

Low Air Velocity Measurement Characteristics' Variation Due to Flow Regime

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Abstract—The paper depicts air velocity values, reproduced by laser Doppler anemometer (LDA) and ultrasonic anemometer (UA), relations with calculated ones from flow rate measurements using the gas meter which calibration uncertainty is $\pm (0.15 - 0.30) \%$. Investigation had been performed in channel installed in aerodynamical facility used as a part of national standard of air velocity. Relations defined in a research let us confirm the LDA and UA for air velocity reproduction to be the most advantageous measures. The results affirm ultrasonic anemometer to be reliable and favourable instrument for measurement of mean velocity or control of velocity stability in the velocity range of 0.05 m/s – 10 (15) m/s when the LDA used.

The main aim of this research is to investigate low velocity regularities, starting from 0.05 m/s, including region of turbulent, laminar and transitional air flows. Theoretical and experimental results and brief analysis of it are given in the paper. Maximum and mean velocity relations for transitional air flow having unique distribution are represented. Transitional flow having distinctive and different from laminar and turbulent flow characteristics experimentally have not yet been analysed.

Keywords—Laser Doppler anemometer, ultrasonic anemometer, air flow velocities, transitional flow regime, measurement, uncertainty.

I. INTRODUCTION

LITHUANIAN air velocity national standard is designed for air velocity units reproduction and its transfer to working standards and various type anemometers according to traceability chain. Declared and approved expanded uncertainties are $\pm (7 - 1) \%$ for the velocity range (0.2 – 60) m/s, respectively. The validation of these values is found by air velocity measurement in an aerodynamic facility channel using convergent nozzles (CN) and static Pitot tubes (SPT). Reference SPT was calibrated at the laboratory of PTB (Germany) in a range of (1 – 40) m/s with the expanded uncertainty $\pm (3 - 0.3) \%$, CNs were calibrated by reference volumetric gas meters with the expanded uncertainty $\pm (0.25 - 0.3) \%$. Despite the calibration of CNs is quite precise, only mean velocity values' reproduction at the measuring channel cross-section is warranted. Local velocity value, eg., in channel axis or flow core, could be calculated only after cognition of real velocity distribution in the cross-section. That means all fluid flow characteristics in the channel had to be investigated. It should be noticed that, in general, SPT usage for low velocity ((3 – 1) m/s) measurement is complicated because of precise measurement difficulties of

low differential pressure values.

According to the national laboratories of European countries, velocity unit values measurement capabilities and used methods are of very wide variety (Table I). The most reliable values are produced by Switzerland and Germany standards.

Switzerland standard is the primary standard because it reproduces velocity values according to velocity unit definition, i.e. measured distance is divided by meter travelling time at a constant velocity. Germany standard is based on flow velocity measurement by laser Doppler anemometer (LDA). This method is very precise especially when a system is calibrated using rotating disc. Calibration uncertainty totals $\pm (5 - 0.08) \%$ in a velocity range (0.2 – 60) m/s.

Since 2006, LDA was applied for air velocity measurement research in the laboratory and the first investigations revealed air velocity reproduction and transfer in a range of (0.5 – 30) m/s with the uncertainty of $\pm (2.8 - 0.3) \%$ [1]. The accuracy of measurement increased up to 3 times.

Further investigation aims are:

- research of LDA application capabilities, especially for low velocities;
- the minimum velocity value identification capable to be reproduced in workable aerodynamic facility, up to nowadays practical needs 0.05 m/s or less; to evaluate influence quantities for this velocity range that determine measurement accuracy and to confirm the investigations by other method based on usage of ultrasonic anemometer (UA) that is of high resolution and need no particles in a flow;
- measurements comparison with the ones of European countries national standards;
- research on reproduced values transferring peculiarities to mostly used practical velocity measurement devices including relation of their geometrical dimensions to standard channel ones;
- theoretical analysis of velocity distribution consistent pattern in an initial section of measurement channel.

II. EXPERIMENTAL METHODOLOGY

A. Experimental Equipment

Low air velocity measurement range from 0.05 m/s to 0.5 m/s was analysed in order to evaluate measurement reliability. For the purpose, LDA was used to measure local velocity

values, UA was used to measure mean velocities. UA was calibrated with the uncertainty $\pm (0.25 - 0.3) \%$ by gas meter that was installed in series in the measurement channel (Fig. 1). Dimensionless meter distance from an inlet was $x/D = 5$. Principles and measurement capabilities of LDA and UA are depicted in [2 - 3]. Measurement channel could be open or closed.

Reproduced velocity values transfer accuracy was investigated by the mostly usable working devices: hot wire anemometer (TA) with a sensor that is located in protector having the slots for flow inlet as well as SPT with conical amplifiator (Fig. 2) that enlarge the differential pressure values. The characteristic of this kind of SPT is important because it is used in comparison among the laboratories to verify the traceability of measurement and to keep the traceability not only in regional metrological organisations but even for key comparisons [4].

B. Methods of Calculation

The calculations were made for non-fully developed flow in the initial section of channel (Fig. 1) where air flow varies from laminar to turbulent flow regime.

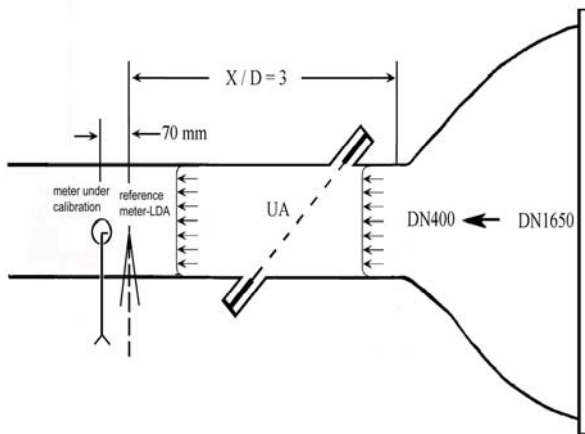


Fig. 1 Measurement channel scheme used in experiments

Velocity distribution in the initial section of channel (pipe) for laminar flow is approximately given by equation [5]:

$$\frac{u}{U_0} = 2 \cdot \left(1 - \left(\frac{r}{R}\right)^2\right) - 4 \cdot \sum_{n=1}^{\infty} \frac{1}{\beta_n^2} \left[1 - \frac{I_0(\beta_n \cdot r/R)}{I_0(\beta_n)}\right] \cdot \exp(-4 \cdot \beta_n^2 \cdot X) \quad (1)$$

here I_0 – zero series Bessel function; $\beta_n (n=1,2,3,\dots)$ – root of the second order Bessel function I_2 ; $X = (1/Re)(x/D)$. U_0 – inlet flow velocity, u – velocity value at the initial stage.



Fig. 2 SPT with conical amplifiator scheme

The nondimensional length of initial section where the velocity distribution approaches the fully developed one is given by equation [5]:

$$L/D = 0.055 \cdot Re_D \quad (2)$$

here L – initial section length; Re_D – Reynolds number.

For laminar, isothermal and incompressible fluid flow velocity profile is in a form of parabola and local velocity relation to mean velocity is given by equation:

$$v = 2v_{av} \left[1 - \left(\frac{r}{r_0}\right)^2\right] \quad ; \quad (3)$$

here r_0 and r – pipe radius and radius under consideration respectively.

The latter equation shows that the ratio of local velocity in a channel axis and mean velocity in a cross-section of a pipe for fully developed laminar flow is equal to 2.

The turbulent fluid flow is calculated by FLUENT (version 6.0.12) standard axi-symmetrical $k-\omega$ model for incompressible steady-state fluid flow. For the developed turbulent flow maximum and mean values relation consistent pattern is known [6] and given in a Table II. The results made by Fluent and experimental ones coincide and confirm stable and regular velocity profile increase in the channel with velocity increase [2].

TABLE II

V_{max}/V_{av} VALUES FOR THE FULLY DEVELOPED TURBULENT FLOW IN A

ROUND CHANNEL (PIPE)

Re_D	$4 \cdot 10^3$	$2.3 \cdot 10^4$	$1.1 \cdot 10^5$	$1.1 \cdot 10^6$	$2 \cdot 10^6$
V_{max}/V_{av}	1.264	1.238	1.224	1.177	1.156

The relation V_{max}/V_{av} change in a wide Re_D region is not intense due to turbulent profile flatness (comparing it with the laminar one). The change is seen in a Table and varies from 1.26 to 1.16. The known fact is that transition from laminar to turbulent flow regime is attended by more intensive increment of boundary layer the thickness of that is proportional to $5.5 \cdot Re_x^{-0.5}$ and $0.37 \cdot Re_x^{-0.2}$ for laminar and turbulent flows over the flat surface respectively. That's why the initial section of transition to fully developed flow for turbulent flow is more shorter than for laminar flow. For $Re_D = 10^4 - 1.2 \cdot 10^5$ the length of initial section could be approximately evaluated from equations [5]:

$$L/D = 4.5 \cdot 10^5 / Re_D, \text{ when } Re_D \leq 5 \cdot 10^4 \text{ and} \quad (4)$$

$$L/D = 0.6 / Re_D^{0.25}, \text{ when } Re_D > 5 \cdot 10^4. \quad (5)$$

III. RESULTS OF REFERENCE VALUE REPRODUCTION

Air velocity measurements and their results analysis were done in order to define velocity distribution influence to reproduced air velocity values in a range (0.05 – 0.5) m/s in measurement channel.

Measurement results given in Fig. 3 are obtained comparing UA measured mean velocity values with the calculated ones from gas meters installed in series and LDA values measured in a channel axis. Gas meters measured air volume was used for calculation of mean air velocity and comparison with UA readings.

Measurements showed the resolution of UA is 0.003 m/s and it's values are in stable and good relation to values calculated according to meters' readings from 0.03 m/s. This relation could be expressed by linear dependence for (0.04 – 0.40) m/s measurement range with a standard deviation ± 0.0056 m/s. Rate of proportionality 0.9 is explained by the fact that UA measures mean velocity along the way of ultrasound beam through the cross-section of the measurement channel [7], whereas the meter integrates overall flow volume. Thus UA measured values are a little bit higher than ones calculated from the meter readings.

UA also showed a good correlation with the LDA values in velocity range from 0.17 m/s and higher. 8 measurements were done for every velocity value. Experimental standard deviation from relation expression is ± 0.0083 m/s. LDA values are higher because it measures local velocities at the axis. It should be noticed that velocity value 0.17 m/s corresponds $Re_D = 4 \cdot 10^3$, i.e. flow is turbulent if velocities are higher than this value and if it is lower the flow is getting laminar and velocities ratio V_{LDA}/V_{UA} is also changing. When $Re_D = 1.28 \cdot 10^3$, velocity is 0.05 m/s, the flow is clearly laminar.

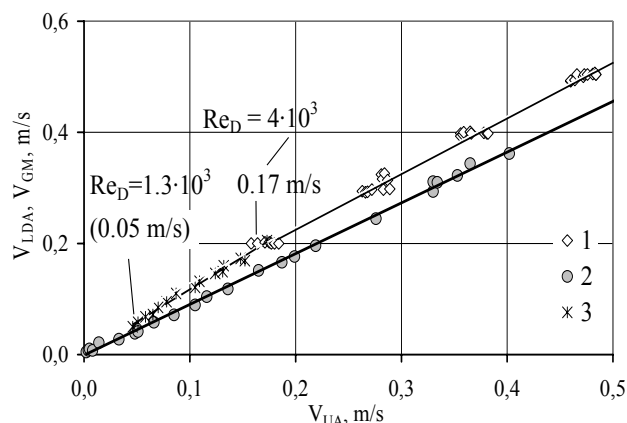


Fig. 3 Relation of velocity values measured by LDA (V_{LDA}), UA (V_{UA}) and calculated from reference gas meter readings (V_{GM}): 1 – relation of V_{LDA} and V_{UA} according to expression $V_{LDA} = 1.0084 \cdot V_U + 0.0271 \pm 0.0083$; 2 – values calculated from meter relation to UA according to $V_{GM} = 0.90 \cdot V_U \pm 0.0056$; 3 – V_{LDA} relation with V_{UA} according to $V_{LDA} = 1.138 \cdot V_U \pm 0.0041$

From the results above, one can suppose that UA and LDA application for velocities down to 0.05 m/s is feasible. Both methods complement one another and warrant high reliability. Experimental results' comparison with the theoretical ones is essential. So relation V_{LDA}/V_{UA} or V_{max}/V_{av} variation in the

channel enable to evaluate velocity value correlation with a predictable uncertainty.

For low Reynolds number flow could be analysed by laminar flow equation (1) and for turbulent flow – FLUENT solutions or experimental data could be applied.

Making comparison of velocities measured by various methods should be taken into consideration that UA measures mean velocity integrating only velocity distribution along the ultrasound beam, i.e. along channel diameter. This corresponds mean velocity calculation from equation:

$$V_u = (1/R) \int V_i D r ; \quad (6)$$

here V_i – local value from velocity distribution along ultrasound beam; R – channel radius.

Usually mean velocity is calculated using velocity-area method from equation:

$$V_u = (1/\pi R^2) \int V_i 2\pi R dR . \quad (7)$$

Mean velocity value calculated by this way, should correspond to value, calculated from air volume measured by meters.

The results displayed in a Fig. 4 reveal that local, maximum, velocity calculated by (1) equation and mean velocities calculated by (6) or (7) equations relation (V_{max}/V_{av}) for laminar flow approaches an asymptotical value close to 1.5 (curve 1). At the dividing line of laminar and transitional flow regime ($Re_D = 10^3 - 2 \cdot 10^3$) the relation decreases up to 1.12 – 1.09. The relation is approaching 1 as boundary layer is getting thinner.

The relation V_{max}/V_{av} calculated by equations (1) and (7) for laminar flow (curve 2) approaches the asymptotical value 2 typical for developed laminar flow. This relation approaches another asymptotical value 1.28 – 1.24 at the dividing line of laminar and transitional regime, when $Re_D = 10^3 - 2 \cdot 10^3$. One could confirm that values of this relation at the beginning of the transitional region are limitary and could reliably reveal velocity distribution within this limit.

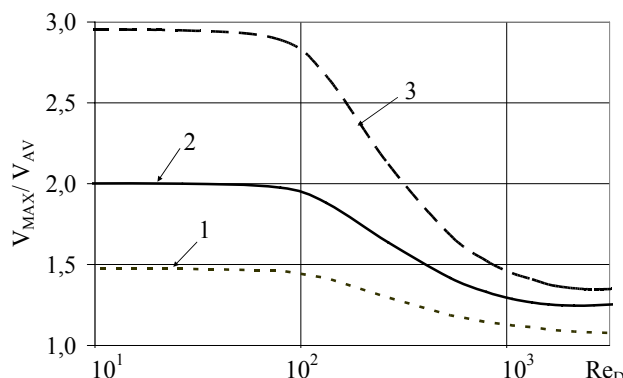


Fig. 4 Mean and local velocities ratio dependence on Re_D when $x/D = 3$ for laminar flow: 1 – ratio of mean velocities V_{av}/V_u calculated by (1), (6) and (7) equations; 2 – V_{max}/V_{av} according to (1) and (7); 3 – V_{max}/V_{av} according to (1) and (6)

Curve 3 in a Fig. 4. shows relation V_{max}/V_{av} variation when mean velocities are calculated by (6) equation in the same way as UA measures.

Since analogue variation of parameters for transitional regime could be analyzed only by experimental data, it should be expedient to analyze turbulent flow region as the flow transit to it when $Re_D = 4 \cdot 10^3$ or air velocity in the channel increases up to 0.17 m/s.

Fig.5. shows the comparison of experimental and calculated results for turbulent, transitional and laminar flow regimes. They reveal the relation V_{max}/V_{av} values approximately to be equal to 1.26 that could be treated as asymptotical ones at the dividing lines of laminar-transitional flow as $Re_D = 10^3 - 2 \cdot 10^3$ and transitional-turbulent flow as $Re_D = 4 \cdot 10^3$.

Data about velocity distribution in a transitional flow region have not been carefully analyzed yet. Though one could conclude from fulfilled measurements that theoretical calculations and two independent methods for local and mean velocity value measurements enable to define the variation of V_{max}/V_{av} reliably and warrant the uncertainty of reproduced low air velocity values close to 0.05 m/s.

Results in Fig. 5 are of great importance because it supplements fundamental hydrodynamics consistent pattern within transitional range and confirm the possibility to reproduce air velocity values in aerodynamic facility measurement channel in explored limits.

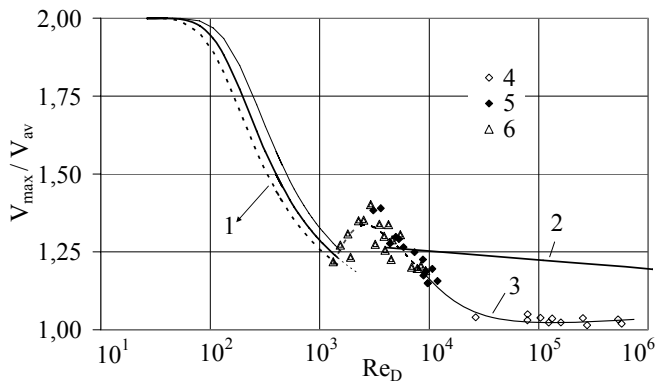


Fig. 5 Dependence of ratio V_{max}/V_{av} on Re_D : 1, 3 – laminar and turbulent flow calculation in the initial section of channel; 2 – fully developed turbulent flow; 4 - 6 – experimental results given in Fig. 2

It should be noticed that transitional flow is highly turbulent and even unstable (Fig. 6). Instability could be somewhat generated by open outlet of measurement channel. Fig. 6. shows sharp flow turbulence increase and dispersion of results for velocities lower than 1 m/s. This inevitably should affect velocity value reproduction uncertainty and influence velocity transfer to various type of working meters also. High turbulence and instability influence may also have a significant dependence on the type of velocity measurement device and the principle as it operates.

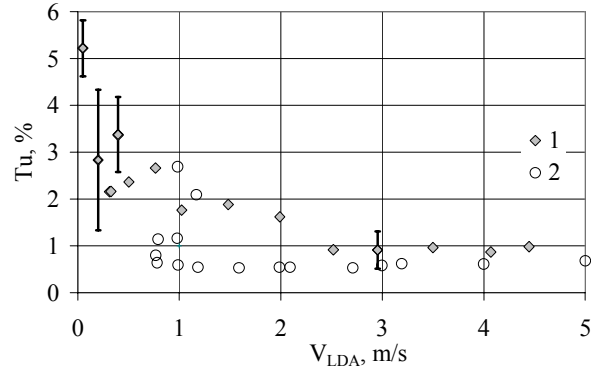


Fig. 6 Turbulence intensity change in a measurement channel dependence on velocity value: 1, 2 – measurement channel respectively is open (at distance $x/D = 1$ beyond the device under calibration, Fig. 1) and closed

IV. RESULTS OF REFERENCE VALUE TRANSFER

As it was mentioned above, 2 types of air velocity measurement devices operating according different principles were used for investigation of reference velocity values transfer: thermoanemometer and static Pitot tube. The latter was investigated with differential pressure amplifier (Fig. 2). This type of SPT is used in comparison among the laboratories and the operation in low velocities is disputable because of additional flow separation point region behind the amplifier impact on measurement results. The separation point region is sensitive to flow regime and also to pressure field behind the tube when measurements are made in an open channel.

Thermal anemometer is sensitive device and it is difficult to say whether low velocity values are affected by turbulence degree, transitional regime instabilities or it reacts to the complex velocity influencing factors. As it is seen in Fig. 7., velocity value relation of LDA and TA is almost constant for velocities higher than 0.2 m/s whereas Tu degree is varying 0.5 – 1 % for the same velocity range. When velocity comes into the limit of 0.2 m/s where as it was already mentioned various effects are increasing, the relation of LDA and TA changes as well. TA values become higher than LDA values, Tu degree and deviation of results are increasing as well.

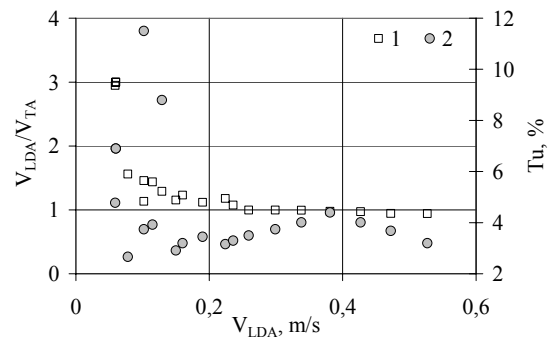


Fig. 7 LDA and TA velocity relation depending on velocity magnitude and turbulence degree: 1 – relation of V_{LDA} to V_{TA} ; 2 – Tu

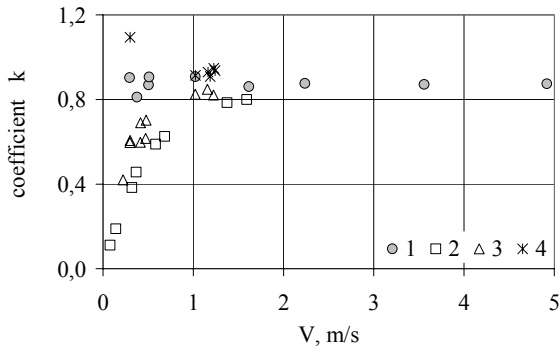


Fig. 8 SPT with a conical amplifier readings dependence on V and installation conditions: 1, 4 – respectively closed and open channel where flow $Tu = 1\%$; 2, 3 – open channel with flow turbulizator respectively ahead and behind SPT ($Tu = 8\%$)

Conventional SPT action is unknown in the dependence on Tu . SPT with a conical amplifier is very sensible to pressure pulsation field, which determines the structure of abruption region and static pressure variation in it when velocity value is low, though it is very useful when flow conditions are stable. Fig. 8. shows an obvious affect of Tu degree on calibration coefficient of SPT. It decreases from the same velocity limit as in previous investigations. Velocity values decreases when Tu degree increases in low velocity region.

V. CONCLUSION

1. Consistent pattern of air velocity distribution variation in a transitional flow region is analyzed. Values of asymptotical maximum and mean velocities' relation are defined by numerical methods at the dividing lines of laminar-transitional-turbulent flow regimes. These values

are confirmed by experimental measurements carried out using ultrasonic and laser anemometers.

2. Defined consistent pattern of maximum and mean velocities relation for transitional flow and asymptotical values within this region dividing lines have great importance for investigations of transitional flow characteristics.
3. It is pointed out that ultrasonic anemometer remains a very important measurement device with a 0.003 m/s resolution and could be used as a reliable velocity measurement device complementing LDA.
4. It is determined that reproduced air velocity value transfer to working anemometers has a significant dependence on their type and operation principle.

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TABLE I
 AIR VELOCITY MEASUREMENT CAPABILITIES BY THE NATIONAL STANDARDS OF SOME EUROPEAN COUNTRIES

Country, laboratory	Method	Measurement range, m/s	Uncertainty	
			± m/s	± %
Switzerland, METAS	Meter travelling in the channel	0.02 – 13	0.1 + 0.5/v	25 – 0.14
Germany, PTB	1. LDA - rotating disc	0.1 – 15	-	0.10
	2. LDA –open channel	0.2 – 60	0.01 – 0.05	5.0 – 0.08
	3. LDA – closed channel	0.5 – 60	-	0.50
Holland, NMI	Mobile standard in the open channel	0.1 – 1.0	3.2/v – 2.2	30 – 1.0
		1.0 – 50	-	1.0
Turkey, UME	Static Pitot tube	0.50 – 20	-	0.90
Lithuania, VMT/LEI	Convergent nozzles, static	0.2 – 3.0	-	7.0 – 3.0
	Pitot tube in closed channel	3.0 – 60	-	3.0 – 1.0
Estonia, UTC	Calibrated nozzle	4.0 – 40	-	4.0 – 2.0