Comparative Analysis of Tests under Real Conditions and CFD Model for Selected Operation Parameters of a Mobile Fan Used by Fire Protection Units

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Abstract. Mobile overpressure fans are popular tools used in rescue and extinguishing operations carried out by Fire Protection Units. They are used for exhaust and venting buildings from harmful products of thermal decomposition occurs due to fire. Health and human life may depend on the proper operations of this type of equipment. The aim of the article is to compare the results of real research with numerical analysis. The Scientific and Research Centrum for Fire Protection – National Research Institute test infrastructure was used for research. These test conditions were correlated during CFD (Computional Fluid Dynamics) analysis. The parameters resulting from the operation of the mobile overpressure fan are as follow: the shape of the stream and the distribution of the air flow velocity profile for the distances: 1.5 and 3.0. To perform tests, the representative ventilator was used – being a part of Fire Protection Units equipment. The obtained result provided information on discrepancies in the results of real and simulation studies, indicating further development directions of the research methodology of numerical studies, enabling future support for real studies. The error of the CFD model in relation to the actual tests for measuring the velocity of the flowing air is 0.18 to 18%.

1 Introduction

During fires in buildings, several dangerous phenomena can be distinguished, for instance the effect of high temperature [10], emission of harmful products of thermal decomposition [9,11], limiting the strength of the structure [12, 13] or the possibility of an explosion [14]. Even small fires can be dangerous to humans. This risk also exists after the fire has been extinguished. The main cause of such a situation are harmful fire gases, the concentrations of which may pose a threat to human life and health [9]. In order to clean rooms in buildings, for instance from fire gases, tactical ventilation is used. According to the definition presented by Paul Grimwood [1], tactical ventilation is a set of activities consisting of creating conditions for gas exchange or fire isolation, carried out by rescuers, aimed at taking control in the fire environment, for the purpose of gaining tactical advantage during rescue and firefighting activities in buildings. One of the basic systems used in activities related to tactical ventilation is Positive Pressure Ventilation (hereinafter referred to as PPV). Mechanical overpressure ventilation is an activity aimed at creating an overpressure in the facility and then directing the flow of gases and forcing them outside the facility. This operation is carried out with the use of mobile overpressure fans by performing the following steps:

- locating the fan, in an appropriate configuration, in front of an inlet opening (for instance in front of a door),
- providing an outlet (e.g. by opening a window) located in a different part of the building (for this operation, it is necessary to take into account proper assessment of the direction route of gas flow – the distance from the inlet),
- start the fan and start pumping gases through the air stream generated by the mobile fan.

One way to remove smoke from areas necessary for human evacuation is to use overpressure ventilation. The first studies related to the use of tactical overpressure ventilation were carried out by Ziesler in the mid-90s [3]. At that time, he pointed out that the use of PPV ventilation affects: the reduction of temperature value and the concentration of toxic gases in the fire environment. This type of action also improves the visibility range on escape routes. In 1997 Tuomisaari presented the thesis that the probability of survival increases when the air flow generated by the fan is high enough [4]. In 2000 Vaari and Hietaniemi confirmed the findings of Ziesler and showed that heat release rate (HRR) of a fire increases as a result of overpressure ventilation [5]. This phenomenon is confirmed by Svensson’s thesis from 2001, which indicates that material combustion rate increases due to the use of PPV [6]. Moreover, the researcher showed that the value of fire temperature, in the area of overpressure ventilation, increases on the leeward side and decreases on the windward side. In 2002 Lougheed et al. conducted an analysis of the effectiveness of PPV ventilation in high-rise buildings [7]. In their research, they showed that the fan’s efficiency increases when it is placed closer to the building’s inlet. In contrast, in 2005 Kerber and Walton showed that the use of PPV in high-rise buildings is effective only for a limited number of floors [8].

Literature studies show that the use of overpressure ventilation is an important aspect of the implementation of rescue operations carried out by Fire Protection Units. With regard to facilities (e.g. residential buildings, multi-family buildings) where the use of fire ventilation is not required by law, the use of overpressure ventilation may be the only option to:

- enable evacuation of people staying in the facility,
- facilitate access for rescue teams and,
- minimize the loss of property by removing hot combustion products of destructive nature.

The success of using overpressure ventilation depends on many factors, including the ability to use a fan with conscious use of its technical parameters. One of the scientific and research issues of institutions supporting rescue and firefighting operations is the development of a methodology for assessing the technical and operational properties of devices supporting tactical ventilation processes. The contemporary trend is for these methods to use numerical simulation tests. In order to do that it is essential to develop CFD models to support such assessments. However, the implementation of such a methodology in the Laboratory of Combustion Processes and Explosions of the Scientific and Research Center for Fire Protection (hereinafter referred to as ZL BW CNBOP-PIB) requires a series of real, analytical and numerical tests to determine and verify the accuracy of the models. The tests presented in the article will make it possible to determine the criteria and indicate the parameters and their ranges necessary to develop the testing methodology. The article presents the results of pilot experimental studies and numerical CFD analyzes mapping similar conditions of use of a tactical fan in the laboratory infrastructure of ZL BW CNBOP-PIB. The tested parameters are the characteristics of air flow velocity profile and the size of the air stream generated by the mobile overpressure fan.

2 Materials and Methods

2.1 Experimental research

A representative mobile fan was used for the tests, which is a common tool used by fire protection units. Selected fan operation parameters are presented in Table 1.Tests on the shape of the generated air stream, produced by the fan, were carried out using a dedicated measurement plane and tools for recording the visual image. In order to improve image contrast smoke from a set of two Vulcan 5000 smoke generators was forced through the fan. Smoke generators were placed 0.3 m from the rear edge of the fan body. The device was located centrally in the center, in the axis of the measurement plane, on which lines were drawn indicating distances in the horizontal (with a 0.1 m scale) and vertical (0.5 m scale) part of the plane (Figure 1).

Table 1. Selected operating parameters of the mobile overpressure fan.

No.	Parameter	Value
1	Efficiency	25000 m^3/h
2	230V efficiency	17000 m^3/h
3	AMCA efficiency	15187 m^3/hl
4	Impeller	447 mm, 5-blade
5	Weight	≤ 25 kg
6	Dimensions (length/width/depth)	56/53/30
7	Engine	0.6 kW
8	IP protection (engine/battery/controller)	IP 66
9	Battery	40V lithium-ion, 423 Wh
10	Working time at max. power on 1 battery	~23 minutes
11	Working time at max. power	~40 minutes
12	AC output (Universal)	85-264V
13	Current (start/run)	<8A/3.5A

Then, the maximum speed of the fan was set by means of an inverter regulating the engine speed. After reaching the maximum value of the fan rotor speed and stabilizing the air stream, the registration of the geometric characteristics of the air stream was started.

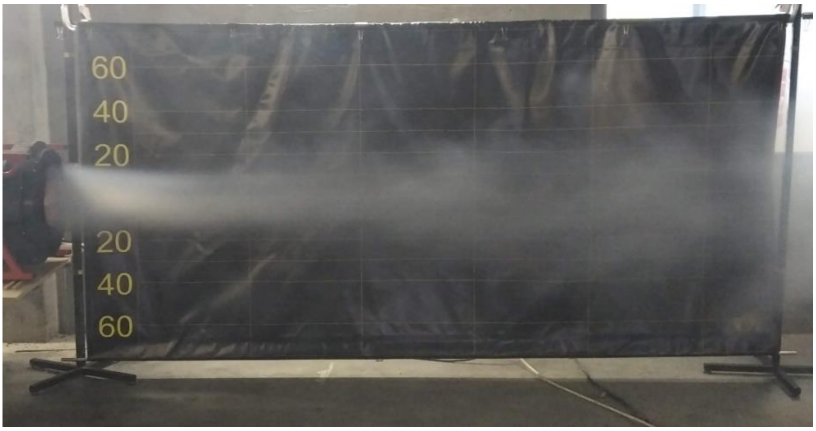

Fig. 1. A stream of air generated by an overpressure fan – experimental test.

The characteristics of the air flow velocity profile in the stream generated by the overpressure fan were recorded using a resistance thermoanemometer (with a range of 0 – 30 m/s and accuracy of 0.01 m/s), testo 405i model, and a mesh plane with external dimensions of 2590 x 2590 mm (Fig. 2) functioning as a measuring grid. The intersecting lines of the measuring grid showed the measuring points. The nylon line was introduced in such a way that the measuring points in the central part of the mesh (1000x1000 mm) were spaced 100 mm apart and at the edges 150 mm. The diagram of the test stand is presented in Figures 2 and 3.

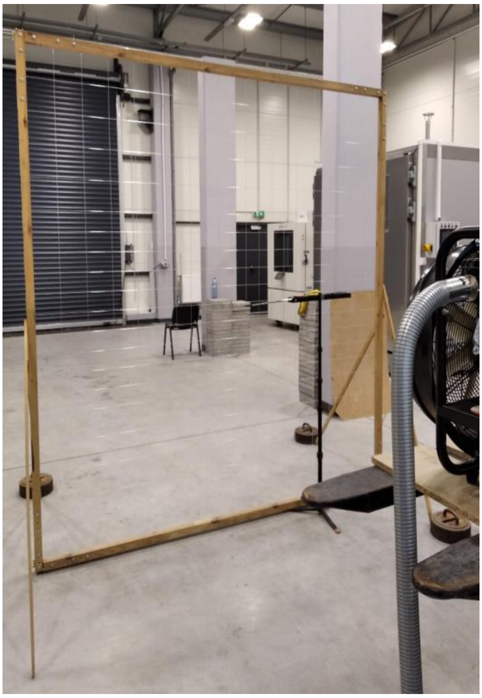

Fig. 2. Test stand (measurement plane) for assessing the characteristics of velocity profile of the air stream generated by the mobile overpressure fan.

For the purposes of the experimental tests aimed at determining the characteristics of the speed profile, the fan was positioned perpendicularly to the surface of the grid, so that the axis of the fan rotor was directed horizontally and centered on the grid's center point. The test scenario assumed testing the flow velocity of the stream generated by the fan at a distance of 1.5 and 3.0 m from the measuring point of the anemometer. After making sure that the device was properly leveled and that the fan is at the right distance from the anemometer, the device was started. Then, after setting the maximum engine speed through the inverter and stabilizing the air stream, data acquisition was started (lasting 30 s). This process was repeated for selected measurement points located on the mesh surface (Figure 3).

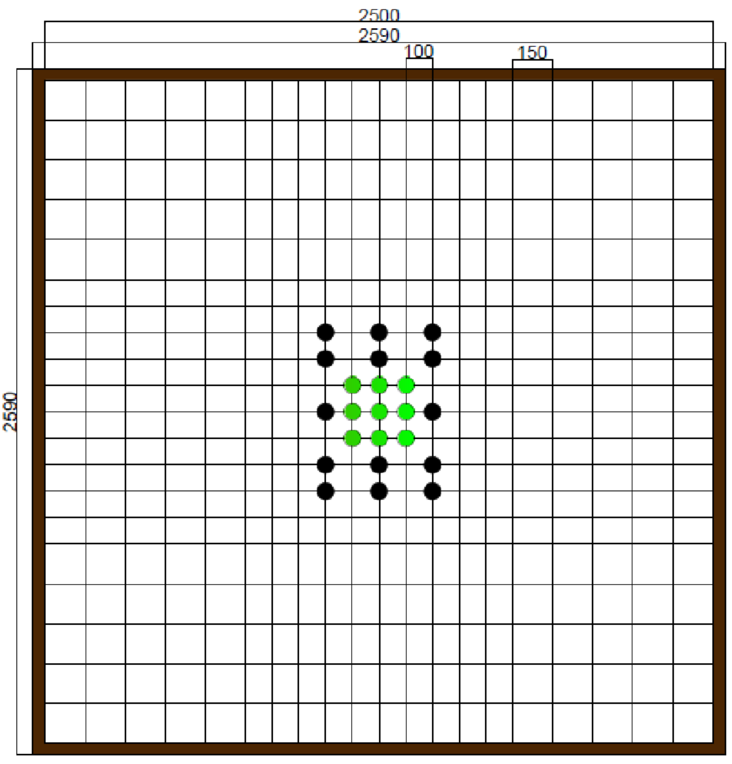

Fig. 3. Arrangement of measurement points on the mesh surface.

2.2 Testing in the CFD environment

The computer simulation was performed with the use of the FDS (Fire Dynamics Simulator) program, which is a tool that uses computational methods of numerical fluid dynamics CFD (Computional Fluid Dynamics). The CFD model, used in the FDS program, is used on many levels, including: heating, testing of fire development, assessment of the effectiveness of fire ventilation and the utility of comfort ventilation. The CFD tool describes fluid movement on the basis of solutions to a system of Navier-Stokes differential-partial equations (using the principle of conservation of mass, momentum and energy).

With regard to the performed experimental tests, in terms of the evaluation of the effectiveness of selected parameters of the operation of mobile overpressure fans, the personnel of ZL BW CNBOP-PIB made an attempt to reproduce the verified features during a computer simulation, i.e.:

- Characteristics of the speed profile of the overpressure fan at distances of 1.5 and 3.0 m and,
- The shape of the generated air stream.

The model for the verification of the parameters mentioned above was created using a computational grid with external dimensions of 9.75 x 4.55 x 3.0 m, divided into 8 517 600 calculation cells with dimensions of 2.5 x 2.5 x 2.5 cm (15.625 cm^3). For the needs of numerical calculations, the LES (Large Eddy Simulation) simulation method was used. The basic assumption of this method is the separation of the continuous spectrum of turbulent fluctuations energy into a solved (numerically) and modeled (analytically) part. The model visualization is presented in Figure 4.

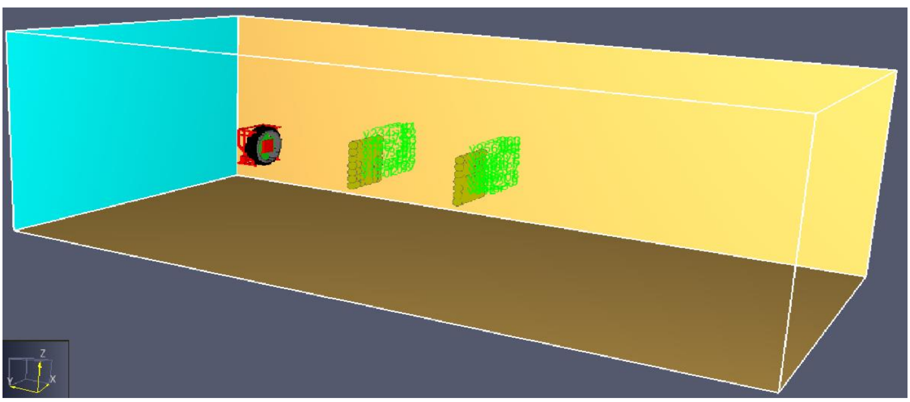

Fig. 4. Illustrative visualization of the created CFD model.

The housing of the mobile overpressure fan was made in such a manner as to reflect all the structural elements of the device. For the purposes of making the model, all structural elements were taken into account, including body, handles and the rotor cover (Figure 5). An obstacle simulating the rotor axis is also built into the outer side of the shield. The air supply openings (vents), placed on the inner surface of the fan plane, were assigned a speed value of 17.85 m/s. The constructed model was also equipped with devices for measuring the speed of the generated air stream (98 pcs), located at a distance of 1.5 and 3.0 m from the fan. The Smokview software was used to visualize the described model, which is dedicated to the visualization of numerical calculations performed by the FDS program.

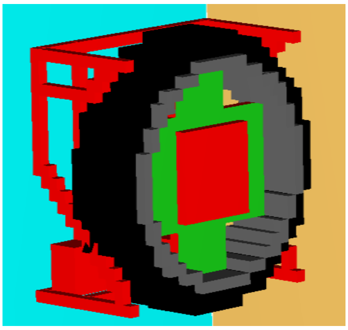

Fig. 5. Visualization of the fan model.

3 Results and discussion

The shape of the air stream blown by the fan from the experimental tests and CFD analysis is shown in Figure 6.

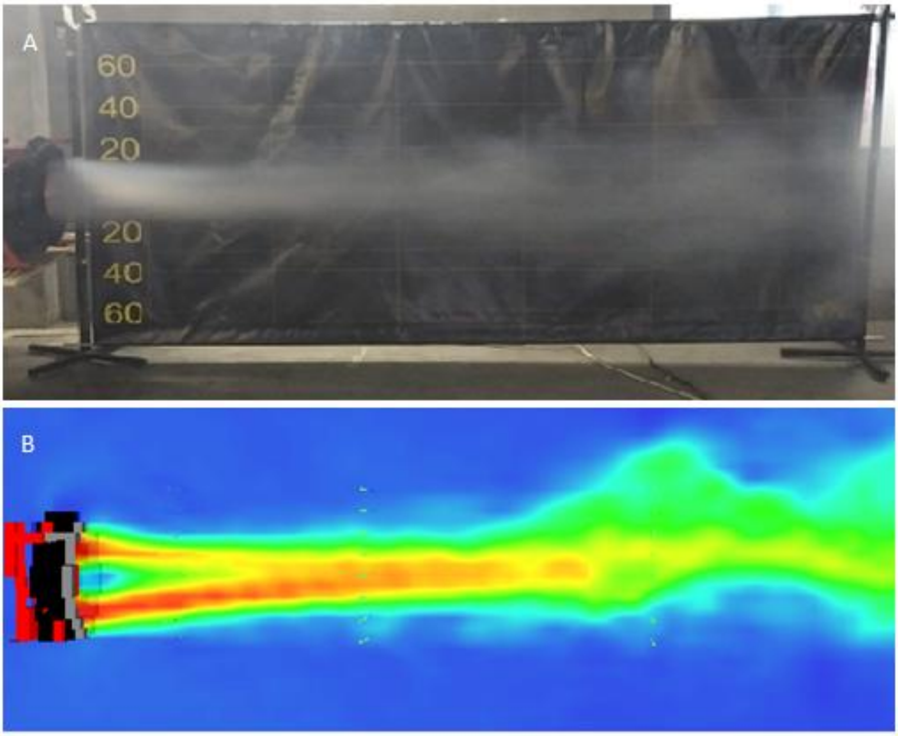

Fig. 6. Visualization of the air stream shape generated by the fan: a) experimental tests, b) CFD simulation tests.

Measurements of the air stream velocity, generated by the mobile positive pressure fan in real conditions and during CFD simulation, were made for a distance of 1.5 and 3.0 m. The location of the measurement points (23 items) is presented in Figure 3. The results of the obtained tests (average values of the air stream speed) are presented in Table 2. Average speeds have been compiled taking into account the following number of measuring points:

- 9 points, located in the middle of the measurement plane,
- 23 selected points, spread over a wider range of the measurement plane.

The detailed location of the indicated measurement points is presented in Figure 3.

With regard to the tests conducted in real conditions, the average velocity values measured for 23 measuring points were respectively 7.30 m/s (for 1.5 m) and 6.64 m/s (for 3.0 m). In the case of 9 measurement points located in the middle of the measurement plane, these speeds were 9.96 (1.5 m) and 8.39 m/s (3.0 m), respectively. The characteristics of the air stream velocity plane for selected distances (in real conditions) are presented on graphs 6 and 8.

Simultaneously, with the use of CFD tools – Fire Dynamics Simulator software, a comparative simulation was performed, aimed at reproducing the operating conditions of the mobile fan. The average speed values (for 23 points) were respectively 8.33 (1.5 m) and 7.13 (3.0 m) m/s. With regard to 9 points located in the central part of the measurement plane, these values were: 11.74 (1.5 m) and 8.40 (3.0 m) m/s. The characteristics of the air stream velocity plane for selected distances (during CFD analysis) are presented in graphs 9 and 10.

The model error in the flow velocity range ranges from 0.18% to 18%. The inaccuracy in mapping the air flow velocity is greater at 1.5 m (14% to 18% error) than at 3.0 m (0.18 to 7.4%). The discrepancies in the obtained results could have been influenced by the vibrations generated during the nominal operation of the fan.

Table 2. Averaged speed values obtained during tests in real conditions and simulations in the FDS program.

Parameter	Average speed values [m/s]			
Distance from the anemometer	1500 mm (23 selected points)	3000 mm (23 selected points)	1500 mm (9 points – the middle plane)	3000 mm (9 points – the middle plane)
Experimental tests	7.30	6.64	9.96	8.39
FDS simulation	8.33	7.13	11.74	8.40
Difference	14.10%	7.41%	17.94%	0.18%

A slight difference in speed for the distances of 1.5 and 3.0 m during the experimental tests is related to the dispersion of the air stream, which began to expand with the increase in the distance from the fan outflow.

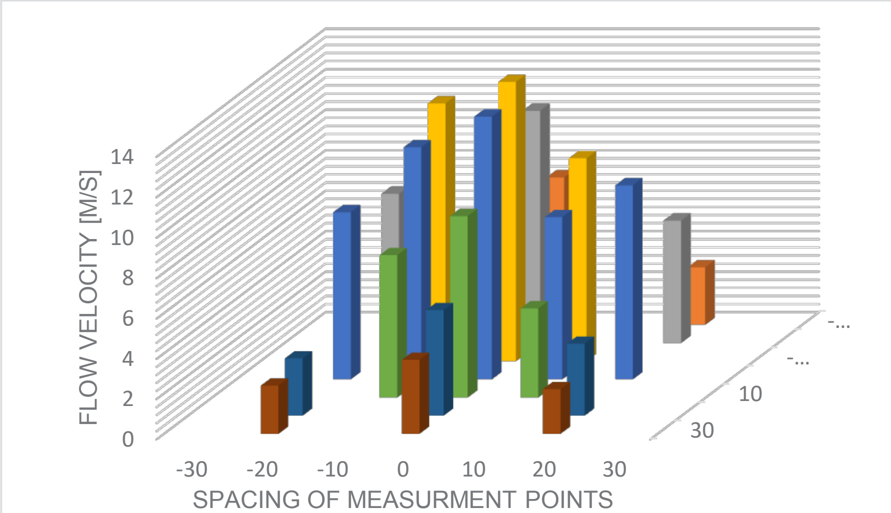

Fig. 7. Distribution of the velocity profile of the generated air stream at a distance of 1.5 m – tests under real conditions.

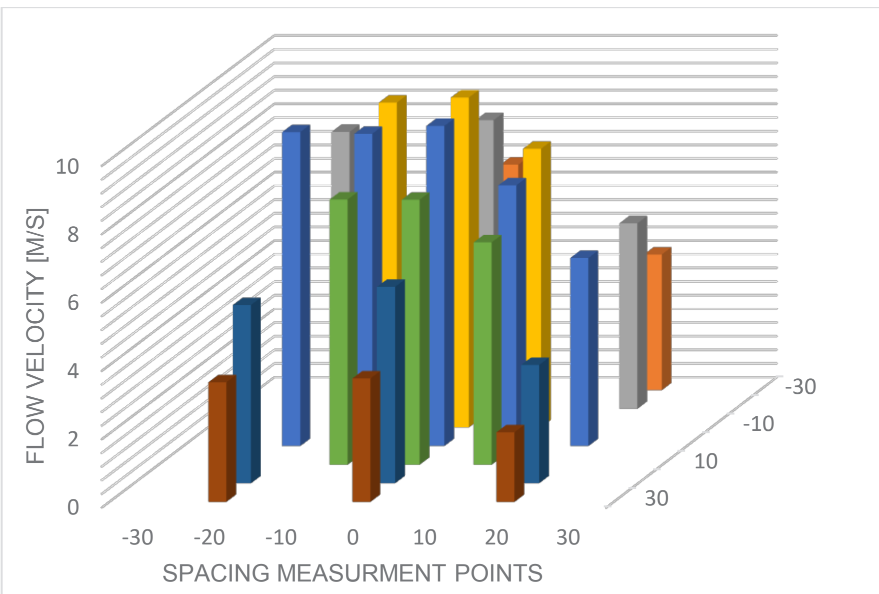

Fig. 8. Distribution of the velocity profile of the generated air stream at a distance of 3.0 m – tests under real conditions.

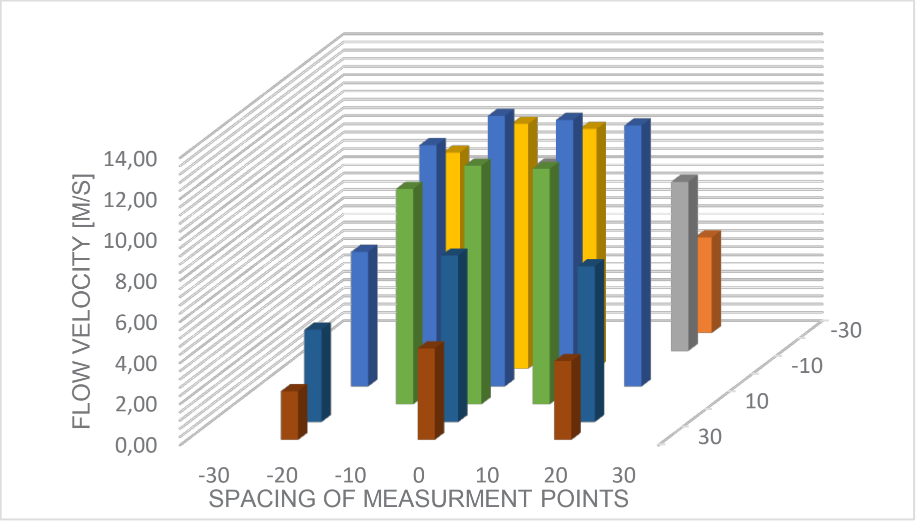

Fig. 9. Distribution of the velocity profile of the generated air stream at a distance of 1.5 m –CFD simulation.

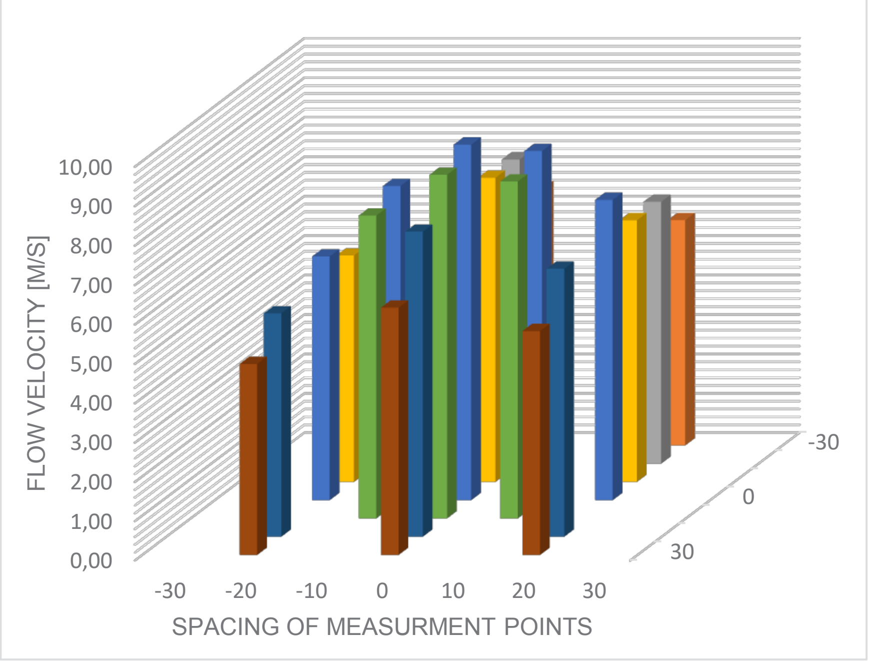

Fig. 10. Distribution of the velocity profile of the generated air stream at a distance of 3.0 m – CFD simulation.

4 Summary

The performed activities allowed to assess the shape and characteristics of air stream velocity profile, generated by the mobile overpressure fan. The results obtained during the numerical analysis showed proper correlation with the tests carried out in real conditions, both with regard to the flow velocity and the shape of the generated air stream. Currently, the personnel of ZL BW CNBOP-PIB is working on extending the test program, taking into account additional distances (3, 5 and 8 m) for measuring the flow velocity profile, and obtaining new samples of mobile overpressure fans. The authors of this study assume that future work related to the assessment of the flow of the fan stream inside buildings will be carried out, taking into account the obstacles constituting the construction barriers present in the building structures. Knowledge obtained this way regarding the correlation of aerodynamic parameters of the fan with the parameters related to the layout of rooms in facilities and the presence of obstacles in the form of partitions, will allow to predict the usefulness and effectiveness of using this type of devices in complex systems of buildings, based on numerical CFD calculations.

With regard to the obtained test results, aimed at designing research methodologies to assess the effectiveness of mobile overpressure fans, the authors of this study drew the following conclusions:

- Assessment of the shape of the air stream is a very important parameter that determines the method of carrying out rescue operations. The visualization of the stream shape allows to assess the nature of the supplied air flow – the degree of approximation to the laminar flow.
- The speed characteristics of the air stream is a very important parameter that allows to assess the ability to pump the generated air stream, taking into account losses caused by air resistance. Verification of this parameter may be helpful in relation to the correct location of the fan in front of the inlet opening during rescue operations carried out by Fire Protection Units.
- With regard to CFD simulation, an important aspect that has a significant impact on the obtained results is the correct representation of the fan structure. This parameter has a significant influence on the shape of the generated air stream.

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