ESTUDO DA INTERAÇÃO DE CORRENTE COM O FLUXO SUPERSÔNICO DE ACORDO COM O PARÂMETRO DA INTENSIDADE DA IMAGEM DE VÍDEO

STUDY OF INTERACTION OF A JET WITH SUPERSONIC FLOW ON THE PARAMETER OF THE INTENSITY OF THE VIDEO FRAME IMAGE

ИССЛЕДОВАНИЕ ВЗАИМОДЕЙСТВИЯ СТРУИ СО СВЕРХЗВУКОВЫМ ПОТОКОМ ПО ПАРАМЕТРУ ИНТЕНСИВНОСТИ ИЗОБРАЖЕНИЯ ВИДЕОКАДРА

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RESUMO

O artigo é dedicado ao estudo do sistema de apoio à decisão na análise de efluxo de gás no fluxo de cisalhamento transversal supersônico de acordo com os resultados do processamento de fotografias (quadros de vídeo) conforme o parâmetro da intensidade da imagem. Estudos de matrizes de intensidade de imagem usando análise de contorno e modelos de receptores tornam possível determinar com grande certeza a posição de qualquer seção (ou conglomerado de seções) de efluxo de gás com avaliação de sua geometria e área com uma dada faixa de intensidade de imagem. Tudo isso possibilita que um especificado intervalo de intensidade de imagem determine áreas com uma determinada lei de mudança na densidade de efluxo de gás, para identificar os contornos dos limites de um fluxo dado. O estudo da lei da mudança na intensidade da imagem em determinadas áreas nos permite identificar padrões de fluxo dentro deles. A utilização do código de cadeia de Freeman, análises de correlação e regressão permite determinar com considerável certeza os parâmetros geométricos das ondas de choque, em particular a inclinação da curva em qualquer ponto. Tendo em conta a análise multivariada na presença de dados estatísticos suficientes, determina-se a relação de correlação entre a densidade, a pressão no fluxo de gás e a intensidade da imagem nas fotografias.

Palavras-chave: *ondas de choque, fluxo dinâmico de gás, fluxo transversal, densidade, camada limite.*

ABSTRACT

The article is devoted to the study of the decision support system when analyzing the outflow of a gas jet into a supersonic transverse shear flow based on the results of processing photographs (video frames) in terms of the image intensity parameter. Studies of image intensity matrices using contour analysis and receptor models make it possible to determine with great certainty the position of any section (or a conglomerate of sections) of the gas stream with an estimate of its geometry and area with a given range of image intensities. All this makes it possible to determine regions with a given law of variation in the density of the gas flow from a given interval of image intensity, to reveal the contours of the boundaries of a given flow. The study of the law of

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change in the intensity of the image in given sections makes it possible to reveal the laws of the flow within them. The application of the Freeman chain code, correlation and regression analyzes allows determining with great certainty the geometric parameters of shock waves, in particular, the slope of the curve at any point of the curve. Taking into account multifactor analysis, if sufficient statistical data are available, the correlation relationship between the density, the pressure in the gas stream and the intensity of the image in the photographs is determined.

Keywords: *shock waves, gas-dynamic flow, transverse flow, density, boundary layer.*

АННОТАЦИЯ

Статья посвящена исследованию системы поддержки принятия решений при анализе истечения газовой струи в сверхзвуковой поперечный сдвиговой поток по результатам обработки фотографий (видеокадров) по параметру интенсивность изображения. Исследования матриц интенсивности изображения с применением контурного анализа и рецепторных моделей позволяет с большой достоверностью определять положение любого участка (или конгломерата участков) газового потока с оценкой его геометрии и площади с заданным диапазоном интенсивности изображения. Все это дает возможность по заданному интервалу интенсивности изображения определять участки с заданным законом изменения плотности газового потока, выявить контуры границ данного течения. Исследование закона изменения интенсивности изображения в заданных участках позволяет выявить закономерности течения внутри них. Применения цепного кода Фримена, корреляционного и регрессионного анализов позволяет с большой достоверностью определять геометрические параметры скачков уплотнения, в частности угол наклона кривой в любой ее точке. С учетом многофакторного анализа при наличии достаточных статистических данных определяется корреляционная взаимосвязь между плотностью, давлением в газовом потоке и интенсивностью изображения на фотографиях.

Ключевые слова: *скачки уплотнения, газодинамический поток, поперечный поток, плотность, пограничный слой.*

INTRODUCTION

The problem of jet flow in a supersonic transverse flow is extremely complicated in its processing (Abashev *et al.*, 2017a; Abashev *et al.*, 2017b; Beketayeva and Naimanova, 2011; Ben-Yakar *et al.*, 2006; Fric and Roshko, 1994; Muppidi and Mahesh, 2007; Kozlov *et al.*, 2010; Dobroselsky, 2011; Taira *et al.*, 2017). Interest in studying the interaction of a circular jet with a transverse shear flow is due, first of all, to the development of new aircraft structures, aircraft engines. It is relevant in the development of promising ramjet air-jet engines, in the circuit of which circuits with non-conventional nozzle devices are realized (Abashev *et al.*, 2017a; Abashev *et al.*, 2017b). In such nozzle devices, very complex three-dimensional flow structures are realized, a special class of flows – "jet in the cross-flow". They are characterized by a complex gas dynamic picture (Beketayeva and Naimanova, 2011; Ben-Yakar *et al.*, 2006; Fric and Roshko, 1994; Muppidi and Mahesh, 2007; Kozlov *et al.*, 2010; Dobroselsky, 2011; Taira *et al.*, 2017; Karyshev *et al.*, 2016; Bodryshev *et al.*, 2016; Tarasenko *et al.*, 2016; Bodryshev *et al.*, 2018; Giskes *et al.*, 2017; Tynybekov and Orozaliev, 2008; Tynynbekov, 2008; Cui *et al.*, 2013), where there are: shock waves; the transition from supersonic to subsonic speeds and back; zones of recirculation and a system of vortex formations in the zones of mixing of flows. It is extremely important for each design decision to evaluate their geometric position and shape, to determine the quantitative characteristics characterizing the given process of gas flow outflow at a given "point".

To describe the flow pattern, the results of the test are used mainly with the simultaneous measurement of the pressure at many points of the streamlined surface in the interaction region of flows, the flow video, the boundaries of the disturbed zones on the streamlined surface are determined, and the results of theoretical studies of the penetration of a gas jet and the interaction of a supersonic flow with a jet obstacle (Rangel *et al.*, 2018). To find the location, shape, "strength" of the shock wave, various algorithms and software products are developed. An algorithm for estimating the slope angles of a shock wave with the use of digital processing of shadow images in terms of the image intensity parameter is developed (Tarasenko *et al.*, 2017). It shows the applicability of each method. In (Bulat *et al.*, 2016), various edge detection algorithms are presented, including Roberts, Prewitt, Sobel, Canny and Laplacian of Gaussian. In contrast to Ref. (Bulat *et al.*, 2016), the authors of (Tarasenko *et al.*, 2017) give the physical justification of this method, considering three options for determining the slope angle: at boundary points, using the Freeman chain code, from the correlation field with an estimate of the correlation coefficient. In (Bodryshev *et al.*, 2018), the first results on the applicability of the video-image intensity parameter for stream flow problems in transverse shear flow for subsonic and supersonic flow regimes are given. The analysis of the development of a circular jet with a parabolic velocity profile in a shear cross-flow is constructed with plotting the intensity-of-image graphs for specific sections of the jet. The dynamics of the change in the intensity of the image and the area of the jet body are studied, depending on the distance from the origin of the outflowing jet for the subsonic flow of the incoming jet (Formalev *et al.*, 2018; Formalev et al., 2015).

Shadow images (shadowgraph), schlieren images (schlieren images) are widely used for supersonic currents. When visualizing the field of gas flow by the shadow method, the intensity of the image is proportional to the degree of change in the density gradient. The Schlieren imaging method is a sophisticated shadow method in which a reference light flux is cut out. The basic principle of the Schlieren system is that part of the light, which is unconfined as it passes through the inhomogeneity of the gas density, is delayed by the edge of the razor installed in the focal plane of the beam. In this case, the visualization of the gas flow field, the intensity of the image is proportional to the gradient of the gas density in the region under investigation in a direction perpendicular to the edge of the razor, and not the degree of change in the density gradient, as in the direct shadow method. In the schlieren method, vortices and rarefaction waves are visualized, and the shadow method is used in most cases to register the position of the discontinuities (Bulat *et al.*, 2016).

There is a large class of computational methods that describe this process in various versions, for example, in (Beketayeva and Naimanova, 2011; Ben-Yakar *et al.*, 2006; Fric and Roshko, 1994; Muppidi and Mahesh, 2007; Kozlov *et al.*, 2010; Dobroselsky, 2011; Taira *et al.*, 2017). The advantage of the computational models is that they can show the flow structure in volumetric expression, which is practically difficult to make under experimental conditions, but the reliability of these results is difficult to confirm, since these calculations do not take into account the nuances of the flow, for example, the presence of shock waves, the exact influence of the geometry of the structure etc.

In this article, it is proposed as a parameter characterizing the process of the outflow of a gas jet into a supersonic transverse shear flow, the intensity of the image of a photograph (video frame). The possibility of this approach was demonstrated by the authors for analyzing the characteristics of supersonic flows in (Bodryshev *et al.,* 2016; Tarasenko *et al.*, 2016; Bodryshev *et al.*, 2018).

MATERIALS AND METHODS

A digital method is proposed for processing shaded and schlieren images of the outflow of a gas jet into a supersonic transverse shear flow. The method is based on the analysis of images of the structure of a gas stream, with its representation in three-dimensional coordinates, where the third dimension the intensity of the image (brightness) $L = f(x, y)$ is chosen. The area of the photo (video frame) is divided into discrete cells containing from *1* to *N* pixels horizontally (the *x*-axis) and from 1 to *M* pixels vertically (ordinate *y*) (Figure 1). The size of the $m \times n$ cell depends on the achievement of the required accuracy of the evaluation of the photography study. Function $l(x, y)$ the intensity of the image is their quantitative characteristic - the level of the white color in the photograph and (in the case of a digital image) is represented by a matrix $L_{M \times N} = \hat{l}(x, y)$ of integers, reduced to the range of gradations 0..255 (quantization), where $M=[kx]+1$, $N=[ky]+1$, $k= \Delta_{of}/\Delta_p$ - the sampling factor, and Δ_{of} , Δ_p - is the proportion of the size of the elements in the digital picture and its value in reality, respectively. The dynamics of the change *L* allows both quantitatively and qualitatively to characterize the gas flow at any point in the image region (video frame).

On the three-dimensional mapping of the function $L=f(x, y)$, the characteristic elements of the given interaction are seen: the system of shock waves, the disk of the move, the core zone of the outflowing jet, the bottom region, and so on. In this video frame, the outflow of a gas jet into a supersonic transverse shear flow is carried out from 2 mm diameter hole, the velocity of the cross-flow M=1.7, the jet is under-expanded (Giskes *et al.*, 2017). This photograph was obtained using the Schlieren method. The ratio of the velocity streams of the jet and the mainstream equals j=3.1

In Figure 2 on the video frame under study, a specific cross section is imposed and the corresponding graph of the intensity of the image is presented below. The trend of intensity change L of *a* given longitudinal section is conditionally divided into the following sections:

1. The section of the gas stream 1-2 before the onset of the jump, where there is a practically inclined wave section of the change in the intensity of the image, characterized by the angle of inclination α.

2. The section of the gas flow at the time of shock wave 2-4, where there is a sharp "peak" change in intensity.

3. The region 5-6 is characterized by an abrupt change in L. In this case, the value of L at point 6 is practically leveled with the data at point 1.

4. The second jump region 6-7 has a wave structure that depends on the choice of the cross-section.

Thus, in all regions, except for the portions of shock waves, the gas flow has a wave character determined by the amplitude of the oscillation ΔL_i and the wavelength λ_i.

It is important to determine the angles of the inclination of the shock wave lines; they determine the velocity of the gas flow ahead of the shock. The disconnected compression shock (curvilinear compression shock) in most cases can be described by a second-order parabola. The parabola regression equation has the following form Equation 1, where $\hat{y}$– the calculated value of the parameter. The values of the coefficients *a, b,* and *c* are determined by solving the following Equations 2, 3, 4, where n is the number of points that determine the regression line. The "ends" of a parabola with a given assumption can be described by a straight line. The linear section characterizes the Mach wave and is determined by the method of least squares from discrete points using the chain code of Freeman, along with the boundary points (Figure 3). Here the cells are given in the form of a sequence of cells according to an eight-linked lattice, $L_i \geq L_{il}$. Here L_i is the intensity in i of the cell, L_{il} is the intensity limit characterizing the shock wave (Tarasenko *et al.*, 2017). This section is determined by the equation of the pairwise linear correlation relation (regression line) and has the form Equation 5, where $\tilde{y}$ – is the calculated value of the y coordinate (the result of the test) at a certain value of the factor sign x; a is the free term of the equation; b is the regression coefficient that measures the average ratio of the deviation of the effective characteristic from its average value to the deviation of the factor characteristic from its average value per unit of its measurement. The coefficients of the regression line are Equations 6, 7, where Equations 8, 9. The oblique compression shock is determined using a straight regression line according to Equation 2.

To determine the areas with given density gradient values, the contour analysis method was used. As a parameter for determining the boundaries of the plot, the range of the image intensity is $L_b=L_{max}- L_{min}$. The area of the site with given values of ΔL_b is determined using the receptor models that discretize the space. Thus if $L_{min}<L_i>L_{max}$ then the fixed value is zero "0" in the cell, the reverse embodiment is put to "1".The obtained matrix with the data "1" allows to estimate the limits of the inclusion, to determine its area. The mathematically receptor geometric model is described by the set $A=\{a_{ij}\}$, where Equation 10. The receptor is considered unexcited if the boundary of the site does not pass through it, and it does not belong to the inner region.

RESULTS AND DISCUSSION:

In Figure 4 shows the part of the photograph shown in Figure 2. It is overlaid with a trace of a gas flow with a given intensity range, according to Equation 3. This method allows us to visualize the shape of the flow of a jet in a gas flow with given conditions $\Delta L_b = L_{max}-L_{min}$. Varying the value of ΔL_b, you can view in detail the flow pattern of the gas flow at any part of it.

This method allows us to determine in detail the characteristics of the flow of the outflowing jet. In Figure 5, *a*, represented by the selected framed portion of the total gas field. On it, an arbitrary section A-A is chosen, and a diagram of the variation of the intensity L in a given section is constructed (Figure 5, b). In this version, the uniform flow of the gas stream is clearly visible.

As an example, Figure 6 is represented as a bar graph comparing video frames for j = 1.4 and 3.1 (Giskes *et al.*, 2017) (j is the ratio of the velocity streams of the jet and the cross flow). A direct relationship between the area of the selected section of the image S with a given range $\Delta L_b = L_{max} - L_{min}$, ΔL_1, ΔL_{sh} and j. Here ΔL_1 is the change in the intensity of the image at the point of flow of the circular jet into the transverse flow, which ultimately determines the rate of flow of the jet.

In Figure 7, and shows a photograph of an under-expanded jet of air is blown into the entraining flow with M=3 (Tynybekov and Orozaliev, 2008; Tynynbekov, 2008). The picture is overlaid with the intensity curve of the image in a specific cross-section. According to the characteristic peaks of the graph, it is possible to determine the positions of the upper, lower boundaries and the axis of the outflowing jet, and also to identify the bottom region. On the discrete points of the image intensity curves in different longitudinal and cross sections (Figure 7, *b*), an upper, lower boundary and an axial line are constructed for the example given and using their approximating second-order function their equations are obtained.

In Figure 8 is a graph of the distribution of the pressure in front of the jet, referred to the static pressure P_1 of the incident flow, given in (Tynynbekov, 2008) for the same experiment (Tynybekov and Orozaliev, 2008), and the corresponding plot of the change in the image intensity in the section near the plate.

In the separation zone, before the obstacle, the pressure rises to a certain value of P_2, then stabilizes at a certain length, followed by a pressure drop to the value P_3 in the region ahead of the spreading line, and then a second maximum of pressure P_4, considerably exceeding the value P_2. The pressure P_4 acts on a narrow strip up to the jet.

It can be seen that the dynamics of the pressure and the intensity of the image are inversely proportional, with increasing pressure, the intensity decreases, but the dynamics of the curves are identical. Thus, according to the dynamics of the change in the intensity of the image, it is possible to carry out a qualitative analysis of the change in pressure.

CONCLUSIONS:

1. A digital method for processing photos (frames) of the interaction of a jet with a supersonic flow is proposed by the criterion – the intensity of the image using the contour analysis, the receptor models that discredit the space of photography.

2. Investigations of image intensity matrices using contour analysis and receptor models make it possible to determine with great certainty the position of any section (or a conglomerate of sections) of the gas flow with an estimate of its geometry and area.

3. The presence of sufficient statistics makes it possible to include a multifactor analysis with the establishment of a correlation relationship between the density, pressure in the gas stream and the intensity of the image in the photographs.

4. These studies provide the basis for creating a system for supporting the adoption of construction solutions, taking into account the analysis of the outflow of a gas jet into a supersonic transverse shear flow in terms of the parameter – the intensity of the image.

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$$\hat{y} = a + bx + cx^2, \tag{1}$$

$$na+b\sum_1^n x_i+c\sum_1^n x^2{}_i=\sum_1^n y_i; \tag{2}$$

$$a\sum_1^n x_i+b\sum_1^n x^2{}_i+c\sum_1^n x^3{}_i=\sum_1^n y_i\, x_i; \tag{3}$$

$$a\sum_1^n x^2{}_i+b\sum_1^n x_i^3+c\sum_1^n x^4{}_i=\sum_1^n y_i\, x^2{}_i, \tag{4}$$

$$\tilde{y}=a+bx, \tag{5}$$

$$a=\bar{y}-b\bar{x}; \tag{6}$$

$$b=\frac{\sum_1^n (x_i-\bar{x})(y_i-\bar{y})}{\sum_1^n (x_i-\bar{x})^2}, \tag{7}$$

$$\bar{x}=\frac{\sum_{i=1}^n x_i}{n}, \tag{8}$$

$$\bar{y}=\frac{\sum_{i=1}^n y_i}{n}. \tag{9}$$

$$a_{ij}=\begin{cases}1, \text{ if } L_{min}<L_i<L_{max}, \\ 0, \text{ if } L_{min}>L_i>L_{max},\end{cases} \tag{10}$$

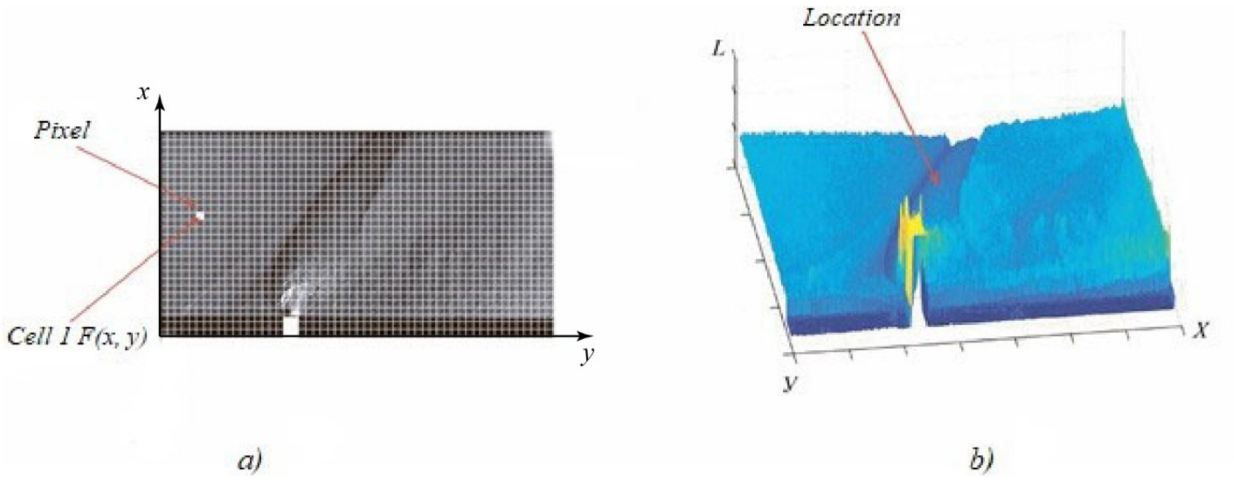


Figure 1. *Photo type (*Giskes *et al*., 2017*): a – gradation of gray color, dividing the xy plane into cells, b – three-dimensional mapping of the function L=f(x, y)*

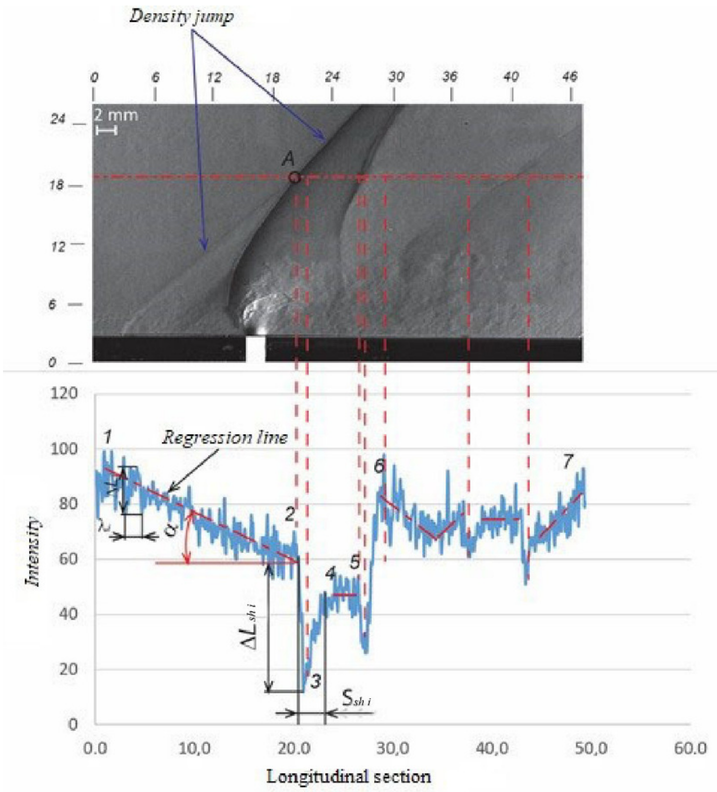


Figure 2. *The photograph of the interaction of the jet and the cross-flow (*Giskes *et al*., 2017*), combined with the graphs of the change in the intensity of the image in a given longitudinal section*

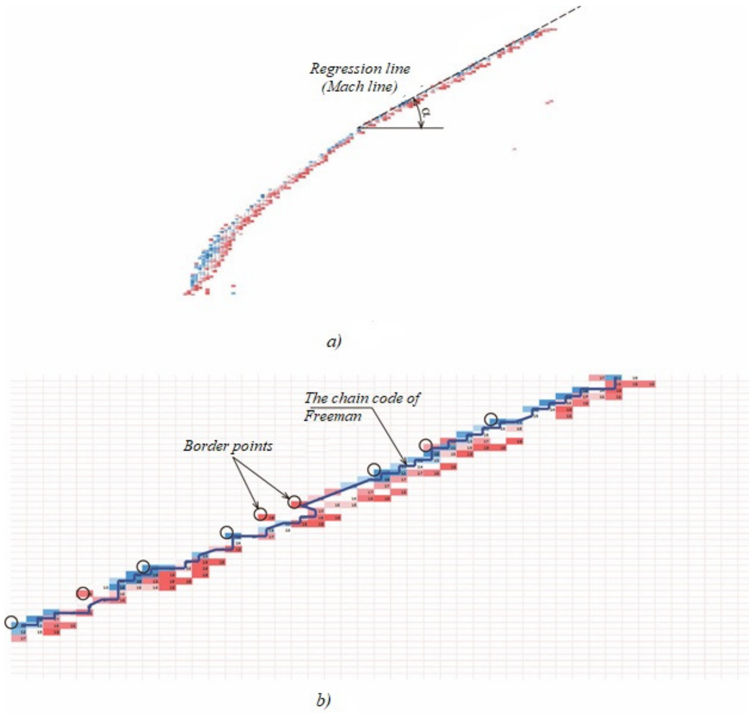


Figure 3. *An example of mapping an array of cells in the shock wave: a – with a specified condition* $L_i \geq L_{il}$*, b – on the Mach jump line*

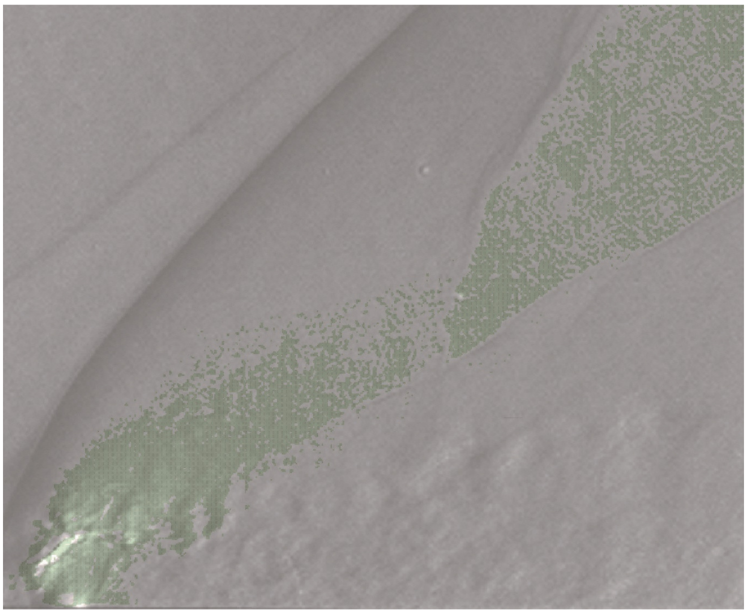
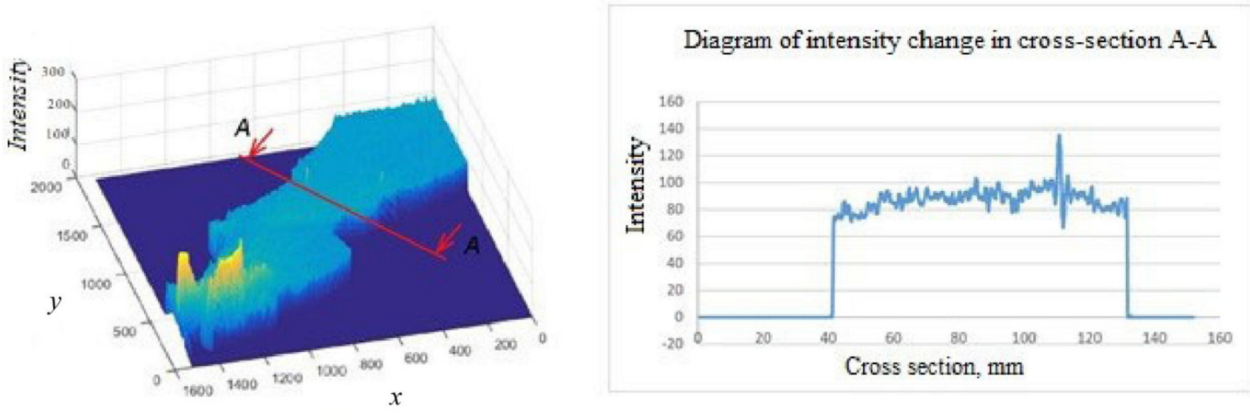


Figure 4. *Example of a photo with a selected area defined by a range* $\Delta L_{sh}=L_{max}-L_{min}$



a) б)

Figure 5. *A three-dimensional mapping of the function L(x, y) with a given range $\Delta L_{sh}=L_{max}-L_{min}$ (a) and the distribution of the density gradient in the cross section A-A (b)*

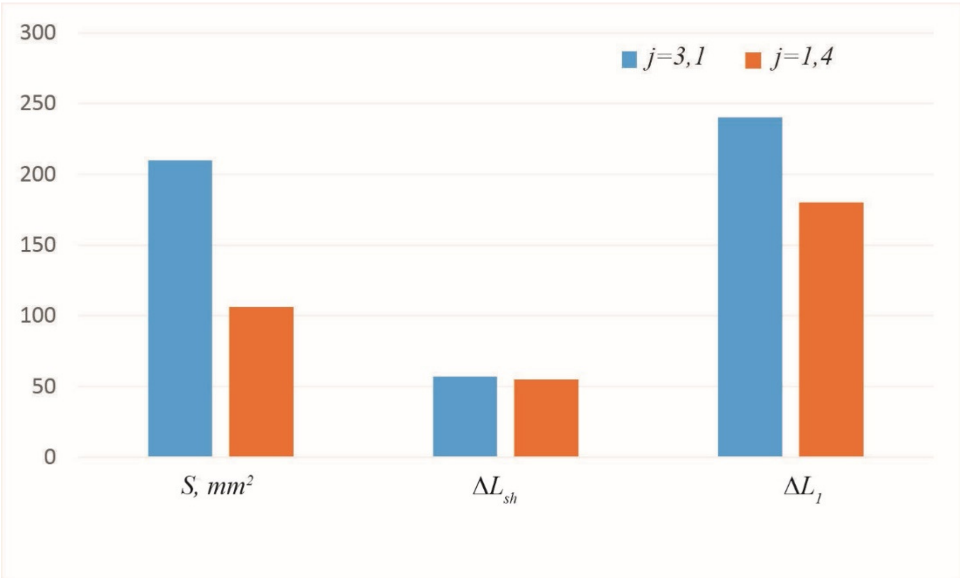
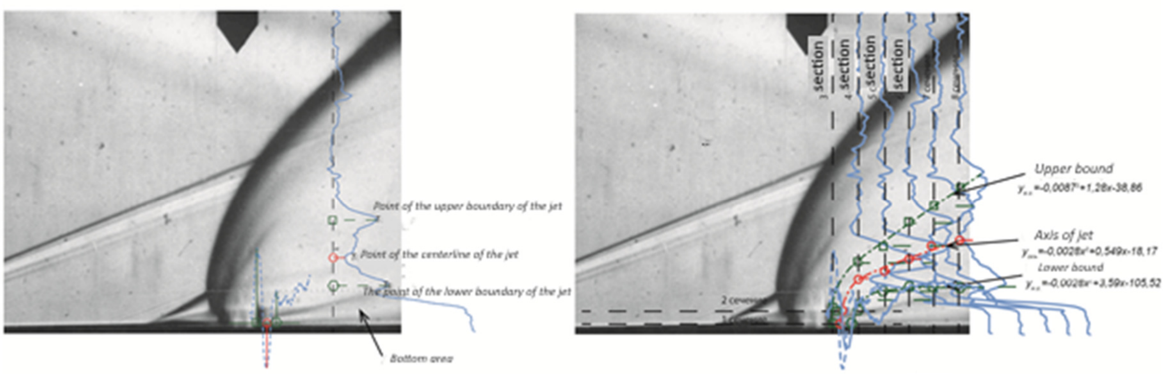


Figure 6. *The bar graph comparing the processed video frames from (*Giskes *et al.*, 2017) *for j=1.4 and 3.1.*



a) b)

Figure 7. *Determination of the boundaries of the outflowing jet*

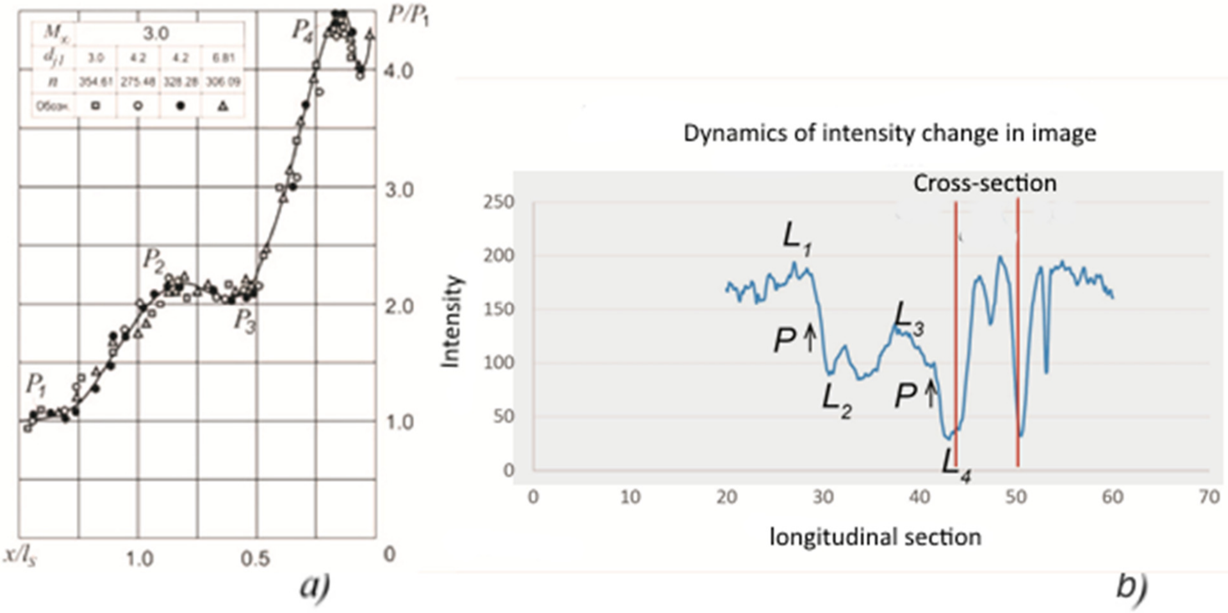


Figure 8. *Comparison of pressure distribution curves before the jet (a) (Tynynbekov, 2008) and changes in the image intensity in the longitudinal section near the plate (b)*