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Influence of entrainment on residual content of pollutants after absorber with sieve trays and wire demister

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Abstract

Entrainment is an important negative process that affects the efficiency of column units with a sieve trays. In sieve trays absorbers, entrainment leads to secondary contamination of the gas being purified by the reflux liquid. The sizes of entrainment droplets range widely from microns to millimeters and are the determining factor affecting the efficiency of demister. A review of studies on the flow rate and dispersion characteristics of entrainment removal from sieve trays is carried out, the research results are summarized in the form of a methodology for calculating the residual liquid content in gas after an absorber with a wire demister. In an absorber with cross-flow foam trays and a wire demister, there is an irreducible residual content of the reflux liquid, about several mg/m^3, which practically does not change up to gas velocities of 1–1.5 m/s.

Keywords

Sieve tray, entrainment, multiphase flow, counterflow sieve tray.

Introduction

Entrainment is an important negative effect affecting the operation of column apparatuses. In sieve tray absorbers, entrainment leads to secondary contamination of the gas being purified by the irrigating liquid. In industry, for some economic efficiency reasons, they tend to use solutions with a certain content of pollutants to irrigate foam scrubbers [1], because this reduces the costs of further processing.

To reduce contaminants in the gas after cleaning in the absorber, various types of demister are installed, the efficiency of which significantly depends on the dispersion composition of the entrained droplets [2, 3].

It is known that the efficiency of trapping liquid and dust particles in gas depends on the dispersion composition of the particles. And there is a large number of works on determining the total flow rate of spray from a foam plate [4, 5, 6, 7], but few studies of the dispersed composition of spray [8, 9, 10]. The results of studies of the dispersion composition are presented for limited ranges of droplet sizes, determined by the capabilities of measurement methods, and not covering the entire spectrum of sizes: from aerosol droplets of the order of 1 micron to large droplets of several mm in size.

In the foam layer of the absorber, there are several mechanisms for the formation of

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droplet entrainment [5], as a result of which, during operation of the foam plate, liquid droplets of a wide range of sizes are formed. The droplet size determines the further mechanism of droplet movement, the possibilities and methods of their capture, and the optimal methods for measuring the dispersed composition of droplets. It is customary to divide the resulting spray into fine and coarse. It is known [5] that coarse spray, with a droplet size of more than 10 microns, makes the main contribution to the mass flow rate of spray from the plate; drops of this size can be effectively captured in the foam layer itself, if it is of sufficient height, and then effectively captured by a splash eliminator (mist eliminator). Drops of fine entrainment, less than 5 microns in size, are practically not captured in the foam layer, and are poorly captured in splash traps [3, 11].

The largest drops and fragments of dynamic foam come off the foam layer of the tray due to the uneven and pulsating nature of the gas movement. The real size of such drops significantly exceeds the theoretical one, determined by the soaring speed, which is equal to the gas speed reduced to the cross section of the apparatus. The content of large droplets decreases with an increase in the height of the separation space above the plate and a decrease in the uneven distribution of gas across the cross section.

Medium-sized droplets are formed during the disintegration of liquid films in the foam layer; the maximum size of such droplets approximately corresponds to the critical size determined by the soaring speed with a uniform distribution of gas flow across the cross section of the apparatus. Droplets of this size account for the majority of entrainment from crossflow trays in the operating range of gas velocities. Consumption of medium-sized Spray entrainment increases monotonically with increasing gas velocity.

Fine droplets, up to 5 µm in size, are formed both during the disintegration of liquid films during the bursting of bubbles [12] and when a high-speed gas jet acts on the liquid in the area of the plate opening [13]. Droplets of this size are practically not captured in the foam layer [5], and are poorly captured in mist eliminators [3, 11].

This article provides a method for calculating the residual content of pollutants in the gas leaving a foam absorber with a wire mist eliminator, with counter-flow or cross-flow trays, with round holes or fixed valves.

Research Brief

Total flow rate of spray cross flow plates

Many correlations have been proposed [4, 5, 6] to determine the flow rate of the spray gun. For cross-flow trays, the flow rate of spray from the tray increases monotonically with increasing gas velocity. For cross-flow trays with fixed valves, the entrainment flow rate is approximately half of that for trays with round holes [9].

For an air-water mixture, the specific spray flow rate is usually calculated by using the empirical formula:

$$L_E = A_E \frac{{U_G}^m}{\sigma^k {h_c}^n}, \quad (1)$$

where L_E is the total relative entrainment of liquid kg/kg, reduced to the gas mass flow rate, A_E, m, n, k are constants, which differ for every source, U_G is the gas velocity reduced to the free cross section of the apparatus, m/s, σ — surface tension, N/m, h_c — height of the separation space above the foam layer, m.

According to [5], for a water-air mixture, a cross-flow plate with a pure liquid layer height of 12 mm: $A_E = 7.49\ 10^{-5}$ kg/kg, $m = 4.3559$, $k = n = 0$.

For other two-phase mixtures, it is proposed [6] to replace the air speed in formula (1) with a modified Froude number:

$$Fr^+ = \frac{{U_G}^3}{gQ_L}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^b, \quad (2)$$

where g is the acceleration of gravity, m/s^2, Q_L is the load on the liquid overflow (the ratio of liquid flow to the length of the overflow), m^2/s, ϱ_G is the gas density, kg/m^3, ϱ_L is the liquid density , kg/m^3, b — an empirical constant depending on the physical properties of the liquid.

Total flow rate of spray from counterflow plates

Our experimental results [15], measuring the specific flow rate of spray for counterflow plates with round holes of 40 mm, free section fraction 0.13, with an irrigation density of 4 m^3/(m^2 h), can be approximated by formula (1) with values: $A_E = 6.52 \cdot 10^{-2}$ kg/kg, $m = 1.398$, $k = n = 0$.

Experiments with counterflow trays with fixed valves [15] show that the total entrainment flow rate has a local minimum in the zone of gas velocities of 1–2 m/s, therefore, dependencies of type (1) cannot be used to calculate the splash entrainment flow rate. For similar counterflow trays with fixed valves, the results are approximated by the formula:

$$L_E = 0{,}0391 {U_G}^3 - 0{,}1527 {U_G}^2 + 0{,}1607 U_G. \tag{3}$$

Consumption of fine spray

The specific consumption of finely dispersed entrainment [5] is several times lower than the consumption of coarsely dispersed entrainment, speaking about its magnitude, however, taking into account the difficulty of capturing micron-sized droplets, it can make a significant contribution to the residual content of pollutants in the gas. For a water-air mixture, a crossflow tray with a pure liquid layer height of 12 mm, the specific consumption of fine spray from one tray can be calculated by the formula:

$$L_E^{1\text{т}} = 3{,}1572 \cdot 10^{-6} {U_G}^3 - 13{,}026 \cdot 10^{-6} {U_G}^2 + 14{,}721 \cdot 10^{-6} U_G. \tag{4}$$

Dispersion composition of splash carryover

Methods for describing the dispersed composition of aerosols are described in [13, 14]. To simplify calculations, it is convenient to use distribution functions, the Rosin-Rammler equation :

$$R_3 = exp\left(-\left(\frac{d_i}{a_m}\right)^{n_R}\right), \tag{5}$$

where R_3 is the volume fraction of drops whose diameter is bigger than d_i (in the total volume of splash water), *and* a_m is the size constant, the average diameter of drops corresponding to a certain value $R_3 = 0.3679$; n_R — distribution constant characterizing the degree of spray heterogeneity.

$$I_{p3} = -\frac{\partial}{\partial d_i} R_3 = R_3 \frac{n_R}{a_m} \left(\frac{d_i}{a_m}\right)^{n_R - 1}, \tag{6}$$

where I_{p3} is the relative frequency of the droplet volume distribution across diameters.

Median droplet diameter:

$$d_m = a_m (\ln 2)^{\frac{1}{n_R}}. \tag{7}$$

Average volume-surface diameter of droplets:

$$d_{32} = \frac{a_m}{\Gamma\left(\frac{n_R - 1}{n_R}\right)}, \tag{8}$$

where $\Gamma(x)$ is the gamma function.

Data on the dispersion composition of splash entrainment aerosols [9] for coarse entrainment, and [8] for fine entrainment. The results of selecting the coefficients of equation (5) are shown in table 1.

Table 1 — Coefficients to the Rosin-Rammler equation

P.	Link	Characteristics of entrainment, operating mode of the plate, plate design	U_G, m/s	n_R	a_m, µm	d_m, μm	d_{m32}, µm
1	[9]	Coarse entrainment, cross-flow plate with round holes, liquid load per overflow 6.3 $m^3/(m·h)$	0.88	3.1	359	319	269
2			1.32	1.96	587	487	325
3			1.76	2,056	1146	959	664
4		Coarse entrainment, cross-flow tray with fixed valves, liquid load per overflow 6.3 $m^3/(m·h)$	0.88	1.72	524	423	247
5			1.32	1.59	736	584	307
6			1.76	1.85	1110	911	576
7	[8]	Fine entrainment, cross-flow plate with round holes, clean liquid layer height 12 mm	0.4	1.08	2.69	1.92	0.207
8			1.6	3.4	2.85	2.56	2.21
9			2.9	1.26	2.62	1.96	0.590

The size constant differs little for trays with round holes and trays with fixed valves, as shown in Figure 1, and increases monotonically with increasing gas velocity, which is explained by an increase in droplet sizes corresponding to the soaring speeds.

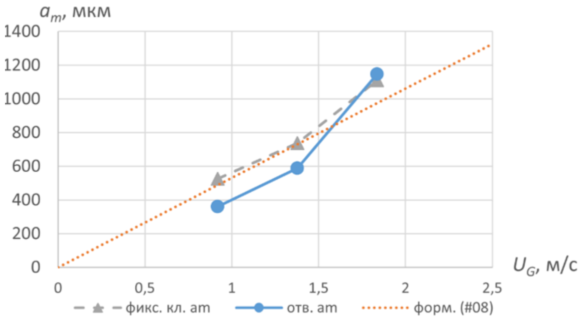

Figure 1 — Size constant of the dispersed composition of coarse spray for crossflow trays with round holes and fixed valves, depending on the gas velocity

Before obtaining experimental data on the dispersed composition in a wider range of gas velocities and types of plates, the size constant of the coarse spray entrainment, µm, can be determined by the formula:

$$a_m = 530U_G. \tag{9}$$

The dependence of the distribution constants on the gas speed shown in Figure 2 naturally is a complex without the obvious nature of the influence of speed. Until more complete experimental data are obtained, the value $n_R = 2.0$ can be taken in calculations.

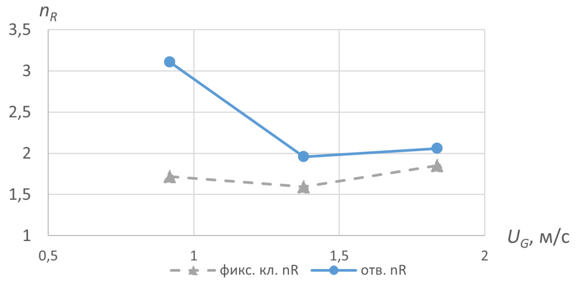

Figure 2 — Size constant of the dispersed composition of coarse spray for cross-flow trays with round holes and fixed valves, depending on the gas velocity

Dispersion composition of fine entrainment

The digital image processing method used to determine entrainment dispersion [10] may underestimate the particle content near the lower limit of the range. Photographs taken with a digital camera are processed by increasing contrast and sharpness, while traces of small drops can be discarded as defects; in addition, fine particles move at high speed and obtaining their images is especially difficult.

The only source found about fine entrainment [8] uses a complex technique of inertial capture of droplets of saline solution, followed by measurement of the mass of settled salt on the filters. The dependence of the dispersion characteristics on the gas velocity, shown in Figure 3, is complex; until more complete data is obtained, the spray characteristics can be assumed to be constant and independent of the gas velocity: $n_R = 1.9$, $a_m = 2.72$ µm.

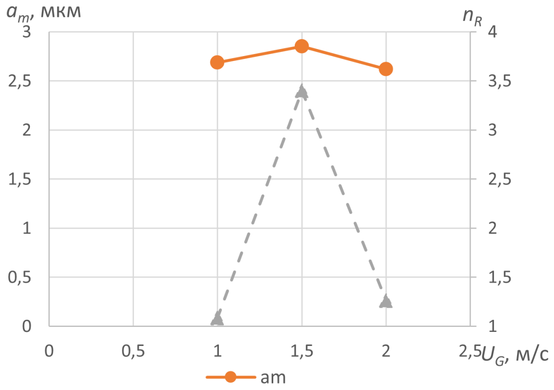

Figure 3 — Size constant of the dispersed spray composition for cross-flow trays with round holes and with fixed valves, depending on the gas velocity

Fine droplets of spray entrainment (fog) are formed directly in the foam layer, but are partially captured on subsequent foam trays, which affects the total consumption of fine entrainment from the multi-shelf foam apparatus.

The efficiency of fog collection in a foam layer is considered in [5], it is noted that the collection efficiency in is determined by the height of the foam layer, irrigation density, gas velocity and, most importantly, particle size. Coarse entrainment particles are captured in the foam layer with an efficiency above 99.9%. The collection efficiency of fine particles is significantly lower; for fine particles, up to 1 micron, sulfuric acid mist, the collection efficiency on one cross-flow shelf of a foam apparatus is about 50%.

It is noted that the efficiency of mist collection in the foam layer mainly depends on the height of the foam on the plate; with an increase in the height of the drain threshold, an increase in the irrigation density, the height of the foam increases and the collection efficiency increases. Data on the dispersed composition of fog particles are not given, but it is noted that the efficiency varies depending on the technological process mode that affects the dispersion.

Efficiency of wire mist eliminator

A review of empirical correlations of the effectiveness of mist eliminators is made in [2, 10]. The calculation methods given below show good agreement with the data on the efficiency of wire mist eliminators declared by the manufacturers [3, 11, 16].

Based on the impact factor proportional to the Stokes criterion:

$$I = \frac{\rho_L {D_d}^2 U_G}{9 \mu_G D_w}, \tag{10}$$

where D_d — drop diameter, m, D_W — wire diameter, m, μ_G — dynamic gas viscosity, Pa·s.

Efficiency of one layer of wire:

$$\eta_t = \left(\frac{I}{I + 0{,}7}\right)^2. \tag{11}$$

Mist eliminator efficiency:

$$\eta_m = 1 - e^{-\frac{2\eta_t a_{sp} t_m}{3\pi}}, \tag{12}$$

where a_{sp} is the specific surface area of the mist eliminator m^2/m^3, t_m is the height of the mist eliminator packing, m.

For gas velocities from 0.9 to 5.5 m/s, accordance with experimental data is shown by the calculation method based on the Stokes criterion:

$$St = \frac{\rho_L {D_d}^2 U_G}{18 \mu_G D_w}, \tag{13}$$

$$\eta_{ST} = \left| \begin{matrix} St \; if \; St < 1 \\ 1 \; if \; St \geq 1 \end{matrix} \right., \tag{14}$$

$$\eta = 1 - \left(1 - \frac{2}{3} a_{sp} \eta_{ST} \frac{z}{\pi}\right)^n, \tag{15}$$

where z is the distance between the mesh layers, m, n is the number of mesh layers in the mist eliminator.

$$n = t_m / z. \tag{16}$$

Calculation method

When calculating, it was assumed: liquid density $\varrho_L = 997$ kg/m^3, gas density $\varrho_G = 1.29$ kg/m^3, gas viscosity $\mu_G = 17.17 \cdot 10^{-6}$ Pa·s , concentration of pollutants in the liquid on all absorber plates $x_m = 10\%$, cross-flow plates, height of the pure liquid layer is 50 mm. Number of plates: 3 pcs. Mist eliminator parameters $d_w = 250$ µm, specific surface area $a_{beat} = 270$ m^2/m^3, thickness (height) of the wire packing of the mist eliminator $t_m = 100$ mm, distance between packing layers z = 1 mm.

Let us determine the consumption of fine and coarse spray in front of the mist eliminator.

$$L_E^{\text{т}} = L_E^{1\text{т}} \cdot \sum_{i=1}^{N_{\text{т}}} \eta_{p.t.}{}^{i-1}, \qquad (17)$$

where $\eta_{\text{p.t.}}$ — efficiency of capturing finely dispersed entrainment (fog) in the foam layer, N_{t} — number of plates in the foam apparatus, $L_E{}^{1t}$ — consumption of finely dispersed entrainment from one plate, formula (4).

The consumption of coarse entrainment does not depend on the number of plates and is determined by formula (1).

The overall efficiency of the mist eliminator, taking into account the dispersion of entrainment, can be determined by the formula:

$$\eta_{DSD} = \int_0^{D_{max}} I_{p3}(D_d) \cdot \eta(D_d) \cdot dD_d, \qquad (18)$$

where D_{max} is the maximum diameter of entrainment particles, m, D_d is the particle diameter, m, I_{p3} is the frequency function of particle volume depending on the particle diameter, formula (6), η is the efficiency of the mist eliminator depending on the particle diameter , formula (15).

During automated calculations using fle (18), errors may occur due to the fact that the used function (14) is not smooth in the neighborhood of 1, in which case, you can use smoothing of the function according to the method:

$$K_{\text{сгл}}(St) = 0{,}5 - \frac{1}{\pi} arctg\left(K_{\text{точн}} \cdot (St - 1)\right), \qquad (19)$$

where K_{smooth} (St) is the smoothing coefficient, St is the Stokes criterion, formula (13), K_{exact} is the accuracy coefficient, in further calculations $K_{\text{exact}} = 40$ is taken. Then, the smoothed efficiency function of one layer of the mist eliminator mesh:

$$\eta_{ST}^{\text{гл}} = St \cdot K_{\text{сгл}}(St) + \left(1 - K_{\text{сгл}}(St)\right). \qquad (20)$$

Next, the smoothed function is used in formulas (15) and (18).

Residual liquid content in gas after the mist eliminator:

$$L_E^{\text{ост}} = L_E^g \cdot \left(1 - \eta_{DSD}^g\right) + L_E^t \cdot \left(1 - \eta_{DSD}^g\right), \qquad (21)$$

where $L_E{}^g$ is the flow rate of coarse entrainment, formula (1), $\eta_{DSD}{}^g$ is the efficiency of the mist eliminator for coarse entrainment, $L_E{}^t$ is the flow rate of fine entrainment, form (17), $\eta_{DSD}{}^g$ is the efficiency of the mist eliminator for fine entrainment.

Residual content of pollutants:

$$L^{\text{ост}} = L_E^{\text{ост}} \cdot x_m. \qquad (22)$$

The results of calculating the residual liquid content in the gas are shown in figure 4.

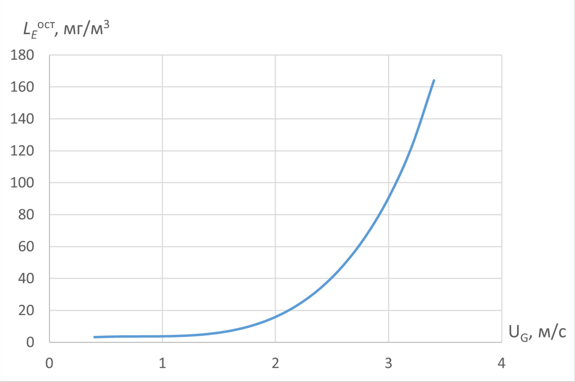

Figure 4 — Residual liquid content in gas after an absorber with cross-flow trays

To calculate an absorber with countercurrent foam trays, we use flu (3) for the flow rate of coarse entrainment; the calculation results are shown in figure 5.

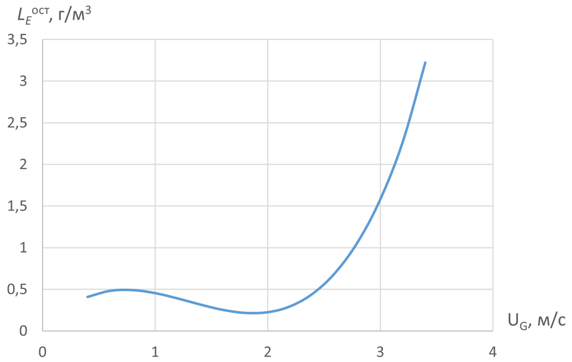

Figure 5 — Residual liquid content in gas after an absorber with flow-through trays with fixed valves

The discussion of the results

When purifying gas in absorbers with counterflow foam trays and wire mist eliminators, there is an irreducible residual entrainment content of the order of several mg/m^3 due to the presence of a finely dispersed component. For an air-water system, when the gas velocity decreases below 1.5 m/s, the residual splash content practically does not decrease due to a decrease in the efficiency of the wire mist eliminator for the finely dispersed component. At gas velocities above 1.5 m/s, the residual content of spray entrainment increases due to an increase in the consumption of coarse entrainment, while the efficiency of the mist eliminator for coarse entrainment becomes high, about 99–99.7%, but does not reach 100% and changes little with increase in gas speed.

In absorbers with counterflow plates, the influence of the finely dispersed component is negligible. The total flow rate of spray entrainment from a counter-flow tray is orders of magnitude higher than from a cross-flow one, which leads to a higher content of residual entrainment due to the limited, although high, efficiency of the mist eliminator.

Conclusion

When designing absorbers with cross-flow trays, it is necessary to take into account the residual content of spray after the mist eliminator. To minimize the residual content of pollutants, it is necessary to increase the purity of the irrigation liquid; reducing the gas velocity below 1.. 1.5 m/s is ineffective. To increase the degree of capture of mists and fine particles in the absorber, it is necessary to take measures to increase the size of the particles entering the absorber.

To reduce the residual content of foam absorbers with counter-flow trays, it is necessary, first of all, to take measures to reduce coarse entrainment from the tray, for which purpose reduce the pulsations of the liquid distribution over the tray, the pulsation component of the vertical gas velocity.

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Влияние брызгоуноса на остаточное загрязнение газа после пенного абсорбера с проволочным туманоуловителем

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Аннотация

Брызгоунос является важным негативным процессом, влияющим на эффективность работы колонных аппаратов с пенным слоем. В пенных абсорберах унос приводит к вторичному загрязнению очищаемого газа орошающей жидкостью. Размеры капель брызгоуноса находятся в широких пределах от микрон до милиметров и являются определяющим фактором, влияющим на эффективность работы брызгоуловителя. Проведён обзор исследований по расходным и дисперсным характеристикам брызгоуноса с пенных тарелок, результаты исследований обобщены в виде методики расчёта остаточного содержания жидкости в газе после пенного абсорбера с проволочным туманоуловителем. В абсорбере с перекрёстноточными пенными тарелками и проволочным туманоуловителем существует неснижаемое остаточное содержание орошающей жидкости, порядка нескольких мг/м^3, практически не изменяющееся до скоростей газа 1–1.5 м/с.

Ключевые слова

Пенный абсорбер, пенная тарелка, брызгоунос, эффективность туманоуловителя.

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