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Application of computer image analyzes in the investigation of refrigerants condensation in minichannels

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Abstract The image analysis consists in extracting from the information which is available to the observer of the part that is important from the perspective of the investigated process. This process usually accompanies a considerable reduction in the amount of information from the image. In the field of two-phase flows, computer image analysis can be used to determine flow and geometric parameters of flow patterns. This article presents the possibilities of using this method to determine the void fraction, vapor quality, bubble velocity and the geometric dimensions of flow patterns. The use of computer image analysis methods is illustrated by the example of HFE 7100 refrigerant methoxynonafluorobutane condensation in a glass tubular minichannel. The high speed video camera was used for the study, and the films and individual frames received during the study were analyzed.

Keywords: Condensation; Flow structures; Image analyze; Minichannels

1 Flow structures in the condensation process

The refrigerant condensation and boiling process are phenomena often used in various heat engines. The refrigerant flow and thermal parameters have a significant influence on the performance of these refrigerants. The flow patterns occur in this process also have an impact on that. They depend on the thermal and flow parameters and affect the stability and efficiency

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of the device operation. The knowledge of two-phase flow structures during condensation is beneficial for optimizing the parameters of the devices work. During the condensation phenomenon, slightly different flow patterns are observed than those known from the boiling process or these in adiabatic flow [7,8,14]. When the channel diameter is reduced to the mini- and microchannel ranges, there are three main groups of structures: intermittent, stratified and annular. The intermittent flow structures include slug and bubble structures, and the stratified flow structures include the wavy structure. There are also transitional structures like annular-wavy [3]. Figure 1 shows these flow patterns described above.

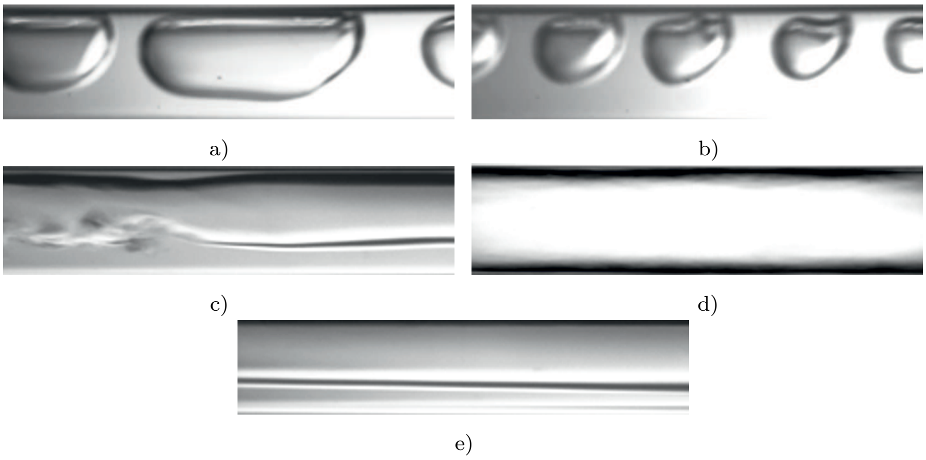

Figure 1: The most common flow structures in mini- and microchannels: a) slug, b) bubble, c) wave, d) annular, e) stratified.

Kawaji and Chung [4] presented a more detailed division of the flow structures for both mini and microchannels. This division is based on the adiabatic two-phase flow and is showed in Fig. 2.

To determine what kind of flow structure occurs at a given moment in the process, the visualization investigations should be conducted. Registered structures and thermal and flow flow parameters of the phenomenon are the basis for developing maps of flow structures. Research of this kind has been dealt for a long time by different scientists. Most often these are studies of adiabatic flow structures. Less often, can be found the results of condensation visualization in conventional and minichannels.

In the paper [10], the authors presented the results of thermal and flow investigations combined with visualization of R22, R407C, and R134a refrigerants condensation in finned channels of internal diameter ranging from 8 to 9 mm. Based on this research, the flow map for R134a refrigerant was established and presented in paper [10]. In [15] presented were the results of R134a refrigerant condensation visualization in a glass channel with internal diameter of 6 mm and length 0.2 m. This channel was cooled by water and the two-phase flow was recorded with a slow motion camera. The authors, in addition to identification of the flow patterns, made measurements of the condensate film thickness in the stratified flows.

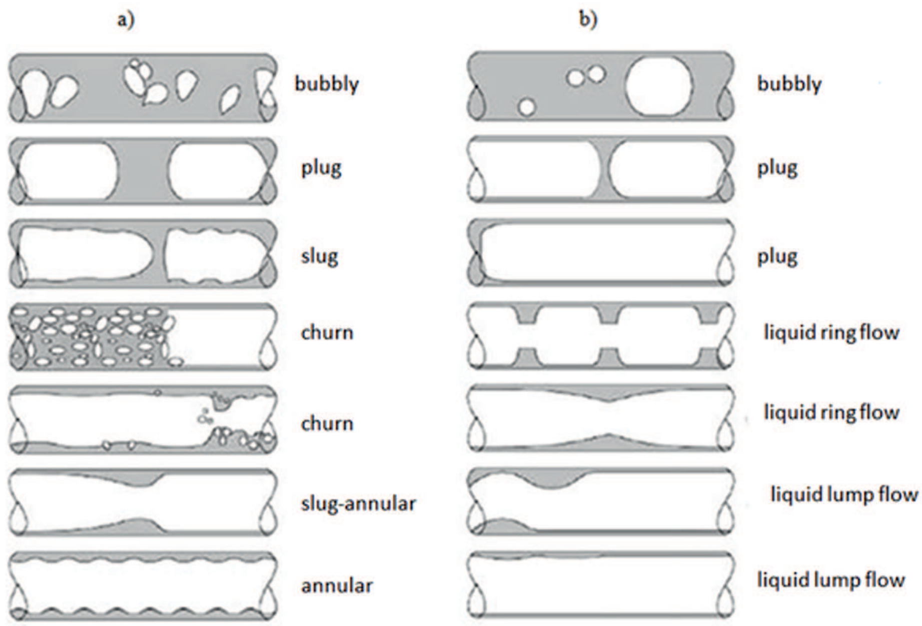

Figure 2: Classification of two-phase flow structures according to Kawaji and Chung [4] for: a) minichannels, b) microchannels.

The studies of two-phase flow structures during condensation in mini and microchannels have started relatively recently. Ong and Thome [11] conducted this type of study on three refrigerants: R134a, R236fa, and R245fa in channels with internal diameter d = 1.03; 2.2 and, 3.04 mm. During the study, they observed the transition from micro to macro-scale and they determined this transition by application of the Co number proposed by Kew and Cornwell [5]:

$$Co = \frac{1}{d}\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}\,, \tag{1}$$

where: d – internal diameter of the channel, g – gravitational acceleration, ρ_l – density of refrigerant liquid, $\rho_{\rm v}$ – density of refrigerant vapor, σ – surface tension. They observed such structures in micro-scale as bubble, annular-wave and annular. On the basis of presented results a new map of flow structures was made.

A little earlier research on the flow patterns in minichannels was undertaken by Chen [2]. He observed the process of condensation in triangular minichannels gouged in a silicon chip. In this case were observed: droplet, annular-slug and bubble flow structures.

Kim *et al.* presented the results of visualization of FC72 refrigerant condensation in parallel water-cooled rectangular minichannels. This time, mainly annular, annular-wavy, bubble and slug structures were observed. The author compared his own investigation results with existing flow maps [6].

As it can be seen, the type of flow structures during condensation depends on the diameter of the channel, physical properties of refrigerant and the process parameters. During visualization studies it is possible to analyze the images on the basis of which certain flow parameters can be determined. Void fraction and the vapor quality are the parameters belonging to the geometric dimensions. These values characterize individual flow patterns and help in their identification and development of flow maps. In the next part of this paper, will be presented the image analysis method used by the authors to determine the flow parameters.

2 Test stand

The heat and flow investigations of methoxynonafluorobutane – HFE 7100 refrigerant – condensation, was performed at the test stand shown in Fig. 3. Results of these investigations are used for identification of flow structures in this process.

The research facility is divided into two measuring sections. Section A is used for carrying out the thermal and flow analysis of refrigerant condensation in stainless steel minichannels. Section B is built of a glass minichannel in which the visualization of two-phase flow is made. The self-contained high speed video camera Olympus i-speed with the software was used to study flow structures.

In this system, the HFE 7100 refrigerant fluid is suctioned by a ceramic pump *1* and pumped to a heat exchanger *5* which works as an evaporator. An electronic flowmeter *4* was mounted on the inlet of liquid to the heat exchanger *5*. The liquid of refrigerant is heated by using electronic heaters, what causes evaporation of refrigerant (the vapor parameters in the outlet of heat exchanger *5* were monitored, and their constant level was maintained by the thermostat). On the inlet to the measuring section *12*, a water-cooled pre-heater *8* is mounted, the balance of which allows to determine of the vapor quality at the inlet to the measuring section. At the outlet from the measuring section, a refrigerant exchanger *14* and a tank *16* for HFE 7100 refrigerant liquid were mounted.

The condensation process in section B occurred in the glass minichannel, shown in Fig. 4. As a result of visualization tests, short films with high frame frequencies were obtained, and then the particular frames selected from the film were analyzed. This investigations was made in glass pipe with internal diameter $d = 2.0$ mm and outer diameter $D = 8.0$ mm.

3 Computer analysis of images

In the area of flow structures investigations there can be used many image analysis methods such as for example particle image velocimetry PIV, quantitative stereology, linear method of Cavalier-Hacquert [8,14], to determine geometry parameters of flow structures, velocity of each phase, vapor quality, and void fraction. The void fraction is defined as the volume fraction of the gas phase to the total volume of refrigerant and is described by dependence:

$$\varphi = \frac{V_v}{V_l + V_v}\,, \tag{2}$$

where: V_v – volume of vapor phase, V_l – volume of liquid phase.

The value of void fraction can be determined in many ways, one of them is image analysis. For this purpose, the ratio of the areas occupied by the gas to the total cross-section area of the visible channel is determined. This is possible on the assumption that in a circular channel, the flow patterns are circularly symmetrical. In this way, it can be assumed that the proportion of the gas phase in the total volume determined for the two-

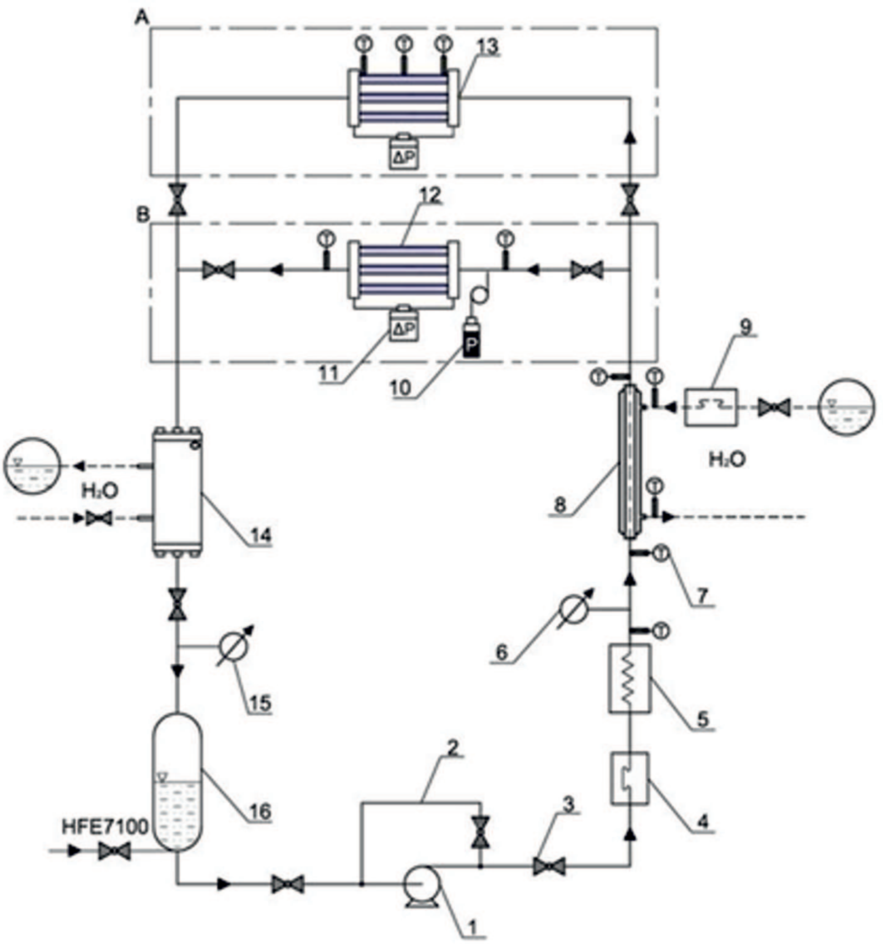

Figure 3: Schematic diagram of the test stand for thermal and flow investigations, and visualization of diabatic flow: A – section for thermal and flow investigations of refrigerant condensation, B – section for visualization studies of two-phase flow structures; 1 – pump, 2 – bypass for the flow control, 3 – valve, 4 – refrigerant electronic flowmeter, 5 – evaporator, 6 – manometer, 7 – temperature sensors (K type thermocouple), 8 – preheater 'pipe in the pipe' type, 9 – electronic flow meter for the water, 10 – refrigerant pressure sensor for the inlet to the measuring section, 11 – differential pressure meter, 12 – horizontal flow visualization section, 13 – horizontal section for thermal tests 14 – heat exchanger (subcooler), 15 – manovaccuometer, 16 – tank for liquid refrigerant.

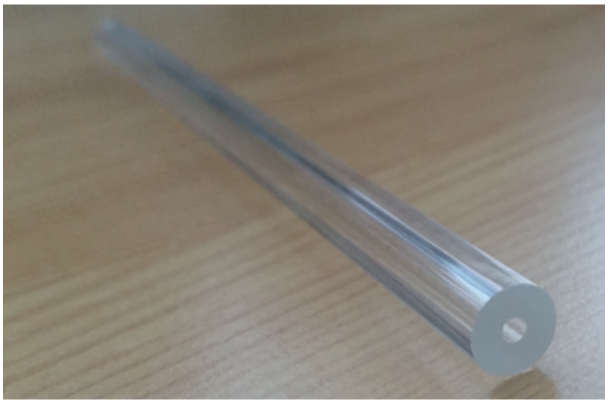

Figure 4: Glass pipe minichannel with internal diameter of 2.0 mm and length of 0.15 m

dimensional image is close to the real participation, and the designated value is static void fraction of the channel [1]. Authors in the presented investigations used the method described in the paper [9]. To determine the static void fraction, the image should be properly prepared. This image is the frame from the film recorded with the high speed camera. Then the image was processed in a graphical program to obtain a binary structure and represented only the interior of the minichannel. Figure 5 shows every steps of image processing. Black pixels occupy the fields filled by liquid, while white denote the gas phase (Fig. 5c). This image can be analyzed using an algorithm written in Matlab. This algorithm was described by its authors in [9]. It was used primarily for composite testing, but was also adapted to determine the void fraction of the minichannel. This algorithm includes elements for alignment: shape, color, contrast and brightness, as well as filtering. Based on the dimensions of the image and the number of black and white pixels counted by the program, the area occupied by the image in the phases is determined. The ratio of the black pixel surface (after conversion and image filtration by the algorithm – Fig. 5e) to the total surface of the image describes the void fraction. On this basis, dependence (3) can be determined vapor quality

$$x = \frac{\rho_v}{\left(\frac{\rho_l}{\varphi} - \rho_l + \rho_v\right)} , \tag{3}$$

where: φ – void fraction, ρ_l – density of refrigerant liquid, ρ_v – density of refrigerant vapor.

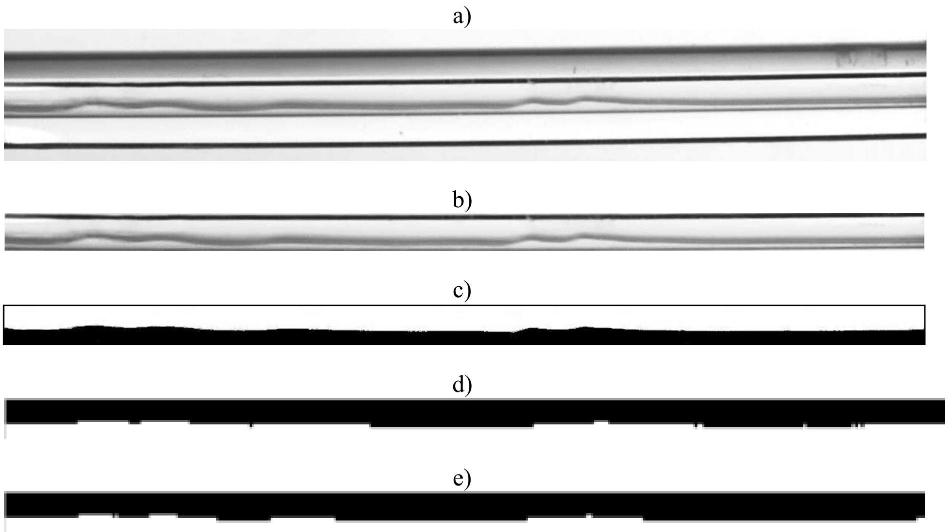

Figure 5: Subsequent steps of image processing before the analysis: a) film cage, b) image after minichannel interior cut, c) binary image, d) image after color inversion by algorithm, e) image filtered by algorithm.

A similar method of image analysis was used by Taminnen *et al.* [13]. Using the Matlab algorithm, they determined the size of the droplet, its speed, and the concentrations of copper particles in the droplet. Similar method is stereological analysis described by Masiukiewicz and Anwailer [8]. Authors use this method to analyze flow structures in adiabatic conditions. It can be used in investigations of flow structures during condensation, especially in minichannels.

Computer image analysis of flow structures is also possible with the software included with the Olympus i-speed unit. This program allows to determine the geometrical dimensions of the flow structures based on the number of pixels, after given a single dimension (for example channel diameter). The method of defining bubble dimensions is shown in Fig. 6. The camera software also allows for determining the speed of each phase. It is enough to mark a point on the image whose speed will be calculated by the program.

3.1 Sample image analysis results

The pictures of flow structures made during the condensation of the HFE 7100 refrigerant in a glass minichannel with an internal diameter of $d = 2.0$

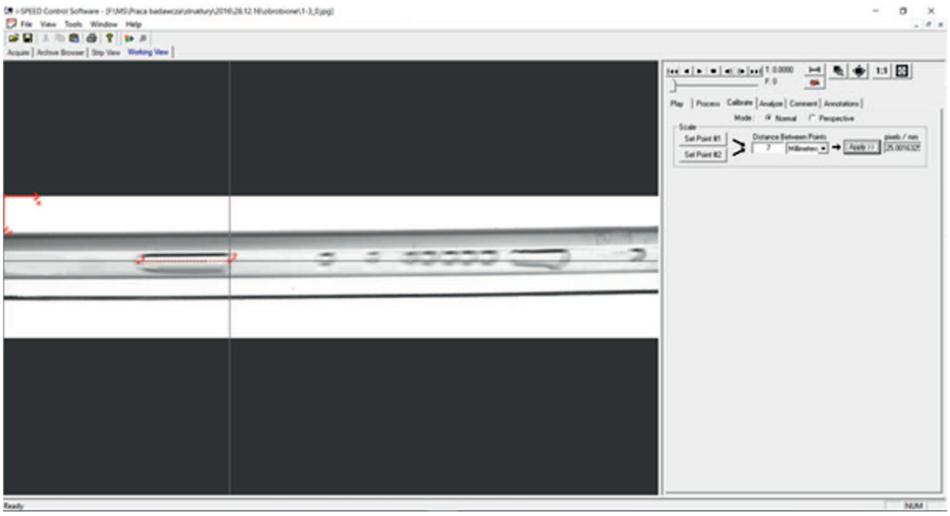

Figure 6: Measurement of the gas slug length during the flow in the minichannel.

mm have been subjected to image analysis. Figures 7 and 8 show the results of the analysis of two flow structures images for two mass flow densities of refrigerant. The flow parameters shown in description of these figures, such as the vapor quality and void fraction were determined by the method described in the previous section. Other parameters (T_s – saturation temperature and G – mass flux density) were measured directly.

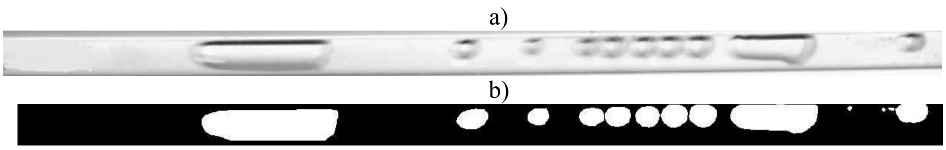

Figure 7: Results of the image analysis of bubble-slug structure during condensation of HFE7100 refrigerant in minichannal with internal diameter of 2.0 mm, G = 280 kg/m^{2}s, T_s = 40 °C, φ = 0.22, x = 0.036: a) analyzed image; b) image converted by algorithm.

Figure 9 shows the theoretical dependence of the vapor quality determined from Eq. (3) on the void fraction. As can be seeing this dependence is exponential, which explains the relatively small change in vapor quality relative to significant changes in the void fraction in Figs. 7 and 8.

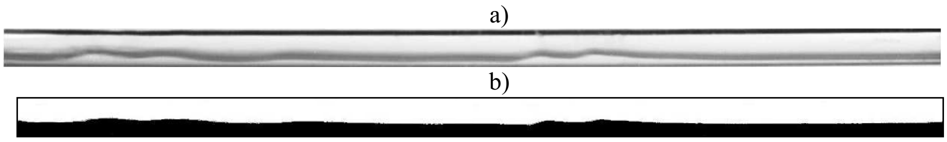

Figure 8: Results of the image analysis of annular-wavy structure during condensation of HFE7100 refrigerant in minichannels with internal diameter of 2.0 mm, $G = 287$ kg/m^{2}s, $T_s = 44\,^\circ$C, $\varphi = 0.65$, $x = 0.22$: a) analyzed image; b) image converted by algorithm

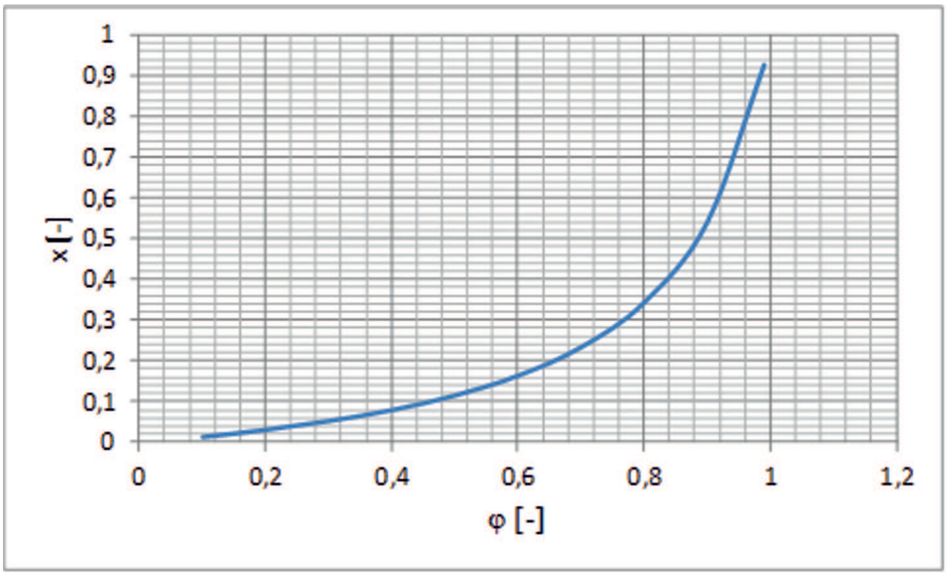

Figure 9: Theoretical dependence of the vapor quality, x, calculated from Eq. (3) on the void fraction, φ, of the minichannel for HFE 7100 refrigerant at $T_s = 40\,^\circ$C.

4 Conclusions

Computer image analysis is a very useful tool in investigations of two-phase flow structures. Its allows to directly measure the size of parameters determined in other cases indirectly. Such way reduces the measurement error of a given parameter. Measurement of this type does not require the installation of additional sensors, while reducing the cost of building a test stand. Due to the small diameter of the channel and the increase in the influence of surface tension on the condensation phenomenon, the diameter of the vapor bubbles is not much smaller than the internal diameter of the channel, thus eliminating the problem of overlapping of several bubbles in the image.

This reduces the measurement error in determining the void fraction. Determining the parameters of the two-phase flow during condensation process in minichannels and identification of the flow structures is essential in the process of flow structures maps designing. These allow to determine the most optimal operating parameters of the condenser, make work of designers and operators of refrigeration systems, easier.

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