Drop entrainment in two-phase non concurrent film flow

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Abstract. When the motion vectors of the media are collinear, well-known experimentally obtained empirical criteria are used to assess the conditions for the drop entrainment by the gas flow from the surface of a moving liquid film. However, blowing a liquid film at an angle with gas causes a tangential component in the film movement, which is an additional factor affecting its thickness and the velocity profile. The paper presents the correctness of the criterion of the conditions for the drop entrainment and the effect of the noncollinearity of the vectors of the media counterflow on the dynamics of a liquid film estimated from the results of numerical simulation.

1. Introduction

When designing power plants with the liquid film flow on the walls of the operating line, developers usually rely on well-known empirical correlations gained from the results of many experimental studies and industrial experience. In [1], on the basis of simple two-dimensional physical models, five mechanisms of drop entrainment by air flow from the surface of a liquid film were described, and a criterion for the emergence of this process including for the turbulent flow regime was formulated.

However, comparison with a wide range of experimental data showed the inconsistency of the latter among themselves and some inconsistency with analytical models of drop entrainment. Probably, the three-dimensional flow pattern, namely, the noncollinearity of the velocity vectors of the liquid film flow and the gas flow was one of the reasons for this inconsistency. A widely occurring example is the flow of a liquid film on the walls of a vortex gas separator (Fig. 1) where the washing of the film takes place under conditions of the tangential component of the gas velocity.

However, in current world standards [3-5] for separation devices in the gas industry, this feature of the film flow has not been taken into account. From the point of view of separation efficiency, the probability of a negative effect of drop entrainment is usually estimated in standards by the dynamic pressure head of a gas or the K-value parameter, where the velocity vector module is used as the determining parameter, but its direction with respect to the direction of gravity $g$ is not taken into account. This, in turn, often leads to an unjustified decrease in the estimated performance of the separator.

The present paper is the first of a series of works by the authors on the study of film fluid flows in vertical pipe channels and cylindrical chambers under the conditions of the tangential component of the gas velocity. The work is devoted to the conclusion of an addition to the analytical model [1] - a criterion for drop entrainment in the case when the flow of a liquid film is washed by a gas at an angle...
along the direction of the film flow. The assessment of the analytical criterion based on the numerical simulation results of a special case of washing a liquid film with a gas at an angle of 45 degrees was made. The relevance of this study is also due to the need to further create an experimental setup with the use of the experience gained in numerical simulation.

Figure 1. Left: the flow lines of the gas medium in the vortex separator according to the results of numerical simulation [2]; Right: Flow pattern in the Penn Flash Separator (Messplay Machinery Co).

2. Problem statement

According to [6], the liquid phase entrainment becomes possible when the resistance force $F_d$ from shear stresses at the interface becomes greater than the surface tension force $F_\sigma$.

$$F_d \geq F_\sigma. \quad (1)$$

When condition (1) is fulfilled, the wave crest on the liquid film loses its shape. Expressing forces in the relation (1) according to their physical meaning through the parameters of the problem statement, [1] proposed the following entrainment criterion

$$\frac{\rho_g V_r^2 h}{2} \geq \frac{C_5 \sigma}{C_d}, \quad (2)$$

where $\rho_g$ is gas density, $V_r$ is the relative velocity between the phases, $h$ is the height (amplitude) of the wave, $C_5$ is the interfacial shape coefficient, $C_d$ is the drag coefficient. If $\alpha$ is the angle between the directions of the film and gas, then relation (2) can be rewritten as

$$\frac{\rho_g (V_g + V_l \cos \alpha)^2 h}{2} \geq \frac{C_5 \sigma}{C_d}, \quad (3)$$

where $V_g$ is gas velocity vector module, $V_l$ is film velocity vector module.

The second criterion according to [1] is based on the relation between the wave height and the flow inside the wave crest, namely that the motion of the wave crest relative to the film can be expressed by the shear flow model (4), where by analogy with (3), the relative velocity decomposition is used.

$$\tau_i = C_i \mu \frac{V_g + V_l \cos \alpha}{h}, \quad (4)$$
where \( C_w \) is a function of viscous and surface forces, describing the effects of surface tension on the internal flow. In [1], it is proposed to express this parameter as a function of viscosity number \( N_\mu \):

\[
N_\mu = \left( \frac{\mu_f}{\rho_f \sigma \sqrt{g \Delta \rho}} \right)^{0.5},
\]

(5)

where \( g \) is gravity acceleration, \( \Delta \rho \) is the density difference between the liquid and gas phases.

On the other hand, the shear force at the interface can be expressed through the friction coefficient of the fluid

\[
\tau_i = f_i \rho_f \left( V_g + V_f \cos \alpha \right)^2, \quad (6)
\]

where \( f_i \) according to the experiments of [Hughmark]

\[
\sqrt{f_i} = 1.962 \ Re_f^{-1/3}, \quad (7)
\]

or gas

\[
\tau_i = f_{gi} \rho_f V_f^2, \quad (8)
\]

where \( f_{gi} \) according to [Wallis]

\[
f_{gi} = 0.005 \left( 1 + \frac{300 \delta}{D} \right), \quad (9)
\]

\( D \) is the hydraulic diameter of the channel, \( \delta \) is the thickness of the liquid film. In [1], after substituting relations (4)-(9) into (3) and estimating the dependence \( C_w(N_\mu) \) from the experimental data of other authors, the final criterion for the condition of the drop entrainment at \( N_\mu < 1/15 \) is derived:

\[
\frac{\mu_f \left( V_g + V_f \cos \alpha \right)}{\sigma} \geq \sqrt{1 + \frac{300 \delta}{D}} \left[ \frac{\mu_f}{\rho_f \sigma \sqrt{g \Delta \rho}} \right]^{0.5} \left( \frac{\rho_f}{\sigma} \right)^{0.8}. \quad (10)
\]

By analogy with the study [1], in order to reduce computational resources and simplify the technique of conducting future experiments, the present paper considers the case of an infinitely large diameter \( D \). Under these conditions, the large curvature of the surface allows us to assume that a film of liquid flows along a straight surface. In accordance with this assumption for a particular case of washing a film of water with an air under atmospheric conditions, relation (10) takes the form

\[
\left( V_g + V_f \cos \alpha \right) \geq 2.844. \quad (11)
\]

### 3. Computational fluid dynamics (CFD)

The geometrical model for numerical modeling (Fig. 2) in scale and scheme corresponded to the planned experimental setup. The liquid film flow is realized in a two-dimensional rectangular channel with a height of 3 mm, a width of 50 mm, and a length of 500 mm. The fluid flow rate was chosen so that the film thickness at the beginning of the air flow section \( \alpha \) was less than the height of the channel. The gas blowing section is located at an angle \( \alpha \) to the direction of the film flow and is located at a distance of about 230 mm from the inlet section of the flat channel. The cross section of the channel for air flow in the form of a rectangular trapezoid with an angle of 45 degrees at the lower
base was chosen from considerations of neutralizing possible disturbances when the interphase boundary hits a hard surface.

![Image](image.png)

**Figure 2.** Scheme of the calculated area.

Numerical simulation was carried out in the Ansys Fluent 19.2 package. The flow of the two-phase mixture was described by the unsteady Reynolds-averaged Navier-Stokes equations (URANS) with the closure of the k-ω SST isotropic turbulence model. Solver parameters were chosen based on the general practice of solving such problems: pressure-velocity coupling - coupled scheme, spatial discretization: volume fraction - QUICK, momentum, turbulent kinetic energy and turbulent dissipation rate - third-order MUSCL. The Eulerian multiphase model is used in Fluent simulations. The Eulerian model is the most complex multiphase model used in Fluent. It solves a set of momentum equations for each phase.

The computational grid with hexahedral cells was generated in the geometric area. Subsequently, during the calculations, the adjustment of the nodes on the model walls and in the interphase boundary area was carried out. The final value of $y^+$ in the near-wall cells did not exceed 1.

When conducting experiments before the inlet section of the channel, it is planned to install a smooth inlet, which will give the required uniform velocity profile. Therefore, as a boundary condition in the gas inlet section (Fig. 2), a constant velocity value was used. In the output sections, a constant static pressure equal to atmospheric 0 Pa (gauge) was fixed.

4. Results

For the analysis of the prerequisites for the drop entrainment, the shape of the interfacial surface at different air flow rates can be considered in Figures 3 and 4. The air flow at a velocity of 1 m/s has a stabilizing effect on the surface of the film, aligning its surface. At a velocity of 3 m/s and more, visible waves appear on the surface. In addition to the appearance of waves at the outer edge of the film, the air flow also affects the flow of the liquid inside the film. The design of our setup prevents the flow direction of the film from changing; therefore, under the action of a dynamic head, the film thickness in the cross section begins to depend on the air flow rate, which leads to a strong non-uniformity of the film velocity both in height and in channel width. Considering the above-mentioned waves on the film surface, this will all lead to one of the mechanisms for the occurrence the drop entrainment described in [1]. The obtained critical value of the air flow rate on the order of 3 m/s agrees well with the analytical criterion (11).
Figure 3. Interphase boundary in the area of a liquid film flowing by air at different velocities. The arrows indicate the direction of the phase flow.

Figure 4. The air velocity fields in the central section of the gas path, the black colour indicates the liquid phase. The section is chosen in such a way that the air flows from left to right, the flow of liquid film in the direction of the X axis.
Conclusion

The results of the study showed that the flow of air to the flow of a liquid film at an angle of 45 degrees causes similar conditions for the occurrence of drop entrainment as in the case of parallel blowing. The nonuniformity of the shape of the interface, namely the appearance of waves, occurs when the dynamic pressure of the gas flow is of the order of 6 Pa. The noncollinearity of the motion vectors of the media leads to a change in the thickness of the liquid film in cross section, which contributes to the appearance of the tangential component of the fluid motion. However, relation (11) does not take into account this phenomenon. On the contrary, according to (11), with an increase in the angle between the directions of motion of the media, their relative velocity can be increased, which is probably not correct. Thus, relation (11) can be used as a criterion, but in order to formulate a criterion that is correct from the point of view of continuum mechanics, further experimental and numerical studies of this problem are needed.

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