DEPOSITION OF LIQUID FILMS FROM NEAR-WALL SPRAY JETS IN A CYLINDRICAL CHANNEL

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Abstract

Formation of liquid films from the near-wall gas-drop jets in a vertical cylindrical channel was experimentally studied at variations in velocity of accompanying gas flow. Distributions of the local film thickness and flow rate of deposited liquid at different distances from the inlet to the test section were obtained. The instantaneous thickness of a liquid film was measured by a capacitance probe. The precipitation character was compared with the known empirical dependencies obtained for the turbulent gas-drop flows at hydrodynamically stable region of the tubes.

Introduction

Near-wall spray jets offer a very promising tool for protecting surfaces against high-temperature gas flows. In recent years, extensive experimental and theoretical studies [1-3] of the shielding efficiency of such jets have been carried out. It should be noted however that available theoretical models are too simplified: they do not take into account all factors that affect the protective properties of near-wall gas-droplet flows and their dynamics. In particular, these theories ignore possible liquid precipitation onto channel walls that gives rise to a flowing liquid film that may induce substantial changes in the estimated cooling efficiency. Besides, precipitation of liquid droplets from highly turbulent flows onto channel walls is often met in practice, thus being a problem of considerable significance.

Experimental setup

The studies were carried out in the vertical cylindrical channel with the diameter D=100 mm and length l=640 mm. A ring slot of the 5-mm height was located at the channel inlet. Inside this slot, there were 0.5-mm nozzles for liquid spreading situated uniformly over the perimeter. The channel was assembled from separate sections, one of that was equipped with a probe for liquid film thickness measurements. This allowed us to measure dynamic characteristics of the film and amount of precipitated liquid at various distances from the inlet with the help of channel length alterations. The co-axial flow consisting of the central single-phase gas flow (the main flow) and gas-liquid near-wall jet (the secondary flow) was fed into the channel. To observe the film flow pattern and register the point of film detachment from the wall, channel walls were made from a transparent material. The mass concentration of liquid in the near-wall jet was 1.6; 2.6; 5; 10% from the mass of injected gas. Distilled water was used as the liquid phase. Liquid concentration in the near-wall jet corresponded to experiments, which studied the cooling efficiency of gas-liquid screens [1, 2]. The secondary flow velocity at the channel inlet was not changed, and made up ~25 m/s. The main flow velocity was 0; 16; 29; 39 m/s, and this corresponded to the range of Reynolds numbers of the gas flow calculated by the main flow velocity and channel diameter Re_D= 0-2.6*10^5. Thus, the effect of injection parameter $m=\rho_S V_S/\rho_0 V_0$ on the precipitation process was studied. In this formula, ρ_S, ρ_0 are the gas densities in the near-wall jet and the main flow, V_S, V_0 are the corresponding velocities. Temperatures of the main and secondary flows were not changed and they equaled to ~20^{o}C.

The system of measurements

To determine the wave characteristics of a liquid film, the capacitance method was used for local thickness measurement [4]. The main advantages of the capacitance method are the following: possibility to measure the film thickness without distortion of the flow pattern, quasi-continuity of measurements, high sensitivity and relative simplicity of equipment. The capacitance probe is made in accordance with the heterodyne scheme and includes two high-frequency generators, mounted into a primary converter. The drive circuit of measuring generator includes the co-axial capacitance probe, mounted in the measurement section on the working surface of the channel. The precipitated liquid film acts on the sensitive area of the probe and changes the frequency of measuring generator. The outlet signal of the primary converter is the difference signal from the generator, whose alteration is proportional to a change in the film thickness above the probe ($\Delta F(t) \equiv \delta$). To convert functions of frequency vs. time $\Delta F(t)$ into the liquid film thickness, we used dependencies $\delta = \Delta F(t)$ obtained experimentally with the help of a special device.

In experiments, we measured the amount of liquid precipitated from the formed liquid film. It was collected through the ring slot in the channel wall into a special collector. The liquid was supplied into a volumetric test-tube. Simultaneously, the liquid film thickness was measured by the capacitance probe. Thickness was measured at the distances of 67, 170, 267, 370, 467, and 570 mm from the channel inlet. The liquid was collected at the distances of 80, 240, 280, 440, 480, and 640 mm.

Temperatures of supplied liquid and the main and secondary air flows were measured by the Chromel-Copel thermocouples of the 0.2-mm diameter situated at the inlet of the working section.

Distribution of the liquid film thickness

At the first stage we measured the thickness of precipitated film, when only the near-wall gas-liquid jet was fed. Then, the main air flow was added. The total superficial velocity of the gas flow calculated over the channel cross-section was 4.78 m/s for the near-wall jet, and 16, 29, 37 m/s in the general case. At the joint flow of high-enthalpy gas and protective near-wall jets, the injection parameter *m* (see above) is the important characteristic of flow dynamics. At that, the injection parameter was 1.8; 1; 0.6, correspondingly. Alteration in the liquid film thickness averaged by time is shown in Fig.1 depending on droplet concentration in the jet and injection parameter.

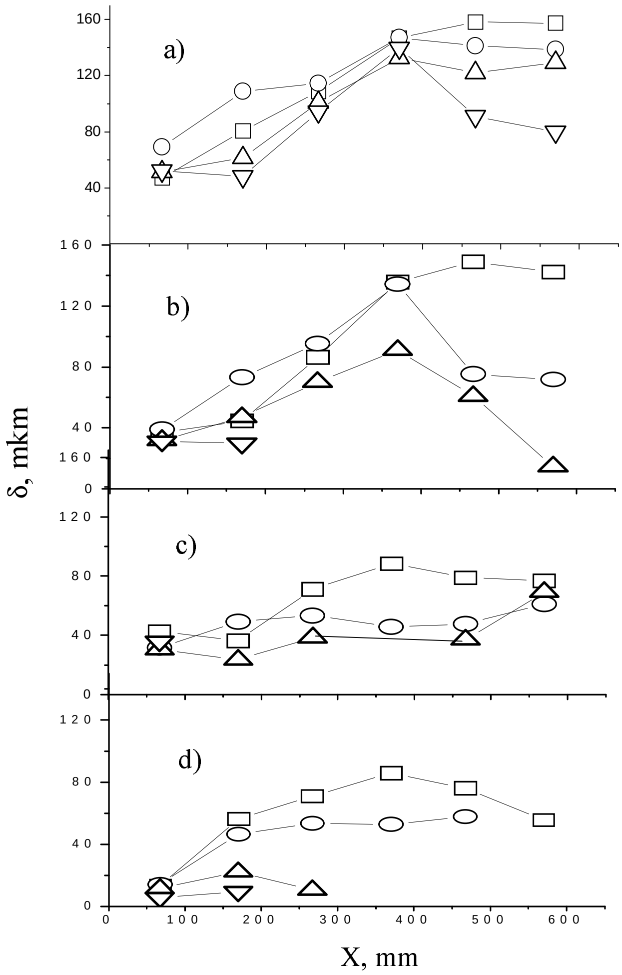

Figure1. Average thickness of the liquid film deposited from near-wall gas-liquid flow: a- V_g=4,78 м/s; b- V_g=16 м/s, *m*=1,8; c- V_g=29 м/s, *m*=1; d- V_g=37 м/s, *m*=0,6; □ - K_L=10%; ○ - K_L=5%; △- K_L=2,6%; ▽ - K_L=1,6%.

A change in film thickness at supply of the near-wall gas-drop jet with different liquid concentrations is presented in Fig. 1a. It is obvious from the figure that from the distance of ~400 mm, film thickness changes slightly, and it equals approximately to 130-150 μm. An exception is the regime with liquid concentration of 1.6%, when the film thickness decreases downward the flow.

Figures 1b-d demonstrate a change in the average film thickness under the effect of the flow velocity. It should be noted that measurements were carried out only for the case of a continuous stable film over the whole channel perimeter. Thus, an absence of data indicates that there was no continuous film on the channel walls, but perhaps, liquid was presented in the form of droplets and small rivulets.

An increase in the flow velocity provides reduction of the average film thickness. At the flow velocity of 37 m/s (*m*=0.6 Fig.1d), the film is continuous only at liquid concentration of 10% in the near-wall jet. At liquid concentration of 2.6%, the stable film was observed only near the working section inlet, and at concentration of 1.6%, there was no film at all.

Distribution of the rate of droplet precipitation

The precipitation rate was determined by the liquid flow rate measured in the given cross-section by the following formula:

$$J_W = \frac{Q}{\pi Dx} \tag{1}$$

Where $\boldsymbol{Q}$ is the liquid flow rate measured in the given cross-section; $\boldsymbol{D}$ is the channel diameter; $\boldsymbol{x}$ is a distance to the considered cross-section. Finally, the value of J_W is the average mass velocity of the liquid phase, normal to the surface.

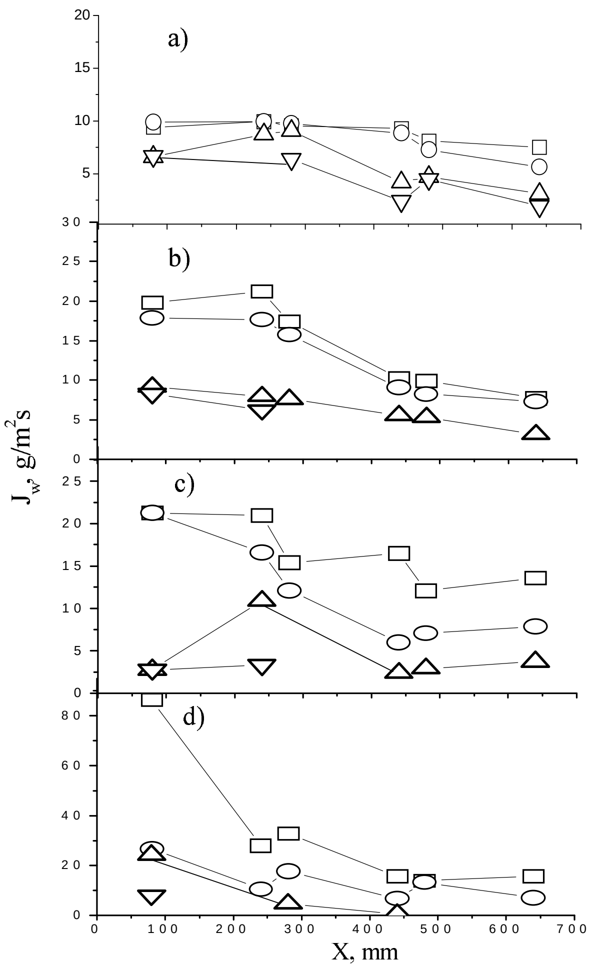

Figure 2. Distribution of precipitation rate along the vertical cylindrical: a- V_g=4,78 m/s; б- V_r=16 m/s, m=1,8; c- V_g=29 m/s, m=1; d- V_g=37 m/s, m=0,6; □-K_L=10%;○ - K_L=5%;△ - K_L=2,6%; ▽- K_L=1,6%.

Distribution of precipitation rate along the vertical cylindrical channel is shown in Fig. 2. The flow rate was measured almost in the same cross-sections as the liquid film thickness. Data in Fig. 2a corresponds to the regime with supply of the gas-drop jet only, and Figs. 2b-d demonstrate the effect of the main flow velocity on the precipitation process.

According to the above results, an increase in the main flow velocity provides intensive precipitation of liquid, especially for the inlet cross-sections. With a decrease in concentration of liquid in the near-wall jet, the precipitation rate also decreases. Moreover, with a rise in the flow velocity, more intensive data scattering is observed depending on concentration.

Instantaneous film thickness and its frequency spectrum

Due to results shown in Fig. 2, we can estimate the Reynolds number for the liquid film. According to analysis, its maximal value is $Re_L=V_L\delta/\nu_L \approx 30$, what corresponds to the wave flow regime. The wave flow regime can be easily proved by data shown in Fig. 3. The character of film thickness alteration in time (Fig. 3a) and frequency pulsation spectrum (Fig. 3b) are shown below. It is necessary to note that maximum in distribution of pulsation density is located in the area of low frequencies (F< 50Hz). At that, the Reynolds number of the film for data from Fig. 3 was $Re_L \approx 3$, and this corresponds to the laminar regime of gravitation film draining. Perhaps, droplet precipitation and the effect of accompanying flow provide earlier transition to the wave flow regime.

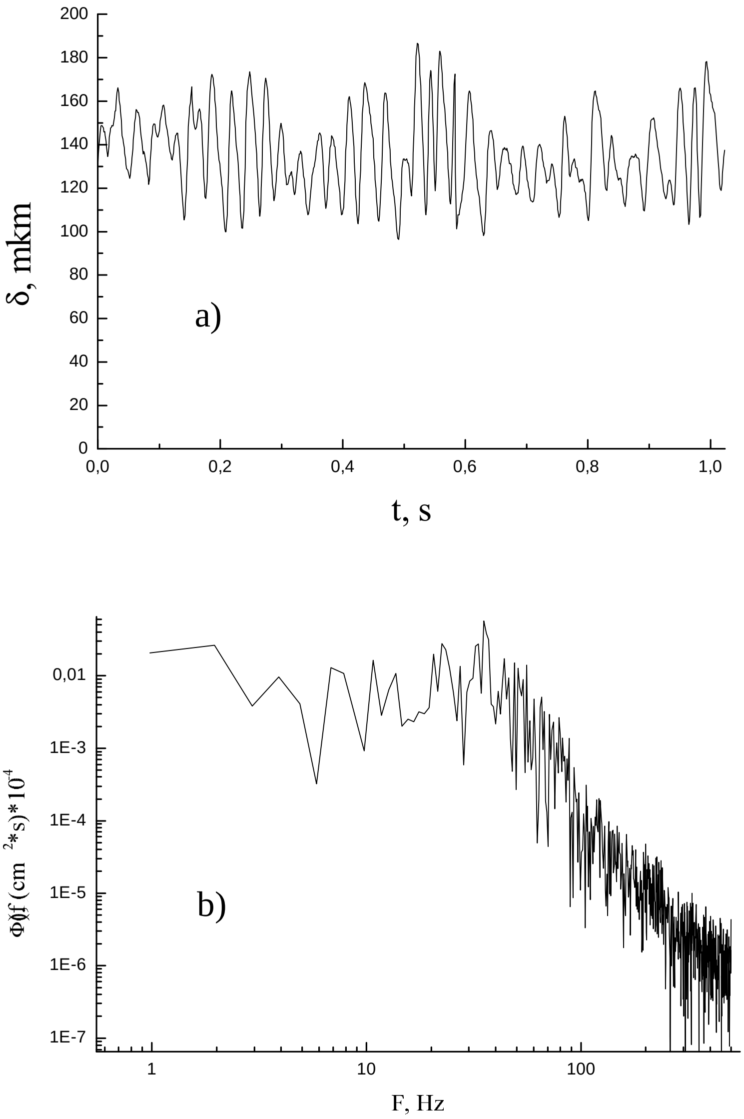

Figure 3. The character of film thickness alteration in time (a) and frequency pulsation spectrum (b).

Generalization of experimental results

Liquid precipitation on the channel walls from the two-phase gas-drop flows occurs in many technical devices, and by now many theoretical and experimental data was accumulated in this field [5,6]. However, most works deal with stabilized gas-drop flows, which occupy the whole cross-section of the channel.

There are no results for the initial section and in the presence of a central flow, free from particles. Nevertheless, it is interesting to compare experimental results on liquid precipitation with published empirical dependencies for particle precipitation at stabilized two-phase flows in vertical tubes [6].

Comparison results were shown in the form of dependency between dimensionless precipitation rate k_D^+ and dimensionless time of particle relaxation τ^+, determined by the following formulas:

$$\boldsymbol{k}_{\boldsymbol{D}}^{+} = \frac{\boldsymbol{J}_{\boldsymbol{W}}}{\boldsymbol{v}^{*}},\qquad \tau^{+} = \frac{\boldsymbol{d}^{2}\boldsymbol{v}^{*}\rho_{\boldsymbol{g}}\rho_{\boldsymbol{L}}}{18\mu_{\boldsymbol{g}}^{2}}. \tag{2}$$

Here $\boldsymbol{v}^{*}=\sqrt{\tau_W/\rho}$ is the dynamic shear stress rate; $\boldsymbol{d}$ is the diameter of liquid particles; ρ_g ,ρ_L are densities of gas and liquid; μ_g is the dynamic gas viscosity. The dynamic shear stress rate was calculated from integral relationships for the boundary layer [7]. According to [8], the particle diameter was assumed to be equal to 200 μm.

Comparison of experimental results with empirical dependencies from [6] is presented in Fig. 4. Despite data scattering, we can say that, in general, dependencies for the stabilized gas-drop flow satisfactorily describe the process of liquid precipitation from the near-wall gas-drop jets.

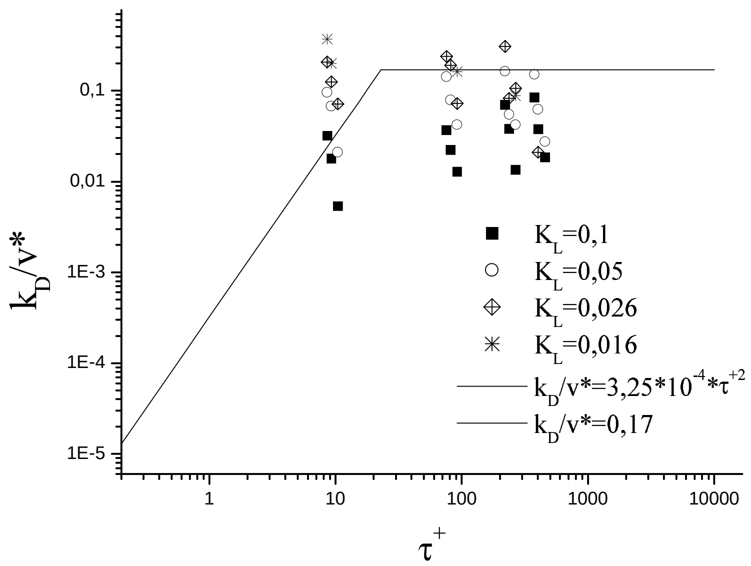

Figure 4. Generalization of experimental results and comparison with empirical dependencies for annular two-phase flows in vertical ducts.

Observed data scattering can be explained by discrepancy in model presentations and conditions of the studied process. First of all, it is caused by the rivulet character of the gas-drop flow near the wall and significant decrease in liquid concentration in the jet due to its precipitation on the surface. The model [6] does not consider these factors.

Conclusions

1. Liquid precipitation from the near-wall gas-drop jets with formation of a liquid film was studied experimentally.
2. The effect of central accompanying gas flow decreases the average film thickness, and at low liquid concentrations it provides complete disappearance of a liquid film.
3. The rate of liquid precipitation increases with a rise in the main flow velocity.
4. The film has the wave character, and the wave regime starts earlier than that at the free fall.

5. It is shown that liquid precipitation from the near-wall gas-drop jets at the initial section can be satisfactorily described by empirical dependencies for the stabilized gas-drop flow in tubes.

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Nomenclature

D	tube diameter
l	length
F	frequency
m	injection parameter
V	velosity
δ	film thickness
ρ	density
μ	dynamic viscosity

Subscripts

g	gas
L	liquid
0	main flow
s	secondary flow

References

[1] Terekhov V.I., Pakhomov M.A., Sharov K.A., Shishkin N.E. “Simulation and experimental study of heat screen efficiency with injection of a gas-droplet jet,’’ *Forth International Conference on Multiphase Flow “ISMF-2001”*. New Orleans, LA, U.S.A. CD-ROM. Paper No. 702. 11 p.

[2] V.I.Terekhov, K.A.Sharov, N.E.Shishkin, and V.P.Lebedev, “Transpiration Cooling of Surface by Near-Wall Two-Phase Co-Current Jet,” *International Symposium on the Phisics of Heat Transfer in Boiling and Condensation, Moscow,* pp.387-390, 1997.

[3] V.M.Repukhov and A.I.Neduzhko, “Thermal Protection of Wall Through Blowing a Two-Phase Gas/Liquid Coolant,” *Dokl. Akad. Nauk Ukr. SSR*, ser.A., N8, (1988).

[4] Кротов С. В., Назаров А. Д., Павленко А.Н., Печеркин Н.И., Серов А.Ф., Чехович В.Ю. “Емкостной измеритель локальной толщины пленки жидкости.” /Приборы и техника эксперимента,1997, №1, сс. 149-152.

[5] G.F. Hewitt, N.S. Hall-Taylor, *Annular Two-Phase Flow*, Chemical Engineering Division, Pergamon Press, Oxford, 1970.

[6] McCoy D.D. and Hanratty T.J. ”Rate of deposition of droplets in annular two-phase flow”, *Int. J. Multiphase Flow*. 3, 319-331, (1977).

[7] S.S. Kutateladze, A.I.Leont’ev, *Heat Transfer, Mass Transfer and Friction in Turbulent Boundary Layer*, Hemisphere, New York, (1990).

[8] E.P.Volchkov, V.P.Lebedev, V.I.Terekhov, and N.E.Shishkin, “An experimental study of the effect of the concentration of finely-dispersed liquid drops on the effectiveness of gas screen”, *Sib. Phys.-Techn. Zhurn*. 1, 28-32, (1992).