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Using PIV for measuring wind velocity fields in front of and behind bulkheads made from nets of different solidity ratios

Pomiar systemem PIV pola prędkości wiatru przed i za przegrodą wykonaną z siatki o różnym współczynniku wypełnienia

Abstract

This article presents description and results of an investigation using PIV for measuring wind velocity fields in front of and behind bulkheads made from nets of different solidity ratios. The basic aim of the work is to determine the characteristic features of the wind velocity field on the windward and leeward sides of nets of different solidity ratios and to present an example of the usage of a PIV system in tests in an aerodynamic tunnel. The tests were performed in a mini aerodynamic tunnel especially prepared to test the PIV system. In the work, the regulations of measurement by means of a PIV system are presented, the main elements of the system are characterised and the main advantages and difficulties of realising measurements using this type of technique are described.

Keywords: wind tunnel tests, PIV system, wind velocity field, solidity ratio, permeable wind curtain

Streszczenie

Artykuł przedstawia opis i wyniki pomiarów systemem PIV pola prędkości wiatru przed i za przegrodą wykonanej z siatki o różnym współczynniku wypełnienia. Podstawowym celem pracy jest określenie charakterystycznych cech pola prędkości wiatru po stronie nawietrznej i zawietrznej siatek o różnych współczynnikach wypełnienia oraz przedstawienie przykładowego wykorzystania systemu PIV w badaniach w tunelu aerodynamicznym. Badania przeprowadzono w mini tunelu aerodynamicznym przygotowanym specjalnie do testowania systemu PIV. W pracy ponadto przedstawiono zasady pomiaru systemem PIV, scharakteryzowano główne elementy sytemu oraz opisano podstawowe zalety i trudności realizacji pomiarów tego typu techniką.

Słowa kluczowe: badania w tunelu aerodynamicznym, PIV system, pole prędkości wiatru, współczynnik wypełnienia, przewiewne zasłony

1. Introduction

One of the basic problems concerning wind engineering using test models in aerodynamic tunnels is checking the air flow structure. Measurements of this type are used to: determine the wind-environmental comfort of passers-by in urbanised areas; investigate the propagation of pollutants; identify the flow structure of unusually shaped constructions or constructions in conditions of aerodynamic interference; identify the structure of reference fields; identify complex flow structures in cases of the occurrence of aerodynamic phenomena. Wind velocity measurements are most often performed using thermo-anemometers, or vane or cup anemometers. Measurements of this type are conducted, in most cases, at a small number of points, these devices introduce disturbances to the measurement area and the obtained velocity values in the points of the measurement area are usually given in the form of mean values.

Other measurement techniques are used in cases where there is a requirement to measure instantaneous wind velocity fields and there is a need to determine the velocity vector in many points of space at a given moment of time. One of these other measurement techniques is a method of optical, non-invasive measurement of the wind velocity field using PIV (particle image velocimetry) methodology.

This paper presents the principle of measuring by means of a PIV system. The main elements of the PIV system at the Laboratory of Wind Engineering at Cracow University of Technology are described. The paper also presents an example of work performed using this system. The study presents a description and results of PIV measurements of a wind velocity field in front of and behind a bulkhead made from nets of different solidity ratios. Solidity ratio η is defined as the ratio of the effective area of a net material, normal to the wind direction, divided by the area enclosed by the boundary of the whole net normal to the wind direction. Five net cases were considered. Measurements were made in flat areas both in front of and behind the net in which one-way flow was observed.

2. Description of the experiment

The measurements were conducted in a MTT250 mini aerodynamic tunnel, especially built for PIV applications by the author of this study and described in point 4. The measurement configuration in the tunnel space is shown in Fig. 1. On the measuring stand, the analysed nets were spread in the form of a rigid flat plastic square meshed net, the solidity ratio of which was $\eta = 0.25$. The net itself was analysed as a mesh with a solidity ratio of 0.25. Six cases were considered: N0 – no net, flow uniformity in the measurement fields was analysed; N25 – rigid mesh in the form of a net with a solidity ratio of 0.25; N50 – net with a solidity ratio of 0.5; N60 – solidity ration of 0.6; N75 – 0.75; N90 – 0.9. All analysed nets were square meshed and made of plastic. The nets were maintained in a flat geometric form due to them being spread on rigid frames during the experiment.

The square area of the 150 mm x 150 mm stand was set perpendicularly to the incoming air stream. The PIV system measured the air velocity in a flat vertical field of 250 mm x 250

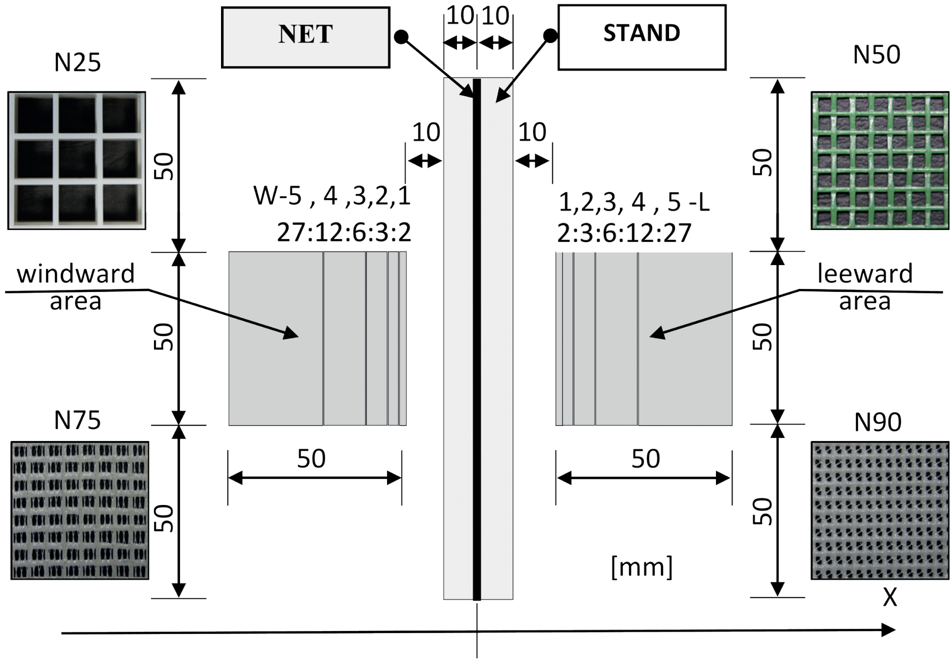

Fig. 1. Measurement configuration with photos of the example nets

mm, which included both the windward and leeward area with respect to the mesh partition. Further velocity analysis was performed in the windward and leeward fields of 50 mm x 50 mm placed at the same distances from the net in comparable positions in relation to the measurement stand as shown in Fig. 1. In these fields, one-way flow was observed with small values of vertical components. Nets with values of the solidity ratio η higher than 0.9 had the features of solid partitions, which meant that in the measurement fields, flows with significant vertical components (along the Y axis) were observed; therefore, this type of net was omitted in the present study. The windward field 'W' and the leeward field 'L' were divided into 5 rectangular sub-areas W1 to W5 and L1 to L5 with side dimensions parallel to the X axis equal to: 2, 3, 6, 12, 27 mm, respectively, as shown in Fig. 1. The measurements were performed at a sampling frequency of 500 Hz for a period of 1 s. The reference velocity during the experiment was 7 m/s, the flow turbulence was characterised by a turbulence intensity factor of 8%. Following the performing of measurements, the mean velocity field was determined on the basis of 500 instantaneous velocity field values obtained from the PIV system (time averaging). The average velocity value was then determined for each of the sub-areas (W1–W5 and L1–L5) using spatial averaging. The sub-areas were arbitrarily adopted on the basis of the wind velocity field structure analysis in the windward and leeward areas; the condition of the symmetry division of the areas was introduced in relation to the net plane. Analysis of individual measurement cases was performed on the basis of ten average air velocity values determined for individual sub-areas W1–W5 (5 values) and L1–L5 (5 values).

3. Principle of PIV system measurement

The PIV (particle image velocimetry) system provides an optical, non-invasive measurement of the fluid velocity field. The Laboratory of Wind Engineering at Cracow University of Technology is equipped with the HS (high speed) version of the LaVision system for measuring flat wind velocity fields (2D version). This type of system makes it possible to measure the field of wind velocity on a plane with a high level of flow turbulence. The basic condition for the measurement possibilities of this type of system is the lack or relatively small value of the component of the wind velocity perpendicular to the measurement plane [1–3]. The advantages of the system are non-invasive measurements occurring simultaneously across the whole measurement area with the presence of a high level of turbulence, which makes it possible to track variable wind velocity fields.

Figure 2 presents the principle of measurement by means of a 2D PIV system [4]. An air stream flow with atomized, fine molecules of the fluid called seeding is illuminated by a pulsed laser with a light of a specific wavelength in the visible range. The atomisation of these liquid particles (seeding) is performed thanks to a special device called a seeding generator. Monochrome laser light is reflected by the seeding particles and recorded using a fast camera equipped with a polarising filter that transmits light with a wavelength equal to the wavelength of the laser beam. A camera sensor of a specific resolution registers the particle system in the form of configuration of clear points at the moment of taking a picture. In HS systems, a double-frame mode is used, in which pictures are taken in pairs at times *t* and *t+dt*, where *dt* is an arbitrarily assumed time of the time shift. In the case of recording high flow rates, the time *dt* is very short and measured in microseconds (μs-10^{-6} s). The pairs of two consecutive frames in *dt* time are recorded with the selected frequency which is the frame rate. The limit values of the sampling frequency of the signal and *dt* time are dependent and limited by the parameters of the measuring equipment. The measurement process is the recording of a sequence of good quality images with an appropriate level of seeding density

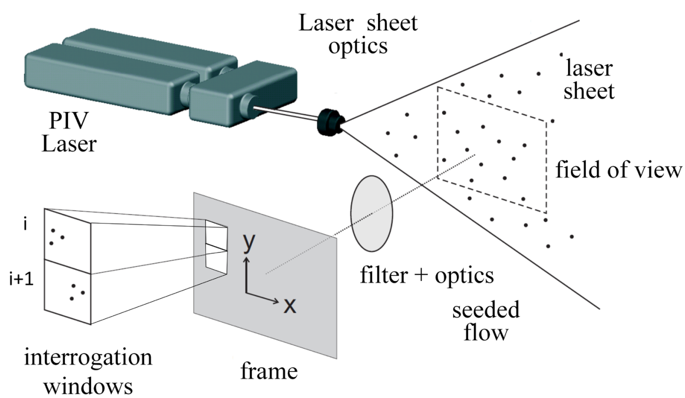

Fig. 2. Scheme of PIV2D system measurement configuration [4]

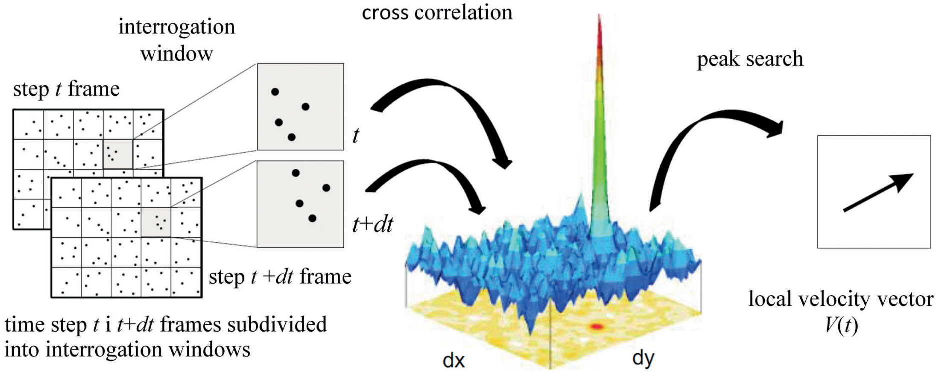

Fig. 3. Scheme of velocity vector calculations by using a cross correlation function in a double frame recording mode [4]

and correctly selected in relation to the wind velocity field structure, the signal sampling frequencies and the *dt* shift time.

During the experiments, the density of particle seeding was around 300 particles/cm^2 and the shift time parameter value *dt* was approximately 200 μs.

The calculation process based on the sequence of images of velocity vectors in a given measurement field is made by determining the cross correlation of frames differing in execution time by *dt* (see Fig. 3).

The calculation is performed by dividing the images from the moment *t* and *t*+*dt* into interrogation windows of a specific size, measured in relation to the pixels of the camera sensor. A basic requirement of the measurement is that the system of seeding particles in a given interrogation window at time of *t* and *t*+*dt* does not differ from each other significantly. Of course, the particle system changes its location in the interrogation window. If a number of particles leaves the given interrogation window, the distances and the arrangement of particles change slightly. Nevertheless, if the time *dt* is correctly matched to the stream flow structure, in the cross correlation product of the data image of the two interrogation windows in moments *t* and *t*+*dt*, a clear maximum of the cross correlation function is observed. The location of this maximum indicates the translational translocation of the interrogation window in a given plane, and using the known time of shifting *dt*, the desired value of velocity can be calculated. Thus, the movement of each interrogation window is of a translational nature described by one velocity vector. In the simplest form, when there is no possibility to overlap interrogation windows on each other, the field of wind velocity in a given area is described by the number of vectors equal to the number of interrogation windows into which images with resolution equal to the resolution of the camera were divided. It should be emphasised that the structure of the frame division into the interrogation windows during the calculations is of fundamental importance in the process of determining the correct wind velocity field [5].

4. Research stand

The measurements were made using the LaVision HS PIV 2D system and were performed in a MTT 250 PIV mini wind tunnel built by the author of this study. The mini tunnel with an open circuit had cylindrical inlet and outlet channels of 400 mm in diameter. The cube-shaped measuring space had interior dimensions of 500 mm. The square measuring field of 250 mm by 250 mm was located in the vertical plane, and its geometric centre overlapped the geometric centre of the measurement space. The measuring space section was equipped with laser-sight glasses and cameras, so that there are no distortions of the laser plane and the image recorded by the camera. A horizontal rotary table for mounting models, in such a way as to enable manipulation of their vertical position, was placed in the measurement space. An openwork screen was installed in the intake duct, ordering the air stream at the inlet into the space of the tunnel measurement section. The air circulation is generated by the suction of the fan located at the end of the outlet duct. The average air velocity in the measuring area of the tunnel is regulated by the rotation of an inverter-controlled fan and can reach a maximum value of 10 m/s. The average value of the turbulence intensity factor for the reference field of the measurement field (measuring area without the model) is 8%. The system's camera can take 1280 photos per second with at full resolution (2016 pixels x 2016 pixels). This means that in the double frame mode, the maximum sampling frequency of the signal can be 640 Hz. A pulsed laser with two laser heads generates a laser beam with a wavelength of 527 nm (green laser) with regulated single-pulse energy of up to 30 mJ (class IV laser). The laser head

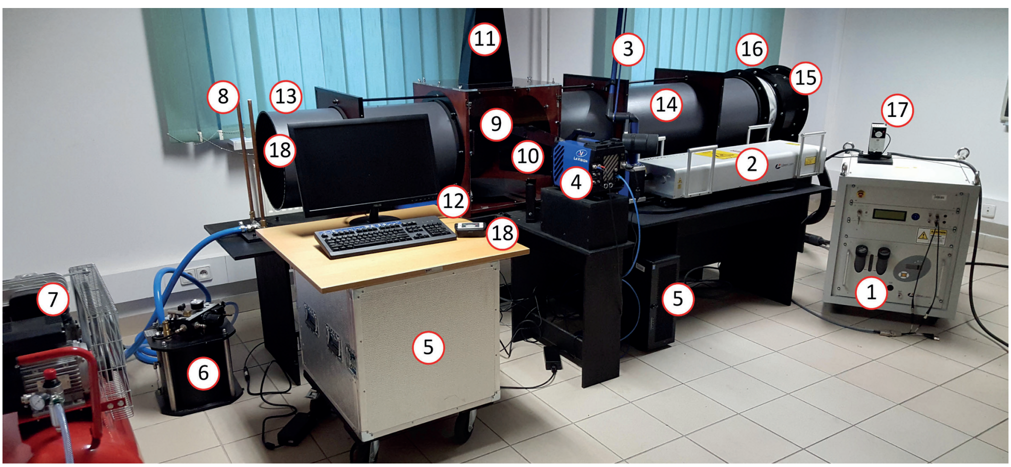

Fig. 4. Main elements of MTT 250 PIV mini tunnel and HS PIV 2D LaVision system: 1) power supply and laser cooling system unit, 2) LDY304PIV laser head, 3) optic system with laser beam guiding arm, 4) ImagerProHS4M fast camera, 5) computer system, 6) PIVPart45 seeding generator, 7) compressor-supplied seeding generator, 8) seeding distributor at the tunnel inlet, 9) working section of the tunnel, 10) window for photographing tunnel working section 11) laser beam inlet to the tunnel working section, 12) LaVision HSC v.2 high-speed controller, 13) inlet tunnel tube, 14) outlet tunnel tube, 15) fan placed on the anti-vibration elements, 16) anti-vibration connection, 17) inverter controlling fan rotation, 18) openwork screen (inside of the inlet tube)

is cooled with deionised water of specified parameters. The whole system is supported by LaVision's DaVis 8.4 software. Figure 4 presents the main elements of the mini tunnel and the PIV system of the Laboratory of Wind Engineering at Cracow University of Technology.

5. Results of the performed tests

The results of the PIV system measurement were averaged over time (see Section 2), obtaining the fields of average wind velocity presented for individual net cases in Fig. 5. Case N0 presents the measurement in the absence of a net. Case N25 is the measurement situation for the stand and the rigid net frame with the 0.25 solidity ratio. The next four cases are situations where the nets of the following solidity ratios are distributed: N50- $\eta = 0.5$, N60- $\eta = 0.6$, N75- $\eta = 0.75$, N90- $\eta = 0.9$.

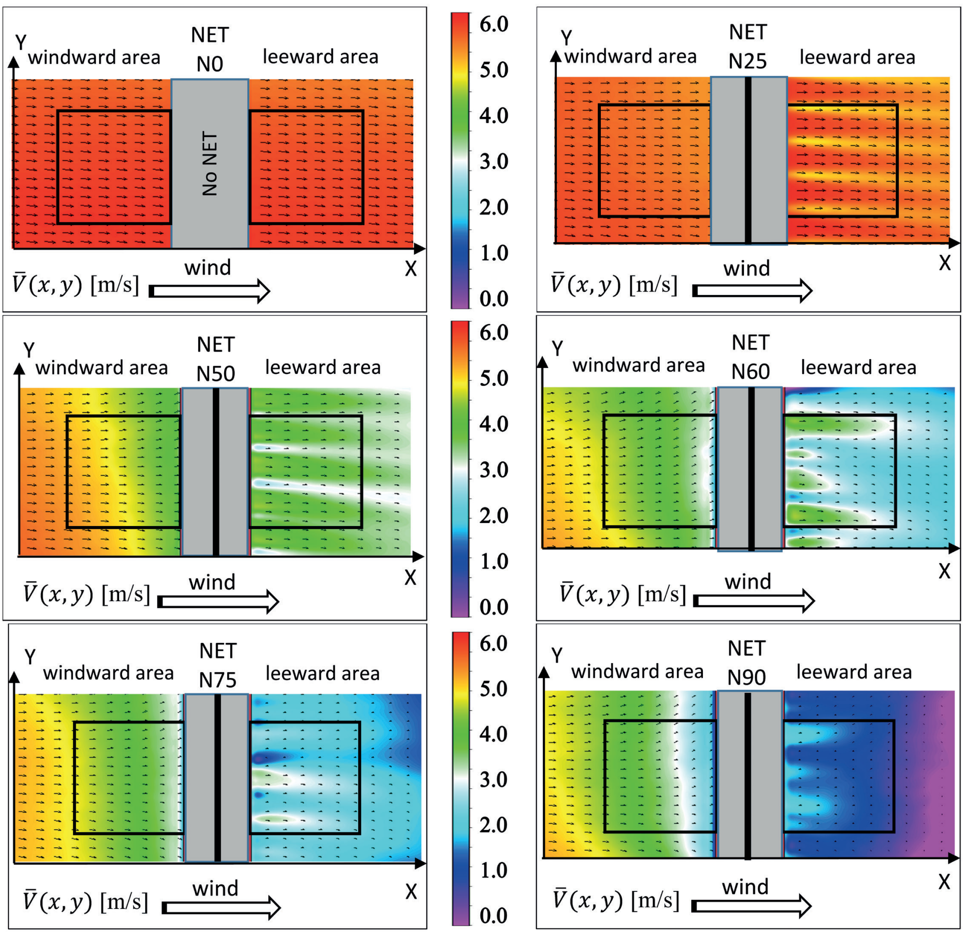

Fig. 5. Maps of mean (time averaged) wind velocity over windward W and leeward L fields obtained in the analysed measurement configurations

The coefficients of average wind velocity values were then determined for individual sub--areas (W1–W5, L1–L5) in accordance with formula (1):

$$C_v = \frac{\overline{V}}{V_{ref}} \tag{1}$$

where: $\overline{V}$ - mean velocity value in particular subarea, *Vref* – reference velocity.

The results are presented in Fig. 6.

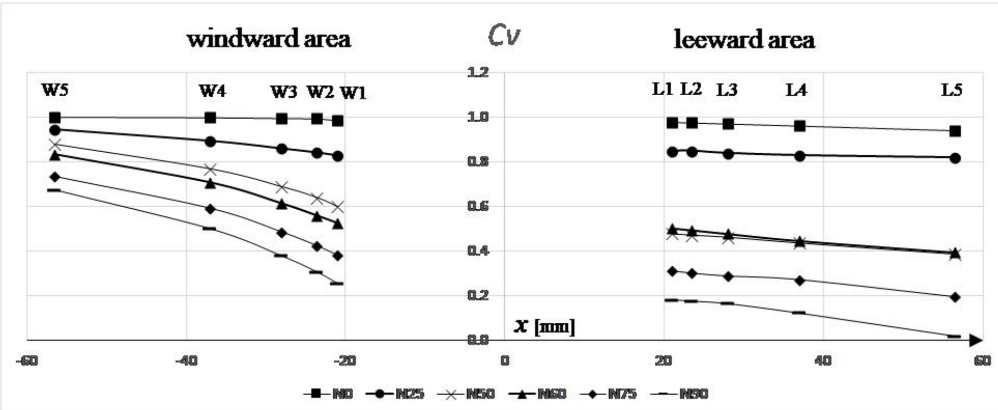

Fig. 6. Mean (time & spatial averaged) wind velocity distributions over windward and leeward subareas in the analysed measurement configurations

As a measure of the air velocity coefficient size change in the windward field Δ*VW* and leeward field Δ*VL*, the velocity coefficient difference in the extreme sub-areas of the given field was considered in accordance with formulas (2). The difference in the air velocity coefficient on both sides of the Δ*VN* baffle was calculated according to formula (3).

$$\Delta V_W = C_V(W1) - C_V(W5),\ \Delta V_L = C_V(L5) - C_V(L1) \tag{2}$$

$$\Delta V_N = C_V(L1) - C_V(W1) \tag{3}$$

Next, the quotient Δ*VL*/Δ*VW* was calculated. The above-defined values for individual meshes of different solidity ratio η, calculated using the results of measurements, are presented in Fig. 7.

Analysis of the results shows that:

- the decrease in the velocity coefficients in the windward field Δ*VW* and the leeward Δ*VL* field is directly proportional to the mesh solidity ratio η; the windward field is characterised by greater dynamics of the velocity drop than the leeward field;
- the velocity coefficient change on both sides of the Δ*VN* net is directly proportional to the mesh solidity ratio η;

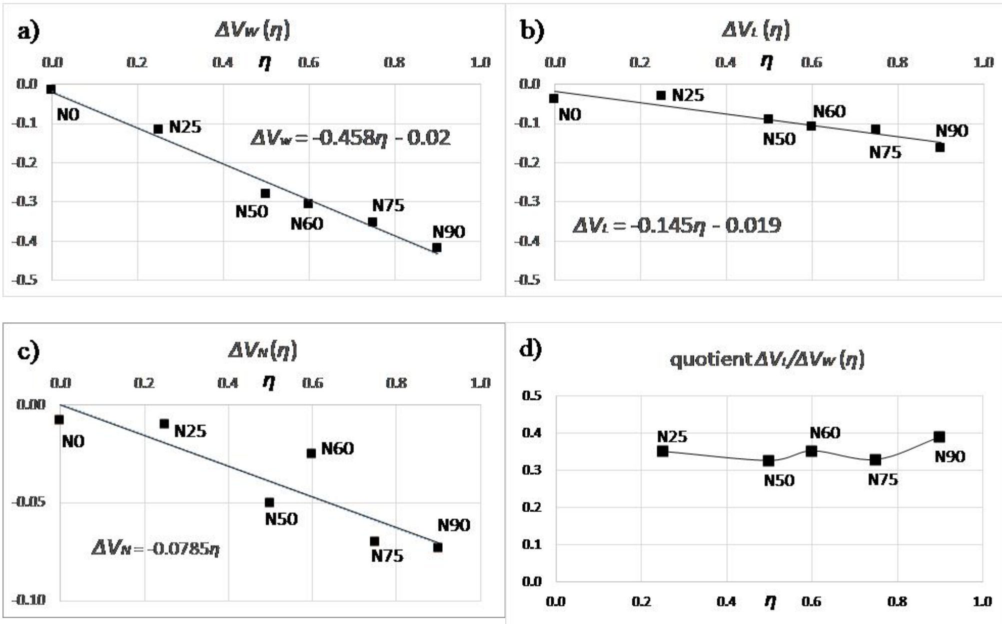

Fig. 7. Values of: a) ΔVW, b) ΔVL, c) ΔVN, d) $\Delta VL\ /\Delta VW$ in the analysed measurement configurations

- in the analysed wind zone configuration, the quotient $\Delta VL/\Delta VW$ is approximately 0.35;
- due to the small dimensions of the measurement areas and the near proximity of the measurement areas to the nets, the values of the analysed quantities can be considered as limited values (with $\Delta x \to 0$).

6. Conclusions

This paper has presented an example of the application of the PIV system for measuring the wind velocity field. As a result of the conducted experiments, the characteristic features of the wind field on the windward and leeward sides of meshes with different solidity ratios were determined. In practice, this kind of analysis could be used in the investigation of solutions for new utility buildings. It is now common to use technology in which ventilation systems are assembled in the form of permeable wind curtains on the side walls of halls and buildings that are mainly used as storehouses, warehouses, driers, cattle sheds, pigsties and stables. Such a solution assures a continuous air exchange inside the object; moreover, it protects against sun exposure and insects, as well as limiting dust getting in from outside. Returning to measurements, due to the flow structure and the small dimensions of the measurement areas, the use of the PIV system for performing non-invasive measurements in the entire analysed area was justified and led to uninterrupted results from measurement equipment. Due to the measurement methodology, the PIV system is a tool that enables high visualisation of the flow structure. Obtaining the air velocity values across a large number of points enables the precise analysis of the vector field structure of the velocity. In the case of variant and serial works, the system enables the rapid assessment of changes in the flow structure [3]. As with any measuring technique, it has its advantages, but it can also have a number of problems, difficulties and limitations. Clearly, the advantages of the system are as follows: the instantaneous measurement of wind velocity fields at many points; the fact that there are virtually no disturbances in the flow structure; the efficiency of flow visualisation; the ability to rapidly track changing flow structures; the obtaining of effective and fast measurement in serial variant tests. The main disadvantages of the use of this system are related, as in any optical systems, to the limited visual accessibility of the area of interest. During the PIV system measurements: the need to expose the measurement area to laser light and the need for camera registration of the points in the analysed area are the basic limits of the technics. In addition, some complex flow structures, such as areas with very large differences in velocity, and turbulences within small spatial cells lead to serious measurement difficulties. A significant consideration regarding the possibility of using the system is its high purchase price, significant operating costs, the requirement for highly qualified and experienced technicians.

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