EXPERIMENTAL INVESTIGATIONS OF THE ACOUSTICAL AND MASS-TRANSFER CHARACTERISTICS OF GAS—LIQUID SYSTEMS WITH SELF-EXCITED OSCILLATIONS OF THE GAS FLOW

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Self-excited oscillations of a gas flow at its site of entry into a liquid layer are utilized for the intensification of mass-transfer processes. The results of experimental investigations of the acoustical and mass-transfer characteristics are given.

One way of intensifying mass transfer in the absorption of highly insoluble gases is to generate high-frequency oscillations in the contacting phases [1]. The high-frequency oscillations are conventionally generated by means of apparatus requiring an external source of energy. Despite the fact that the absorption rate is increased two- to fourfold in this case [1], the efficiency of sectional bubbling equipment is increased only slightly owing to damping of the oscillations in one contact stage. Furthermore, the high-frequency apparatus is complicated, has a short service life, and requires an additional expenditure of external energy.

The objective of the present study is to investigate the feasibility of generating high-frequency self-excited oscillations of a gas flow by means of durable and simple static devices capable of producing oscillations in all the sections of the equipment without an external source of energy. An important aspect is the site of such devices in the equipment. Taking into consideration the fact that the absorption of high-frequency oscillations in a gas—liquid medium is much higher than in a gas alone, it is advisable to generate the oscillations in the gas. Inasmuch as the formation of the gas—liquid flow depends on the manner of entry of the gas into the liquid, and a significant fraction of the total mass-transfer effect is associated with the entry zone, it would be preferable to generate the high-frequency oscillations in that zone [2]. A resonator [3] in the form of annular cavities can be used as the static device for generating high-frequency oscillations in the low-head gas flow.

Low-head contact-type mass-transfer units using resonators of the indicated type to create self-excited oscillations of the gas flow have not been investigated. In the present study, therefore, we have investigated the acoustical, hydrodynamic, and mass-transfer characteristics of contact units with self-excited oscillations of the gas flow.

The acoustical characteristics of an individual contact unit were investigated in a tower of diameter 0.31 mm. A contact unit with an annular resonant cavity was placed at the end of the tower (Fig. 1). The sound pressure was measured at a distance of 0.7 m inside the tower. The resulting integral-mean pressure around the perimeter and along the radius of the tower was used to determine [4] the sound pressure created at the contact unit. The frequency of the oscillations and the sound pressure were measured with a piezoelectric transducer [4] in conjunction with an S4-48 spectrum analyzer and an S1-54 synchroscope. The transducer signal was amplified by a preamplifier with a high-resistance input and an integrated-circuit amplifier. The drop in the hydrostatic pressure was measured by means of piezometric tubes.

The mass-transfer process associated with gas bubbling was investigated in a tower 0.31 m in diameter. The distance between the valve trays was 0.29 m, and the free cross section was 2.8-5.6%. The volume coefficient of mass transfer was determined in the oxidation of sodium sulfite by atmospheric oxygen [5] on a noncirculating tray. The acoustical parameters were measured under the plate at a distance of 0.05 m. The height of the clear liquid layer was 0.066 m.

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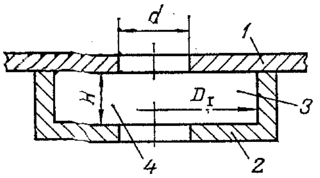

Fig. 1

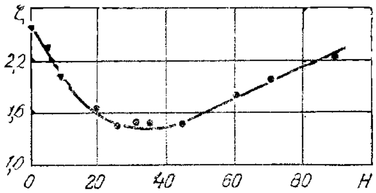

Fig. 2

Fig. 1. Contact unit with annular resonant cavity. 1) Deck; 2) pan; 3) annular resonant cavity; 4) orifice of cavity.

Fig. 2. Hydraulic friction coefficient ζ versus height $H \cdot 10^3$, m, of the orifice of the resonant cavity (v = 28.5 m/sec, d = 0.032 m).

The acoustical characteristics were investigated on contact units with an opening diameter of 0.032 m and a cavity diameter of 0.098 m; the height of the orifice of the resonant cavity varied between 0.0055 and 0.087 m. As the velocity of the air in the opening was varied in the interval 9–30 m/sec it was found that the frequencies of the excited oscillations correspond to the vortex frequencies determined according to the formula [6]

$$\nu_n = \chi \frac{v}{H} n. \qquad (1)$$

The coefficient χ varied from 0.55 to 0.97, depending on the velocity of the gas and the relationship between the dimensions of the unit, and n corresponded to the first or second harmonic. For H = 0.005–0.087 m the average sound pressure at the contact unit for a velocity v = 14–30 m/sec was

$$P_{av} = 0.0115 \rho v^3 - 0.125 \rho v^2. \qquad (2)$$

An analysis of the results of the investigation shows that the maximum sound pressure is attained when the diameters of the openings of the pan and the deck of the contact unit are equal. Deviations of the diameters of the openings of the pan and the deck within 0.001–0.002 m limits do not significantly affect the value of the sound pressure.

Making the opening so that the edge is sharp and widens in the direction of motion of the flow increases the sound pressure threefold in comparison with a cylindrical edge.

When air passes through the contact unit, the pressure drop varies as a function of the design dimensions and the velocity of the gas. The dependence of the hydraulic friction coefficient on the height of the cavity orifice is shown in Fig. 2. The decrease in the pressure drop is evidently attributable to the fact that the energy of the turbulent vortices is converted into energy of high-frequency oscillations of the gas flow, which diminish the vortex-generation process inside the resonant cavity and as the flow exits from the contact unit.

The experiments to determine the volume mass-transfer coefficient on the valve trays indicate that the application of high-frequency oscillations by means of contact units with resonant cavities exerts a significant influence on the mass transfer. The dependence of the volume mass-transfer coefficient for a six-valve tray is shown in Fig. 3. The experimental values obtained in the interval of gas velocities in the tower from 0.15 to 1.2 m/sec are described within ±8% error limits by the relations

$$\beta a = 1.2 \cdot 10^4 \sqrt{D v_t \varphi}, \qquad (3)$$

$$\beta a_{ac} = 1.6 \cdot 10^4 \sqrt{D v_t \varphi_{ac}}. \qquad (4)$$

The approximately 1.5-fold increase in the volume mass-transfer coefficient with the application of oscillations is attributable to the action of the oscillations on the contacting phases under the tray and in the zone of entry of the gas into the liquid.

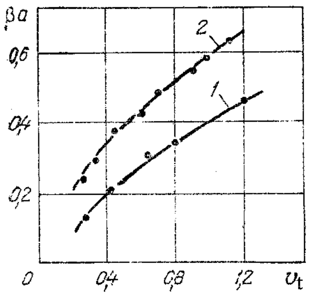

Fig. 3. Volume mass-transfer coefficient βa, sec^{-1}, versus gas velocity v_t, m/sec, in tower with valve tray (F = 5.6, d = 0.03 m, d_v = 0.05 m, h_0 = 0.066 m). 1) Tray without pans; 2) tray with pans (H = 0.025 m, D_r = 0.07 m).

An analysis of the oscillations under the tray shows that the high-frequency oscillations have a sound pressure much lower than 1 Pa without resonant cavities. The presence of the cavities promotes the generation of high-frequency oscillations with a frequency of 600-1350 sec^{-1} for a gas velocity in the tower from 0.25 to 1.15 m/sec. The sound pressure under the tray retained the same order of magnitude: 10-15 Pa.

With an increase in the gas velocity in the tower above 1.15 m/sec, oscillations with a frequency of 9880-10,200 sec^{-1} were additionally recorded under the tray, with a sound pressure of 8-10 Pa.

In an unsprayed valve tray with pans the frequency range for a gas velocity of 0.6 m/sec in the tower was 935-1240 sec^{-1}, and for a gas velocity of 1.2 m/sec it was 700-1500 sec^{-1}. The pressure of the high-frequency oscillations varied from 13 to 26 Pa.

Experiments carried out on a three-valve tray with a valve diameter of 0.06 m and opening diameters of 0.031 for the tray deck and 0.029 m for the pan with H/d = 0.86 and D_r/d = 2.4 have shown that the experimental values of the volume mass-transfer coefficient are described within ±10% error limits by the following relations for a gas velocity of 0.15-0.9 m/sec in the tower:

$$\beta a = 1.5 \cdot 10^4 \sqrt{D v_t \varphi}, \tag{5}$$

$$\beta a_{ac} = 1.7 \cdot 10^4 \sqrt{D v_t \varphi_{ac}}. \tag{6}$$

When the self-excitation regime is used, the volume mass-transfer coefficient is increased by a factor of 1.2, and the gas content by a factor of 1.13-1.35. The frequency spectrum broadens with increasing velocity of the gas in the tower; for v_t = 0.15 m/sec, it is equal to 840-1110 sec^{-1}, and for v_t = 0.8 m/sec it is 620-1310 sec^{-1}. Beginning with a gas velocity of 0.8 m/sec in the tower, an additional frequency band of 2470-2996 sec^{-1} sets in with a sound pressure of 37 Pa.

NOTATION

ν_n, vortex-generation frequency, sec^{-1}; χ, coefficient depending on the configuration of the unit; v, velocity of gas in opening, m/sec; H, height of orifice of resonant cavity, m; n, harmonic order of oscillations; P_{av}, average sound pressure, Pa; d, diameter of opening in contact unit, m; D_r, maximum diameter of resonant cavity, m; D, molecular diffusion coefficient, m^2/sec; βa, volume mass-transfer coefficient, sec^{-1}; βa_{ac}, volume mass-transfer coefficient obtained with the application of high-frequency oscillations, sec^{-1}; v_t, velocity of gas in tower, m/sec; φ, gas content; φ_{ac}, gas content with the application of high-frequency oscillations; F, free cross section of valve tray, %; d_v, diameter of check valve, m; ζ, hydraulic friction coefficient; h_0, height of clear layer of liquid on tray, m; ρ, density of gas, kg/m^3.

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EXPERIMENTAL STUDY OF THERMALLY INDUCED OSCILLATIONS OF GASEOUS HELIUM

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Results of a study of thermally induced oscillations of helium gas in semi-open and closed tubes are presented.

At the present time a number of high-power cryogenic power generation devices have been designed and are undergoing testing [1]. As a rule, the thermal rise in such devices is above the calculated value. One of the more probable causes of excess thermal loading is thermoinduced oscillations of a gas, which can develop in the tubes connecting regions at low and high temperatures [2-8]. A quite broad range of works has been dedicated to study of such oscillations. Nevertheless, up to the present there is no unified approach to describing this phenomenon [4, 9, 10]. In the authors' opinion the model which best explains the conditions for development of thermally induced oscillations is the linear model proposed by Rott [5]. According to the Rott model, oscillations develop in tubes with a sufficiently high temperature gradient. An analysis performed with use of the Rott model shows that oscillations can occur not only in tubes with an open cold end and closed hot end, but also in acoustically closed tubes. However, up to the present oscillations in closed tubes have not been observed experimentally. In contrast to Rott, a number of researchers have related the appearance of oscillations to mass exchange at the open (cold) tube and [4] and to the position of this end relative to the liquid level [2-4].

Experiments were performed to determine the effect of the temperature profile and distance from the open tube end to the liquid level on gas oscillations in the tube, and also to search for oscillations in a closed tube. The experimental units used were tubes of stainless steel with Ø 4 × 0.3 mm, l = 1320 mm and Ø 10 × 0.5 mm, l = 1320 mm. Tube 1 (Fig. 1) is inserted into a collar formed by the larger diameter tube 2. This tube has an orifice 3 for gas escape. Tube 1 and sleeve 2 are fitted into a standard STG-40 helium cryostat. By regulating the flow of gas through the annular gap between tube 1 and sleeve 2, changing the relative position of the tubes, and varying the distance to which the pair was inserted into the cryostat, various temperature profiles were produced in the tube. The required amount of gas flow for cooling of tube 1 was produced by evaporator 7, located at the bottom of the cryostat. Tube temperature was measured by thermocouples, and in addition a resistance thermometer was installed at the cold end, producing temperature measurements with an uncertainty of ~0.01°K. Pressure pulsations were recorded by piezosensor 4. For study of oscillations in a closed

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