

DETERMINATION OF THE CHARACTERISTICS OF DROPLETS GENERATED IN A JET PRINTER

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The process of formation of a droplet in a liquid-filled cavity that is a printing element of a jet printer is studied on the basis of an approach developed earlier.

Introduction. The first report on the principles of jet-printer operation was published in 1985 [1]. Information is available in the literature only about experimental studies of the process of generation of droplets in a jet printer conducted at Munich Technical University in 1987-1993 [2-6].

An approximate theoretical model of the periodic process of liquid boiling in generation of a droplet was developed by Professor D. A. Labuntsov in 1989 and was expounded in brief in [7, 8]. The present study, based on this model, is devoted to determination of the characteristics of droplets generated in a jet printer.

A printing element of a jet printer is a cavity filled with a liquid with a thin square metal plate positioned at the bottom (Fig. 1). In [7, 8], the complete cycle of the process of formation of a droplet is considered as a succession of stages.

The first stage is heating of the plate (due to supply of electric power) from the ambient temperature T_∞ to the temperature of limiting superheating T_* [9] in a time $\tau_1 \sim (4-6) \cdot 10^{-6}$ sec. The termination of plate heating is taken as the end of this stage. We note that setting the required value of τ_1 in the experiments of [2-6] was a labor-consuming problem: a slight increase in the duration of heating led to overburning of the plate, and a reduction in the duration led to deterioration of the quality of printing.

When the plate is heated to the temperature T_* , a layer of vapor nuclei, which then coalesce into a solid vapor film (the second stage), is formed on the plate surface. The time of the second stage, due to its smallness, could not be measured in the experiments and, according to the estimates of [7, 8], is $\tau_2 \sim 10^{-8}$ sec.

During the third stage of the process of duration $\tau_3 \sim (1-2) \cdot 10^{-5}$ sec, the vapor film expands due to excess pressure under conditions of an adiabatic wall. The vapor volume plays the role of a "piston" expelling the liquid column from the outlet of the cavity (Fig. 1). As the vapor piston expands, the pressure in it decreases, thus leading to retardation of the motion of the liquid column. The maximum value of the height of the vapor piston δ_{\max} , which is equal to the height of the cylindrical column of the liquid, which transforms to a spherical droplet after separation from the outlet of the printing cell (nozzle), is taken as the boundary between the third and fourth phases.

During the fourth stage of the process, the vapor bubble collapses in the subcooled liquid surrounding it. The duration of this stage, $\tau_4 \sim (2-3) \cdot 10^{-5}$ sec, was evaluated in [7] based on the analysis in [10, 11] of the dynamics of a bubble at the center of symmetry of an infinite tube filled with an ideal liquid.

The cycle of droplet generation culminates in the fifth, longest stage $\tau_5 \sim (4-6) \cdot 10^{-4}$ sec, during which the cell is filled with the liquid and oscillations of the phase interface in the nozzle cross section attenuate.

Thus, droplet generation in a jet printer occurs during reciprocating motion of the "vapor piston" in the volume of subcooled liquid filling the printing cell. In turn, the parameters of this motion are determined by the characteristics of the periodic process of liquid boiling in the cell (the heat released in the metal plate, duration of plate heating, specific features of explosive boiling, liquid subcooling, etc.).

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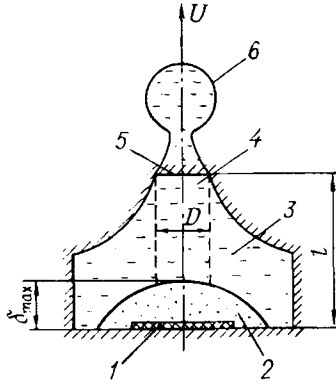


Fig. 1. Schematic diagram of generation of a droplet in a jet printer: 1) heating plate; 2) vapor piston; 3) printing cell (cavity filled with liquid); 4) column of liquid expelled from the nozzle; 5) outlet of the printing cell (nozzle); 6) liquid droplet.

Adiabatic Expansion of the Vapor Piston. To evaluate the field of temperatures in the near-wall layer of the liquid, we use the method of a thermal layer [12]. By the time of plate heating to the temperature T_* , a liquid layer of thickness $\sqrt{6\alpha\tau_1}$ inside which the temperature varies within the limits $T_\infty \leq T \leq T_*$ is able to form on the plate surface. Then, the thickness of the liquid layer superheated above the saturation temperature ($T_s \leq T \leq T_*$) is

$$\delta_0 = \sqrt{6\alpha\tau_1} \left(1 - \left(\frac{T_s - T_\infty}{T_* - T_\infty} \right)^{1/2} \right).$$

Since in explosive boiling the wall surface is occupied by vapor nuclei and the nuclei coalesce into a vapor film virtually instantly, its initial thickness can be taken equal to δ_0 . The difference in pressure between the film and the liquid in the cavity of the generator is approximately equal to the Laplace pressure drop through the surface of a vapor nucleus of diameter δ_0 .

We write the balance of momenta for the column of an ideal liquid in dimensionless form:

$$y [k(1-y)y'' + 1] = A. \quad (1)$$

The initial conditions for (1) are

$$t=0: y=y_0; y'=0.$$

Eliminating the time from Eq. (1), we obtain the solution in the form

$$y' = \left[\frac{2}{k} \ln \left(\frac{y}{y_0} \right)^A \left(\frac{1-y}{1-y_0} \right) \right]^{1/2}. \quad (2)$$

It follows from (2) that the dependence of the velocity of expansion of the vapor piston on its thickness has a maximum with the coordinates

$$y_{\max} = A; y'_{\max} = \left(\frac{2A}{k} \ln \frac{A}{y_0} \right)^{1/2}.$$

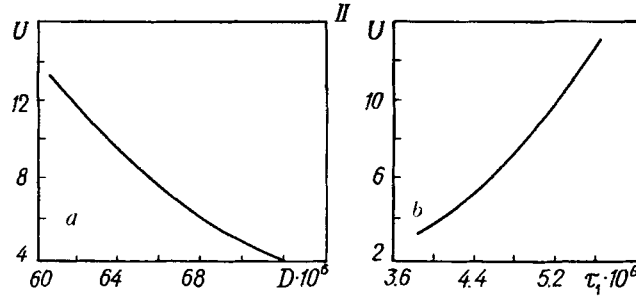


Fig. 2. Dependence of the length of the liquid column expelled from the nozzle (I) and the velocity of the generated liquid droplet (II) on the nozzle diameter (a) and the time of plate heating (b). δ_{\max} , D , m; U , m/sec; τ_1 , sec.

Nonadiabatic Expansion of the Vapor Piston. Calculations by relation (2) show that as the vapor piston expands, the pressure in it decreases sharply; this must lead to a noticeable decrease in the temperature of the saturated vapor.

Since the liquid layer heated during the first stage of the process is adjacent to the phase interface, this layer will play the role of a heat source with respect to both the external liquid volume and the vapor. Contact of the cold saturated vapor with the superheated layer of the liquid will cause a heat flux to the phase interface, due to which the liquid will evaporate into the vapor piston.

Account for the heat source at the upper boundary of the vapor piston leads to replacement of Eq. (2) written in an adiabatic approximation by the following system of equations:

$$y(1-y)y''' + (1-2y)y'' + ky' = f(t)\varphi(y''), \quad (3)$$

$$f(t) = B \frac{\exp(-\sqrt{t})}{\sqrt{t_1 + t}}, \quad (4)$$

$$\varphi(y'') = \left[\left(\frac{T_*}{T_* - T_\infty} \right) \frac{\ln \left(\frac{P_*}{P_\infty} \right)}{\ln(1+y'')} - 1 \right]^{-2}. \quad (5)$$

The initial conditions for Eq. (3) are

$$t=0: y=y_0; y'=0; y'' = \frac{1}{k} \frac{P_*}{P_\infty}. \quad (6)$$

Relation (4) is obtained from simulation of the heat source at the upper boundary of the vapor piston by the Pohlhausen method [12]. An approximation of the saturation line under conditions of nonstationarity, the validity of which is shown in [13], is used in relation (5). The system of equations (3)-(6) was solved numerically for the following values of the parameters: $l = 1.2 \cdot 10^{-4}$ m; $D = (6-8) \cdot 10^{-5}$ m; $\tau_1 = (4-6) \cdot 10^{-6}$ sec; $k = 0.32$; $T_\infty = 373$ K; $T_* = 586$ K; $P_\infty = 1$ bar; $P_* = 1$ bar.

Calculated dependences of the length of the liquid column expelled from the nozzle and the velocity of the droplet generated in the jet printer on the time of plate heating and the nozzle diameter are presented in Fig. 2.

In closing we assess the validity of the assumptions made in the analysis.

With acceleration of the vapor piston, the liquid column forced out of the nozzle will "accelerate" (up to the maximum velocity of vapor-volume expansion). Once the maximum of the velocity of the vapor piston has been passed, the liquid flow rate through the nozzle begins to decrease monotonically, whereas the liquid volume that has already been discharged from the nozzle will actually represent a free jet moving by inertia. Under the effect of capillary forces the head part of the jet will tend to acquire a spherical shape. With time the tail part of the jet will become thinner – up to the point of its separation from the nozzle. Thus, in the printing element of the jet printer reciprocating motion of the vapor piston takes place, resulting in formation of a liquid droplet beyond the nozzle. Physically it is obvious that the velocity of "escape" of the formed droplet from the nozzle will approach the maximum velocity of the liquid jet. Therefore, the velocity of the generated droplet U can be taken approximately equal to the maximum velocity of motion of the vapor piston.

In the foregoing, we assumed implicitly that the time of droplet generation is much smaller than the characteristic times after which the influence of the effects of viscosity ($\tau_{\text{vis}} \sim D^2/\nu$) and capillarity ($\tau_{\text{cap}} \sim (\rho D^3/\sigma)^{1/2}$) begins to manifest itself. As estimates show, for the considered conditions we have $\tau_{\text{vis}} \sim (10^{-3}-10^{-2})$ sec, $\tau_{\text{cap}} \sim (10^{-4}-10^{-3})$ sec. Comparison with the longest – fifth – stage of the process of droplet generation gives $\tau_5 \ll \tau_{\text{vis}}$, $\tau_5 \sim \tau_{\text{cap}}$. Hence it follows that viscous effects can be neglected in calculations, whereas capillary effects can exert a pronounced influence on the process of droplet formation (especially in the stage of its separation from the nozzle). This conclusion is indirectly confirmed by experimental data of [6], where appreciable fluctuations of the size of the droplet in the pre-separation stage of the process were observed. The indicated fact hinders comparison of the theoretical results obtained in the present paper with experimental data of [2-6], which, in addition, are not systematic.

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NOTATION

τ , time; δ , thickness of the vapor piston; D , diameter of the outlet of the cavity; T , absolute temperature; P , pressure of the saturated vapor; ν , a , λ , ρ , c , kinematic viscosity, thermal diffusivity, thermal conductivity, density, and specific heat capacity of the liquid, respectively; l , longitudinal size of the cavity; k , ratio of the area of the outlet of the cavity to the area of the plate; σ , surface tension; $t = \sqrt{P_\infty/\rho} \tau/l$, dimensionless

time; $y = \delta/l$, dimensionless thickness of the vapor piston; $A = \frac{\delta_0 P_*}{l P_\infty}$, $B = 0.03 \frac{T_\infty \lambda^{1/2} c^{1/2} \rho^{3/4}}{l^{1/2} P_\infty^{5/4}}$, dimensionless

parameters; $y' = dy/dt$; $y'' = d^2y/dt^2$; $y''' = d^3y/dt^3$. Subscripts and superscripts: prime, derivative with respect to time; 0, initial value; s, saturation; ∞ , ambient medium; *, limiting superheating; max, maximum value; cap, capillary; vis, viscous.

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