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A Computer Vision System for On-Line Two-Phase Gas–Liquid Flows Recognition Using Fuzzy Methods

1. Introduction

Two phases gas–liquid flows are a part of rapidly growing trend of research in fluid dynamics. Their particular importance is associated with numerous applications in fields such as bioprocess engineering, biotechnology, environmental engineering, energy and many others. In the semi-industrial process tomography laboratory of Computer Engineering Department of Technical University of Lodz some research is being carried out on this issue [8].

In recent years there was significant, but still unsatisfactory progress in developing knowledge about the two-phase process. In particular, this applies to identification and classification of the nature of these processes. Known methods of solving this problem either rely on the employment of an expert to give a judgment about the flow based on his observations and his knowledge and experience, or to use a complicated set of sensors and process the data of the flow by a computer system [3]. The aim of this works is to equip computer data processing system with mechanisms which can imitate of expert behavior. Due to the fact that both the analyzed visual information and the expert's reasoning are not free from imprecision, one of the most convenient tools becomes the theory of fuzzy sets and fuzzy logic.

This article presents an experimental set up created within the hydraulic-pneumatic installation in the process tomography laboratory. Particular attention is paid to correct scene preparation and to build computer vision system which allows various image processing algorithms to be implemented.

2. Two phases gas–liquid structures

The basic issues in the description of two-phase flow hydrodynamics are [2]: determination of the phases share in the following mixture and the flow resistances of the mixture.

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In addition to the description of mass transfer in two-phase systems there is necessity to know the interracial surface area, coalescence of gas bubbles and mass transfer coefficient. None of these issues have been satisfactory developed in the literature so far [4, 5], which is caused, among others, by a considerable degree of complexity of the mechanism of this type of movements and difficulties in its mathematical description. Another problem is the effective implementation of measurement methods used in the study of two phases flows. The most popular flow patterns are characterized as follows (Fig. 1):

- Bubble flow – small gas bubbles are dispersed in the liquid stream which fills the entire cross section, moving with the speed close to speed of the liquid.
- Casting flow – large gas bubbles, usually with a diameter similar to the diameter of the pipeline alternating with portions of the liquid, in which additionally may be tiny bubbles of gas.
- Foam flow (oscillating, unoriented) – chaotic movement of two phases, creating rare form resembling foam.
- Annular flow – the gas flows at high speed in the central part of pipeline while the liquid forms a thin layer of adhering to the walls of the duct.
- Dispersion flow – the gas stream flows around the pipeline caring the cross – tiny liquid droplets.

One of the main challenges in the analysis of two-phase flows is the possibility of flow structure prediction of the mixture basing on known values of apparent velocity and properties of individual phases and the flow geometry (diameter and angle of wire, placement and shape of structures). Numerous research teams use different techniques for observation of the resulting mixture of flow structures, from the simple visual observation [1] through different techniques of photographing and filming [1], the use of optoelectronic sensors [6] and methods using two and three dimensional computer tomography [6].

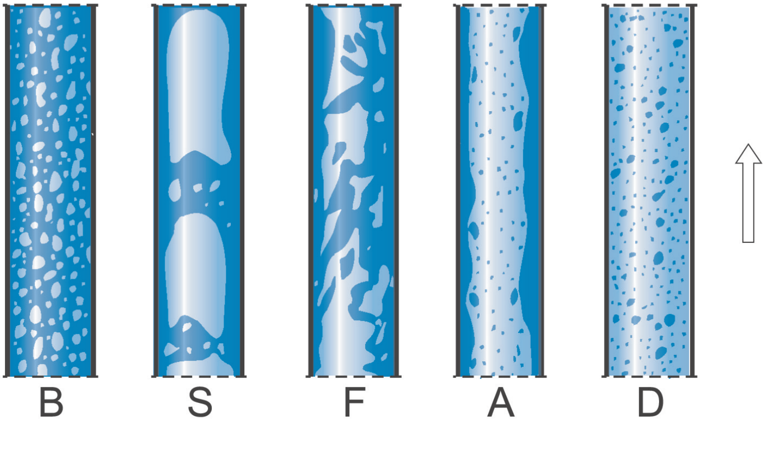

Fig. 1. Two-phases flow structures. B – Bubble flow, S – Casting flow, F – Foam flow, A – Annular flow, D – Dispersion flow

3. The hydraulic-pneumatic installation in process tomography laboratory

Computer Engineering Department of Technical University of Lodz has got a semi industrial installation of hydraulic-pneumatic features which enables to obtain all types of flows listed in section 2 (in horizontal and vertical directions). Installation diagram and the appearance of some of its fragments are shown in Figure 2.

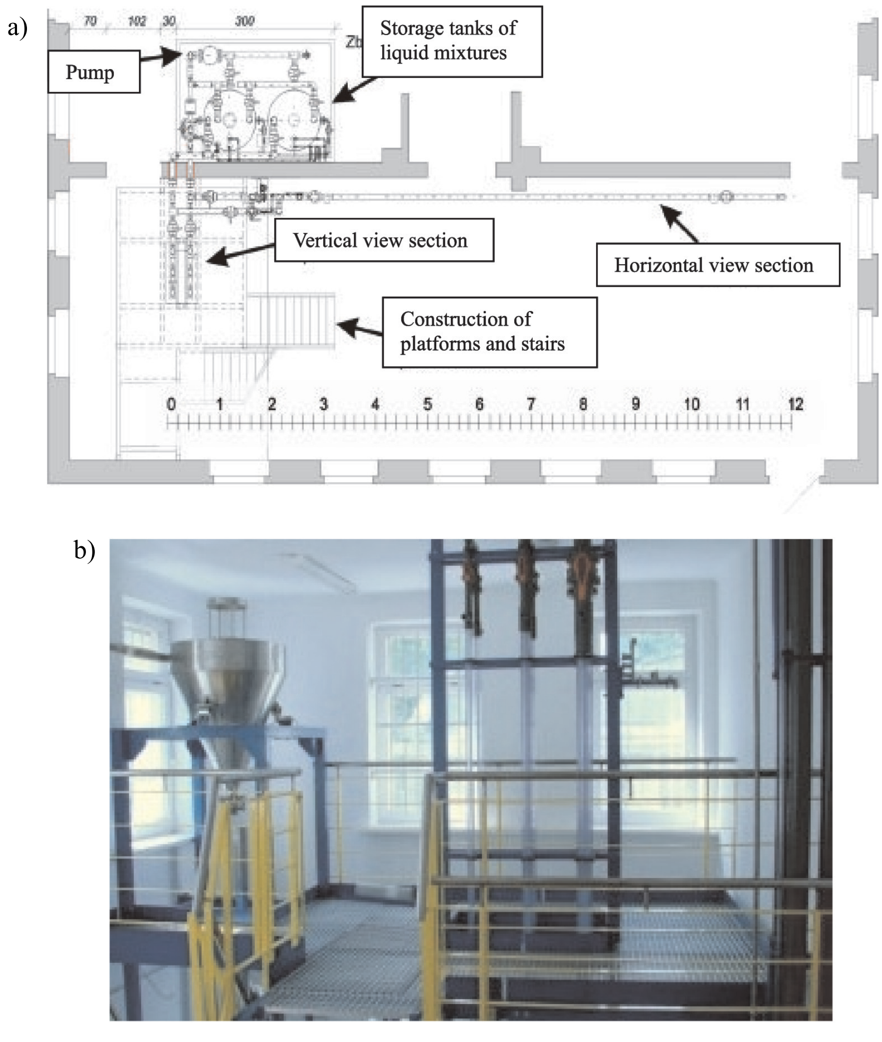

Fig. 2. Installation of hydraulic-pneumatic features in process tomography laboratory of Computer Engineering Department: a) installation schema; b) view of horizontal measurements section

The system facilitates the observations of two–phase flows through the transparent plastic pipe with three diameters (34, 53.6 and 81.4 mm), both horizontal (Fig. 2b) and vertical. The liquid is prepared and stored in two specially designed tanks. High-performance screw compressor and air pump allow fluid flow to get up to 50 m^3/h, and gas up to 1000l/min at 7 bar pressure. The semi-industrial installation allows the measurements of lengths 7.5 m (vertical orientation) and 3 m (horizontal orientation). Furthermore, the installation is equipped with dedicated computer system for data collection and processing (NI PXIe – 1062Q) [7].

4. Preparing of two-phases gas–liquid flows research set up

4.1. General schema of research set up

Automatic recognition of two-phase flow structure based on its image requires computer based data acquisition and processing system in which the efficient digital camera produces series of images of the flow being later processed by the computer system. Preparing the scene also require special care, especially to ensure proper lighting and reduce the impact of external factors. View of the experimental set up build during work reported in this paper is shown in Figure 3.

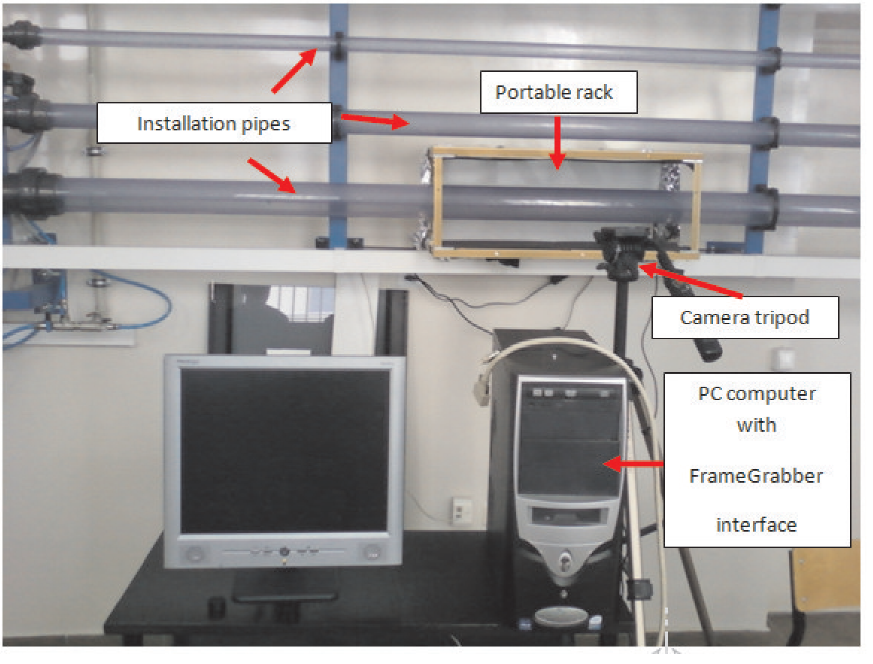

Fig. 3. A general view of the laboratory set up

The basic element of the system, supplementing the camera and the computer, is a portable rack which ensures uniform illumination of the scene. In the situation shown in Figure 3, this rack is mounted on a horizontal pipe with the largest diameter (81.4 mm) available in the plant, while this fragment of the installation is aimed at the camera lens.

4.2. Scene lighting and exposition

One of the important task in preparation of the set up for the automatic recognition of flow structures is to create an optimal conditions for observing two-phase flows. The main problems that had to be solved where related to inadequate lighting of the installation, in particular the significant influence of external light, reflecting in the installation pipes, and the impact of additional lighting of the laboratory. It results in irregularity in scene illumination and its changes during a day, causing underexposure during scene observation with the camera operating in high speed mode (more than 150 frames per second), blurred edges of the observed pipe, especially more illuminated upper edge, and fuzzy border between two phases within the flow.

To minimize the negative impact of inadequate light a portable rack has been constructed with its own lighting system, separating the part of the installation from external light sources. The rack is in the form of a rectangular frame 70 cm × 30 cm × 40 cm, made of aluminum and wooden slats, providing ease of assembly and disassembly in the selected part of the installation. Construction of the rack also allows attachment of various materials and to mount two fluorescent on the back as in Figure 5a.

The next step in the scene preparation was to cover the upper and the lower rack walls by a black cardboard and construction dissepiment with white parchment (Fig. 5b). This technique, derived from artistic photography, caused that the fluorescent light is scattered by the parchment and evenly illuminates the entire pipe. Also the black cardboard, whose image is reflected in the top and bottom of the pipe improves contrast between the edges of the tube and the background (parchment). Figure 4 shows the effect of exposure obtained after the application of the stage constructed lighting system.

a) b)

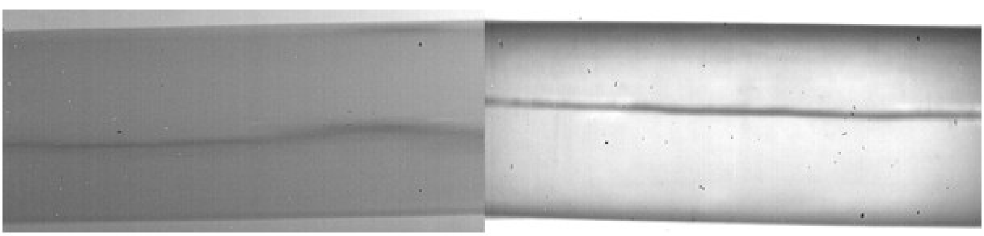

Fig. 4. Image of the hydraulic installation pipe section without (a) and with (b) usage of the dedicated lighting system and scene exposition

a)

b)

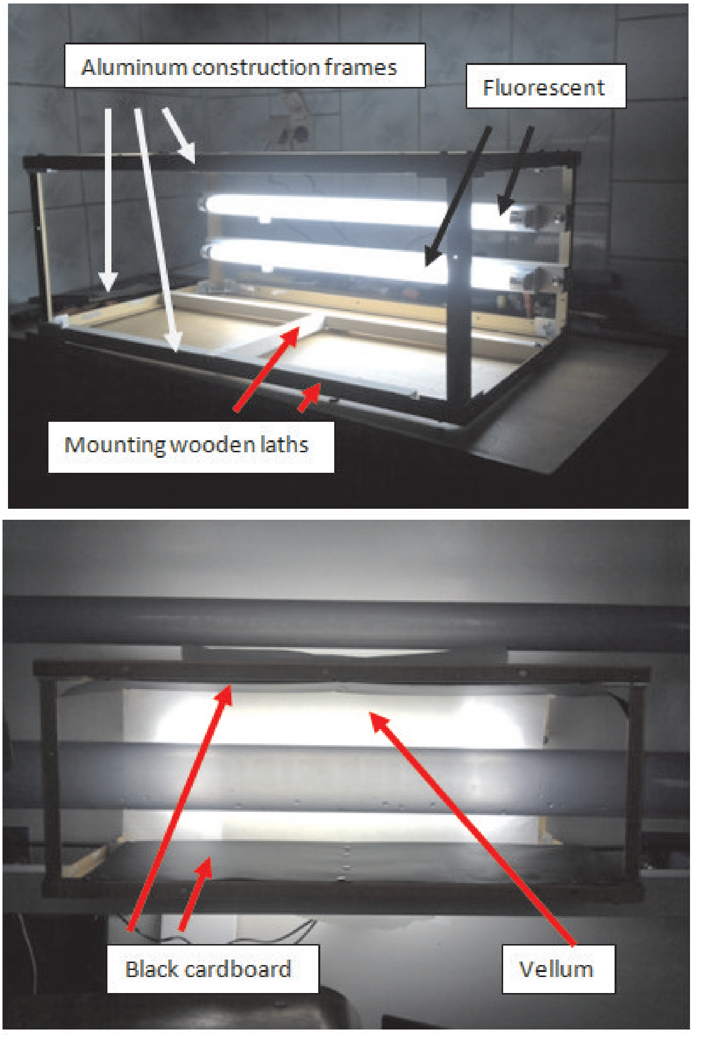

Fig. 5. Rack for proper illumination of the scene in the observation of two-phase flows: a) frame and lighting system; b) the manner of mounting in the installation pipe

4.3. Vision system

Dedicated, computerized vision system consists of three main elements (Fig. 6):

1. Digital camera – very efficient Swiss camera Photo Focus MV-D752-CL CMOS series with the following parameters:
   – resolution: 752×582 pixels;
   – acquisition speed: up to 350 frames per second at full resolution;
   – very low latency trigger;

- the possibility of using in the stereo vision systems;
- logarithmic characteristics sensor LinLog;
- dynamic control of light;
- reduction of noise in the image;
- pre-signal processing;

2. FrameGrabber – the type of expansion card serving as interface between the camera and a PC. This card is for receiving the analog signal from the camera, do the discretization and sampling, generating the appropriate pitch, which converts the analog signal from the camera into a digital signal. The card's controller is responsible for memory management, downloaded images are not automatically saved to disk, it is a reserved memory area, where images are continuously transmitted. The study used Frame-Grabber is made by Silicon Software named microEnable III, and it is characterized by parameters:
   - 12 bit image processing;
   - large buffer support, which results in obtaining detailed images;
   - automatically improvement of the quality of the input image;
   - automatic / manual white balance;
   - automatic image shading Shaft Encoder;
   - automatic shading correction;
   - defective pixel-interpolation;
3. A PC:
   - Windows XP operating system;
   - 2 GB of memory;
   - Intel Core 2.2 GHz;
   - installed .NET software development platform with Visual Studio 2010 Framework 4.0.

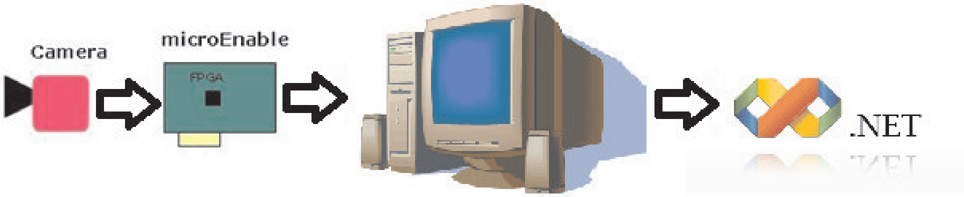

Fig. 6. General schema of the vision system connections

5. Software and algorithms used

For the purpose of research on automatic recognition of two-phase flow structure a special application was created. This application also provides communication with a digital camera through the FrameGrabber card drivers.

The application reads the captured images to the computer's memory and provides features such as:

– locate hydraulic installation's pipes in the analyzed image;
– threshold the images in real time using the Otsu method;
– save images on the disk.

In order to ensure the communication between created in C# language application with supplied by Silicon Software SDK (software development kit) of microEnable III card, dedicated to C++ language, the technique of combining multiple programming languages in one project called Marshalling was used. The technique involves a specific interface in the primary language of the project (C#) that uses some functions written in another language (C++).

Another issue important for the performance of the application is memory management. A cascade management method used for this purpose is shown in Figure 7.

Cascade memory management is based on the initial reservation of a certain amount of memory of the computer and treats it as a vector. Each subsequent downloaded images placed in the vector (memory) on the position of the next index (from 1 to the *n*, where *n* is the index of the last element of a reserved vector) When the entry is occupied by a maximum index (*n*) and the application wants to store more pictures in the vector, it remove a picture with the lowest index (for the first time an vector's element with index 1) and the new picture is saved in its place and the procedure is continued during the acquisition sequence of images.

The most important issue at this stage of application development, was to use an appropriate method for thresholding the image. In the first phase processing procedure correctly locates the installation's pipe, important from the standpoint of the analyzed flow.

This reduces the amount of the processed image (the elimination of a substantial part of the background) and it is very important from the point of view of application performance because the part of used operations are point operations, carried out on the individual pixels. The same thresholding algorithm should be used in the second phase of image processing (manipulating on the image covers only a tested flow) and clearly separate the two phases of the flow.

At the beginning of research on the recognition of characteristic elements of an image such as edges of the pipes or the boundary between the phases of the flow several different approaches were tested. The method, which proved to give the best results based on the observing and analyzing the distribution of colors of pixels in the image. It was noted that the anomalies in the changing colors of pixels along the lines of an image carried from the top to the bottom edge at a right angle, clearly correspond to the position of looked characteristic features as in Figure 8.

Based on these research it was found that to find the edges of the pipe and the boundary between the phases in the flow it should be searched for local anomaly in the evolution of colors values in the columns of the image, it can be also image examination at the very beginning to define the appropriate function of belonging, based on which an image would be threshold. Unfortunately, both approaches, although they give very good results are very time consuming and require many iterations in the subsequent loops, it comes here especially for finding the boundary between the phases, because finding the edges of the pipe can be reduced to two iterations of one image, for two columns, then on the base of founded four points (two on the edge of the top of pipe and two on the bottom edge) to designate the edges of the tube, then transfer founded this way coordinates automatically to other images.

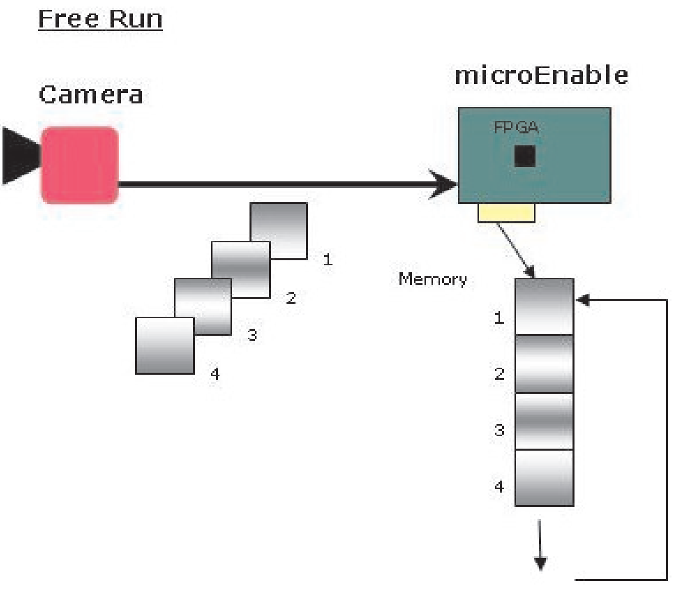

Fig. 7. Schematic of cascade memory management used in the application

Of course, finding the boundary between the phases in the flow can also reduce to the defined by the user number of columns of tested the image, then approximate founded the points by the appropriate function, unfortunately, in this approach, the accuracy in calculating the percentage of phases in the flow is much lower, so the optimal solution is to search for boundary between the phases for each column of the image separately.

After excluding the use of method above it was decided to use the well known image thresholding algorithms. The main task was to implement them so as to maintain their properties at an appropriate speed. Implemented among others: median filtering method, Gauss filter method and the Otsu algorithm. All were tested on the original image and the original images with initial blur aimed at smoothing the edges and remove the small, local anomalies in the image (such as „dead pixels”). Finally the Otsu algorithm was chosen, because it can be fitted to both tasks, in detecting the pipes and the boundary between the phases of the flow.

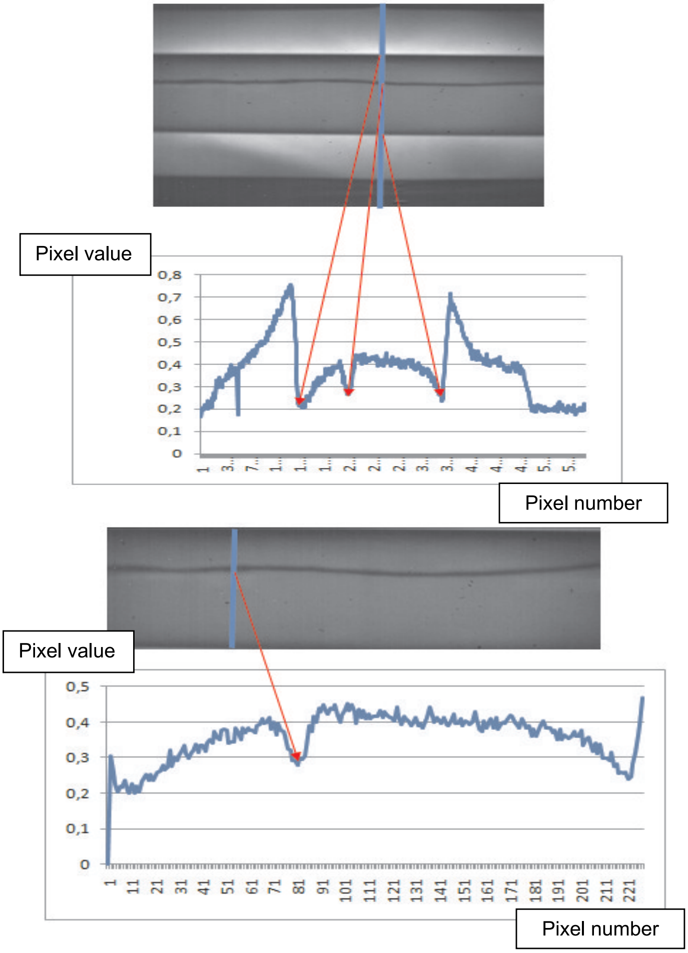

Fig. 8. Example of tracking anomalies in the colors of the image along the designated lines

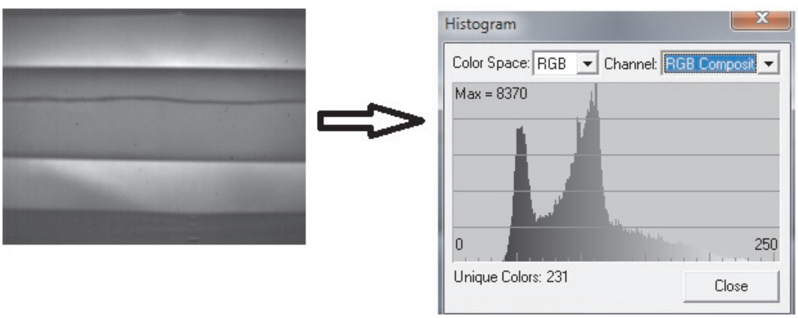

Fig. 9. Generating the histogram

Otsu algorithm is a method of image thresholding based on histogram analysis (Fig. 9–10). Mathematical methods select the optimum value for which the picture is thresholded. The algorithm is as follows:

$$pb = \sum_{k=t+1}^{L-1} pk \tag{1}$$

$$pob = \sum_{k=0}^{t} pk \tag{2}$$

Calculation the probabilities of object and background class

$$\mu b = \sum_{k=t+1}^{L-1} \frac{kpk}{pb} \tag{3}$$

$$\mu ob = \sum_{k=0}^{t} \frac{kpk}{pob} \tag{4}$$

Determination of average values of object and background class

$$\sigma^2 b = \sum_{k=t+1}^{L-1} (k - \mu b)^2 \frac{pk}{pb} = \frac{1}{1 - pob} \sum_{k=t+1}^{L-1} (k - \mu b)^2 pk \tag{5}$$

$$\sigma^2 ob = \sum_{k=0}^{t} (k - \mu ob)^2 \frac{pk}{pob} = \frac{1}{pob} \sum_{k=0}^{t} (k - \mu ob)^2 pk \tag{6}$$

Determination of object and background class

$$\mu T = \sum_{k=0}^{L-1} kpk \tag{7}$$

$$\sigma^2 T = \sum_{k=0}^{L-1} (k - \mu T)^2 pk \tag{8}$$

Calculation of global image descriptors

$$\sigma^2 T = \sum_{k=0}^{t} (k - \mu T)^2 pk + \sum_{k=t+1}^{L-1} (k - \mu T)^2 pk \tag{9}$$

Calculation of global variance

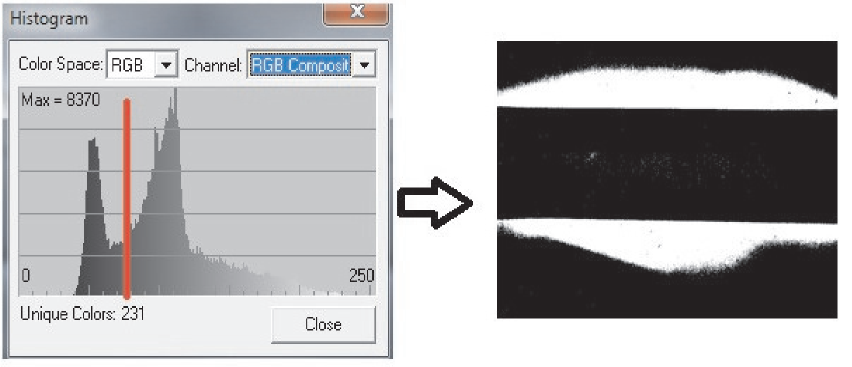

Fig. 10. Selection of the optima threshold value (equation (1)–(9))

Otsu algorithm not only meets the quality requirements of images thresholding in the application, but it is also very efficient.

6. Two phases gas–liquid structures fuzzy recognition

The ultimate and most important objective of the application is the automatic identification of the two-phase gas-liquid flow by analyzing the images captured in a computer vision system using fuzzy set theory and fuzzy logic [9]. It was observed that the definition of the flow structures shown in chapter 2 includes a number of imprecise terms, which in turn are naturally accepted and processed by an expert who evaluate the flow. For example, the expert determines the projective flow as a movement of "long and fast with an average liquid contribution", but bubble flow is" very short to medium speed and very high liquid content [3].

In order to automate this kind of reasoning three parameters whose values can be obtained on the basis of image analysis using the above discussed algorithms, (edge detection algorithm, Otsu algorithm, etc.) were defined as follows:

– flow speed -position change of the identified edge of the two-phase flow (Fig. 11);
– participation ratio of the two phases – the percentage liquid contribution in the image of the whole structure, calculated from the formula:

$$S = \frac{\text{The premis of liquid contribution}}{\text{The premis of whole structure}} \cdot 100\%$$

– „flow length" – the distance between two edges of the recognized structure (Fig. 12).

In the spaces of these three parameters a linguistic variables were defined whose values are the terms found in the descriptions of the various flow patterns. An example of corresponding fuzzy sets is shown in Figure 13.

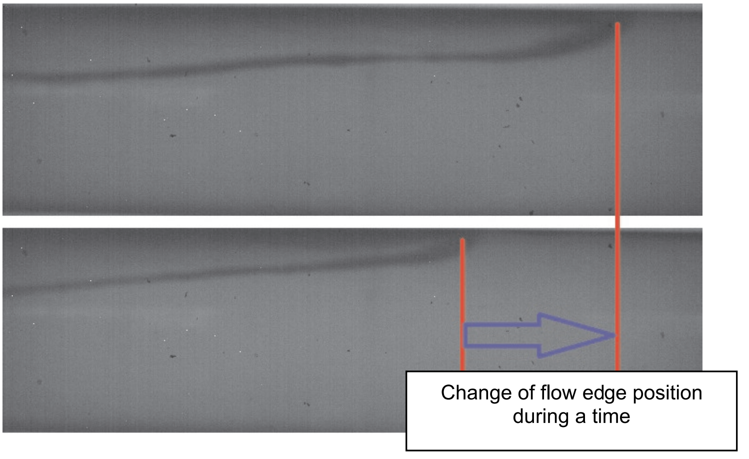

Fig. 11. Position change of the edge of the same structure on different images

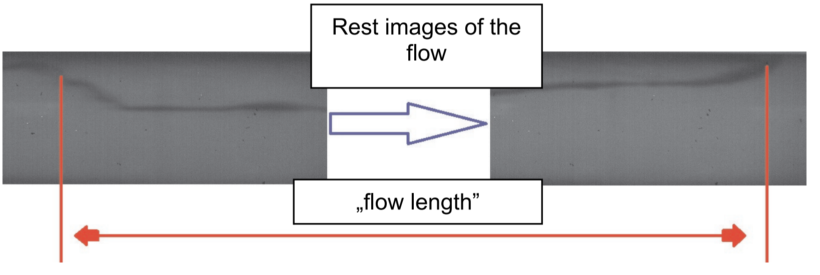

Fig. 12. Graphical interpretation of the concept of „flow length"

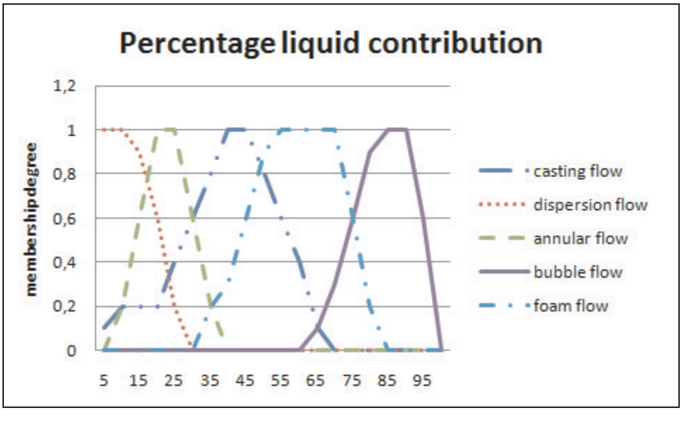

Fig. 13. Example of fuzzy sets describing linguistically percentage of liquid contribution in two-phase gas-liquid structures

Having defined three parameters characterizing the two-phase flow a fuzzy inference system can be build as shown in Figure 14.

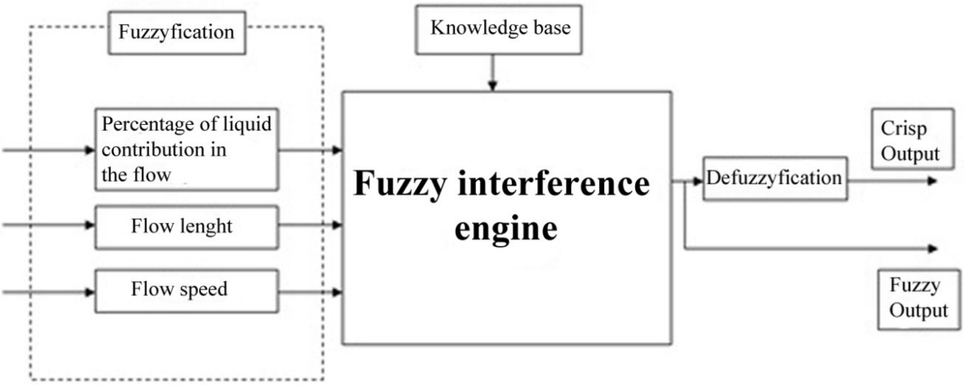

Fig. 14. Fuzzy system for recognition of the flow structures

It should be emphasized that using fuzzy sets makes it possible not only to build a knowledge base containing the man's manner of evaluating of flow structure, but also to express in a convenient way the above-defined values, taking into consideration the natural imprecision of phase boundary. It can be done by a non-singleton method used in the fuzzyfication, phase which takes into consideration an imprecise nature of input data. Similarly, the system output can be crisp (if deffuzyfication is applied), or fuzzy, classifying the analyzed flow to one of the patterns given in section (2), or producing fuzzy information in the form of degrees, which the flow corresponds to each of patterns. This gives the opportunity to build a very flexible system for identifying two-phase flow structures.

7. Conclusions

Taking into consideration the availability of various types of measurement data it seems appropriate to tune proposed fuzzy inference system basing on experimental data. Current work is focused on both the content of the knowledge base and on defining the fuzzy description of the flow of the characteristic values.

Acknowledgements

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References

[1] Fidos H., Wajman R., Banasiak R., Sowioski J., Sankowski D., *Application of electrical capacitance tomography system for non-invasive phases distribution detection in gas-liquid mixtures*. Automatyka (półrocznik AGH), 3, 2010.

[2] Sakaguchi T., Minagawa H., Saibet ., Sahara K., *Dynamics of Two-Phase Flows*. C.J Owen and I. Michiyoski (Eds.), CRC Press, Florida, 1992, 61.

[3] Fidos H., *Hydrodynamika przepływu mieszanin wielofazowych ciecz nienewtonowska-gaz-cząstki ciała stałego w przewodach pionowych*. Rozprawa doktorska, Politechnika Łódzka, Łódź 2001.

[4] Dziubiński M., *Materiały I Ogólnopolskiej Konferencji Przepływy Wielofazowe*. Gdańsk, 1986, 81–88.

[5] Dziubiński M., *Materiały XII Ogólnopolskiej Konferencji Naukowej Inżynierii Chemicznej i Procesowej*. Poznań, 1986, 21–31.

[6] Nowakowski J., Hammer E., Sankowski D., Styra D., Wajman R., Banasiak R., Romanowski A., *New concept of ECT/ERT/GRT tomography for multi phase flow measurements*. Automatyka (półrocznik AGH), 3, 2010.

[7] Delhaye J.M., *Optical Methods in Two-Phase Flow*. Proc. of the Dynamic Flow Conference, Paris 1978.

[8] Nicklin D.J., Davidson J.F., *Symposium in Two-Phase fluid Flow*. London, 1962.

[9] Łachwa A., *Rozmyty świat zbiorów, liczb, relacji, faktów, reguł i decyzji*. Wydawnictwo EXIT, 2001.