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# Two-phase flow phenomena assessment in minichannels for compact heat exchangers using image analysis methods

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ABSTRACT

The paper describes a method of two-phase flow structure evaluation for minichannels. The two-phase flow structure appears in gas–liquid mixture. The research is based on innovative approach, with the use of stereology methods. Evaluation of the flow structure is made by image analysis. The images are obtained with high-speed visualization technique. The applied stereological analysis is based on the linear methods – the random secants method and directed secants method. Development of mini heat exchangers requires knowledge of the two-phase flow phenomena. The major result of conducted research is that for each flow structure there is a set of stereological parameters, enabling the quantitative estimation of the two-phase flow. It has been found that the interrelation of stereological parameters, during the change of the flow structure, can be used for controlling the operating conditions. The basic conclusion is that the knowledge about the character of the changes taking place in the flow structure may be used for constant process adjustment for various two-phase gas–liquid or gas–solid systems.

## 1. Introduction

Miniaturization is an important issue that is valid in multiple spheres of high technology industries. Very rapidly expanding energy industry companies, manufacturing various two-phase fluid flow devices, such as heat exchangers, are searching for new solutions, especially in the mini- and micro-scale. This is true for gas–liquid, solid–liquid as well as for gas–solid two-phase systems. Gas–liquid flow applies mainly in compact heat exchangers [1]. Also many other micro-technologies involve two-phase flow such as pumps, reactors, heat pumps, heat pipes, evaporators, condensers and compressors [2].

There are significant difficulties in the interpretation of flow phenomena that occur in two-phase flow systems, as well as imperfections of two-phase flow diagnostic methods. One of the basic questions regarding the two-phase gas–liquid flow is the flow structure. The structure of the flow influences the intensity of mass and heat transfer processes. Knowledge of the flow structure can be used for assessing the exploitation conditions of two-phase flow devices. That is why conventional and widely accepted approach to the two-phase mixture flow research, strongly indicates the need for determining the type of flow structures and the extent of their occurrence. Two-phase flow regimes are analyzed in dependence of various factors such as smooth or rough walls, energy dissipation, transition from laminar to turbulent flow [3]. Friction, pressure drop, holdup and effects of the tube diameters or aspect ratios of the minichannels are studied [4]. Also mass flow instabilities are investigated in dependence of temperature and pressure drop [5].

The first and the most common methods for the flow structure assessment were based on direct observations made by the investigator. The next step were visualisation methods allowing further development of the classification methods by obtaining images of the process. For image acquisition, a variety of techniques have been used. The image registration techniques include many various methods. Among others there are photographic methods, densitometry radiation methods and various types of process tomography. Photographic methods include axial photography of two-phase gas–liquid flow [6]. Due to high dynamics of the investigated processes, high speed photography can be used [7]. Sometimes photography of flow instabilities is also important [8]. Where the optical observations are impossible, X-ray photography is applied [9].

Densitometry radiation methods include X-rays for dual-beam vapour fraction measurements [10]. Also void fraction measurements is possible [11]. $\gamma$-rays are used to determine cross-sectional distributions of solid concentrations [12]. That technique is used for evaluation of void fraction for transient two-phase flow as well [13]. For densitometry sometimes $\beta$-rays are performed [14].

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## Nomenclature

| | |
|---|---|
| $A$ | total image area, or channel's normal cross-sectional area ($m^2$) |
| $A_A$ | total field of flat sections on the individual β-phase of the image per unit area ($m^2/m^2$) |
| $A'_A$ | total field of flat projections on the individual β-phase per unit area ($m^2/m^2$) |
| $A_\beta$ | total field of flat sections on the individual β-phase ($m^2$) |
| $L$ | total length of the secants marked on the picture (m) |
| $L_\beta$ | total length of the chords on the individual β-phase (m) |
| $L_L$ | total length of the β-phase chords per unit length of secant on the cross-section (m/m) |
| $L'_L$ | total length of the β-phase chords per unit length of secant on the projection (m/m) |
| $\bar{l}$ | average chord length of the cross-sectional image (m) |
| $\bar{l}'$ | average chord length of the projection of the image (m) |
| $l_k$ | length of the *k*th secant (m) |
| $l_{ik}$ | chord length and the *i*th β-phase object on the *k*th secant (m) |
| $N'_A$ | number of cross-sections of objects per unit surface projection (pcs/$m^2$) |
| $N'_L$ | number of objects' chord per unit length of the secant on the projection (pcs/m) |
| $N_V$ | number of bodies in the volume (pcs/$m^3$) |
| $S_V$ | relative interfacial surface area ($m^2/m^3$) |
| $t$ | thickness of the analysed structure (m) |
| $V$ | total volume of the space or total volume of the mixture ($m^3$) |
| $V_\beta$ | total volume of the β-phase ($m^3$) |
| $V_V$ | total volume of the β-phase objects per unit volume of the mixture (%) |
| $w_{Go}$ | superficial gas-phase velocity (m/s) |
| $w_{Lo}$ | superficial liquid-phase velocity (m/s) |
| $\lambda$ | average free distance (m) |

The most popular tomographic technique applied for two phase measurement is electric capacitance tomography ECT [15]. Second is electric resistance tomography ERT used for flow regime identification [16]. There are some experimental attempts for microwave tomography applications [17]. Gas–solid flows require X-ray transmission tomography for fluidization flow pattern determination [18]. X-rays found some applications for void distributions across pipe flow measurements [19]. Another method for two phase flow evaluation is γ-ray transmission tomography [20].

Different approach for investigation of bubbly flows is ultrasonic tomography [21]. This group of methods also contains optical tomography [22]. One of the first observational techniques include a mirror scanner [23]. Also direct axial observation of the annular flow have been presented [24]. Additional technique for two phase flow assessment is Doppler analysis [25]. When particles are small laser systems can be used [26].

The classification of two-phase flow structures and the possibility of their registration solved the problem of their identification. However, in addition to extensive tomographic systems, it is still a subjective assessment made by the observer. Tracking the process under industrial conditions requires an objective identification, based on the evaluation of measurable features, characteristic for the particular two-phase flow. The solutions to this problem were attempted in many different ways. The most popular is by creating flow maps [27]. Another is cross correlation of flow regime maps developed by other authors [28]. Tests are made by using a variety of measurement techniques [29]. The most common methods for two phase flow assessment are measurement probes [30]. Also trapping methods are widely used for void fraction detection [31]. Advancements in computer technology allow using computer processing and analysis of signals [32]. Those signals are obtained from measurements and visualisation of processes [33]. Imaging and image analysis of two phase flow phenomena is made recently with videogrammetric methods [34]. Another approach to velocity profile are PIV techniques [35]. Due to new imaging devices development, imaging industrial flows is now widely available [36]. This allows DPIV techniques utilization [37]. Combination of all mentioned analysis techniques is called dynamic image analysis [38].

The recent development of two-phase flow devices with minichannels is huge. The research carried out for the minichannels is still rising. For example, the analysis of the influence of periodically generated hydrodynamic disturbances in mini compact condenser, with the diameter of channels in the range of 0.64–3.30 mm [39]. Another example is the investigation of frictional pressure drop during adiabatic liquid–vapour flow inside minichannels with hydraulic diameters ranging from 0.96 mm to 2.00 mm [40]. Also an optical measurement methods, using image processing for two-phase flow pattern characterization in minichannel are widely developed. For example the tests performed in a 3.00 mm glass channel. The mass velocity ranging from 100 to 1500 kg/$m^2$s, with heat flux varying from 10 to 90 kW/$m^2$ and the influence of the flow pattern on the heat transfer coefficient analysis [41]. Another investigations were carried for the characteristics of an air–water isothermal flow in minichannels, that is, in capillary tubes with inner diameters of 1 mm, 2.4 mm, and 4.9 mm, also in capillary rectangular channels with an aspect ratio of 1–9 [4].

Therefore it is clear that the development of mini devices for industries is thriving. Our aim is to develop new method for two-phase flow investigation. This will provide quantitative and qualitative assessment of the flow structure. New method can enable system control and additional verification of other numerical two-phase models and measurement methods. All previously described techniques, especially tomographic methods, give the most accurate quantitative and qualitative information, but they need a sophisticated thus expensive devices. Our technique, with the use of hi-speed camera and a common software is capable to achieve similar accuracy in 3D dimension. This is a significant novelty in the field of stereological techniques application for two-phase flow investigation, along with time analysis of flow structure image sequences which, by so far, no one performed. Minichannel technology finds many interesting applications in industry and academic research. Miniaturization of scientific and industrial components is the motivation to carry out the minichannel research. Minichannel technology offers many advantages in automotive heat transfer or in microelectronics for removal of high heat fluxes.

## 2. Stereological methods for quantitative description of the structure

Quantitative stereoscopic and stereological terms were introduced to the literature in the 1960's by a group of material-testing scientists and mathematicians. They were convinced that the images of different types of structures have many common features, if they are analysed with a certain level of generalisation. The progress was made in the area of methods for obtaining a