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## MULTI-PHASE FLOW MIXTURE THROUGH A SUDDEN CHANGE IN CHANNEL CROSS-SECTION

### PRZEPIY W MIESZANINY WIELOFAZOWEJ PRZEZ NAGŁĄ ZMIANĘ PRZEKROJU KANAŁU

#### Abstract

The paper presents the results of a study involving the impact of sudden change of cross-sectional area on the flow patterns and local pressure drops for flow of multi-phase mixture. The experiment was conducted in the conditions of a horizontal and vertical flow through a measuring channel. Pressure drops calculated on the basis Kawahara and Lottes methods are compared with experimental data. A system of two interconnected pipes with internal diameters of 40 and 22 mm as well as 46 and 16 mm and a total length of 7 m formed the measurement channel. The experiments involved air, water and oil.

*Keywords: multi-phase flow, contraction, expansion, flow patterns, pressure drops*

#### Streszczenie

W pracy przedstawiono wyniki badań dotyczących wpływu gwałtownej zmiany pola przekroju poprzecznego kanału na struktury przepływu oraz miejscowe straty ciśnienia w przepływie mieszaniny wielofazowej. Porównano spadki ciśnienia obliczone na podstawie metod Kawahary i Lottes z wartościami eksperymentalnymi. Badania prowadzono w warunkach poziomego i pionowego przepływu przez kanał pomiarowy z przeszkodą lokalną. Kanał pomiarowy stanowił układ dwóch rur o średnicach wewnętrznych 40 i 22 mm oraz 46 i 16 mm i całkowitej długości 7 m. Fazę gazową stanowiło powietrze, a fazę ciekłą olej maszynowy i woda.

*Słowa kluczowe: przepływ wielofazowy, przewężenie, rozszerzenie, struktury przepływu, opory przepływu*

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## 1. Introduction

Multi-phase flow of gas-liquid mixtures takes place in a variety of installations in the chemical, oil, gas, or food industries, to mention just a few. The local obstacles, such as sudden expansions and contractions of the pipe, are inherent components in a number of flow-through systems. As pressure, volume fraction and flow pattern regimes are considerably affected by the design of such systems, it is important to understand the impact of existing elements on the parameters of multi-phase flow. The knowledge of the type of multi-phase flow patterns plays a fundamental role in the calculations of flow parameters [1]. However, the ability to forecast the type of flow pattern is very difficult due to the very nature of multi-phase flow. An additional difficulty is associated with the existence of certain areas of flow pattern disturbance caused by a change in the cross-section of the pipe.

Despite the bulk of research into multi-phase flow in straight channels reported to this date, there is a scarcity of works concerned with the subject of multi-phase flow in the channels including a sudden contraction or expansion of the cross sectional area of a pipe. Only a few methods for calculating the local pressure drop of two-phase flow through a sudden contraction and expansion are available in the literature. However, even the existing methods do not account for all parameters that affect the value of the pressure drop during such flow including, in particular, a study of the impact of flow pattern disturbances. For this reason, experimental research was carried out and is reported by the authors.

To complement and expand the description of the phenomena of the gas-liquid flow resulting from a sudden change in the diameter of a channel, new experiments and studies work were carried out.

## 2. Experiment

The experimental setup was designed and built according to recommendations available in the literature. For clarification purposes, the diagram presents the design of the flow-through system for the case of horizontal flow in Figure 1. The main element of the installation was a measurement channel, which consisted of two interconnected pipes with two internal diameters of  $D = 40$  mm and  $d = 22$  mm in a horizontal layout and a total length of 7 m. An experiment involving flow through a sudden expansion or contraction of the channel was conducted for this purpose. The pipes were made of transparent PMMA, as it enabled the authors to visually assess two-phase flow patterns and their disturbance areas. The length of these areas was determined using a millimetre scale placed along the pipes.

Multi-phase mixture consisted of a mixture of water or low viscosity oil and air. The volumetric flow rates of phases were measured by flowmeters of oil, water and air ( $V_{oil} = 5.0 \div 20.0$  dm<sup>3</sup>/min,  $V_{water} = 2.0 \div 20.0$  dm<sup>3</sup>/min and  $V_{air} = 1.6 \div 509.0$  dm<sup>3</sup>/min). The observations of the flow patterns were performed on a 1 m test section, which was located at a distance of 50 diameters from the inlet to the test section. This made it certain that the flow structure is fully developed and it is not affected by the installation of a local obstacle. In addition, the flow patterns were also observed directly before and after the local obstacle. A series of pressure transducers were installed behind the control section, used for the

measurement of the pressure drops due to the existence of a sudden pipe contraction or expansion. The system of pressure transducers locations used for the measurement along the pipe is the same before and after a local obstacle. The data regarding the local pressure drops was collected by a measurement card, coupled with a computer, which recorded data at a high frequency (i.e. 100 measurements per 1 second) followed by averaging the measured values over time.

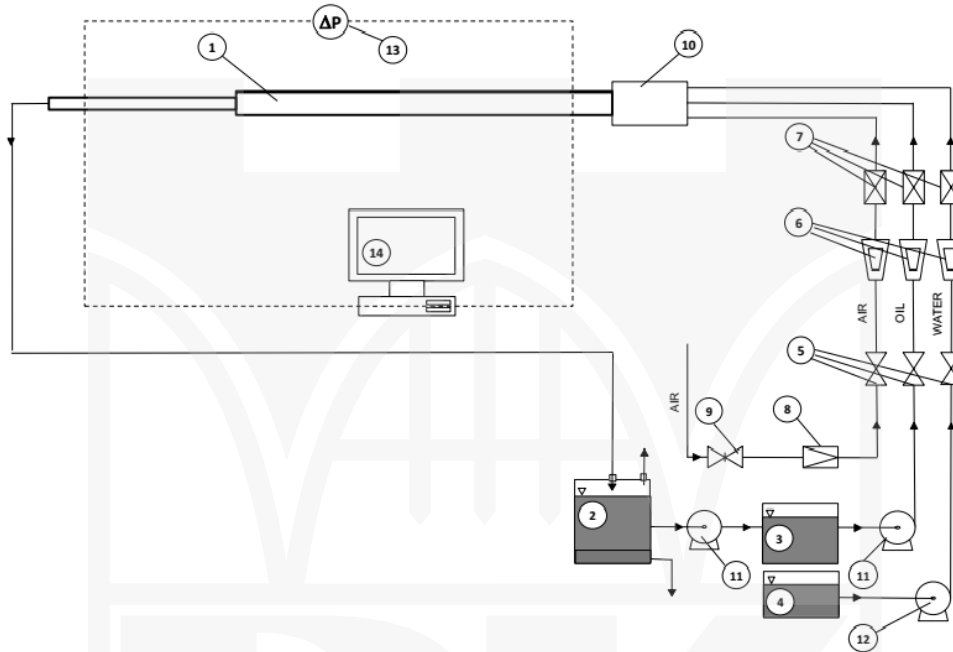


Fig. 1. Experimental set-up

- 1 – measurement channel with sudden expansion, 2 – separator, 3 – oil tank, 4 – water tank,  
 5 – shut-off valves, 6 – flowmeter of oil, water, air, 7 – one-way valves, 8 – pressure regulation valve,  
 9 – air control valve, 10 – agitator, 11 – oil pump, 12 – water pump, 13 – pressure transducers,  
 14 – measurement card coupled with a computer

### 3. Results

During the next stage of research, flow conditions corresponding to the two-phase flow patterns identified during the experiment were subsequently compared with the areas of these patterns found in the flow pattern map created by Ulbrich and Troniewski [1] (Fig. 2). Figure A shows the flow pattern map for a pipe before the local obstacle ( $D = 40$  mm) where the types of flow patterns were marked. In Figure B, the type of flow pattern was marked for the smaller pipe diameter ( $d = 22$  mm).

The figures show that in both cases the observed flow patterns were approximately in conformity with the corresponding areas shown in the Troniewski and Ulbrich map.

However, it was observed that the decrease of the pipe diameter during the flow of gas – liquid results in a change in the flow pattern.

For demonstration purposes, figure 3 shows several photographs taken during the experiment involving oil-air and air-water flow through a sudden expansion. Figure 4 shows several photographs taken during the experiment involving oil-air and air-water flow through a sudden contraction. As can be seen, the presence of a local obstacle always leads to a change in the flow patterns both before and after the pipe contraction. The photographs found above indicate the changes in the flow patterns caused by a sudden increase in pipe diameter. The distances where the flow pattern was not fully developed can be clearly discerned there. Such a length, also known as the length of the disturbance area, is defined here as the distance from an obstacle to the location where a uniform flow pattern is formed again. Beyond this area, the mean square root of the deviation of the local void fraction profile is constant and less than 5%, as reported by the authors of the study in [2].

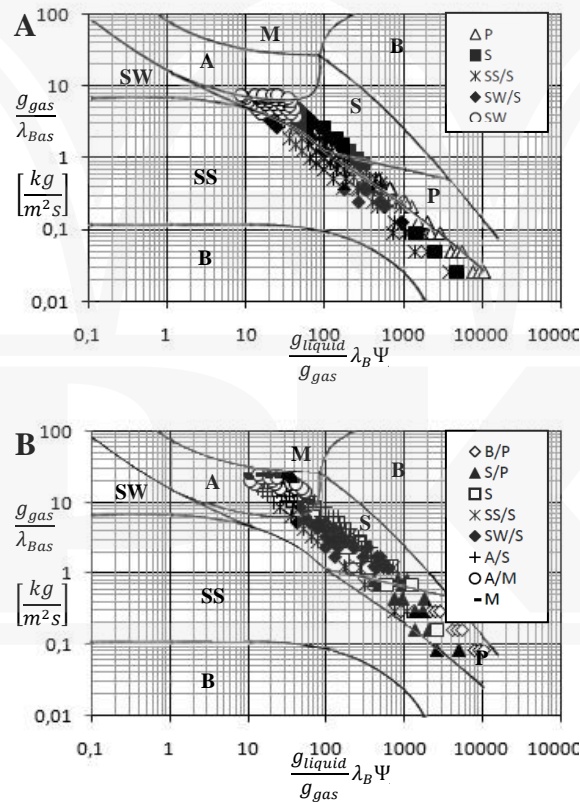


Fig. 2. The flow patterns observed in a pipe before the contraction (A) and after the contraction (B):  
 B – bubble flow, P – plug flow, S – slug flow, SS – stratified flow, SW – stratified-wavy flow,  
 A – annular flow, M – mist flow.

Figure 5 shows one example of the measured change of pressure in two-phase oil-air and water-air flow along the measuring channel. Pressure profiles in the case of flow through a sudden expansion of the channel may vary significantly due to the length of the disturbance zone of flow patterns followed by the area in which the system can recover pressure to its initial value. The pressure recovery due to the sudden expansion is defined as the difference in the pressure when the fully developed pressure gradient lines upstream and downstream of the expansion are extrapolated to a point where a change in the area occurs[3].

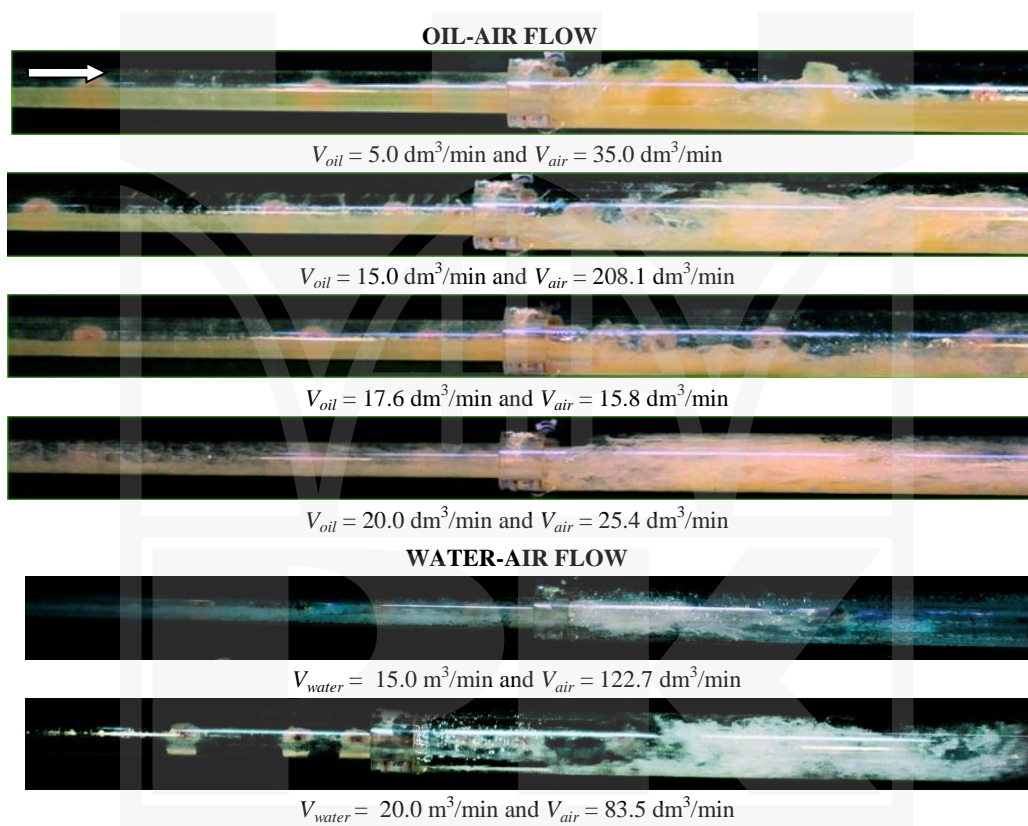


Fig. 3. Flow pattern development during flow of oil-air and water-air mixtures through a sudden expansion

The graphs above (Fig. 6) show the flow patterns developing along the pipe after its sudden expansion. The analysis of the resulting images clearly indicates that the correlations used for calculating the disturbance zones should take into account both the parameters of the liquid phase and the gas phase. If the impact of any of them is disregarded, an adequate assessment of the length of these zones for the sudden expansion will not be possible [4].

On the other hand, during the two-phase flow through sudden contraction of the pipe immediately before this obstacle, the local static pressure decreases due to a sudden acceleration of the flow. After the sudden contraction, the pressure in the pipe gains its minimum value and then increases slightly to the point where a fully developed gradient line of the pressure is achieved. The pressure drop during flow through a sudden contraction is defined as the difference in the pressure in the local obstacle, based on the fully developed pressure gradients upstream and downstream of the contraction.

Figure 7 contains several photographs derived from the research of the characteristics of two-phase oil-air flow through a sudden contraction. Figure 8 is meant to show the areas of flow pattern disturbance in the channel before the contraction.

By analogy to two-phase flows, the pressure drop noted during the three-phase flow is relative to the relations between the volume rates of the components in the flow. On the basis of the data shown in Fig. 9, we can see that an increase in pressure drop occurs for a constant volumetric flow rate of the air accompanied by an increase in volume flow rate of liquid.

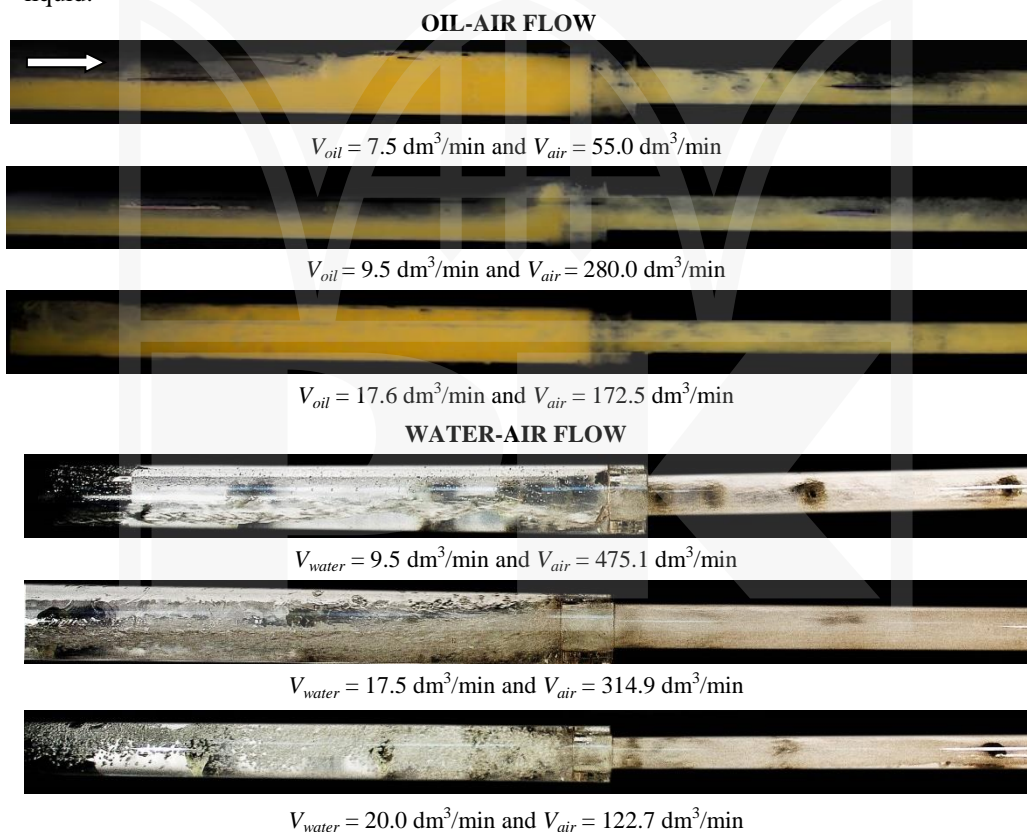


Fig. 4. Changes of flow patterns of oil-air and water-air flow through a sudden contraction

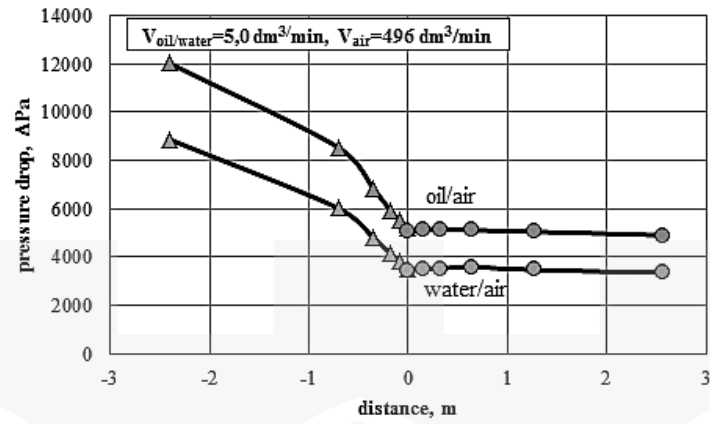


Fig. 5. Pressure drop profiles during the two-phase gas-liquid flow through a sudden expansion

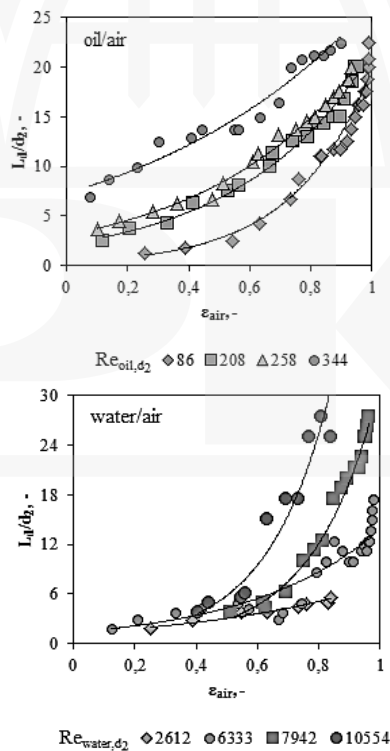


Fig. 6. Developing lengths of flow patterns in the pipe after a sudden expansion

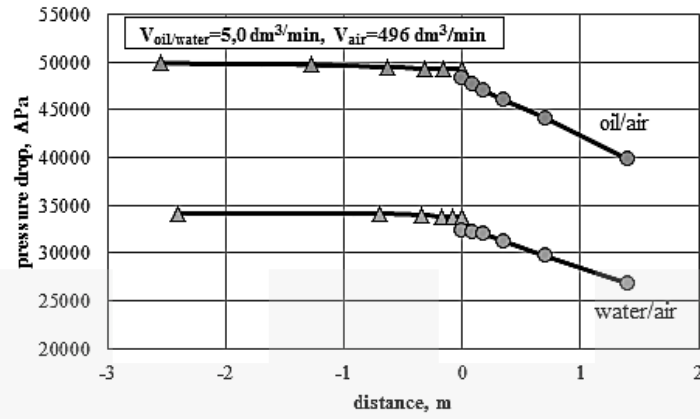


Fig.7. Pressure profiles during the two-phase gas-liquid flow across the channel with a sudden contraction

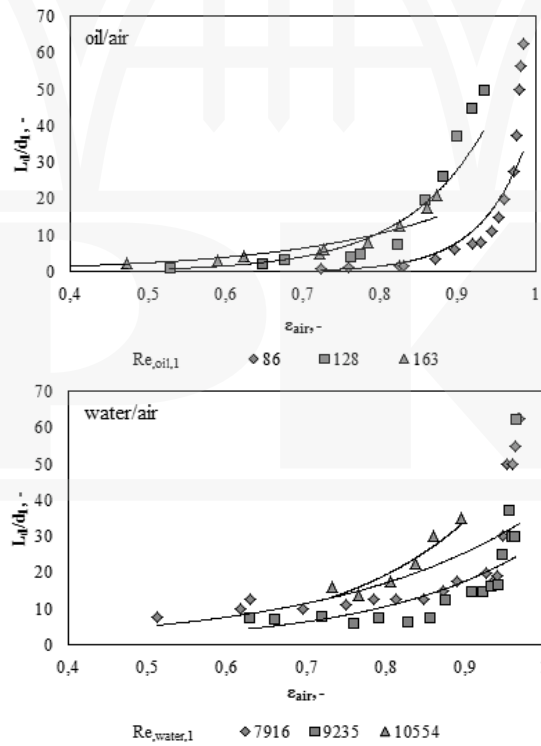


Fig. 8. Developing lengths of flow patterns in the pipe before a sudden contraction



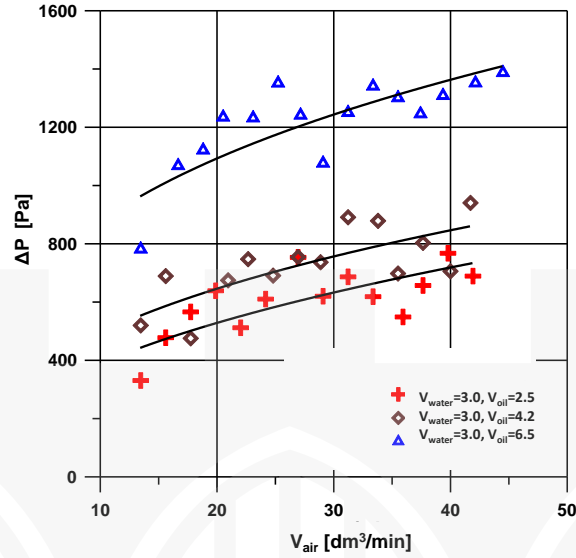


Fig. 9. Pressure drop profiles during gas-liquid-liquid three-phase flow through a sudden contraction

#### 4. Calculation of pressure drops in air-water-oil three-phase flow

The results of statistical tests indicate that the pressure drops for the sudden contraction should be calculated by the use of the Kawahara [5] method, to be equal to:

$$\Delta P_T = \frac{g_T^2}{2 \cdot \rho_{liquid}} \cdot \left[ \left( \frac{1}{C_c} - 1 \right)^2 + 1 - \sigma_A^2 \right] \cdot \left[ 1 + x \cdot \left( \frac{\rho_{liquid}}{\rho_{air}} - 1 \right) \right] \quad (1)$$

$$\rho_{liquid} = \rho_{water} \cdot \alpha_{water} + \rho_{oil} \cdot \alpha_{oil} \quad (2)$$

$$\alpha_{water} = (\varepsilon_{water})^{0.8} \quad (3)$$

$$\alpha_{oil} = 1 - \alpha_{water} \quad (4)$$

$$C_c = \frac{1}{0.639 \cdot (1 - \sigma_A)^{0.5} + 1} \quad (5)$$

$$\sigma_A = \left( \frac{d}{D} \right)^2 \quad (6)$$

where:

- $\Delta P_T$  – total pressure drop, Pa  
 $g_T$  – total mass flux density, kg/(m<sup>2</sup>s)  
 $\rho_{liquid}$  – liquid density, kg/m<sup>3</sup>  
 $\rho_{air}$  – gas density, kg/m<sup>3</sup>  
 $x$  – mass quality, -  
 $\alpha_{water}$  – water volume fraction, -  
 $\alpha_{oil}$  – oil volume fraction, -  
 $\sigma_A$  – area ratio, -  
 $\rho_{water}$  – water density, kg/m<sup>3</sup>  
 $\rho_{oil}$  – oil density, kg/m<sup>3</sup>  
 $d, D$  – internal diameter (contraction, expansion), m.

For gas-liquid flow conditions through expansion, the highest accuracy ensured by application of the Lottes [6] method:

$$\Delta P_T = \frac{g_T^2}{2 \cdot \rho_{liquid}} \cdot \frac{\sigma_A \cdot (1 - \sigma_A)}{(1 - \alpha_{air})^2} \quad (7)$$

$$\alpha_{air} = \frac{\varepsilon_{air}^{0.37}}{1 + \left(\frac{1}{\varepsilon_{air}} - 1\right)^{0.5}} \cdot \left(\frac{1 - \varepsilon_{water}}{1 + \varepsilon_{oil}}\right)^{0.43} \quad (8)$$

$$\varepsilon_{air} = \frac{V_{air}}{V_{air} + V_{water} + V_{oil}}, \quad (9)$$

$$\varepsilon_{water} = \frac{V_{water}}{V_{air} + V_{water} + V_{oil}} \quad (10)$$

$$\varepsilon_{oil} = \frac{V_{oil}}{V_{air} + V_{water} + V_{oil}} \quad (11)$$

where:

- $\alpha_{air}$  – mean real void fraction, -  
 $\varepsilon_{air}$  – inlet void fraction, -  
 $\varepsilon_{water}$  – inlet water volume fraction, -  
 $\varepsilon_{oil}$  – inlet oil volume fraction, -.

The values obtained on the basis of calculations were compared with data obtained in experimental studies, as shown in Figures 10 and 11. The result of less than  $\pm 40\%$  of relative error was obtained for both correlations.

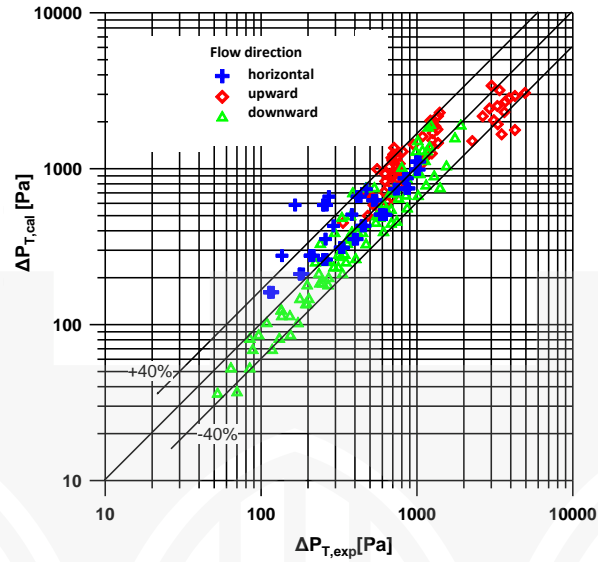


Fig. 10. Comparison of measured pressure drop  $\Delta P_{T,exp}$  of three-phase flow with the calculated value  $\Delta P_{T,cal}$  on the basis of the Kawahara method (1)

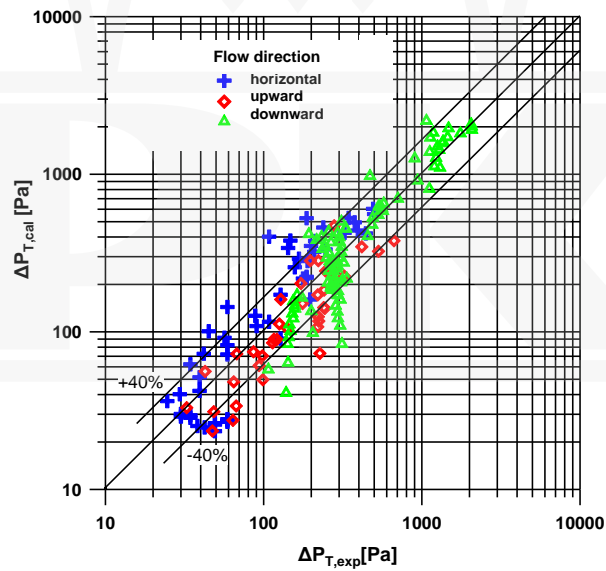


Fig. 11. Comparison of measured pressure drop  $\Delta P_{T,exp}$  of three-phase flow with the ones calculated  $\Delta P_{T,cal}$  on the basis of the Lottes method (4)

## 5. Conclusions

The following general conclusions could be derived from the analysis of the results and review of the literature:

1. Flow pattern disturbances of a multi-phase mixture occur during flow through a sudden change in the cross-section of the pipe.
2. The disturbances of flow pattern form the reason for the local change in the void fraction of the phases, and consequently, properties of the mixture are affected by them.
3. Due to the presence of local disturbances caused by the change in the cross-section of pipe, local pressure drop, it is difficult to calculate the local pressure drop.
4. The current methods of calculating the developing lengths in the two-phase flow of gas-liquid mixture through sudden expansion of the channel are not always effective as they do not enable all flow parameters to be taken into account.
5. Further analysis of the results should be aimed at the development of a mathematical equation used to describe the impact of the length of disturbance of flow pattern on the pressure drop in the multi-phase flow in a channel with a sudden change in the cross sectional area.

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