Experimental study of blockage effect in wind tunnels for calibrations of anemometers

EURAMET project – technical protocol (January 2018)

1 Introduction

When an anemometer is calibrated in a wind tunnel the velocity field in the measuring section is influenced by geometry of the anemometer and the wind tunnel. To some position in the measuring section a reference anemometer is placed and therefore the velocity indication of the reference for a given velocity indication of the meter under test depends on the wind tunnel size and type and on dimensions and type of the anemometer. This effect was observed also in inter-laboratory comparisons of wind-speed calibration laboratories and in [1] it was concluded that the results of the comparisons indicate a need for more attention to blockage effects during air speed calibrations and their effect on air speed uncertainty statements.

To make the calibration results from various wind tunnels comparable the reading of the reference should be corrected to a value corresponding to standardized boundary conditions which are the same for all the wind tunnels – for example to free stream conditions assuming an infinite asymptotically homogeneous velocity field with reference velocity given by the velocity at infinity (far enough from the anemometer). Or at least the size of such correction should be estimated and included in the uncertainty budget.

Denoting v_M the velocity indication of the meter under test, $v_E(v_M)$ the velocity indication of the reference anemometer in a particular wind tunnel when the meter under test indicates v_M and $v_\infty(v_M)$ the velocity of the asymptotically homogeneous free stream at infinity when the meter under test inserted to the stream indicates the velocity v_M, we can define a correction factor for the blockage effect given as

$$\alpha(v_M) = \frac{v_\infty(v_M)}{v_E(v_M)}$$

A theory of velocity corrections of measurements in wind tunnels with closed measurement section to the free stream conditions was developed by Glauert [2] and further extended by Mikkelsen and Sørensen [3]. Their theory for closed measuring sections is reviewed and extended to open measuring sections in [4] or in the monograph [5]. This theory is suitable especially for horizontal axis wind turbines (vane anemometers) and it contains some simplifying assumptions and therefore its experimental validation is necessary.

In standards the blockage effect is addressed e.g. in [6] where a relative uncertainty contribution of 1/4 of the blockage ratio for closed measuring sections and 1/16 of the blockage ratio for open measuring sections is recommended in case of cup anemometer calibrations with Pitot tube as a reference, the blockage ratio being the ratio of the area of the anemometer projected to a plane perpendicular to the flow and the cross sectional area of the measuring section of a wind tunnel. Otherwise quantitative recommendations for blockage corrections or uncertainties are missing.

Experimental investigation of influence of the blockage effect to cup anemometer calibrations can be found e.g. in [7]. Overview and experimental verification of methods for blockage effect corrections for propellers can be found e.g. in [8] and for vertical axis wind-turbines in [9].

The aim of this project is to investigate the influence of blockage effect to calibrations of anemometers. Six anemometers of various types and sizes will be calibrated in 10 laboratories with 13 wind tunnels of various types and sizes and the deviations of the results will be analysed. Comparing the calibration results of the participating laboratories with the results of the largest wind tunnel in the project where the blockage effect can be considered as almost negligible, the correction factor α of the laboratories for the tested anemometers can be found experimentally. At the same time models for the blockage effect correction can be verified by comparing their predictions with the experimental data. If successful, such models can be used for blockage effect corrections or uncertainty estimations by the wind-speed calibration laboratories.

[1] H. Müller, *Final report on EURAMET project No. 827: LDA-based intercomparison of anemometers*, Metrologia, Vol. 50, Technical Supplement
[2] H. Glauert, “Airplane Propellers,” Aerodynamic Theory, edited by Durand, W. F., Dover, New York, 1963, Chap. 7, Div. L, pp. 251–268.
[3] R. Mikkelsen and J. N. Sørensen, *Modelling of Wind Tunnel Blockage*, Proceedings of the 2002 Global Windpower Conference and Exhibition [CD-ROM], www.ewea.org.
[4] J. N. Sørensen, W. Z. Shen and R. Mikkelsen, *Wall Correction Model for Wind Tunnels with Open Test Section*, AIAA Journal Vol. 44, No. 8, August 2006
[5] J. N. Sørensen, *General Momentum Theory for Horizontal Axis Wind Turbines*, Springer 2016
[6] EN 61400-12-1 Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines, Annex F
[7] D. Westermann; N. Balaresque and P.Busche, *Systematic deviation of the anemometer calibration due to geometrical interference*, Report of Deutsche WindGuard Wind Tunnel Services GmbH, 2011
[8] R. E. Fitzgerald, *Wind tunnel blockage corrections for propellers*, Master Thesis, University of Maryland, 2007
[9] I. J. Ross, *Wind Tunnel Blockage Corrections: An Application to Vertical-Axis Wind Turbines*, Master Thesis, University of Dayton, 2010

2 Test schedule and contact information of participants

In the table 1 below there is a timeline of the tests including the shipping address and contact person details. It is supposed that in the time period assigned for each laboratory the laboratory performs all the measurements and send the meters to the following laboratory which should receive the meters at the end of the period of the preceding lab. The transportation is organised and paid by the sending laboratory.

Laboratory	**Date**	**Shipping address**	**Contact**
Czech Metrology Institute (CMI)	1.11.-7.1.	Cesky metrologicky institut, Jan Gersl, Okruzni 31, 63800 Brno, Czech Republic	Jan Gersl jgersl@cmi.cz +420 602 528 299
E+E Elektronik GesmbH (E+E)	8.1.-21.1.	E+E Elektronik GesmbH, ÖKD Kalibrierstelle und designiertes Labor, z.H. Dietmar Pachinger, Langwiesen 7, A-4209 Engerwitzdorf, Austria	Dietmar Pachinger dietmar.pachinger@epluse.at +43 (0)664/8245135
Physikalisch-Technische Bundesanstalt (PTB)	22.1.-11.2.	Physikalisch-Technische Bundesanstalt Department 1.4 - Gas Flow Bundesallee 100 38116 Braunschweig Germany	Harald Müller Harald.Mueller@ptb.de +49 531 592-1310

Deutsche WindGuard Wind Tunnel Services GmbH (DWG)	12.2.-25.2.	C.o. Peter Busche, Deutsche WindGuard Wind Tunnel Services GmbH, Oldenburger Str. 65, 26316 Varel, Germany	Peter Busche p.busche@windguard.de +49(4451)9515/239
Westenberg Engineering (WE)	26.2.-8.4.	Dennis Knabben Westenberg Engineering Vitalisstr. 100 D-50827 Köln Germany	Dennis Knabben knabben@westenberg-engineering.de +49-221-9583232
Lithuanian Energy Institute (LEI)	9.4.-29.4.	Lithuanian Energy Institute, Laboratory of heat equipment research and testing, Breslaujos str.3, Kaunas, LT-44403, Lithuania	Agnė Bertašienė Agne.Bertasiene@lei.lt +37037401865
Testing Centre, University of Tartu (TCUT)	30.4.-13.5.	Testing Centre (TCUT), Martin Vilbaste, Institute of Chemistry, University of Tartu, Ravila 14A, 50411 Tartu, Estonia	Martin Vilbaste martin.vilbaste@ut.ee +372 7 376 034
CETIAT	14.5.-27.5.	CETIAT, Laboratoire Anémométrie - Isabelle CARE, Domaine Scientifique de la Doua, 54, boulevard Niels Bohr, 69100 VILLEURBANNE FRANCE	Isabelle Care isabelle.care@cetiat.fr +33 (0)4 72 44 49 92
Czech Metrology Institute (CMI)	28.5.-24.6.	Cesky metrologicky institut, Jan Gersl, Okruzni 31, 63800 Brno, Czech Republic	Jan Gersl jgersl@cmi.cz +420 602 528 299
METAS	25.6.-15.7. (to be confirmed)	Federal Institute of Metrology METAS, Laboratory for Flow and Hydrometry, Lindenweg 50, 3084 Wabern, Switzerland	Marc de Huu, marc.dehuu@metas.ch +41 58 387 0267
TUBITAK UME (UME)	3 weeks (to be determined)	TÜBİTAK UME Akışkanlar Laboratuarları/ Fluid Flow Laboratories, TÜBİTAK Gebze Yerleşkesi, Barış Mah. Dr.Zeki Acar Cad. No:1, 41470 Gebze / KOCAELİ TURKEY	Hakan Kaykısızlı hakan.kaykisizli@tubitak.gov.tr +90 262 679 5000 - 5102

Czech Metrology Institute (CMI)	4 weeks after UME	Cesky metrologicky institut, Jan Gersl, Okruzni 31, 63800 Brno, Czech Republic	Jan Gersl jgersl@cmi.cz +420 602 528 299

Tab. 1 Time schedule and contact information

3 The tested anemometers

The following anemometers will be used for the project:

1) Vane anemometer Testo 0635 9340 with measuring unit Testo 445
2) Vane anemometer Schiltknecht MiniAir20 with the probe Macro
3) Vane anemometer RM Young Gill Propeller MODEL 27106D/F
4) Cup anemometer Vaisala WAA151
5) Cup anemometer Thies First Class Advanced type 4.3351.10.000
6) Thermal anemometer Airflow TA440

In this section we describe the basic parameters of the anemometers including dimensions, instructions for mounting of the anemometers to the wind tunnels, instructions for electric connections (where applicable), other settings and instructions for packing of the meters for transport.

General remark:
For wind tunnels where the mounting pipes of the anemometers enter the air stream (the large wind tunnels), the pipes and connections contained in the packages (or pipes and connections with the same dimensions) must be used in order to achieve the same mounting conditions for all labs and to eliminate a possible effect of additional blockage due to e.g. a thicker pipe.

The anemometers are transported in three separate packages which are depicted in figures 1 and 2.

The package 1 contains:
- case with the anemometer Testo
- case with the anemometer Airflow
- box with the anemometer Vaisala
- cable and screws for the anemometer Vaisala
- plastic mounting flange for the anemometer Vaisala
- mounting pipes ¾” 7.5 cm, 12 cm, 20 cm and ¾” connecting screw
- reduction from 1” to ¾” female screw thread
- mounting pipes 1” 15 cm, 25 cm, 30 cm and 1” connecting screw
- steel mounting flange

dimensions: 78 cm x 38 cm x 32 cm; weight: 14.3 kg

The package 2 contains:
- box with the anemometer Thies
- box with the anemometer RM Young
- cable for the anemometer Thies
- mounting pipe ¾”, 40 cm

dimensions: 125 cm x 38 cm x 38 cm; weight: 8.25 kg

The package 3 contains:
- case with the anemometer Schiltknecht
- 2 aluminium mounting tubes (30 cm, 50 cm)
- ATA carnet

dimensions: 56 cm x 28 cm x 43 cm; weight: 3.6 kg

Fig. 1 Package no. 1

Fig. 2 Package no. 2 (left), package no. 3 (right)

Vane anemometer Testo 0635 9340 with measuring unit Testo 445

Basic parameters:

Velocity range: (0.1 – 15) m/s
Dimensions:
outer diameter of the rotor head: 10.75 cm
depth of the rotor head: 4.3 cm
length of the telescopic mounting rod: up to 1 m
Velocity indication: reading from the display
Resolution: 0.01 m/s
Serial number: probe: 709, electronics: 61054935

Mounting in a wind tunnel:

The probe (fig. 3 left) is connected to a telescopic mounting rod which can be fixed to a construction outside the wind stream (see e.g. fig. 3 right).

The rotor of the anemometer is not symmetric – the edge of the blades is straight on one side and it is not straight on the other side. The meter is installed in a way that the flow is entering the side with straight edges (see the yellow arrow indicating the flow direction).
The cable from the telescope is connected to the input no. 1 of the measuring unit (fig. 4).

Packing for transport:

The anemometer Testo is transported in a case shown in fig. 5 inside the package no. 1.

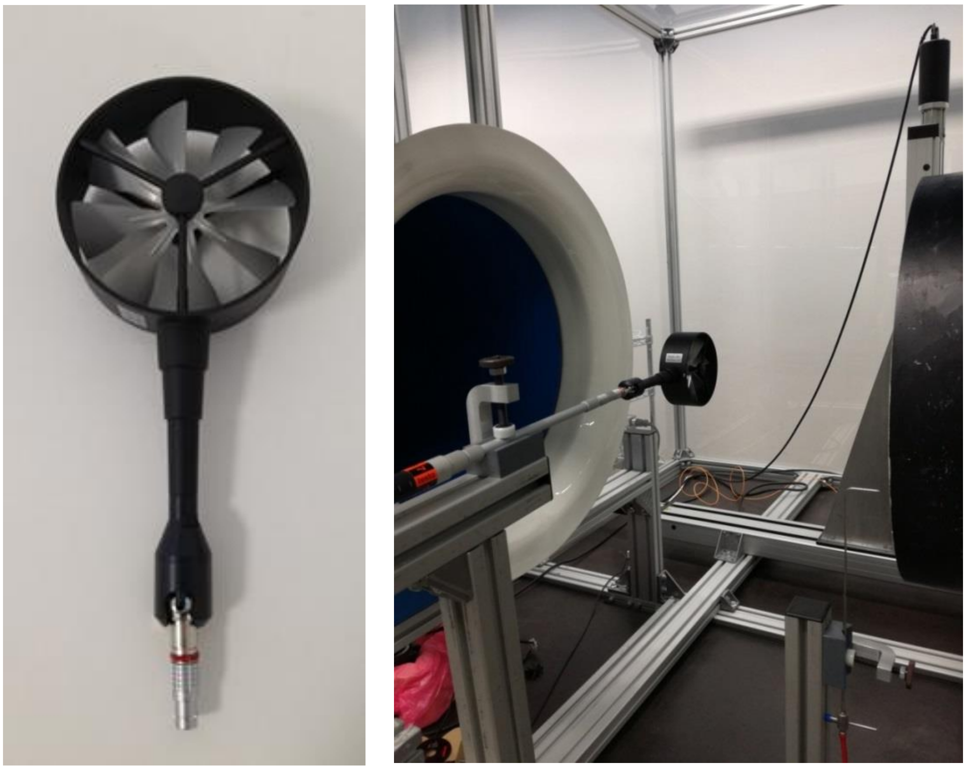

Fig. 3 Vane probe Testo 0635 9340 and its installation with telescopic mounting rod.

Fig. 4 The measuring unit Testo 445 with two input connectors.

Fig. 5 Case with the anemometer Testo

Vane anemometer Schiltknecht MiniAir20 with the probe Macro

The anemometer was provided by METAS.

Basic parameters:

Range: (0.3 – 40) m/s
Dimensions:
    outer diameter of the rotor head: 8.55 cm
    depth of the rotor head: 8 cm
    length of the probe from centre of the rotor to bottom of the handrail: 19 cm
Velocity indication: reading from the display
Resolution: 0.01 m/s
Serial number: probe: C-72268, electronics: 75792

Mounting in a wind tunnel:

There are 2 aluminium mounting tubes in the package no. 3 with lengths of 50 cm and 30 cm (fig. 7). One of the tubes is softly inserted inside the handrail (insertion depth approx. 5 cm) with the cable lead inside the tube (see fig. 8). The mounting tube is attached to a construction outside of the wind stream. Flow direction is given by the arrow on the probe.

Packing for transport:

The meter must be transported separately from the other meters in the package no. 3 together with the ATA carnet. The package contains also a smaller vane probe which is not used for the project but must travel together with the package. The meter is transported in the case shown in figure 9.

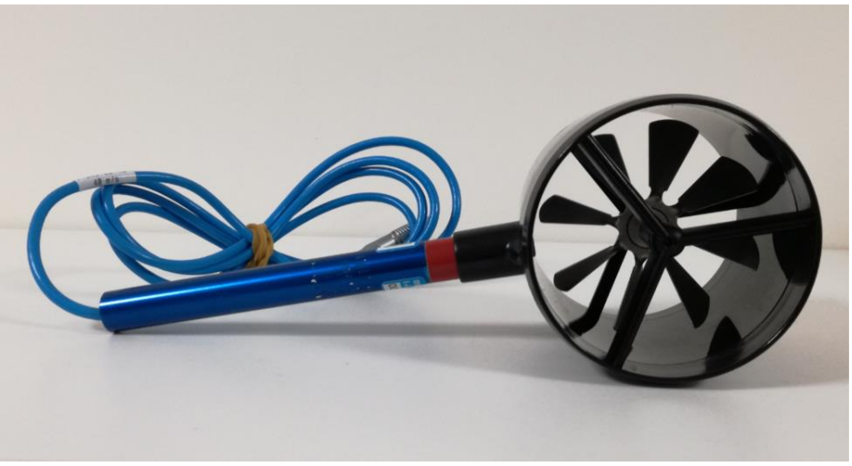

Fig. 6 The vane probe Schiltknecht Macro for anemometer MiniAir 20

Fig. 7 Mounting tubes for the anemometer Schiltknecht

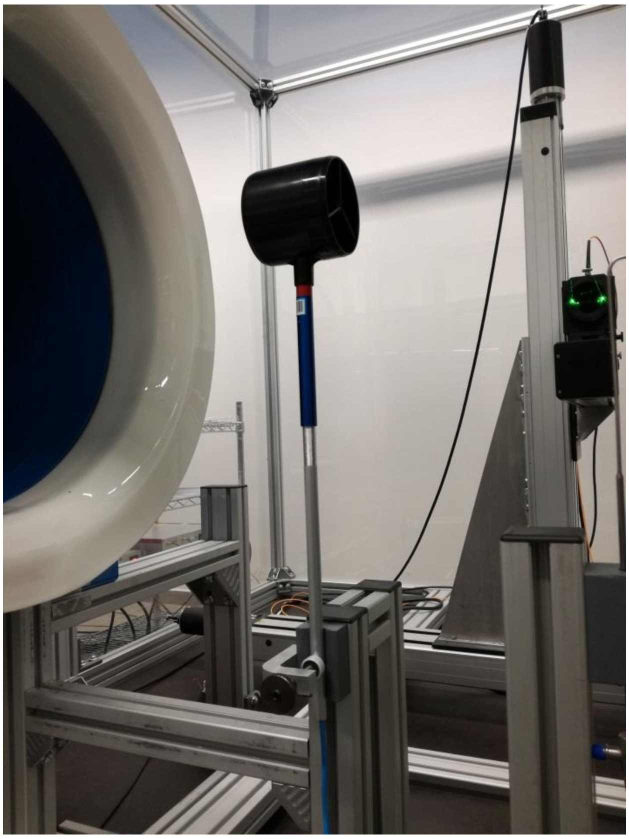

Fig. 8 Mounting of the anemometer Schiltknecht in the wind tunnel of CMI

Fig. 9 Case for the anemometer Schiltknecht

Vane anemometer RM Young Gill Propeller MODEL 27106D/F

The anemometer was provided by Deutsche WindGuard.

Basic parameters:

Range: (0.4 – 35) m/s; The meter must not be exposed to velocities higher than 20 m/s!
Dimensions:
  rotor diameter: 20 cm
  rotor depth: 3 cm
  length from the tip to the mounting elbow: 48 cm
Velocity indication: frequency output with conversion to velocity given by v (m/s) = 0.03 x f (Hz)
Serial number: 02268

Mounting in a wind tunnel:

The tube in the axis of the anemometer ends with a 90° elbow which has a female screw thread for fixing a ¾” pipe (outside diameter 27 mm). The package contains ¾” pipes with lengths of 40 cm and 20 cm with screw threads on both sides and lengths of 12 cm and 7.5 cm with screw thread on one side (fig. 12). The cable of the anemometer must be lead through the pipe. The free end of the pipe can be fixed to a construction either by means of a holder (as in fig. 10) or a flange with a reduction to the ¾” screw thread can be screwed to the pipe and then fixed to a construction. The flange with the reduction is contained in the package (fig. 12). If needed, a pipe can be prolonged with use of a screw junction (included in the package – fig. 12).
For some wind tunnels the tube of the anemometer is too long to be fixed outside of the wind stream and it must be fixed inside the diffusor (see fig. 10 for an example of the CMI wind tunnel).
Flow direction – air coming from the tip side of the rotor.

Electric connections:

The cable (length 4 m) is permanently attached to the anemometer and it contains 6 wires (fig. 11). We use only 3 of them:

- white (pin D): power supply +12V DC (10 V – 14 V according to the manual)
- brown (pin A): ground (0 V)
- yellow (pin C): frequency output (rectangle signal with amplitude approx. = power supply voltage minus 2V)

To connect the meter it is therefore necessary to have the power supply source with 12 VDC and a frequency meter with metrological traceability (e.g. multimeter or oscilloscope). The white wire is connected to (+) of the source, the brown wire to (–) of the source and to the low input of the frequency meter and the yellow wire to the high input of the frequency meter.

Packing for transport:

The meter is transported in a foam case (fig. 13) inside the package no. 2. Any part of the meter (rotor, mounting elbow) must not be dismantled at any time.

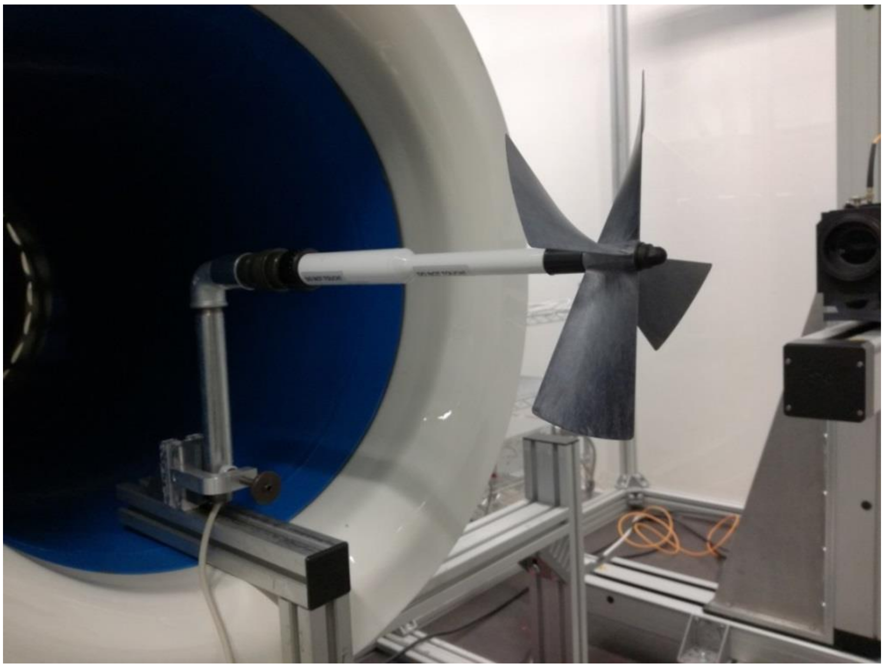

Fig. 10 Installation of the anemometer RM Young in the wind tunnel of CMI

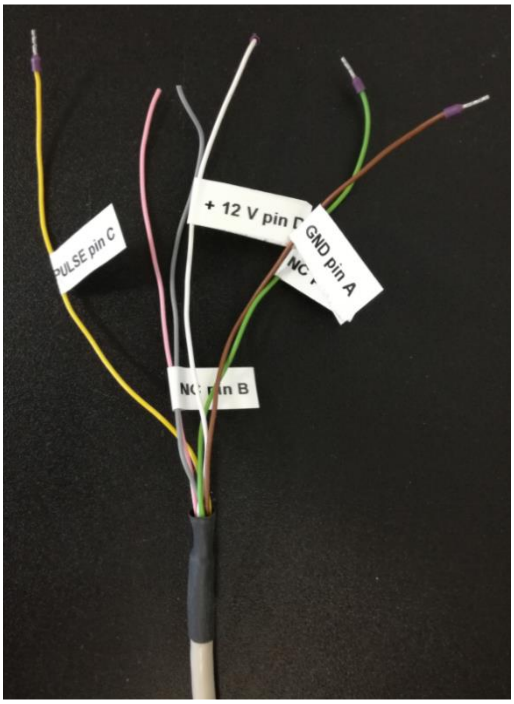

Fig. 11 Wires of the anemometer RM Young

Fig. 12 Set of ¾” pipes and connections

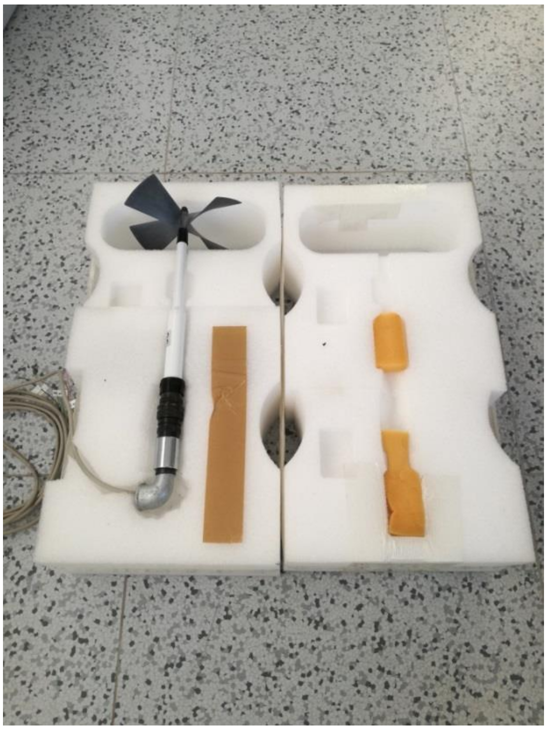

Fig. 13 Packing of the anemometer RM Young for transport

Cup anemometer Vaisala WAA151

Basic parameters:

Range: (0.4 – 75) m/s
Dimensions:
  rotor diameter (2 x distance from axis to outer edge of a cup): 18.2 cm
  cup diameter: 5.4 cm
  height from bottom to the top of the cups: 24.5 cm
Velocity indication: frequency output with conversion v (m/s) = 0.1007 x f (Hz) + 0.3278
Serial number: N3749498

Mounting in a wind tunnel:

The bottom side of the anemometer is shown in fig. 15 left. The package contains a plastic flange which can be attached to the bottom of the anemometer by three screws (fig. 15 right). This part ends with a ¾” female screw thread where a pipe can be connected. The same set of pipes as for the anemometer RM Young is then used for mounting (fig. 12).

Electric connection:

The cable (length 80 cm) which can be connected to the anemometer contains 6 wires (fig. 16). We need only 3 of them:

- red: power supply (9.5 – 15.5)V DC
- blue: ground (0 V)
- green: frequency output (rectangular signal)

To connect the meter it is therefore necessary to have the DC power supply source and a frequency meter with metrological traceability (e.g. multimeter or oscilloscope). The red wire is connected to (+) of the source, the blue wire to (–) of the source and to the low input of the frequency meter and the green wire to the high input of the frequency meter.

Packing for transport:

The anemometer Vaisala is transported in the box shown in fig. 17. The box is tightly inserted into the large aluminium case – package no. 1. Please do not remove the box from the aluminium case – just open the box inside the case, remove the top part of the foam protection and take out the anemometer. The cup wheel must not be disassembled from the anemometer during the project.

Fig. 14 Anemometer Vaisala WAA151

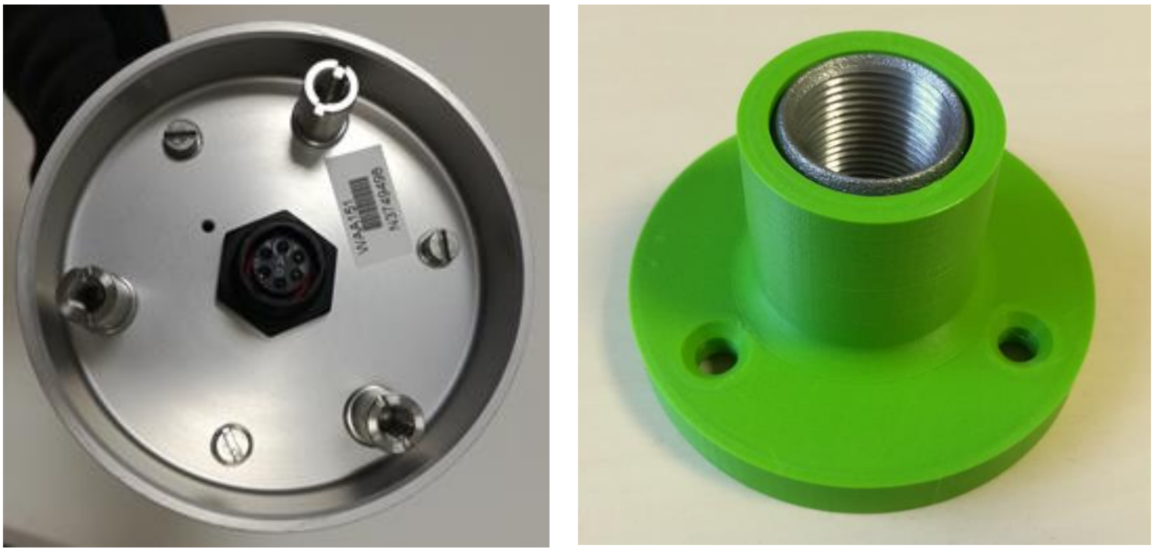

Fig. 15 Anemometer bottom and the connecting flange to a ¾” pipe thread

Fig. 16 Cable for the anemometer Vaisala

Fig. 17 Box for the anemometer Vaisala

Cup anemometer Thies First Class Advanced type 4.3351.10.000

The anemometer was provided by Deutsche WindGuard.

Basic parameters:

Range: (0.3 – 75) m/s; The meter must not be exposed to velocities higher than 20 m/s!
Dimensions: see fig. 19
Velocity indication: frequency output with conversion v (m/s) = 0.0462 x f (Hz) + 0.21
Serial number: 0504057

Mounting in a wind tunnel:

The bottom side of the anemometer is shown in fig. 18 right. A 1” water pipe (outside diameter 34 mm) can be inserted into the bottom and fixed by two screws from side. The package contains two 1” pipes with lengths of 25 cm and 15 cm with screw thread just on one side – the side without the screw thread should be inserted into the meter bottom. There is one more 30 cm long pipe with screw threads on both sides which can be used for prolongation together with a 1” connection (also included in the package). The package contains also a flange which can be screwed to the 1” pipe and fixed to a construction. All the parts are shown in figure 20.

Electric connection:

The cable (length 5 m) with connector to the Thies anemometer (fig. 21) contains 3 wires:

- white: power supply +12V DC (3.3 V – 48 V according to the manual)
- brown: ground (0 V)
- green: frequency output (rectangular signal with amplitude just below the power supply voltage and with a minimum just above 0 V)

To connect the meter it is therefore necessary to have the DC power supply source and a frequency meter with metrological traceability (e.g. multimeter or oscilloscope). The white wire is connected to (+) of the source, the brown wire to (–) of the source and to the low input of the frequency meter and the green wire to the high input of the frequency meter.

Packing for transport:

The meter is transported in a box with foam protection (fig. 22) inside the package no. 2.

Fig. 18 Anemometer Thies First Class Advanced

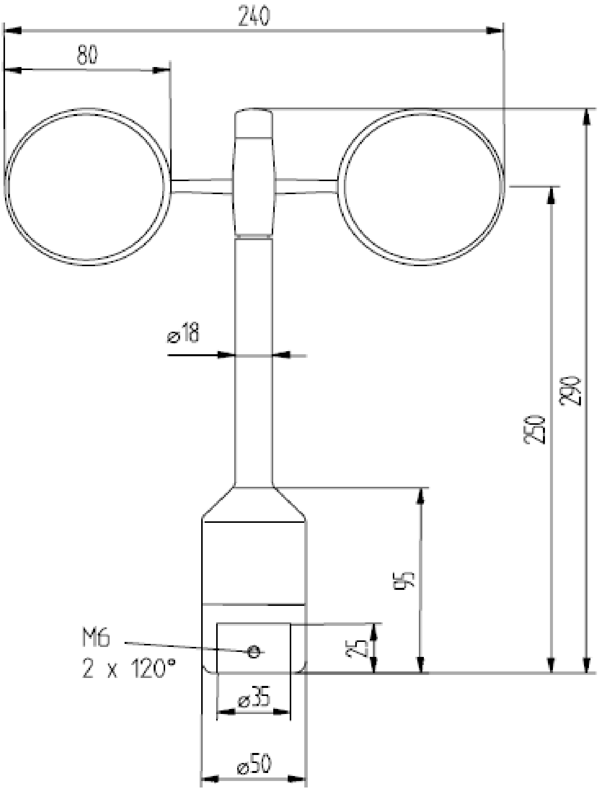

Fig. 19 Anemometer Thies First Class Advanced – dimensions

Fig. 20 Set of 1” pipes and connections for installation of the anemometer Thies

Fig. 21 The cable for the anemometer Thies

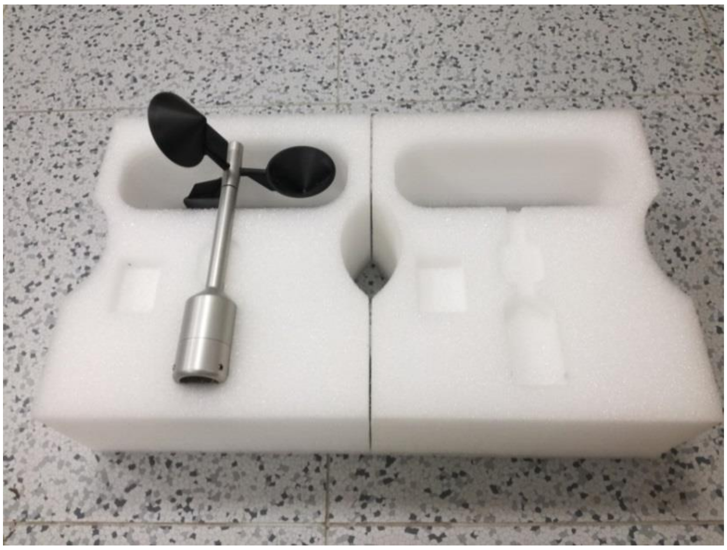

Fig. 22 The foam case for the anemometer Thies

Thermal anemometer Airflow TA440

Basic parameters:

Range: (0 – 30) m/s
Dimensions:
  diameter of the probe tip: 7 mm
  length of the telescopic rod: up to 1 m
Velocity indication: reading from the display
Resolution: 0.01 m/s
Serial number: TA4401237001

Mounting in a wind tunnel and settings:

The first part of the telescope must be pulled out fully since it contains the velocity, temperature and humidity sensors (fig. 23). All sensors must be exposed to the flow to obtain the correct velocity reading. Moreover, the actual barometric pressure must be inserted into the meter since the meter does not contain the pressure sensor and the value is needed for the correct velocity reading.
To set the barometric pressure value:

- go to MENU by pressing the middle button in the upper row
- select “Baro Press”
- set the actual barometric pressure in your lab with the buttons with arrows
- confirm with the middle “enter” button
- press ESC to go back for the velocity reading

Other settings must remain unchanged.
The anemometer is installed with the orientation dimple (see fig. 23) facing upstream.
The telescope can be fixed to a construction outside the stream using e.g. a holder as in the fig. 24.

Packing for transport:

The anemometer is transported in a case as shown in fig. 25 inside the package no. 1.

Fig. 23 The end-part of the anemometer Airflow containing the velocity, temperature and humidity sensors

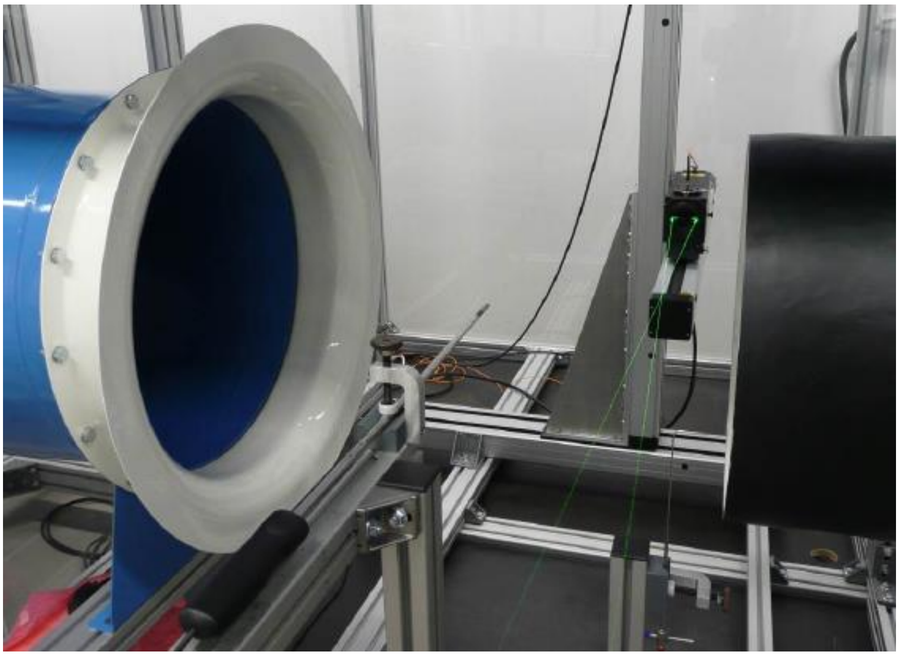

Fig. 24 Installation of the anemometer Airflow in the wind tunnel of CMI

Fig. 25 The transportation case for the anemometer Airflow

4 Overview of the participating wind tunnels

In the table 2 below there is a list of the participating wind tunnels ordered by size and the corresponding blockage ratio of the used anemometers (except the thermal one).

lab	**wind tunnel type**	**meas. section type**	**nozzle shape**	**nozzle diameter /width**	**blockage vane 8.5 cm**	**blockage vane 10.8 cm**	**blockage vane 20 cm**	**blockage cup 18.2cm**	**blockage cup 24 cm**
open measuring section or box									
TCUT	open	box	circular	15.2 cm	31 %	50 %	x	x	x
WE	closed	open	circular	18 cm	22 %	36 %	x	36 % (x?)	x
	closed	open	circular	25.5 cm	11 %	18 %	61 % (x?)	18 %	35 % (x?)
E+E	closed	open	circular	25.5 cm	11 %	18 %	61 % (x?)	18 %	35 % (x?)
UME	open	box	circular	31.5 cm	7.3 %	12 %	40 %	12 %	24 %
PTB	closed	open	circular	32 cm	7.1 %	11 %	39 %	11 %	22 %
LEI	closed	box	circular	40 cm	4.5 %	7.3 %	25 %	7.2 %	14 %
CMI	closed	open	circular	45 cm	3.6 %	5.8 %	20 %	5.7 %	11 %
WE	open	box	circular	60 cm	2.0 %	3.2 %	11 %	3.2 %	6.3 %
	open	box	circular	80 cm	1.1 %	1.8 %	6.3 %	1.8 %	3.5 %
DWG	closed	open	square	100 cm	0.57 %	0.92 %	3.1 %	0.90 %	1.8 %
closed measuring section									
CETIAT	closed	closed	square	50 cm	2.3 %	3.7 %	13 %	3.6 %	7.1 %
METAS	closed	closed	rect.	74cmx49cm	1.6 %	2.5 %	8.7 %	2.5 %	4.9 %

Tab. 2 Overview of the participating wind tunnels

5 Measurement procedure

The meters should be temperature stabilised to the laboratory temperature at least for three hours before the start of the measurement.

If possible the ambient conditions should be kept in the following ranges:
temperature = (19 – 24) °C
relative humidity = (30 – 60) %

Check the level of batteries if used.

The anemometers should be calibrated according to the standard procedure of each lab. The calibration points are given in table 3 below. The calibration velocities are the velocities *indicated by the meter under test* (not by the reference), i.e. the velocity in a wind tunnel should be set in a way that the meter under test indicates values as near as possible to the values prescribed below in the table 3.

The velocities must be set starting from the lowest one and increasing to the highest one in order to avoid the effect of the force acting to the propeller for high velocities to the anemometer indication at low velocities shortly afterwards.

For each anemometer and each velocity point at least 10 repetitions of the velocity measurement will be performed in order to evaluate the repeatability of the measurement. Each repetition will be a 30 s average of the velocity reading with sampling rate at least 10 immediate readings per 30 s. It is possible (especially for the anemometers with display) to read the immediate readings directly from the display.

In ideal case a reference meter should be placed to an area where the air velocity gradient due to the installation of the meter under test is negligible. However, it may not be possible for the large meters. For example of velocity fields in front of some of the anemometers used in this project in the wind tunnel of CMI see the Appendix.

anemometer	**calibration points (m/s)**	**calibration points (Hz)**	**conversion *v* (m/s) =**
Vane Testo	0.5; 2; 5; 8; 12		
Vane Schiltknecht	0.5; 2; 5; 8; 12; 20		
Vane RM Young	0.5 2 5 8 12 20	16.67 66.67 166.67 266.67 400.00 666.67	0.03 x *f* (Hz)
Cup Vaisala	1 2 5 8 12 20	1.71 16.61 46.40 76.19 115.91 195.35	0.1007 x *f* (Hz) + 0.3278
Cup Thies	0.5 2 5 8 12 20	6.28 38.74 103.68 168.61 255.19 428.35	0.0462 x *f* (Hz) + 0.21
Thermal Airflow	0.5; 2; 5; 8; 12; 20		

Tab. 3 Calibration points

6 Data supplied to the pilot laboratory

The following data should be provided to the pilot laboratory (CMI) by email (jgersl@cmi.cz) not later than one month after finishing the measurements.

Measurement error data

- indication of the meter under test (MUT) in m/s or Hz (average from the 10 repetitions)
- indication of the reference (average from the 10 repetitions)
- corrections applied to the indication of MUT or the reference (e.g. a correction for the blockage effect (if applied); a correction of a velocity difference in position of the MUT and the reference (if applied); ...)
- error of the MUT as calculated by a procedure of the particular lab

Uncertainty data

- uncertainty budget – list of all considered uncertainty components and their values, especially uncertainty related to the blockage effect - if applied (see the section 7 below)
- the total combined expanded (k = 2) uncertainty of the meter error

Ambient conditions

- temperature
- barometric pressure
- humidity

Geometry data

- geometry of the measuring section (shape, dimensions, walls, ...)
- position of the meter under test
- position of the reference
- parameters of the reference (type, size (if not LDA))

7 List of the principal components of the uncertainty budget

- type A uncertainties of the meter under test (MUT) and the reference
- resolution of the MUT and the reference
- uncertainty of the calibration factor or error of the reference
- uncertainty due to the blockage effect (if applied)
- uncertainty of the correction of a velocity difference in position of the MUT and the reference
- uncertainty due to non-homogeneity of the velocity field in the area occupied by the MUT
- uncertainties related to the installation angles of the MUT and the reference
- uncertainty of the frequency meter (if used)
- uncertainty of the barometric pressure (for the thermal anemometer)

8 Principle of evaluation of the results

The factor α as defined in the introduction will be estimated experimentally including its uncertainty with the value of $v_\infty(v_M)$ given by the reference velocity value of the largest wind tunnel in the project (Deutsche WindGuard) where the blockage effect can be considered as almost negligible.

The factor $\alpha(v_M)$ will be determined for all wind tunnels and all anemometers in the project and the velocities v_M given in the table 3. Trends in the dependencies of α on the blockage ratio and on the velocity v_M will be investigated.

The data from the small thermal anemometer will be used to correct for the wind tunnel differences caused by other effects than the blockage effect.

Additional measurements at CMI will be defined and performed to test the theoretical blockage effect models and their applicability to the determination of the factor α.

Appendix

The velocity fields below were obtained by measurement with LDA in 2D grids of points shown in fig. 26 and 29. One square of the grid has dimensions 2 cm x 2 cm. The point 0 is 2.5 cm from the nozzle of the wind tunnel. Vertical plane in the centre of the measuring section was used which approximately represents the 3D velocity field because of the axial symmetry of the configuration (vane anemometers only). The axial velocity component was measured only.

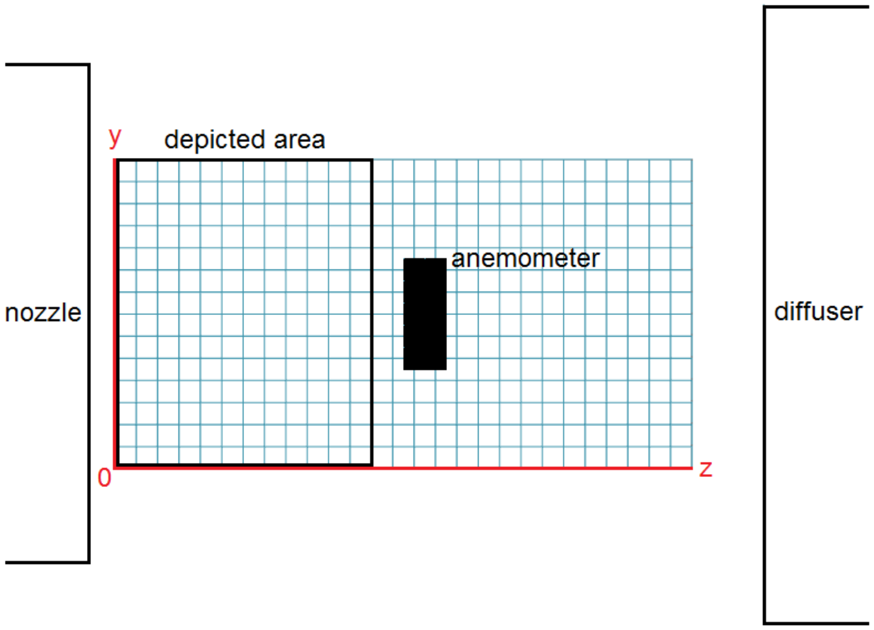

Fig. 26 Grid for the velocity field measurement - Testo anemometer

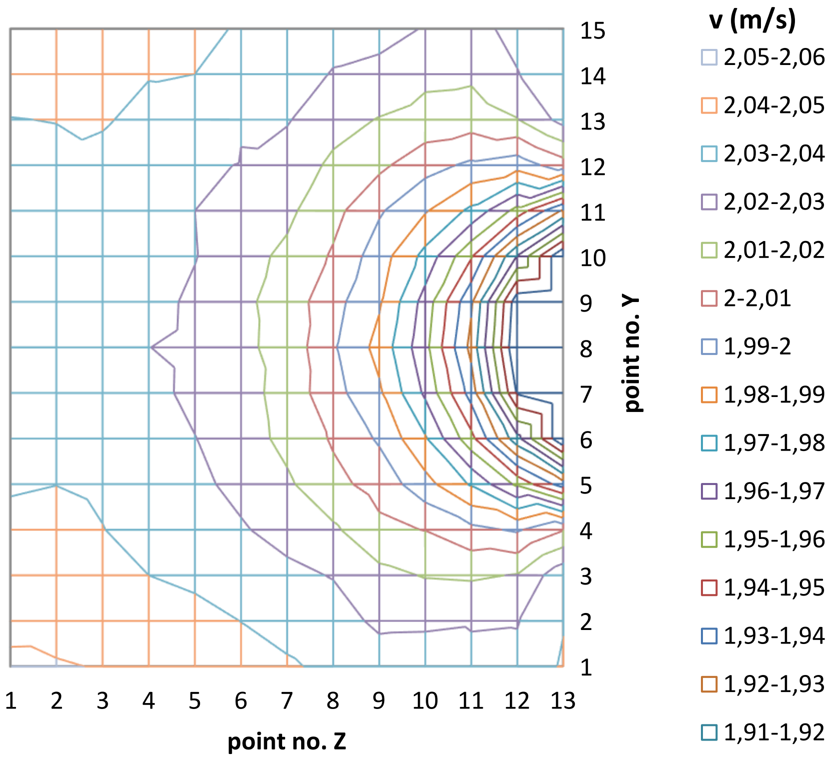

Fig. 27 Velocity field in front of the Testo anemometer – 2 m/s

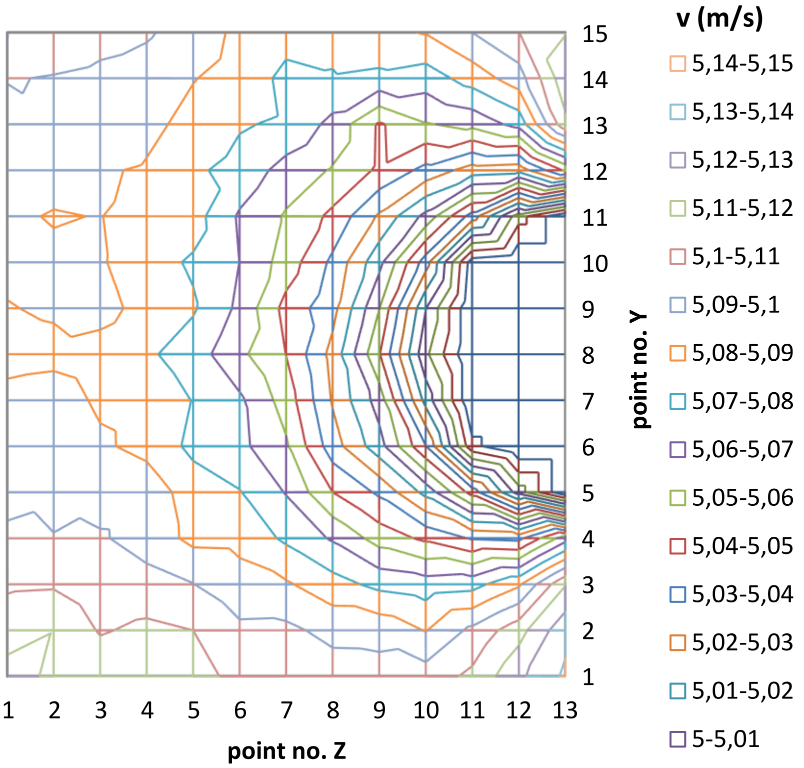

Fig. 28 Velocity field in front of the Testo anemometer – 5 m/s

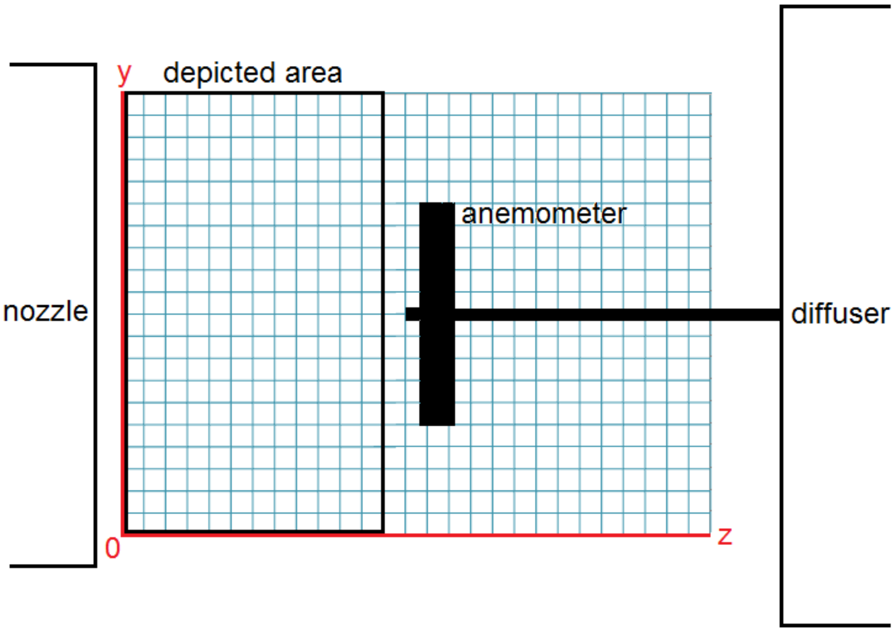

Fig. 29 Grid for the velocity field measurement - RM Young anemometer

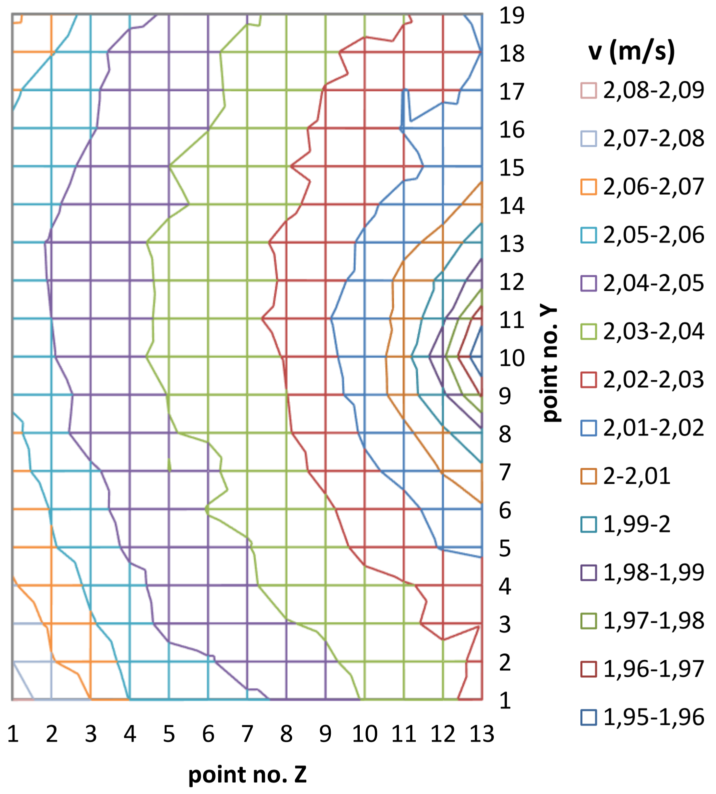

Fig. 30 Velocity field in front of the RM Young anemometer – 2 m/s

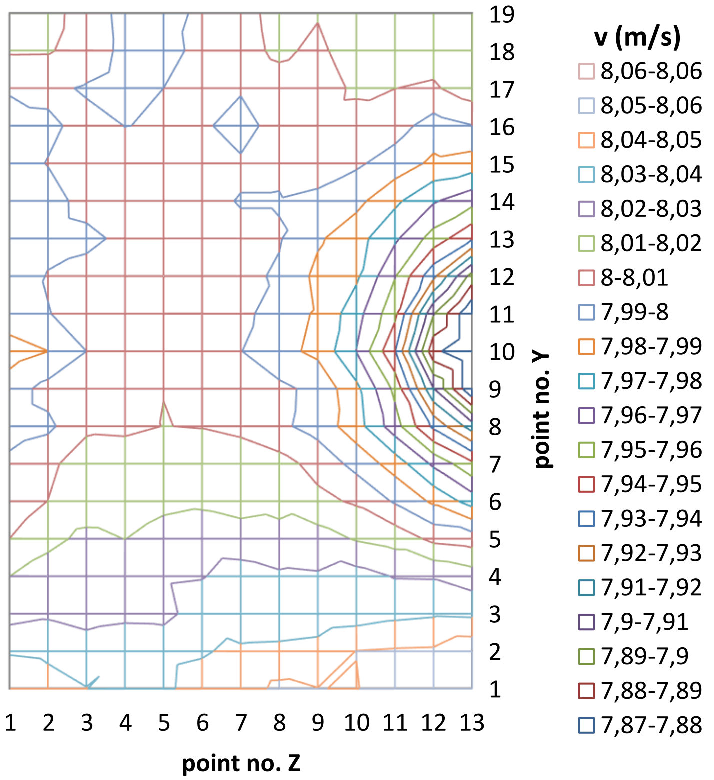

Fig. 31 Velocity field in front of the RM Young anemometer – 8 m/s