Journal of Engineering Physics and Thermophysics, Vol. 71, No. 2, 1998

BOILING OF LIQUID IN THE CELL OF A JET PRINTER

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UDC 536.423.1

An approximate calculation of the main parameters of boiling of a liquid in the cell of a jet printer – the ejection velocity of a liquid drop and the limiting permissible (critical) heat flow density supplied to the thermoresistor – is carried out.

The physical principle of operation of the printing device of a jet printer consists in the formation of a vapor film in a closed cavity (cell) filled with a liquid, due to the explosion boiling process induced by pulsed heat release in the heater (thermoresistor) (Fig. 1). Comprehensive experimental investigations of boiling of a liquid in the cell of a jet printer have been carried out at Technische Universität München under the supervision of Prof. J. Heinzl and published in the series of papers [1-4]. In experiments [1-4], the following parameters of the process were varied: the cell length l_0, heat-flux density supplied to the thermoresistor q, and the duration of the heat pulse t_r (Fig. 1). The objective of investigations [1-4] was to optimize the operation of the printing device of the jet printer from the viewpoint of its operating characteristics (increasing the operation frequency, decreasing energy consumption, and improving the quality of printing).

According to [1-4], the single cycle of the boiling process includes five provisional stages. During the first stage, nonstationary heating of the thermoresistor to the temperature T_* takes place, at which boiling of the adjacent layer of the liquid takes place. The boiling temperature was varied within the range $T_* = 240-400^{\circ}C$ and thus could be both lower and higher than the limiting thermodynamic temperature equal to $\approx 300^{\circ}C$ at atmospheric pressure [5]. Then the electric-power supply to the thermoresistor was terminated. The duration of the first stage t_r depended on the density of the heat flux at the thermoresistor and varied from 1.2 μsec (at $q = 2360$ MW/m^2) to 115 μsec (at $q = 136$ MW/m^2) (see Table 1). At the second stage of the process, explosion boiling of the liquid at the thermoresistor, the growth of vapor bubbles, and their coalescence resulting in the formation of a continuous vapor film on the heating surface take place. The duration of the second stage comprises fractions of a microsecond; thus it has been considered as instantaneous. According to [6], in the case of pulsed heat release with duration t_r, explosion boiling takes place whose characteristic scale equals the length of the heat wave $l_t \sim \sqrt{at_r}$, with a being the thermal diffusivity of the liquid. At the third stage of the process, further growth of the vapor volume takes place, with the shape of the volume approaching that of the truncated sphere expanding toward the exit from the cell and pushing a liquid drop out though the exit opening (Fig. 1). At the fourth stage, condensation of the vapor cavity with the subsequent emergence of vibrations of the liquid level at the exit from the cell took place. Finally, in the course of the fifth stage these vibrations decayed, and the cycle was repeated again. Each of the last three stages lasted for several tens of microseconds.

In what follows, we present an approximate calculation of the main parameters of boiling of the liquid in the cell of a jet printer: the ejection velocity of a liquid drop U and the limiting permissible (critical) density of the heat flux q_* supplied to the thermoresistor.

Inasmuch as the overheat of the boundary layer of the liquid (ink with thermophysical properties close to those of water) is about 200°C, the corresponding Jacob numbers (for atmospheric pressure conditions realized in the cell) will be rather high: $\mathrm{Ja} \equiv \rho' c_p \Delta T / r\rho'' \geq 10^3$. According to [7, 8], in this case the limiting scheme of vapor-bubble growth must take place. The scheme is characterized by the fact that the main share of heat expended

Moscow Power Engineering Institute, Moscow, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 71, No. 2, pp. 218-221, March-April, 1998. Original article submitted March 14, 1996.

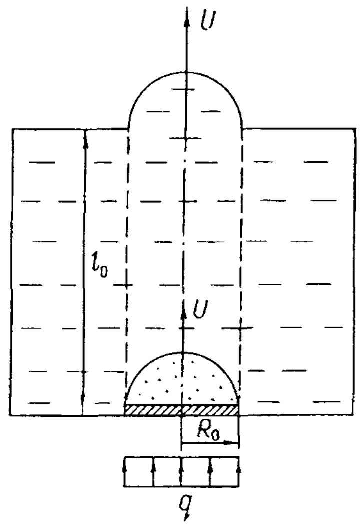


Fig. 1. Diagram of drop ejection out of the exit opening of a jet-printer cell.

TABLE 1. Parameters of the Printing Device of a Jet Printer Relevant to Experiments [4]

T_*, °C	q, MW/m^2	t_r, μsec
240	136	115
260	270	14.0
285	540	5.1
325	1081	2.4
360	1620	1.6
400	2360	1.2

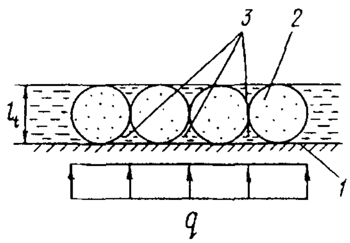
for evaporation of the liquid into the bubble is removed toward the bulk around the bubble, and the heat removal from the wall can be neglected to a first approximation.

For definiteness, we consider the problem of the growth of a hemispherical vapor bubble on the heating surface at the bottom of the filled cell of a jet printer. In this case, we arrive at what appears to be half of the symmetrical problem of the growth of a hemispherical bubble in the center of a pipe considered in [8]. It is natural to assume that the velocity U of a drop being ejected from the cell will be approximately equal to the velocity of the boundary of the spherical vapor bubble at the instant when it fills the entire cross section of the provisional pipe $R = R_0$ (Fig. 1), and it can be evaluated from the solution [8]:

$$U \approx \frac{dR}{dt} = \beta_1 \left(\frac{c_p\lambda}{\rho^{n} r l}\right)^{1/3} \left(\frac{T_s}{R_0}\right)^{2/3}, \quad \beta_1 \approx 0.3 . \tag{1}$$

Figure 3 presents a comparison of the results of calculations by Eq. (1) with results of the experimental investigation [4] of the effect of cell length on the drop ejection velocity. In this case, the base length was $l_0 = 240$ mm.

According to the theoretical model [9], the emergence of the boiling crisis under conditions of natural convection is conditioned by the termination of the supply of the liquid to boundaries of dry spots on the heating surface through adjacent portions of the liquid film, which are evaporating meniscuses in which the flow takes place under the effect of the curvature gradient of the interphase surface. The hydrodynamics of evaporating meniscuses has been investigated both experimentally and numerically in [10]. In [11], an approximate analytical solution was obtained whose correctness was substantiated by its direct comparison with results of a detailed numerical



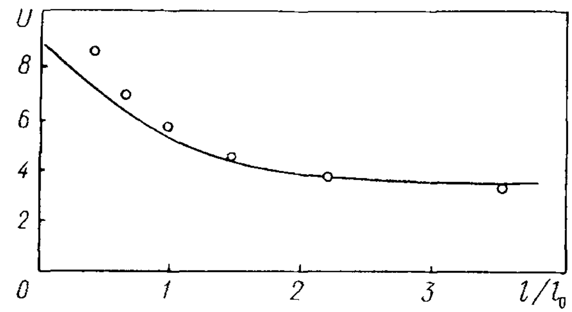


Fig. 2. Scheme of close-packed bubble layer formed on thermoresistor during explosion boiling. 1) surface of thermoresistor; 2) vapor bubbles; 3) evaporating meniscuses of liquid films.

Fig. 3. Comparison of calculations of the velocity of drop ejection out of the exit opening of a jet-printer cell with experimental data [4]. U, m/sec.

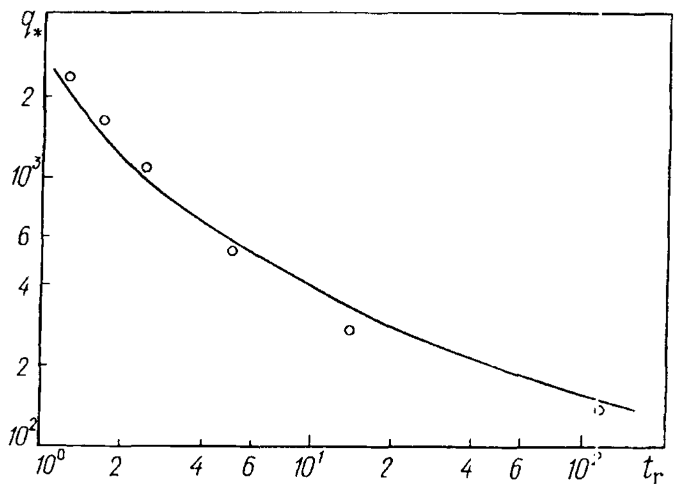


Fig. 4. Comparison of calculations of limiting permissible (critical) heat-flux density q_* supplied to a thermoresistor with experimental data [4]. q_*, MW/m^2; t_r, μsec.

investigation [12]. According to [11], geometrical dimensions of the meniscus (length l_m and thickness δ_m) and the density of the heat flux q_m transmitted through the meniscus are related by the following formulas:

$$\frac{\delta_m}{l_m} = \beta_2 \left(\frac{\nu \rho'' \Delta T}{\sigma T_s} \right)^{1/4} r^{1/8}, \qquad (2)$$

$$q_m = \beta_3 \frac{\lambda \Delta T}{\delta_m} \ln \left(1 + \frac{\rho'' \delta_m r^{3/2}}{\lambda T_s} \right). \qquad (3)$$

Here the numerical constants β_2 and β_3 are close to unity. According to the theoretical model [9], the length of the meniscus under precrisis conditions is proportional to the size of the vapor conglomerate on the heating surface prior to separation. In the case under consideration, it is quite natural to assume the meniscus length l_m to be approximately equal to the radius of vapor bubbles in their close packing that exists by the end of the explosion boiling stage prior to their coalescence into a continuous vapor film (Fig. 2).

Assuming the diameter of the vapor bubble to be equal to the length of the heat wave under the condition q = const realized on the resistor, we obtain the expression for the meniscus length $l_m = \sqrt{(3/2)at_r}$. The boiling temperature T_* and heating times of the thermoresistor relevant to experiments [4] are presented in Table 1.

Now, with the use of formulas (2) and (3), one can find the limiting permissible (critical) heat flux density $q_* = q_m$ supplied to the resistor. It should be noted that one of the main objectives of the series of investigations [1-4] was exploration of the possibilities of increasing the working frequency of the printing device of the jet printer. This was achieved mainly by the maximum possible increase in the electric power supplied to the thermoresistor (up to burning of the resistor) at a fixed pulse duration t_r. Therefore, up to an approximation, one can assume that each value of the heat-flux density taken from Table 1 based on results [4], corresponds to the critical one: $q = q_*$.

Figure 4 presents the comparison of results of calculations carried out with the constants in (2) and (3), taken to be equal $\beta_2 = 1.3$ and $\beta_3 = 0.8$, with experimental data [4].

This work was carried out with support from the Russian Foundation for Basic Research, grant No. 95-02-04960-a.

NOTATION

ρ', density of liquid; ρ'', density of vapor; c_p, specific heat of liquid; λ, thermal conductivity of liquid; a, thermal diffusivity of liquid; ν, kinematic viscosity of liquid; σ, surface tension on liquid-vapor interface; r, specific heat of evaporation; t, time; t_r, duration of heat pulse; R, bubble radius; R_0, radius of a provisional pipe; l, length of jet-printer cell; l_m, δ_m, length and thickness of liquid film and meniscus, respectively; $l_0 = 240\ \mu$m, base length of cell in experiments; $l_t = \sqrt{at_r}$, length of heat wave; U, velocity of liquid drop ejection out of jet-printer cell; q, density of heat flux supplied to thermoresistor; q_*, maximum permissible ("critical") heat-flux density; q_m, density of heat flux transferred through liquid film meniscus; T_*, boiling temperature of liquid; T_s, saturation temperature; $\Delta T = T_* - T_s$, temperature drop between wall and saturated liquid. Super- and subscripts: ′, conditions in liquid; ″, conditions in vapor; r, resistor; 0, basic conditions; s, saturation conditions; m, meniscus; t, thermal; *, limiting (critical).

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