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HEAT EXCHANGE IN COOLING A GENERATOR GAS IN AN EDDY-GENERATING BUBBLING APPARATUS

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We present results of an experimental investigation of the contact heat exchange between a liquid and a gas in a vortex bubbling layer for initial temperatures of the gas of up to 300°C and carry out a comparison with a previously obtained relation for lower temperatures.

The high heat- and mass-exchange characteristics of eddy-generating bubbling contact apparatuses provide good possibilities for their use in various fields of engineering and technology. A developed interphase surface and the high degree of its renewal and mixing make it possible to intensify substantially the processes of transfer in comparison with traditional devices.

At the present time, there are a sufficient number of works devoted to the study of the various characteristics of eddy-generating bubbling apparatuses and, in particular, the coefficients of heat exchange between the gas and the liquid [1-3]. However, the relations given in these works were obtained for relatively low gas temperatures (of up to 100°C), whereas higher temperature levels are characteristic for many of the cases of contact heat and mass exchange (utilization of the heat of tail gases, a number of chemical-technology processes). Justified calculation and design of eddy-generating bubbling apparatuses require an investigation of the heat- and mass-exchange characteristics in a wider temperature range.

The aim of the present work is to study the heat- and mass-exchange characteristics of eddy-generating bubbling apparatuses in cooling of gases with temperatures of up to 300°C.

The scheme of the device is shown in Fig. 1. For the purpose of simultaneously cooling and cleaning the generator gas, an eddy-generating bubbling apparatus with an immobile casing was installed at the exit of a reversion-type generator, which operated on wood wastes. The apparatus consisted of gas distributor 1, guiding device 2, top cap 3, and ring 4, which determined the thickness of the bubbling layer. The generator gas was supplied to the apparatus through branch pipe 5, it exited through separator 6, and then it was burned in burner 7. Liquid (water) was delivered tangentially to the upper portion of the layer and was drained through branch pipe 8.

The guiding device consisted of 12 tangentially located blades that formed gas-supply slits of width 1 mm and height 20 mm, which corresponded to the height of the vortex chamber (h_{ch}). The inside diameter of the swirler was 100 mm (the relative flow cross section was equal to 3.82%) and the thickness of the bubbling layer H_{layer} was 15 mm.

In the experiments we measured the hydraulic resistance of the apparatus, the flow rates of the liquid and the gas, their temperatures at the entrance to the apparatus and the exit from it, and the gas composition.

The gas temperatures were determined by Chromel-Alumel thermocouples, and the liquid temperatures, by mercury thermometers graduated to 0.1°C. The flow rates of the gas and the liquid were measured by rotameters 9 and 10. Upstream of the rotameter 9 a changeable filter 11 was installed. The gas flow rate was measured periodically by switching of valves 12 and 13. The gas composition was determined by drawing samples with subsequent analysis on a chromatograph.

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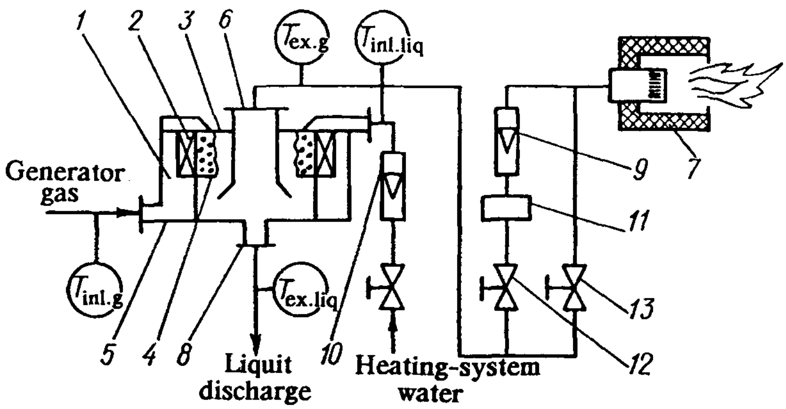


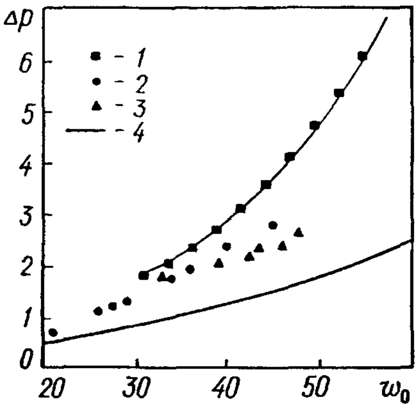


Fig. 1. Scheme of the experimental apparatus.

Fig. 2. Hydraulic resistance of the eddy-generating bubbling apparatus as a function of the gas velocity in the slits of the swirler: 1) apparatus with a slit-type swirler [4]; 2, 3) apparatus with a vane swirler in the case of operation on air and the generator gas, respectively; 4) resistance of the gas-liquid layer. Δp, kPa; w_0, m/sec.

The coefficients of viscosity and thermal conductivity of the gaseous mixture, which are necessary for processing the results, were calculated respectively by using the Mann and Wilkie formulas. From relations given in [1, 3, 4], we also calculated the speed of rotation of the gas-liquid layer, the diameter of the bubbles, and the volumetric gas content.

In all, 35 series of experiments were carried out. The main operating parameters of the experiments were: the gas flow rate $G_g = 9 \ldots 13$ g/sec; the liquid flow rate $G_{liq} = 35 \ldots 60$ g/sec; the gas temperature at the inlet of the apparatus $t_{inl.g} = 50 \ldots 300^\circ$C; the mean composition of the gas (vol.%): CO 20; H_2 14.5; CO_2 11.3; N_2 52; CH_4 1.5; Ar 0.6; O_2 0.1.

Figure 2 presents data on the hydraulic resistance of the eddy-generating bubbling apparatus as a function of the gas velocity in the slits of the swirler. Results of [4] for an apparatus with a slit-type swirler are also presented here. As is seen from the figure, installation of the vane guiding apparatus leads to a considerable decrease in the hydraulic resistance. The values of Δp in the case of operation on the generator gas turned out to be smaller than with operation on air, which is associated with the lower density of the gas. The solid line shows the resistance of the gas-liquid layer, which corresponds approximately to $\rho_g w_0^2/2$ (w_0 is the gas velocity in the slits, since in the gas-liquid layer virtually all the kinetic energy of the tangentially supplied gas is lost).

In processing the heat-exchange results, we determined the values of the mean coefficient of heat transfer from the relation

$$\alpha = \frac{Q_g}{F\,(t_{m.g} - t_{m.liq})},$$

where $F = aV_{layer}$; $a = 6\varphi/d_{bub}$; $V_{layer} = \pi h_{ch} H_{layer}(R_{ch} + R_1)$; R_{ch} and R_1 are the outer and inner radii of the gas-liquid layer; $t_{m.g}$ and $t_{m.liq}$ are the mean temperatures of the gas and the liquid; $\varphi \approx 0.7$.

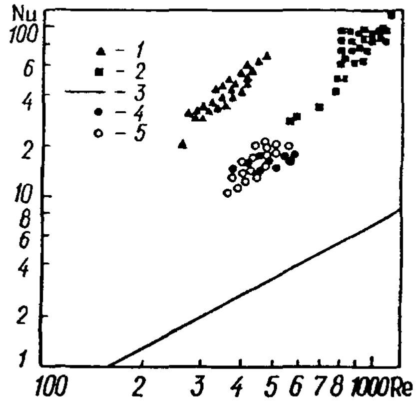
Under the present experimental conditions gas cooling occurred, i.e., the heat released by the gas was spent on heating and evaporation of the liquid. Data on heat exchange for some of the experiments are listed in Table 1. Within one experiment, the gas temperature at the inlet of the apparatus increased with time, which was associated with heating up of the elements of the working channel.

The results were processed in the form of the dependence of the mean number $\mathrm{Nu} = \alpha d_{bub}/\lambda_g$ on $\mathrm{Re} = w_{bub} d_{bub}/\nu_g$, where $w_{bub} = G_g/(\rho_g 2\pi R_{ch} h_{ch} \varphi)$. The dependence $\mathrm{Nu} = f(\mathrm{Re})$ for different apparatuses is given in Fig. 3. As seen from the figure, the heat exchange in the rotating gas-liquid layer is several times more efficient than that in traditional bubbling apparatuses. This result is achieved first of all due to a developed interphase surface and the high degree of its renewal.

TABLE 1. Heat-Exchange Results for Some of the Experiments

Time from start-up of gas generator, τ, min	$t_{inl.g}$	$t_{ex.g}$	$t_{inl.liq}$	$t_{ex.liq}$	G_{liq}, g/sec	w_{layer}, m/sec	d_{bub}, mm	a, m^2/m^3	Re	Nu
	°C									
Start-up No. 4, G_g = 10.6 g/sec										
25	72	26	10.6	21.1	46	2.3	3.8	1110	540	22.4
30	104	28	10.1	22.0	46	2.5	3.7	1140	505	20.6
35	130	31	9.9	24.4	46	2.6	3.6	1170	470	19.2
40	147	33	9.8	25.5	46	2.7	3.5	1200	460	18.6
50	173	40	9.8	30.5	46	2.8	3.4	1240	440	17.6
Start-up No. 7, G_g = 9.9 g/sec										
40	162	33	8.7	25.8	46	2.7	3.5	1200	455	18.9
50	203	38	8.8	30.5	46	2.9	3.3	1270	420	17.3
60	227	37	8.8	30.2	46	3.0	3.3	1270	410	16.4
70	244	41	8.8	29.5	60	3.1	3.2	1210	390	15.2
80	253	40	8.8	29.3	60	3.1	3.2	1310	390	15.1
90	265	42	8.9	29.5	60	3.2	3.2	1310	380	14.6
Start-up No. 11, G_g = 12.0 g/sec										
20	53	19	8.9	14.3	38.5	2.7	3.5	1200	600	19.8
25	102	28	9.0	23.0	38.5	2.9	3.3	1270	530	18.2
30	145	33	9.1	26.7	38.5	3.1	3.2	1310	490	16.6
40	205	42	9.3	31,9	38.5	3.5	3.0	1400	430	13.6
50	248	48	9.4	36.5	38.5	3.7	2.9	1450	390	12.2
60	271	52	9.6	38.8	38.5	3.8	2.9	1450	380	11.5
70	293	54	9.6	40.4	38.5	3.9	2.9	1450	360	10.7
Start-up No. 19, G_g = 11.6 g/sec										
20	98	29	7.8	23.8	36.5	2.8	3.5	1220	530	18.8
25	139	33	7.8	26.5	36.5	3.0	3.3	1270	480	17.0
30	165	31	7.8	29.0	36.5	3.1	3.2	1310	450	17.3
40	203	36	7.7	34.0	36.5	3.3	3.1	1360	420	15.2
50	233	44	7.8	39.3	36.5	3.4	3.0	1400	400	15.0
60	275	48	7.9	46.0	36.5	3.6	2.9	1450	370	12.5
70	293	48	7.8	50.0	36.5	3.7	2.9	1450	360	12.3
Start-up No. 28, G_g = 12.4 g/sec										
40	134	32	8.2	27.7	38.5	3.1	3.2	1310	500	18.0
50	200	41	8.4	35.5	38.5	3.5	3.0	1400	440	14.4
60	233	48	8.6	39.6	38.5	3.7	2.9	1450	410	13.1
70	245	44	8.8	34.6	38.5	3.7	2.9	1450	400	12.8

Analysis of the relations for heat transfer in the case of passage of gas bubbles through the rotating liquid layer indicates that here it is necessary to take into account the scale factor (d_{bub}/H_{layer}). Heat-exchange experiments in the case of operation of the apparatus on air, carried out earlier [3], made it possible to obtain a relation to calculate the mean heat-transfer rate:



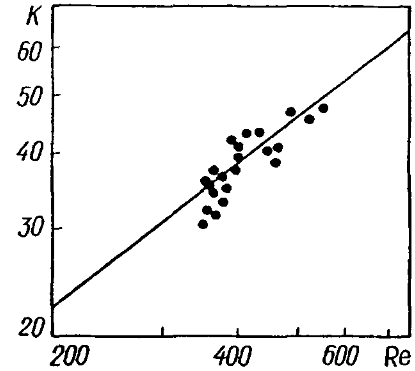


Fig. 3. Dependence of the mean Nusselt number on the Reynolds number: 1, 2) eddy-generating bubbling apparatus with a rotating casing for $n = 350$ and 200 rev/min, respectively [1]; 3) data on bubbling on grid plates [5]; 4) eddy-generating bubbling apparatus with an immobile casing [3]; 5) data of the present work for an eddy-generating bubbling apparatus with an immobile casing in cooling of generator gas.

Fig. 4. Generalization of data on mean heat transfer ($K = \mathrm{Nu}/(d_{bub}/H_{layer})^{0.57}$): line, the dependence from [3]; points, data of the present work for cooling of generator gas.

$$\mathrm{Nu} = 0.32\,\mathrm{Re}^{0.8}\left(\frac{d_{bub}}{H_{layer}}\right)^{0.57}.$$

A comparison of results obtained in the present work in cooling the generator gas with the above relation is presented in Fig. 4. As seen from the figure, rather good coincidence of the data is obtained, which indicates the absence of the effect of the temperature factor. Evidently this result is explained by intense mixing in the layer both inside the bubbles and in the liquid phase. Thus, this relation turned out to be suitable for calculating the heat exchange in a wider temperature range of the gas (up to 300°C).

NOTATION

G, mass flow rate, g/sec; Q_g, heat flux from the gas to the liquid, W; F, true surface of heat exchange, m^2; α, coefficient of heat transfer, W/(m$^2\cdot$K); a, specific surface of phase contact, m^2/m^3; V_{layer}, volume of the gas-liquid layer; d_{bub}, diameter of the bubbles; φ, volumetric gas content; w_{bub}, radial component of the bubble motion velocity, m/sec; $\mathrm{Re} = w_{bub}d_{bub}/\nu_g$, Reynolds number; $\mathrm{Nu} = \alpha d_{bub}/\lambda_g$, Nusselt number; ν, coefficient of kinematic viscosity, m^2/sec; λ, coefficient of thermal conductivity, W/(m$\cdot$K); ρ, density, kg/m^3. Subscripts: g, gas; liq, liquid; m, mean; inl, inlet; ex, exit.

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