Demonstration of Non-Uniformity of Velocity Profiles Using 2D PIV

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Abstract. This paper deals with the demonstration of the non-uniformity of velocity profiles in a DN 200 air circular pipe as part of the development of a newly designed tomographic ultrasonic flowmeter. The flowmeter should measure the flow quality independently. Therefore, different aerodynamic conditions were created by placing mechanical obstacles at the entrance of the measuring chamber, and these conditions were experimentally verified. As an experimental channel substituting a section with ultrasonic sensors, a glass segment was placed at the inlet of a suction pipeline, in front of which perforated plates were inserted to break the uniformity of the velocity profile. The two-dimensional Particle Image Velocimetry (2D PIV) method was used to measure in a plane lying in the longitudinal axis of the channel. The experimental setup and PIV system parameters are described. The results are presented as velocity profiles and contour diagrams in cross-sections at different longitudinal positions in the channel. The results show that the requirement of non-uniformity is satisfied. The used disturbing plates disturb the axial symmetry of the profiles and create a backflow.

Keywords: *tomographic ultrasonic flowmeter, disturbing of flow, non-uniform profile, particle image velocimetry.*

1 Introduction

This paper builds on a previous publication by Barraclough et al. [1], which describes the development of the ultrasonic flowmeter itself. Two methods of measuring flow with ultrasonic probes are being developed to measure flow independently of flow quality. Therefore, it is necessary to set different aerodynamic conditions and to prove that the conditions are indeed other and how.

A suitable method to verify the quality of the flow is the Particle Image Velocimetry method (PIV). PIV is an optical method for velocity field measurement. The principle of this technique is the pulsed illumination of tracer particles with a laser and the recording of a light intensity signal of an illuminated plane (planar and stereoscopic PIV) or volume (3D PIV), from which velocity vectors are calculated in sub-regions called interrogation areas according to the change in particle positions between two exposures [2].

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An example of similar applications of the PIV method can be found in the paper by Novosád et al. [3], which dealt with the applicability of the method in a DN 80 pipe. It described the limits of measurement in a circular pipe of a smaller cross-section. Similar study was carried out by Wangxu et al. [4] in DN 100 tube. Zheng et al. [5] were solving a problem of 3D reconstruction of velocity field based on a 2D PIV data in water. Due to the reflections of light on the solid wall, the suitable data processing must be applied, following the methodology published by Adatrao [6] and Amaral et al. [7].

This paper presents results from 2D PIV measurements in several planes lying along the longitudinal axis of the DN 200 glass air channel. The aim is to prove that the velocity profile does not have an axisymmetric paraboloid shape or a shape close to it.

2 Methods

The FlowMaster system by LaVision company [8] with all apparatus for recording 2D PIV data was used for all experiments. The system has the following specifications:

- FlowMaster system from LaVision for 2D, stereo-PIV, and tomo-PIV.
- 4 pcs sCMOS 5.5 MPx camera, resolution 2560 × 2160 pixels, 16 bit, a minimum time interval of two frames 120 ns, exposure time 15 μs to 100 ms, spectral range 370 nm to 1100 nm, maximum frame rate 50 Hz.
- Nd: YAG double-cavity laser, 340 mJ per pulse, wavelength 532 nm, maximum repetition frequency 15 Hz, pulse duration up to 10 nm, class 4 laser. The minimal delay between double pulses dt = 1 μs.
- One PC for recording and evaluation, one independent PC for evaluation, Windows 10, DaVis 10.2 software.
- LaVision aerosol generator producing 1 μm diameter droplets of Di-Ethyl-Hexyl-Sebacat (DEHS).

3 Experimental setup

In Figure 1, you can find a scheme of the whole experimental track. The track consists of DN 200 segments like straight sheet-metal pipeline, control valve, Y-connection, flanges etc. The air is driven by two parallel axial suction fans. The maximum flowrate is under 800 $m^3 \cdot h^{-1}$, and the control valve is used to set lower flow rates. In one-third of the 2-meters-long straight segment before the valve, an anemometric probe SVH-14 connected to the KIMOC310 datalogger is placed to determine the velocity parameters for the PIV setup like dt. A glass tube is placed in front of the straight section as a measurement section. A toroid-shaped confuser is placed at the channel entrance. There is a top view PIV setup scheme in Figure 2. A laser sheet is fed through the wall from above. The glass cylindrical segment is internally black matt painted on the back half from the camera view. Therefore, the laser light passes through the upper wall only. The reverse side is blackened. Various plate obstacles can be placed between the confuser and the flange of the measuring segment. A measurement area is placed in the laser sheet and starts 100 mm behind the inlet edge of the glass channel, and it is 210 mm long. A region in the distance of 4 mm from the wall is an uncalibrated area. However, this area is covered to prevent wall reflections (see Figure 2b).

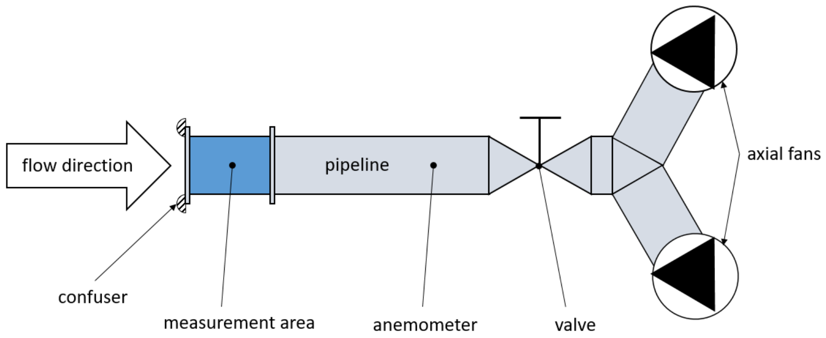

Fig. 1. Scheme of the experimental track, top view.

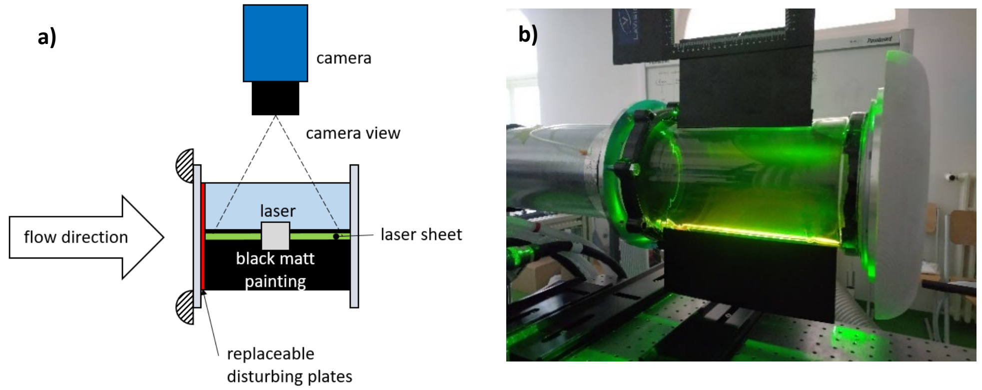

Fig. 2. PIV setup : ***a)*** scheme (top view), ***b)*** experiment.

Monitored regimes are listed in Table 1. Regime 1 symbolizes the measurement of undisturbed flow. Regimes 2 and 3 are measured with disturbing plates according to Figure 3a and Figure 3b, respectively. Different measuring planes are set by rotating the disturbing plates by 45°. All regimes were measured for five flow rates represented by the control valve position (CVP), where 0° means maximum open valve. The currently used control valve includes the mechanism with a scale to set the flap angle. The precision of ±5° fits the customer requirements. However, it was challenging to maintain the same flow rate for all angles of the plates because data for all flow rates for one plate angle were recorded firstly, and then the plate angle was changed. The data was measured in four longitudinal sections {0°, 45°, 90°, 135°} by rotating the plates around the axis. An example of the plate-sheet orientation is shown in Figure 3c.

Table 1. Monitored regimes.

Regime	**Plate**	**Control valve position**				
		0°	**40°**	**60°**	**70°**	**80°**
1	-	1a	1b	1c	1d	1e
2	I	2a	2b	2c	2d	2e
3	II	3a	3b	3c	3d	3e

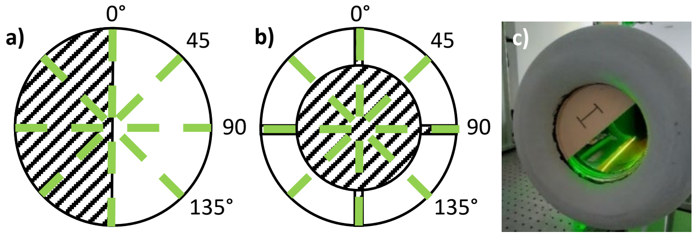

Fig. 3. Disturbing plates: ***a)*** plate I, ***b)*** plate II, ***c)*** plate I, 135°.

For every regime, 450 double frames were taken at 15 Hz. The delay time d*t* was set according to indicatively measured velocities ranging from 30 µs to 400 µs. The laser pulse A energy was 68 mJ, and pulse B was 17 mJ. The data was pre-processed by image background subtraction.

The raw data was evaluated in DaVis 10.2 software with a standard 2D PIV solver. The interrogation area was 32 pixels, overlap of 25 %. The presented data are obtained by averaging all 450 vector maps of every dataset, i.e., 30 seconds of raw data.

4 Results and discussion

The experimental results are in the form of the velocity vector maps in the laser sheet planes. A pack of measured data consists of the data for three different geometries, and each contains vector maps in 4 laser sheet planes.

4.1 Results assessment

The obtained 2D vector maps were analyzed in several cross-section lines, illustrated in Figure 4. The horizontal position *x* of the cross-sections was defined with respect to the dimensions of the ultrasonic flowmeter prototype [1], with 200 mm in length measured from the inlet. The combination of the flowmeter geometry and PIV data leads to the selection of the cross-section at the beginning of the measuring area X100, then the final position of the flowmeter X205, and finally the cross-section X152.5 in the middle.

The vector map data files were loaded and processed in the MATLAB environment. The whole process could be divided into several steps to obtain:

- Reading of the vector map.
- Cross section definitions.
- Calculation of the maximum and dimensionless velocity.
- Scatter plot of the velocity profiles in each cross-section (see Figure 5).
- Velocity profiles in X100, X152.5, and X205 according to the flow rate.
- Contour plot in each cross-section X100, X152.5, X205 for various flow rates.

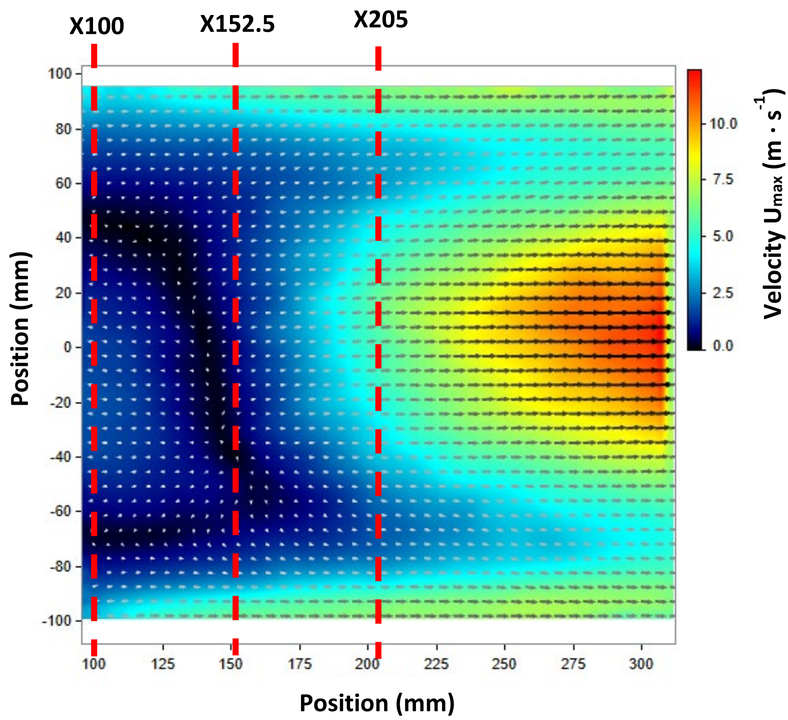

Fig. 4. Velocity vector fields – cross sections for the velocity profiles assessment.

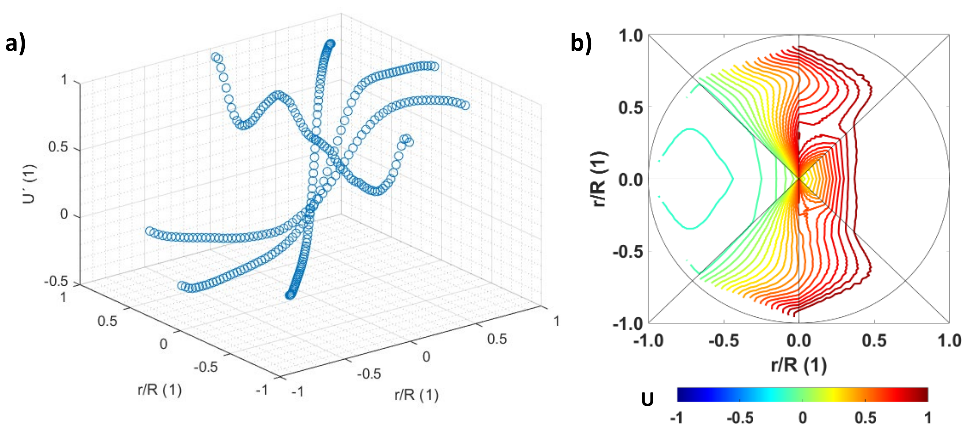

Fig. 5. Example for regime X100, CVP40°: ***a)*** velocity profiles, ***b)*** contours.

4.2 Velocity profiles

Velocity profiles have been evaluated for all cases. *X*-direction velocity profiles are presented in Figure 6 as the comparison for representative cases shows a flowrate dependence. The horizontal axis symbolizes dimensionless pipe radius r/R and the vertical coordinate is the dimensionless velocity $U'=U/U_{max}$ based on the maximum velocity. Markers are color-coded according to the legend for each valve angle or flow rate setting. All plots are plotted at position X152.5 according to Figure 4, i.e., 152.5 mm behind the inlet edge of the experimental channel. Figure 6a represents regime 1, Figure 6b regime 2, and

Figure 6c regime 3. You can notice the strong influence of the plate. Regime 1 forms an almost flat and uniform profile where most values are close to 1. Regime 2 on the left side includes a backflow, which is an order of magnitude lower than the maximum velocity on the right side. Regime 3 forms axisymmetric profiles where backflow is more significant in the central region. Position X152.5 is an area of still evolving velocity profile. Therefore, even in its dimensionless form, there is a velocity difference of up to 20 % between the maximum and minimum flow rate curve. A small drop of velocity in the area near r/R = (-0.5) is probably due to signal noise caused by reflections on the inner wall.

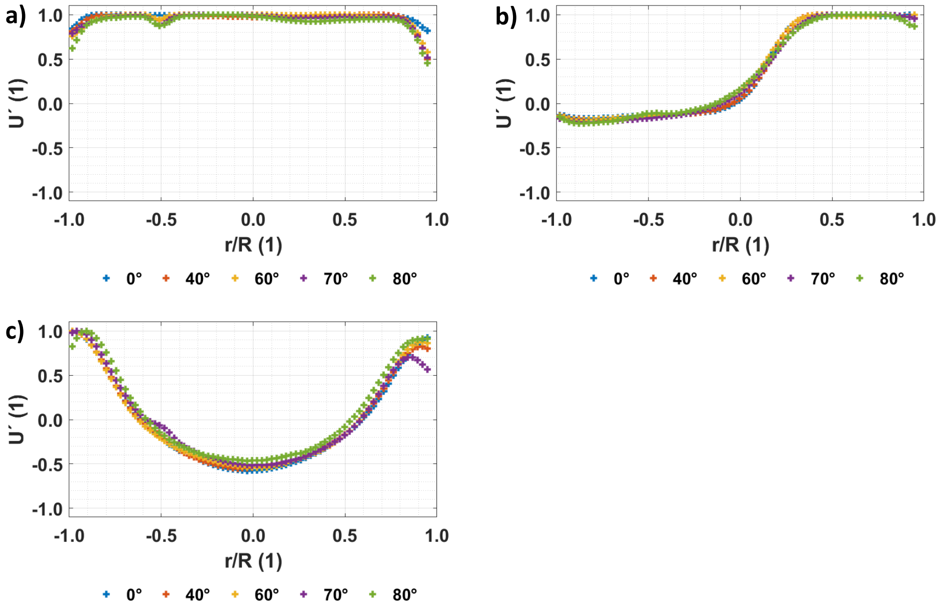

Fig. 6. Velocity profiles at X152.5 for various CVP: ***a)*** regime 1, ***b)*** regime 2, 90°, ***c)*** regime 3, 45°.

Velocity contours of *x*-velocity are shown in Figure 7, Figure 8, and Figure 9. Four-lines cross represents the measured planes. Curves between these crosses are connections of discrete values. The individual lines are graduated by 5 % of the whole velocity range. The dimensionless presentation, as in Figure 6, is maintained. The contours are plotted for three positions, X100, X152.5, and X205, according to Figure 4 to illustrate profile development. The rows are selected modes of closing the control valve in Table 1. The combination of the plotting methodology and the not quite equal flow rate while measuring the different plate angles creates non-smooth curves, i.e., unrealistic loops. The corresponding velocity can only be observed along the 45° crosses. This results presentation was chosen for better visualization.

Figure 7 shows a set of diagrams where the contours in a peripheral part of the pipe are approximately centrally symmetrical, and a higher velocity gradient is evident. Dependence on the valve closing is less noticeable.

Figure 8 shows the contours of regime 2. A half-moon plate causes the highest velocity on the right side and even backflow in the area behind the plate. From the comparison of the *x*-positions, it is evident that the flow also fills the area behind the obstacle. This can also be observed with decreasing flow rates due to lower flow momentum.

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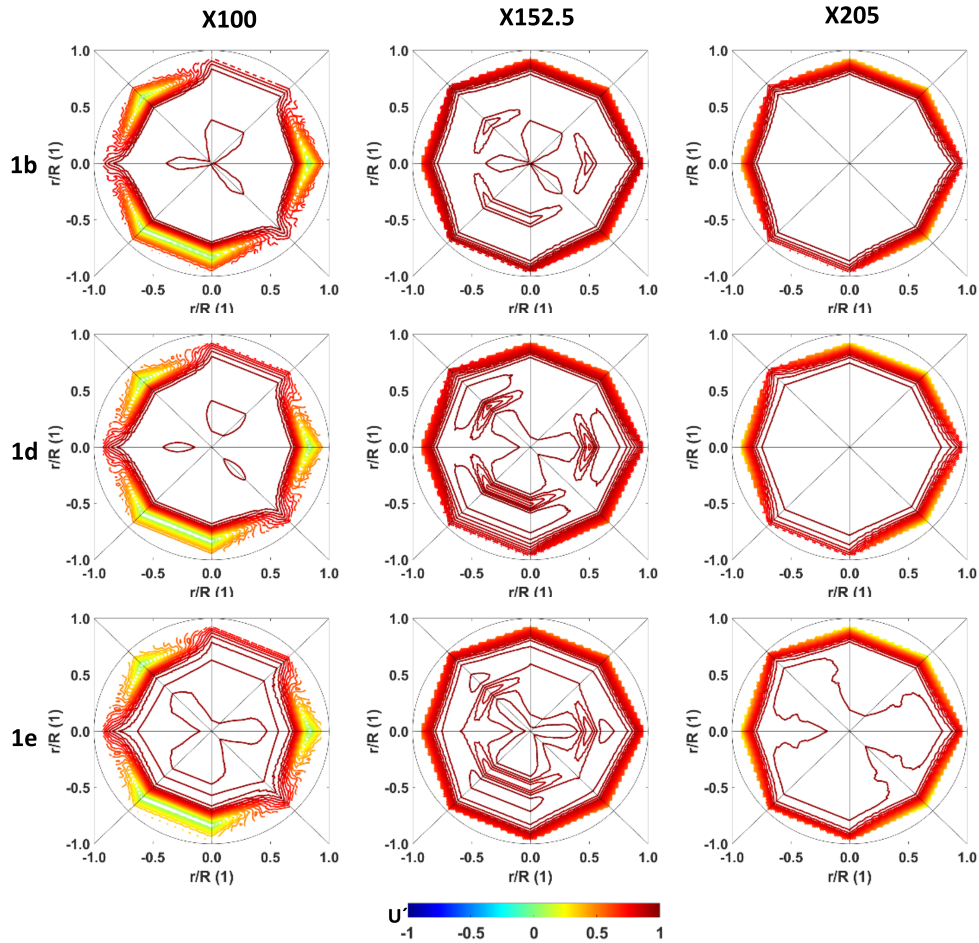

Fig. 7. Regime 1 - velocity contours at X100, X152.5, X205 for various CVP: 1b, 1d, 1e.

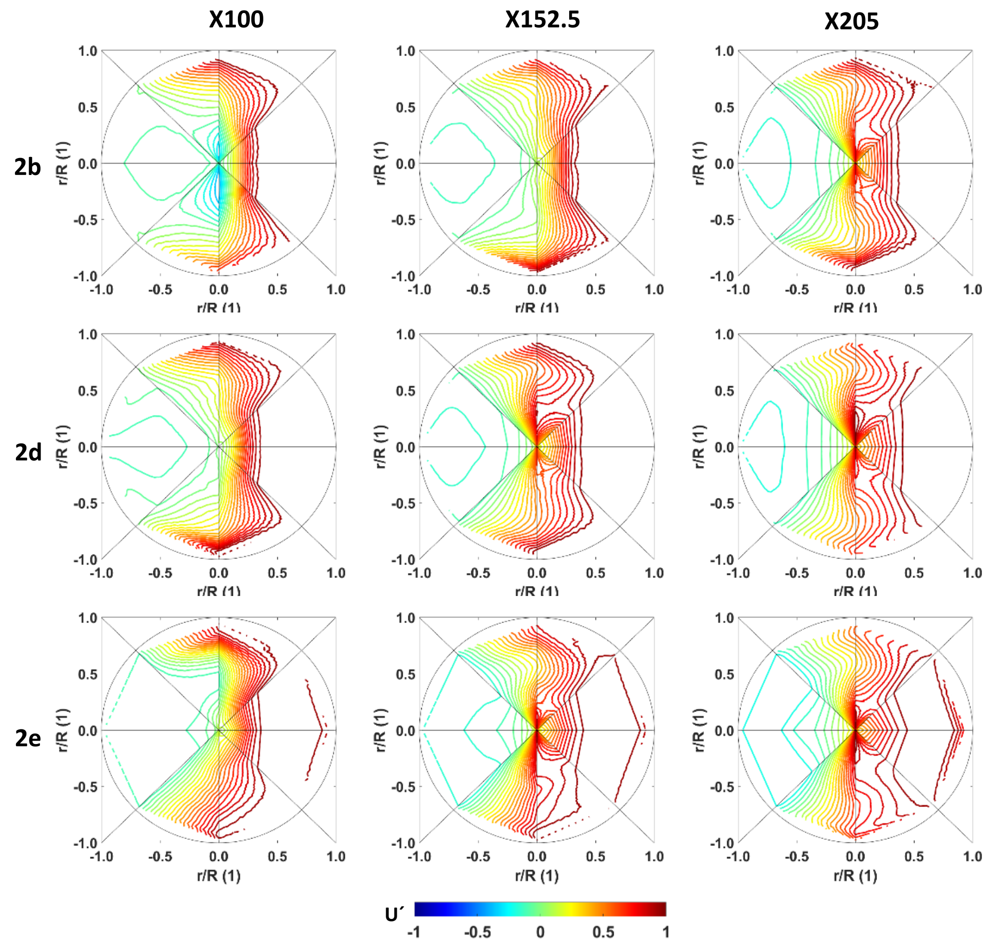

Fig. 8. Regime 2 - velocity contours at X100, X152.5, X205 for various CVP: 2b, 2d, 2e.

Figure 9 shows the contours of regime 3. This regime forms an approximately symmetrical profile. The highest velocities are in the region near 75 % of the radius. In the middle, on the other hand, the flow is backward because of the disc in the central part of the plate. In positions closer to the entrance, the high velocities contours are more densely distributed, which means a higher gradient. With lower flow rates, on the contrary, they become thinner.

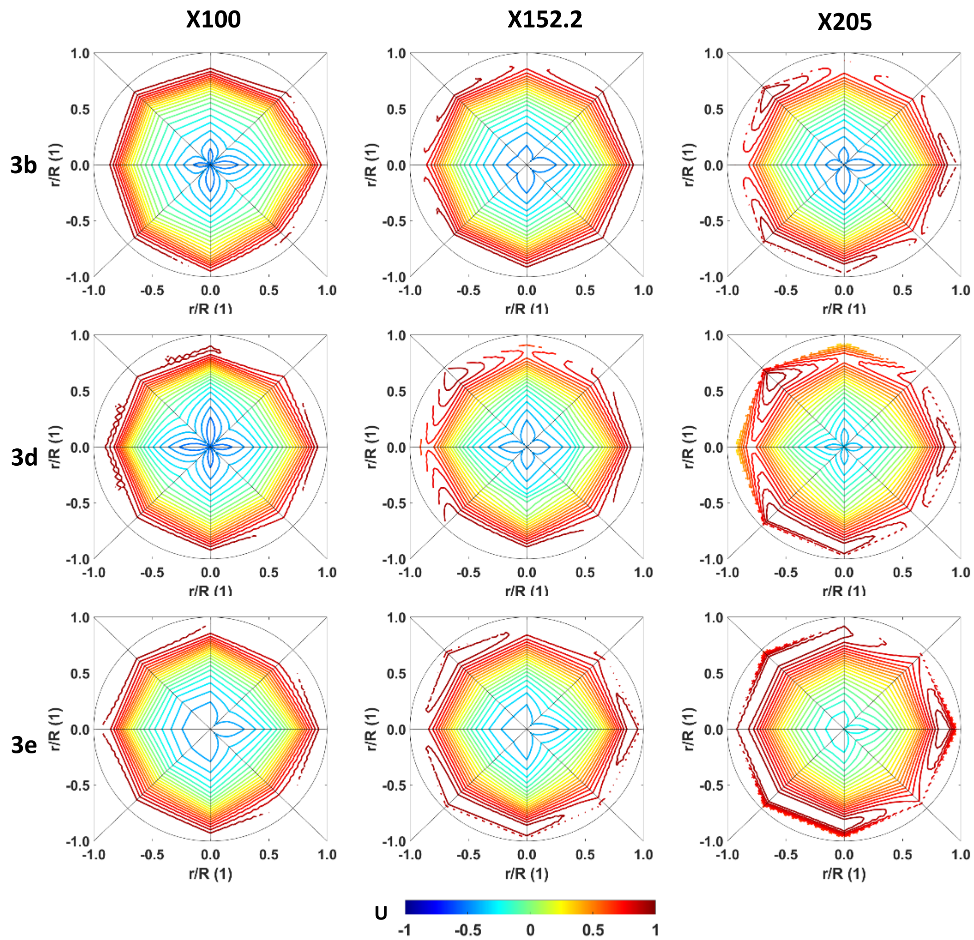

Fig. 9. Regime 3 - velocity contours at X100, X152.5, X205 for various CVP: 3b, 3d, 3e.

4.3 Results discussion

The presented results show that the velocity profile is disturbed by the plates and causes backflow in some areas. From a nearly flat profile, an axisymmetric profile is created using plate I and a centrically symmetric shape using plate II. It is also clear from Figure 6 to Figure 9 that the velocity profile is continuously evolving in the measured area. The flow gradually fills the space behind the obstacles. And with advancing distance, a uniform parabolic profile would form. It can be said that the slow plates satisfy the requirement for proving the independence of the measured values obtained by the developed flowmeter of the velocity profile in the channel.

5 Conclusion

In this paper, the experimental study related to the development of the ultrasonic flowmeter is presented. The setup of the 2D PIV experiment and data processing and post-processing are described. Circular pipe velocity profiles depending on the flow rate and disturbing plates were measured, and the approximate 3D shape of the velocity profiles was reconstructed using MATLAB environment. The data was presented in the form of 2D plots and velocity contour maps. The data showed that the disturbing plates have sufficient influence on the shape of the velocity profile. The dependence on the flow rate is also obvious. It also showed that in the part of the channel where the ultrasonic probes of the developed flowmeter will be located, there is a continuous development of the profile behind the disturbing plates. The two chosen plates are suitable for demonstrating independence of the measured flow rate on the hydrodynamic flow characteristics.

The measurements also showed deficiencies in the obtained data. A better interpolation of the obtained 2D profiles with the surface requires that the flow rate is maintained during the measurement of all positions of the disturbing plate. As a consequence of the continuous evolution of the velocity profile in the measured area, its shape is flow dependent.

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Nomenclature

dt	s	laser pulse delay
r	m	radial distance; $r = \|y\|$
R	m	pipe radius
U'	1	dimensionless velocity $U/U_{\max}$
U	m · s^{-1}	local velocity
$U_{\max}$	m · s^{-1}	maximum velocity of profile
x, y	m	Cartesian coordinates

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