

## NON-INVASIVE EVALUATION OF WAVY LIQUID FILM

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The study presents the possible use of optoelectronic system for the measurement of values specific for hydrodynamics of two-phase gas very-high-viscosity liquid flow in vertical pipes. An experimental method was provided, and the findings were presented and analysed for selected values which characterise the two-phase flow.

**Keywords:** high viscosity, hydrodynamic flow, two-phase flow

### 1. INTRODUCTION

Multi-phase flow is a common phenomenon in numerous engineering installations in industry and, in particular, in various types of apparatus that apply this type of flow on an industrial and laboratory scale. The concurrent occurrence of gas and very viscous liquid phases in such systems result in many impediments in ensuring adequate operating conditions for apparatus in which we have to do with the process of the exchange of heat, momentum and mass (such as heat exchangers, evaporators, reactors). The basic reasons behind these problems are due to the largely stochastic characteristics of two-phase gas-liquid flow in which various flow structures and forms are encountered – as the specific flow structures are relative to the void fractions of the liquid and gas phases as well as mechanical properties of the components of the mixture. Various process conditions that correspond to these structures thereby constitute basic obstacles in ensuring adequate flow regimes and, concurrently, maintenance of required process parameters along the entire flow path. An important role is attributed to such solutions that secure the optimum operation of the process apparatus within maximum time ranges, which has to be accompanied by the elimination of adverse phenomena that can be associated with the course of the processes. The information found in the literature of the subject indicate that annular two-phase gas-liquid flow is applied more and more commonly, owing to its efficiency with regard to heat and mass exchange with the concurrent possibility of applying in these processes substances that vary in terms of physical properties.

Thin-film evaporators, film heat exchangers, film absorbers and thin-film condenser apparatus are examples of devices in which annular two-phase flow is applied. All of these devices are encountered in a range of construction varieties that are relative to process parameters and manufacturer's design. Modifications and improvements in them are predominantly aimed at improving heat exchange efficiency and, thereby, lowering the operating costs and reducing their size. Apparatus that use this type of flow within a wide variety of operating conditions, and in particular, various types of two-phase annular gas-liquid flow has resulted in the necessity of more in-depth analysis of the processes and phenomena that accompany their use. Specific attention has been directed at the co-current, two-

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component, two-phase gas-very viscous liquid flow in vertical pipes with an aim at assessing and describing hydrodynamic conditions that are encountered in this type of flow.

To this date a large number of papers (Czernek et al., 2008; Schmidt et al., 2008; Wojtan et al., 2005; Xu, 2007) have been disseminated in description of almost all types of flow structures in multi-phase flow. The research covered in these papers includes issues pertaining to identification and description of forming flow structures, areas of their occurrence (flow maps), determination of pressure drops and volume fractions of specific components of a mixture as well as thickness of fluid films and characteristics of their wavy structures - all of which are standard issues put forward in the description of hydrodynamics of two-phase gas-liquid stream. However, regardless of the means in which two-phase gas-liquid stream is formed, in flow channels we have to do with various structures that originate as a consequence of the mutual configuration of the phases. The form and type of such structures are relative to phase streams, geometry of the channel, its configuration (vertical, horizontal, other layouts) as well as the physical and chemical properties of the components of two-phase mixture, and in particular that of the liquid phase. These remarks are based on original experimental research by these authors (Czernek, 2004; Czernek, 2009; Czernek et al., 2006; Czernek et al., 2008; Troniewski et al., 2006) conducted within liquid viscosity range up to 3500 mPa·s.

The classification of flow structures is usually undertaken on the basis of visual observation of the flowing mixture. For cases when such observation is impossible, various visual systems are applied, or unconventional observation techniques are applied, including:

- special photography systems (Czernek, 2009; Czernek et al., 2006; Czernek et al., 2008; Troniewski et al., 2006),
- single- or multi-areas image capture in the cross-section of the stream (Du et al., 2002),
- photography by means of a beam of X rays (Saito et al., 2004; Stahl et al., 2004),
- optoelectronic cross-section image structure detectors (Oriol et al., 2008),
- computer tomography (Ikeda et al., 1983),
- holographic filming (Lee et al., 1986).

From the application viewpoint, and in particular from the perspective of design, it is more practical to gather information regarding specific flow structures in a manner that enables the user to predict the occurrence of a particular flow structure. From process perspective, it is well justified and even favourable since it can offer adequately high process results (increase of heat exchange efficiency improvement of flow rate, etc.). The areas of the occurrence of specific forms of two-phase flow are usually presented in charts that are called flow maps. They form a graphical interpretation of flow conditions, by indicating particular flow structures that are separated into boundary lines. In the literature of the subject, one comes across a large number of such studies that only differ in terms of the approach to the descriptions following them. However, one can note that there is a lack of conformity between the authors with regard to the way in which relative co-ordinate systems are described. As a consequence, there is a deficiency in terms of universal flow maps that can be applied in various process conditions. This is undoubtedly due to complex hydrodynamic conditions during two-phase gas-liquid flow. It is so since such flows are made by various and variable in their form structures. Large number of papers indicates both large complexity of the phenomenon connected with hydrodynamics of the two-phase gas-liquid flow. These difficulties also stem from the fact that flow structures are drawn up on the basis of observation through the application of transparent channels in research. This is definitely one of the major reasons why we now lack unequivocal criteria that determine the transfer boundaries between one phase and another one. These boundary lines are often in the form of conventional transfer areas with a large similarity between the changes occurring in them.

In the consideration of the large number of flow maps encountered in literature, whose overview can be found in papers by Czernek (2004), Dziubiński (2005) the problem that appears is the one associated with the selection of a flow map that is adequate for given process conditions. According to these

authors it is very beneficial to apply maps (even map models) that have been developed for conditions that are similar to the actual ones even at the expense of smaller precision.

A very relevant element that affects the course of heat and mass exchange process is the one connected with the surface of the exchange. For the co-current downward gas- very viscous liquid flow there is a possibility of disturbance in the interfacial surface in the form of an occurrence of waves. Such disturbance increases the surface of the contact between the phases. The knowledge of the flow parameters, for which the contact surface is possibly the largest and has no influence on the reduction of the flow rate or other complication, offers the possibility of conducting the process in an apparatus with virtually too small interfacial surface. Hence, the characteristic of interfacial surface forms an important component in conducting thin-film processes.

## 2. EXPERIMENTAL TESTING

The development of engineering methods and improvements in measurement devices has made it possible to gain results that had been otherwise impossible previously. Optoelectronic devices form an example of a measurement system that is applied in experiments. A general view of the test stand that was applied for the measurements of annular two-phase gas-very viscous liquid flow is presented in (Figure 1).

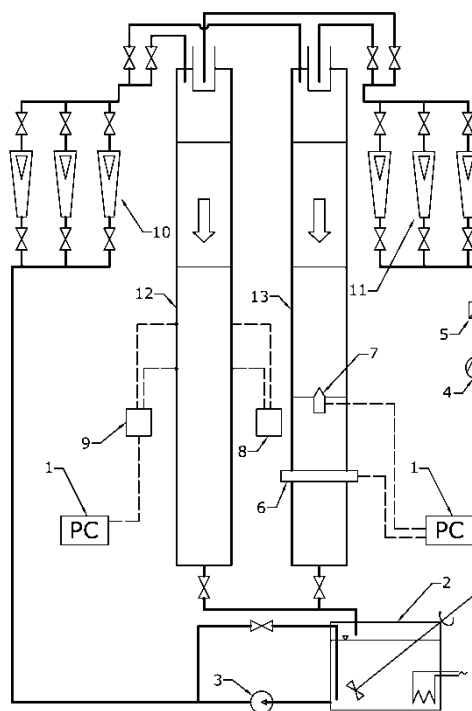


Fig. 1. Diagram of test stand;

- 1-PC, 2-oil tank with agitator and heater, 3-oil pump, 4-air compressor, 5-reducing valve, 6-laser knife, 7-camera, 8-laser illumination, 9-light detector, 10-oil rotameter assembly, 11-air rotameter assembly, 12-measurement channel with laser illumination, 13-measurement channel with laser knife

Machine oil and air with various viscosities were applied in the installation as circulating media. Channels 12 and 13 (with the respective dimensions of 22 and 40 mm) are fed with compressed air. As a result of application of a reducing valve, constant pressure was maintained in the installation, which enabled correct measurements of its stream. The air was subsequently directed into the initial section of the feeding system that was built in the form of a system with a central nozzle. The oil was pumped

into the installation by means of a pump into the feeding chamber (one with the gas) as a result of which two-phase mixture was obtained.

The streams of oil and gas were selected in such ratios that the resulting mixture, annular structure of two-phase gas-liquid flow was obtained. By means of optoelectronic sensors 8 and 9 local thickness of liquid films was determined along with the characteristics of the wavy structures occurring in them. For this purpose, linear measurement system was applied (Figure 2), which consisted of four single-axis measurement sensors situated along the cross section of the channel, which applied the principle of dilution of light spectrum passing through an oil film.

The measurement of the thickness of oil film involved the measurement of damping of optical signal by means of a photodetector that was lit from the opposite side by an LED illuminator. The length of the light waves emitted by illuminators was selected on the basis of a calibrating measurement of the absorption spectrum for each type of film. This length was equal to 470 nm (blue color) for ITERM-12 oil and 535 nm (green color) for ITERM-30MF oil. Within the two ranges the oils revealed the highest level of signal damping.

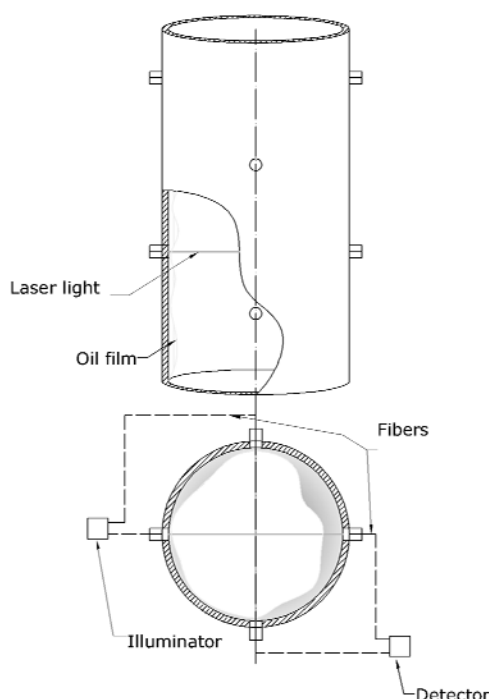


Fig. 2. Optoelectronic single-axis probe

The methodology of determining geometrical parameters of liquid films resulting from the operating principle of single-axis measuring probe (Figure 2) was relatively simple. It involved registration of the thickness of downward liquid film flow and its shape at a given point of a local longitudinal cross-section of a channel. An idea about the distribution of these parameters along the cross-section of a pipe was arrived at by while using four types of probes, which were installed diagonally along the circumference of a pipe over its length of 200 mm. The results were averaged for local conditions, which made it possible to determine such parameters of downward film flow as:

- thickness as the value measured for local states and its averaged value,
- wavy structures along the interfacial surface that was possible to map along the longitudinal surface of a given probe (measurement in time domain),
- local phenomena on the boundaries of the liquid and gas phases resulting from this state, such as amplitude and speed of wave propagation as well as their height.

The averaging of the local conditions has consequently led to determination of the mean interfacial surface for a given structure of annular gas-very viscous liquid flow. Examples of the measurements performed with the aid of a linear system are presented in Figure 3.

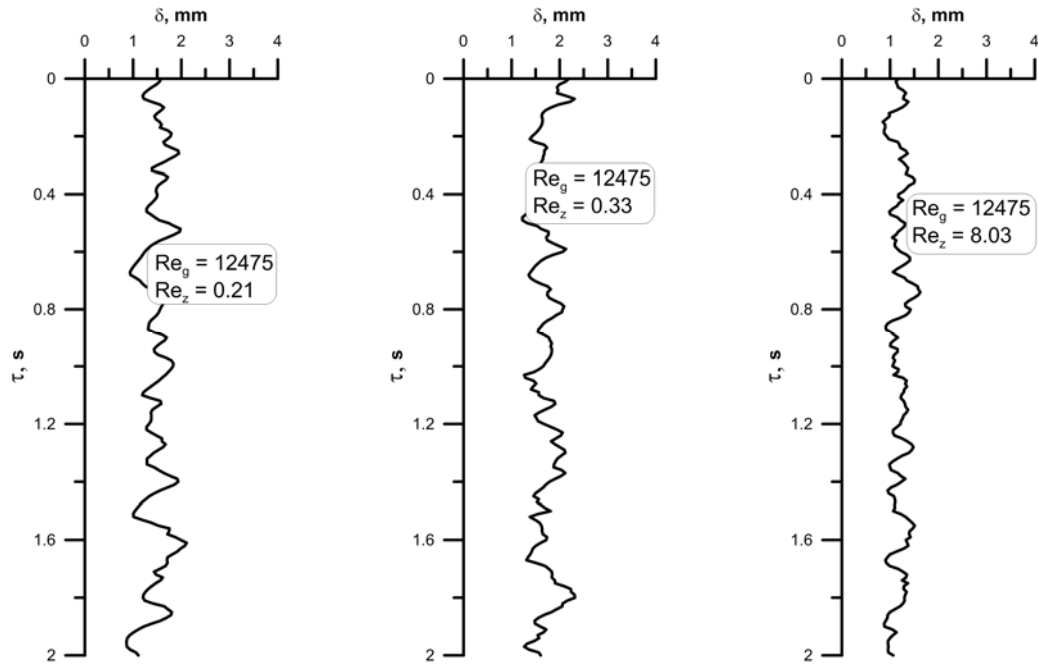


Fig. 3. Representation of variable liquid film thickness along the flow route

Reynolds number for gas and liquid is defined as follows:

$$Re_g = \frac{w_{g,0} \rho_g d}{\eta_g} \quad (1)$$

$$Re_z = \frac{4\Gamma}{\eta_l} \quad (2)$$

The distribution of lines in these profiles indicates that for the highest gas streams (Figure 3), regardless of the equivalent Reynolds number we will have to do with hydraulic flow structures of viscous liquid, while in other cases the transfer to such flow structure will be considerably relative to the occurring liquid streams.

A relatively low value of Reynolds number leads to the formation of wavy flow structures which transform the flow into hydraulic (for a constant equivalent Reynolds number). Additionally, relative velocity of waves (in relation to the mean liquid film velocity) considerably decreases along with an increase of the equivalent Reynolds number.

Whereas the above described point based system of optical probes made it possible to capture the linear state of the configuration of gas-liquid flux, the other applied system – multi-channel system of object-oriented image analysis – enabled the authors to assess the state with regard to the entire cross-section of the channel (Figure 4).

In its principle the system is formed by an optoelectronic image registration and analysis system based on a similar principle as a point-based one (light spectrum damping on the boundary of the liquid and gas liquid phase). However, in contrast to it, in this case a beam of light focusing on the entire cross-section of the channel was applied and the image was captured by means of an endoscope digital camera situated in the axis of the measuring channel. Overall, this system is based on the principle of a

laser knife, which involves registration of image that is visible in a vertical light beam focused in the cross-sectional plane of the channel with adjusting of the image resulting from the application of an optical system. This system, in consideration of the technical limitation associated with the geometry of the endoscope camera (12 mm), was used in a channel with the diameter of 40 mm.

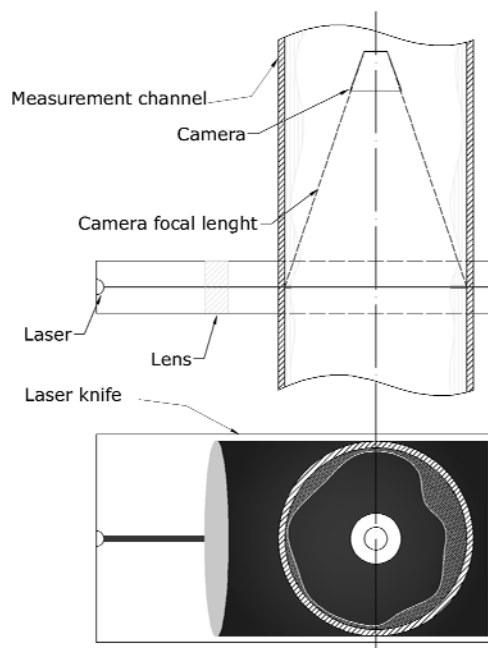


Fig. 4. Diagram illustrating the operating principle of a laser knife

Measurements with a laser knife were performed in accordance with the following principle. The first stage involved the registration of the representation of the interfacial surface in the lateral cross-section of the channel, whose schematic diagram for a given instantaneous state is presented in Figure 5. This contains two marked characteristic parameters of the configuration of the annular structure in such cross-section, i.e. local thickness of liquid film ( $\delta_i$ ) and the geometrical interval over the total circumference ( $\Delta\beta_i$  angle), which correspond to thickness in an arbitrary point of the lateral cross-section of the observed liquid film. In the function of time this mapping, as a set of subsequent figures, brought the information regarding the state of the interfacial surface along the axis of the pipe.

As a consequence, for a given time interval this set formed a sort of semi-continuous mapping of the image of interfacial surface that appeared in the mirror of the laser knife. A schematic diagram of this is presented in (Figure 6).

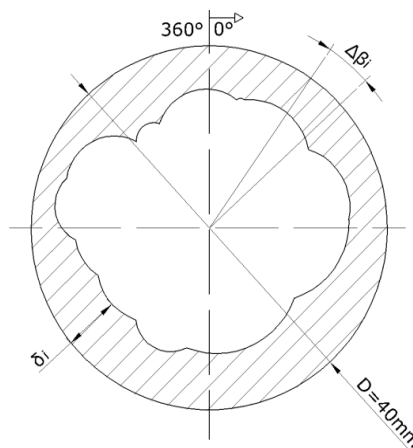


Fig. 5. Diagram of the image gained from the system of object image analysis:  
 $D = \text{const.}$ ,  $\Delta\beta_i = 1, 2, 3, 6, 10, 36, 45, 90, 180, 360 \text{ deg.}$ ,  $\Delta\beta_i$  – interval of the capture angle

The qualitative and quantitative analysis of the image captured by means of object image analysis involved an adequate transformation of a specific optical configuration into actual conditions. Within the range of these calculations it was possible to quantitatively assess such flow parameters as:

- thickness of liquid film (local and mean values) both in the cross-section of the channel as well as along the flow route for a given time and geometrical interval,
- state of the development of interfacial surface in a given time interval,
- volume fraction by comparing the cross-sections occupied by the liquid and gas phases.

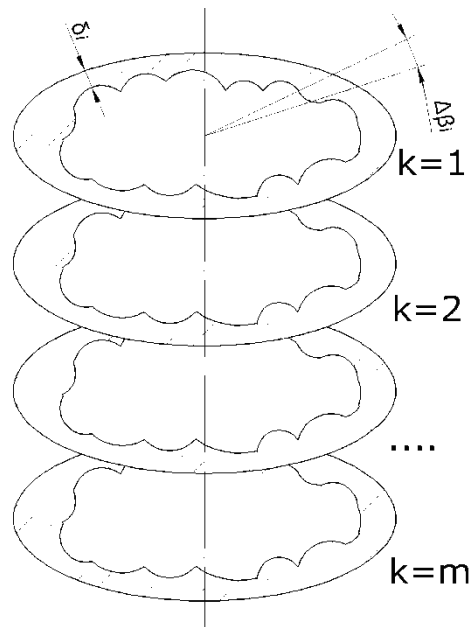


Fig. 6. Image structure captured in the plane of the laser knife ( $\Delta\tau = \text{idem.}$ )

The application of optoelectronic measuring system in the form of laser knife offered supplementary output to the optoelectronic linear system and enabled the authors to extend the range of identification to geometrical parameters that are specific for the downward flow of liquid film.

In order to illustrate changes occurring on the surface of the liquid film as a result of the increase of the velocity of co-current gas phase, Figure 7 presents examples of planar images of this surface captured over the total circumference of the channel (with a geometrical interval). These images concurrently reflect annular flow structure and in quantitative framework ( $\eta_c = \text{const.}$ ) – they indicate the change in downward liquid film referred to local conditions.

Notably, an increase in the velocity of gas flow results in the occurrence of increasingly higher waves on the surface of liquid film. Beside the smooth and light wavy structures they often have irregular character and the appearances of wavy states on the boundaries between phases have spatially and temporally variable amplitude and length. The spectrum of these changes indicates that regardless of the initially smooth liquid films, within the Reynolds numbers (4000÷10000) of the gas there will always be wavy structures and the nature of the development of waves and their dimensions are considerably relative to the viscosity of the liquid (the more viscous liquid, the larger wave damping) (Czernek et al., 2008; Troniewski et al., 2006).

Exemplary results of calculations which illustrate the distribution of liquid film over the cross-section of the pipe in a given time interval are graphically illustrated in Figure 8.

These results confirm the previously stated remarks concerning the fact that two-phase gas- highly viscous liquid flow forms a considerably complex hydrodynamic phenomenon, which is accompanied by multidimensional asymmetry of the liquid film profile. This is further accompanied by stochastic characteristics of flow phenomena, whose scale is varied depending on the flow conditions. This is

particularly discernible within the range of very wavy and hydraulic flow structures, in which we have to do with very variable in time values of liquid film thickness. As a consequence, there is an occurrence of variable volume fractions of phases along the flow route. In addition, some role is played by the variable interfacial surface in these conditions.

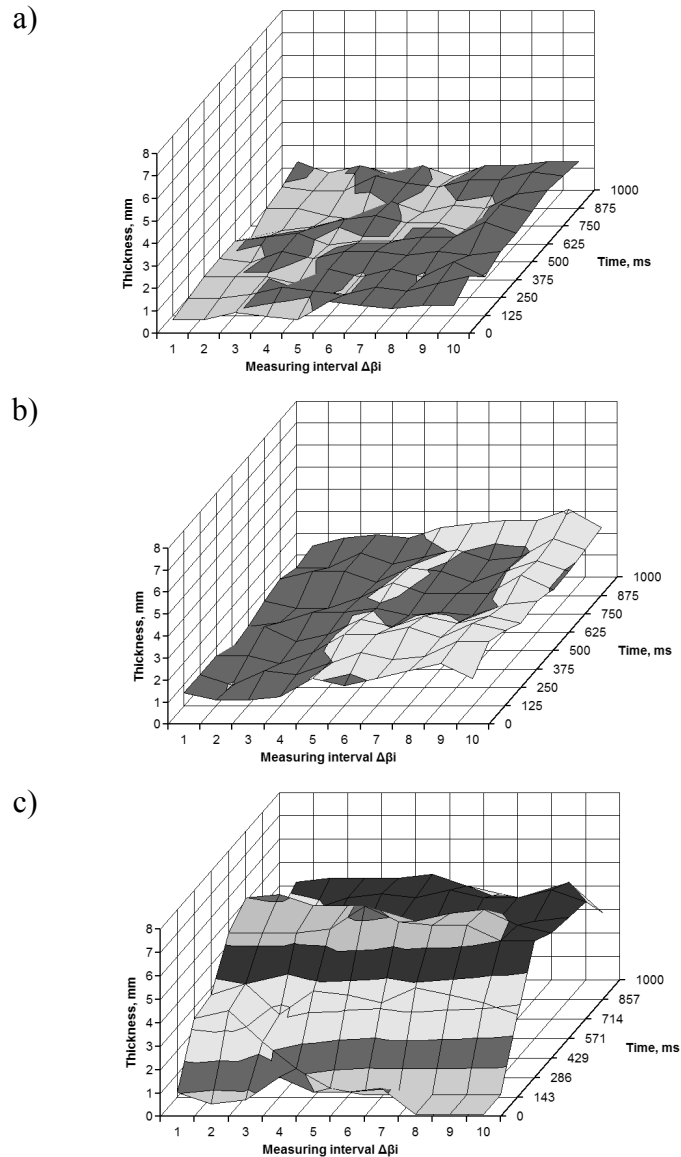


Fig. 7. Development of interfacial surface and distribution of oil film thickness along the flow route:  
a) smooth flow ( $Re_g = 1300$ ), b) wavy flow ( $Re_g = 7800$ ), c) hydraulic – high waves ( $Re_g = 14300$ )

In order to indicate the formation of interfacial surface for various values of flow parameters, Figures 9 and 10 contain a spatial stylisation of the conditions of this surface related to specific internal surface of the channel.

Changes of the liquid film thickness versus time were used for numerical calculations of the contact surface of gas and liquid,  $F_{2F}$ . In order to determine  $F_{2F}$  in relation to the internal surface of the pipe,  $F_p$ , it was assumed that:

$$F_p = \pi d \Delta L_{cal} \quad (3)$$

where

$$\Delta L_{cal} = w \Delta \tau \quad (4)$$



The calculated length,  $\Delta L_{cal}$ , determines in this case a way, which a liquid film passes with velocity,  $w$ , determined for the average layer thickness,  $\delta$ .

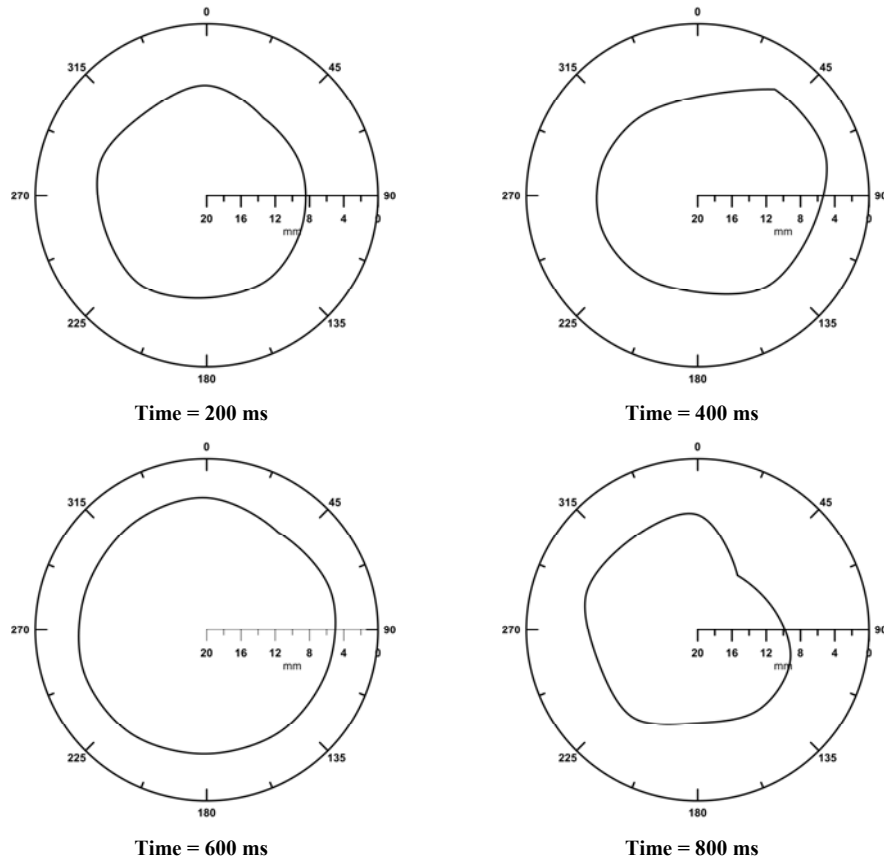


Fig. 8. Distribution of hydraulic film thickness

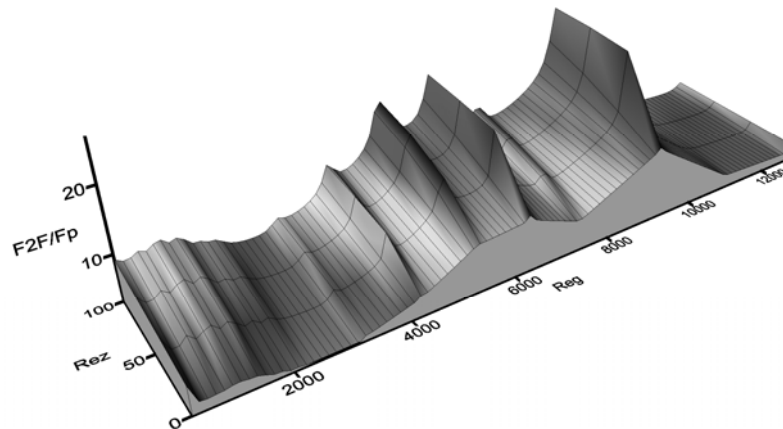


Fig. 9. Representation of interfacial surface in relation to the distribution in experimental points

The following equation was obtained from theoretical considerations and correlation calculations:

$$\frac{F_{2F}}{F_p} = 46,73 \left( \frac{\varepsilon}{1-\varepsilon} \right)^{0,635} Re_g^{-0,679} Re_z^{-0,108} \quad (5)$$

where:  $\varepsilon = \frac{w_{g,0}}{w_{g,0} + w_{c,0}}$

Results of calculations (according to Eq. 5) were presented in Figure 10.

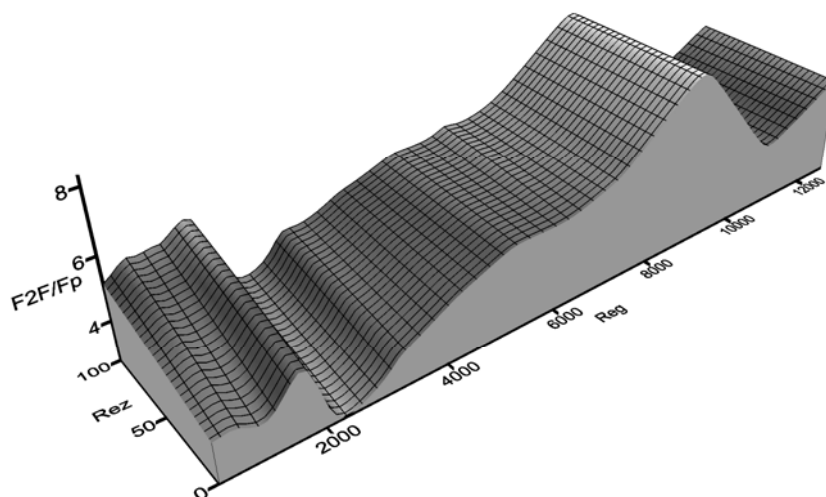


Fig. 10. Averaged representation of interfacial surface the flow parameters as in Fig. 9

The presented states with respect to the equivalent Reynolds number and Reynolds number for the gas indicate a variable distribution of this surface, in particular in the upper range of Reynolds number for the gas. This is undoubtedly due to the variable wavy structures of liquid film which promote the formation of additional capillary waves and consequently affect the size of the wave.

On the other hand, higher dynamics of gas flow (in a certain range) promotes the development of interfacial surface, thus, as a consequence of these conditions brings an opposite effect for the ultimately ever thinner and thinner hydraulic film in this range. It is fair to state that the size of interfacial surface is decided predominantly by the structures of the forming annular film, but not film thickness which results from a given structure.

### 3. CONCLUSIONS

The presented optoelectronic measurement systems made it possible to identify such flow parameters as: liquid film thickness, velocity of wave dispersion on the surface as well as their dynamics. Whereas the system of optical probes applied a point-based system and thus enabled the capture of a linear configuration of the gas-liquid stream, the multi-channel system of object-based image analysis provided means for the assessment of the state with regard to the entire cross-section of the channel and operated on a laser knife principle.

The applied measuring systems made it possible to perform a detailed analysis of dynamic states of the measured quantities, which enabled the authors to undertake quantitative assessment of variability of parameters which accompany annular flow. They are relevant in the determination of the development of interfacial surface. A considerable reduction of wave amplitude was noted on the interfacial surface as a result of damping of pulsations of annular flow by the very viscous liquid.

It was additionally indicated that an increase in the velocity of gas flow promotes the occurrence of higher waves on the surface of liquid film. With the exception of smooth films or light wavy ones these changes are irregular, which is manifested by the varied development of the interfacial surface. The occurrence of waves on the surface of phase separation is characterised by amplitude and length that are variable in time and space, which considerably complicated a quantitative description of the hydrodynamics of such phenomena.

From the analysis of experimental data obtained with the presented optoelectronic measurement systems one can conclude that within the entire range of variable process parameters all of them have a considerable effect on the formation of liquid film thickness. An increase in liquid viscosity always promotes an increase of mean thickness of liquid film. Concurrently, an increase in the stream of the gas phase for a constant Reynolds equivalent number for the liquid density leads to a thinner liquid film only in the flow area with a strongly developed interfacial surface, just as in the case of hydraulic flow. These conditions are often accompanied by phenomena of wave interference, which promotes their accumulation or results in formation of additional capillary waves, which in some occasions leads to the occurrence of locally greater thickness (also with regard to the mean value). This peculiarity is particularly characteristic with regard to a very viscous liquid.

## SYMBOLS

$d$	diameter, m
$g$	densities of mass stream, kg/(m <sup>2</sup> s)
$Re$	Reynolds number
$w$	superficial, m/s

### Greek symbols

$\Gamma$	unitary spraying intensity, kg/m·s
$\delta$	liquid film thickness, m
$\eta$	viscosity, Pa·s
$\rho$	density, kg/m <sup>3</sup>
$\varrho_z$	equivalent linear dimension, m

### Subscripts

0	apparent values, calculated for full cross-section area of passage
2F	two-phase flow
cal	calculated value
$i$	local
$l$	liquid
$g$	gas
$z$	equivalent values for liquids

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Received 20 November 2012

Received in revised form 08 April 2013

Accepted 10 April 2013