HEAT EMISSION OF GAS BUBBLES IN A ROTATING BUBBLING LAYER

I. I. Borisov, A. A. Khalatov,
E. E. Ikonnikova, G. V. Kovalenko, and
S. V. Shevtsov

UDC 66.021.32:536.248.2

Based on an experimental study of contact heat transfer between a liquid and a gas in an eddy-generating bubbler and on results processed using the equation of nonstationary heat conduction, we obtained a dimensionless relation for calculating the coefficient that characterizes heat transfer in a gas bubble within the framework of a model based on effective coefficients of heat conduction.

The use of eddy-generating bubblers in chemical technology, gas purification, and a number of other engineering applications makes it possible to substantially enhance, as compared to gravitational-bubbling apparatus, the processes of contact heat and mass transfer between liquid and gas and thus improve significantly the weight and size characteristics of equipment and increase its specific energy capacity. This intensification is achieved by means of the influence of the field of centrifugal inertial mass forces on a two-phase medium, leading to breaking of gas bubbles, an increase in the specific contact surface of the phases, and practically instantaneous renewal of it.

The study of heat transfer in eddy-generating bubbling apparatus was the concern of [1, 2]. These works suggest similarity equations making it possible to perform calculations of the overall (over the entire gas-liquid layer) heat transfer coefficient as a function of geometric and operational parameters of the apparatus. However, this approach does not permit us to take into account the layer thickness; i.e., the presence of a gas bubble is virtually ignored.

The aim of the present work was to implement, on the basis of an experimental study of heat transfer in an eddy-generating bubbling apparatus, a local approach to the processing of results, i.e., to consider the motion of a single bubble and develop a semiempirical computational procedure that would take into account the residence time of the bubble in a rotating gas-liquid layer.

The experiments were conducted on the setup depicted schematically in Fig. 1. The eddy-generating bubbling apparatus with a motionless body consists of gas collector 1, guiding device 2, upper cover 3, and ring 4, which determines the thickness of the bubbling layer.

Air from a compressor passes through flowmeter (orifice plate) 5, then enters ohmic heater 6, and is supplied to the apparatus through branch pipe 7. The air is vented through separator 8, in which virtually complete separation of the phases takes place. Liquid (water) enters into the apparatus from the water-supply line through rotameter 9, then is supplied tangentially to the upper part of the layer, and is discarded through branch pipe 10.

The guiding device is an organic glass ring with internal diameter $D_k = 0.18$ m and height $H_k = 0.029$ m in which 15 slits of width $b = 0.001$ m and depth 0.0145 m (the relative flow cross section is $s = 2.65\%$) are located uniformly at the top and bottom in a staggered manner along the ring perimeter. The angle at which the slits are inclined to the radius is 70°. The thickness of the bubbling layer H_{lay} is varied in the experiments from 0.015 to 0.025 m by replacing ring 4.

In the experiments we measured the flow rates of liquid and gas as well as their temperatures at the inlet to the two-phase layer and at the outlet from the apparatus by means of Chromel-Copel thermocouples whose cold ends were placed in a null thermostat. Moreover, we controlled the temperature of the gas at the exit from the ohmic heater to prevent overheating of it.

Institute of Technical Thermophysics, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 68, No. 1, pp. 9-12, January-February, 1995. Original article submitted October 6, 1993.

1062-0125/95/6801-0006$12.50

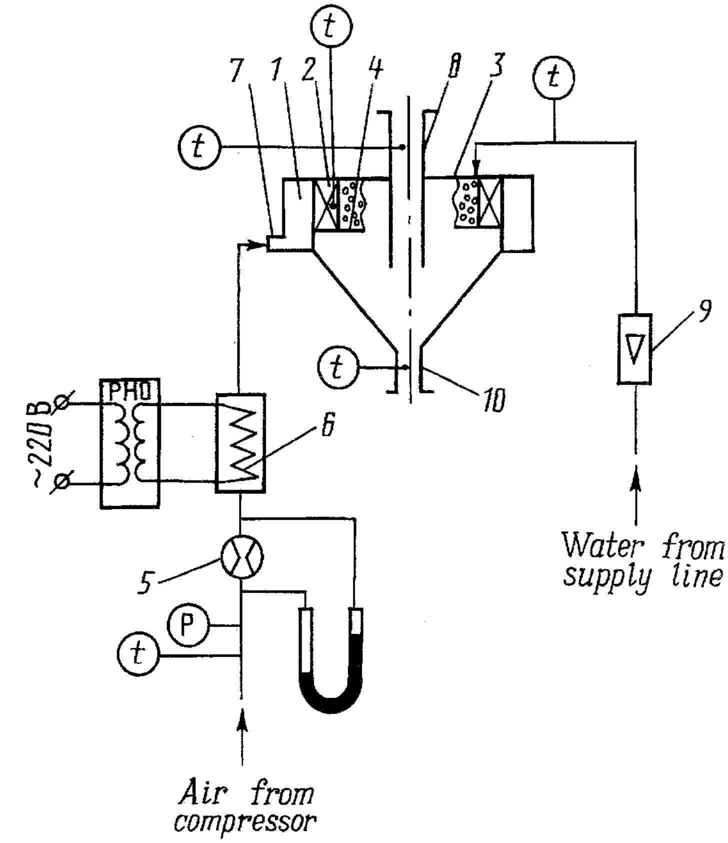

Fig. 1. Schematic of the experimental setup.

The gas flow rate in the experiments varied within the range $(2.1-4.1)\cdot 10^{-2}$ kg/sec, the water flow rate from $2.5\cdot 10^{-2}$ to $7.5\cdot 10^{-2}$ kg/sec, and the gas temperature at the inlet to the layer from 20 to 90°C.

Besides the above-indicated measurements, we determined the angular velocity of the layer by means of an impeller-anemometer with its blade elements placed in the two-phase medium. To increase the frequency of the output signal of the lamp, it was passed through a modulator installed on the axis of the impeller and then arrived at a photodiode connected to a frequency meter.

The experimental data were processed using the nonstationary heat conduction equation for a sphere, with partial mixing of the gas in the interior of the bubble taken into account by the coefficient of effective thermal diffusivity:

$$\frac{\partial t(r,\tau)}{\partial \tau} = a_{\mathrm{ef}}\left(\frac{\partial^2 t(r,\tau)}{\partial r^2} + \frac{2}{r}\frac{\partial t(r,\tau)}{\partial r}\right) \tag{1}$$

subject to the initial and boundary conditions

$$t(r,0) = t_{\mathrm{g}}^{0}, \quad t(r_{\mathrm{b}},\tau) = t_{\mathrm{liq}} = \mathrm{const}, \quad \frac{\partial t(0,\tau)}{\partial r} = 0,$$

where a_{ef} is the coefficient of effective thermal diffusivity; r_{b} is the radius of the gas bubble; t_{g}^{0} is the temperature of the gas at the inlet to the layer; t_{liq} is the liquid temperature.

The boundary condition $t_{\mathrm{liq}} = \mathrm{const}$ is used because the heat capacity of the liquid exceeds that of the gas by more than a factor of 4, while evaporation from the liquid surface to the bubble additionally stabilizes the temperature of the interface. Under the conditions of the present experiments the value of Δt_{liq} did not exceed 10^{0} in the limiting cases. This fact, as well as the high degree of surface renewal attained in eddy-generating bubbling apparatus, permits one to assume in processing that $t_{\mathrm{liq}} = \mathrm{const} = (t_{\mathrm{liq}}^{0} + t_{\mathrm{liq}}^{\mathrm{f}})/2$ (t_{liq}^{0} and $t_{\mathrm{liq}}^{\mathrm{f}}$ is the temperature of the liquid at the inlet to the layer and at the exit from the apparatus, respectively).

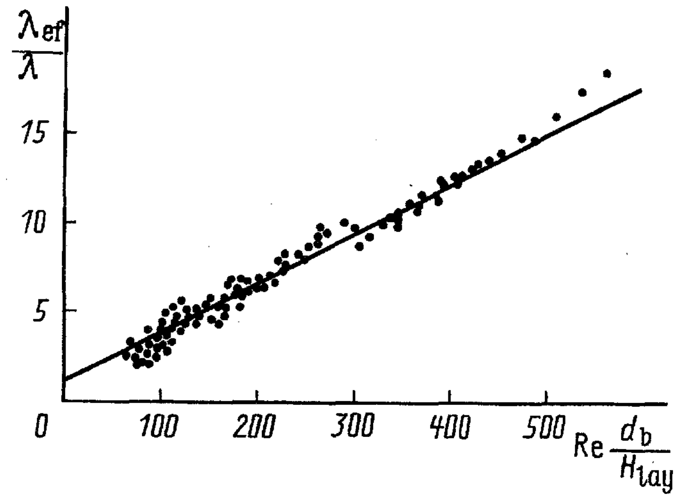

Fig. 2. Generalization of data on the reduced effective coefficient of heat conduction. Points, experimental data; line, relation (6).

Equation (1) was solved in a time interval corresponding to the residence time of the bubble in the layer. In [2] the velocity of the radial motion of bubbles, used for processing results, was found from the condition of free rise. However, under the conditions of the present experiments such a regime is not realized, since for all of the series the value of w_{free} turns out to be smaller than that of w/φ (where $w = G_g/\rho_g \pi D_k H_k$ is the mean flow rate; G_g is the mass flow rate of gas; φ is the gas content of the layer), which cannot be the case if one proceeds from the condition of a constant flow rate. Therefore, when processing the results we assumed that the bubble rise velocity w_b is equal to w/φ (the value of φ was assumed to be equal to 0.7, proceeding from the experimental data of [2]) and the residence time is equal to

$$\tau_{res} = \frac{H_{lay}}{w_b} = \varphi \frac{H_{lay}}{w} . \tag{2}$$

The radius of the bubble was determined from relations suggested in [2] with the use of the values of the angular velocity of the layer obtained in our experiments.

Solving Eq. (1) with substitution of different values of a_{ef} into it we found the time-average specific heat flux through the surface of one bubble

$$q_1 = \int_0^{\tau_{res}} \frac{q(\tau)\, d\tau}{\tau_{res}} \tag{3}$$

and determined the total heat flux from the relation

$$Q^{calc} = q_1 F_b N , \tag{4}$$

where $F_b = 4\pi r_b^2$ is the surface area of one bubble; $N = G_g \tau_{res}/\rho_g V_b$ is the number of bubbles occurring in the layer in the time τ_{res}; $V_b = 4/3\pi r_b^3$ is the volume of the bubble. Then, the values of Q^{calc} found were compared with those determined experimentally from the balance relation for the overall heat flux

$$Q^{exp} = G_g C_p (t_g^0 - t_g^f) . \tag{5}$$

Equating Q^{calc} and Q^{exp} gave the value of the effective thermal diffusivity.

Since the ratio $\overline{R} = a_{ef}/a = \lambda_{ef}/\lambda$ is determined by the hydrodynamic conditions, we made an attempt to represent it as a function of the main geometric and operational parameters. It turned out that $\overline{R} = f(\text{Re})$, where $\text{Re} = w_b d_b/\nu_g$, separates depending on the thickness of the bubbling layer. This separation virtually disappears when we take into account the scale factor d_b/H_{lay}, whose form is determined on the basis of an analysis of Eq. (1) by a similarity theory method.

Figure 2 presents the dependence $\overline{R} = f(\mathrm{Re}\, d_b/H_{lay})$, which is linear with an error of ±20% and can be represented by the following relation

$$\overline{R} = \frac{\lambda_{ef}}{\lambda} = 1 + 0.0277\,\mathrm{Re}\,\frac{d_b}{H_{lay}}. \tag{6}$$

Thus, the solution of Eq. (1) that incorporates λ_{ef} found from relation (6) makes it possible, with allowance for Eqs. (2)-(4), to calculate the overall heat flux with allowance for the residence time of bubble in a gas-liquid layer. Assuming an analogy between the processes of heat and mass transfer, it is also possible, with the use of this procedure, to calculate mass transfer processes in such apparatus.

NOTATION

D_k, H_k, inner diameter and height of the guiding device, m; b, width of the slits of the guiding device, m; H_{lay}, thickness of the bubbling layer, m; s, relative flow cross section; a, thermal diffusivity, m^2/sec; λ, thermal conductivity, W/(m·K); r_b, radius of bubbles, m; d_b, diameter of bubbles, m; t, temperature, °C; w, mean discharge flow rate, m; w_b, velocity of radial rise of bubbles, m/sec; q, specific heat flux, W/m^2; Q, overall heat flux, W; Re = $(w_b d_b)/\nu_g$, Reynolds number. Subscripts: ef, effective; g, gas; liq, liquid; 0, initial; f, final.

REFERENCES

1. A. P. Burdukov, A. R. Dorokhov, V. I. Kazakov, and N. V. Nechaeva, Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 13, Issue 3, 9-12 (1982).
2. A. P. Burdukov, M. A. Gol'dshtik, V. I. Kazakov, and T. V. Li, in: Calculation of Heat and Mass Transfer in Power-Engineering Chemical Processes [in Russian], Novosibirsk (1981), pp. 37-58.