Study of the Effect of Heat Supply on the Hydrodynamics of the Flow and Heat Transfer in Capillary Elements of Mixing Heads Jet Thrusters

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Abstract. The article presents the results of experimental studies of hydrodynamics and those of loobman single-phase and two-phase flows in capillary nozzle elements propellant thrusters and the proposed method of their calculation. An experimental study was performed in capillaries with a sharp entrance edge of the internal diameter of 0.16 and 0.33 mm and a relative length 188 and 161, respectively, in pouring distilled water and acetone in the following range of parameters Reynolds number $Re = (0,3...10)\cdot 10^3$, Prandtl number $Pr = (2...10)$, pressure $p = (0,1...0,3)$ MPa, the heat flux $q = (0...2)\times 10^6$ W/m^2, the difference of temperature underheating of liquid $\Delta t_n = (5...80)K$. The dependences for calculation of single phase boundaries, the undeveloped and the developed surface of the bubble and film key singing of subcooled liquid. It is shown theoretically and experimentally confirmed the virtual absence of areas of undeveloped nucleate boiling in laminar flow. The dependence for calculation of hydraulic resistance and heat transfer in the investigated areas of current. It is shown that in the region of nucleate boiling surface in the flow in capillary tubes, influence of the formed vapor phase on the hydrodynamics and heat transfer substantially higher than in larger diameter pipes.

1. Introduction

The need to consider the hydrodynamics of the flow in capillary elements propellant thrusters with supply of heat due to their characteristic working conditions – heating of the capillaries in the process of their work [1]. It is therefore important to know not only the hydraulic characteristics of the capillaries for flow of liquid from supply of heat, but the values of densities of heat flows to the capillaries that lead to the implementation of the possible flow regimes of the liquid with the supply of heat to either account for them or avoid these modes.

Currently there is no General model of fluid flow in tubes with supply of heat, however, a large number of theoretical and especially experimental work performed on pipes of large diameter and is devoted to the study of individual regions of the considered flow.

The aim of this work was research of features of hydrodynamics flow and heat transfer in capillaries with supply of heat, the detection realized with flow regimes and to develop a method of calculation of the boundaries of these modes of heat transfer coefficients and hydraulic resistance.

2. Facilities and experimental conditions

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The hydrodynamic study was performed on capillaries made of stainless steel. The experimental study was carried out in a pouring plant, which used the displacement supply of working fluid to the capillary by means of compressed air. The supply pressure of the liquid was monitored by a pressure sensor, the flow rate of the working fluid was measured volumetrically by means of a level gauge, and the time of fills was recorded with an electric stopwatch. The supply of heat flux to the liquid was ensured by passing through the capillary the electric current of constant voltage, the value of which was determined by the voltage drop across the shunt. The voltage drop across the shunt and the capillary was measured with voltmeters. Fluid temperature at the inlet and outlet of the capillary and the temperature of the capillary wall in five sections with flow with supply of heat was measured by a chromel-kopelove thermocouples. An experimental study was performed in capillaries with a sharp inlet edge, an inner diameter of 0.16 and 0.33 mm and a relative length 188 and 161, respectively, in prolivka water and acetone in the following range of parameters the Reynolds number Re = (0,3...10) $\cdot 10^3$, Prandtl number Pr = 2...10, fluid pressure p = 0,1...0,3 MPa, the density supplied to the capillary heat flux q = (0...2) $\cdot 10^6$ Вт/м^2, subcooled to the temperature of boiling liquid $\Delta t_n = (t_l - t_s)$ =5...80 K. In the capillary phase heat-was preceded by a phase isothermal flow, where they provide hydrodynamic stabilization of the flow of fluid.

3. The physical picture of the fluid flow in the capillaries for supply thereto of heat

The physical picture of the fluid flow in the capillary nozzle elements of the thrusters, taking into account all possible stages of the implementation flow with milk.-the house of heat can be represented as follows (Figure 1): the inlet portion AB is implemented isothermal fluid flow without heat supply; in the subsequent parts of the flow with heat supply BL, which can be liquid-phase flow BC, flow boiling of subcooled liquid CL, consisting of undeveloped plots of CD and DK developed nucleate boiling and film boiling area KL.

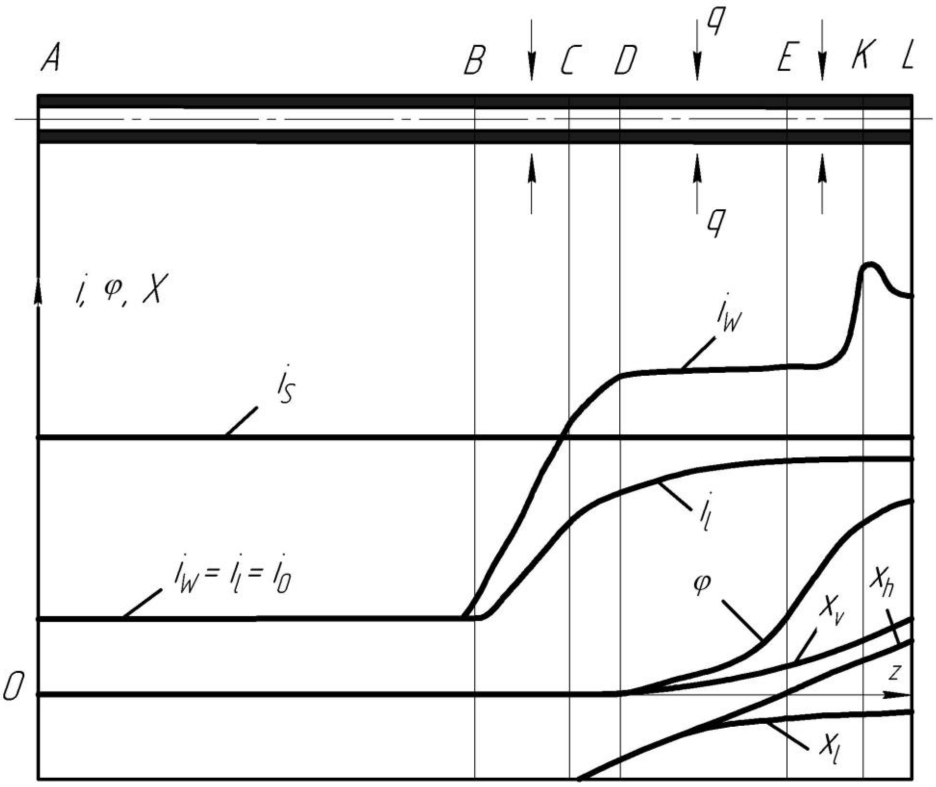

Figure 1. Physical picture of the fluid flow in the capillary elements of the mixing head with supply of heat

In Figure 1 shows the changes of the parameters of the liquid along the channel axis of the capillary, where i_0, i_l, i_w, i_s - the enthalpy of the fluid respectively at the inlet of the capillary, the length of the channel, the wall temperature t_w and temperature of the saturated vapor t_s; φ - is the true volume steam content; x_h – relative enthalpy, determined by heat balance; x_l - is the relative enthalpy of the working fluid, the average over the cross section; x_v – the actual mass vapor content; q – heat flux density; z - is the coordinate along the channel axis of the capillary. Describes the field of real case can have a different length depending on the length of the heat supply, the heat flux, fluid flow, etc.

Studied the field of single-phase current, undeveloped and developed nucleate boiling of subcooled liquid.

4. A study of the boundaries of the regions of fluid flow in capillaries with supply of heat

The transition to undeveloped nucleate boiling occurs at a certain overheating of the capillary wall $t_w > t_s$ and higher density of the heat flow $q_b > q_s$, than that at which $t_w = t_s$:

$$q_s = (i_s - i)\frac{\alpha}{c_p} \quad . \tag{1}$$

The expression to calculate the heat flux at the beginning of the boil q_b can be found under the assumption that the temperature change ($t_w - t_s$) occurs within the layer as the characteristic dimension which is the diameter of the gas bubble at the moment of conception [2], then:

$$q_b = \left\{\left[\frac{\alpha\,\sigma}{r\,\rho_c\,\lambda_h(1 - T/T_s)}\right]^{1/2} + \left[\frac{\alpha\,\sigma}{r\,\rho_c\,\lambda_h(1 - T/T_s)} + 1\right]^{1/2}\right\}^2 \cdot q_s \quad . \tag{2}$$

The last equation is obtained theoretically and considers fluid properties, and the mode of its flow, and to determine the upper boundary region of single-phase flow.

Under steady laminar flow and heat transfer profile of the enthalpy of the flow is parabolic. This allows proindeksirovat variation i in the section and based on the assumption [3] about the proportionality (ratio about 1) the true volumetric vapor content of the flow area at i > is, given φ = 1 – rs2, to obtain [4]

$$q_d = \frac{q_s}{1 - 2\varphi} \quad , \tag{3}$$

that is, when φ = 0,01, which can be taken abroad developed a boil, qd / qs = 1,02. This indicates an extremely small extent on q region undeveloped boiling in laminar flow.

Experimental determination of the boundaries of two-phase flow regimes showed (Figure 2) that the lower border of the area is undeveloped boiling satisfactorily described (2), and top with turbulent flow – the equation is derived [5]:

$$q_d = \left\{\left[\frac{\alpha\,\sigma}{r\,\rho_c\,\lambda_h(1 - T/T_s)}\right]^{1/2} + \left[\frac{\alpha\,\sigma}{r\,\rho_c\,\lambda_h(1 - T/T_s)} + 2\right]^{1/2}\right\}^2 \cdot q_s \quad . \tag{4}$$

The upper border region of developed nucleate boiling (heat-transfer crisis) in laminar flow is satisfactorily described by the dependence [6]:

$$q_{cr} = \left\{K_\infty\, r\left[\rho_c\sigma\, g\,(\rho_s - \rho_c)\right]^{1/2} + K_0\, r\, u\left(\frac{\rho_s}{\rho_c}\right)^{1/2}\right\}\left[1 + 0{,}0065\left(\frac{\rho_s}{\rho_c}\right)^{4/5}\left(\frac{c_p\Delta t_n}{r}\right)\right], \tag{5}$$

where K∞ = 0.13 and K0 = 0,0012 – empirical coefficients. In turbulent flow the experimental data can also be described by the dependence (5), putting K0 = 0,007.

5. The study of the linear coefficient of hydraulic resistance

In the field of single-phase flow experimentally shown the validity of the ratios to calculate the relative linear coefficient of hydraulic resistance [7]:

$$\overline{\lambda}_l = \frac{\lambda_l}{\lambda_0} = \left(\frac{\eta_w}{\eta_0} \right)^n , \tag{6}$$

moreover, for turbulent flow n = 0.25 for laminar $n = 2{,}3\,\overline{z}^{\,0,3} (\eta_w / \eta_0)^{-0,062}$ if $\overline{z}$ = (0,7...12) ·10³.

Experimentally determined values of the Nusselt criterion for stable current, the supply of heat Nu∞ are different from the values of Nu∞=is 4.36 for laminar flow regime at Re > 1,5 ·103 [4], which proves that the single-phase flow in the flow in capillary tubes, turbulent fluctuations and corresponds to the boundary of the transition determined at isothermal pouring.

The study area of undeveloped nucleate boiling surface in turbulent flow showed that the influence of the vapor phase on the hydrodynamics of the flow is negligible, and the linear coefficient of hydraulic resistance can be described by equation (6), which η_w is determined by the wall temperature.

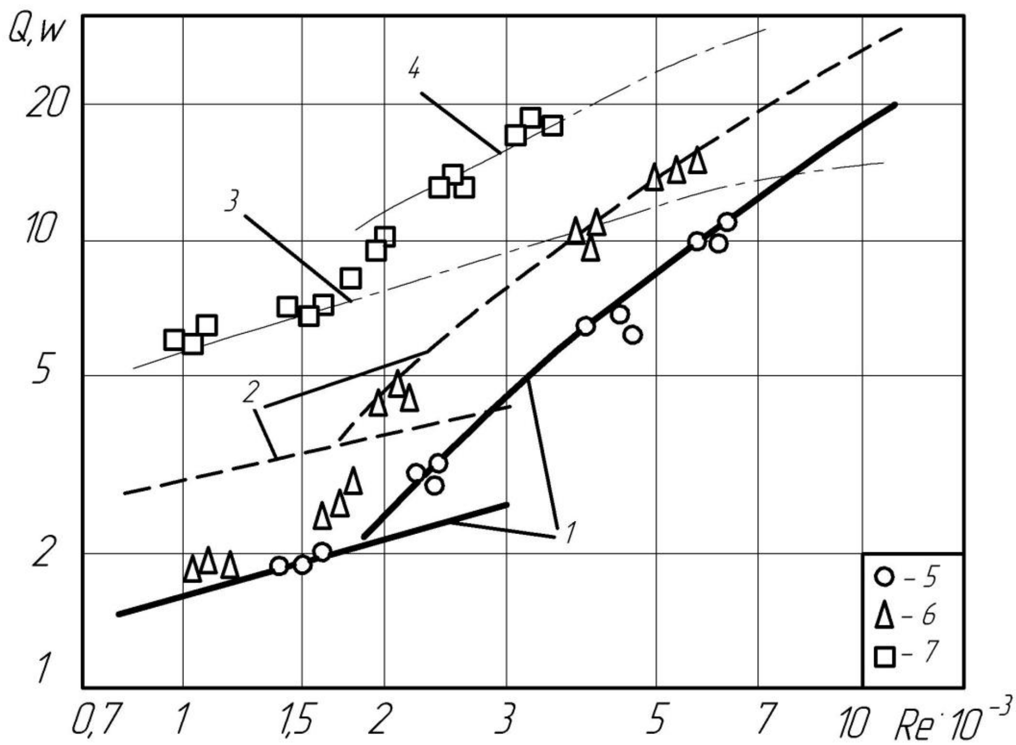

Figure 2. Comparison of calculated and experimental data on determination of boundaries of the regions of the flow with heat supply: 1 – calculation according to (2); 2 – calculation according to (4); 3 – calculation according to (5) with K_0=0,0012; 4 – calculation of (5) with K_0=0,007; experimental results: 5 – the border is boiling; 6 - boundary of the beginning of developed bubble boiling surface; 7 – the upper boundary region of developed nucleate boiling

Generalization of experimental values of relative linear coefficient of hydraulic resistance in the region of developed nucleate surface boiling of subcooled liquid was performed using the complex [8]

$$A = 20 \left(\frac{q}{r \rho_c u} \right)^{7/10} \left(\frac{\rho_s}{\rho_c} \right)^{8/100} \left\{ \left(\frac{1{,}32\,(i_s - i_b)}{(i - i_b)} \right) \left\langle \ln \left[\frac{1 - (i - i_b)}{1{,}32\,(i_s - i_b)} \right] \right\rangle^{-1} \right\} \tag{7}$$

The results are shown in Figure 3a in dependence of the relative (compared with those calculated according to the formula of Poiseuille [9] in laminar flow and the Blasius formula [9] - turbulent) linear coefficient of hydraulic resistance, indicating a more significant effect of the vapor phase on the hydrodynamics of the flow in capillary tubes (line 2) in comparison with the flow in larger diameter pipes (d > 1 mm - 1 line [10]).

The obtained experimental data can be described by a linear dependence in the range $\mathrm{Re} = (1...5)\cdot 10^3$, $\Delta t_n = (5...25)K$

$$\overline{\lambda}_d = 1 + 3A\,, \tag{8}$$

allow the calculation of hydraulic resistance of two-phase flow in capillary tubes with a diameter of (0,15...0,35) mm in the region of developed nucleate boiling.

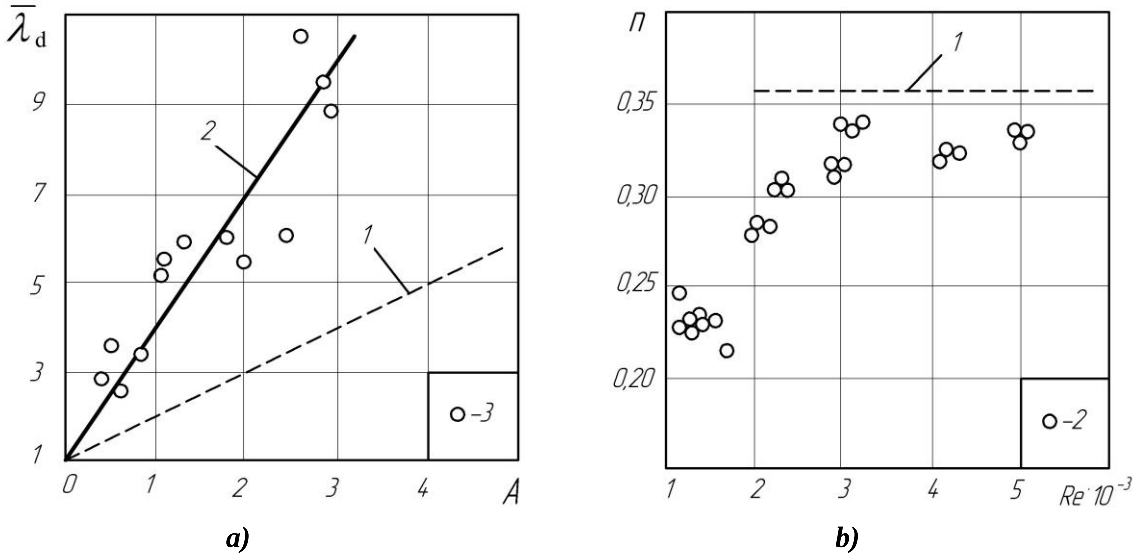

Figure 3. The linear hydraulic resistance factor (a) and exponent "n" according to (9) (b) in the field of developed nucleate surface boiling: a) 1 – calculation according to [10], 2 – calculation according to (8), 3 – experimental data; b) 1 –according to [8], 2 – experimental data

For calculation of heat transfer in this region it is necessary to know the value of the exponent in the generalized dependence [11]

$$t_w^d - t_s = c\left(q - q_s\right)^n,\ \ c = 28\,T_{cr}^{41/50}\left(p_{cr}\cdot 10^5\right)^{-9/25} M^{\,9/50}\exp\left(-5{,}6\frac{T_s}{T_{cr}}\right), \tag{9}$$

where Tcr, pcr – critical parameters of the liquid, M – is the molar mass.

The experimental values of the exponent "n" in the expression (9) depend on the Reynolds number and is shown in Figure 3b, which shows the influence of flow regime on the exponent "n": in turbulent flow n=0,33, which is close to the results of [11], the transition to laminar flow of "n" decreases and is 0.23 at $\mathrm{Re} < 1500$. This can be explained by the influence of void fraction on the heat transfer.

6. Conclusion

Obtained on the basis of wide experimental investigations of the mathematical model integral describing one - and two-phase flow in the capillary nozzle elements of the thrusters is only true at low differential pressure, when the pressure and hence saturation temperature along the length of the capillary is almost unchanged. When a significant pressure gradient and variable heat-flux density to extend the range of applicability of the models considered are infinitely small in length section of the capillary when the pressure gradient can be neglected. This allows to determine at each integration step for a given heat flux constant hydrodynamic and heat transfer characteristics of flow and total pressure drop on the section and then hold a sum of the length of the capillaries and clarify the flow.

Based on the authors experimental results on the effect of heat input on hydrocortisone and heat transfer under single phase and two phase flow in capillaries has been proposed a method of calculating the hydrodynamics of fluid flow with heat supply. The authors studied single-phase flow field and the undeveloped and developed nucleate boiling of subcooled liquid, while the basic parameters were changed in the following range: $\mathrm{Re} = (0{,}3 \ldots 10) \cdot 10^{3}$, $\mathrm{Pr} = (2 \ldots 10)$, $p = (0{,}1 \ldots 0{,}3)$ МПа, $q = (0 \ldots 2) \times 10^{6}$ Вт/м2, $\Delta t_{n} = (5 \ldots 80)K$.

7. Symbols used in the above ratios

p - pressure; ρ *- density;* $\dot{m}$ *- the average mass flow rate; d - the diameter of the capillary;* λ *- the linear hydraulic resistance coefficient; z – the current coordinate, length;* $\bar{z} = z/(d\,\mathrm{Re}\,\mathrm{Pr})$ *- dimensionless length; Re, Pr, Nu - the criteria of Reynolds, Prandtl, Nusselt; T, t - temperature;* Δt *the temperature difference between the; q - heat flux density;* η *- dynamic viscosity coefficient; r - heat of vaporization;* σ *- surface tension;* λ_{h} *- thermal conductivity coefficient; i - is the enthalpy;* α *- heat transfer coefficient;* c_p*- - specific heat;* φ *- true volumetric vapor content; M - is the molar mass.*

Indexes: *0 - parameters at the entrance of the channel; the s - parameters of the liquid on the saturation line; w - parameters at the temperature of the wall; l - liquid phase flow region; cr - critical; n - underheating; b - initial boiling point; d - developed nucleate surface boiling; c - steam parameters on the saturation line;* ∞ *- parameter stable current.*

References

[1] Nigodjuk V E and Sulinov A V 2013 The effect of thermal factors on instability of the hydrauliccharacteristics of the capillary nozzle elements LTRE *Proceedings of the Samara scientific center, Russian Academy of Sciences* (Samara) T. 15, No 6 (4), pp 901-904.

[2] Chernobay V A 1970 Determination of the conditions of occurrence of nucleate boiling in forced motion of subcooled liquid Heat Power Engineering (Moscow) No 6, pp 65-67.

[3] Zakharova E A, Kolchugin B A, Labuntsov D A 1970 Calculation of the true volume promotergene in heated channels Heat Power Engineering (Moscow) No 6, pp 58-60.

[4] Godlewski V E, Nigodjuk V E and Sulinov A V 1983 Features of calculation of hydraulic resistance and heat transfer for single-phase and two-phase flows in capillary tubes Engineering-physics journal of (Minsk) 45, No 2, pp 327. (Manuscript, 16 p, ill., bibliographer. 17 the name. DEP. 1.04.83 in VINITI, No 1670).

[5] Bergelson B R and Gerasimov A S 1979 Hydraulic characteristics and the steam content in the channel during boiling of the liquid subcooled to the saturation temperature Engineering-physics journal of(Minsk) T. 37, No 23, pp 784-792.

[6] Leonteva A N 1979 Heat and mass transfer theory (Moscow Higher school) p 495.

[7] Petukhov B S, Genin L G, Kovalev S A 1974 Heat transfer in nuclear power plants (Moscow Atomizdat) p 407.

[8] Tarasova N B, Khlopushin V I, Boronina L V 1967 Local hydraulic resistance at superficial boiling of water in the pipe Thermophysics of high temperatures (Moscow) T. 5, No 1, pp 130-136.

[9] Stoczek N P and Shapiro A C 1978 Hydraulics LRE (Moscow Mashinostroenie) p 118.

[10] Ornatsky A P 1965 Generalization of experimental data on hydraulic resistance at superficial boiling Journal of applied mechanics and technical physics (Moscow) T. 3, No 3, pp 444-451.

[11] Bahvalov J E, Cronin I B, Kurganov I V 1966 Generalization of data on heat transfer during boiling of liquids netegrity Heat Power Engineering (Moscow) No 5, pp 63-68.