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Reproduction of air velocity in the entrance region of the pipe

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Abstract

Information about the airflow development in pipes in the entrance region is still not thoroughly investigated due to the complexity and restricted access for experiments. However, the reproduction of air velocity values, as well as calibration of the devices, is usually made in free streams from the nozzles or in the entrance region of the channels (pipes). In this study, different flow regimes have been investigated using different air velocity measurement methods for mean velocity to define. Experimental and numerical results in the entrance region of the pipe and in the test chamber of higher dimensions give a broad spectrum of information about the developing flow. Ultrasonic anemometer (UA) installed into the entrance region of the aerodynamic test facility shows reliable and highly comparable results in a wide range of velocities with another non-intrusive method – laser Doppler velocimetry (LDA). Due to the fast response, it enabled to analyse fluctuations in the flow. The mean air velocity values were determined from the singe path sound propagation time in the pipe with a defined distance between the transducers placed at an angle of 45 degrees with the main axis. Local vortices identified in the flow might have influenced the low-frequency fluctuations and the scatter of measurement results. Moreover, high-frequency fluctuations found in the flow originated from the flow turbulence and the electronic or acoustic noise. The stabilisation of the entrance region and the boundary layer of the pipe influenced mean velocity value, velocity distribution and axial velocity development in different test sections of the pipe. Along with the recirculation zones in cavities of ultrasonic transducers they are the essential impact factors on velocity value defined.

1. Introduction

The airflow distribution is one of the most important characteristics used to judge the internal structure of the flow, the intensity of the mass and heat transfer processes and energy consumption. National laboratories initiate studies aimed at harmonizing the conditions and procedures for the investigation of various physical quantities, like pressure, temperature, air speed, humidity etc. measurements thus ensuring a high level of measurement accuracy with ever-increasing demands on it. Due to the lack of airflow field research, it is difficult to identify sources that influence airspeed reproduction under different conditions and provide a high level of accuracy that is important for international traceability linked to practical challenges, the transfer of accurate metrological parameters, the fulfilment of legally regulated conditions, and operational functionality.
Airspeed is one of the most common measures in practice, which allows evaluating the health and safety conditions at workplaces, to ensure safe work in the air and seaports and the functioning of lifting mechanisms, as well as measurements of emissions to the environment and wind energy [1]. However, different measuring instruments with different spatial and temporal characteristics provide different parameters and allow for different treatment of the flow. The main problem is how to determine the influence of the flow structure on the accuracy of the measurement result covering a specific and wide range of air velocities. It comes from the scientific, industrial and economic needs of the country that must meet the measurement levels achieved by National Measurement Institutes (NMI) within the European countries or even globally (USA, Japan, China etc.) as well.
The EU NMIs, responsible for the international measurement interface, proper market functioning and the competitiveness of the production in a certain country, are making systematic investigations but more confined to legitimizing a particular device or studies based on measurement comparisons aiming to standardize measurements conditions and procedures of different physical

quantities. However, methodological actions to standardize the impact factors that define the structure of the flow, changes in it and the characteristics (or response) of the measuring instruments consistently are scarce. Recently some specific research activities [2-4] within the metrology platform arose on that purpose but still encounter difficulties in definition of certain and essential impact factors evoking result scattering. Nevertheless, differences in airflow reproduction conditions should be emphasized as the key factor.
In this case, the analysis and discussions remark the changes of flow structure in the entrance (developing) region of the pipe after convergent nozzles and rectangular chambers. Section 2 consists of a representation of wind tunnel specific features. Section 3 reveals the discussion concerning reproduction of air velocity value based on different measurement methods concluding into main factors emerging result scattering and flow development in the entrance region specific features. In the last section 4 the conclusions and future prospects are highlighted.

2. Experimental setup

Mostly used wind tunnels for airspeed measurement consist of the test section of the type like free streams, open test chambers after the closed loop and fully closed conduits with either round or rectangular shape [5-7]. All of them are restricted due to the cross-sectional area for devices under test (DUT) to place.
The aim of this investigation is to develop stable and controllable conditions reproducing low-velocity values under two different conditions. In many of analysed studies [5-8], the range of low velocities is very distinct, thus in this work, the boundaries are from 5 cm/s to 30 m/s covering the laminar, transitional and turbulent flow regimes. Experimental investigations were performed in the test facility (Figure 1, a) in the entrance region of the round channel (i.e. a pipe) with the diameter of 400 mm (D) and in the free stream from the pipe into the chamber with the length, height and width of 1000 mm (Figure 1, b). The test section as the semi-closed aerodynamic facility conditions treated due to the existing chamber. High contraction ratio of convergent nozzle (CN) (1650 / 400 mm) and the set of flow straighteners ensured low turbulence degree of about 0.5-1 % for higher than 1 m/s (later discussed more in Chapter 3). Moreover, the uniform velocity distribution in the largest part of the channel cross-section maintains the flat core along the channels' length up to the outlet into the chamber and within it for at least 1 D.

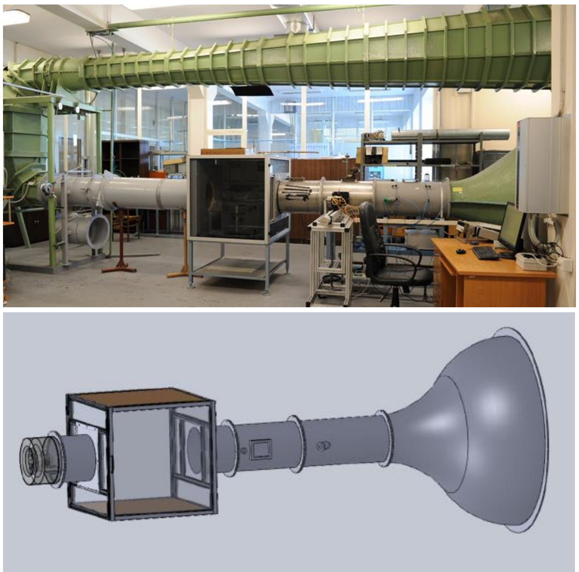

a)
b)

Figure 1: air velocity test facility general view (a) and measurement channel with CN, the straight channel and the chamber of enlarged dimensions (b)

As the main measurements are performed at the entrance region of the pipe the transversal velocity distribution is not evolved into the shape of the fully developed laminar or turbulent profile. Consequently, it is essential to have them clearly defined beforehand as the testing devices are located 1-4 D after the CN in the straight channel. The single path ultrasonic anemometer (UA) as one of the working standards is based at the distance of 1 D from the CN and the test section for laser Doppler anemometer (LDA) as the main standard is at 3 D where all DUTs are normally placed. UA anemometer gives the average velocity values as it measures velocity value at a certain angle with the axis, in this case at 45°, along some certain distance, here of 0.57 m. The transducers of UA are placed in the niches outside the pipe in order not to disturb the flow. Niches are covered with specific grids to weaken the vortices in these cavities. CN is a very accurate mean of velocity reproduction through the differential pressure measurements well related to the primary standard LDA as well as the UA. Having predefined relations of UA, CN and LDA any measurement in the test channel from the UA plane up to the chamber centre (6 D) has clear and certain evaluation with proper uncertainty level. The blockage or shielding effects with the available wake regions are also evaluated for the most common measurement devices as the hot wire anemometers of different types and the Pitot tubes of different forms with some rotating anemometers with the appropriate diameters suitable for the test section [1, 4, 9]. The limitation concerning the dimensions of DUT in the testing plane is no more than 0.06. This is the ration of the frontal area of the DUT and the pipe taking into consideration 10 % as for open test sections.

3. Flow development in the entrance region. Discussion on the experimental and numerical results

The peculiarities of the entrance region, in this case, is summarized in this section and is highlighted especially for the most sensitive velocity value regions. Velocity distribution transversally and axial flow development with the turbulence degree variations are represented. Some comparison is made of experimental results with the numerical simulation based on ANSYS Fluent commercial package (CFD).

The main experimental results are from the airflow measurements in the test pipe section and the chamber using the LDA. Well-defined flow core in the pipe is evident from the velocity profiles made gradually in the straight pipe, and the chamber, for wide velocity range. As the core region of velocity distribution for higher velocities, starting from 1 m/s up to 30 m/s is not changing significantly even at different planes of the pipe (1-4 D) and in the chamber (5-7 D), basic results are depicted for lower velocities than the maximum possible value where changes and fluctuations exist.

It is clearly evident from the LDA time records, the profiles and the turbulence distributions that the test facility enables stable and repeatable air velocity values with a certain core region transversely (Figure 2) and longitudinally (Figure 3-4). Taking into consideration laminar-transitional flow regime it should be emphasized that some velocity values up to approx. 8 cm/s have not very flat profile at the centre and suffer from specific concave form, sometimes even slightly fluctuating. It is also observed in CFD results (Figure 3) though with all models in ANSYS Fluent 17.2 calculated this kind of concavity exists for higher velocities as well. Experimental results for higher than 0.1 m/s do not show it. Numerically investigated transition in pipes is represented by spatial or temporal coherent structures of vortices or travelling waves [10-12] but for experimental case transition results in contradictory states depending much on initial conditions and observation time.

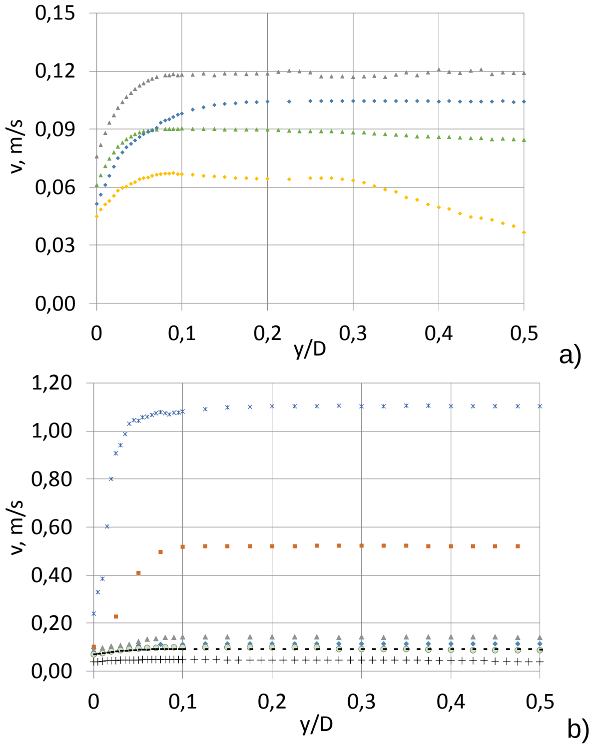


Figure 2: Velocity distribution across the diameter of the pipe. Different flow velocity and regimes: a) laminar-transitional flow, b) transitional to turbulent flow

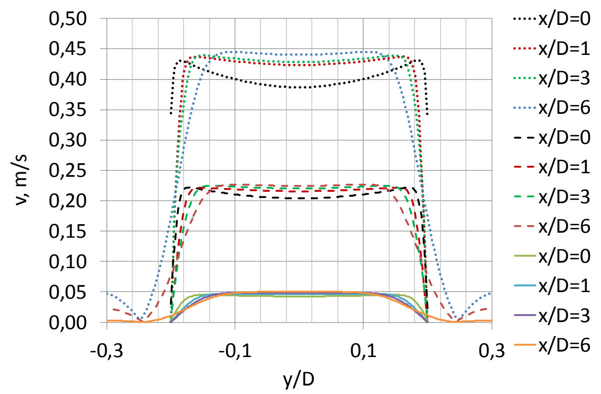


Figure 3: Velocity distribution across the diameter of the pipe for different flow velocity (0.45; 0.22 and 0.05 m/s) and axial distances from the inlet (x/D=0) up to the centre of the chamber of higher dimensions (x/D=6). The CFD results

The measured profiles in the test facility have a flat profile that covers 80-90 % of the cross section of the pipe diameter. Comparing experimental and simulation results could be stated similar distributions either in the pipe or in the test chamber (Figure 4). For testing simplicity velocity value in the test chamber is selected 10 m/s and compared with simulated value of 8.5 m/s that do not differ from each other due to the same flow regime selected and do not suffer from transition effects.

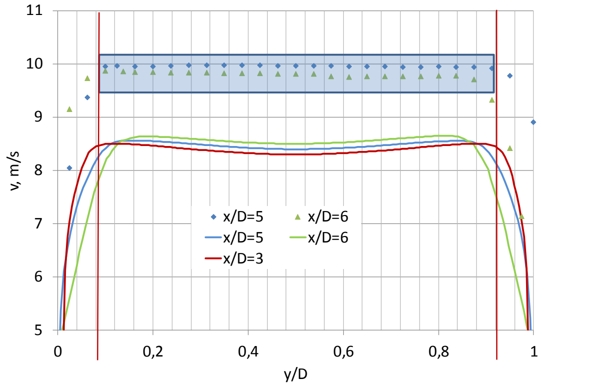
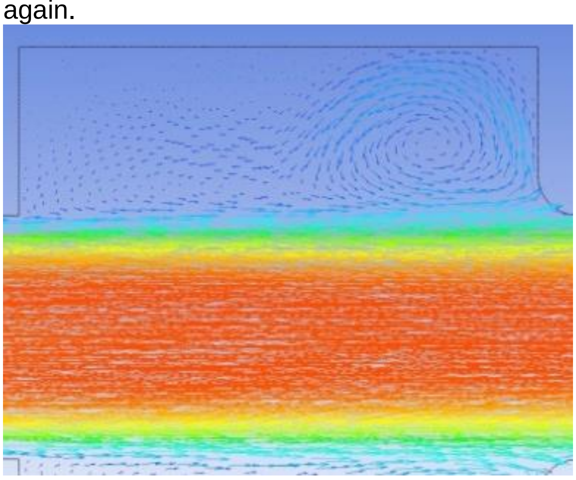


Figure 4: Comparison of velocity distribution calculated and measured at the outlet of the pipe (x/D=5) and in the centre of the chamber (x/D=6). In the CFD results x/D=3 plane is the measurement plane of the LDA in the pipe

To analyse in details the changes of the flow in the chamber CFD results make it easier to reveal. A clear development of vortices in the chamber corners is noticed from Figure 5 which represents three different flow regimes. It should be noticed that in some regimes different simulation models slightly differs resulting in either still several vortices structure or one vortex in the whole chamber cavity above and under the core region covering not only one corner. As the chamber has an axial symmetry only one side of the chamber is shown in the pictures. Single elongated vortex from the almost laminar case of 0.05 m/s (a) is evolving into a several vortices in case of 0.2 m/s (b) (still transition flow regime) that develop from the right towards the left corner of the chamber near the outlet of the pipe. While transition to turbulent case with velocity value of 0.45 m/s (c) has already formed vortex covering the whole space of the side chamber niche. It is also clearly evident that flow core in the chamber is narrowing reaching the centre and more approaching the inlet to the pipe again.



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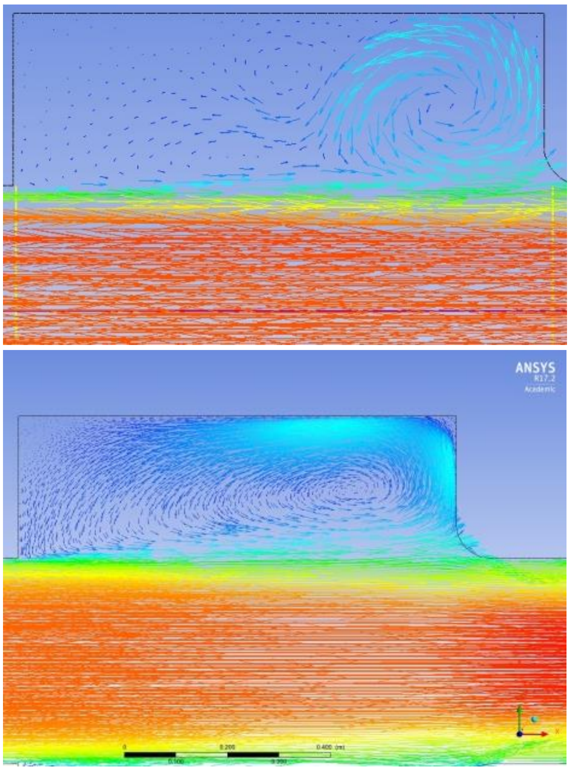

b)

c)

Figure 5: Comparison of velocity development in the chamber calculated for different flow regimes. Velocity value is in a) 0.05; b) 0.22; c) 0.45

Flow regime changes can also be noticed from the time records from LDA in Figure 6. Laminar to transition regime is accompanied with accidental disturbances. Similar results are gained using UA records. Due to its high response to fluctuation in the flow and measuring them not across the pipe but with an angle and quite a long distance low and high frequency pulsations may be raised due to some temperature effects, flow recirculation in the niches of the transducers or flow turbulence and noise in electric and acoustic fields.

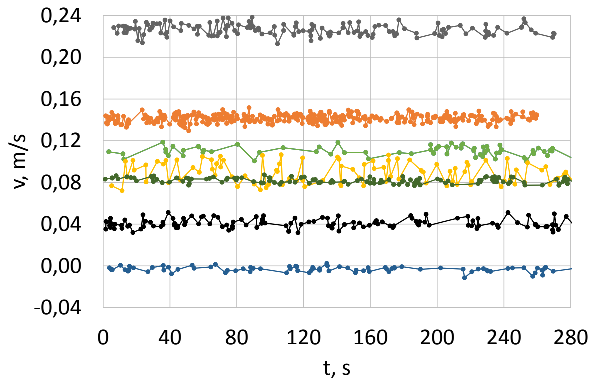

Figure 6: LDA time records for a series of velocities.

Wind tunnels of different types and configurations are presented with the very different degree of turbulence. Very low turbulence degree of 0.07 %

is declared in the laboratory of NIST [7]. However, starting from the velocity value of 0.2 m/s is not clear if this turbulence degree is for this velocity as it is stated that this degree if for the most air speed range that is up to 75 m/s. In this wind tunnel turbulence is higher due to some reasons and differs much on conditions and flow regimes. Figure 7 represents turbulence degree variations at different planes from the pipe to the chamber and different conditions for velocity to be achieved. It is noticed that turbulence degree is slightly increasing with the approach to the outlet of the pipe (x/D from 1 to 4.5). Moreover, with the decrease of velocity value it increases more significant starting from 0.5 m/s and extremely from 0.2 m/s. It also depends on velocity reproduction case as two different fans are used for low and higher velocities to achieve, as well as additional different grids are inserted to stabilize velocity fluctuations. Consequently, these grids increase the degree of turbulence. It is evident from the results for low velocities reproduced using different fan without any additional grid (fan 1, Figure 7). Distribution of turbulence degree across the pipe shows results relative to the velocity distribution (Figure 8). Consequently, with the decrease of velocity value approaching the wall, turbulence degree is increasing.

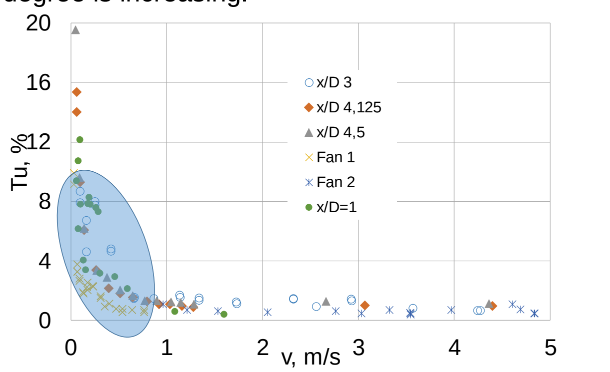

Figure 7. Turbulence degree at different planes and conditions. Fan 1 and 2 are different fans used to achieve lower and higher velocities, respectively

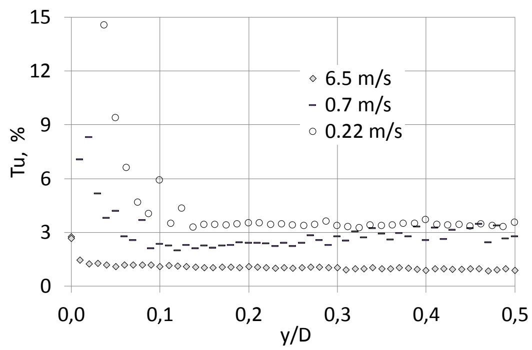

Figure 8. Distribution of turbulence degree across the pipe for different velocity values

Concluding about the flow stability and air velocity reproduction in the test facility from the results of LDA and UA repeatability is calculated and it shows the same tendency and level during the last ten years (Figure 9).

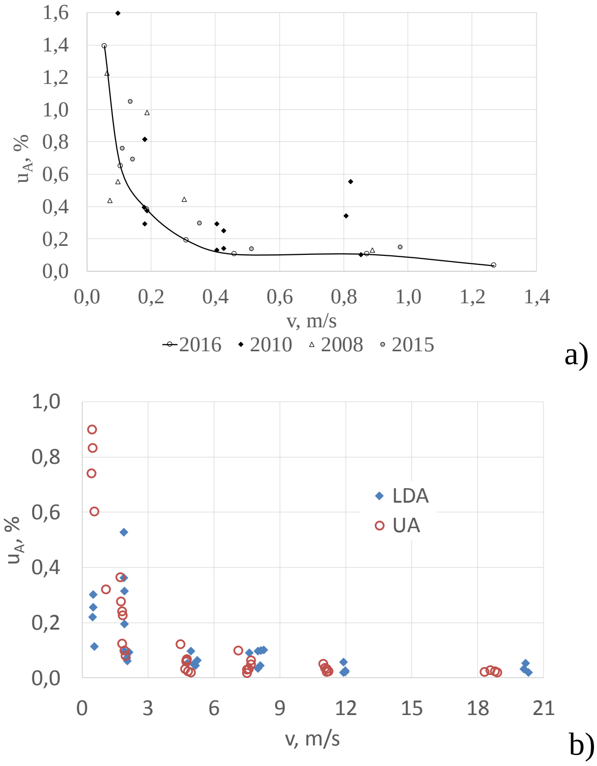

Figure 9. Standard type A uncertainty results: a) 2008-2016 years, LDA; b) 2018-2019 years, LDA and UA

The results of both standards (LDA and UA) show good agreement and repeatability except very low velocity range. This is a consequence of several factors such as flow regime, mean velocity definition procedure and recirculation zones. Recirculation cavities were covered with grids but they just stabilized the zones with still existing vortices as the results did not show any significant changes. It should be noted that scatter in the results is in the transition regime due to the profiles that are changing significantly in the stabilization region and especially at low velocities. Thus mean velocity value differs measured with UA and LDA as LDA measures it in the flat and already stable profile plane. Recirculation will make less impact with the velocity value increase. It was found from literature [13] that for small pipe and laminar flow the simulated results are significantly affected by these vortices in the niches.

Mean velocity value depends on the profiles as well. Moreover, it depends on the method used to calculate it. They are already discussed. And the LDA is measuring a local velocity under conditions of predefined profile. Results of mean velocity changes along the axis from the inlet into the pipe

up to the outlet into the chamber show changes up to 2-3 %. In the chamber up to its centre significant changes is not found experimentally though simulation results show a tendency of growing of velocity value.
Finally, the uncertainty of the measurements in the test facility is defined. For velocity range of 0.05 to 30 m/s it covers 8 to 0.45 % respectively. Detailed analysis is in Table 1.

Table 1: Example of a table.

Velocity value, m/s	Expanded Uncertainty, %	Factors for uncertainty		
		Type B, %	Repeatability	Reproducibility
0.05	8.0	0.22	3.55	1.8
0.15	4.9	0.22	2.15	1.1
0.5	2.3	0.22	1.0	0.5
1	1.9	0.22	0.83	0.42
3	1.1	0.22	0.45	0.22
5	0.8	0.22	0.3	0.16
10	0.55	0.22	0.15	0.075
30	0.45	0.22	0.04	0.02

4. Conclusion

The paper reveals airflow development features in the entrance region of the pipe as the test section of the wind tunnel and in the chamber of larger dimensions.
The results of standards, Laser Doppler Anemometer and Ultrasonic anemometer show good agreement and repeatability except very low velocity range. This is a consequence of several factors such as flow regime, mean velocity definition procedure and recirculation zones.
Due to the fast response, UA enabled to analyse fluctuations in the flow. Local vortices identified in the flow might have influenced the low-frequency fluctuations and the scatter of measurement results. The high-frequency fluctuations found in the flow originated from the flow turbulence and the electronic or acoustic noise. The stabilisation of the entrance region and the boundary layer of the pipe influenced mean velocity value, velocity distribution and axial velocity development in different test sections of the pipe. Along with the recirculation zones in cavities of ultrasonic transducers they are the essential impact factors on velocity value defined.
The uncertainty of the measurements in the test facility for velocity range of 0.05 to 30 m/s covers 8 to 0.45 % respectively.
Simulation and experimental results have some differences that need to be further analysed.
For future tasks conditions of UA using simulation tools also is a key action as experimentally it is not available due to the lack of optical access.

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