DE GRUYTER
OPEN

Arch. Min. Sci., Vol. 60 (2015), No 1, p. 341–358

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.1515/amsc-2015-0023

WIKTOR FILIPEK*, KRZYSZTOF BRODA*, MARIAN BRANNY*

FREE SURFACE OF THE LIQUID-GAS PHASE SEPARATION AS A MEASURING MEMBRANE OF A DEVICE FOR MEASURING SMALL HYDROSTATIC PRESSURE DIFFERENCE VALUES

POWIERZCHNIA SWOBODNA ROZDZIAŁU FAZ CIECZ-GAZ JAKO MEMBRANA POMIAROWA URZĄDZENIA DO POMIARU MAŁYCH WARTOŚCI RÓŻNICY CIŚNIENIA HYDROSTATYCZNEGO

To obtain a correct reading of fluid flow through a porous medium, it is necessary to know the pressure distribution. While in the case of large Reynolds numbers (turbulent flows) finding pressure measurement devices on the market is not a major problem, there are currently no available devices with sufficient accuracy for measurement of laminar flows (i.e. for Re numbers (Bear, 1988; Duckworth, 1983; Troskolański, 1957) in the range from 0.01 to 3). The reasons of this situation has been discussed in a previous articles (Broda & Filipek, 2012, 2013). Therefore, most of the work on this issue relates to testing velocity distribution of the filter medium (Bear, 1988) or pressure distribution at high hydraulic gradient levels (Trzaska & Broda, 1991, 2000; Trzaska et al., 2005). The so-called measurements of the lower limit of the applicability of Darcy's law for liquid, as well as determining a threshold hydraulic gradient J_0 (Bear, 1988) tend to cause especially great difficulty. Such measurements would be particularly important application in determining the infiltration of water into the mine workings, filtering through the foundations of buildings, etc.

For several years, the authors (Broda & Filipek, 2012, 2013) have been engaged in the development of methods and measuring instruments (patent applications: P.407 380 and P.407 381), which would allow for measurement of hydrostatic pressure (differences) below 1 Pa. In the course of research, a new concept of methodology for measuring low values of hydrostatic pressure differences was developed, which is the subject of this article.

This article seeks to introduce a new concept of using the free surface of liquid-gas separation as the measuring membrane of a device used in measurement of small values of hydrostatic pressure. The focus is mainly on the possibility of building such a device – describing the technical difficulties that occurred during the execution of the idea. Consequently, less attention was paid to the broader considerations related to uncertainty of the proposed method's measurements, due to the authors' awareness that this is the first prototype of such a device and, on the basis of this experience, another one will be built and tested.

The observations and numerical analysis of the image formed on the screen by the passage of a laser beam through the free surface of the liquid-gas separation show that at low values of pressure difference, the bubble acts as a membrane shifting in the direction of lower pressure, in such way that the displacement is proportional to the pressure difference at both ends of the bubble.

The proprietary method of numerical data processing presented in this article, based on analysis of the intensity of color change in a frame moving along a selected line outside of visual changes in the image of

---

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF MINING AND GEOENGINEERING, AL. A. MICKIEWICZA 30, 30-059 KRAKOW, POLAND

the laser beam after passing through the test structure, provided a tool to create first mathematical models to describe the observed changes (2),(3).

Presented in this article method of measuring the difference between the free surface levels in two containers, and hence the measurement of hydrostatic pressure difference provides a new tool for laboratory measurements in the fields of science, which were previously unattainable.

Keywords: small values of differential pressure measurement, filtration, pressure gauges.

Do poprawnego opisu przepływu płynu przez ośrodek porowaty niezbędna jest znajomość rozkładu ciśnienia. O ile dla dużych liczb Reynoldsa (przepływy turbulentne) pomiar ciśnienia dostępnymi na rynku przyrządami nie stanowi większego problemu, to dla przepływów laminarnych cieczy (tj. dla liczb Re (Bear, 1988; Duckworth, 1983; Troskolański, 1957) z zakresu 0.01 do 3) nie ma na rynku przyrządów o wystarczającej dokładności. Przyczyny powodujące taką sytuację zostały omówione w poprzednich opracowaniach (Broda i Filipek, 2012, 2013), Dlatego większość prac dotyczących tego zagadnienia dotyczy badań rozkładu prędkości medium filtrującego przez badany ośrodek (Bear, 1988) lub rozkładu ciśnienia przy wysokich spadkach hydraulicznych (Trzaska i Broda, 1991, 2000; Trzaska i in., 2005). Zwłaszcza pomiary w zakresie tzw. dolnej granicy stosowalności prawa Darcy'ego dla cieczy oraz dotyczące określenia progowego spadku hydraulicznego J_0 (Bear, 1988) sprawiają wielkie trudności. Pomiary takie miałyby duże znaczenie aplikacyjne zwłaszcza przy określaniu infiltracji wody do wyrobisk górniczych, filtracji przez fundamenty budowli itp.

Autorzy od kilku lat (Broda i Filipek, 2012, 2013) zajmują się opracowaniem metody oraz przyrządu pomiarowego (wnioski patentowe: P.407 380 i P.407 381) pozwalających na pomiary wartości ciśnienia (różnicy ciśnienia) hydrostatycznego poniżej 1 Pa. W tym okresie opracowali nową metodę pomiaru, skonstruowali stanowisko badawcze i przeprowadzili pomiary różnicy ciśnień hydrostatycznych z dokładnością do 0.5 Pa znacznie ograniczając zjawisko histerezy (Broda i Filipek, 2012) (wniosek patentowy: P.407 380). W oparciu o zdobyte doświadczenie prace kontynuowano opracowując metodę pomiaru i budując nowe stanowisko do pomiaru bardzo małych różnic ciśnień z kompensacją wpływu ciśnienia atmosferycznego o dużo prostszej budowie, co znacząco zwiększyło dokładność i wiarygodność pomiarów (Broda i Filipek, 2013) (wniosek patentowy: P. 407 381).

W trakcie prac badawczych narodziła się nowa koncepcja metodologii pomiaru niskich wartości różnicy ciśnienia hydrostatycznego, która jest przedmiotem niniejszego artykułu.

Na rysunku 1 przedstawiono zdjęcie stanowiska pomiarowego służącego do określenia wpływu zmiany wartości różnicy ciśnienia hydrostatycznego na kształt a co za tym idzie przemieszczenie powierzchni swobodnej rozdziału faz ciecz-gaz, oraz omówiono jego budowę zwracając uwagę na istotne szczegóły konstrukcyjne. Przedstawiono także sposób kalibrowania przyrządu, wykonywania i obróbki zdjęć fotograficznych w celach pomiarowych z wykorzystaniem napisanego w języku Delphi autorskiego programu do obróbki numerycznej zdjęć. Występujące trudności ilustruje rysunek 2 przedstawiający przesunięcie linii odniesienia w trzech kolejno po sobie wykonanych zdjęciach. Następnie omówiono sposób przygotowania stanowiska do pomiarów oraz sposób ich przeprowadzania czego ilustracją są rysunki 3 i 4. Przedstawiono występujące problemy oraz zastosowane sposoby ich rozwiązania.

Zarejestrowany przykładowy obraz po przejściu promienia lasera przez badaną strukturę dla wybranych wartości różnicy ciśnień hydrostatycznych uzyskany za pomocą kulek ceramicznych przedstawiono na rysunku 5. Rysunek 6 wyjaśnia metodę obróbki numerycznej zdjęć w oparciu o autorski program i zależności (1),(2),(3). Na rysunkach 7 i 9 zestawiono otrzymane krzywe zmienności intensywności barw uzyskane w trakcie opracowania numerycznego. Zwrócono także uwagę na rozkład zmian intensywności barw dla różnicy między powierzchniami swobodnymi cieczy w cylindrach (Rys. 8-11) dla wybranych serii pomiarowych. W dalszej części artykułu dokonano analizy otrzymanych obrazów zwracając uwagę na włączenie metody transformacji Fouriera lub „Falkowej" (Ziółko, 2000) do numerycznej analizy posiadanych danych (Rys. 12-14). Na rysunku 12 pokazano wybrane trzy zależności opisujące zmienność natężania barwy w funkcji położenia ramki (1), dla których dokonano transformacji Fouriera według zależności (3). Analizy dokonano metodą arytmetyczna Perry'ego (Ziółko, 2000) w okienku o szerokości $n = 2300$ przyjmując jako położenie startowe wartość $x = 1600$. Rysunek 13 przedstawia wartości współczynnika A_k a rys.14 przedstawia wartości kąta przesunięcia j_k dla pierwszych 58 harmonicznych. Prace nad udoskonaleniem metody trwają. W dalszej części artykułu autorzy podsumowują osiągnięte wyniki

zwracając uwagę na uzyskaną precyzję pomiarów oraz korzystne zastosowanie powierzchni swobodnej rozdziału faz ciecz-gaz jako membrany pomiarowej urządzenia do pomiaru małych wartości różnicy ciśnienia hydrostatycznego (Rys. 15-16) sugerując wprowadzenie do analizy trzeciego wymiaru co wiąże się z koniecznością kosztownej modernizacji stanowiska pomiarowego.

Słowa kluczowe: małe wartości różnicy ciśnień, pomiary, filtracja, manometry.

1. Introduction

To obtain a correct reading of fluid flow through a porous medium, it is necessary to know the pressure distribution. While in the case of large Reynolds numbers (turbulent flows) finding pressure measurement devices on the market is not a major problem, there are currently no available devices with sufficient accuracy for measurement of laminar flows (i.e. for Re numbers (Bear, 1988; Duckworth, 1983; Troskolański, 1957) in the range from 0.01 to 3). Therefore, most of the work on this issue relates to testing velocity distribution of the filter medium (Bear, 1988) or pressure distribution at high hydraulic gradient levels (Trzaska & Broda, 1991, 2000; Trzaska et al., 2005). The so-called measurements of the lower limit of the applicability of Darcy's law, as well as determining a hydraulic gradient threshold J_0 (Bear, 1988) tend to cause especially great difficulty. This is due to the lack of measurement methods for measuring very low hydrostatic pressures (Duckworth, 1983; Troskolański, 1957), because even a difference of 1 mm between two free surface levels of water generates a pressure of about 10 Pa (Troskolański, 1957), which actually represents the resolution of modern measurement devices. Unfortunately, due to surface phenomena or capillarity (Adamson, 1997), the solutions used in piezometers (Duckworth, 1983; Troskolański, 1957) do not render a satisfactory accuracy in the measurement of hydrostatic pressure below 10 Pa, which has been widely discussed in previous studies (Broda & Filipek, 2012, 2013).

For several years, the authors (Broda & Filipek, 2012, 2013) have been engaged in the development of methods and measuring instruments (patent applications: P.407 380 and P.407 381), which would allow for measurement of hydrostatic pressure (differences) below 1 Pa.

In 2012, the authors (Broda & Filipek, 2012) proposed a new method of measuring very small pressure differences, constructed a test site consisting of two separate measuring tanks and carried out measurements of hydrostatic pressure difference with an accuracy of 0.5 Pa, significantly reducing the hysteresis phenomenon (Broda & Filipek, 2012). Unfortunately, the accuracy of the measurement was affected by ambient temperature and atmospheric pressure having a large impact on the measurement process. This experience became an incentive to work – taking into account the lessons learned – on new methods of measurement, and for developing a test site for measuring very small pressure differences while compensating for the impact of atmospheric pressure (Broda & Filipek, 2013).

The method developed on the basis of previous experiences and the subsequently constructed measurement site (patent pending: P. 407 381) was characterized by a much simpler structure. The authors eliminated the excessively complicated control system and the additional reference pressure function module. Only one pressure transducer was used. Moreover, compensating for the atmospheric pressure and ambient temperature with two identical measuring tanks significantly increased the accuracy and reliability of measurements (Broda & Filipek, 2013). In the course of research, a new concept of methodology for measuring low values of hydrostatic pressure differences was developed, which is the subject of this article.

2. Description of the test site and the experiment procedure

Fig. 1 shows the test site used to determine the impact of changes in value of the hydrostatic pressure difference on the shape and thus displacement of the liquid-gas separation free surface. We can see the two cylinders (A) with inner diameter of 50 ±0.01 [mm] and a height of about 60 mm, connected to a glass tube (B) with an internal diameter 3.0 [mm] and external diameter of 6 [mm]. A manual indexing unit taken from a Proxxon precision lathe PD 230 / E (F) is mounted on a cross table (E), removed from a Proxxon MF70 precision milling machine. An aluminum rod with a diameter of 12 [mm] is placed inside the jaws of the indexing device. At the end of the rod is a head equipped with a low power laser (4.5 [mW], wavelength of 655nm) together with an adjustable collimator (C) and an additional collimator (D) in form of a converging lens. The additional collimator serves to improve the operating parameters of the laser, reducing the diameter of the laser beam from 3 [mm] to about 1 [mm]. Such prepared testing site allowed for precise positioning of the laser beam on the plane with an accuracy of 0.05 [mm] along both the x axis (the axis of the glass tube) and the y-axis (perpendicular to the axis of the glass tube). In addition, the indexing unit allowed to rotate the laser head (C) together with the additional collimator (D) around the y-axis at any angle with an accuracy of 0.2 [°].

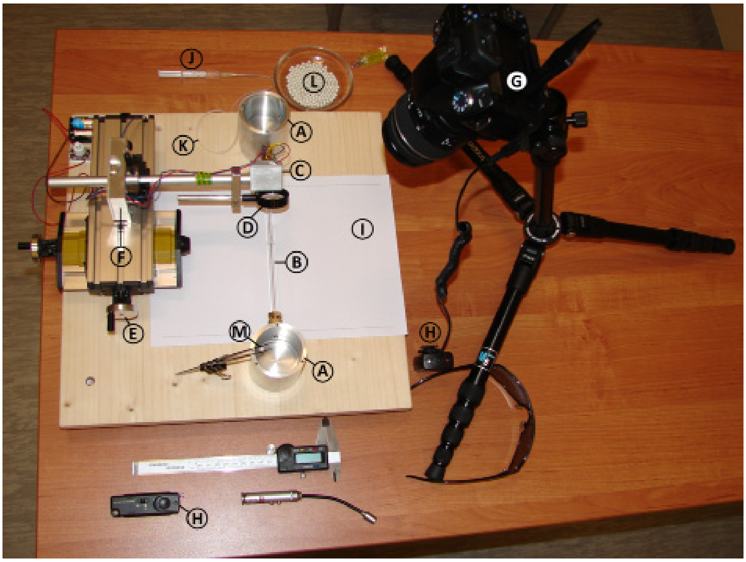

Fig. 1. Picture of the laboratory station used for testing the deformation of free surface of the gas-liquid phase separation

After passing through the test structure, the laser beam formed an image on the screen (I), which was then photographed by a Sony SLT-A33 camera (G) in the so-called "auto" mode, that is, with the camera automatically adjusting the aperture, shutter speed, white balance settings, ISO settings and focus. Additionally, long edges of the screen (I), made of a sheet of A4 paper, were marked using dashed lines with the same length of both strokes and gaps between them to ensure precise calibration (control peak #1, control peak #2) of the obtained results in the course of numerical processing of the images.

Standard mode of recording images in *JPG* format cameras is not suitable for numerical processing due to the so-called compression loss (Przybyłowicz, 2007). Thus, images were saved in *RAW* mode, that is, exactly as the image is seen by the camera lens without any “automatic” processing rendered by the *JPG* format. Unfortunately, the structure of recording in *RAW* mode is not standardized and is therefore unique to a specific camera. This entailed an additional, longer way of obtaining data for numerical processing. Files saved in *RAW* format had to be converted to *TIF* format, without compression, using the Sony Image Data Converter SR application dedicated to the camera used. Then, using the Paint.NET 3.5.11 application, *TIF* files were converted to *BMP* format, which enabled the authors to develop proprietary software for numerical processing of images using Delphi programming language.

In the course of digital image processing, the authors first focused on automatic detection of the calibration line. Unfortunately, as it turned out, despite the authors’ best intentions and placing the camera on a tripod, manual shooting causes significant random position shifts in the plane of the focus area (Fig. 2). Therefore, the Sony SLT-A33 camera was fitted with a radio device (H) for taking photos from a distance, non-disruptive to the measurement process.

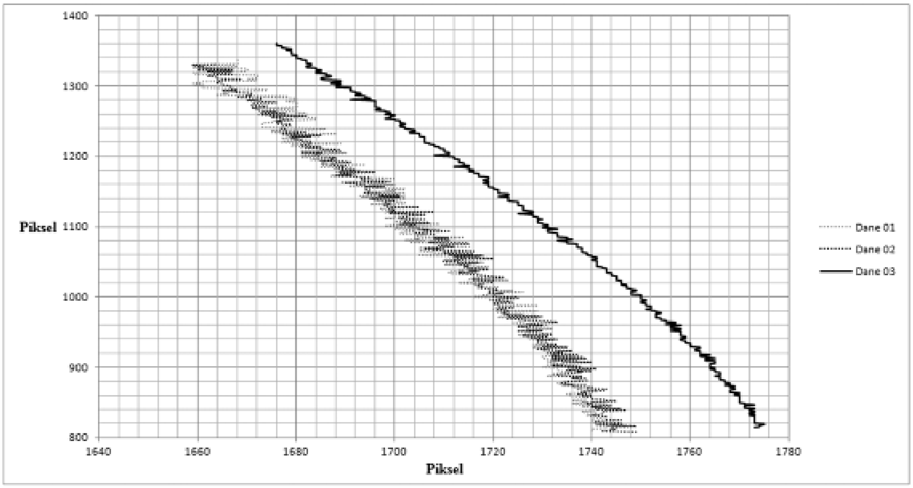

Fig. 2. Graph showing the shift of the reference line (control peak #1) in three consecutive photographs taken

The process of preparing the test site began with filling the two cylinders (A) with distilled water to a height of about 5 mm above the glass tube holes (B), then the site was abandoned for 24 h, so that the levels in the two tanks could equalize. Of course, the platform with mounted components (A), (B), ..., (F) was previously leveled. The next step was to create a gas bubble (air) (Fig. 3a) inside the glass tube (B).

The main difference between the gas bubbles in a spirit level and the glass tube (Fig. 3) is their size relative to the cross-section. In a spirit level, the bubble does not clog the entire cross-section. It would seem that under the influence of hydrostatic pressure difference between

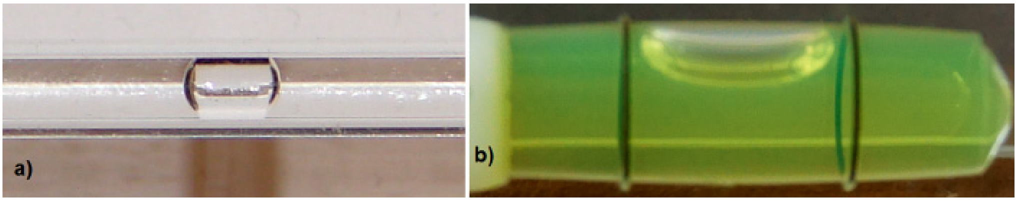

Fig. 3. Gas bubble: a) – measuring site, b) – spirit level

cylinders (A) the bubble should shift, as it is observed in a spirit level, where a small deviation from the horizontal (gravity) level will automatically cause the indicator to move.

Thus, the experiment was carried out. One of the cylinders (A) was connected to one end of the silicone tube (K) with inner diameter of 1 [mm] and the second end of the tube was connected to a syringe 2 [ml] (J). The plunger was set to the start value of 1 [ml], so that its position could be changed by ±1 [ml]. If the air bubble under the influence of the resulting hydrostatic pressure difference of approximately ±19 [Pa] per ±1 [ml] change in the position of the plunger, sought to compensate for the free surface levels in the two cylinders (A), it should shift its position by about ±141 [mm] (glass tube with an inner diameter of 3.0 [mm]). It is large enough change to the position of the bubble that if the process proceeded it would be noticeable to the naked eye. No change in the position of the bubble has been observed. However, after switching on the laser and the setting it to the position corresponding in relation to the position of the bubble in the tube, a clear change could be observed in the recorded images (Fig. 4). Therefore, the authors concluded that the bubble does change its position inside the tube under the influence of a pressure difference. This change, however, is so small that it is insignificant to the naked eye. It is further noted that the bubble in the tube returns to its starting position, as if it were a membrane, after the pressure causing it to shift is removed.

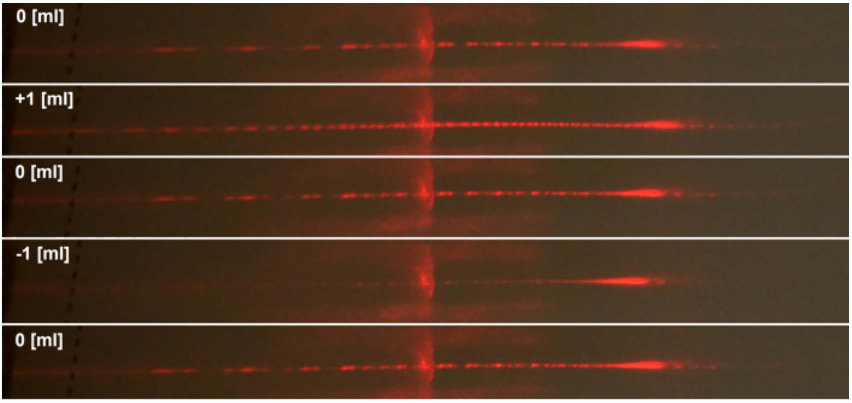

Fig. 4. Image captured after passing of the laser beam through the test structure for free surface change in the cylinders of ±1 [ml]

3. Free surface of the liquid-gas phase separation as a measuring membrane

Assuming that the considered gas inside the bubble behaves as an ideal gas, which is justified by the value of the considered pressure differences (Broda & Filipek, 2012, 2013; Górniak & Szymczyk, 1999; Szargut, 1997), the change in volume at constant temperature can be determined using the Clapeyron equation. As indicated, it is about 1.01^{-5} starting volume per Pascal. This would correspond to a change in the position of the face of the liquid-gas separation phase surface by about 0.1 [µm], assuming that the gas bubble is a geometrical figure comprising: a cylinder with a diameter of 3.0 [mm] and a height of 10 [mm], and two halves of a sphere with a diameter of 3.0 [mm]. This change is so small that it can be assumed that no offset is caused by compression and expansion of the bubble under the influence of external stresses.

In this article, the authors deliberately did not dig into the issues of the forces of attraction between molecules of liquid, gas and solid. Without considering the issues of: surface tension, contact angle, cohesion, adhesion, contact angle hysteresis, in which the explanation of the process described above actually lies, the authors focused mainly on the presentation of results and the technical possibilities of using the membrane formed at the surface of liquid-gas phase separation for measuring small values of hydrostatic pressure difference.

The use of a plunger connected to one of the cylinders (A) as part of the element regulating the free surface level difference between the two cylinders, and thus the hydrostatic pressure difference, appears to be justified. In addition to a convenient setting of the desired value of the difference in free surface levels, it allows to obtain a method enabling determination of reproducibility of the measured values. Unfortunately, not having the right plunger with known parameters prevented us from continuing measurements using this methodology. Of course, using a syringe for this purpose makes it possible to carry out such measurements, but does not guarantee the required accuracy of the set value.

We decided to use bearing balls (L in Fig. 1) to set the value of free surface level difference between the two cylinders. The method consists in throwing balls of specified geometry, one after another, into the cylinder. Knowing the geometry of the ball and the cylinder, we are able to determine by how much the free surface level inside of the tank rises. We concluded that the bearing balls best suited for this purpose. The reproducibility of the geometry in the series is so high, that any errors are more likely to be the result of measurements of the difference in hydrostatic pressures than their deviations from the desired geometry. The main disadvantage of such a method is the lack of reproducibility of measurements in a given series. The reason being that during the extraction of the ball from the tank a certain amount of liquid remains on the surface of the ball and on the device used to extract it. The amount of this liquid is substantial enough to significantly affect the accuracy of measurement. It would be possible to throw balls into both cylinders instead, depending on the value we wish to set. In this way, it would be possible to obtain the same free surface values in both cylinders without taking the balls out of the water. Note, however, that when using this method based on balls sequentially thrown into both cylinders the errors would be greater (large number of balls used to make measurements) than if we threw the balls into one cylinder only.

To set the desired free surface value, we decided to use precision ceramic balls made of zirconium dioxide with a diameter of 5 [mm] and accuracy class of G10 (M in Fig. 1). Assuming: cylinder diameter of 50 [mm], water temperature of 15 [°C], distilled water density of

999.0986 [kg/m^3] and acceleration of gravity for the city of Kraków of 9.8105 [m/s^2], the results indicate that dipping a ceramic balls in the cylinder increases the free surface level inside of it by 0.0333(3) [mm], which, after conversion to hydrostatic pressure difference gives the value of 0.327 [Pa], assuming a fixed position of the free surface inside of the second cylinder.

The first measurement was began by setting the laser beam so as to obtain on-screen image shown in (Fig. 5), described as “0.000 [Pa], 0.000 [mm]”. This image is characterized by the fact that a small shift of the laser head (less than 0.05 [mm]) in the direction of the analyzed gas-liquid separation surface resulted in the appearance of laser beam traces on the left side of the screen.

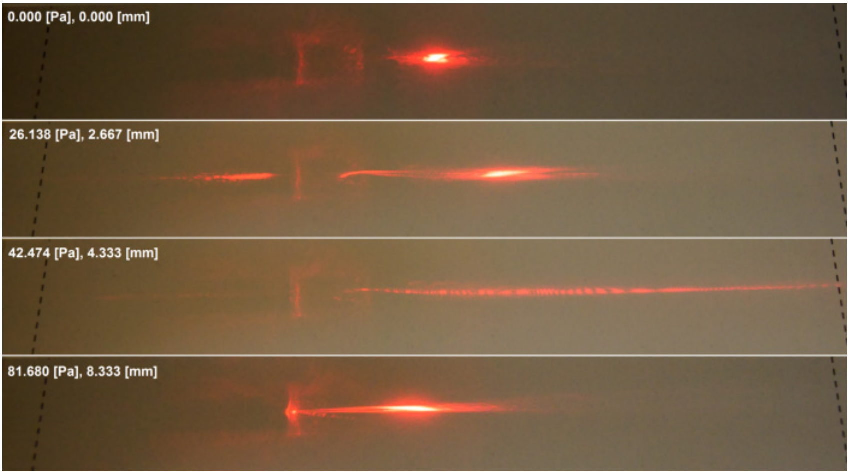

Fig. 5. Image recorded after passing of the laser beam through the test structure for the selected values of hydrostatic pressure difference obtained with the use of ceramic balls

Subsequent measurements were made by throwing 251 consecutive balls into the cylinder, at intervals of about two minutes. During this time, a spontaneous wave attenuation of free surfaces inside the cylinders occurred, induced by disruption arising from balls being thrown into the cylinder. Photo image of the laser beam – passing through the tested liquid-gas separation surface – on the screen was made remotely by radio (Fig. 5).

4. Method for processing and interpretation of data

Images that have been numerically processed by us had the following parameters: height of 3056 pixels, width of 4592 pixels, sRGB color reproduction, and depth of 48 bits. After various attempts at adopting a concept of numerical analysis of the obtained images, we adopted a proprietary method based on the analysis of the intensity of color change in a frame moving along a selected line.

$$y(x) = \frac{\sqrt{\sum_{i=-n}^{n}\left(\sum_{j=-n}^{n}\left(\frac{A(x+j)+B}{2n}\right)-A(x+i)-B\right)^{2}}}{2n} \tag{1}$$

For this purpose, two points would be manually selected, thus enabling determination of the symmetry axis of the image obtained after passage of the laser beam through the test structure (Fig. 6). Then, on the basis of these two points, the program automatically marked the parameters A, B of the linear function $y(x) = Ax + B$, being the axis of symmetry. At the same time it was assumed that the origin of the coordinates $\{x, y\}$ corresponds to the point $\{1, 1\}$ and the maximum coordinate value is $\{4592, 3056\}$ in pixels. Then, the shorter side of the frame equal to one pixel and longer equal to $2n + 1$ pixels was moved along the x-axis, with the longer side always parallel to the adopted y-axis. Therefore, the angle between the linear function and the longer side generally varied from 90 [°]. The n-values adopted for the analysis were: 100, 50, 25, 13, 7, 5, 3. In contrast, the results presented below (Fig. 7-11) were developed for frame $n = 100$. Intensity

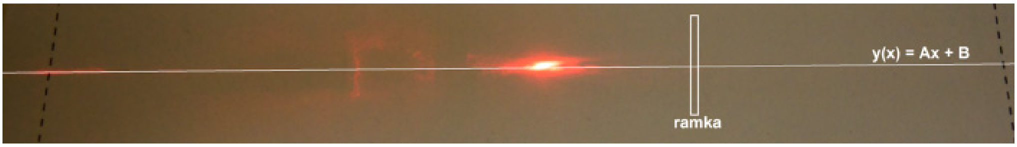

Fig. 6. Figure explaining the method of numerical processing of images

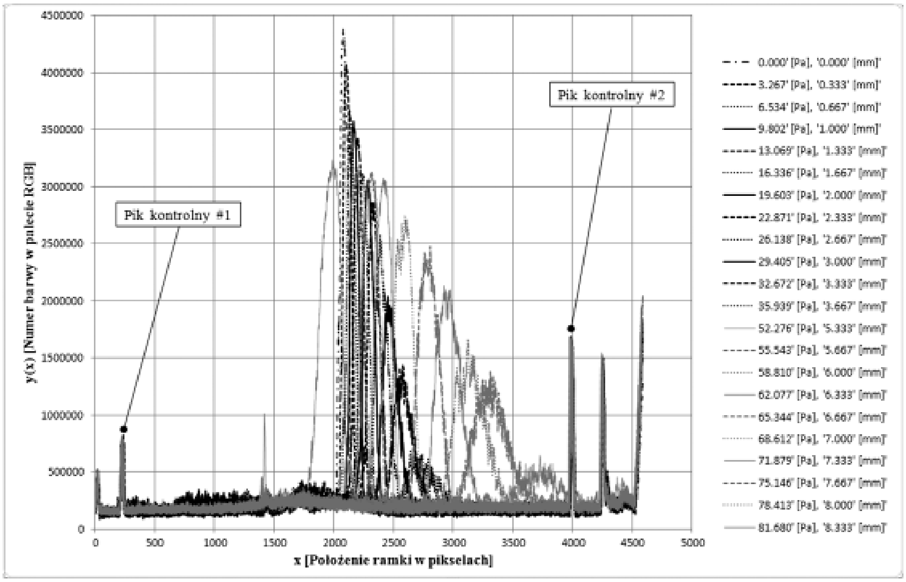

Fig. 7. The graph shows the distribution of changes in color intensity with marked control peaks

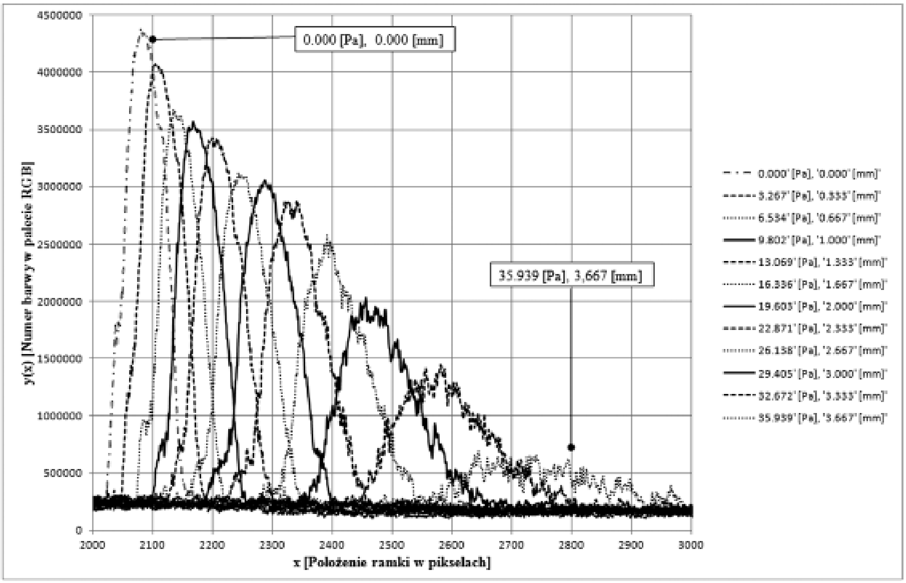

Fig. 8. The graph shows distribution of changes in color intensity for the difference between the free surfaces of liquids in cylinders ranging from 0 to 3.6 [mm]

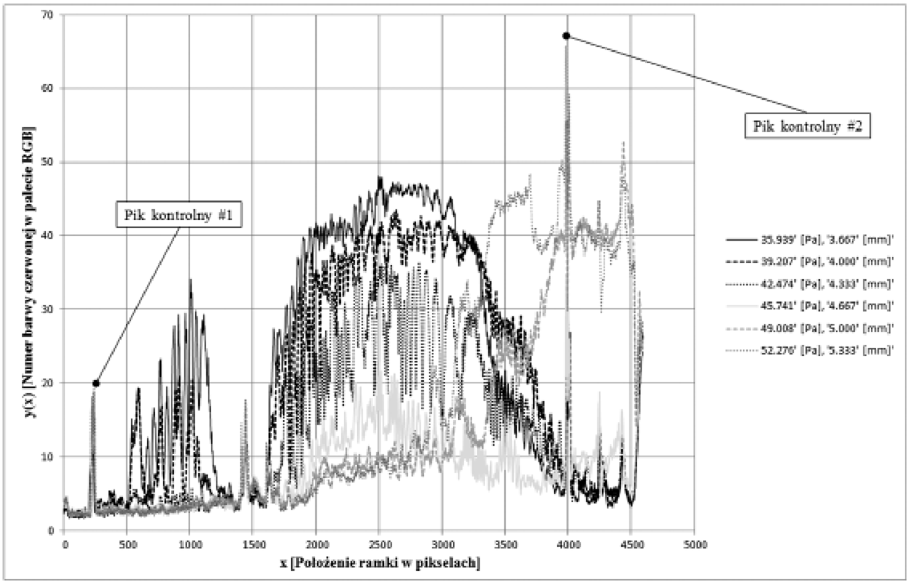

Fig. 9. The graph shows the distribution of changes in the intensity of the color red for the difference between the free surfaces of liquids in cylinders ranging from 3.6 to 5.3 [mm]

of the color changes in the frame moving along the selected line were defined by a computer program using equation (1), which really expresses a standard deviation from the average color.

(Fig. 7 and 9) show color intensity variation curves obtained for different numbers of balls thrown into the cylinder. They show that the control peaks (#1 and #2) derived from different curves overlap. Therefore, the observed differences between them cannot be the result of a shift in the photographed area. The increase in difference of the free surface levels between the cylinders was followed by a clear shift in the maximum variation of color intensity distribution to the “right” with a concomitant decrease in its value and increased blur (Fig. 8). This process was observed for changes in hydrostatic pressure in the range of 0 to 36 [Pa].

Then, beginning with the value of about 53 [Pa], the process is reversed (Fig. 10). This time, the increase in difference between the free surface levels of the cylinders is followed by a clear shift of the maximum distribution of color intensity variation to the “left” with simultaneous increase in its value and reduced blur (Fig. 10). At the same time, in analyzing (Fig.7), it can be noted that the process for values from 0 to 36 [Pa] is more dynamic than the reverse process which begins at about 53 [Pa].

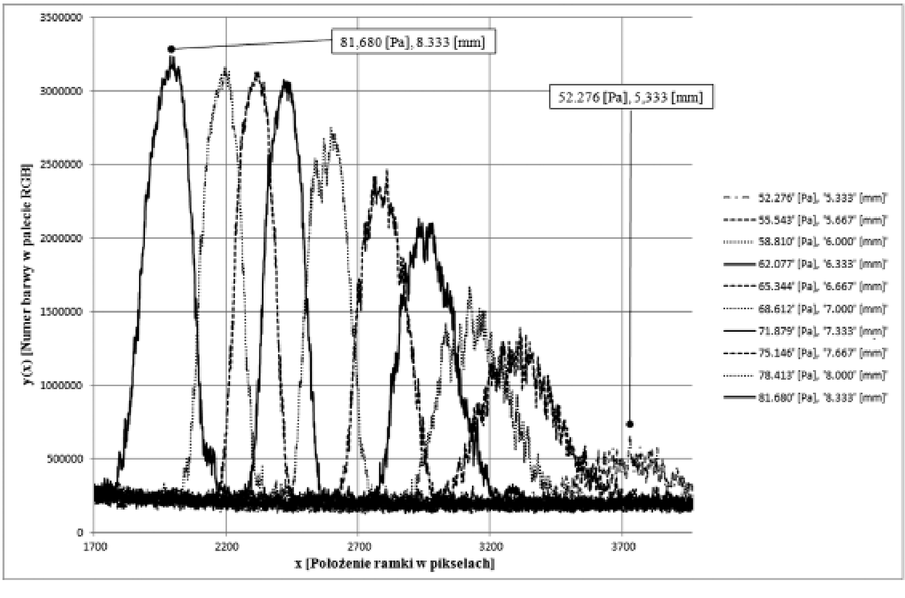

Fig. 10. The graph shows distribution of changes in color intensity for the difference between the free surfaces of liquids in cylinders ranging from 5.3 to 8.3 [mm]

In the range between 36 [Pa] and 53 [Pa] (Fig. 9), the adopted method of color intensity variation distribution turned out to be unsatisfactory. To improve the resolution of the method, it was extended by the analysis of the change in the intensity of three primary colors: red, green, and blue. Converting a file from *TIF* to *BMP* entailed an automatic conversion of the color gamut from sRGB to RGB. This conversion consisted only of removing information about the so-called transparency, a non-essential parameter in our numerical analysis of the image. In the

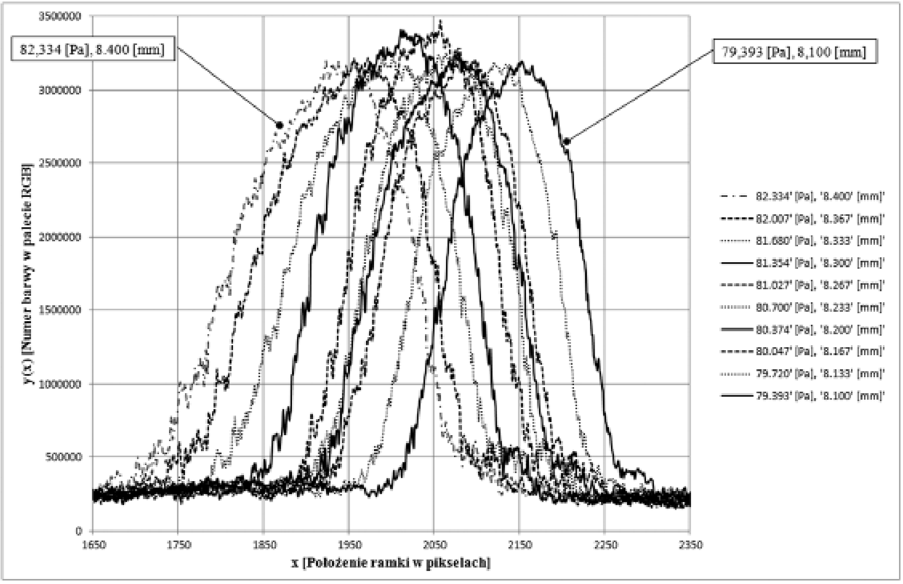

Fig. 11. The graph shows distribution of changes in color intensity for the difference between the free surfaces of liquids in cylinders ranging from 8.4 to 8.1 [mm]

RGB standard, any color can be broken down into the three primary colors (Przybyłowicz, 2007) according to the following relation:

$$\text{Color.RGB Color.Red x} = 65536 + 256 + \text{x Color.Green Color.Blue} \qquad (2)$$

The (Fig. 7-10) show every 10th measurement out of 252 performed in each series of measurements, starting from the first measurement (0.000 [Pa], 0.000 [mm]). On the other hand (Fig. 11) shows the curve obtained for consecutive ten measurements performed (243, 244,... 252). As you can see clearly on the presented graphs (Fig. 11), we are able to measure pressure differences smaller than that of adding one of the ceramic balls with a diameter of 5 [mm] to the tank, giving rise to the difference between the free surface levels inside of the cylinders amounting to 0.033 (3) [mm]. Analyzing the spacing between the curves (Fig. 11) led us to the conclusion that it should be possible to clearly define the difference between the two free surfaces below 10 [μm], which in units of pressure corresponds to values below 100 [MPa]. Furthermore it has been noted, that the process of shifting the wave of maximum amplitude as a function of changes in hydrostatic pressure difference (Fig. 7, 8, 10) is certainly not a linear function, which means that the resolution of the presented method of measuring the difference between the two free surfaces will also depend on the position of the laser head in relation to the gas-liquid phase separation surface. All observed changes, both in the image of the laser beam after passing through the test structure and the numerical analysis of these images using a method based on the analysis of the intensity of color change in a frame moving along the selected line, led us to put forward a hypothesis of wave-like nature of the observed phenomena. This can be seen clearly in (Fig. 4 and 9) as well in (Figs 7-9 and 11), where local disturbances propagate along with changes in maximum amplitude, displacement and blur. Therefore, the

Fourier transform or the "wavelet" method (Ziółko, 2000) should be included in the numerical analysis of data.

Fig. 12 shows three selected ratios describing the color intensity variation as a function of the position of the frame (1), in respect of which the Fourier transform was applied based on the following equation:

$$y(x) = A_0 + \sum_{k=1}^{n} A_k \sin(k\omega x + \varphi_k) \tag{3}$$

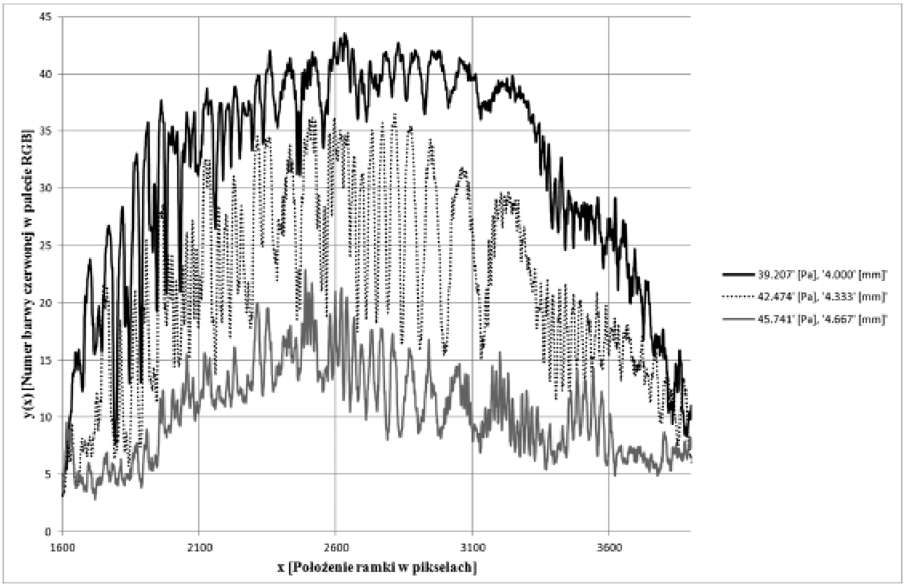

Fig. 12. The graph shows three curves chosen to present application of the Fourier transform for numerical processing of data

The analysis was made using Perry's arithmetic method (Ziółko, 2000) in a window of width $n = 2300$, assuming the starting position value of $x = 1600$ (Fig. 12). In formula (3), the values for the coefficient A_k ($A_0 = A_k$ dla $k = 0$) are shown in (Fig. 13), the values for angle φ_k are shown in (Fig. 14), and the parameter k denotes the k-th harmonic. Unfortunately, this is not a simple matter so the works on development of new methods of image processing are still underway.

It remains to comment on the assumption that the free surface level of the liquid in the second cylinder is fixed. From the foregoing considerations, it is clear that the bubble moves inside of the glass tube under the influence of applied hydrostatic pressure difference between its two ends. This movement, as shown in (Fig. 15), is less than 3 [mm] (the glass tube has an outer diameter of 6 [mm]) for hydrostatic pressure difference of up to 82 [Pa]. Assuming that the phase shift is directly proportional to the applied pressure difference, the free surface level in the second cylinder will increase by less than 0.3 [μm] per Pascal. This change corresponds to the change in hydrostatic pressure of about 3 [mPa], so the error margin will be less than 0.3 [%].

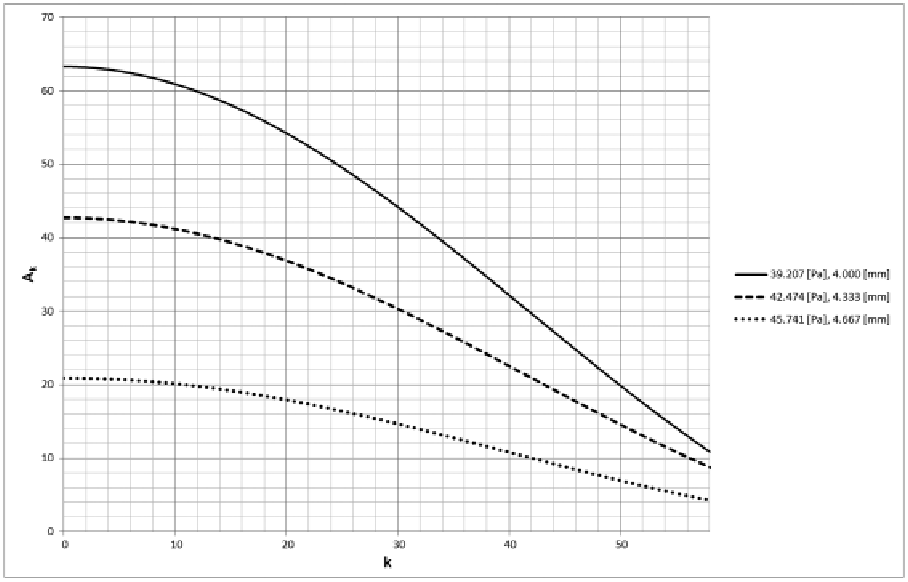

Fig. 13. The graph shows values of the coefficient A_k for the first 58 harmonics

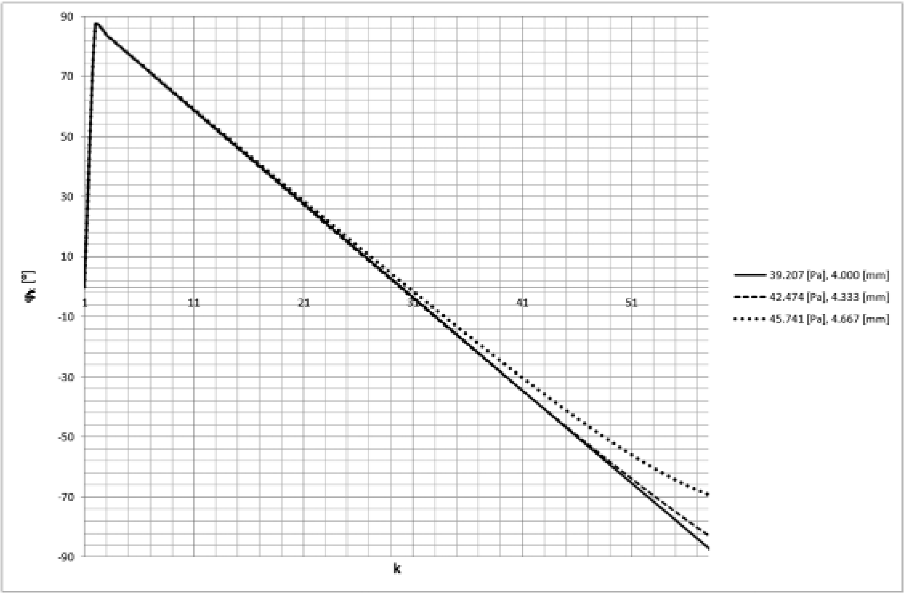

Fig. 14. The graph shows the displacement angle φ_k for the first 58 harmonics

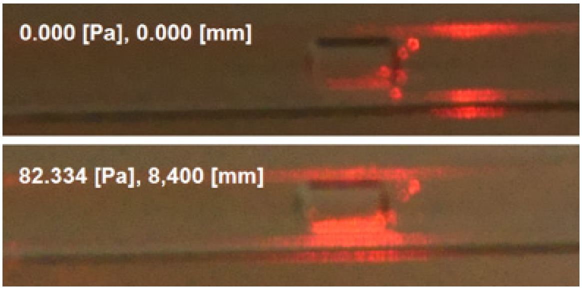

Fig. 15. The figure shows the bubble's shift under hydrostatic pressure difference applied between the two ends of the glass tube

5. Summary and conclusions

This article seeks to introduce a new concept of using the free surface of liquid-gas separation as the measuring membrane of a device used in measurement of small values of hydrostatic pressure. The focus is mainly on the possibility of building such a device – describing the technical difficulties that occurred during the execution of the idea. Consequently, less attention was paid to the broader considerations related to uncertainty of the proposed method's measurements, due to the authors' awareness that this is the first prototype of such a device and, on the basis of this experience, another one will be built and tested.

Modern science has at its disposal devices for measuring pressure ca. 0.1 Pa (e.g. Fluke 7050i allows for measurement of pressure in the range of 0-2500 Pa with accuracy of 0.005%, which corresponds to 0.125 Pa). Unfortunately, these devices cannot be used in our current research due to the fact that they are intended only for measurements carried out with the use of a dry gaseous medium.

The observations and numerical analysis of the image formed on the screen by the passage of a laser beam through the free surface of the liquid-gas separation show that at low values of pressure difference, the bubble acts as a membrane shifting in the direction of lower pressure, in such way that the displacement is proportional to the pressure difference at both ends of the bubble. After the pressure difference subsides, the bubble returns to its original position. At the same time, higher pressure differences cause the bubble to shift toward the source of lower pressure, but the bubble does not return exactly to its original position after the pressure subsides.

The proprietary method of numerical data processing presented in this article, based on analysis of the intensity of color change in a frame moving along a selected line outside of visual changes in the image of the laser beam after passing through the test structure, provided a tool to create first mathematical models to describe the observed changes. However, it seems to the authors that without "wavelet" analysis the presented method is an incomplete model for mathematical description of the observed changes. We classified this method as a 1D analysis model, because it analyzes color variation along a selected straight line. You can also adjust the laser head so that the changes in color intensity (change of texture in the image of the laser beam passing through the test structure) occur in a plane (Fig. 16), i.e., changes are observed in two dimensions (2D analysis). We believe that adding a third dimension would improve the resolution in both the 1D as well as 2D method. Unfortunately, the laboratory site did not allow for such observation.

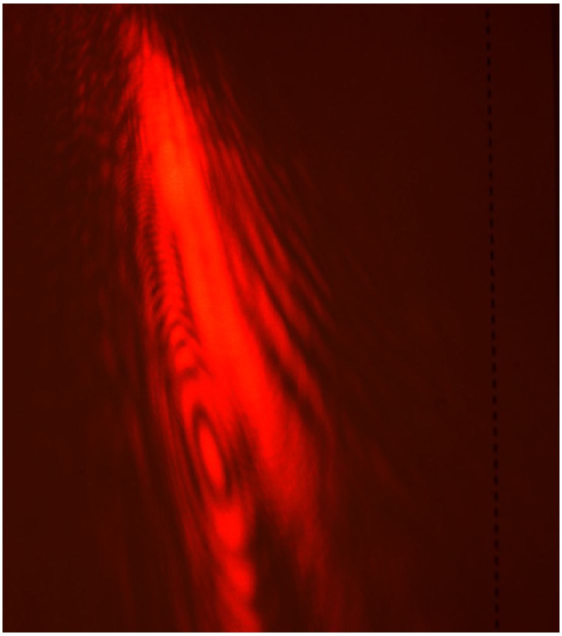

Fig. 16. Image obtained of the laser beam passing through the test structure of the liquid-gas phase separation by setting the laser head to a two-dimensional analysis

Presented in this article method of measuring the difference between the free surface levels in two containers, and hence the measurement of hydrostatic pressure difference provides a new tool for laboratory measurements in the fields of science, which were previously unattainable. Aside from the obvious measurement of a difference between free surface levels of the two containers, the authors envision the presented measurement method being applied in, among others: measurements in range below the so-called lower limit of the applicability of Darcy's law, determining a hydraulic gradient threshold J_0 (Bear, 1988), investigating the physico-chemical processes occurring in liquids for a range of up to about 1000 Pa with a resolution of 0.01 Pa, measurements of microfluidics using microventuris in cases where known methods of measuring expenditure cannot be applied in view of the need to use high pressure at a certain flow rate (currently microfluidics are not measured, instead the desired value is set at the pump, for example: flow through the chromatograph column – piston pump controlled by a computer), and other technical fields, e.g. precision spirit level allowing for level setting with an accuracy of greater than 0.01 [°]. Special attention should be paid to application of the presented method to validation of measurement data obtained from computer simulation of fluid flow through the tested real models. Despite increasingly more powerful computers, often computer simulation still require us to analyze only a portion of the actual test model (Filipek, 2011). Due to the lack of proper measuring devices, we need to use sufficiently large laboratory models in order to carry out measurements (e.g. expansion of the column to measure pressure drop in flows through a porous medium), so as to obtain a measurable value of a physical quantity of interest to us. Unfortunately, the size of the model and its internal structure in many cases does not allow to map it on a scale of 1: 1 in the computer simulation. With smaller size measuring apparatus with satisfactory accuracy, we can reduce the measurement model (correcting the calibration scale of the model in computer simulation) thereby obtaining a more accurate validation.

Our research stem from the desire to construct a measuring instrument that will allow to continue studies initiated in the Laboratory of Fluid Mechanics, Ventilation and Industrial Air Conditioning by Professor Alfred Trzaska, and concerning the study of colmatage (in Western literature often referred to as "deep filtration") – flows with mass and momentum exchange (Trzaska, 1965, 1972, 1983; Trzaska & Sobowska, 1998; Trzaska et al., 1999; Trzaska et al., 2005 and many others). This phenomenon is undesirable, for example, in the case of limiting the flow of water into well drilling, etc.. By contrast, it can be used anywhere where we need to reduce or even eliminate the permeability of porous media. That is, sealing of levees, dams as well as rock mass and underground workings. Most of the experimental work on this subject was carried out at high hydraulic drops (Trzaska & Broda, 1991, 2000; Trzaska et al., 2005), hence it would be very interesting to extend the study by measurement of flows at very low pressure differences.

Acknowledgments

This article was written within Statutes Research AGH, No. 11.11.100.774

References

Adamson W., 1997. *Physical chemistry of surfaces*. New York: John Wiley & Sons, Inc, s. 355.

Bear J., 1988. *Dynamics of Fluids in Porous Media*. Dover Publications, INC. New York.

Broda K., Filipek W., 2012. *Measurement of Small Values of Hydrostatic Pressure Difference*. Arch. Min. Sci., Vol. 57, No 1, p. 157-167.

Broda K., Filipek W., 2013. *Measurement of small values of hydrostatic pressure with the compensation of atmospheric pressure influence*. Arch. Min. Sci., Vol. 58, No 3, p. 901-912.

Duckworth R.A., 1983. *Mechanika płynów*. Wydawnictwa Naukowo-Techniczne, Warszawa.

Filipek W., 2011. *Badania modelowe hydrodynamicznych własności ośrodków porowatych zbudowanych z sieci komórek elementarnych*. Praca doktorska AGH Kraków.

Górniak H., Szymczyk J., 1999. *Podstawy termodynamiki*. Część I i II, Wydawnictwo Politechniki Śląskiej, Gliwice.

Przybyłowicz P., 2007. *Matematyczne podstawy kompresji JPEG*, CMM Sigma.

Szargut J., 1997. *Termodynamika techniczna*. Wydawnictwo Politechniki Śląskiej, Gliwice.

Troskolański A.T., 1957. *Hydromechanika techniczna tom III Pomiary wodne*. Państwowe Wydawnictwa Techniczne, Warszawa.

Trzaska A., 1965. *Experimental Research on the Phenomenon of Colmatage*. Bull. Acad. Polon. Sci., Ser. Sci. Techn., 13, 9.

Trzaska A., 1972. *New Kinetics Equations of the Colmatage Process and their Application*. Archiwum Górnictwa, 17, 4, 361-384.

Trzaska A., 1983. *The Effect of Colmatage on the Porosityof Heterogeneous Porous Media*. Archives of Mining Sciences, 28, 1, 3-11

Trzaska A., Broda K., 1991. *Comparison of the Actual Course of the Phenomenon of Colmatage with Its Theoretical Description*. Arch. Min. Sci., Vol. 36, No. 4.

Trzaska A., Broda K., 2000. *Possibility of Determining Colmatage Parameters and Functions Basing on the Theory of Colmatage and Experiment*. Arch. Min. Sci., Vol. 45, 4, p. 527-542.

Trzaska, A., Broda, K., Filek, K., 1999. *Experimental Research of the Influence of the Colmatage Process on Pressure Distribution and Variability of Flow Discharge and Flow with Free Surfaces*. Arch. Min. Sci., Vol. 44, No 4, p. 531-532.

Trzaska A., Broda K., Filipek W., Sobowska K., 2005. *O zjawisku kolmatacji i jego wpływie na otoczenie*. (The Phenomenon of Colmatage and Its Effect on the Environment). Arch. Min. Sci., Vol. 50, Special Issue, p. 43-56.

Trzaska, A., Broda, K., Rapacz, R., 2001. *O możliwości ograniczenia dopływu wód do wyrobisk górniczych*. Górnictwo Kwartalnik Akademii Górniczo-Hutniczej w Krakowie, 25, 2, 113-120

Trzaska, A., Sobowska K., 1998. *The Phenomenon of Colmatage as a Generalization of Filtration*. Journal of Theoretical and Applied Mechanics, 3,36, 807-817

Ziółko M., 2000. *Modelowanie zjawisk falowych*. Wydawnictwo AGH, Kraków.

Received: 28 March 2014