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# Experimental investigation of heat transfer from a horizontal flat surface to aqueous foam flow

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## ABSTRACT

Usage of aqueous foam flow as a coolant allows relatively large heat transfer intensity with very small coolant mass flow rate in foam apparatus and heat exchangers. Our previous experimental investigation of the heat transfer between a vertical flat surface and longitudinal upward aqueous foam flow showed dependence of the surface cooling intensity on the foam flow velocity and the volumetric void fraction. In the case of an inclined flat surface, liquid drained from the foam and formed a film on the inclined heated surface. The direction of movement of liquid particles in this film depended on experimental conditions.

An experimental investigation of the heat transfer between a horizontal flat surface and longitudinal foam flow was performed and the results are presented and discussed in this paper. It was observed that the particles of drained liquid film moved in the same direction as the foam flow. The cross-sectional velocity distribution of the foam bubbles influenced on the amount of draining liquid across the channel. Higher inflow of draining liquid of lower temperature gave rise to better conditions for the cooling of the side parts of the heated surface.

## 1. Introduction

Environmental responsibility, depletion of fossil fuel resources and rising energy prices all drive the development of energy efficient technologies. An application of multiphase systems such as aqueous foam can open new technological possibilities in this area. Aqueous foam has especially large inter-phase contact surface and reduced surface tension, which can be put to use in diverse applications: fire-fighting, protection of plants against frost [1], dust removal from gas [2], preparation of concrete with novel characteristics [3] and more.

Usage of aqueous foam flow as a coolant allows relatively large heat transfer intensity with very small coolant mass flow rate in foam apparatus and heat exchangers [4–6]. The heat transfer rate can be controlled by changing the foam flow velocity as in the case of single-phase fluid flow [4,7]. However, in the case of foam, the additional possibility to change heat transfer rate by changing foam volumetric void fraction arises, increasing the control limits of the heat transfer process [5,8]. Apart from the mentioned advantages, the generation and application of aqueous foam flow is complex due to specific peculiarities of foam such as drainage of liquid from foam [9–11], diffusive gas transfer between bubbles [9,12], and division, merging and destruction of the foam bubbles [13,14]. One of the main tasks for foam coolant is to keep its structure for the time necessary to pass through the heat transfer zone [4].

The characteristics of foam able liquid depend on the type and concentration of surfactants and on the type and temperature of liquid. The generation conditions, cross-sectional shape, the dimensions and properties of channel influence on the characteristics of foam and foam flow also. Therefore, it is difficult to compare the results of different experimental researches. The influence of the channel inclination angle on characteristics of two-phase flow and on the intensity of the heat transfer process from heated surface to two-phase flow got the attention of scientists. For inclination angles close to horizontal, suppression of shear stress and heat transfer of 10% and 25% respectively, was registered [15]. The processes of liquid film formation, flow and film heating or cooling on vertical and inclined surfaces are frequent in industrial heat exchanges and are under investigation [16,17]. The investigation of the effects of inclination angles on foam rheology in pipes was performed [18,19]. The results showed that foam rheology was not significantly altered as long as the slug flow or plug flow pattern was formed because of a viscous-force dominant environment. However, if flow conditions fell within the segregated flow pattern, foam rheology was governed by

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## Nomenclature

| | |
|---|---|
| $A$ | area, $m^2$ |
| $B$ | channel width, m |
| $c$ | coefficient, dimensionless |
| $G$ | flow rate, $m^3/s$ |
| $h$ | heat transfer coefficient, $W/(m^2 K)$ |
| $I$ | amperage, A |
| $L$ | heated surface length, m |
| $l$ | path of foam flow, m |
| $m$ | coefficient, dimensionless |
| $n$ | coefficient, dimensionless |
| Nu | Nusselt number, dimensionless |
| $P$ | power, W |
| $q$ | heat flux density, $W/m^2$ |
| Re | Reynolds number, dimensionless |
| $T$ | temperature, K |
| $u$ | local velocity, m/s |
| $V$ | voltage, V |
| $W$ | heated surface width, m |
| $w$ | mean velocity of the foam flow, m/s |
| $x$ | distance along the channel, m |
| $y$ | distance across the channel, m |

*Greek symbols*

| | |
|---|---|
| $\beta$ | volumetric void fraction, dimensionless |
| $\lambda$ | thermal conductivity, $W/(m \cdot K)$ |
| $\nu$ | kinematic viscosity, $m^2/s$ |

*Subscripts*

| | |
|---|---|
| *av* | average |
| *ch* | channel |
| *cr* | cross-section |
| *f* | foam flow |
| *g* | gas |
| *i* | location of thermocouple along the surface ($i = 1, 2, \ldots, 6$) |
| *in* | inflow |
| *j* | location of thermocouple across the surface ($j = 1, 2, 3$) |
| *l* | liquid |
| *out* | outflow |
| *s* | heated surface |

the gravitational force rather than the viscous force, and therefore the flow characteristics were sensitive to inclination angles [18,19].

Our previous experimental investigation started from experimental investigation and analysis of the heat transfer between a vertical flat surface and a longitudinal upward aqueous foam flow [20,21]. Analysis of results showed the evident dependence of the surface cooling intensity on the foam flow velocity and volumetric void fraction. The situation changed in the case of an inclined flat surface cooled by longitudinal upward foam flow [22,23]. Liquid drained from the foam and formed a film on the inclined heated surface. The cooling rate of the heated surface depended mainly on the film thickness and on the velocity of the drained liquid in it. The thickness of the drained liquid film depended on the distribution of the volumetric void fraction of the foam, foam flow velocity across and along the surface and the inclination angle of the surface. It was determined that the heat transfer rate increased with the increase of the foam flow velocity up to a critical value. When the foam flow velocity exceeded the critical value, the thickness of the drained liquid film began to grow and the heat transfer rate decreased. Further augmentation of the foam flow velocity resulted in an increase in the heat transfer rate again [22,23]. Having investigated cooling of vertical and inclined surfaces by foam flow, the question arises: how will the situation change in the case of horizontal surface cooling by longitudinal foam flow? The current paper presents the results of the experimental investigation of the heat transfer process between a heated horizontal flat surface and longitudinal aqueous foam flow.

## 2. Experimental set-up and methodology

An experimental investigation of the heat transfer between a heated horizontal flat surface and longitudinal foam flow was performed using the experimental set-up shown in Fig. 1. The main parts of the experimental equipment were the foam flow generation system, horizontal channel, flat surface and its electrical heating system, foam destroyer (not shown in Fig. 1), measurement devices and auxiliary equipment. The walls of the horizontal channel were made from transparent material (Perspex) so that the foam flow could be observed visually. The channel was of square cross-section ($A_{ch\_cr} = B \times B = 0.14 \times 0.14$ $m^2$). A stainless steel flat surface ($A_s = L \times W = 0.5 \times 0.12$ $m^2$, thickness 0.0001 m) was installed in the bottom wall of the channel. This surface was heated electrically. The magnitude of electric current generated by the experimental set-up electrical heating system was limited. The nominal current was equal to $I = 80.0 \pm 4.0$ A and voltage was equal to $V = 1.90 \pm 0.07$ V. Temperature of the experimental surface was measured by eighteen calibrated type-T (copper-constantan) thermocouples (Fig. 2). Two thermocouples were used for the measurement of the temperature of the inflowing foam: one at the center of the channel's bottom wall (Fig. 1) and the other at the center of the cross section of the channel. Both thermocouples were positioned 0.025 m upstream of the channel part with the heated surface. Three thermocouples were used for the measurement of the temperature of the outflowing foam. First thermocouple was installed at the center, second at 0.04 m distance from the center across the channel and both thermocouples were at channel's bottom wall (Fig. 1). The third thermocouple was at the center of the cross section of the channel, and all three mentioned thermocouples were positioned 0.025 m distance downstream of the channel part with the heated surface. Accordingly to nominal electric current, the temperatures of the heated surface varied from 287.7 to 315.5 K; the foam flow temperatures varied from 283.9 to 288.9 K; the temperatures of the drained liquid film varied from 283.9 to 308.3 K. It is known that the increase of the temperature to 343.2 K and more has destructive effect on foam bubbles [4,9]. Therefore, the temperatures of heated surface let to keep foam flow stability during all experiments.

Foam flow was generated during gas and liquid contact by gas moving through the layer of the foam-able solution on the perforated plate. Foam-able solution was prepared from water and surfactant (washing powder TIDE absolute, concentration 0.5%) [4]. Solution characteristics at the 293.15 K temperature were as follows: surface tension: 0.0375 N/m, viscosity: 0.00995 $cm^2/s$, density: 1003.0 $kg/m^3$. Air bubbled through the perforated stainless steel plate (thickness 0.002 m). The orifices (diameter 0.001 m) of this plate were located in a staggered order; spacing between the centers of the orifices 0.005 m.