Experimental research on a phase slip and pressure loss during boiling of the refrigerant R134a in a mini-channel

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Abstract. This article is devoted to the development of a methodology for calculating the hydrodynamic characteristics of liquids boiling in mini-channels. In contrast to the well-known methods, the proposed methodology is based on the use of the true volumetric steam content and prediction of two-phase flow regimes in the field of a steady flow. The article presents experimental data on the true volumetric steam content, pressure loss, and two-phase flow pattern in mini-channels

1. Introduction

The solution to the problem of energy saving in low-temperature technology is largely due to the intensification of heat exchange in refrigeration apparatuses, optimization of heat-hydrodynamic processes and the development of new technologies for heat exchange apparatus engineering.

The study of the hydrodynamic characteristics of boiling refrigerants in pipes \( D_h > 6 \) mm is discussed in [6].

Recently, the use of boiling in pipes or channels with a diameter of \( D_h > 2.5 \) ÷ 6 mm [6] or mini-channels with \( D_h <1.5 \) mm [1, 2, 3] has become relevant.

Mini-channel technologies in heat exchange apparatus engineering have a number of advantages over known types of devices:

– high heat transfer rate. The heat transfer coefficient in mini-channels is 2 ÷ 3 times higher than the similar coefficient in the slot channels of plate evaporators [2];
– a decrease in 3 ÷ 4 times of the level of filling with the working substance;
– improved weight and size characteristics. Devices are made of aluminum casting;
– high durability at high pressures.

Up till now, mini-channel technologies have been mainly used in electronics and automotive air conditioning. Since 2012–2014, the research on the prospects of using mini-channel evaporators and condensers in refrigeration has appeared.

The monograph by P. Hrnyak [2], as well as the works by A. V. Baranenko and D. Khovalyg [1] are among the most comprehensive studies in this area. The authors [3, 4, 5] obtained a very interesting experimental material on the study of heat-hydrodynamic processes with the flow of various media in mini-channels \( D_h = 0.25 \) ÷ 0.5 mm. At the same time, the question of modeling and summarizing the accumulated experimental material remains open.
A.A. Malyshev [6] formulated the main provisions of the integrated method for the analysis of thermo-hydrodynamic processes during boiling of liquids in pipes, including:

– study of the phase slip and the calculation of the true parameters of two-phase flows;
– methodology for predicting flow patterns;
– methodology for calculating local heat transfer based on true parameters;
– methodology for calculating pressure losses in various two-phase flow regimes.

The research shows that the value of true volumetric steam content (phase slip) is the basis of a comprehensive method that provides the most correct modeling of heat-hydrodynamic processes in a wide range of mode, geometric and physical parameters.

2. Results and Discussion
In order to implement the integrated method in relation to boiling in mini-channels, experimental studies were conducted on the stand shown in figure 1.

![Figure 1](image)

**Figure 1.** Scheme of the experimental stand: 1 – condenser; 2 – measuring container; 3 – receiver; 4 – subcooler; 5 – freon pump; 6 – flow meter; 7 – steam generator; 8 – experimental section; 9 – measuring container; 10 – thermostat; 11 – brine pump; 12, 15 – contact thermometers; 13, 14 – electric heaters; 16 – submersible pumps; 17 – storage tank; 18 – refrigeration machine.

In front of the experimental section 8 there is a steam generator 7, in which the initial steam content Xin is set with electric heating. Having passed the experimental section, the two-phase flow is sent to the measuring container 9, in which the phases are separated: the steam is sent to the condenser 1, and the liquid flows to the receiver 3. In the measuring container 9, the flow rate of the liquid phase is measured by the volumetric method. In the condenser 1 there is the heater 14 included in the circuit of the contact thermometer 12. The condensation temperature (equal to the boiling point) is regulated in steps using electric heating and cold refrigerant supplied from the storage tank 17. The amount of condensate is determined by the volumetric method using the measuring container 2. The condensate flows into the receiver 3, and then with the pump 5 through the flow meter 6 is supplied to the steam generator 7. In order to prevent boiling up in the pipelines and the pump, the liquid is slightly cooled down in the subcooler 4.

Figure 2 shows an outline of an experimental unit consisting of an inner steel pipe 2 and an outer transparent pipe 1, a mini-channel with a gap of $D_h = 0.5 \div 1$ mm is formed between the centers. Section B is a section of hydrodynamic stabilization, and the part of pipe A isolated from section B is a
measuring section. At the measuring section, due to electric heating, the density of the heat flow is set and the wall temperature is measured, on the basis of which the heat transfer coefficients and steam content are determined. Visualization is accompanied by high-speed filming.

Figure 2. Outline of the experimental block
1 – transparent tube, 2 – steel tube, 3 – gasket, 4 – mini-channel, A – heat section, B – section of hydrodynamic stabilization.

The experiments were conducted on the refrigerant R134a under the following conditions:
- saturation temperature –10 ÷ +20 °C;
- mass velocity \( \omega \) 100 ÷ 500 kg / s. m²;
- mass steam content \( x \) 0.1 ÷ 0.9.

The error in determining the mass velocity based on the experimental determination of the flow rate was 5–10%. The relative error in determining the true volumetric steam content was within 1–3%. The relative error in calculating the mass consumable steam content was in the range: at \( x = 0.1 \) – 5%, at \( x = 0.9 \) – 15%.

The results of a true volumetric steam content study are presented in figure 3.

![Figure 3](image-url)  
**Figure 3.** Dependence of true volumetric steam content (\( \varphi \)) on mass steam content (\( X \)) at boiling of refrigerant R134a in a mini-channel with \( D_0 = 0.5 \) mm and at \( G = 450.12 \) kg / s m².
The presented data were obtained at a mass velocity \( G = 450.12 \text{ kg/s m}^2 \), which, according to [1], corresponds to the section of steady flow.

As the figure shows, with a decrease in temperature, the true volumetric steam content significantly increases and, accordingly, increases the slip coefficient \( S \).

This is primarily due to the increase in the specific volume of steam with a decrease in temperature. So, when the saturation temperature falls from 0 to \(-8 \degree C\), the specific volume of steam increases from 0.069 to 0.092 m\(^3\) / kg (in 1.3 times). At the same time, \( \varphi \) increases by an average of 33\%, depending on the mass vapor content \( X \). It is important that this flow range is characterized by a circular flow pattern and the growth of true steam content is mainly due to an increase in steam volumes with decreasing temperatures.

In the range from 0 to \(+20 \degree C\), the value sharply decreases. This is explained by the fact that with increasing temperatures in the positive range, not only steam volumes decrease and, accordingly, true steam velocities, but also the mode from the annular one goes into the projectile mode, at which the hydrodynamic mechanism changes qualitatively and the slip decreases.

Figure 4 shows the pressure drop values at the experimental site.

\[ \text{Figure 4. Dependence of pressure loss from steam content during boiling of refrigerant R134a in a mini-channel with } D_e = 0.5\text{mm and at } t = -8 \degree C. \]

The increase in pressure drop with the increasing speed is quite understandable. It is important to note that for all values of the mass velocity at \( X = 0.85 \), an extremum of the function \( \Delta P \) is observed, followed by a decrease in pressure drops.

As the observations of the flow regimes prove, at these values of the mass consumable steam content, a transition from the annular flow mode to the emulsion one is observed. The emulsion flow is characterized by the liquid film carried away from the channel surface to the center of the flow. The absence of a liquid film on the wall leads to a decrease in friction forces in the boundary layer, which causes a certain decrease in pressure loss.

In general, the transition to the emulsion flow (dry wall mode) is of a crisis nature, since it is accompanied by a sharp decrease in heat emission in these sections of the channel.

It should be noted that the “dry wall” mode is most typical for boiling in mini-channels, because in them (unlike pipes) on a significant part of the heat transfer surface, steam generation processes occur at high values of mass steam content (\( X > 0.5 \)). Therefore, one of the tasks is to develop a methodology for predicting the crisis regime of a dry wall.

As noted above, one of the tasks of the complex analysis of heat-hydrodynamic processes is the study of boiling modes.
To predict the flow modes of refrigerants, boiling in mini-channels, a modified diagram (map) of modes was developed. The coordinates of $\varphi - Fr_{cm}$ were used in this diagram. The flow modes were identified on the basis of visual observations and photo-filming of the stream.

The characteristic of the observed modes (figure 5) is in qualitative agreement with the results of [7].

One of the main tasks of the analysis is the calculation of the true volumetric steam content $\varphi$, on which all the stages of the integrated approach are based.

![Shooting of modes of two-phase flows: a – bubble; b – projectile; c – transitional; d – annular.](image)

In contrast to the method obtained for pipes in which the inertia forces mainly determine the phase slip (true steam content), when calculating the true parameters of two-phase flows in channels with an equivalent diameter of less than 2 mm, the surface tension forces were taken into account through the Weber criterion [6].

$$We = \frac{\rho \cdot D_h \cdot \omega^2_{cm}}{\sigma}$$  \hspace{1cm} (1)

As a result, the general form of the modified dependence in dimensionless parameters acquired the form:

$$\varphi = \beta - 0.06 \cdot \beta \cdot (1 - \beta)^{0.5} \cdot \left( \frac{\sigma \cdot \nu_p}{\varphi \cdot \sigma^2} \right)^{-0.23} \cdot \left( \frac{P_0}{P_{cr}} \right)^{-0.15}$$  \hspace{1cm} (2)

In this equation, $\beta$-volumetric steam content, calculated from the heat balance equation.

The results of the calculation according to equation (2) indicate satisfactory agreement with experiments on channels with $Dh \geq 1.6$ mm [2]. For mini-channels with an equivalent diameter of less than 1 mm, which are quite promising, additional experimental study is required, which is the focus of this research.

Using equation (2), a modified mode diagram was developed. The graph with satisfactory accuracy summarizes the boiling data of R134a, R12, R22, NH3 in pipes with $Dh$ greater than 5 mm, as well as...
the authors’ data for R134a boiling in a mini-channel with Dh = 0.5 mm at mass velocities in the range of 100–500 kg/cm.

It should be noted that, according to [1], a steady flow in mini-channels occurs at \(\omega p\) more than 160 kg/cm\(^2\), and at lower values of the mass velocity, flow reversal, pulsation and hydrodynamic instability are observed. This indicates that the selected mass velocity range is the most promising.

The new diagram of two-phase flows in the mini-channels is shown in figure 6.

**Figure 6.** Modified map of boiling modes of refrigerants R134a, R22, R12, NH3 with Dh = 0.5–1.6 mm and wp = 50–500 kg/(s m\(^2\)). Modes: I – bubble (\(\times\)); II – projectile (\(\square\)); III – wave; IV – stratified; V – transitional (\(\Delta\)); VI – annular (\(\Phi\)).

In the diagram presented, in comparison with the well-known diagram [6], the range of values of the criteria Fr\(_{cm}\) = 10\(^4\)–10\(^7\) is extended, which is most typical for the section of stable flow in mini-channels. The modified diagram describes the experimental results quite satisfactorily.

3. Conclusion

As a result of the research, the following results were obtained:

– new experimental data on true volumetric steam content in mini-channels;
– new experimental data on pressure loss in mini-channels;
– the boundary of the crisis mode of flow in the mini-channel with Dh = 0.5 mm under certain conditions was determined;
– a modified map of boiling regimes of liquids in mini-channels was obtained;

The obtained results allow us to continue the development of a general model for the flow of boiling liquids in a confined space.

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