HEAT AND MASS TRANSFER WHEN A TWO-COMPONENT, TWO-PHASE FLOW PASSES INTERNALLY AROUND A CYLINDRICAL SURFACE

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The criterial equations of heat and mass transfer are derived for the evaporation of a liquid boundary film in the dispersed-annular mode. The adiabatic and nonadiabatic processes are considerable under the conditions of the internal problem.

There have been a large number of investigations into the heat transfer which occurs during the motion of two-phase flows inside vertical, sloping, and horizontal tubes; these have been mainly concerned with emulsion and projectile conditions of flow.

Usually an analogy has been drawn with a single-phase flow, and the deviation has been estimated by introducing certain characteristics of a two-phase flow into the calculating relationships.

This approach cannot be justified when considering sparsely-filled, dispersed-annular flows (the volume content of the liquid phase being no greater than 1%), since it fails to reveal the physical picture of the phenomenon. It is well known that dispersed-annular flows are characterized by the existence of a liquid boundary film and a gas core carrying drops of liquid inside it. The velocity of the film is low compared with that of the gas, and a continuous exchange of liquid mass takes place between the gas core and the boundary film.

For high gas contents such as occur in the dispersed-annular mode, the convective component of thermal flow becomes commensurable with the heat of the phase transformation; hence in flows of this kind the structural method of studying heat transfer, i.e., separate consideration of heat and mass transfer, is preferable.

We are not aware of any systematic investigations into heat and mass transfer in the dispersed-annular mode [1, 2]. It is very important that such investigations should be carried out in view of the fact

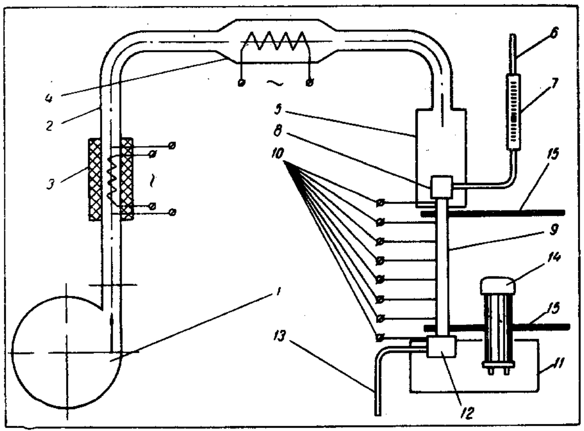

Fig. 1. Arrangement of the experimental apparatus. 1) High-pressure blower; 2) air conduits; 3) thermal flow meter; 4) electric heater; 5) upper working chamber; 6) supply of liquid; 7) liquid flow meter; 8) feeder used to form the annular boundary film; 9) working section; 10) copper –Constantan thermocouples in the working section; 11) lower working chamber; 12) liquid collector; 13) selection of liquid; 14) psychrometer; 15) electrical conductors for directly heating the working section with current from a welding transformer.

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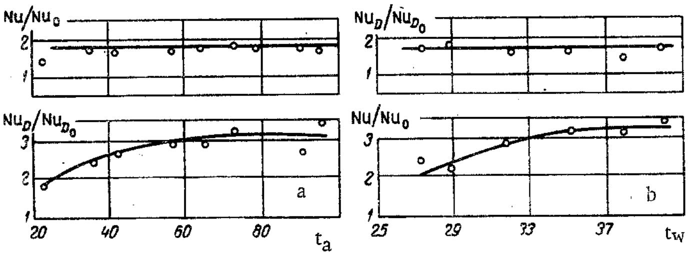

Fig. 2. Intensification of heat and mass transfer in dispersed-annular flows under adiabatic (a) and nonadiabatic (b) conditions (ϕ = 0.14 m; Re = 34,000 (a) and 32,000 (b); t, °C).

that the dispersed-annular mode is a working condition of practical importance in devices based on the principle of film-type evaporative cooling.

Our experiments were conducted in vertical steel tubes with an internal diameter of 0.010, 0.012, and 0.014 m and a length/diameter ratio of $l/d = 91$; 67.5; 44.0, with a wall thickness of $\delta = 0.001$ m, and also in copper tubes with an internal diameter of 0.014 m, an l/d ratio of 5, 10, 20, 30, and 40, and a diameter of 0.035 m ($l/d = 40$).

The fact that the flow of the two-phase mixture in these experiments corresponds to the dispersed-annular mode was confirmed by direct observation and also existing data [7].

The experiments were conducted under adiabatic and nonadiabatic conditions.

The arrangement of the experimental apparatus is shown in Fig. 1.

The moisture content at the entrance into the apparatus and at the exit from the working section was determined with an Asman psychrometer.

The annular boundary layer of liquid at the exit from the working section was collected in a collector, and a vapor–gas phase containing only a small amount of suspended liquid passed into the lower working chamber. The readings of the psychrometer in the lower working chamber were verified by reference to the absolute humidity field in the exit section of the working part, recorded with a "wet" thermocouple and a laboratory probe [3]. Tests showed that the effect of the suspended phase passing into the lower working chamber could be neglected.

The wall temperature was taken as equal to the temperature of the film. The Nu, Nu_D, Re, Pr, and Pr_D numbers were calculated in the usual manner for calculations of air-evaporative cooling [4]. The accuracy of the experimental work was verified by reference to the heat and material-balance equation; it was no worse than ±10%.

The Nu and Nu_D numbers determined in the experiments were compared with the Nu_0 and Nu_{D0} numbers calculated for the annular motion of a two-phase medium in a tube [4].

The experiments showed that heat and mass transfer was characterized by a greater intensity in the dispersed-annular mode than in the case of annular flow. By way of example, Fig. 2 shows the dependence of Nu/Nu_0 and Nu_D/Nu_{D0} on the air temperature at the entrance into the working section under adiabatic (a) and nonadiabatic (b) conditions in relation to the mean wall temperature. The influence of the thermal field is considerable; it also differs under adiabatic and nonadiabatic conditions.

The influence of the thermal field on heat-transfer processes may be allowed for by introducing the complex

$$\Theta = \frac{\Delta t}{T},$$

where Δt is the absolute temperature difference between the wall and the core of the flow, T is the mean temperature of the gas core under adiabatic conditions (°K) and the mean wall temperature under nonadiabatic conditions. In both cases the power index of Θ is approximately 1/3.

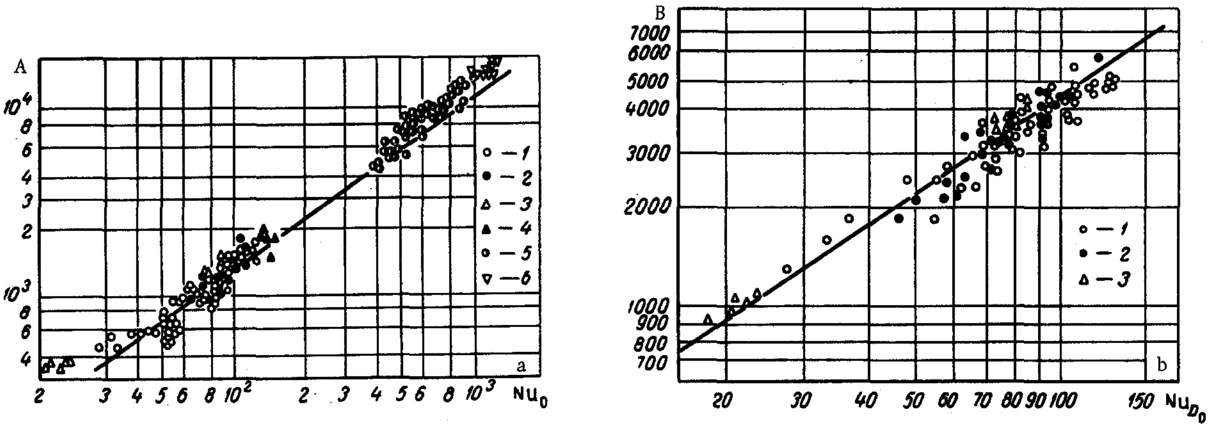

Fig. 3. Correlation between the experimental data relating to heat transfer under adiabatic conditions in tubes with different internal diameters [a) authors' data (1-4); data from [1] (5, 6); b) authors' data]; $A = \mathrm{Nu}\sqrt{\mathrm{Re}''}/\sqrt[3]{K^2}\left[\frac{d}{\sqrt{\frac{\sigma}{g(\rho'-\rho'')}}}\right]^{1/2}\left[\frac{\mu''}{\mu'}\right]^{-1/4}$, $\mathrm{B} = Nu_D\sqrt{\mathrm{Re}''}/\sqrt[3]{K^2\Theta}\left[\frac{d}{\sqrt{\frac{\sigma}{g\cdot(\rho'-\rho'')}}}\right]^{1/2}\left[\frac{\mu''}{\mu'}\right]^{-1/4}$:

1) 0.01 m; 2) 0.012; 3) 0.014; 4) 0.035; 5) 0.0508; 6) 0.1016

The fact that the heat and mass transfer is more vigorous in the dispersed-annular mode than in the annular flow of a two-phase mixture i.e., (without flow disruption of the drops) may be explained by the interaction of the liquid boundary film with the gas core of the flow as well as the disruption and precipitation of the drops, i.e., by hydrodynamic circumstances, which are very complicated and depend on a whole number of factors. These circumstances are primarily affected by the velocity and density of the gas flow, the density of the liquid phase, the surface tension of the liquid, the geometrical size of the heat-transfer element, the drop exchange coefficient between the core and the liquid film, the viscosity of the liquid and gas phases, and so on.

According to [5-12] these variables may be united into the following dimensionless complexes:

$$\left\{K = \frac{w''\sqrt{\rho''}}{\sqrt[4]{\sigma g(\rho'-\rho'')}};\ \mathrm{Re}'';\ \frac{l_1}{l_2} = \frac{d}{\sqrt{\frac{\sigma}{g(\rho'-\rho'')}}};\ \frac{\mu''}{\mu'}\right\}. \tag{I}$$

In order to obtain generalized criterial relationships from the heat and mass transfer we made a closer study of the effect of the gas-phase density, the surface tension of the liquid, and the viscosity of the liquid on the transfer processes.

The effect of the density of the gas phase on heat and mass transfer in a dispersed-annular flow was studied under adiabatic conditions, varying the absolute pressure in the working section from $1.0 \cdot 10^5$ N/m^2 to $0.2 \cdot 10^5$ N/m^2. The effect of the surface tension was studied in solutions of sodium oleate of various concentrations. The surface tension was varied in these experiments from $29.6 \cdot 10^{-3}$ N/m to $72 \cdot 10^{-3}$ N/m.

In order to study the effect of viscosity we used aqueous solutions of glycerin of various concentrations. The ratio μ''/μ' in these experiments varied from $2.5 \cdot 10^{-2}$ to $3 \cdot 10^{-3}$.

Analysis of published data [8-12] showed that the exchange of drops between the core of the flow and the liquid boundary film in dispersed-annular flows with a low concentration of the suspended phase was characterized by a coefficient proportional to $(\mathrm{Re}'')^{-0.5}$.

We found that the complexes (I) in the criterial equation had the following power indices:

$$\left\{\sqrt[3]{K^2};\ (\mathrm{Re}'')^{-0.5};\ \left(\frac{l_1}{l_2}\right)^{0.5};\ \left(\frac{\mu''}{\mu'}\right)^{-0.25}\right\}. \tag{II}$$

Figure 3 presents a correlation between the experimental data under adiabatic conditions, expressed in the coordinates

$$\frac{\mathrm{Nu}\,(\mathrm{Re}'')^{0.5}\left(\frac{\mu''}{\mu'}\right)^{0.25}}{\sqrt[3]{K^2}\left(\frac{l_1}{l_2}\right)^{0.5}} \div \mathrm{Nu}_0,$$

$$\frac{\mathrm{Nu}_D\,(\mathrm{Re}'')^{0.5}\left(\frac{\mu''}{\mu'}\right)^{0.25}}{\sqrt[3]{K^2\Theta}\,\left(\frac{l_1}{l_2}\right)^{0.5}} \div \mathrm{Nu}_{D_0}.$$

A similar correlation was obtained under nonadiabatic conditions.

Figure 3a incorporates the results of [1] analyzed by the method here proposed.

The correlation of the experimental data yielded the following criterial equations for describing the processes of heat and mass transfer under adiabatic conditions:

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 12\,\sqrt[3]{K^2}\,(\mathrm{Re}'')^{-0.5}\left(\frac{l_1}{l_2}\right)^{0.5}\left(\frac{\mu''}{\mu'}\right)^{-0.25}, \quad (1)$$

$$\frac{\mathrm{Nu}_D}{\mathrm{Nu}_{D_0}} = 45\sqrt[3]{K^2\Theta}\,(\mathrm{Re}'')^{-0.5}\left(\frac{l_1}{l_2}\right)^{0.5}\left(\frac{\mu''}{\mu'}\right)^{-0.25}, \quad (2)$$

$$0.025<\Theta<0.1;\quad 10^4<\mathrm{Re}''<10^5;$$

$$4<K<20;\quad 3.8<l_1/l_2<13$$

and under nonadiabatic conditions:

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 70\,\sqrt[3]{K^2\Theta}\,(\mathrm{Re}'')^{-0.5}\left(\frac{l_1}{l_2}\right)^{0.5}\left(\frac{\mu''}{\mu'}\right)^{-0.25}, \quad (3)$$

$$\frac{\mathrm{Nu}_D}{\mathrm{Nu}_{D_0}} = 12\sqrt[3]{K^2}\,(\mathrm{Re}'')^{-0.5}\left(\frac{l_1}{l_2}\right)^{0.5}\left(\frac{\mu''}{\mu'}\right)^{-0.25}, \quad (4)$$

$$0.025<\Theta<0.1$$

for

$$10^4<\mathrm{Re}''<10^5,\ 4<K<20,\ 3.8<l_1/l_2<13.$$

Since in the experiments the length of the working parts was 40-90 diameters, we made some special experiments to establish the influence of the entrance section. The experiments showed that under dispersion-annular conditions of flow the influence of the entrance section made itself felt for l/d values of under 40 diameters. This conclusion agrees with existing data regarding the influence of the length of the entrance section on the hydrodynamics of the dispersion-annular mode [8].

NOTATION

w reduced velocity of the phase, m/sec;
ρ density of the phase, kg/m^3;
σ surface tension of the liquid, N/m;
μ dynamic viscosity, N·sec/m^2;
g gravitational acceleration, m/sec^2;
l linear dimension, length of the working section, m;
d internal diameter of the working section, m.

Superscripts

$''$ gaseous phase;
$'$ liquid phase.

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