EPJ Web of Conferences **269**, 01007 (2022)
*EFM 2019*
https://doi.org/10.1051/epjconf/202226901007

# Analysis of velocity profile measurements obtained by different methods in low-speed, small-scale wind tunnel

*Ondřej* Cejpek[1,*], *Jan* Šíp[1], *Milan* Malý[1], *Jan* Jedelský[1], and *Zdeněk* Tomáš[2]

[1]Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic
[2]Provyko s.r.o., Vinařská 558/3a, Pisárky, 603 00 Brno, Czech Republic

**Abstract.** A low-speed small-scale wind tunnel was designed for spray investigation under cross and co-flow conditions. Precisely defined profiles of mean velocity and turbulent intensity in the wind tunnel test section are crucial parameters for any rigorous flow study. Different velocity measurement techniques were used to evaluate the velocity and turbulent intensity profiles in the test section. Two non-intrusive techniques, Phase-Doppler Anemometry and Laser-Doppler Anemometry (PDA, LDA), and two intrusive techniques, Constant Temperature Anemometry (CTA) and pitot static tubes of S and L-type were applied. The velocity was measured in 19 equidistantly spaced positions in a centrally placed horizontal plane. The data were obtained for four different mean velocities in the test section (7, 14, 21, 28 m/s). Results of different measurement techniques were mutually compared, and repeatabilities and uncertainties of PDA and CTA measurements were assessed. Turbulent velocity spectra measured by the CTA were analysed. The effect of declination of the pitot static tubes (L-type and S-type) was briefly discussed and compared with an industrial velocity probe QuadraTherm® 640i In-Line Mass Flow Meter with a measuring range of 5–300 m/s. Velocity and declination of pitot static tubes were analysed only in the central point of the test section. The results show that a fully turbulent and uniform flow is developed 15 mm upstream the test section area. Mean velocity and turbulent intensity profiles obtained by different techniques are in a good agreement. Uncertainties of type B of PDA and CTA measurement method are below 5%. Turbulent intensity in the main stream is under 5%. Advantages and drawbacks of the presented measurement techniques were discussed. The PDA was found to be the most suitable measurement technique due to its precision and non–intrusive flow probing.

## 1 Introduction

Wind tunnels have been used for more than a century. Their size can range from several meters to more than ten meters. Two designs of a wind tunnels used are closed and open loop wind tunnels [1, 2]. The wind tunnels can be also divided according to the velocity in the test section into four groups to subsonic, transonic, supersonic, and hypersonic wind tunnels [3, 4, 5]. Each wind tunnel design is suitable for different types of experiments and required flow characteristics in the test section. Wind tunnels can simulate velocity conditions in combustion chambers, turbines, conditions in the atmosphere and in many other situations related to air movement and air-structure interaction.

Precisely defined velocity profiles and controllable and sufficiently low turbulent intensity in the test section of the wind tunnel are crucial parameters for any rigorous flow study. A new small-scale low-speed wind tunnel was built at Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, Spray laboratory.

Together with Phase-Doppler Anemometry (PDA), Laser-Doppler Anemometry (LDA), Constant Temperature Anemometry (CTA) and other velocity measurement techniques, wind tunnels create a tool for investigation of high complex, spatially and temporally unstable flows, i.e. flow around the turbine blades, velocity profile around a car, investigation of fluid structure interaction, and spray flows in cross and co-flow.

Laser-Doppler Velocimetry (LDV) or Laser-Doppler Anemometry (LDA) were first implemented and described in 1964 [6]. After this publication, various systems of LDV were proposed. Over a decade, new systems were probed, and improvements of the system were made. The first commercial system was available in 1970. Because of a wide field of application of LDV, many set-ups of the system arise during the LDV commercial use [7].

* Corresponding author: 182752@vutbr.cz

The PDA measurement system is an extension of LDA concept used for velocity measurement. A need to measure the velocity and the size of the particles in investigated flows simultaneously resulted in the development of PDA measurement system. PDA is a very complex system, hence the process of invention, development, and acceptance of laser–based system took a long time. Crucial was the invention of laser in the 1960s, a measurement concept in 1975, and extensive work done by many research groups during 1980s. [8]. The PDA measurement system was not fully accepted at the early stage; the results were verified by other well-known measurement techniques to prove the PDA system accuracy and measurement abilities. After almost 30 years of application of PDA, this measurement technique becomes a standard for the experimental fluid flow studies, and a major part of the flow research is done by the PDA system. Nowadays, PDA is used to validate newly designed techniques, i.e. Particle Image Velocimetry (PIV) [9]. PDA can be also used to validate volumetric measurement methods.

LDA and PDA are optical-based non-intrusive measurement techniques. These techniques identify velocities of the seeding particles introduced into the flow, based on the scattered light by the particles. These techniques can provide results with high spatial and temporal resolution and with high accuracy. LDA measures the velocity of the tracer particles; in addition, PDA is capable of measuring the particle/droplet diameter. The inspected flow had to be seeded with particles which will scatter sufficient light and will follow the flow with high accuracy to identify the finest vortices in the flow. An optical access to the flow is also required [10]. The PDA and LDA system responses are a liner function of the fluid flow velocity in contrast with CTA which is sensitive to the ambient temperature.

Two used intrusive techniques are pitot static tube and CTA. The pitot static tube is a well-known measurement device which has been used in industry for more than two centuries. A simple and robust design, function principle, and accurate results ensure the pitot static tube a wide range of applications in industry (racing cars, aircraft speed measurement, measurement of the flow velocity in duct or pipes, laboratory use). The pitot static tube was initially used only in laboratory for more than a century. After the improvements by Henry P.G. Darcy, the pitot static tube started to be used in industry. [11]

CTA is a measurement technique based on a principle of hot-wire anemometry, where the constant temperature of the measurement element is maintained. A cooling effect of the flow is compensated by the Wheatstone bridge, and the temperature of the element is kept constant. The voltage drop across the circuit is proportional to the inspected fluid flow velocity. The CTA system needs to be calibrated prior to every measurement. CTA is a very useful tool for measurement of the turbulent flow because this system has a very high response to the fluid flow change and can capture the finest vortices in the flow. The probe is usually a thin wire with a diameter of several micrometres; therefore, it has a low thermal inertia.

A fundamental principle of CTA was discovered in 1888, when the relation between the convection and the fluid velocity was experimentally derived. In 1907, cooling of a thin wire in the air stream was observed, and the first suggestion for measuring of the fluid flow velocity appeared. Experimental work continued for the next 30 years; during this period, 2D and 3D probes were designed, and two main principles of hot-wire anemometry emerged (CCA, CTA). Many other improvements of the CTA system arose during this period [12]. Further work was devoted mainly to maximisation of the response of the electrical circuit in the CTA measurement system [13]. The first CTA system was commercially available in 1950s.

## 2 Experimental setup

Experiments were performed at Spray Laboratory, Faculty of Mechanical Engineering, Brno University of Technology. Mean velocity profiles and turbulent intensities were measured in a newly designed small-scale low-speed wind tunnel test section with cross-section of 200×200 mm. The measurement of mean velocity flow was performed in one plane and in 19 equidistantly spaced positions. Figure 1 shows the schematic layout of the measurement points in the wind tunnel test section.

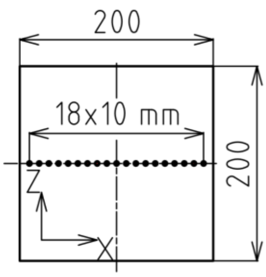


**Fig. 1**. Measurement points.

### 2.1 PDA Experimental Setup

Particle sizes and velocities were probed by two-component Phase Doppler anemometer (PDA) Dantec Dynamics A/S, see a schematic layout in Figure 2. In each position, 5 kHz sampling frequency was used, and the measurement took 5 s in each point. Information about the PDA are outlined in Table 1.

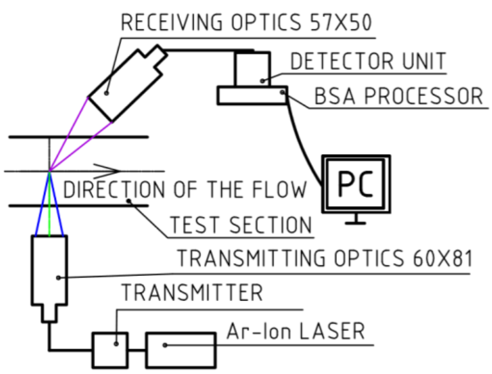


**Fig. 2.** PDA experimental setup.

**Table 1.** PDA experimental setup.

| Parameter | Value |
|---|---|
| **Laser power output** | 1 W |
| **Wavelength** | 514.5 nm |
| **Focal length of transmitting optics** | 310 mm |
| **Focal length of receiving optics** | 500 mm |
| **Scattering angle** | 45 ° |
| **Mask** | A |
| **Spatial filter** | 0.1 mm |
| **Sensitivity** | 1100 V |
| **SNR** | 0 dB |
| **Signal gain** | 20 dB |
| **Level validation ratio** | 6 |

## 2.2 CTA Experimental Setup

A thermoanemometry method was applied (HWA), specifically the CTA measurement technique. StreamLine hot-wire anemometry from Dantec Dynamic was used. Velocity measurement was performed with the wired 1D 55R01 probe. The length of the wire was 3 mm, the measuring part of the wire was 1.25 mm long.

Calibration was performed prior to the measurement. The Dantec streamline Pro Automatic calibrator was used. The wire probe was calibrated in the velocity range of 1–45 m/s in fifteen points. A sampling frequency was set to 10 kHz, and the duration of the measurement was set to 5 s in each point.

The Linear traverse system (ISEL AUSTRIA GMBH & CO. KG) was used to traverse the probe. The span of 3 s was set before the measurement to suppress the vibration of the traverse. The CTA experimental setup is illustrated in Figure 3.

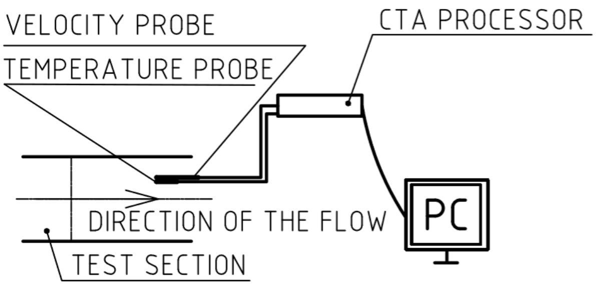


**Fig. 3.** CTA experimental setup.

## 2.3 LDA Experimental Setup

FlowExplorer (Dantec Dynamics A/S, Skovlunde, DK) 1D LDA system with Diode Pumped Solid State (DPSS) laser was used. Wavelength of the laser was 660 nm. The system was working in backscatter mode; the receiver and the transmitter were placed in one body. The beam was split into two parallel beams with the power of 30 mW each. One of the beams was shifted by 80 MHz. A converging transmitting/receiving lens with the focal length of 300 mm was used. Dantec BSA P80 signal processor was used to process the measured signal. BSA flow software v5.20 was used to control the data acquisition. A schematic layout of the LDA measurement system is shown in Figure 4.

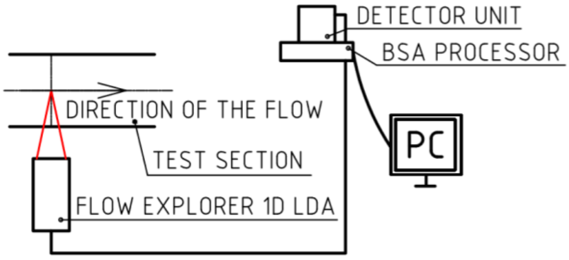


**Fig. 4.** LDA experimental setup.

## 2.4 Seeding Particles

A fog generator was used to generate seeding particles. The particles with a diameter D [μm] in the range of 1-3.5 μm were applied on the suction side of the driving fan. The diameter of particles was measured by the PDA measurement system. The particles are small enough to follow the flow reasonably well; the particle Stokes number was below 0.1. A histogram of the particles diameter measured by the PDA is shown in Figure 5.

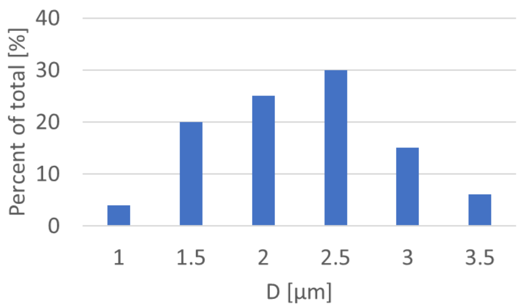


**Fig. 5.** Histogram of seeding particles diameter measured by PDA system.

## 2.5 Experimental Setup of Pitot static tube

The L-type pitot static tube was used. The measuring device with accuracy of ±0.1% of measurement value was used. A pressure difference measurement range was 0–1000 Pa. The measurement system does not allow for PC connection or data export; the values were read on the device display. The measurement system can be seen in Figure 6.

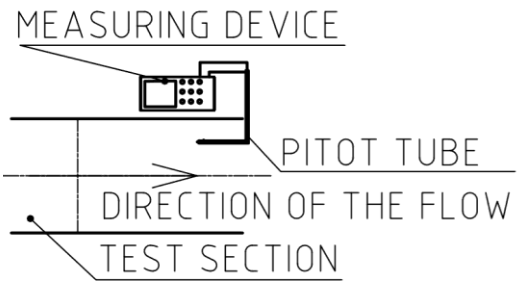


**Fig. 6.** Pitot static tube experimental setup.

## 3 RESULTS AND DISCUSION

Important characteristics of every wind tunnel are the velocity profile and turbulent intensity in the tunnel test section. Uniform velocity profile and low turbulence are required in the test section of almost all kinds of wind tunnels. As was mentioned before, velocity and turbulent intensity measurement were performed by different measurement systems, which were described in the foregoing section.

### 3.1 Velocity Profiles

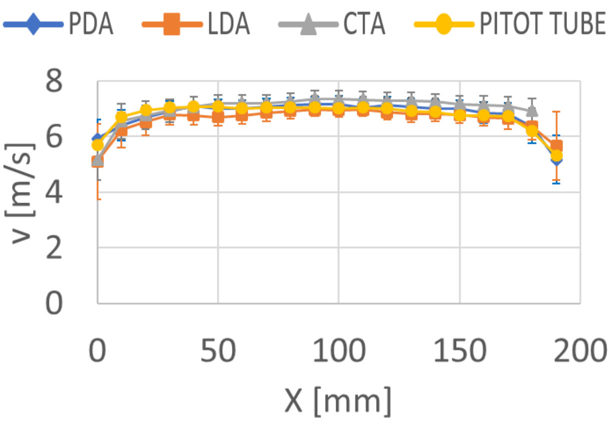


**Fig 7.** Velocity profile, mean velocity of 7 m/s.

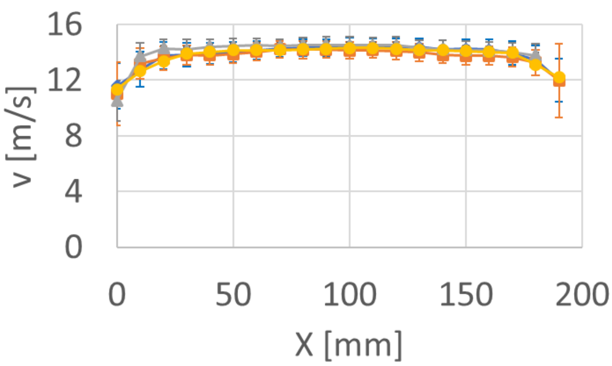


**Fig 8.** Velocity profile, mean velocity of 14 m/s.

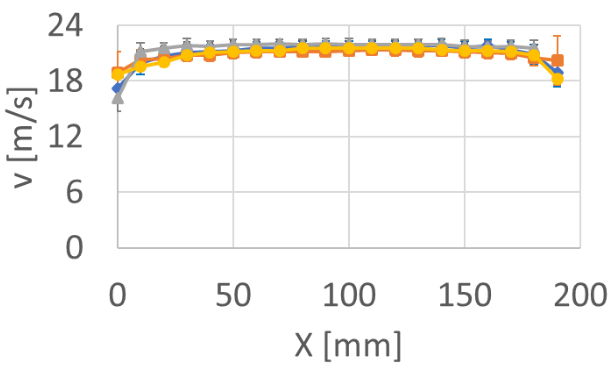


**Fig. 9.** Velocity profile, mean velocity of 21 m/s.

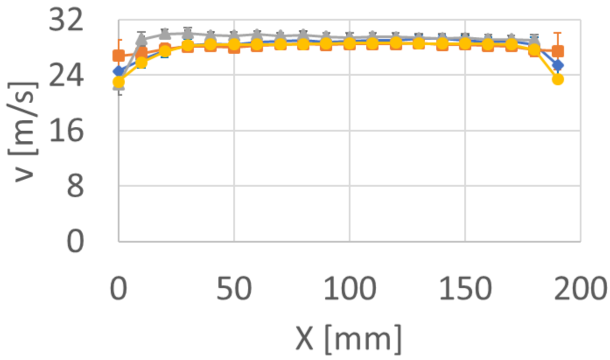


**Fig. 10.** Velocity profile, mean velocity of 28 m/s.

Figures 7–10 show velocity profiles for different mean velocities in the test section and for different measurement systems. As seen in these images, the results obtained by different measurement methods are in a good agreement. Velocity profiles in Figures 7 to 10 are uniform across the cross-section of the test section. The thickness of boundary layer is defined as the distance from the wall, to the point, where the velocity magnitude reaches value of 99% of free stream velocity. A boundary layer thickness is represented in Table 2. In the boundary layer region, velocity decreases and the largest deviations between the measurement systems are observed.

**Table 2.** Boundary layer thickness.

| Mean velocity [m/s] | Free stream velocity [m/s] | Boundary layer thickness [mm] |
|---|---|---|
| **7** | 7,02 | 15 |
| **14** | 14,31 | 18 |
| **21** | 21,42 | 20 |
| **28** | 28,2 | 23 |

### 3.2 Turbulent Intensity

The pitot static tube did not allow to measure the turbulent intensity; a comparison of turbulent intensity is performed only for the PDA, LDA and CTA measurement techniques. Turbulent intensity of four different regimes is illustrated in Figures 11–14. Turbulent intensity in the main flow reaches the values under 5%*. In the boundary layer, turbulent intensity is higher. It is caused by the spatial and temporal instabilities in the boundary layer near the surface. As seen in Figures 11–14, turbulent intensity is slightly different when measured by different techniques, which is most visible in Figure 14. The CTA measurement system measures a lower turbulent intensity than the LDA or PDA systems. According to [14], turbulent intensity measured by the PDA and LDA measurement systems will always be higher (broadening effect).

A lot of improvements of the flow quality can be obtained in the test section. Turbulent intensities in well-designed wind tunnels are under 0.1% [15]. At Tokohu University in Japan, a closed loop wind tunnel with 0.02% turbulent intensity in the free stream was designed [16]. Steps to reduce the turbulent intensity in the test section will be taken in the future.

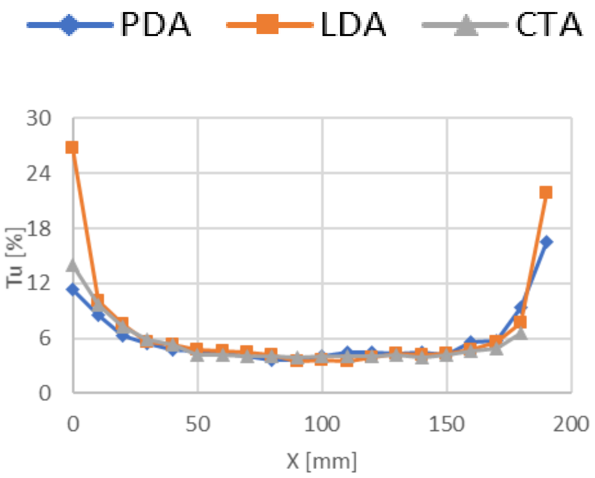


**Fig 11.** Turbulent intensity, mean velocity of 7 m/s.

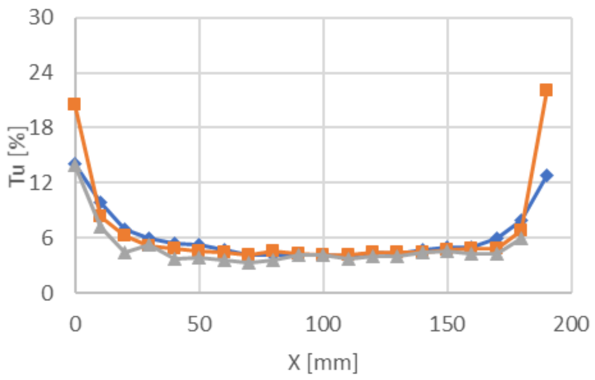


**Fig. 12.** Turbulent intensity, mean velocity of 14 m/s.

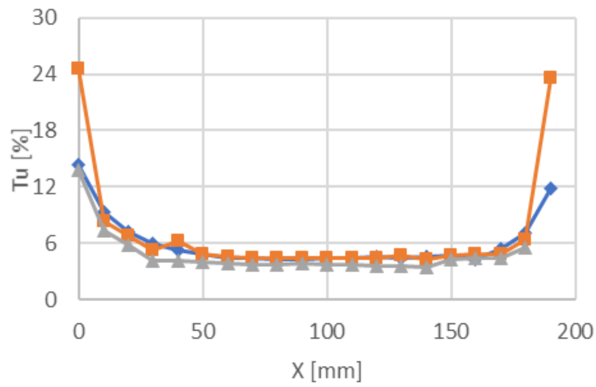


**Fig. 13.** Turbulent intensity, mean velocity of 21 m/s.

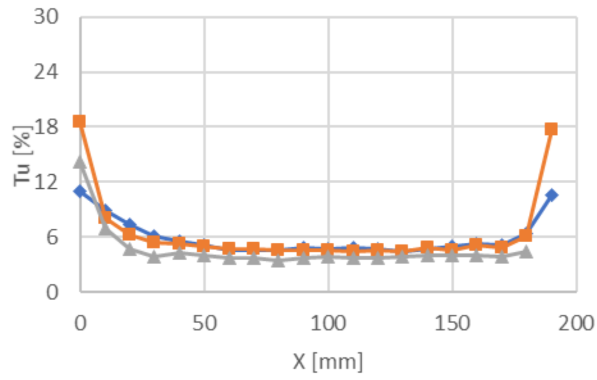


**Fig. 14.** Turbulent intensity, mean velocity of 28 m/s.

### 3.3 PDA and CTA Repeatability and Uncertainties

Six measurements were made to determine the PDA and CTA measurement system repeatability. The attempt was made to assess systematic and random errors of measurement. Combined uncertainty for the PDA measurement system was determined according to [17] to be 1% of the measured value for the velocity measurement. Combined uncertainty of the CTA measurement was determined to be 3.5% of the measured value. Uncertainty was determined according to the procedure described in [18]. There are incorporated uncertainties of the calibration (2%), anemometers (0.2%), linearization (0.5%), resolution of A/D converter (0.02%), uncertainty of position of the probe (0.01%). Uncertainty of temperature change of hot wire, ambient temperature change, atmospheric pressure change and humidity of air change are low comparing to aforementioned uncertainty and are not incorporated. In Figures 15 and 16, the uncertainty for one regime of the velocity and turbulent intensity measurement can be seen (mean velocity of 21 m/s). According to the results shown in Figures 15 and 16, the PDA and CTA velocity, turbulent intensity results can be declared to be the same. The uncertainties are higher in the boundary layer region, where the flow has an unstable and unpredictable behaviour. Also, the uncertainties are lower for the PDA measurement system.

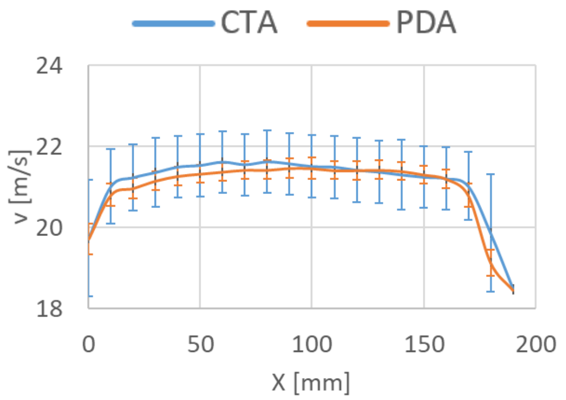


**Fig. 15.** Uncertainty of velocity measurement for PDA and CTA systems.

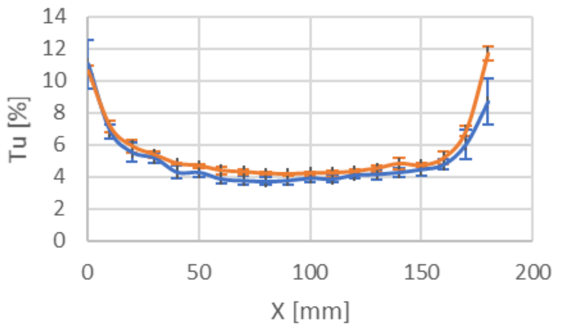


**Fig. 16.** Uncertainty of turbulent intensity measurement for PDA and CTA systems.

### 3.4 Turbulent Spectra

Turbulent spectra for the CTA measurement were analysed. The shape of the Fast Fourier transform (FFT) is pictured in Figure 17. Results in Figure 17 contains a dissipation range, the inertial subrange with slope of −5/3, and the energy-containing range. The difference in the dissipation range and the energy-containing range between the regimes is caused by different Reynolds numbers.

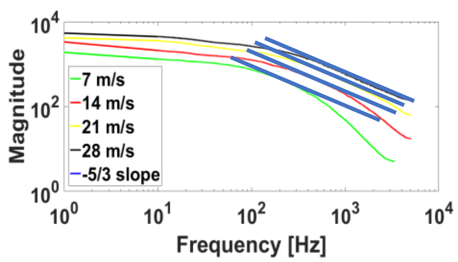


**Fig. 17.** Results obtained by FFT analysis for different velocity regimes.

### 3.5 Pitot static tube Declination

Declination α [°] of the pitot static tube from the velocity vector direction and its influence on the flow velocity was measured. The L-type and S-type pitot static tubes were investigated for two regimes (mean velocity of 7 and 28 m/s). A schematic drawing of the pitot static tubes can be seen in Figure 18 and the experimental setup in Figure 19.

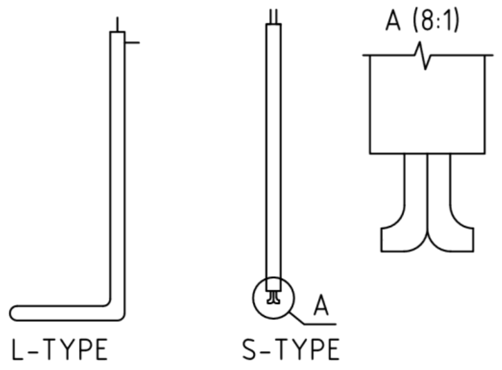


**Fig. 18.** L-type and S-type pitot static tubes design.

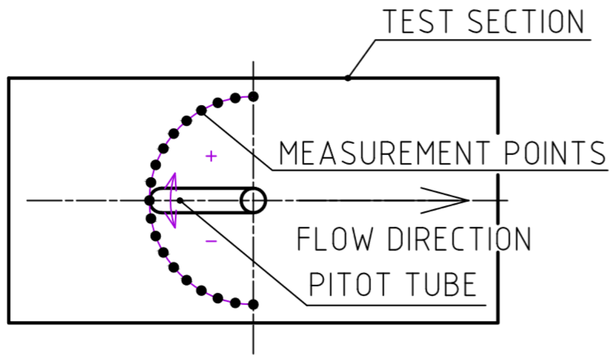


**Fig. 19.** L-type and S-type pitot static tube experimental setup.

Both types of pitot static tubes are relatively insensible to the probe declination because the first declination derivative of velocity is zero when the declination reaches 0´°. As indicated in Figures 20 and 21, the characteristics are symmetrical. There are small asymmetries on mean velocity of 28 m/s; this asymmetry can be caused by the flow instability or inaccurate measurement. Velocities measured by the S-type Pitot static tube need to be calibrated by the factor of 0.84 according to the standard ČSN ISO 10780. Both S-type and L-type measured the velocity very precisely when there was no declination of the probe. A comparison with the industrial measurement system, QuadraTherm® 640i In-Line Mass Flow Meter, referred here as a “QuadraTherm”, can be also seen in Figures 20 and 21. The data obtained by QuadraTherm® 640i In-Line Mass Flow Meter are not symmetrical and the measurement system shows a sensitivity to the probe declination because the first declination derivative of velocity is not zero when the declination is 0 °. This asymmetrical behaviour is caused by non-symmetrical probe location of the measurement system. On the other hand, the measurement range of this industrial system is in the range of 1–300 m/s, and the system is very robust and stable for a wide velocity range. The system can be used in the flow with relatively large polluting particles because of robust probes. The system is able to measure the volume and mass flux.

According to ČSN ISO 10780 S and L-type pitot static tubes accuracy is under 3% of measurement value for declination in range of ±15 ° from velocity vector direction. For higher declination accuracy is under 5% of measurement value. QuadraTherm® 640i has an accuracy in range of ±0.5 of readings plus 0.5% of full scale, when the measured velocity is bellow 50% of full scale. Accuracy of QuadraTherm® 640i measuring the velocity above 50% of full scale is ±0.5 of readings. QuadraTherm® 640i is not suitable for measuring velocities bellow 150 m/s. The results in Figures 20 and 21 show a relatively good agreement with S and L-type Pitot static tubes for zero declination.

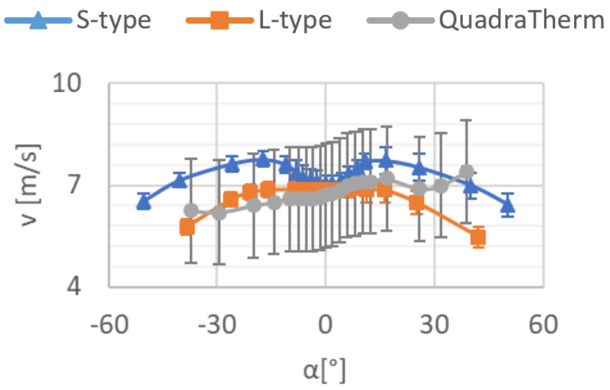


**Fig. 20.** S, L-type and QuadraTherm velocity probe declination measurement, mean velocity 7 m/s.

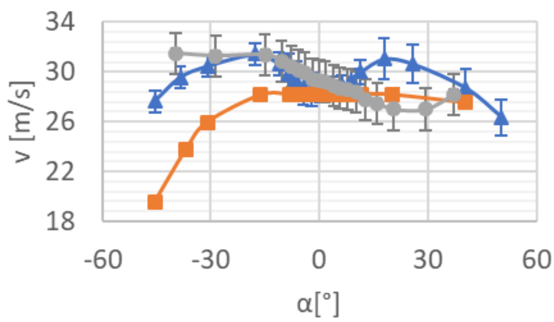


**Fig. 21.** S, L-type and QuadraTherm velocity probe declination measurement, mean velocity 28 m/s.

## 4 CONCLUSIONS

The average velocity in the newly designed low-speed small-scale wind tunnel was measured by different velocity measurement techniques (PDA, LDA, CTA, and the pitot static tube.) PDA, LDA, CTA and pitot static tube experimental setups are briefly discussed in the first section. Velocity profiles in the test section are uniform across the cross-section area for all the assumed cases. A uniform flow is developed 15 mm from the test section sides. Turbulent intensity measured by PDA, LDA and CTA in the free stream is under 5% with an increase near the wall where the velocity gradients are present. Turbulent intensities measured by PDA and LDA show expectably higher values than for the CTA measurement system.

The uncertainties of PDA and CTA measurement systems was assessed to be 1% and 4.8%, respectively, and it is worse in the boundary layer region. Both techniques are in a good agreement for both the average velocity and the turbulent intensity.

Declination of different types of pitot static tubes (S and L-type) and its influence on the flow velocity measured was briefly discussed. The experimental setup is briefly described and the comparison with Industrial QuadraTherm® 640i is provided. The results show the independence of S and L-type Pitot static tubes of declination, and the probes have a symmetrical behaviour. The industrial probe shows a dependence on the probe declination and a non-symmetrical dependence on the probe declination. Systems measures the average velocity with relatively high accuracy when declination of the probes is 0 °.

The results obtained by different measurement systems are in a good agreement. For the velocity measurement in the transparent test section of the wind tunnel, the PDA measurement system can be readily used because of the measurement abilities and easy introduction of the measurement volume into the flow. Another advantage of PDA is non-intrusive measurement which does not disturb the flow in the test section.

## Acknowledgements

The authors acknowledge the financial support from the project No. 18-15839S funded by the Czech Science Foundation and the project “Computer Simulations for Effective Low-Emission Energy engineering” funded as project No. CZ.02.1.01/0.0/0.0/16_026/0008392 by Operational Programme Research, Development and Education, Priority axis 1: Strengthening capacity for high-quality research and project No. RV9090000335 founded by Faculty of Mechanical Engineering, Brno University of Technology. Authors would like to express their gratitude to Radek Kalík, Provyko s.r.o, Petr Komp and Milan Hladký, KROHNE for their effective support during probes testing.

## References

1. S. Mauro, S. Brusca, R. Lanzafame, F. Famoso, A. Galvagno, M. Messina, IJAER, **12**, pp. 13649-13662 (2017)
2. Rahman, Md. Ali, Md. Sidique, F. Pabel, IJERT, **3** (2014)
3. O. Almeida, F. Miranda, O. Neto, F. Saad, JATM, **10** (2018)
4 T. Kumaraswamy, V. V. S. Nikhil Bharadwaj, P. Garre, GJRE-D, **14** (2014)
5. Y. Dwivedi, B. PARVATHAVADHANI, N. Mishra, IJTP, **1**, pp. 14-23 (2012)
6. Y. Yeh, H. Z. Cummis, Appl. Phys. Lett., **4**,176 (1964)
7. A. Boutier, Laser Velocimetry in Fluid Mechanics, **21,** (2012)
8. E. D. Hirleman, Part. Part. Syst. Charact., **13**, pp. 59-67 (1996)
9. B. Husted, P. Peterson, I. Lund, G. Holmstedt, FIRE SAFETY J., **44**, pp. 1030-1045 (2009)
10. F. Lízal, J. Jedelský, K. Morgan, K. Bauer, J. Llop, U. Cossio, S. Kassinos, S. Verbanck, J. Ruiz-Cabello, A. Santos, E. Koch, Ch. Schnabel, Eur. J. Pharm. Science, **113,** pp. 95-131 (2018)

11. Glenn O. Brown, Third National Congress on Civil Engineering History and Heritage, pp. 360-366, (2001)
12. G. Comte-Bellot, ANNU REV FLUID MECH, **8**, pp. 209-231 (2003).
13. Knoblock, Frederick Delbridge (1939) Investigations on the applications of the hot wire anemometer for turbulence measurements. Dissertation (Ph.D.), California Institute of Technology. http://resolver.caltech.edu/CaltechETD:etd-04252008-094935
14. Zh. Zhang, LDA Application Methods - 2010, Laser Doppler Anemometry for Fluid Dynamics, pp. 224-226 (2010)
15. D. Quinn, A. Watts, T. Nagle, D. Lentink, R. Soc. Open sci., **4**, (2017)
16. Y. KOHAMA, R. KOBAYASHI, H. ITO, 28th Joint Propulsion Conference and Exhibit, (1992)
17. Particle Dynamic Analyser (PDA) User´s manual, Skovlunde, Denmark, Dantec Measurement Technology, 1992.
18. F. JØRGENSEN, How to measure turbulence with hot-wire anemometers: a practical guide. 1st edition. Dantec Dynamics A/S, pp. 40-45 (2001)