Research of the process of crushing liquid in a swirl gas flow

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Abstract. Liquid spraying is a common process in the chemical, oil and gas industries. For its implementation, nozzles of various designs are used. The outflow of liquid from the nozzle leads to the fragmentation of the continuous jet into separate drops. This process depends on many factors, including the movement of the continuous phase in which spraying is carried out. This article discusses the relative motion of a liquid when it flows from a nozzle into a rotating gas flow and the conditions for re-crushing of liquid particles.

1. Introduction
Liquid atomization is a complex process that depends on many factors. The jet at the exit from the atomizer under the action of external and internal forces breaks up into separate drops, in the future it is possible to re-crush large drops into smaller ones.

External - aerodynamic forces include the interaction of the sprayed component with the medium into which it is injected. Their value depends on the density of the environment, the speed of the jet and the size of the liquid droplets. External forces also include the forces of interaction when the jets intersect or when the jet meets a solid wall.

Internal forces include molecular forces and turbulence. Turbulent pulsations arise in the flowing liquid stream, the intensity of which depends on the density, viscosity, pressure drop, and also on the design of the atomizer. An increase in the outflow rate contributes to an increase in the intensity of turbulent pulsations, which in turn improves the quality of liquid dispersion [1-6].

2. The physical basis of the process of crushing liquid droplets
Liquid crushing and the formation of droplets occurs as follows. During injection, a sheet is formed, which, under the action of external forces and turbulent pulsations, breaks down into particles of various shapes and sizes. Small particles, under the action of surface tension, take the shape of a ball and form drops, while large ones continue to disintegrate.

The scheme of the primary crushing of the jet into droplets due to the turbulent action can only serve as a simplified model of the liquid spraying process. And they propose a decay scheme based on the assumption that cavitation processes are the cause of the destruction of a single fluid flow into droplets.

The appearance of cavitation recesses in the liquid occurs when the pressures in the considered volume are equal and the saturated vapor of the liquid under the given conditions. In the injector nozzle, cavitation occurs due to an increase in the hydrodynamic head of the liquid, at which the hydrostatic head and, accordingly, the pressure decrease. An increase in the flow rate, which increases the hydrodynamic head, is achieved by a decrease in the flow area of the channel [7-11].
Caverns formed in the injector nozzle at the nozzle exit, where the pressure is usually close to atmospheric, disappear, destroying the integrity of the jet. The formation of cavitation recesses is periodic, with a frequency that depends on the flow rate. With an increase in the flow rate, cavitation bubbles are formed not only on the surface, but also inside the jet, and a vapor-liquid mixture comes out of the nozzle. The swirling movement of the flow also contributes to the intensification of cavitation in the entire section of the jet.

The maximum drop size that can exist in a plume is determined from the condition of equality of the surface tension force [4, 12-15]:

\[ F_{\text{surf}} = 2\pi \cdot r_d \cdot \sigma_l, \]  

(1)

and the forces of aerodynamic pressure:

\[ F_{\text{aer}} = \frac{\pi \cdot r_d^2 \cdot \rho_l \cdot u^2}{2}. \]  

(2)

Where is the maximum drop diameter:

\[ d_d = \frac{2 \cdot \sigma_l}{\zeta \cdot \rho_l \cdot u^2}. \]  

(3)

The mode of crushing a liquid droplet in a gas flow depends on the physical properties of the contacting media (surface tension of liquid - \( \sigma_l \), medium resistance coefficient - \( \zeta \)), the droplet diameter and the velocity of the gas blowing over it. It is difficult, and sometimes impossible, to influence the physical properties of gas and liquid under given technological conditions. The maximum droplet size is limited by the outflow rate, since large droplets formed at the initial stage, even with a small impact, are deformed and destroyed, resulting in smaller ones. Therefore, the main criterion that determines the mode of droplet crushing and dispersion of the liquid at the outlet from the nozzle as a whole is the difference in the velocities of the liquid droplet and the surrounding environment.

3. Liquid phase injection unit in vortex apparatuses

In industrial devices, liquid is injected into a moving medium, which makes it necessary to take this fact into account when designing and selecting nozzles. So, for example, in spray absorbers, when entering the apparatus, the liquid interacts with a swirling gas stream that enters through a tangential pipe located at the periphery of the mixing chamber. To increase the difference between the velocities of the liquid and the gas blowing over it, it is possible, using a swirling device located in the nozzle body, to impart a tangential component to the liquid velocity vector, and the swirling of the flow should be carried out in the direction opposite to the gas (figure 1).
Figure 1. Swirl-chamber of the absorber.

4. Change in the velocity difference during the movement of the dispersed phase in a swirling flow

Let us consider the change in the difference between the velocity vectors of a single drop and the swirling gas flow blowing over it when the liquid outflows at an angle to the radial-axial direction. To do this, consider the projections of the corresponding velocity vectors on a plane perpendicular to the axis of rotation [16].

The angular velocity of swirling of a continuous medium will depend on the design features of the gas supply device, its flow rate and other factors. We denote it by $\omega_g$, then the gas velocity at an arbitrary point:

$$V_{qi} = \omega_q \cdot R_i.$$  (4)

Without taking into account the friction forces, the liquid flowing out of the injector nozzle with an initial velocity $V_l$ will retain the magnitude and direction of the velocity vector when moving to the periphery of the mixing chamber.

We divide the initial speed of movement of the liquid droplets leaving the nozzle into axial, radial and tangential components. The magnitude of the velocity in the axial and radial directions is most influenced by the angle of deviation of the velocity vector from the axis of rotation; with an increase in this angle, the radial component increases and the axial component of the velocity vector decreases and vice versa. The tangential component appears when using various swirling devices in the nozzle body or nozzle. Swirling the flow allows you to increase the spray angle due to the appearance of centrifugal forces, as well as increase the difference in the velocity vectors when injecting a rotating gas into the flow (see figure 2).
Figure 2. Projections of the vectors of gas and liquid velocities on a plane perpendicular to the axis of rotation.

When changing the distance to the axis of the nozzle.

The axial component of the fluid velocity vector will be constant and equal to:

$$V_{ina} = V_i \cdot \cos \beta \cdot \cos \frac{\alpha}{2}. \quad (5)$$

The tangential component of the fluid velocity vector, at the point the distance, to the axis of rotation $R_i$:

$$V_{lt} = \frac{R_n \cdot \sin \beta'}{R_i} \cdot V'_l. \quad (6)$$

The radial component of the fluid velocity vector, at the point under consideration:

$$V_{rt} = V_i \cdot \sqrt{1 - \cos^2 \beta \cdot \cos^2 \frac{\alpha}{2}} \cdot \frac{R^2 - R_n^2 \cdot \sin^2 \beta'}{R_i^2}. \quad (7)$$

The vector of the difference between the velocities of a gas and a liquid, as well as the velocity vector of a single drop, can be divided into the same mutually perpendicular components axial, radial and tangential. Moreover, the first two of them will be numerically equal to the corresponding projections of the velocity vector of the liquid drop, and the tangential component is determined by the formula:

$$u_{li} = V_{li} + V_{qi} = V_i \cdot \frac{R_n \cdot \sin \beta'}{R_i} \cdot \sqrt{1 - \cos^2 \beta \cdot \cos^2 \frac{\alpha}{2}} + \omega_i R_i. \quad (8)$$

The total value of the velocity difference vector is:
\[ u = \sqrt{u_{\text{init}}^2 + u_{r_i}^2 + u_{r_i}^2} \quad (9) \]

After substitution of (5, 7, 8) in (9) and transformation, the dependence of the value of the vector of the difference in velocities at the outflow of liquid from the injector nozzle at an angle to the radiaxial direction on the distance to the axis of rotation was obtained:

\[ u = \sqrt{V_i^2 + \omega_i^2 \cdot R_i^2 + 2V_i \cdot \left(1 - \cos^2 \beta \cdot \cos^2 \frac{\alpha}{2} \right) \cdot R_i \cdot \sin \beta \cdot \omega_i} \quad (10) \]

In real conditions, the movement of the contacting phases is significantly influenced by resistance forces, under the influence of which the direction and magnitude of the velocity vectors change. In this article, we examined the radiaxial outflow of liquid from the injector nozzle, provided that the momentum of the gas is much greater than the momentum of the liquid, that is, provided that the movement of the gas changes insignificantly.

5. Conclusion

Based on the studies carried out, a method has been developed for calculating the process of crushing a drooping liquid in a swirling gas flow, which includes the following main stages:

1) Determination of the difference between the velocities of the liquid and the gas blowing over it at the outlet of the nozzle \((u_{\text{init}})\).

2) Depending on the physicochemical properties of the components and the initial speed difference, finding the maximum diameter of the resulting liquid droplets \((d_{\text{max}})\).

3) For the largest particles, determining the change in time and the largest value of the vector of the difference between the velocities of the dropping liquid and the gas flow blowing over it \((u=f(t); u_{\text{max}})\).

4) Re-finding the maximum size of the particle diameter of the dispersed phase depending on the largest difference in velocities \((d_{\text{max}})\).

After the calculations, it is possible to determine the specific surface area of the liquid phase and, accordingly, the contact area of the “liquid-gas” system to calculate the efficiency of mass exchanging processes.

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