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Figure 1

Figure 1: Figure 1

Abstract

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SOME REGULARITIES OF DROPLET CARRYOVER

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In the present work, carryover was investigated in evaporating apparatuses and evaporators of the bubbling (B) type (Fig. 1*a* and *b*) and in non-bubbling (BB) apparatuses, i.e., with the steam–liquid mixture introduced above the level (Fig. 1*c*).

Theoretical approach to the description of carryover. Carryover consists of entrainment ω and transported carryover ω. The latter consists of droplets whose settling velocity w is less than the velocity in the separator w''. Let $\rho(r)$ be the weight distribution function of droplets by size. Then, in apparatuses of large diameter, for which separation of droplets on the walls can be neglected,

Fig. 1. Experimental apparatuses: *a–c* —evaporators (separator diameter 400-600 mm), *d* —bubbling column 200 × 200 mm. 1 —heating steam; 2 —condensate; 3 —steam outlet; 4 —device for measuring the droplet spectrum; 5 —brine inlet; 6 —air inlet

$$\omega = \omega_0 \int_0^{r_{\max}} \rho(r)\, dr = \omega_0 (1 - I), \tag{1}$$

where ω is carryover (kg liquid/kg steam)*; ω_0 is carryover at the evaporation surface (kg/kg); $r_{\max}$ is the maximum droplet size at the given height (determined by the initial velocity of the droplet in the entrainment zone or by the settling velocity in the zone of transported carryover); I is the weight fraction of droplets whose size is greater than $r_{\max}$.

It may be expected that, when liquid is atomized in steam generators, the distribution $\rho(r)$ will be close to lognormal. The latter may be approximated by the simpler expression

$$1 - I = 1 - \exp[-(1/m)!\, d/\bar{d}]^m, \tag{2}$$

where $\bar{d}$ is the weight-average droplet diameter, and m is a constant approximately inversely proportional to the dispersion $\bar{\sigma}$.

For separators whose height H_c is large compared with the radius R, separation of droplets due to their being carried to the wall must be taken into account. Let $w_\perp$ be the horizontal component of the initial entrainment velocity of a droplet, and w the vertical component. A droplet leaving at an angle θ to the vertical ($\mathrm{tg}\,\theta = w_\perp/w$) will strike the wall if $\mathrm{tg}\,\theta > R_i/H$, where R_i is the distance to the wall in the direction of flight of the droplet. Assuming that $\mathrm{tg}\,\theta$ is a random variable (probability density $\rho'(\mathrm{tg}\,\theta)$), and that $R_i = R$, we find

$$\omega = \omega_0 \int_0^{r_{\max}} \rho(r) \int_0^{R/H} \rho'(\mathrm{tg}\,\theta)\, d(\mathrm{tg}\,\theta)\, dr. \tag{3}$$

* It is sometimes more convenient to express carryover in kilograms of liquid from 1 m^2 of evaporation surface per hour (G). Then $\omega = G\ /(w''\gamma''3600)$.

The reduction of entrainment due to separation of predominantly large droplets on the walls is characterized by the curve ODC in Fig. 2a; in this case the entrainment should depend on the ratio R/H.

We shall use equations (1) and (2) to calculate entrainment and to estimate the effect of the steam velocity on entrainment. For this purpose we shall make use of the laws of atomization ([2,3]), according to which $\bar{d}/l \approx C(\mathrm{We})^{-0.5}$, where the Weber number is $\mathrm{We} = w''^2\gamma'' l/g\sigma$. Here γ'' and w'' are the specific weight and velocity of the gas (steam), and σ is the surface tension. As the determining dimension l for bubbling apparatus we take a parameter characterizing the bubble size: $l = \sqrt{\sigma/(\gamma - \gamma'')}$, and for non-bubbling apparatus, the diameter of the inlet nozzle D_{sh}; as the velocity, in the first case w'', and in the second the reduced steam velocity in the nozzle $\bar{w}''_{\text{sh}}$. Then

$$(\bar{d}/\sqrt{\sigma/\Delta\gamma})_{\text{B}} = C_1(\mathrm{We})_{\text{B}}^{-0.5} = C_1(w''^2\gamma''/g\sqrt{\sigma\Delta\gamma})^{-0.5}; \tag{4}$$

$$(\bar{d}/D_{\text{sh}})_{\text{BB}} = C_2(\mathrm{We}_{\text{BB}})^{-0.5} \quad \text{or}$$

$$(\bar{d}/\sqrt{\sigma/\Delta\gamma})_{\text{BB}} = C_2(w''^2_{\text{sh}}/gD_{\text{sh}})^{-0.5}(\gamma''/\Delta\gamma)^{-0.5}.$$

Let us note that $\mathrm{We}^{0.5}$ is a characteristic of the two-phase layer ([1]):

$$\sqrt{\mathrm{We}} = w'' \sqrt[4]{\gamma''/\sqrt{g^2\sigma\Delta\gamma}} = K_1,$$

Fig. 3

Figure 2: Fig. 3

and

$$w''^2/gD_{\text{sh}} = \text{Fr}_{\text{sh}}.$$

Fig. 2. Droplet-size distribution curves: **a**—distribution functions: *OBM*—at the evaporation surface, *OBC*—the transported part of the spectrum, *ODC*—the same with allowance for carryover of droplets to the wall. **b**—integral distribution at $w'' = 1.5$ m/sec: 1—in a probability-logarithmic grid at $H = 600$ mm, 2—at $H = 1800$ mm, 3—approximation by equation (2) at $H = 600$ mm, 4—at $H = 1800$ mm.

As d_{max} in equations (1)–(2), for the transported entrainment one should substitute the diameter of a floating droplet d_{v} (for $1 < \text{Re}_d < 10^3$ the floating velocity $w_{\text{vit}} \approx C_3 d$, and d_{v} is proportional to the steam velocity).

Substituting (2) and (4) into (1) and assuming that $d_{\text{v}} < \bar{d}$, we expand equation (2) in a series. Restricting ourselves to the first term, we find for the transported entrainment in bubbling apparatus of large diameter:

$$\omega_{\text{B}} = C_1\omega_0 \left[(d_{\text{v}}/l)\text{We}^{0.5}\right]^m = C_1\omega_0 \left[(d_{\text{v}}/\sqrt{\sigma/\Delta\gamma})K_1\right]^m \sim \omega_0(w'')^{2m}. \quad (5)$$

Since, as will be shown below, $m \approx 1.6$, for the bubbling regime the theory gives, at $\omega_0 = \text{const}$, the dependence $\omega_{\text{B}} \sim (\bar{w}'')^{3.2}$, and at $\omega_0 = cw''$, a fourth-power law. At the same time, the use of the series expansion indicates the limited applicability of the power dependence. Over broader ranges, entrainment should be described by an exponential dependence. For non-bubbling apparatus, assuming that ω_0 is determined by the fraction of liquid atomized in the nozzle, while the latter depends on the ratio of the kinetic energies of gas and liquid ([1]), $K_2 = w''\sqrt{\gamma''}/w\sqrt{\gamma}$, and that $\omega_0 \approx C'k_2^{m_1}$, we find

$$\omega_{\text{BB}} = C_3' k_2^{m_1} \text{Fr}_{\text{sh}}^{m_2} (\gamma''/\Delta\gamma)^{m_3} (d_{\text{v}}/\sqrt{\sigma/\Delta\gamma})^{m_4}. \quad (6)$$

Thus, for the non-bubbling regime the steam velocity in the separator does not uniquely determine entrainment, and it is necessary to take into account both droplet formation (Fr) and their removal from the separator (d /$\sqrt{\sigma/\Delta\gamma}$).

Fig. 3. Dependence of entrainment ω on the height of the separation space. **1, 2**—apparatus B, $w'' = 3$ m/sec (1) and $w'' = 2$ m/sec (2); **3**—bubbling column, $w'' = 2$ m/sec; **4, 5**—apparatus BB, $w'' = 2$ m/sec (4) and 1 m/sec (5)

Experimental part*. Studies were carried out on evaporators (Fig. 1a–e) and a bubbling column (Fig. 1e). The height of the separation space was varied from 600 to 2800 mm. The steam velocity in the separator w'' was from 0.5 to 4.5 m/sec at $p = 1$ ata and 1-8 m/sec at $p = 2$ ata. In the BB apparatus, independently of w'', within the range 5-200 m/sec the reduced steam velocity w'' in the feed nozzle was also varied. The experiments were conducted on a sodium chloride solution at a salt content above the critical value characteristic of evaporators (25-40 g/l). The droplet spectrum was determined by trapping them on a plate coated with a layer of soot and magnesium oxide, followed by photographing the imprints, and also by drying the droplets and trapping salt particles on a filter. Both methods made it possible to measure droplets ranging in size from 5 to 600 μ.

Results of the studies and their discussion. Droplet-size distribution. From Fig. 2b it is seen that, as we assumed, the droplet-size distribution is close to lognormal. The variance of the distribution proved to be close to unity ($\bar{\sigma} = 1 \pm 0.1$) and practically did not change with height. Splashing did not change the character of the distribution, but led to an increase in the mean droplet size as the evaporation mirror was approached (at $w'' = 1.5$ m/sec, at a height of 1800 mm $\bar{d} = 80\ \mu$, and at 600 mm $\bar{d} = 230\ \mu$). For BB apparatus, as w'' increased, $\bar{d}$ decreased, since in this case droplet breakup and generation occur precisely in the nozzle ($\bar{d} \sim \mathrm{We}^{-0.5}$). From Fig. 2b it is also seen that the distribution is satisfactorily approximated by equation (2), with $m \approx 1.6$. The considerations concerning the screening out of large droplets were also confirmed: in the region of transported entrainment the droplet spectrum proved not to be truncated (curve OB in Fig. 2a), but complete (curve ODC). Mainly large droplets fell out, whose velocity $w_\mathrm{k} = w'' - w$ is small and whose residence time is large.

Effect of separator height. Usually, splashing and transported entrainment are not separated, and the dependence of gross entrainment on separator height is described by a power equation $u \sim H^{-n}$, where $n = 2.3 \div 5.6$ [4]. As is seen from Fig. 3, such a description is incorrect: there is a region of a sharp dependence of entrainment on height, determined mainly by splashing (ω), and a second region with a weak dependence of entrainment on height, characterizing the transported entrainment ω and partial separation of droplets on the walls of the apparatus due to the horizontal component of the initial velocity and turbulent diffusion. The data are described by the equation:

$$\omega = \omega^0 e^{-\lambda H} + \omega^0 \times \exp[-\kappa(H - h\ )/D], \tag{7}$$

* G. I. Gostinin and A. N. Krasikov participated in the experiments.

where λ and χ are constants (for apparatuses B, $\lambda \approx$ 8-10, $\chi \approx 0.36$; for BB, $\lambda = 1 \div 2$, $\chi \approx 0$); h_p is the maximum height of droplet throw-up (at $p = 1$ ata, for apparatuses B, $h_\mathrm{p} = 0.6 \div 0.9$ m, and for BB, 1.4-1.6 m); D is the

Fig. 4. Correlations of transported entrainment.

Figure 3: Fig. 4. Correlations of transported entrainment.

apparatus diameter; ω_p is the entrainment at the evaporation surface; ω_T^0 is the entrainment at the boundary between throw-up and transported entrainment.

Effect of vapor velocity. Bubbling regime. When the data are approximated by a power-law dependence, at least two regions are obtained (Fig. 4): in the first region entrainment depends only weakly on vapor velocity; at high velocities (the second region), $G_\mathrm{un} \sim w''^{5.5}$, while $\omega \sim w''^{4.5}$. Thus, for the second region the experimental dependence of entrainment on velocity is very close to the theoretical one. The exponent is determined by the laws of fragmentation, hovering, and size distribution of the droplets. The different dependence in the first region indicates another mechanism of fragmentation (destruction of bubbles). It is also seen from Fig. 4 that the power law is approximate: as the velocity increases, the exponent increases continuously. A better description of the experimental data is obtained by setting $K_\mathrm{B} = (d_\mathrm{v}/\sqrt{\sigma/\Delta\gamma})K_1$, using the equation:

Fig. 4. Correlations of transported entrainment.
1 –experimental evaporators at $p = 1$ ata;
2 –same at $p = 0.21$ ata;
3 –air bubbling at $p = 1$ ata;
4 –industrial evaporators at $p = 0.1 \div 1.3$ ata.

$$G_\mathrm{un} = 5.4 \cdot 10^{-4} K_\mathrm{B}^{1/3} \left(1 + 8.65 \cdot 10^3 K_\mathrm{B}^{2.5}\right) (\gamma''/\Delta\gamma)^{-1} \exp[-0.36(H - h_\mathrm{p})/D]. \tag{8}$$

Non-bubbling regime. It has been shown that entrainment depends primarily not on the vapor velocity in the separator w'', but on the vapor velocity in the nozzle w''_sh. This agrees with the idea of droplet formation due to fragmentation in the feed nozzle. As with apparatuses B, there are two regions: in the first, entrainment depends only weakly on w''_sh, while in the second $\omega \sim w''^{1.5}_\mathrm{sh}$. Processing the data in accordance with Eq. (6) gives

$$G_\mathrm{un} = 8.2 \cdot 10^{-3} K_2^{-1} (\gamma''/\Delta\gamma)^{-0.5} K_\mathrm{BB}^{0.5} \left[1 - 4.23 \cdot 10^3 K_\mathrm{BB}^2\right], \tag{9}$$

where $K_\mathrm{BB} = (d_\mathrm{v}/D_\mathrm{sh})\sqrt{\mathrm{We}_\mathrm{BB}} = (d_\mathrm{v}/\sqrt{\sigma/\Delta\gamma})\sqrt{\mathrm{Fr}_\mathrm{sh}(\gamma''/\Delta\gamma)}$. Equation (9) also satisfactorily describes entrainment data in industrial apparatuses with heating surface up to 250 m^2 (Fig. 4).

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Note: Figure translations are in progress. See original paper for figures.