity.

The experimental results of the dependence of mean heat transfer on mean gas velocity were generalized by using the dependence of Nusselt and Reynolds number similarity criteria. This dependence within interval 190 < $\overline{Re}_g$ < 430 can be expressed by equation:

$$\overline{Nu}_f = k \cdot \beta^n \cdot \overline{Re}_g^m . \qquad (8)$$

On average, for entire middle line in the bundle:
m =205.75-205.65·β;
n = 993;
k = 113.3.
On average, for entire side line in the bundle:
m =225.99-225.95·β;
n = 1014.1;
k = 175.5.
On average, for entire tube bundle allocated staggered order:
m =217.21-217.15·β;
n = 1002.5;
k = 144.

5. CONCLUSIONS

The heat transfer intensity from tubes bundle to foam flow depends greatly not only on foam flow velocity but on the volumetric void fraction of the foam flow also.

At maximum gas velocity and minimum foam volumetric void fraction β=0.996, the values of heat transfer rate are nearly twice larger like those of the largest void volumetric fraction β=0.998 at the same gas velocity.

Experimental results of tube bundle's heat transfer to downward cross foam flow were generalized by criterion equations. The obtained criteria equations can be used for the calculation and design of the statically stable foam heat exchangers.

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