DETERMINING THE PARAMETERS OF ENTRAINMENT OF DROPS IN ELECTRIC FIELD DURING BUBBLING AND BOILING OF LIQUIDS IN ENERGETICAL INSTALLATIONS

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Abstract:
A method is proposed for investigating the parameters of entrainment of drops due to their inertial path, ponderomotive forces of the electric field, and viscous friction of the phases. The concept entrainment coefficient characterizing the portion of drops being transported is introduced. It is shown that the use of the electric field is most advisable for an experimental determination of the parameters of entrainment. Processing of experimental data on electro convective entrainment of drops from the surface of a bubbling layer of distilled water was carried out by the proposed method.

Keywords: entrainment coefficient, rate of entrainment, relative entrainment coefficient.

1. INTRODUCTION

A study of drops entrainment during bubbling and boiling of liquids, begun more than 50 years ago, is being carried out mainly in two directions[1]. Some authors investigated problems related to the motion of a gas bubble, formation of drops upon its collapse, fractional composition of the drops being formed, their movement in free space, and fragmentation. The majority of investigators determine the entrainment coefficient as a function of the load of the liquid surface, pressure, and height of the free space of the apparatus.

2. DEFINITION OF THE DROPS ENTRAINMENT PARAMETERS

By *entrainment coefficient* is meant the ratio of the rate of entrainment of drops W to the unit flow rate of the gas

$$\omega = \frac{W}{G \cdot \rho_{gs}} \tag{1}$$

where G is the reduced gas velocity; ρ_{gs} is the gas density. A number of factors affect ω: reduced gas velocity G, height of the free space H_{fs}, physical properties of the phases, geometry of the bubble tower, etc. [1,2].
The dependence of ω on G is described by an empirical equation of the type

$$\omega = c \cdot G^n \tag{2}$$

where c is a constant for the given tower. The exponent in eq. (2) for small is n = 0.5 ÷ 0.7, for average n = 3 ÷ 4, and for large n = 5 ÷ 16, Physically, the entrainment coefficient characterizes the relationship of the portion of drops being transported and the flow rate of the bubbling gas, but it does not always reflect the transport function of the gas or its ability to generate drops and does not give information about their relationship. Thus, in regimes when entrainment of the liquid is accomplished partially or completely due to “bouncing” of the drop, the entrainment coefficient will be substantially greater than ω under conditions of their transport by gas at the same velocity, but in the absence of “bouncing” effect. In such regimes far from all drops being generated by the gas are transported to the section of the apparatus in which entrainment is measured, since the height of “bouncing” of these drops strongly depends on their size [3]. In the case of electroconvective entrainment [4] the liquid is transported also due to the electric field, which aggravates still more an understanding of the character of entrainment just on the basis of the value of coefficient ω (Figs. 1 and 2).

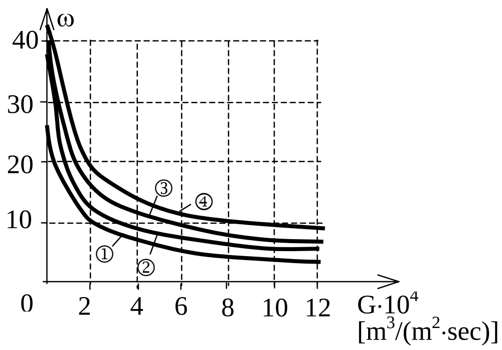

Fig. 1. Dependence of the drop entrainment coefficient on the reduced gas velocity: H_{fs} = 5cm; E = ①1, ②2, ③4, ④6 [kV/cm].

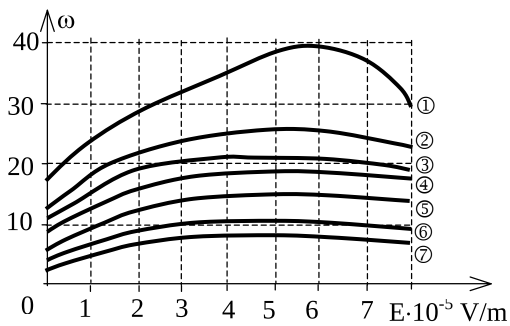

Fig. 2. Effect of the electric strength on the drop entrainment coefficient: H_{fs} = 5cm; G = ①0.08, ②0.29, ③0.63, ④1.45, ⑤2.44, ⑥3.99, ⑦6.04

The *rate of entrainment* W characterizes the density of the flow of the liquid mass being entrained in the examined cross section. In drop-separation regimes drainage of the liquid not being transported occurs and continuity of the flow of the mass is disturbed, which leads to a distribution of W over the height of the free space. This explains the dependence of ω on H_{fs}. The value $W = W_s$ on the surface of the layer being bubbled characterizes the quantity of drops being generated, but in separation regimes it cannot be measured. Thus, the coefficient and rate of entrainment of drops insufficiently completely characterizes single-factor entrainment, when the latter depends only on one factor and does not reflect at all the components of the process during multifactor entrainment such as the rate of generation W_S and sedimentation W_g of the drops, the rate of their entrainment by the gas W_{gs} and electric field W_E, and due to the inertial path W_{in}. Between these quantities there exist the obvious relation

$$W = W_s - W_g = W_{gs} + W_{in} + W_E . \tag{3}$$

Having divided all terms of this equation by W_s, we obtain

$$k = 1 - k_g = k_{gs} + k_{in} + k_E . \tag{4}$$

We will call the quantity $k = W/W_s$ the *relative entrainment coefficient*. It characterizes the portions of generated drops which is entrained up to the investigated cross section of the free space of the apparatus. Similarly, $k_{gs} = W_{gs}/W_s$, $k_{in} = W_{in}/W_s$ and $k_E = W_E/W_s$ characterize the portions of drops being entrained due to viscous friction of the gas, their inertial path (“bouncing”), and the relative sedimentation coefficient k_g determines the portion of drops not being transported. The relative entrainment coefficient and ω are related by the dependence

$$k = \omega \frac{G\rho_{gs}}{W_s} = \frac{\omega}{\omega_s} \tag{5}$$

where ω_s is the entrainment coefficient under conditions of complete transport of the drops.

The numerical values of the coefficients k, k_g, k_{in}, k_{gs}, and k_E vary in limits from zero to unity. When k = 0 and k_g = 1 complete sedimentation of the drops occurs and their entrainment to the given section is absent. These values are most favourable for operation of condensed moisture separators in steam power plants. If k = 1 and k_g = = 0, then all drops being generated are transported to the investigated section. Such parameters are acceptable for aerosol generators. In the absence of an electric field and for small gas velocities $k_{gs} = k_E = 0$ and $k = k_{in}$, and entrainment is determined by the size of the drops and length of their inertial path (k_{in} = 1 when H_{fs} = 0). When the gas velocity is greater than the sedimentation rate of the largest drops in the spectrum being generated ($G > G_2$), k= k_{gs} = 1 and the gas transports the entire liquid being dispersed. Complete entrainment is realized also under certain electric field strengths (E = E*), the ponderomotive forces of which exceed the forces of gravity of the largest drops and, moreover, entrainment is accomplished just due to the electric field when $G < G_1$ and $H_{fs} > H_{fs}$*, where G_1 and G_2 are the values of the gas velocity for which the gas begins to transport the smallest and largest drops, respectively, and H* is the maximum height of spattering of the drops.

3. DETERMINATION OF THE DROPS ENTRAINMENT PARAMETERS.

The method of experimental determination of the indicated parameters consists in the following. Conditions of complete entrainment of the generated drops to the measurement cell are provided for measuring W_s. As was indicated above, this is possible in three cases: with maintenance of the gas velocity along the path to the cell at the level $G > G_2$, with location of the working surface of the cell directly on the surface of the bubbled layer ($H_{fs}\delta 0$), and with the application between these surfaces of an electric field with strength E = E*, providing appropriate charging of the drops. A shortcoming of the first variant is that measurement of W_0 is possible only for gas velocities $G > G_2$, and the measured quantity can differ substantially from its true value as a consequence of the fact that some drops can be entrained by the gas past the cell. A close location of the cell to the surface of the liquid in the second variant is impossible due to fluctuations of its level as a result of collapse of the gas bubbles and secondary sprouting. Only the use of an electric field [4] provides measurement of W_s regardless of the gas flow rate and, as was shown in [5], when E = 6kV/cm the field does not affect the rate of drops generation.

A determination of k in the case of single - factor entrainment does not present any difficulties. The method of determining the components of k in the case of multifactor entrainment is somewhat more complex. For example, for small gas velocities and in the absence of an electric field, entrainment is accomplished due to "bouncing" of the drops with a rate $W_i = W_{in}^0$, the subscript i determines the component of entrainment and the superscript 0 denote the absence of an effect on the quantity of other factors except that under consideration. However, if several factors can simultaneously affect entrainment (i =1, 2, 3, ...). Then $W_1 < W_i^0$ and W_i depends on how substantial is the effect of each of them. Let the entrainment of drops be determined by the effect of their inertial path, gas velocity, and electric field strength (i = in, gs, E). Then according to Eq. (3)

$$W = \sum_{i=1}^{3} W_i \tag{6}$$

if the regimes characterizing each given factor are maintained at the same level and the effect of the remaining factors are eliminated in turn, then the sum W_i^0 will be greater than W and will be

$$W^0 = \sum_{i=1}^{3} W_i^0 \,. \tag{7}$$

We can assume with sufficient accuracy that

$$\frac{W_i}{W_s} \cong \frac{W_i^0}{W_s^0} \tag{8}$$

or

$$W_i = W_i^0 \cdot \frac{W_s}{W_s^0} \tag{9}$$

where W_i^0 is determined by eq. (7) for the same regime parameters as W_s. If elimination of the electric field when determining W_i^0 does not change the degree of effect of the remaining factors, then elimination of the remaining ones is no longer possible. Therefore, for determining W_{gs}^0, W_{in}^0, and W_E^0, it is necessary to use certain relationships.
It is known that entrainment of a liquid by a gas is realized due to forces F_c of viscous friction of the phases and is possible for drops whose gravitational force is less than F_c. For characteristic gas flow regimes (Re < 400) this condition has the form

$$\frac{1}{a^2} + \frac{1}{6}\left(\frac{2\rho_{gs}G}{a^2\mu_{gs}}\right)^{2/3} \geq \frac{\rho_l q}{g\mu_{gs}G} \tag{10}$$

where a is the radius of. the drop; ρ_l is the density of the liquid; μ_{gs} is the dynamic viscosity of gas; g is the acceleration of gravity. An investigation of this inequality shows the following. According to the Gauss theorem, eq. (10) has an even number of real roots, but not more than six, and in conformity with the Descartes theorem three or one of them is positive. The limits of the positive roots can be determined from the Maclaurin inequality

$$0 < a_{gs} < 1 + \sqrt{\frac{27\mu_{gs}G}{2\rho_l g}} \tag{11}$$

An investigation of the extremes of the equation showed that it has one positive root a_{gs}, which proves the uniqueness of the solution of inequality (10) in the form

$$a \leq a_{gs} \tag{12}$$

In a Stokces regime (Re < 0.5)

$$a_{gs} = \sqrt{\frac{9\mu_{gs}G}{2\rho_l g}}\,. \tag{13}$$

In addition to determining the size of entrained drops, it is necessary to carry out analysis of variance of all drops being generated for a given gas flow rate and to establish the form of their size distribution function *f(a)*-. Thus, during bubbling of distilled water by air with a flow rate G < 6 $m^3/(m^2 \exists hr)$, the sizes of the drops obey a lognormal distribution law [4]. Then

$$W_{gs}^0 = \frac{4\pi\rho_l}{2m} W_s \int_0^{a_{gs}} a^3 f(a)\, da \tag{14}$$

where $\overline{m}$ is the mean mass of the drops which is determined by the formula

$$\overline{m} = \frac{4\pi\rho_l}{3}\int_0^{\infty} a^2 f(a)\, da \tag{15}$$

The method of determining entrainment due to the inertial path of the drops consists in the following. As was established in [3], the height of spattering of drops depends on their size and is determined by the relationship

$$h = (\tau / k_c)v_0 - \tau^2 g / k_c^2 \cdot \ln[(k_c v_0 / \tau_g) + 1] \tag{16}$$

where $\tau = 2a^2\rho_l/(g\mu_{gs}); k_c = 1 + (2a^2\rho_{gs}v_0/\mu_{gs})^{2/3}/6$. The initial velocity of the drops v_0 found from the energy conservation law [5], is expressed by the formula

$$v_0 = \sqrt{1{,}8\sigma\left(\frac{2a}{3\delta}-1\right)\Big/(a\rho_1)} \tag{17}$$

where σ is the surface tension of the liquid; $\delta = 15\sqrt[4]{3kT\overline{R}^2/(8\pi\sigma)}$ is the effective thickness of the film of collapsing bubbles; k is the Boltzmann constant; T is the absolute temperature of the liquid; $\overline{R}$ is the mean radius of the bubbles of the layer being bubbled at a given gas flow rate G (usually when $\overline{a} < 100\,\mu m$, $\overline{R} = 10\cdot\overline{a}$). Substituting into (16) h = H_{fs}, where H_{fs} is the height of location of the free surface of the measuring trap above the liquid surface of the drops a_{in} flying up to level H_{fs}. It is obvious that all drops with a size a > a_{in} are entrained to this height. In this case the .rate of entrainment due to the inertial path of the drops is determined by the relationship

$$W_{in}^0 = \frac{4\pi\rho_1}{3\overline{m}} W_s \int_{a_{in}}^{\infty} a^3 f(a)\, da \tag{18}$$

The condition

$$qE > \frac{4}{3}\pi a^3 \rho_1 g \tag{19}$$

establishing the relationship of the electric and gravitational forces, is written for calculating W_E^0.
When a > 1μm the charge of the drop is proportional to a^2:

$$q = ba^2\varepsilon_0 E \tag{20}$$

where the factor b depends on the charging conditions (in the case of contact charging b = $2\pi^3/3$). The maximum size a_E of drops being transported by a field of a given strength E is determine from (19) and (20):

$$a_E = \frac{3b\varepsilon_0 E^2}{4\pi\rho_1 g}. \tag{21}$$

Consequently,

$$W_E^0 = \frac{4\pi\rho_1}{3\overline{m}} W_s \int_0^{a_E} a^3 f(a)\, da \tag{22}$$

On the basis of the values of $W_{gs}^0, W_{in}^0, W_E^0, W_s^0$ and W, the relative entrainment coefficients k_{gs}, k_{in} and k_E are calculated with the use of Eq. (5) with consideration of Eqs. (1), (7) and (9).

Such a calculation was performed for representing the experimental results on drop entrainment in an electric field [4] in the form of a graphic functional relation k = *f*(G, E, H_{fs}), Figs. 3 + 7.
For a lognormal drop-size distribution - function the integral characteristics (14), (15), (18), and (22) have the form

$$\overline{m} = \frac{4\pi\rho_1}{3}\overline{a}^3\left[1+\left(\frac{a_a}{\overline{a}}\right)^2\right]^3; \tag{23}$$

$$W_{gs}^0 = W_0 + W_0\cdot erf\left\{\frac{2\ln(a_{gs}/\overline{a}) - 5\ln[1+(a_a/\overline{a})^2]}{2\sqrt{2\ln[1+(a_a/\overline{a})^2]}}\right\}; \tag{24}$$

$$W_{in}^{0} = W_0 - W_0 \cdot erf\left\{ \frac{2\ln(a_{in}/\bar{a}) - 5\ln[1+(a_a/\bar{a})^2]}{2\sqrt{2\ln[1+(a_a/\bar{a})^2]}} \right\}; \quad (25)$$

$$W_{E}^{0} = W_0 + W_0 \cdot erf\left\{ \frac{2\ln(a_{E}/\bar{a}) - 5\ln[1+(a_a/\bar{a})^2]}{2\sqrt{2\ln[1+(a_a/\bar{a})^2]}} \right\}. \quad (26)$$

where $\bar{a}$ is the mean radius of the drops; a_a is the dispersion of their size distribution.

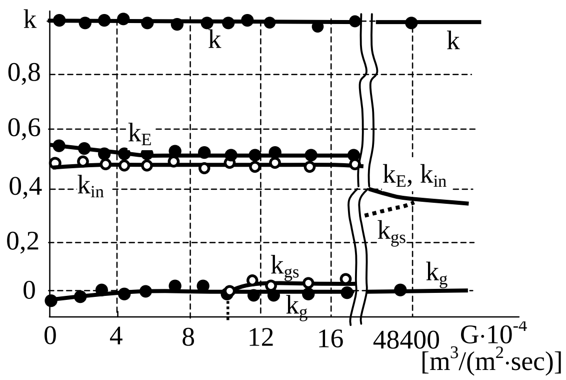

Fig. 5. Components of multicomponent drop entrainment as a function of the reduced gas velocity for E = 6 kV/cm and H_{fs} = 5 cm.

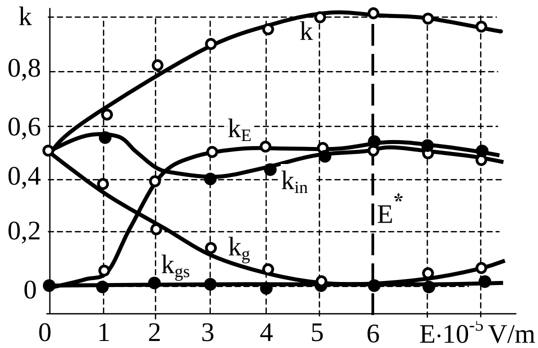

Fig. 6. Effect of field strength on components of drop entrainment for G = 2.44 $m^3(m^2/hr)$ and H_{fs} = 5 cm.

4. EXPERIMENTAL RESULTS. CONCLUSION.

Processing of the experimental data given in [14] showed that with an in [4] showed that with an increase of the reduced gas velocity to $(0.5 \div 2)\exists 10^{-4}$ $m^3/(m^2\exists sec)$, the relative entrainment coefficient increases, and the rate of increase of k depends on the electric field strength (see. Figs. 3 and 14). When E = 0 and E = E* = 6 kV/cm the values of k are practically .independent of the gas flow rate and are equal in the first case to k_{in} and in the second case to unity. The independence from G of the relative coefficient of entrainment due to the inertial path of the

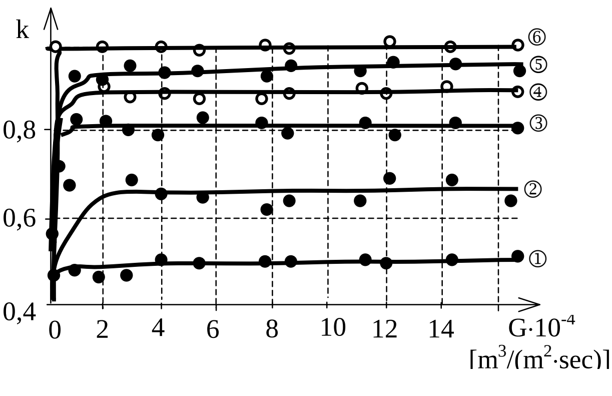

Fig. 3. Relative drop entrainment as a function of the reduced gas velocity: H_{fs} = 5cm;
E = ① 0; ② 1; ③ 2; ⑤ 3; 5) 11; ⑥ 6 [kV/cm].

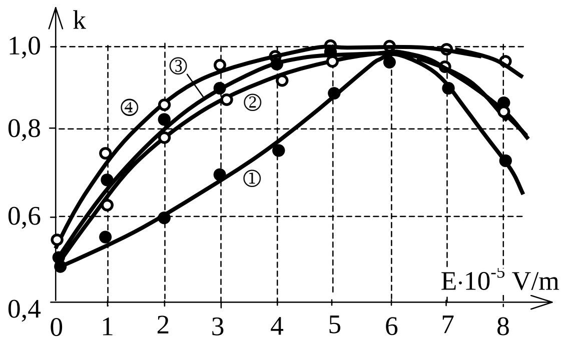

Fig. 4. Effect of field strength on the relative drop entrainment coefficient: H_{fs} = 5cm; G = ①0.08, ②0.29, ③0.63, ④6.04 [$m^3/(m^2 \cdot hr)$].

drops k_{in} is due to the fact that the gas velocity depends little on the height of rise of the drops [3].

When $2\exists 10^{-4} < G < 17\exists 10^{-4}$ $m^3/(m^2\exists sec)$, the relative entrainment coefficient is also self-similar relative to the gas flow rate. Actually, if k, with consideration of Eqs. (2) and (5) is represented in the form $k = cG^{n-m}$, where m is the exponent for the curve $\omega_s(G)$, then, as is seen from Fig. 1, $m < n$ when $G < 2∃10^{-4}$ m^3 /(m^2∃sec) and $m = n$ when $G ƒ 2∃10^{-4}$ m^3 /(m^2∃sec). Consequently, for very small gas velocities, the relative entrainment coefficient increases, and when $G > 2∃10^{-4}$ m^3 /(m^2∃sec) it is equal to the constant c, which depends on the electric field strength, as is seen from Fig. 3.

With an increase of the field strength to 6 kV/cm the relative entrainment coefficient increases to unity; when the field strength $E > 6$kV/cm again decreases, this is due to the effect of the opposite separation of drops from the receiving electrode (see Fig. 4). The effect of the electric field, gas velocity, and inertial path of the drops on entrainment is shown in Figs. 5 + 7.

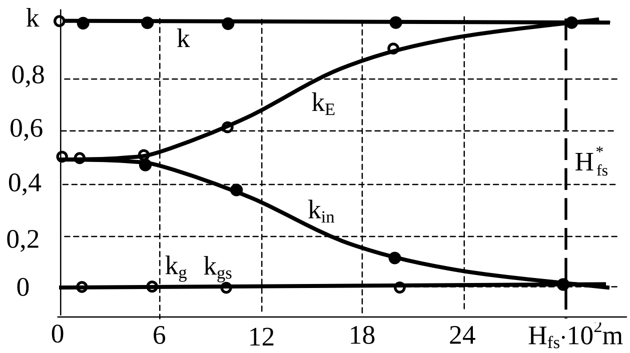

Fig. 7. Components of multicomponent entrainment as a function of the height of the free space for G = 2.44 m^3(m^2∃hr) and E = 6 kV/cm.

Under conditions of complete entrainment (E = E* = 6 kV/cm) for $H_{fs} < 5$ cm the mass portions of drops being transported by the field and due to the inertial path are commensurate in the entire investigated range of gas velocities (see Figs. 5 and 7). Transport of the smallest drops beings when $G_1 = 1.21∃10^{-4}$ m^3/(m^2∃sec), but they are entrained to level $H_{fs} = 5$ cm at gas velocities not less than $1∃10^{-3}$ m^3/(m^2∃sec) (Fig. 5).. An extrapolation estimate of the velocity at which gas entrains the entire spectrum of drops being generated (1 + 200 μm) to the given level is G_2 =4.84 m^3/(m^2∃sec). Therefore, if the free space is not bounded, a gas velocity up to 17 m^3/(m^2∃sec) does not affect drop entrainment.

The effect of the electric field on k_E is most noticeable in a small range of E, which depends on the spectrum of the generated drops. Thus, for $G = 6.787∃10^{-4}$ m^3/(m^2∃sec)m^3 the diameter of the drops varies within 5 + 1.80 μm and the most substantial effect of the electric field on their transport is observed when E = 0.5 + 3 kV/cm (Fig. 6). Since the gas does not affect entrainment, the curve of $k_{in} = f(E)$ is determined by the difference of the rates of change in k and k_E and and has a more complex character. When $H_{fs} > 5$ cm, k_{in} decreases, reaching at the maximum height of ejection of the drops $H_{fs} = H^*_{fs} = 30$ cm a zero value, whereas the role of the electric field increases and becomes determining when $H_{fs} \geq H^*_{fs}$ (Fig. 7). The indicated factors affect the relative drop sedimentation coefficient k_g diametrically opposite to their etfect on the total entrainment k.

Thus, the method ot investigating the characteristics ot multifactor entrainment clearly reflects both the combined and individual effect of each of the acting factors, which makes it possible to determine the optimal regimes of the process under various conditions of its use in practice. The use of an electric field has for the problem of drop entrainment not only an applied significance, but also has a methodological character when determining its characteristics.

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