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Structure of low-head two-phase flow in flat nozzles during outflow of the liquid into rarefied medium

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Abstract: Outcomes of experimental researches of the low-pressure adiabatic flow of the boiling liquid through two-dimensional Laval nozzles in a vacuum atmosphere were adduced. Requirements of critical conditions of flow were determined. Structural forms of a stream were investigated and their connection with crisis of flow was shown. It was established periodic non-stationary macrostructures of a stream which was stipulated by the rotational gear of origin of a vapor phase.

Key words: component; low-head flow; flow structure; flat nozzle; rarefied medium;
the mechanism of vaporization; mass flow rate

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Nomenclature

p_0	initial pressure	l	convergence part length
p_1	outlet pressure	β	relationship between outlet and initial pressure
p_s	pressure of saturation	j	relative mass flow rate
t_0	initial temperature	F_s	the area of nozzle shear
α	convergence part angle	F_t	the area of nozzle throat

Introduction

Results on an experimental research of structure of two-phase flow in diverging-converging nozzles outflow into rarefied medium are presented. When the difference pressure between inlet and outlet of channel is less than one atmosphere, low-head regime occurs, and relative mass flow rate is less than $20\,000\text{ kg}/(\text{m}^2 \cdot \text{s})$. There is no information about the structure and characteristics of low-head flow in diverging-converging nozzle, because majority previous investigations were deal with high-head flow^[1-6].

Low-head flow is realized in a hydraulic

path of various power equipments. For definition of throughput of channels, maintenance of an operated and safe mode of power equipments operation the information on structure and characteristics of the stream which is taking place at low-head flow of the boiling liquid through channels of the various form is demanded. In the literature there is a limited quantity of the works, devoted to definition of an achievable overheat of a liquid in conditions of the rarefied medium^[7-8]. Among works on research of characteristics and structure of low-head two-phase flow in cylindrical channels and flat nozzles it is possible to allocate only individual works^[9-12].

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The main problem of this work is an experimental investigation and analysis of experimental data of the structure of low-head boiling flow in diverging-converging channels during outflow into rarefied medium.

1 Experimental stand

For solving this problem experimental stand is created (Fig. 1). The stand consists of three main parts: liquid preparation system, operating unit and exhaustion system. The plane channels under research were mounted in operating unit, which are installed horizontally. Basic geometry of converging part is shown in Table 1. The minimal section represents a rectangular with height 2 mm and width 4 mm. In experiments initial pressure and temperature, outlet pressure and mass flow rate are measured. During experiments it was carried out a photo and a video shooting of structure of a stream in a path of the channel and behind its cut. Experimental condition is initial pressure $p_0 = (80 \pm 3)$ kPa, initial temperature $t_1 = 3 \sim 70$ °C, and outlet pressure $p_0 = 8 \sim 72$ kPa.

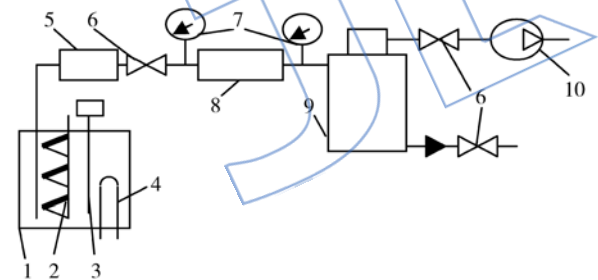


Fig. 1 Basic scheme of the stand for researching low-head two-phase flow

Table 1 Geometry of nozzle convergence part

Nozzle number	$\alpha/(^{\circ})$	l/mm
1	6	152
2	12	157
3	12	248
4	17	174

2 Flow structure

In experiments three main structure forms of liquid low-head flow are detected. The realization of these regimes depends on initial temperature and betta (β). β is a relationship between outlet and initial pressure.

When $\beta > 0.65$ break-off liquid flow from the top wall of channel converging part (Fig. 2) is observed. Stratified flow in convergence part is observed. When betta increases, point of flow separation moves to the channel shear. On this regime of flow of a vapor phase in the channel it was not observed.

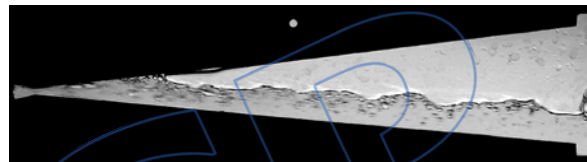


Fig. 2 Stratified structure (flat nozzle No. 3, $\beta > 0.65$, $F_s/F_1 = 27$, $t_0 = 46$ °C, $p_0 = 80$ kPa, $p_1 = 73.1$ kPa)

When $\beta \leq 0.65$, the liquid occupies all volume of the channel (Fig. 3). However, in minimal cross-section area inertial forces act on liquid. Therefore break-off zones are observed near the wall behind minimal cross-section area (Fig. 3(a)). Forms, quantity and size of this break-off zones depend from angle of convergence part of nozzle. When this angle equals 6° two long and narrow break-off zones are observed. Relationship between cross-section area of this break-off zones and nozzle cross-section area in this place is very small value. Break-off zones in nozzle in which angle of convergence part equals 6°, as shown in Fig. 3(b). Creating, growing and shading of eddies occur in this break-off zones. More over, eddies grow near one wall and drop main liquid flow to other wall. Eddy in break-off zone near one wall and curved main liquid flow are shown in Fig. 4. When betta is less then 0.65 the stream is characterized by periodic eddies creating and oscillating of main liquid stream behind minimal cross-section, i. e.

flow is periodic non stationary. When angle of convergence part increases, height of break-off zones and size of eddies also increase. In nozzle with angle of convergence part more than 10° one break-off zone has volume more other. Under the gravitation in experimental condition, top break-off zone is greater than bottom zone. In nozzle with angle of convergence part equals 6° and 12° eddies path seems like eddies path of the pocket (Fig. 3 (b) and 3 (c)). Fig. 3 (e) shows there is only one big break-off zone near top wall in nozzle with angle of convergence part equals 17° . Similar modes of separated flow of a liquid in the channel of variable section are described in Ref. [13]. In this nozzle consecutive movement of eddies is observed.

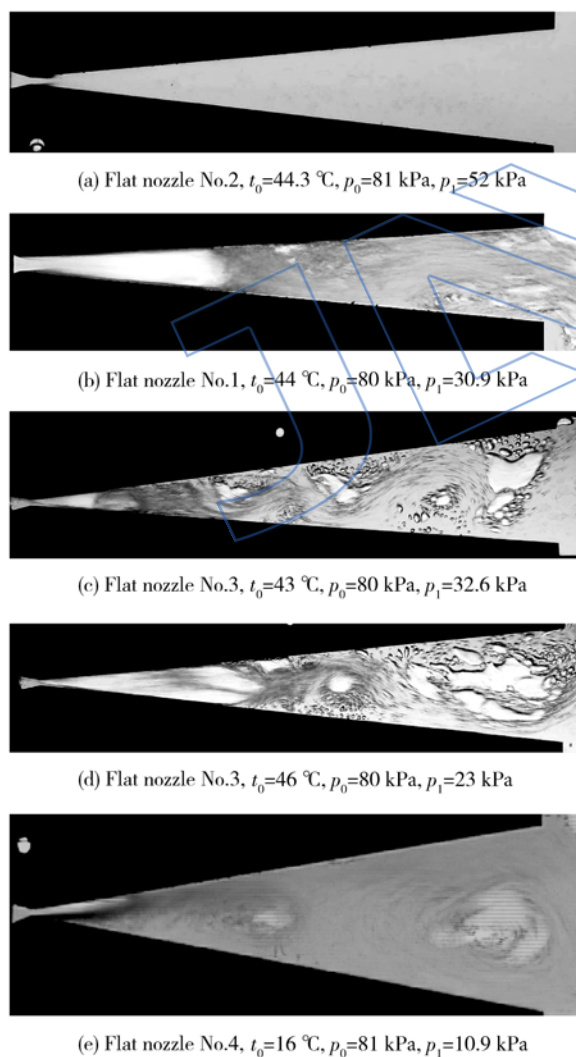


Fig. 3 Eddy flow (flat nozzles, $\beta < 0.65$, but $p_1 > p_s(t_0)$)

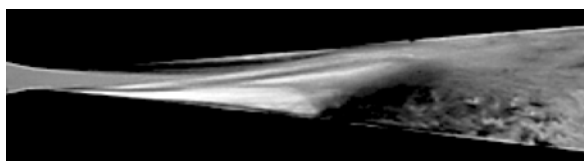


Fig. 4 Dropped main liquid flow by eddy (flat nozzle No. 3)

In this regime average pressure in convergence part of nozzle is more than pressure of vaporization, but inside swirling eddy pressure is less than pressure of vaporization, therefore when $\beta > 0.65$ we can see rotation vapor cluster inside eddies, which consist of one big bubble in the center and many small bubbles around (as shown in Fig. 3(b), (c), (d), (e)). The biggest eddy is born in the biggest break-off zone, and its vapor cluster has the biggest diameter (Fig. 3(c)).

When outflow pressure is equal to pressure of vaporization plus $3 \sim 5$ kPa in the minimal cross-section on the wall the process of vaporization begins (Fig. 3(d)). Behind minimal cross-section oscillating liquid jet, like wedge, is observed, and behind it two-phase flow takes place. Not far from it condensation front is placed, where the condensation of vapor phase into liquid occurs. The vapor clusters rotating and growing in the downstream inside eddies are observed. Reducing outflow pressure leads to moving of condensation front to the channel shear.

When outflow pressure is equal to or less than pressure of vaporization heterogeneous two-phase flows at the all convergence part of the nozzle are observed (Fig. 5). Behind minimal cross-section we can see a liquid jet, like as it is described above. When oscillating liquid jet touches one of the wall, the part of liquid sticks to a wall, and creates thin liquid films on the wall. Some parts of liquid come off this film and carry away from the nozzle by main two-phase stream (Fig. 5(b)). The film thickness decreases with the decrease of outlet pressure, and it evaporates completely at some pressure value.

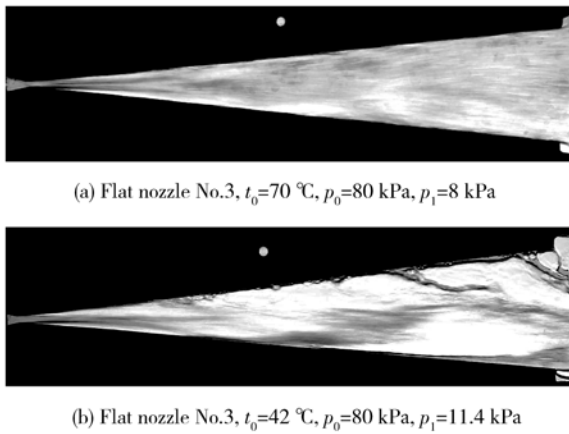


Fig. 5 Heterogeneous two-phase flow
($p_1 < p_s(t_0)$)

3 Critical mass flow rate

As shown in Fig. 6, liquid relative mass flow rate depends on beta for different initial temperatures. In the researched range, parameters of the critical regime of the expiration are realized, when liquid mass flow rate is independent on outflow pressure. When $\beta > 0.65$ mass flow rate slightly decreases independently on initial temperature. But if $\beta < 0.65$ mass flow rate is independent on beta, and several horizontal line, which depends on initial temperature. When initial temperature decreases critical mass flow rate increases.

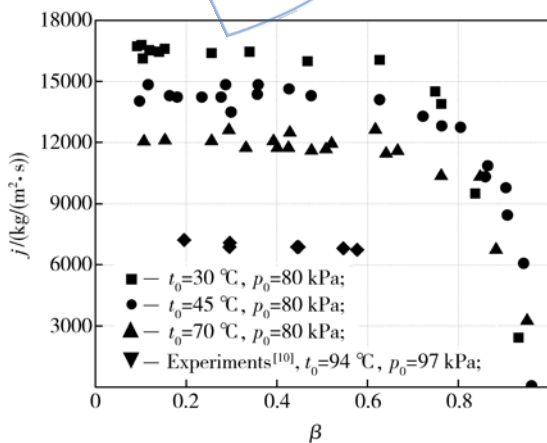


Fig. 6 Liquid relative mass flow rate depending
on initial temperature and outlet pressure
(flat nozzle No. 3)

The comparison of mass flow rate data shows that if noncritical regime of expiration is

realized the stratified flow occurs in nozzle. At a critical regime in nozzle eddies structure or heterogeneous two-phase flow structure are realized.

4 Conclusions

1) The experimental research of structure low pressure two-phase flow of water in the rarefied medium is shown.

2) Characteristic structural forms of a flow are established at low pressure expiration of water in the rarefied medium

(a) stratified flow — when $\beta > 0.65$;

(b) eddies flow — when $\beta < 0.65$, but $p_1 > p_s(t_0)$;

(c) heterogeneous two-phase flow — when $p_1 < p_s(t_0)$.

3) In the researched range, parameters of the critical regime of the expiration are revealed.

4) For the noncritical regime of the expiration there corresponds the stratified structure of flow, critical-eddies structure and heterogeneous two-phase flow structure.

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