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Vertical channel's heat transfer to the upward foam flow

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ABSTRACT

Paper presents the semi empirical model of the heat transfer process between the internal surface of the vertical channel (tube) and the laminar longitudinal upward macro foam flow. Model is based on the assumption that the amount of the liquid which drains from the macro foam per second in the *n* vertical zones of the channel is proportional to the *n*th part of the liquid which comes to the appropriate zone with the foam.

The relationship between the foam flow parameters, such like foam flow rate (velocity), volumetric void fraction and temperature was analyzed. Investigation showed that the heat transfer rate monotonically increases with the increase of the foam flow velocity, with decrease of the volumetric void fraction and with increase of the temperature difference between foam flow and channel wall.

Comparison of the results of the modeling of the vertical channel with the experimental data, obtained for the vertical flat surface, showed its satisfactory agreement.

1. Introduction

Nowadays aqueous two-phase foam has wide practical application in different technological processes. Foam can be used for cleaning of the material or surfaces [1], for fire-fighting [1,2], for plant protection against the frost [3], for gas clearing from the dust [4,5], for drilling and gas or oil recovery [5,6] and etc. Comparatively new direction of the foam application is to use it as a coolant in the heat exchangers [7,8]. The foam with relatively high content of the liquid and very small dimension of the bubbles (micro foam) showed good results as a coolant in micro channels and micro equipment [9]. Another kind of the foam, so called, macro foam (foam with a polygonal structure and very high content of gas) can be used as a coolant also [7]. Main advantage of the macro foam is a relatively high heat transfer rate at a low mass flow rate [7]. Today wider application of the macro foam as a coolant is complicated due to the instability of its structure. Liquid drainage from the macro foam [10,11], diffusive gas transfer [12], junction and collapse of the foam bubbles [1] and other complicated processes take place inside the macro foam flow. Therefore the heat transfer rate depends on the foam flow velocity, volumetric void fraction, bubbles dimension, on the heat transfer surface geometry, shape, orientation and etc.

The experimental investigation of the heat transfer from the various surfaces to the flow of the macro foam showed relatively high heat transfer rate [7]. Some works were devoted to the investigation of the heat transfer from the single tube [7] or tube row [7] to the macro foam. It was noticed that the heat transfer coefficient of a single tube (of 0.014 m diameter) to the macro foam flow (of 0.4 m/s velocity) varied from 350 to 682 W/(m^2 K) depending of the foam volumetric void fraction [7]. Heat transfer coefficient of the single tube to the air flow was equal to 16 W/(m^2 K) and to the water flow $-$3963 W/(m^2 K) under the same flow velocity (0.4 m/s) of coolant. At the same time, a density of the air was equal to 1.2 kg/m^3, 3.2–5.2 kg/m^3 for foam and 998.2 kg/m^3 for water [7].

An investigation of the heat transfer process between the staggered [13], in-line [14] and nonstandard [15] tube bundles to vertically upward and downward statically stable foam flow was made as well. The results of the investigations showed that, like in the case of the single-phase flow, heat transfer rate increased with the increase of the foam flow velocity [13–15]. But there were some differences also. For example, the highest heat transfer rate was reached for the first tube (or tube line) of the vertical row (or tube bundle), and further heat transfer rate decreased with each following tube (or line) [14,16].

Another works [17,18] were devoted to the investigation of the heat transfer between the inclined flat surface and the longitudinal upward flow of the macro foam. Investigation showed, that one of the main factors, which influenced on the heat transfer process,

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Nomenclature

c_p	heat capacity, kJ/(kg K)
d	diameter, m
G	mass flow rate, kg/s
h	heat transfer coefficient, W/(m^2 K)
i	number of zone ($i = 1,2,\ldots,n$)
n	quantity of zones
Q	heat flux, W
q	heat flux density, W/m^2
Re	$w_g \cdot d_b/\nu_g$ gas flow Reynolds number
T	temperature, K
w	flow rate, m/s

Greek symbols

β	volumetric void fraction, dimensionless
ϑ	temperature, K
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
Σ	total

Subscripts

av	average
b	bubble
dr	drainage
f	foam
g	gas
l	liquid
m	mass
in	input
out	output
w	wall

was liquid drainage from the foam flow. The drained liquid leaved the foam flow and formed a thin film on the heated surface. The thickness of this film depended on the distribution of the volumetric void fraction of the foam along the channel, on the foam flow velocity change across and along the surface and on the inclination angle of the surface. The cooling rate of the heated surface was influenced mainly by the film thickness and by the velocity of the drained liquid in it. Equations for heat transfer process calculation were proposed and the results were compared with the experimental results, obtained by the authors [17,18].

One of the recent works [19] was related to the experimental investigation of the heat transfer between the vertical flat surface and the longitudinal upward macro foam flow. The experiments showed that an irregular cross-sectional distribution of the foam flow velocity influenced on the heat transfer rate at the different parts of the surface. Distribution of the volumetric void fraction across and along the surface also had impact on the cooling rate. Heat transfer rate of the vertical flat surface mainly depended on the foam flow velocity and increased according to the increase of the foam flow rate [19].

The results of the experimental and theoretical investigation of the heat transfer between the single phase (water, air) or two phase (water–vapor, water–air) flow and the wall of the vertical channel have been published widely [20–22] and etc. Although there is no data, related to the investigation of the vertical channel cooling by the aqueous two-phase macro foam flow.

This paper presents the semi empirical model of the heat transfer process between the internal surface of the vertical channel (tube) and the longitudinal laminar upward macro foam flow. Cooling mechanism of the vertical channel is quite different from the cooling of the inclined surface [17]. In the case of the vertical channel drained liquid does not leave the foam flow and does not form additional separate liquid film on the channel's wall. That liquid, passing to the lower levels of the foam flow influenced additionally on the void fraction distribution along the channel's height. The drained liquid directly did not change the thickness of the film, which separated foam flow from the channel's wall. The influence was indirect – via alteration of the void fraction, change of the bubbles dimension and foam flow velocity.

Proposed model allows calculating heat transfer rate using heat transfer and heat balance equations for the case if are known the following parameters: heat power, transferred from the channel to the macro foam flow; foam flow temperature at the entrance to the channel and at the exit; temperature of the channel's wall.

2. Foam flow hydrodynamics

In order to calculate heat transfer rate from the channel to the upward foam flow initially it is necessary to find the distribution of the foam's liquid flow along the channel. Liquid drainage from the macro foam has significant influence on the heat transfer between the surface and foam flow. Foam flow loosing liquid becomes dryer and therefore heat transfer rate decreases. In the case of the inclined rectangular channel drained liquid formed a thin liquid film on the lower surface of the channel [17].

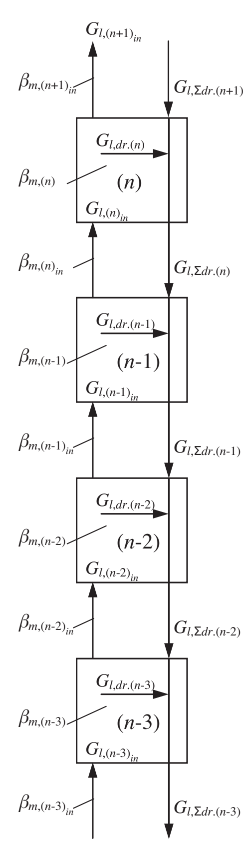

Fig. 1. Principle scheme of the liquid flows in the foam channel.