HardwareX 15 (2023) e00440

Contents lists available at ScienceDirect

HardwareX

journal homepage: www.elsevier.com/locate/ohx

Setup of a 3D printed wind tunnel: Application for calibrating bi-directional velocity probes used in fire engineering applications

Jan Smolka [a,*], Kamila Kempná [a], Petr Kučera [a], Kamil Kempný [b], Eleni Asimakopoulou [c], Pavel Danihelka [d]

[a] VSB - Technical University of Ostrava, Faculty of Safety Engineering, Lumirova 630/13, Ostrava – Vyskovice 700 30, Czech Republic
[b] Majaczech, z.s., Bile Policany 1, 544 52, Czech Republic
[c] University of Central Lancashire, School of Engineering, Fylde Rd, Preston PR1 2HE, UK
[d] Occupational Safety Research Institute, Jeruzalemska 1283/9, Praha 1 – Nove Mesto, 110 00, Czech Republic

A R T I C L E I N F O

Article history:
Received 15 January 2023
Received in revised form 25 May 2023
Accepted 7 June 2023

Keywords:
Bi-Directional Velocity Probe
Velocity
3D printing
Wind Tunnel
Fire Engineering
Arduino

A B S T R A C T

The research presented here focuses on the development of a 3D printed wind tunnel and the relevant equipment to be used for calibrating bi-directional velocity probes (BDVP). BDVP are equipment to be used for measuring velocity flow by determining the pressure difference of hot gases generated during fires. The manufactured probes require calibration to determine the calibration factor. The calibration is usually performed in wind tunnels which can be difficult to access due to costs, complexity and the various pieces of equipment required. The aim of the current study is to develop and assemble an inexpensive and easy-to-build bench-scale wind tunnel, with a data-logging system and fan control functionalities for fast and effective calibration of BDVP. A 3D printer with a PET-G filament is used, able to produce parts for the wind tunnel system which are durable and easy to handle and assemble. The system additionally includes an Arduino-based measuring unit with a hot-wire anemometer and temperature correction: Rev. P. This takes precise measurements; continuously logging data on a computer through a USB interface and capable of saving data on an SD card. This design provides users with parameters of velocity flow up to 4 m/s with standard deviation of 1.2 % and turbulence intensity of 1 %. The main advantages of this wind tunnel are its simplicity to build and portability.

* Corresponding author.
E-mail address: jan.smolka@majaczech.cz (J. Smolka).
@@majaczech_cz (J. Smolka)

https://doi.org/10.1016/j.ohx.2023.e00440
2468-0672/

Specifications table

Hardware name	*3D printed Wind Tunnel for Fire Engineering Applications*
Subject area	Educational tools and open-source alternatives to existing infrastructure
Hardware type	Measuring physical properties and in-lab sensors
Closest commercial analog	*Wind tunnel*
Open-source license	*CC BY-SA*
Cost of hardware	*274 €*
Source file repository	*https://doi.org/10.5281/zenodo.7863983*
OSHWA certification UID	*CZ000006*

Hardware in context

One of the important parameters measured in fire engineering is pressure difference, this is used to calculate the velocity flow of hot gases and gas concentrations. The measurement of these parameters is complicated due to the high temperatures which can reach more than 1000 °C. For measurements under these conditions, metal pitot tubes are used to measure uni-directional flows and bi-directional velocity probes (BDVP) for bi-directional flows. The pressure differences are usually very low, which requires the use of low-pressure transducers. Although BDVP are easy to use, it is necessary for them to be calibrated in wind tunnels to determine the calibration factor which ensures precise measurements and results [1]. In the current work Setra C264 differential pressure transducers were used, having maximal reading pressure +/- 0.25 WC or +/- 62.27 Pa [1,2]. The relevant gas velocity flow is determined by Equation 1 [1,2],

$$v = \frac{1}{k_p}\sqrt{\frac{2\Delta p}{\rho}} \tag{1}$$

where k_p is the calibration factor [-], Δp is pressure difference [Pa] and ρ is density of measured gas [kg/m^3]. The density of gas can be determined in relation to temperature using Equation 2 [1,2].

$$\rho = \frac{352.6}{T} \tag{2}$$

Applications of BDVP

An example of BDVP measuring gas flows during a fire scenario is shown in Fig. 1. BDVP are positioned at different heights along the centerline of an opening during a compartment fire, measuring the relative pressure. The aim is to determine the neutral plane that marks the level below which air will be drawn into the fire compartment, and above which combustion gases will flow out of the compartment. The right-hand side of Fig. 1 depicts the determination of the neutral plane.

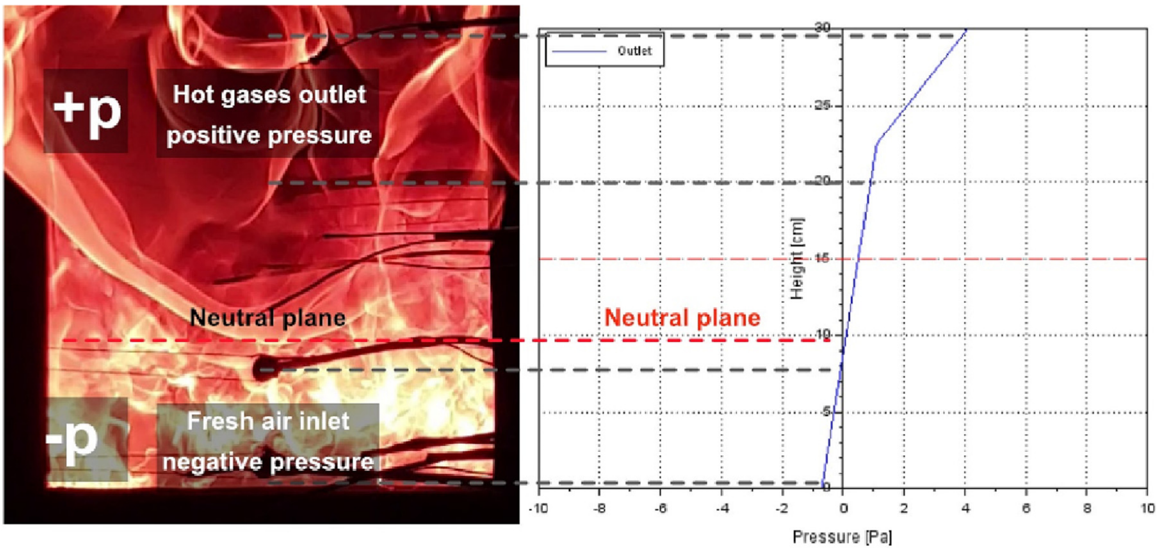

Fig. 1. Location of BDVP in opening (left) and measured pressure difference for determination of the neutral plane and pressure difference below and above neutral plane (right).

Another application of BDVP is measuring the volumetric flow of hot gas extraction for determination of the heat release rate using oxygen calorimetry [1]. The estimation is performed by measuring volumetric flow of hot gases and combustion gases e.g., O_2, CO_2 and CO. Based on the oxygen consumed by the fire and the generated CO and CO_2, heat released from fire can be calculated for potential determination of combustion efficiency. The implementation in the hot gas extraction system is depicted in Fig. 2.

The practical application, as shown in Fig. 2, demonstrates that 4 m/s maximal velocity in the wind tunnel is sufficient to calibrate the BDVP. For further application in areas with higher velocity flows it is necessary to use a stronger fan in the wind tunnel.

The aim of the current work is to develop a wind tunnel system to calibrate BDVP to be used in fire experiments with forced draught wind velocity up to 3.5 m/s. A fan is selected for the purpose with the ability to deliver velocity flows up to 4 m/s.

Wind tunnel system

The lack of space in a wind tunnel can make it difficult to access and calibrate the BDVP. This wind tunnel is specifically designed for BDVP calibration and has the advantages of simplicity of use, ease of construction and meets the requirements for fast and efficient calibration. In addition, data logging of the measured data for further post-processing and analysis, including data backup, facilitates the necessary portability of the equipment without the need for special space in the laboratories.

To achieve the previously mentioned benefits, all the parts are designed to guarantee easy assembly; and an Arduino is used as the basic data logging and calculating unit. Measured data is continuously recorded on a PC via USB and the measured velocity data is continuously displayed on the LCD display. There is also an option to store the data on an SD card. Major benefits of this equipment include its low cost; light weight; compact size; simplicity of construction and transport. It can be easily adapted for other applications with no need to use expensive equipment.

Hardware description

The current small-scale, low-speed wind tunnel setup consists of three units: the wind tunnel, the control unit and the measuring unit connected to the PC which provides appropriate airflow velocity up to 5 m/s. The wind tunnel unit parts are printed using a 3D PRUSA MK3S Printer with a 0.3 mm resolution. PET-G was selected as a material for its superior mechanical properties that include increased durability, strength, and ease in further manufacturing stages, e.g., drilling, gluing, cutting. The wind tunnel unit is divided and printed in parts according to the requirements of the 3D printer. After printing, parts are glued and sealed using silicone. 3D printing is also suitable for more complicated and sophisticated parts, e.g., the diffuser of these wind tunnels which would have been difficult to build under conventional construction techniques.

The electronic circuit includes components which are easily accessible in local shops or in e-shops. The only part that is difficult to acquire is the velocity sensor Rev. P; this can be ordered from the US or the UK. The measuring unit is based on

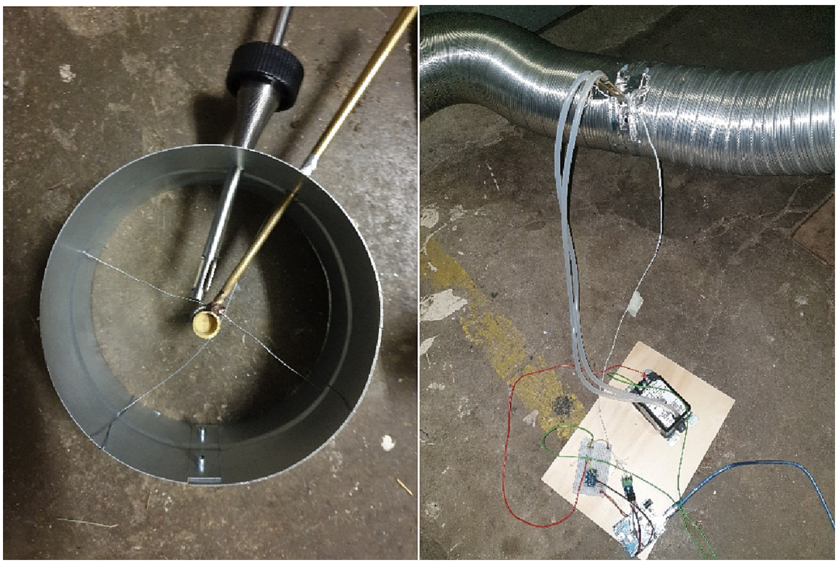

Fig. 2. Application of BDVP in combustion gases exhaust for measuring volumetric flow of hot gases to calculate heat release rate (HRR) by oxygen calorimetry.

Arduino UNO with an LCD 16x2 monochromatic display for visualization of current velocity and Datalogging Shield for storing data on an SD card without connecting to a PC. Arduino is popular in prototyping for its user-friendly application, large community support and large number of tutorials and source codes determining it as the best solution for special application in fire engineering. The Arduino provides the means of connecting a measuring unit to a PC through a USB port and storing data online on the Arduino's Serial Monitor.

This wind tunnel is not to be placed near or exposed to the fire. This equipment is intended to be used for the calibration of BDVP for use in fire engineering.

Advantages and disadvantages of this equipment

This hardware is useful for low-speed and low-cost applications. The wind tunnel is easy to use and simple to assemble. Due to its small size and mobility, it can work in the following applications:

- calibration of bi-directional velocity probes and pressure sensors
- aerodynamics research on 3D printed models using a higher flow velocity fan
- teaching wind tunnel applications.

The main advantage of this unit is its price, portability, and size. The fact that it can be printed facilitates reproduction and construction almost anywhere without space requirements or expensive equipment. The unit can be easily upgraded with 3D modelling software, customized for specific needs including size, speed, robustness, etc.

The need for hands-on skills, including operating a 3D printer and 3D modelling software, could be considered a drawback. In addition, machinery, such as a drill, is required and electrical engineering knowledge or supervision in this area is necessary. Compared to commercial units, this unit requires testing and basic knowledge of calibration. Since this unit is designed for low flow velocities, it has limited intensity compared to commercial units.

The 3D printed wind tunnel can be considered less robust, than other do-it-yourself units made of, for example, wood or steel plates [3,4]. However, the construction of a wind tunnel from these other materials may require a workshop, expensive machine tools, etc., and the built unit may be heavier and require more storage space.

The dimensions of this wind tunnel can be used for small-scale applications, such as BDVP calibration, small-scale wind models, vehicles, etc.

Design files summary

Design file name	File type	Open-Source license	Location of the file
Testing-Chamber	*.stl*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Testing-Chamber	*.3mf*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Side-Door	*.stl*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Contraction	*.stl*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Contraction	*.3mf*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Diffuser	*.stl*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Diffuser	*.3mf*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Settling	*.stl*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Settling	*.3mf*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Top-Bottom-Case	*.stl*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Front-Back-Panels	*.stl*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Control-Unit-Scheme	*.png*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Power-Supply-Scheme	*.png*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
3D-Model-WT	*.png*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*
Wind_Tunnel.ino	*.ino*	CC-BY-SA	*https://doi.org/10.5281/zenodo.7863983*

Settling Chamber.stl /.3mf –.stl file provides original 3D model for further improvements,.3mf file provides cut model in 8 printable parts on Prusa MK3s prepared for slicing in PrusaSlicer. It is recommended to print parts with brim.

Contraction.stl /.3mf –.stl file provides original 3D model for further improvements,.3mf file provides cut model in 5 printable parts on Prusa MK3s prepared for slicing in PrusaSlicer. It is recommended to print parts with brim.

Testing-Chamber.stl /.3mf –.stl file provides original 3D model for further improvements,.3mf file provides cut model in 2 printable parts on Prusa MK3s prepared for slicing in PrusaSlicer. It is recommended to print parts with brim.

First Diffuser.stl /.3mf –.stl file provides the original 3D model for further improvements; the.3mf file provides a cut model in 3 printable parts on Prusa MK3s prepared for slicing in PrusaSlicer. It is recommended to print parts with brim.
Side-Door.stl – 3D model of side door of Testing Chamber.
Top-Bottom-Case.stl – Improved case parts (top and bottom case) from [5] for measuring unit.
Front-Back-Panels.stl – Improved case parts (front and rear panels) from [5] for measuring unit.
Control-Unit-Scheme.png – basic connection scheme of Arduino UNO, LCD Display 16x2 and Rev. P circuit.
Power-Supply-Scheme.png – basic connection scheme of fan power supply and velocity control with PWM regulator.
3D-Model-WT.png – Image of 3D model assembled wind tunnel and description of individual parts.
Wind_Tunnel.ino – Arduino UNO code for control unit (improved code from [6]).

Bill of materials summary

The Bill of materials can be downloaded from the repository https://doi.org/10.5281/zenodo.7863983.

Bill of materials

Designator	Component	Number	Cost per unit [€]	Total cost [€]	Source of materials	Material type
Arduino UNO	Arduino UNO	1	24.00	24.00	Arduino	Electronics
LCD Display	Standard LCD 16x2 + extras– white on blue	1	9.18	9.18	Adafruit	Electronics
i2c backpack	i2c / SPI character LCD backpack	1	9.18	9.18	Adafruit	Electronics
12 V DC power adapter	12 V DC 1000 mA (1 A) regulated switching power adapter – UL listed	1	8.25	8.25	Adafruit	Electronics
Rev. P	Rev. P – Hot-wire anemometer	1	39.95	39.95	The JeeLabs Shop	Electronics
PWM regulator control	Fan Regulator – PWM regulator 6–28 V 3 A	1	3.02	3.02	Dratek	Electronics
Fan	Fan – Ventilator SUNON PMD2412PMB1-A(2).GN	1	20.16	20.16	GM electronic	Electronics
24 V DC power supply	Mean Well, 15 W Embedded Switch Mode Power Supply SMPS, 24 V DC, Enclosed	1	16.91	16.91	RS Components	Electronics
Filament	Filament Prusament PET-G	2	29.99	59.98	Prusa	PET-G
M3 screws	Uxcell a15070200ux0058 M3 × 12 mm 304 Stainless Steel Phillips Head Screws (Pack of 60)	1	9.14	9.14	Amazon	Steel
M3 nuts	M3 Full Nut (50 Pack) 3 mm A2 Stainless Steel Hex Hexagon Nuts	1	4.29	4.29	Amazon	Steel
Transparent shield	Rayher 3873600 Transparent Film PET, 30 × 40 cm, Thickness 0.4 mm, Windmill Film, Mobile Film, Sturdy, Transparent Film for Crafts	1	3.04	3.04	Amazon	PET-G
Wires	YV Gear Wire Assortment, 0.50 mm, copper Tinned, 2x 25 m Reel Red/Black	1	10.12	10.12	Amazon	Wires
IEC Socket	IEC Male Chassis Power Plug with Fuseholder	1	2.42	2.42	GM electronic	Electronics
Fuse	Fuse 5x20 – 1.6 A	1	0.21	0.21	GM electronic	Electronics
Power Switch – Fan	ON - OFF Power Switch MIRS-201A-C3-R/B 230 V	1	1.1	1.1	GM electronic	Electronics
Power cable	PremiumCord Power Cable	1	7.37	7.37	Amazon	Electronics
Solder wire	Solder Wire	1	10.15	10.15	Amazon	Solder

(*continued on next page*)

(*continued*)

Designator	Component	Number	Cost per unit [€]	Total cost [€]	Source of materials	Material type
Jumper	Premium Female/Female Jumper Wires – 20 × 6″ (150 mm)	1	1.95	1.95	Adafruit	Wires
Jumper	Premium Male/Male Jumper Wires – 20 × 6″ (150 mm	1	1.95	1.95	Adafruit	Wires
Jumper	Premium Female/Female Jumper Wires – 20 × 6″ (150 mm)	1	1.95	1.95	Adafruit	Wires
Mesh	Onpira Fly Net / Fly Screen 1 m / Aluminium	1	8.95	8.95	Amazon	Mesh
Screws M2	sourcing map Pack of 50 Self-Tapping Screws Phillips Head 304 Stainless Steel Connection Bolts 2 × 8 mm	1	7.61	7.61	Amazon	Steel
Silicone	Fischer premium construction silicone, 53,090	1	12.9	12.9	Amazon	Silicone

Additional required equipment:

- Soldering station
- Crimping pliers and cable lugs
- Glue gun
- Cartridge gun
- Screwdrivers

Additional required skills:

- Basic practice with soldering
- Electrician knowledge / education

WARNING:

This assembly is made for experienced users. The assembly uses electrical power and equipment and may cause serious damage and injuries or death. FOLLOW SAFETY RECOMMENDATIONS OF MANUFACTURERS and responsible persons with an adequate qualification in electrical engineering.

Build instructions

The construction of the wind tunnel can be divided into three separate parts: the 3D printing and assembly of the wind tunnel; the assembly of the control unit including the fan control and the measurement unit. the third part involves uploading the code in the Arduino.

Wind tunnel assembly

Fig. 3 is a 3D design of the assembled wind tunnel prepared for conversion to.stl file and printed with the 3D printer. As depicted, the wind tunnel consists of the first fan diffuser, the testing chamber, the contraction section, and the settling chamber with dense wire mesh for decreasing airflow turbulence. The Rev. P sensor is placed in the testing chamber containing a transparent side opening for maintenance and easy access.

As mentioned earlier, all sections of the wind tunnel are printed on a 3D printer, but due to their large dimensions it is necessary to separate each section into printable parts which fit the printing area of the printer. All 3D models are compatible with 3D printer Prusa MK3s. Objects larger than the area of Prusa's printer bed are improved and saved in files.3mf compatible with PrusaSlicer software. Fig. 4 shows all printed parts of the wind tunnel that further need to be glued and sealed by transparent sealing silicone.

For the next step, stiffened parts are to be screwed together. Also, all connections between sections should be sealed with silicone to eliminate any leakages which could cause pressure or velocity drop during the measurement. Fig. 5 presents the assembled wind tunnel, and the fan installed.

When all main parts are assembled, dense wire meshes are installed. The wire mesh is 1x1 mm dense and made from aluminum or stainless-steel wire with a diameter of 0.23 mm. The first wire mesh is placed on the inlet to the Settling Chamber, the second wire mesh is placed in the connection between Settling Chamber and Contraction. Placement of the mesh

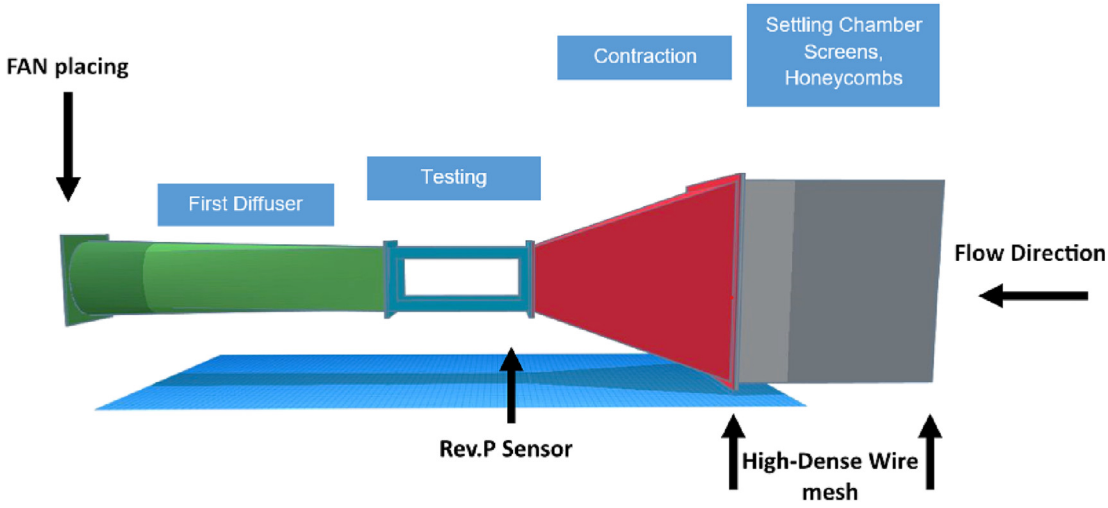

Fig. 3. 3D design of the small-scale 3D printed wind tunnel.

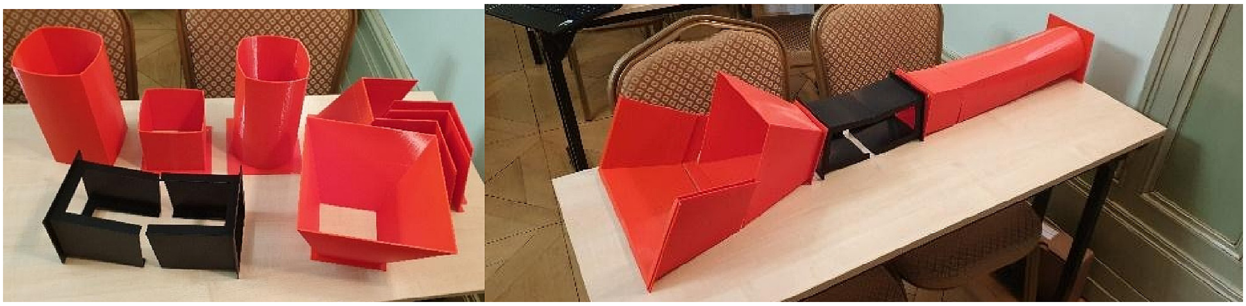

Fig. 4. 3D printed parts of wind tunnel.

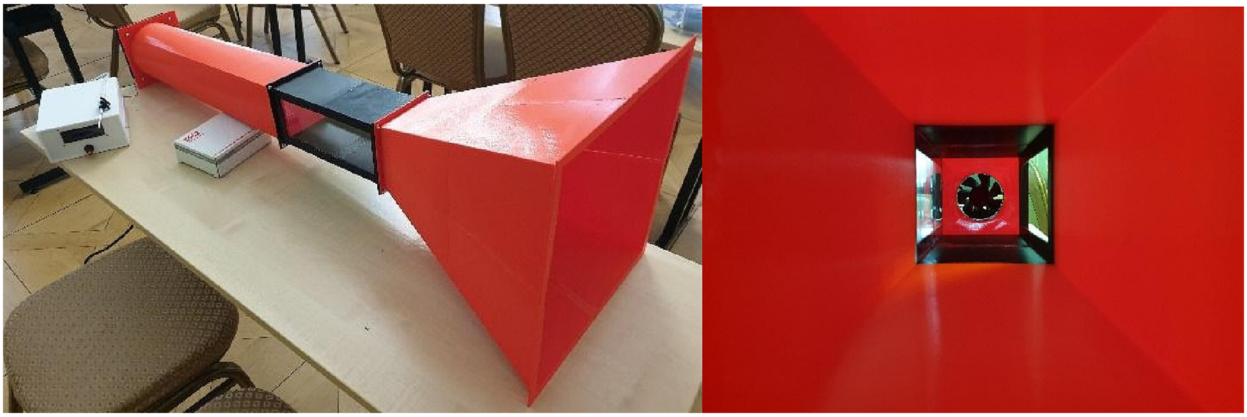

Fig. 5. Assembled and glued wind tunnel.

ensures low turbulence of airflow in the tunnel during measurement. The fan is screwed to the first diffuser. It is important to be aware of the right orientation of the fan. Fig. 6 shows signs located on the side of the fan which specify the direction of airflow. The airflow should be oriented as Fig. 7 represents.

After tunnel assembly, and fan and mesh installation, the Rev. P hot-wire anemometer is placed in the testing section. Location of the sensor and its orientation are illustrated in Fig. 3 and Fig. 7.

Fig. 6. Signs on ventilator specify fan blades rotation and airflow direction [7].

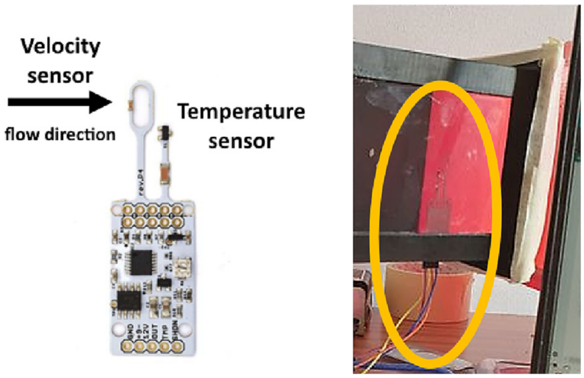

Fig. 7. Rev. P – hot wire anemometer with temperature sensor and its location in the wind tunnel [6,8].

Fig. 7 shows the location of the Rev. P measuring sensor and its orientation. The sensor is glued in the chamber with a glue gun and the connector is left outside of the testing section for connection with wires to the control unit.

Control unit assembly

The control unit consists of a power supply and a microcontroller Arduino UNO which is used for velocity measurement. Two power supply units are required: one is for powering a 24 V fan and another is 12 V for the Arduino, which is required for powering the Rev. P.

Measuring module

Main components for the assembly of the measuring module of the Wind Tunnel are:

- Arduino UNO
- LCD Display
- i2c backpack
- 12 V DC power adapter
- Rev. P
- Jumpers
- Solder Wire

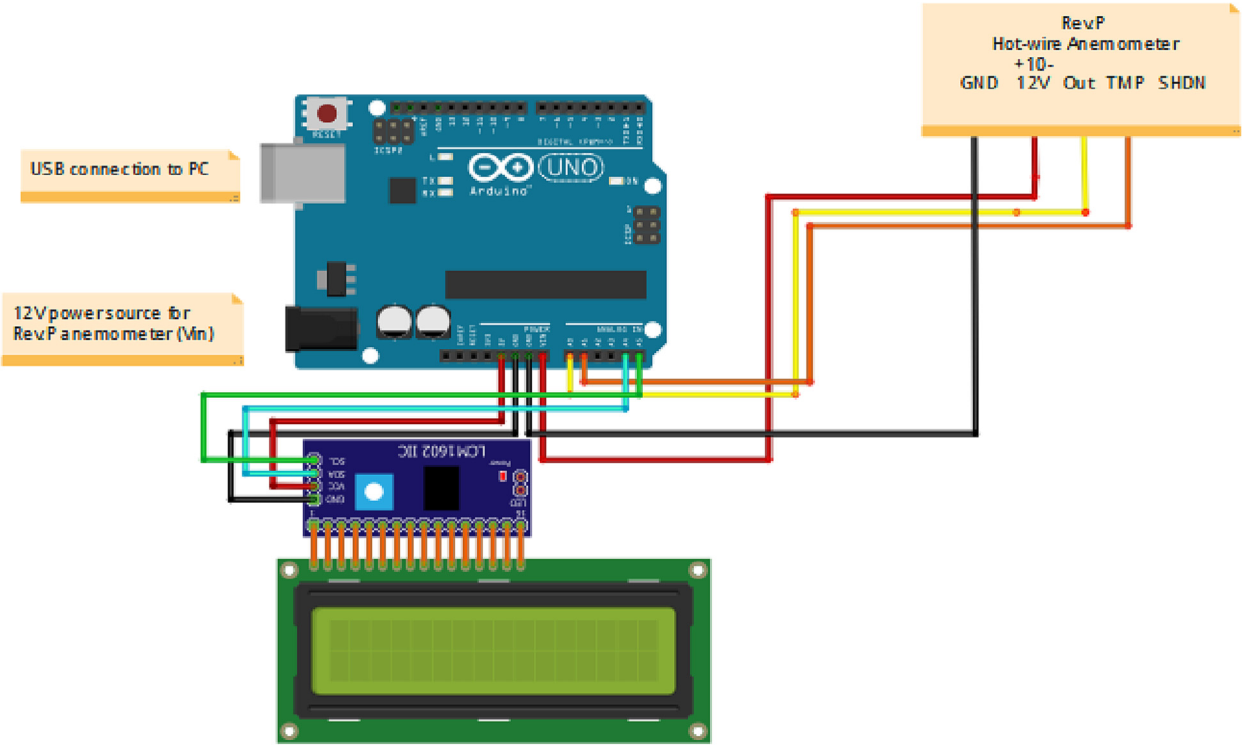

Fig. 8. Connection diagram of measuring module in control unit.

The electronic items are connected by soldering or using jumpers as Fig. 8 demonstrates. Usually, it is necessary to solder an i2c / SPI character LCD backpack and a 16x2 LCD Display. The remaining items can be connected via jumpers.

During this procedure, it is important to follow the manufacturers' instructions and the signs on each piece of equipment (in / out connection, etc.).

The fan is connected to the PWM Regulator control connected to the 24 V DC power supply. The connection is made with wires, using crimping pliers and cable lugs. The 24 V DC power supply is connected to the switch. The switch is then connected to the IEC Socket with fuse protection (Fig. 9).

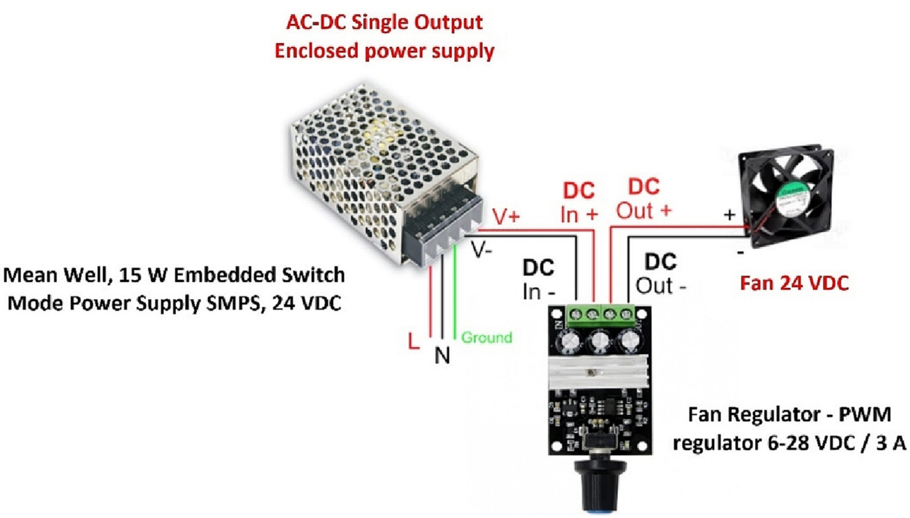

Fig. 9. Connection diagram of fan control in control unit.

WARNING: Be careful and follow the manufacturers' instructions and double check every connection. An incorrect connection can cause serious damage to property, serious injury or death.

Assembly of the control unit

Fig. 10 and Fig. 11 depict the positioning of the electronic parts. All electronic circuit and items are inserted in outer case. The 24 V DC power supply can be fixed to the bottom of the case by a glue gun, as well as an Arduino microcontroller and display.

The complete assembly procedures of 3D printed parts of the control unit [9] and final assembled unit are shown in Fig. 12.

Before measurement can start, it is important to insert the fuse in the fuse holder of the IEC Socket. When assembled, IEC cable to IEC Socket, 12 V DC power adapter and USB cable to Arduino UNO can be connected.

Control software of measuring unit

The code for measuring unit control is Arduino based, which allows starting and measuring through an Arduino IDE. This platform is used also for data reading and plotting through a Serial Monitor. The reading software is adapted Wind Sensor Rev.P Arduino sketch [6]. The improved code is uploaded in the OSF repository, where the link is included in the Design file summary. Main changes of the code included unit conversion and data visualization on the LCD 16x2 display. The sketch code includes conversion of raw data, ADC data regression from which are converted to velocity and temperature. Equation (3) was derived from the regression curve of Rev. P as follows [6]:

$$W = \left[\frac{0.087288(V - V_0)}{3.038517 \cdot T^{0.115157}}\right]^{3.009364} \tag{3}$$

where W is wind speed in $[mi/h]$, V is measured voltage $[V]$, V_0 is voltage for zero velocity $[V]$ and T is temperature $[°C]$.

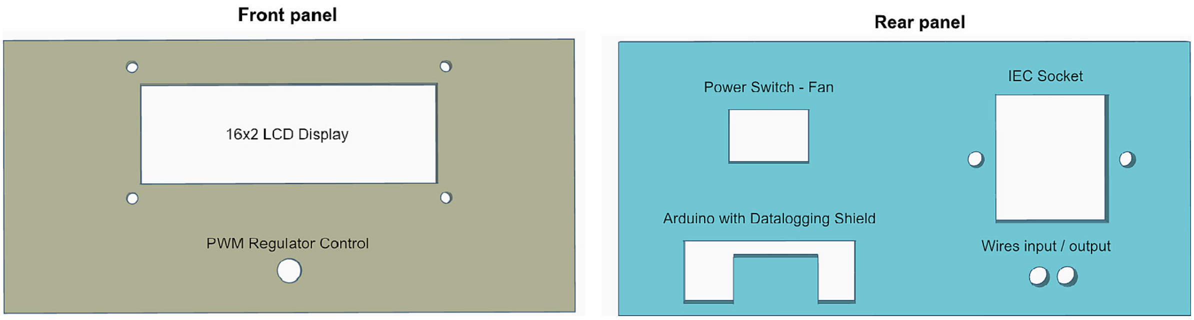

Fig. 10. Location of electronics in the control unit case (Front-Back-Panels.stl).

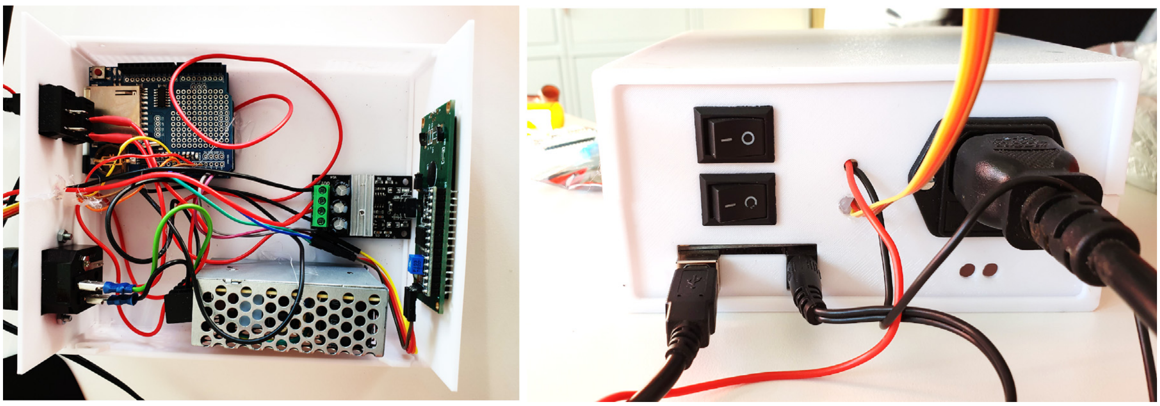

Fig. 11. Final assembly of electronic circuits.

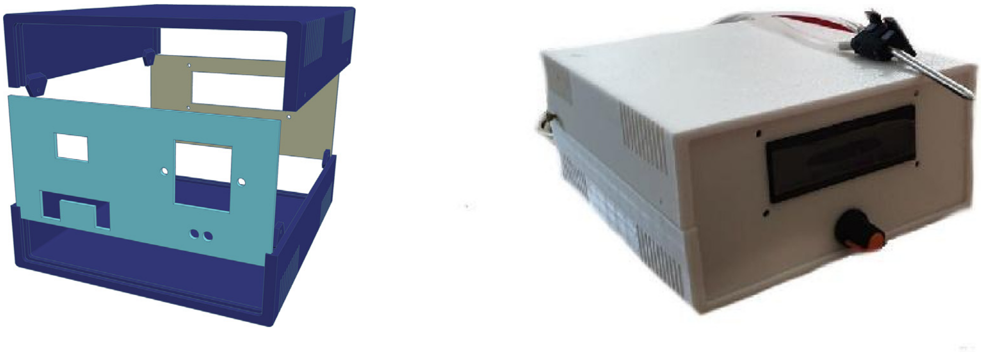

Fig. 12. Assembled control unit (Front-Back-Panels.stl and Top-Bottom-Case.stl).

Operation instructions

Ten main steps need to be followed.

1. Connect the IEC cable to the power supply.
2. Connect 12 VDC adapter to power supply.
3. Start the fan by switching ON-OFF.
4. Start LCD display and verification of velocity flow and ambient temperature (Fig. 13).

At this stage, the wind tunnel can work offline with only an LCD Display without logging data on a PC (see Fig. 13)

1. Regulate fan airflow by PWM regulator.
2. Connect the USB cable to the PC.
3. Start the Wind_Tunnel.ino file in the Arduino app.
4. Select the type of the Arduino board by clicking to *Tools -> Board -> Arduino UNO*
5. Select the port, where the Control Unit is connected, by clicking to *Tools -> Port ->* and select USB port *COM*, where the microcontroller is connected.
6. Start online data logging of the wind tunnel in Serial Monitor by clicking to *Tools -> Serial Monitor* (Fig. 14)
7. Fig. 15 shows the Graphic User Interface of the Serial Monitor. where it is possible to insert a timestamp, auto scroll or clear output. After measurement it is recommended that the user should stop auto scroll, select all data and *Copy – Paste* to spreadsheet file.

Validation and characterization

The wind tunnel provides measurements with reading speeds up to 125 m/s. The operational velocity can be between 0 and 4 m/s. Hot-wire sensor Rev. P, used for measuring velocity flow, is equipped with built-in temperature calibration. The manufacturer used static pressure data from a pitot tube along with humidity and temperature data, for the conversion of pitot tube data to wind velocities. The collected data were set up as a regression to derive an equation that matched the curve of the sensor which is used for measurement [10].

The wind tunnel provides live reading on an LCD Display with background data logging in through the USB port to the Serial Monitor on the PC. Fig. 16 presents the application of a wind tunnel for the calibration of a McCaffrey [1] bi-directional pressure probe.

Fig. 13. Data visualization on LCD Display.

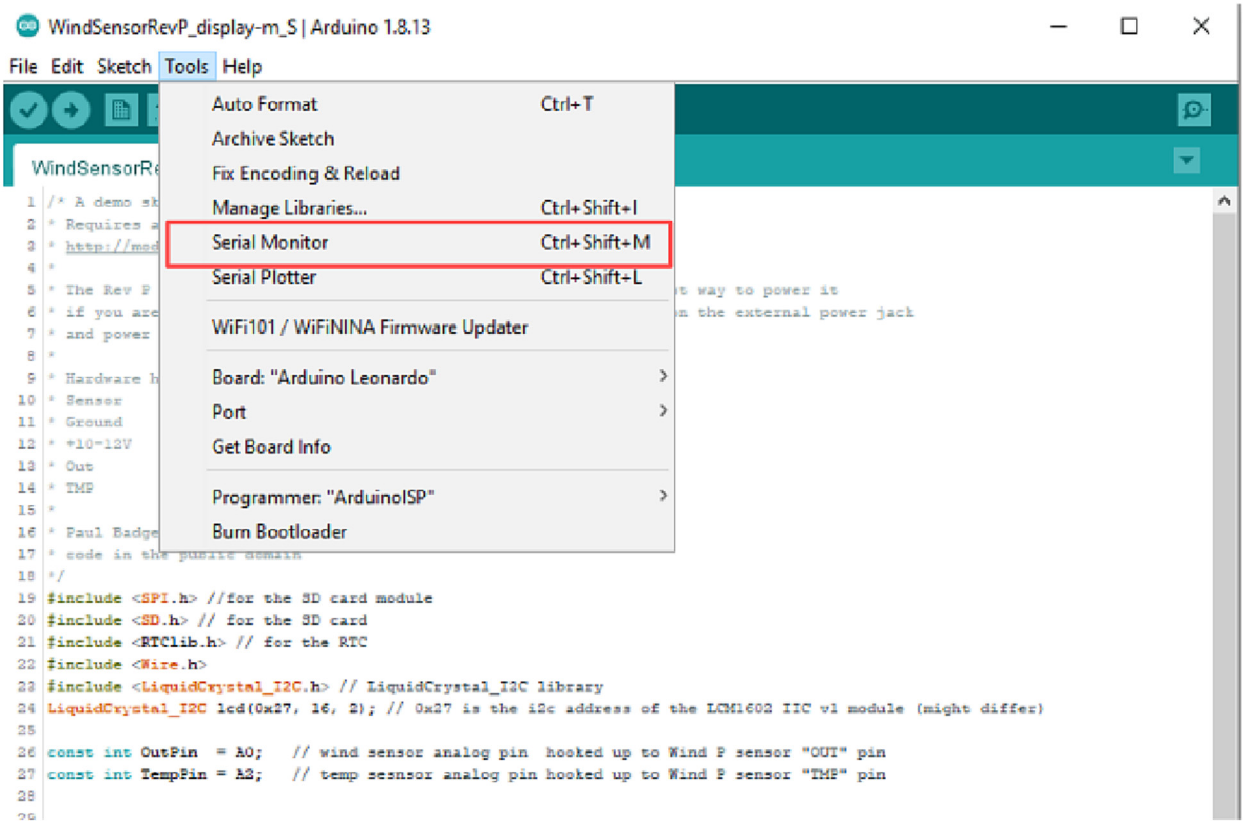

Fig. 14. Setting Arduino UNO.

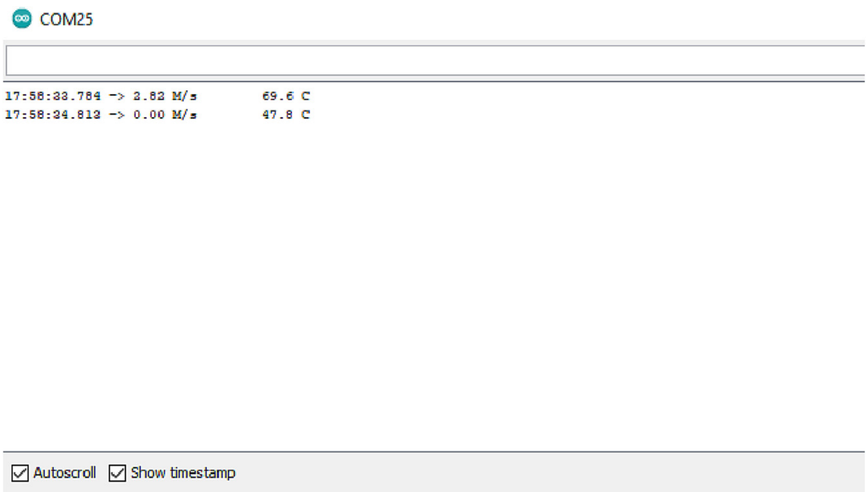

Fig. 15. Graphic User Interface of the Serial Monitor.

For measuring steady-state airflow, measurement was taken of the velocity in the wind tunnel at different levels of airflow. The reading speed was set to 125 m/s (8 Hz) and velocities were set to 1, 2, 3 and 4 m/s; the measuring sample lasted for 9 s. Velocity measurements are visualized as depicted in Fig. 17. The standard deviation σ of measurement was estimated by Equation (4).

Fig. 16. Assembled wind tunnel during calibration of bi-directional pressure probe.

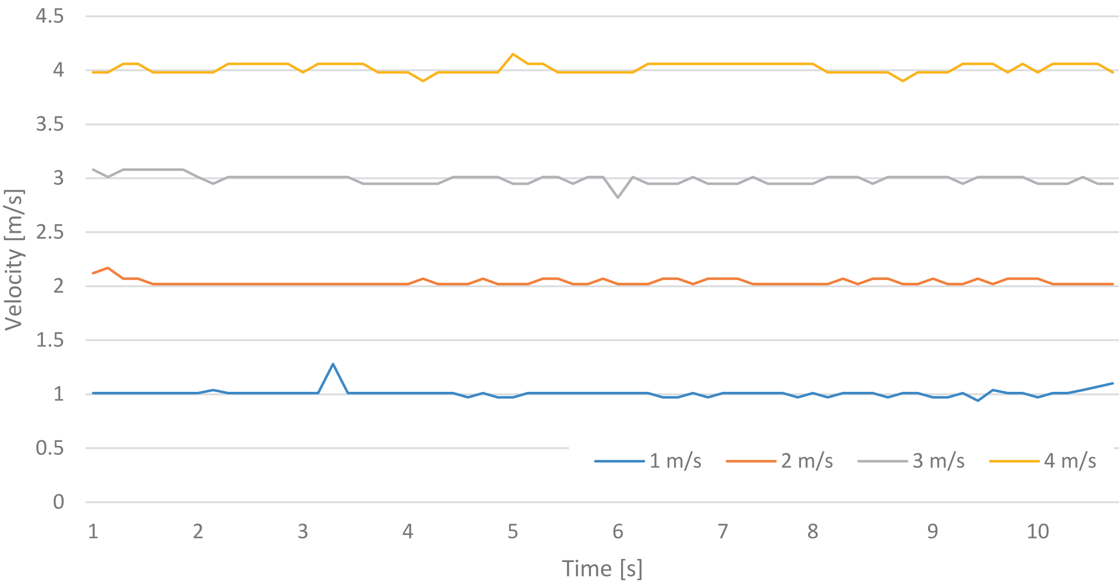

Fig. 17. Diagram of measurements acquired for 10 s with reading speed 125 m/s.

$$\sigma = \sqrt{\frac{\Sigma|x-\mu|^2}{N}} \tag{4}$$

where x is the value in the data set, μ is the mean of the data set and N is the number of values in the data set. The measured velocity and its deviation were verified for 4 levels of velocity which were 1, 2, 3 and 4 m/s (8 Hz) as depicted in Table 1. The standard deviation for velocity was on average 0.04 m/s with +/- 0.01 m/s deviation from mean values. The deviation was highest for 1 m/s wind speed, for which it is 4 % deviation. Based on these values, flow can be considered stable for the intended application. Values measured over 10 s are shown in Fig. 17 for velocity flows of 1 – 4 m/s.

$$t_i = \frac{\sqrt{u^2}}{u_{mean}} \tag{5}$$

Table 1
Standard deviation of 10 s measurements with sampling rate.

Required Velocity [m/s]	u_{est}	1	2	3	4
Mean velocity [m/s]	u_{mean}	1.01	2.04	2.99	4.02
Standard deviation [m/s]	σ	0.04	0.03	0.04	0.05
Standard deviation [%]	σ	4.0	1.4	1.5	1.2
Average turbulence intensity [%]	t_i	1	1	1	1

Table 2
Average deviation between calibrated BDVP and hot-wire sensor.

	1 m/s	2 m/s	3 m/s	4 m/s	5 m/s
Rev. P [m/s]	1.0	2.0	3.1	3.9	5.1
McCaffrey PP [m/s]	1.0	2.1	3.0	4.0	5.0
σ [m/s]	0.1	0.1	0.1	0.1	0.1
σ [%]	6	3	3	3	3

Using Equation (5), average turbulence was estimated which was approximately 1 % of measurement (Table 1), which was sensitive enough for calibration of bi-directional pressure probes.

The following Table 2 compares results of Rev. P and calibrated BDVP connected to Setra C264 pressure transducer, where maximal observed deviation was 0.13 m/s at 4 m/s velocity flow. Standard deviation was observed between 3 and 6 % during 10 s measurements.

Conclusion

This hardware is easy to use and affordable for anyone who has access to a 3D printer without the need for access to a workshop or the ability to build a wind tunnel out of more difficult working materials (wood, steel, etc.). The wind tunnel is easy to use and manipulate, becoming advantageous even for educational purposes. This tunnel is relatively inexpensive and provides the utilities needed for research and educational purposes.

The wind tunnel is essential equipment for calibrating the bi-directional velocity probes designed to measure flame velocity and pressure differences in compartments as shown in Fig. 17. These measurements are essential to quantify the neutral plane level, wind impact to fire or oxygen calorimetry. Based on experience collected from this project, further development is focused on the development and building of a pressure measuring unit that will include a microcontroller for data acquisition, pressure transducers and velocity probes. Relevant pressure measurements will be compared to commercial and open-source transducers.

CRediT authorship contribution statement

Jan Smolka: Conceptualization, Software, Writing - original draft. **Eleni Asimakopoulou:** Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported through funds provided by the Czech Fire Protection Association – Majaczech, z.s. Additionally, the authors wish to thank the Central Firefighting School in Bile Policany for providing space and equipment for this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ohx.2023.e00440.

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Jan Smolka has an international and interdisciplinary background in fire safety and risk management, mostly focused on firefighting, fire dynamics, fire safety plans designing, protection of buildings, creating guidelines and training on national and international level. His expertise encompasses open-source laboratory development. He is a doctoral candidate at VSB-Technical University of Ostrava in the Czech Republic and researcher at Occupational Safety Research Institute under Ministry of Labour and Social Affairs. He is active in CFPA-Europe commissions as vice chair of Czech association Majaczech.

Kamila Kempna is a PhD candidate at VSB-Technical University of Ostrava. Her research in fire safety and disaster resiliency includes various areas such as experimental procedures development, data analysis or risk management. As a researcher at Occupational Safety Research Institute, she deals with aspects as health and safety issues for volunteer firefighters, disaster resilient societies or impacts of climate change on health and safety. She chairs Czech fire protection association Majaczech established to provide research, training and guidelines and is Czech member of at CFPA-Europe.

Dr. Petr Kucera is head of Fire Safety Protection Department at VSB-Technical University of Ostrava. As assistant professor he provides courses of Fire Dynamics and Modelling. His field is modelling, material reaction to fire and evacuation. He is a member of Fire Prevention Commission at CTIF, member of CEN TC 127/ WG 8 – Fire Safety Engineering. He is the main author of Methodology for specific assessment of high-risk fire safety conditions, 2015 or Methodology of fire suppression and extinguishing modeling using sprinkler protection, 2019.

Kamil Kempny is formal manufacturing director of Czech Coal Mines and has strong interdisciplinary background in industrial safety, business continuity management and crisis management. Currently, he is researcher at Occupational Safety Research Institute and association Majaczech as vice-chair.

Dr. Eleni Asimakopoulou is a Lecturer in Fire Engineering at the University of Central Lancashire. Her major research interests cover the computational and experimental investigation of fire spreading in buildings and façade systems, flammability and fire testing of innovative foam and glazing systems, the impact of phase change materials in fire development, material properties at elevated temperatures and solid reaction kinetics. Eleni has authored over 50 journal/conference publications and participated in 8 UK and EU-funded projects. She works with standardization and scientific committees, is a reviewer in 20 journals, funding bodies (e.g., EPSRC), book chapters, conferences and supervising several undergraduate and graduate students. She is a member of member of the Editorial Board in Fire Technology journal, International Association of Fire Safety Science, Society of Fire Protection Engineers, Institute of Fire Engineers.

Prof. Dr. Pavel Danihelka, is a head of the Risk Research and Management Department at Occupational Safety Research Institute and professor at Faculty of Safety Engineering of VSB-TUO and Faculty of Medicine of OSU. He is recognised for his activities in the research and management of risks and environmental safety. In terms of disaster risk reduction, he cooperates with UNDRR, UNDP or UNECE, he is also a member of Independent Scientific Expert Group of NATO SPS programme and was delegate of the Czech Republic in Horizon 2020 Secure Societies Programme Committee.