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ENERGY ASPECTS OF WET DUST COLLECTION PROCESSES

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Abstract

Gas purification is of considerable interest for many types of industry (chemical, metallurgical). However, gas cleaning processions are carried out in devices of various operating principles and various designs that are familiar to this industry. Accordingly, the theoretical justification for the choice and calculation of gas cleaning devices is an urgent task, the solution of which will increase the efficiency of capturing gas emissions with minimal energy consumption for the process.

Key words: fluidized, gas-liquid, efficiency of dust and gas cleaning, average size, aerosol particles, energy costs, correlation coefficient.

INTRODUCTION

Dust cleaning is described by a number of theories, of which the energy theory is the most general and at the same time the least developed. According to this theory, the degree of purification unambiguously correlates with the total energy consumption of the gas-liquid flow, including the energy for spraying the liquid; using the principle of additivity of energy loss components, we can write

$$\Delta\rho = \Delta\rho_1 + \Delta\rho_2 + \Delta\rho_3 + \Delta\rho_4, \qquad (1)$$

$\Delta\rho_1$ - head loss (specific energy consumption) during the movement of the transporting phase of a two-phase flow (gas phase);

$\Delta\rho_2$ - head loss for weighing the dispersed phase of a two-phase flow.

In a three-phase fluidized system, gas-liquid packing, this also includes losses due to weighing packing bodies. In this way

$$\Delta\rho_2 = \Delta\rho_{ж} + \Delta\rho_{и}$$

$\Delta\rho_{ж}$ - head loss for weighing liquid droplets in the flow;

$\Delta\rho_{и}$ - head loss for weighing packed bodies;

$\Delta\rho_3$ - head loss due to energy costs for the acceleration of liquid droplets to the speed of

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soaring;

$\Delta\rho_4$ - head loss for crushing liquid into droplets of average size.

METHODS

The determination of the head loss components can be carried out according to known formulas [1, 2]. Let us dwell on the energy costs associated with overcoming the forces of surface tension. Single drops, the totality of which constitutes the liquid phase in the gas-liquid spray layer, are equilibrium formations. Internal equilibrium is determined by the opposing forces of surface tension and internal pressure. With an increase in the droplet size, the internal pressure (Laplass pressure) becomes greater than the pressure determined by the forces of surface tension, and the liquid is crushed into drops of a certain critical size without the expenditure of external energy. If the condition of critical tension, then the critical diameter of the drop is determined by the expression

$$D_K = \sqrt{\frac{6\sigma}{\rho g}}, \qquad (2)$$

The critical diameter of a water drop calculated by equation (2) is 6.6 mm. The crushing of droplets in the gas flow occurs due to the kinetic energy of the gas flow. The droplet size depends on the gas velocity. The equation that determines the average size of droplets in a gas flow is obtained based on the constancy of the critical value of the Weber criterion [3].

A similar expression can be obtained from the condition of equality of surface tension forces and aerodynamic drag forces during the motion of a drop in a gas flow. The force of dynamic pressure on a drop of diameters d_k, is determined by the expression

$$\rho_g = \frac{C\rho V_{OT}^2}{2} \cdot \frac{\pi d_k^2}{4}. \qquad (3)$$

C - Aerodynamic coefficient;

V_{OT} – relative drop velocity;

Surface tension force

$$\rho_\sigma = \sigma \cdot \pi d_k \qquad (4)$$

From equality (3) and (4) it follows

$$d_k = \frac{8\sigma}{C\rho V_{OT}^2} \qquad (5)$$

Or

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$$d_k = \frac{13\sigma}{\rho V_{OT}^2} \quad (6)$$

at $C - 0.6$.

Let us consider the energy costs associated with the direct crushing of drops. The work expended by the gas on the formation of the interfacial surface due to the crushing of drops is determined by the size of the formed surface and the coefficient of surface tension

$$A_g = \sigma F_k \quad (7)$$

Where F_k – the droplet surface formed due to the energy of the gas flow.

$$F_k = F_k^{(1)} - F_k^{(2)} \quad (8)$$

Where $F_k^{(2)}$ – the surface of formation due to the energy of gravity

$$F_k^{(2)} = ng\pi D_k^2 \quad (9)$$

Due to the energy of the gas, a drop of critical diameter D_k is broken up into drops n with a diameter of d_k. From the equality of volumes follows

$$\frac{\pi D_k^3}{6} = n\frac{\pi D_k^3}{6},\ n\left(\frac{D_k}{d_k}\right)^3 \quad (10)$$

Total droplet surface $F_k^{(1)}$

$$F_k^{(1)} = ng \cdot n\pi d_k^2 = ng\pi\left(\frac{D_k}{d_k}\right)^3 d_k^2 = ng\frac{\pi D_k^3}{d_k} \quad (11)$$

Where ng - the number of drops into which a liquid is crushed without expending gas energy

$$ng = \frac{6V_{ж}}{\pi D_k^3} \quad (12)$$

$V_{ж}$ – volume of fluid retained in the device.

Using expressions (2), (8), (9), (10), (11), (12) we obtain

$$F_k = \frac{6V_{ж}}{\sqrt{\frac{6\sigma}{\rho g}}} \cdot \frac{\sqrt{\frac{6\sigma}{\rho g}} - d_k}{d_k} \quad (13)$$

The amount of liquid that is simultaneously in the apparatus if there is no accumulation in the

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apparatus due to the sliding of liquid droplets in the gas stream

$$G_{жс} = V_{ап}\rho_r \cdot B \tag{14}$$

The amount of liquid passing through the apparatus per unit time, at a density of irrigation α

$$q_{жс} = \alpha F_c \rho_{жс} \tag{15}$$

Amount of gas at speed U_{cp} per unit time

$$q_r = U_{cp} F_c \rho_r \quad 16)$$

Specific irrigation, B, is determined by the expression

$$B = \frac{q_{жс}}{q_r} = \frac{\alpha \rho_{жс}}{U_{cp} \cdot \rho_r} \tag{17}$$

In equations (14) - (17)

$V_{ап} = F_c H$ – the volume of the working area of the device;

$\rho_r, \rho_{жс}$ – density of gas and liquid;

F_c - section of the apparatus.

The volume of liquid in the apparatus is obtained using expressions (14) - (17)

$$V_{жс} = \frac{G_{жс}}{\rho_{жс}} = \frac{\alpha F_c H}{U_{cp}} \tag{18}$$

Taking into account the slip of drops

$$V_{жс} = \frac{\alpha F_c H}{i U_{cp}} \tag{19}$$

Where $i = \frac{V_{OT}}{U_{cp}}$ - the slip coefficient.

After substituting the expression (18) - (13) we get

$$F_k = \frac{6\alpha F_c H}{i U_{cp}\sqrt{\frac{6\sigma}{\rho g}}} \cdot \frac{\sqrt{\frac{6\sigma}{\rho g}} - d_k}{d_k} \tag{20}$$

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Surface per unit volume of a gas-liquid system

$$F_k = \frac{F_k}{V_{OT}} = \frac{F_k}{F_c H} = \frac{6\alpha}{iU_{c\rho}} \cdot \frac{\sqrt{\frac{6\alpha}{\rho g}} - d_k}{\sqrt{\frac{6\alpha}{\rho g}}\, d_k} \qquad (21)$$

In accordance with (7), (20), the work spent on the creation of the interfacial surface due to the crushing of drops will be equal to

$$A_g = \frac{6\sigma\alpha F_c H}{iU_{c\rho}\sqrt{\frac{6\alpha}{\rho g}}} \cdot \frac{\sqrt{\frac{6\sigma}{\rho g}} - d_k}{d_k} \qquad (22)$$

Specific work, α_g, per unit volume of the apparatus

$$\alpha_g = \frac{6\sigma\alpha}{iU_{c\rho}\sqrt{\frac{6\sigma}{\rho g}}} \cdot \frac{\sqrt{\frac{6\sigma}{\rho g}} - d_k}{d_k} \qquad (23)$$

When a liquid is crushed into small drops, when $D_k \rangle\rangle d_k$.

RESULTS:

Note that the droplet diameter is related to the relative velocity by dependence (6) and, therefore, decreases with increasing gas velocity. Thus, as the gas velocity increases, the specific crushing work tends to increase. Assessing the contribution of direct energy costs to overcome the surface tension forces during droplet crushing, we can conclude that it has a small share in the overall balance of energy costs in dust and gas cleaning devices. This value is more significant when crushing liquid in pneumatic nozzles at significant and small d_k.

A significant proportion of energy losses is associated with the kinetic energy of the gas flow and, therefore, increases with increasing gas velocity. Let us consider the influence of the average gas velocity on the parameters directly related to the efficiency of dust and gas cleaning.

If the volumetric flow rate of the liquid supplied for irrigation is - $Q_{ж}$, the average static droplet size resulting from crushing is - d_k, then the droplet surface formed per unit time has the form

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$$F = \frac{Q_{ж}\pi d_k^2}{\frac{\pi d_k^3}{6}} = \frac{6Q_{ж}}{d_k} \tag{25}$$

Substituting d_k from (6) into (25) we get

$$F = \frac{Q_{ж}V_{OT}^2\rho_r}{2\sigma} \tag{26}$$

Let us introduce the value of specific irrigation $B = \frac{Q_{ж}\rho_{ж}}{G_r}$, whence

$$Q_{ж} = B\frac{G_r}{\rho_{ж}} \tag{27}$$

Here G_r, is the gas flow rate. Taking $G_r = \rho_r U_{cp} F_c$ and taking into account (27), we obtain

$$F = \frac{BU_{cp}V_{OT}^2\rho_{ж}^2}{2\sigma\rho_{ж}} \tag{28}$$

In the case of pneumatic transport of droplets by a gas flow, one can use the known regularities of pneumatic transport of solid particles [2]. Taking into account the constraint of the flow by drops, we obtain

$$\frac{V_{OT}}{\varepsilon} = \frac{U_{cp}}{\varepsilon} - V \tag{29}$$

V – Speed of translational movement of particles;

ε – is the porosity of the drop layer.

$$Q_{ж} = F_c \cdot V \cdot C_{об} \text{ and } Q_{ж} = \alpha \cdot F_c$$

Then

$$C_{об} = \frac{\alpha F_c}{VF_c} = \frac{\alpha}{V},\ \varepsilon = 1 - C_{об} = \frac{V-\alpha}{V} \tag{30}$$

$C_{об}$ - Volume concentration of drops. From equation (29), (30) we obtain

$$V_{OT} = U_{cp} - V + \alpha$$

And since with pneumatic transport

$$V = U_{cp} - V_B$$

Where V_B - the speed of the particles (drops), then

$$V_{OT} = V_B + \alpha \tag{31}$$

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In direct-flow gas-liquid systems used in gas cleaning, low irrigation densities of 10 + 50 m3 / m^2 h or 0.003 + 0.01 m / s, respectively, are used, which makes it possible to calculate $V_{OT} \approx V_B$ and determine the soaring velocities for single particles. However, in contrast to the pneumatic transport of solid particles, the droplet size depends on the relative velocity (equation (6)), and the soaring velocity depends on the droplet size and can be determined by the well-known expression

$$V_B = \frac{V_r}{d_k} \cdot \frac{A_r}{18 + 0.6 A_r^{1/2}} \qquad (32)$$

Where $A_r = \frac{g d_k^3}{Q^2} \cdot \frac{\Delta\rho}{\rho}$ Archimedes criterion

Analyzing the joint solution of equations (6) and (32), it is easy to establish that for the water-air system the only common solution corresponds to $d_{k\rho} = 5{,}5\,мм$. Thus, at $d_k \langle d_{k\rho}$ there is a condition for the pneumatic transport of the drop. In this region, the relative velocity of a drop in a gas flow is below the limiting rate of fragmentation of a drop of a given size. Therefore, when a drop is pneumatically transported at $d_k \langle d_{k\rho}$, crushing a drop directly by a gas stream is impossible. At $d_k \rangle d_{k\rho}$, the drop cannot be in a state of pneumatic transport, because it is crushed at a speed less than the speed of its soaring. When a drop moves at a soaring speed, crushing does not occur in the area of the steady movement (except for the collision of drops between themselves by solid bodies), and the formation of drops of a given size occurs in the areas of liquid input into the apparatus at the moment of acceleration of the bulk of the liquid. Under these conditions, the relative droplet velocity is close to the gas velocity, and in accordance with Eq. (28) we obtain

$$F = \frac{B U_{c\rho}^3 \rho_r^2}{2\sigma\rho_{ж}} \qquad (33)$$

Thus, the gas velocity has a very significant effect on the intensity of the formation of the interfacial surface.

The gas velocity, which determines the energy of a moving aerosol particle, affects the possibility of its penetration into the droplet upon impact. Penetration of a particle into a liquid can occur when the kinetic energy of the collision is greater than the energy expended to overcome the forces of surface tension. The work of penetration of a particle into a drop is determined by the expression [4]

$$A_n = \frac{8}{3}\pi r^2 \sigma_{жr} \cos\beta \qquad (34)$$

Where β the angle between the direction of surface tension of the solid σ_{Tr} and liquid $\sigma_{жr}$, $\theta + \beta = 180^0$, where θ the contact angle.

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For completely wettable particles $\beta = 180^0$ and in accordance with (34) $A_n = 0$.

Of interest is the case of capturing poorly wetted particles and non-wettable particles. Let us refer expression (34) to the unit volume of a spherical particle

$$\alpha_n = \frac{\frac{8}{3}\pi r^2 \sigma_{жг} \cos\beta}{\frac{4}{3}\pi r^3} = \frac{2\sigma_{жг}\cos\beta}{r} = \frac{4\sigma_{жг}\cos\beta}{d_4} \qquad (35)$$

For non-wettable particles $\beta = 0$, $\cos\beta = 1$ and therefore, the work of penetration will be maximum. The minimum speed required to capture a particle and penetrate into a drop is determined from the equality of the specific kinetic energy of the particle and the work expended to overcome the forces of surface tension

$$\frac{\rho_4 V_4^2}{2} = \frac{4\sigma_{жг}\cos\beta}{d_4}$$

Where

$$V_4 = \sqrt{\frac{8\sigma_{жг}\cos\beta}{d_4 \rho_4}} \qquad (36)$$

Based on formula (36), it is easy to make an approximate calculation showing the minimum values of the relative velocities of non-wettable particles for their penetration into the drop. So, at a density of particles $\rho_4 = 2000 кг/м^3$, to capture a particle with $d_4 = 100 мкм$, you need a relative speed $V_4 = 17 м/с$.

Thus, the gas flow rate is directly correlated with the parameters that affect the efficiency of aerosol particle capture. The energy costs associated with the creation of a certain dynamic pressure depend on the design of the apparatus and can be characterized by a general dependence.

$$\Delta\rho_1 = \xi_c \frac{U_{cp}^2}{2g} \qquad (37)$$

Where ξ_c the system resistance coefficient.

In highly trumpeted flows of gas scrubbers, energy costs are correlated with turbulent intensity. pulsations [5]. In this case, it can be assumed that the efficiency of the process will increase with an increase in the turbulent effect of hydraulic resistances in the gas-liquid system. Consider the volume of a gas-liquid system in which liquid drops are uniformly and randomly distributed. Estimating the probability of capturing an aerosol particle flying between drops by one of these drops, we arrive at the expression

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$$\eta = 1 - e^{-kh} \quad (38)$$

Where h - the path traveled by a particle in a turbulent flow;

η capture efficiency.

The path traveled by a particle in a turbulent flow depends on the degree of flow turbulence and the inertia of the particle. Path estimation is carried out as follows: by integrating the differential equation of particle motion

$$\frac{dV_4}{dt} + \beta V_4 = \beta \overline{U} \quad (39)$$

Where $\overline{U} = const$ - velocity within one turbulent impulse, within the limits of one turbulent impulse we obtain the expression

$$V_4 = \overline{U} - \left(U - V_4^0\right)\varepsilon^{-\frac{t}{\tau}} \quad (40)$$

Where $\frac{1}{2} = \tau = \frac{d^2 \rho_4}{18\mu}$ inertia parameter.

We took into account that after repeated integration we have

$$h = \overline{U}t - \tau\left(\overline{U} - V_4^0\right)\left(1 - 1/e^{-\frac{t}{\tau}}\right) \quad (41)$$

Where V_4^0 - speed at the initial time.

DISCUSSION

Further calculation was carried out on an EC 10-22 computer according to the following algorithm:

1. A specific geometric system is set: pipe length α_T and radius R.

2. The physical parameters of the particles and the gaseous medium are set.

3. The number of particles introduced into the gas flow is set.

This number should be large enough to provide statistically significant results.

4. The speed of the turbulent impulse is determined. This speed depends on the coordinate of the point and energy costs in the system.

5. The maximum value of the velocity and path of the particle in the field of the turbulent momentum is calculated.

6. According to the Monte Carlo method, using a random number generator, a random value of the speed is set, which does not exceed the possible maximum.

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7. For each particle in each next quantum of time, determined by the scale of turbulence, the speed and distance traveled are calculated and new coordinates are determined.

8. Calculation of the distance traveled is carried out before the departure of the particle from the pipe. A detailed analysis of the model is the subject of a special report.

On the basis of a computer experiment carried out in a wide range of motion parameters and particle sizes, an equation was obtained that determines the path of a particle traveled in a turbulent gas flow

$$\bar{h} = 1.18\alpha_T + 0.250R\frac{\Delta\rho}{\rho_r U_{c\rho}^2} - 2.57\tau U_{c\rho} \qquad (42)$$

Equation (42) describes statistical data with high accuracy. Correlation coefficient 0.925 Fisher test 132.8. Of particular interest is the second term of Eq. (42). Because

$$\xi_\varepsilon = \frac{\Delta\rho}{\rho_4 U_{c\rho}^2}$$

The path traveled by the particle is largely determined by the drag coefficient of the system, provided that this coefficient is associated with the turbulence of the flow. From equation (42) it is clear that the increase in the efficiency of capture (38) is directly related to the turbulent resistances of the system. Therefore, an increase in the collection efficiency can be achieved both by increasing the speed and by introducing turbulence devices into the design, a particular case of which is a fluidized packing. With the same particle trapping efficiency, the total energy costs in the second case are significantly lower. A comparative numerical calculation was carried out for the Ventura tube and apparatus with a fluidized packing. The comparison was based on the aerosol trapping efficiency determined in accordance with the data of [6] and the best experiments carried out on experimental and industrial PN apparatuses [7, 8]. Parameters for which the calculation was carried out: a) in a Ventura pipe $U_{c\rho} = 100 м/с$, $B = 0.23 кг.жидк./кг.$ gas, the ratio of the length of the neck to the diameter $l/d = 3$. b) In the device PN $U = 10 м/с$, $B = 0.33 кг.жидк./кг$ gas.

The ratio of the height of the working area to the diameter.

CONCLUSION

The total pressure loss in the working area of the PN apparatus is 430 Pa, Ventura tubes are 5000 Pa, 91% of all pressure losses in the PN apparatus are turbulent pressure losses for weighing the nozzle. In the Ventura tube, the share of such energy costs is 30%. Thus, in PN devices, a more complete use of energy is realized. The good trapping of poorly wetted aerosols in PN apparatuses noted by us [8] is obviously associated with intensive renewal of the phase contact surface, carried out with the participation of surface forces (processes of coalescence and crushing of drops, spreading of liquid on the walls and packed bodies with subsequent separation).

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In this regard, the optimal approach to the issue of trapping aerosols is to create structures with a rational organization of gas and liquid flows, characterized by a significant renewal rate of the phase contact surface and high efficiency use of gas flow energy.

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