APPLICATION OF VIDEOGRAMMETRY IN THE MECHANICS OF MULTI-PHASE SYSTEMS

by

Stanislaw ANWEILER*[*] *and Roman ULBRICH

Faculty of Mechanical Engineering, Opole University of Technology, Opole, Poland

Original scientific paper
https://doi.org/10.2298/TSCI200323278A

This paper is a description of the evolution of long-term research work on two-phase flows using parallel studies of dynamic image analysis and stochastic processes analysis. The state of current knowledge on the research of gas-solid and gas-liquid systems as well as a review of research relating to these issues are also presented. The work grants the principles of videogrammetric surveys based on stochastic analysis for a series of photographs taken with video techniques. The method applies the analysis of changes in selected features and parameters in the time domain. Especially in application to multiphase gas-liquid and solid-gas mixture flows, which are characterized by strong variabilities. Parameters such as flow patterns of the mixture were determined as time-space distributions of phase concentration, displacement velocities of separated two-phase structures, volume partitions of phases, and velocity field distributions are evaluated. The changes of certain parameters characterizing the flow in the time domain often hide more useful information. The subject of this study covers the basics of videogrammetry with a description of two-phase mixture motion for co-current flow in channels, mapping of the phase velocity field, also across the tube bundle in shell-and-tube apparatus, phase motion at the flow of a two-phase gas-liquid mixture in mini-channels, transport of liquids in air-lift pump and fluidization of solid particles.

Keywords: *multiphase systems, flow pattern, image analysis, stochastic process, videogrammetry*

Introduction

In contrast to the mechanics of homogeneous fluids flow, the simultaneous flow of non-mixable components in fluids is a much more complex problem. Depending on the physical and chemical properties of the mixture components, the velocity of individual phases, the space in which the mutual phase movement takes place, a characteristic phase distribution in the flow space is created. Thus, in the two-phase mixture flow inside a channel, many different flow patterns are observed. For many years the visual observation of the flow structure in a transparent channel was used and the decisions about the maintaining desired flow regime depended on the observer. This inherently subjective method was gradually supported by imaging methods using image registration through various techniques. Most often these are photographic techniques in the range of visible length of the electromagnetic wave [1], but

[*]Corresponding author, e-mail: s.anweiler@po.edu.pl

when the flow channel or mixture is opaque, other imaging techniques are used as well, like X-ray [2] or capacitance [3] tomography. In the situation when one of the phases dominates and the other one is quite well dispersed, substitute models may be used as for the homogeneous fluid flow with equivalent properties, such as density and viscosity of the two-phase mixture's components.

The paper presents visualization techniques used in the laboratory of multiphase flows. Such research allows, on the one hand, to learn the mechanics of the flow of multiphase mixtures related to the determination of flow structures, mapping of the boundary surface of phases, and on the other hand, to optimize the working conditions of much industrial equipment. Especially the research was applied for shell-and-tube heat exchangers and chemical reactors. Where the conditions of the two-phase mixture flow in multi-tube apparatus, the flow of the gas-liquid mixture outside the pipes, and the flow in the complicated inter-pipe (shell-side) space were investigated. A lot of effort has been spent on research on gas-solids systems as well. For many years, visualization studies have been conducted to study the flow of multiphase mixtures, which in the case of photographic (photogrammetric) methods allow us to overcome many limitations.

Methods

The basic problem during the visualization and later analysis of the image is the representativeness of a single photo taken, both in terms of the choice of location and the moment of taking the picture. With the development of image recording techniques it is possible to record a series of images with a significant frequency. Sampling frequency easily reaches thousands of Hz, sometimes even millions Hz. In this case, information is obtained about the dynamic characteristics of the process, which allows the use of dynamic image and stochastic analysis. It turns out that photogrammetry and its dynamic derivative – videogrammetry – is an extremely powerful tool. This development is in the form of supplementing the photogrammetry method with the possibility of studying the process dynamics and thus changes in the time domain. It can be used in the research of multi-phase mixture flows due to its non-invasive nature. It gives the possibility for targeted flow evaluation, in the time domain using stochastic process analysis. This method allows omitting, from the metrological point of view, the system calibration process, which is often very tedious.

Selected results of several years of research are presented, including the creation of the foundations of image analysis [4], including videogrammetric techniques [5]. The solution to the interpretation problem by reducing the 3-D system to a 2-D or even 1-D system is also possible [6]. A common description of the motion of a two-phase mixture for co-current ascending and descending flow in vertical channels [7]. Application of the particle image velocimetry (PIV) technique to map the phase velocity field [8]. Studies on the two-phase flow across the tube bundle [9] or in the complex geometry of a shell-tube apparatus with segmented baffles [10]. Flow structure evaluation of the two-phase gas-liquid mixture in cooperating parallel channels [11]. Mechanics of phase movement during the flow of two-phase gas-liquid mixture in mini channels [12], taking into account the influence of the channel diameter on the flow structures and the velocity of the mixture [13]. Mechanics of phase movement in systems, when the inflow of gas-phase induces liquid transport in air-lift type apparatus, especially for air-lift pumps [14]. Application of the PIV method to assess the segregation process at gas-solid mixture outflow from the horizontal channels [15, 16] and in the drum mills [17-19]. Analysis and identification of fluid structures with particular emphasis on the possibility of using videogrammetry to automate flow control processes [20, 21].

A very important problem in the study of multi-phase mixtures is the representativeness of the sample, both in terms of selecting the placement of the interrogation zone and the sampling frequency. Usually, the choice of a feature in the form of a specific physical quantity to be measured imposes the interrogation zone. Figure 1 shows examples of these zones.

Still, at the beginning of the 1980's, the first studies on the objectification of two-phase gas-liquid flow structure identification, *i. e.* the rejection of subjective visual observation through the use of physical quantities, started with electric resistive probes and the analysis of changes in voltage values as a function of time [23]. This moment can be considered the beginning of the implementation of stochastic analysis methods [24] in the research for multiphase mixtures flow. It was found that obtained time series are characteristics for particular flow structures and a good basis for further analysis with the probability functions.

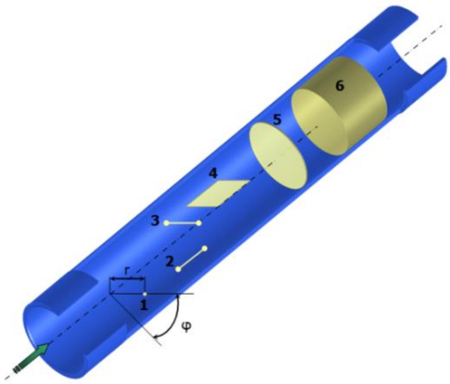


Figure 1. Shaping and configuration of the phase concentration test zones: *1 – point, 2 – line (axial), 3 – line (radial), 4 – surface (axial), 5 – surface (cross sectional), and 6 – volume* **[22]**

Further work on flow visualization indicated new application fields of digital image acquisition, image analysis, and objective recognition methods. Thanks to the pioneering Ph. D. thesis work [4] on the methods of object recognition, a tool for the analysis of different types of gas-solid and gas-liquid flow systems was developed.

As a measure of one of the phases shares in the two-phase flow, an image brightness level (grey level) parameter was used in the selected interrogation zone. The brightness level is determined from:

$$M_k = \frac{1}{(r-l)(b-t)} \sum_{j=l}^{r} \sum_{i=t}^{b} p_{j,i}^{k} \tag{1}$$

This is a feature that applies as both a local and a global parameter. If used locally, *i. e.* for relatively small sub-zones, it is sensitive to local flow phenomena. Although larger objects can overload this parameter quickly and structure recognition may fail. For large areas strong averaging appears, which results in an "equalizing" of the gray levels. This parameter is sometimes used to determine the volumetric share of phases. The second parameter is the length of the phase boundary which is the average share of coast points concerning all points in a given area and is determined from:

$$E_k = \frac{1}{(r-l-2)(b-t-2)} \sum_{j=l-1}^{r-1} \sum_{i=t-1}^{b-1} edge(p_{j,i}^{k}) \tag{2}$$

where

$$edge(p_{j,i}^{k}) = \begin{Bmatrix} 1 \quad gdy \quad \underset{m\in\{-1,0,1\}}{\exists} \ \underset{n\in\{-1,0,1\}}{\exists} p_{j,i}^{k} \neq p_{j+m,i+n}^{k} \\ 0 \quad gdy \quad \underset{m\in\{-1,0,1\}}{\forall} \ \underset{n\in\{-1,0,1\}}{\forall} p_{j,i}^{k} = p_{j+m,i+n}^{k} \end{Bmatrix} \tag{3}$$

This is a global parameter that determines the degree of fragmentation of objects in the image. An increase in the number of pixels belonging to the edges of the structure with all the pixels in a given area is the level of dispersion. It is also possible to determine the local gradient as an average difference in the brightness levels calculated between these pixels and their neighbors according to:

$$G_k = \frac{1}{(r-l-2)(b-t-2)} \sum_{j=l-1}^{r-1} \sum_{i=t-1}^{b-1} \left(\frac{1}{8} \sum_{m=j-1}^{j+1} \sum_{n=i-1}^{i+1} \left| p_{m,n}^k - p_{j,i}^k \right| \right) \tag{4}$$

This is a local feature, as it only applies to the neighboring pixels. This is the measure by which the homogeneity of the two-phase mixture is evaluated. A significant increase in the value of this parameter occurs in the case of an increased number of small objects, or when a large object disperses creating many bright fields. Finally, the fourth parameter, variance. as a difference between the brightness level of a given pixel and the average brightness level of the whole area is measured according to:

$$V_k = \frac{1}{(r-l)(b-t)} \sum_{j=l}^{r} \sum_{i=t}^{b} \left(p_{j,i}^k - M_k \right)^2 \tag{5}$$

It is a measure of the deviation of pixel brightness from the average brightness of the whole area. The nature of this feature is more global but can also be used for local assessment. This feature is sensitive when the image has high contrast, *i. e.* the pixels take the maximum and minimum brightness values. An increase in this feature means a coalescence of objects from a fuzzy and dispersed phase into compact objects.

Acquisition and analysis of images in the time domain generate a time series of brightness fluctuations. These fluctuations are analyzed stochastically, for example, looking for a correlation between different image features. Probability density and stochastic functions are used: autocorrelation R_{xx} (τ) and cross-correlation R_{xy} (τ). Autocorrelation allows us to assess whether the process is random or periodic. The cross-correlation allows us to determine the velocity of selected structures. The stochastic analysis allows us to determine the dynamics of processes, its so-called own frequency.

For the phase velocity evaluation, the Zuber and Findley [25] drift flux model was used. This model allows determination of the actual phase velocity as opposed to superficial velocity and is related to the cross section of the flow. The actual velocity, w_G, of the structure is a superposition of the structure's lifting velocity in an unlimited volume, w_∞ and the sum of the apparent velocities of gas and liquid, often called the velocity of a two-phase mixture, w_T corrected by the distribution coefficient, C_0, as in eq. (6). The volumetric share of the gas phase is the ratio of the gas velocity, w_{sG} to the mixture velocity, w_G, eq. (7). Figure 2 shows a graphical interpretation of the phase drift model [26].

$$w_G = C_0 w_T + w_\infty \tag{6}$$

$$\alpha_G = \frac{W_{sG}}{w_G} \tag{7}$$

Sufficient accuracy (image resolution) and frequency of registration allows, thanks to the PIV techniques additional correlation analysis, to obtain information about the velocity distribution field, or about the movement trajectories of flow structures [27].

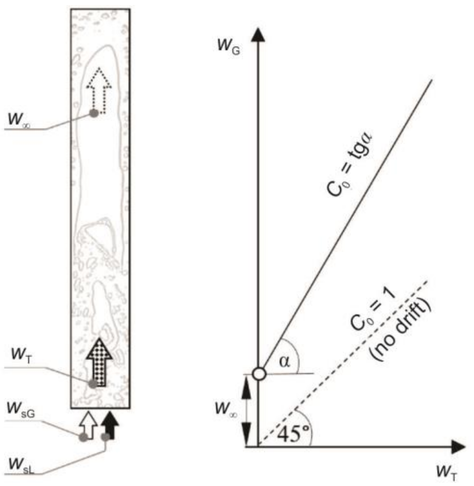


Figure 2. Graphical interpretation of eq. (6) [26]

Described experimental methods are suitable for verifying numerical models of multiphase fluid flow and for designing control systems based on feedback. Especially videogrammetry allows for a precise quantitative description of the process [20]. Figure 3 presents a diagram of a designed system for automatic videogrammetric regulation of the fluidization process with on-line visualization and a decision system based on stochastic and stereological analysis and maintenance of the flow regime.

Results

Figure 4 presents the classification of the basic parameter, commonly quoted in the literature, *i. e.* the flow structures of a two-phase gas-liquid mixture in vertical channels, while fig. 5 presents the result of flow visualization in a rectangular channel. A very good representation of the boundary surface for individual flow structures can be observed.

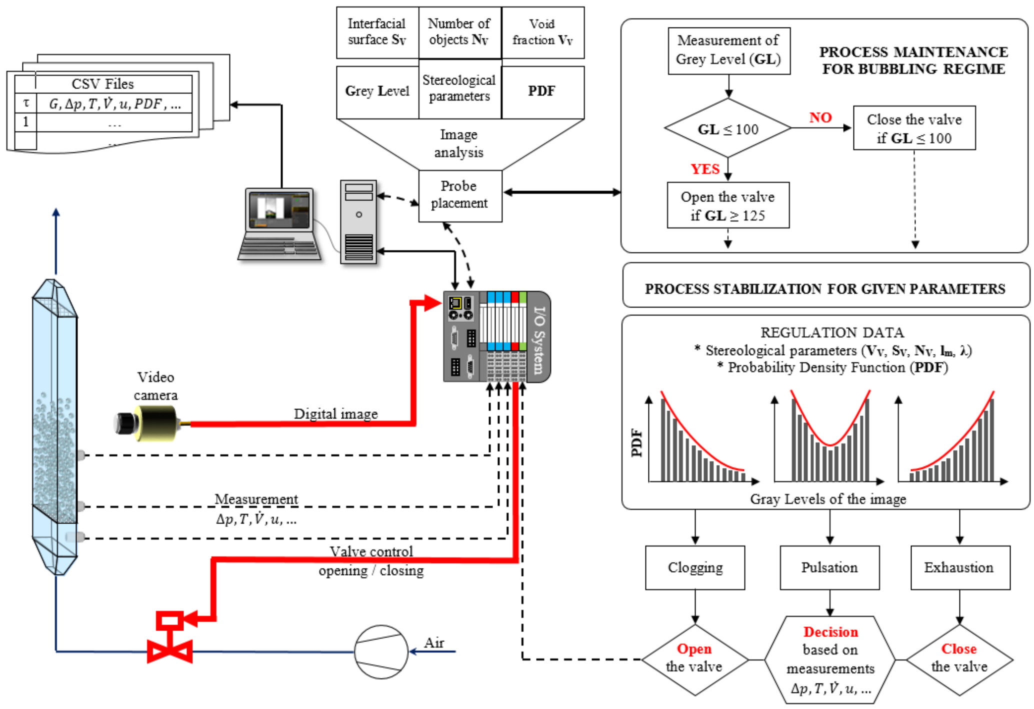


Figure 3. The idea of the videogrammetric feedback process regulation system [21]

Figure 6 shows the results of structure recognition based on stochastic analysis of voltage changes between two electrodes in time and the nature of the distribution of the PDF probability density function (PDF).

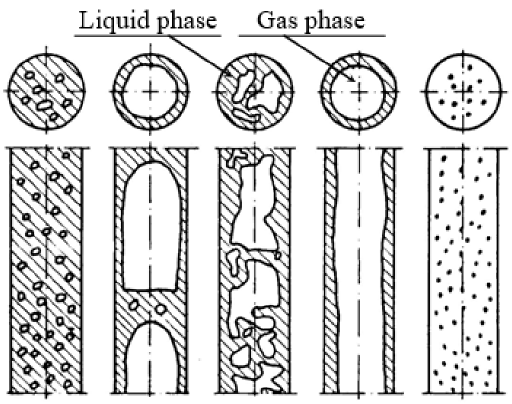


Figure 4. Axial and radial phase distribution at ascending gas-liquid flow in the vertical channel [22]

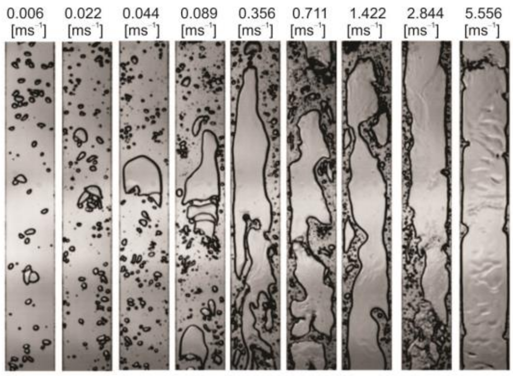


Figure 5. Visualizations of the structures of the two-phase gas-liquid flow in a vertical channel for different gas velocities (constant liquid phase) [6]

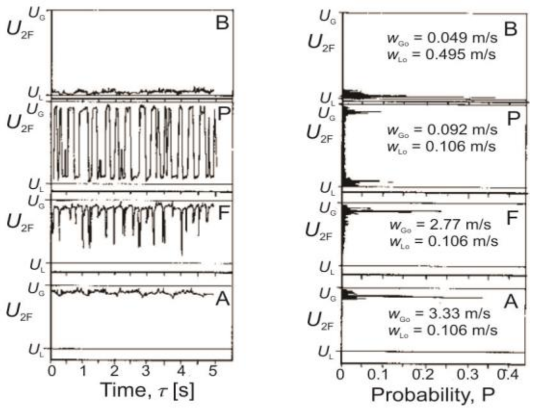


Figure 6. Time distribution of phase concentration distribution and PDF for two-phase gas-liquid flow structures in the vertical pipe: *B–bubble, P–plug, F–foam, A–annular* **[23]**

Figure 7 presents the evaluation results of gas-liquid flow in a vertical channel using the cross-correlation function between the grey levels for selected zones shifted by a known value in the direction of the flow. The autocorrelation function (ACF) shapes indicate a random character of the examined process, while a clear local extremum of the cross-correlation function indicates that between the signals (in this case shifted by a known distance) there is a clear time shift with a w_G velocity common for all moving plug structures.

Figure 8 shows the results of investigations of the velocity field and flow trajectories of gas structures in a barbotage apparatus for different gas velocities dosed through a nozzle at the bottom of the device. In this way, the working conditions of the apparatus with the two-phase flow in a large volume can be optimized. The works also concerned the visualization of the two-phase gas-liquid flow velocity field across the tube bundle, for the triangular and square system, fig. 9. In this way, the influence of the pipe bundle geometry on the disturbance of the mixture flow is analyzed, mainly the occurrence of the so-called dead zones that reduce the performance of the apparatus. Even more complex flow occurs in the multi-pipe apparatus when there are transverse segmental baffles in the shell-side space, which intensify the flow, fig. 10. It was found that depending on such geometrical parameters as window size in transverse segmental partitions and spacing of partitions, there are a flow disturbance and local heterogeneity in the form of dead zones and turbulence zones, significantly affecting the heat flux.

Another interesting research area is the flow of a two-phase mixture in an airlift pump, in which the introduction of gas into a liquid-filled pipe is inducing the flow of the liquid. Figure 11 shows the results of the pump's efficiency evaluation with the

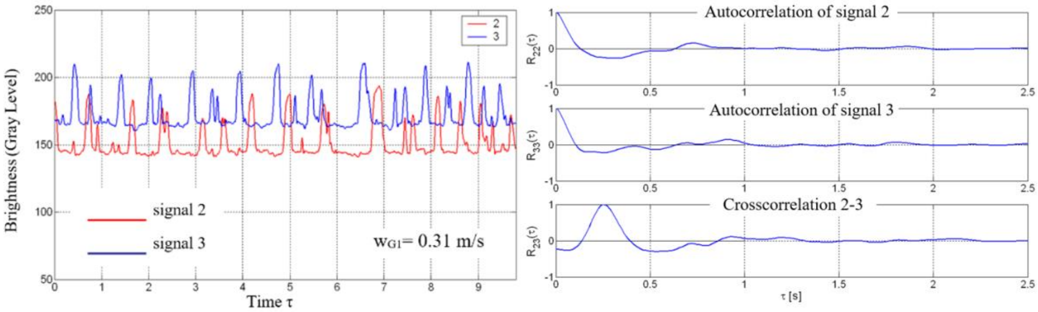
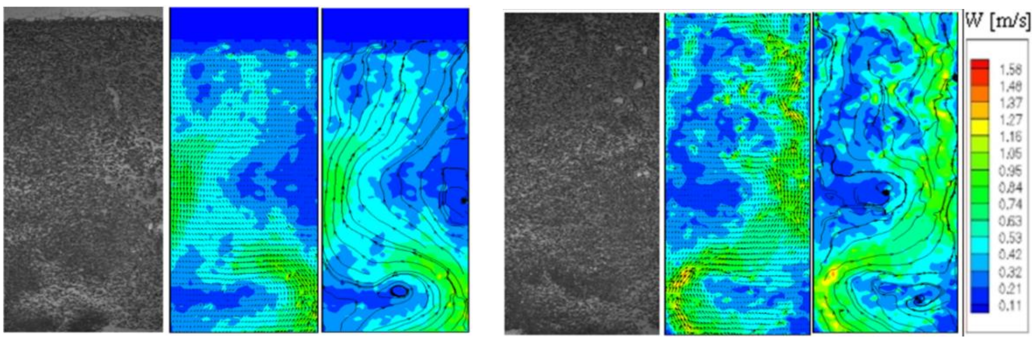
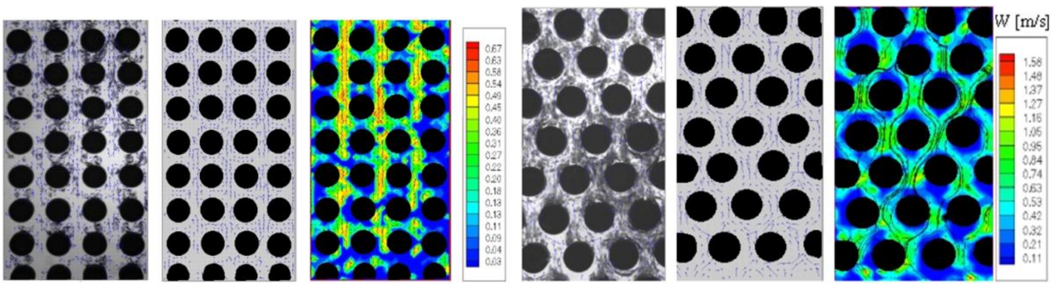


Figure 7. Time series of image brightness fluctuations and functions of auto- and cross-correlation for the studies of plug structure displacement in the vertical channel [11].



(a) **(b)**

Figure 8. Bubble flow images, velocity vector fields, and bubble trajectories for airflow 0.7 m^3/h (a) and 0.9 m^3/h in the barbotage column (b) [8].



(a) **(b)**

Figure 9. Two-phase flow image, velocity vectors and velocity distribution field in the shell-side space of shell and tube heat exchanger: (a) serial (w_{Lo} = 0.14 m/s and w_{Go} = 0.69 m/s), (b) triangle tube bundle setup (w_{Lo} = 0,21 m/s and w_{Go} = 0,69 m/s) [9].

Figure 10. Visualizations of the velocity vector field in the shell-side space of the heat exchanger with segmented baffles depending on the baffle spacing [10].

use of videogrammetry - image's gray level analysis in the time domain. Thanks to the cooperation with Hochschule fur Technik in Mannheim [29-31], visualization studies of the movement of gas bubbles in the micro-reactor - channel with a diameter of 1 mm were carried out, fig. 12.

The study of the two-phase mixture hydrodynamics is important due to the strong influence of the flow structure on heat and momentum transfer processes and is often a prelude to the study of analogy between heat and/or mass transport processes with the use of controlled chemical reactions. In the works [32, 33], studies of the heat exchange process in the multi-pipe apparatus were undertaken, using the analogy between heat and mass transfer. Also an electrochemical method was a subject of verification with the use of videogrammetry. This method is based on electric current measurements during the chemical reaction on the surface of the tube. The method allows the evaluation of pipe bundle geometry and hydrodynamic conditions influence on the unevenness of the heat exchange around pipes in the bundle. Thanks to these studies, the information on the stabilization zone size for the flow around the tube bundle [32] and the dead zone size behind individual pipes in the bundle during a two-phase mixture flow in the shell-side space [33] were verified, fig. 13.

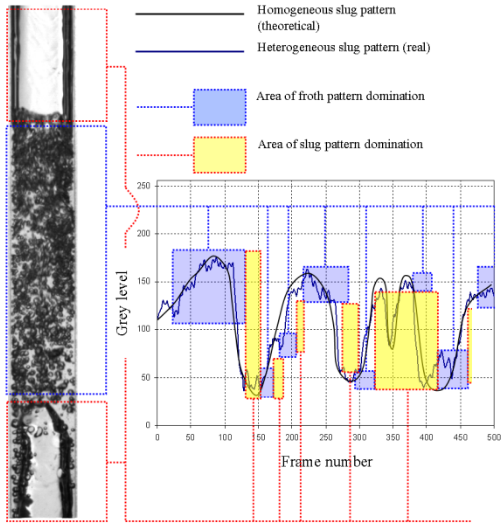


Figure 11. Influence of heterogeneous flow pattern on grey level fluctuations [28]

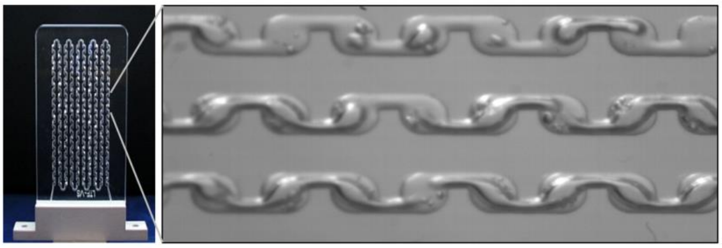
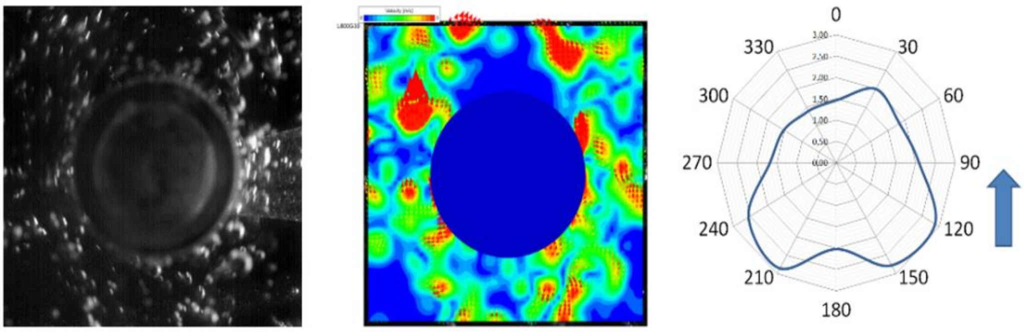


Figure 12. View of the LTF Ilmenau microreactor and the image of the two-phase structure in the microchannel [29].

Videogrammetry allows the visualization and evaluation of a wide variety of fluidization apparatus designs. Below, fig. 14, there is presented a set of several fluidized bed apparatuses and visualization of different two-phase flow regimes.

Figure 15 shows an exemplary result of stochastic process analysis of the fluidization process from the grey level fluctuation point of view. In particular, changes in the grey level over time can be observed for three different flow regimes and the corresponding stochastic function breakdown – PDF and ACF. Based on this analysis, the idea of the videogrammetric feedback process regulation system has been developed (see fig. 3).

Although the testing of two-phase fluid flow is still being intensively studied [34, 35], there is still no definite general model describing the process. The constantly evolving methods of analysis allow the verification of emerging numerical models that facilitate the design process of equipment implementing two-phase flow [36], both gas-liquid and gas-solid [37] or even liquid-solid [38].



a) b) c)

Figure 13. Results of investigations for simultaneous measurement of velocity field distribution and heat transfer coefficient distribution using the electrochemical method; (a) bubble flow around the pipe, (b) visualization of velocity field around the pipe, and (c) distribution of local Nusselt number on the circumference of the pipe [33]

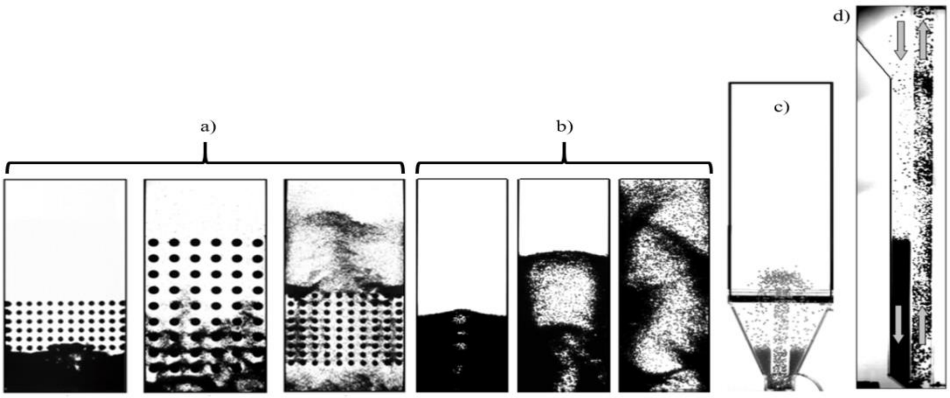


Figure 14. Example images of different fluidization types; (a) with immersed tube bundle, (b) classical (from the left: bubbles, plugs, turbulent), and (c) jet-spouted, d) fast circulating.

Conclusion

The review of the conducted research certainly does not exhaust all possibilities of using the videogrammetry. Videogrammetry is a combination of photogrammetry with a dynamic analysis of images in the time domain and analysis of stochastic processes. From the metrological point of view, the key feature of videogrammetry is non-invasiveness, the possibility of a qualitative and quantitative parametric description of the two-phase flows, and the ability to add other measurement techniques to itself. Measurements taken on the so-called videogram enable reliable parameters that accurately describe the process in many aspects. And those parameters are capable to provide monitoring, control, and maintenance of the processes employing online feedback. A technique that combines visualization with a simultaneous examination of the momentum, heat, and mass transfer processes along with synchronization and automation of data acquisition, which have been presented in this publication, shows how powerful and novel is the videogrammetry.

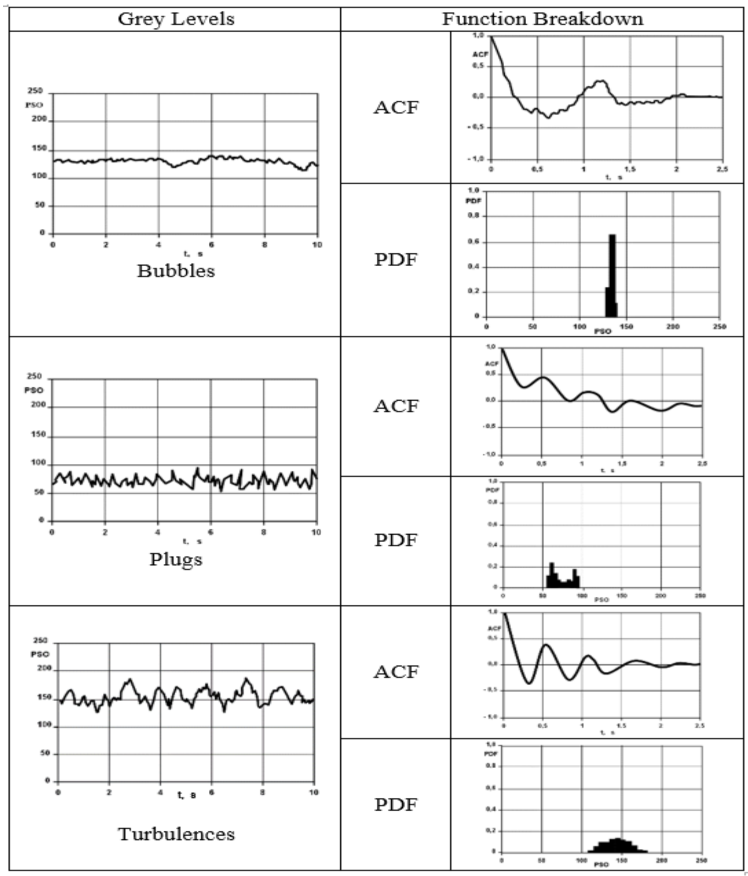


Figure 15. Dynamic image analysis of specific two-phase flow structures (grey levels) and features of stochastic functions: PDF and ACF, determined for structures in fluidized bed heat exchanger based on videogrammetry

In the age of miniaturization the flow structures consist of very small objects reaching down to nanofluids. The presence of usually used measurement sensors would disturb the flow. The combination of this knowledge with industrial automation will allow us to achieve remarkable precision in process engineering, enabling us to control the flow conditions precisely.

Nomenclature

- C_0 – distribution parameter [−]
- E_k – average share of coastal points in relation to all points in a given area
- G_k – average difference in brightness levels calculated between pixels and their neighbors
- M_k – average brightness level of the pixels inside the test area [px]
- (l, t) – co-ordinates of the upper left corner of the survey area
- (r, b) – co-ordinates of the lower right corner of the survey area
- $p_{j,i}$ – value of the pixel brightness level by coordinates j, i for a scene with k index
- V_k – average of squares of the difference in brightness level of a given pixel and average brightness level of the whole area
- w_∞ – drift velocity [ms^{-1}]
- w_G – gas velocity [ms^{-1}]
- w_{Go} – apparent gas velocity

w_{Lo} – apparent liquid velocity
w_{sG} – gas superficial velocity [ms^{-1}]
w_{sL} – liquid superficial velocity [ms^{-1}]
w_T – two phase mixture superficial velocity [ms^{-1}]

Greek symbol

α_G – gas volume fraction [%]

Acronims

ACF – autocorrelation function
PDF – probability density function
PIV – particle image velocimetry

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Paper submitted: March 24, 2020
Paper revised: June 11, 2020
Paper accepted: June 15, 2020