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Effect of the Volumetric Flow Rate Measurement Methodology of Positive Pressure Ventilators on the Parameters of the Drive Unit

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Abstract: The nature and conditions of the execution of tests (open or duct flow) in terms of evaluating the flow rate generated by positive pressure ventilators (PPV) may affect the parameters of the drive unit recorded during testing. In this article, popular PPVs (conventional type—W1 and turbo type—W2) of about 4.2 kW were tested under open flow (Method A) and duct flow (Method B) conditions. During the tests, engine load values were recorded: torque, speed, horsepower and, using portable emissions measurement systems (PEMS), exhaust gas emissions: carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NO_x) and fuel consumption. Depending on the method used to measure ventilator flow rates, drive units can have different drive power requirements (from 3.2% to 4.5%). Changes in drive unit operating conditions induced by the flow measurement method are observed in the results of fuel consumption (from 0.65% to 9.8%) and emissions of harmful exhaust compounds: CO_2 up to 2.4%, CO up to 67%, HC up to 93.2% and NO_x up to 37%. The drive units of turbo type fans (W2) are more susceptible to the influence of the test methods in terms of flow assessment, where they have higher emissions of harmful exhaust gases when tested by Method A. Flow measurement methods affect the oscillation of propulsion power, which contributes to disturbances in the control of the fuel–air mixture composition. The purpose of this article is to analyse the impact of testing methods for measuring the flow rate of positive pressure ventilators on the performance of the drive unit.

Keywords: portable emissions measurement systems (PEMS); fuel consumption; non-road small engine; methods of measuring fan flow rates; positive pressure ventilators (PPV); mobile fan

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1. Introduction

Machines and equipment tested under laboratory conditions often have different characteristics than when tested under real operating conditions [1,2]. The results of studies published by manufacturers are characterised by an obvious conflict of interest, as their main aim is to sell a product and present it in the best possible light [3,4]. The analysis of test results published by manufacturers is subject to a high risk of uncertainty in the reliable selection of a device. Assuming that the tests are performed diligently, one should be aware of the fact that a manufacturer may publish those results in which a device presents itself favourably in relation to the competition, or choose a test method that presents his/her product more favourably [5]. Machines and equipment specialised for working under special conditions, e.g., hazardous working conditions or where there is a high responsibility for human life, are often subject to additional restrictions and requirements [6,7].

In many countries, equipment and machines used in rescue operations are subject to special inspection by specialised testing bodies [8–10]. For positive pressure ventilators, it is observed that there are several methodologies on the market that can be used for testing volumetric flow rates. When describing the standardised methods used for flow rate tests, two methods should be specified, i.e., according to EN ISO 5801 (duct flow) and ANSI/AMCA 240-15 (open flow). However, it should be mentioned that, depending on which methodology is chosen for the study, the obtained results may vary significantly, and their misinterpretation may cause potential users (firefighters) to be misled into choosing a fan as an important tool dedicated to the implementation of rescue operations. With regard to positive pressure ventilators, it is important that the test methodology for volumetric flow assessment reflects the actual and final operating conditions of this type of device (i.e., free-flow operation).

Kaczmarzyk et al., in 2021, described test methods for evaluating the volumetric flow rate and efficiency of positive pressure ventilators [9]. In the article, test methods selected are carried out under ducted conditions—Method A, EN ISO 5801—and in open flow—Method B; i.e., ANSI/AMCA 240-15 and (the authors' methodology) the evaluation of the characteristics of air jet velocity profiles [9], respectively.

As intended, Method A was designed to test fans operating in ducted systems. Method B, on the other hand, is made up of tests to assess the volumetric flow rate under conditions of actual use of such fans. Positive pressure ventilators operating in free flow constitute a kind of discharge system, the effectiveness of which depends on parameters such as the type of ventilator, the characteristics of the airflow, the positioning parameters (distance and angle of the impeller) and, in addition, the accompanying free turbulence and, if applicable, the size of the door opening (which constitutes the discharge opening). Therefore, by carrying out free-flow tests, it is possible to make a comprehensive assessment of the flow rate of a mobile fan, considering all the components and flow phenomena that affect its efficiency. With regard to Method A—the assessment of flow capacity in pipe channels—this would not be possible. The indicated thesis is also supported by Firtsche et al., 2018, who pointed out that the volumetric flow rate parameter declared by different fan manufacturers may vary due to the lack of standardised regulations for testing of such fans [10]. The tests conducted by Kaczmarzyk et al., 2022, show that the tests performed by Methods A and B affect the parameters of the drive unit in terms of torque, speed and power [5]. The results of these tests showed that, depending on the design of the fan impeller, the choice of methodology can determine the demonstration of higher benefits of one device over another. Changes in the characteristics of the parameters described above, such as power, strongly influence other external characteristics of the device, such as fuel consumption and emissions of harmful exhaust gases [11–13].

The aim of this article is to examine how the conditions and nature of the flow parameter test method (duct or open flow) affect the performance parameters of the power unit, such as speed, torque, power, fuel consumption and emissions of harmful exhaust gases. A new approach to the analysis of the impact of air volumetric flow rate measurement methods on drive unit parameters, focused on the analysis of fuel consumption measurements and harmful exhaust emissions, may show problems in controlling the air–fuel mixture during operating conditions corresponding to the air volumetric flow rate test method. The research can also show which research test is more favourable for which type of fan impeller, due not only to the air flow parameters, but also the characteristics of the drive unit in terms of fuel consumption and air pollution through exhaust gases.

2. Materials and Methods

With regard to the standardised methods used on the market for flow rate testing, two methods are mainly specified; i.e., in accordance with EN ISO 5801 (duct flow) and ANSI/AMCA 240-15 (open flow). The first method (A), in accordance with EN ISO 5801, uses a test duct equipped with a flow-throttling section, a static and dynamic pressure flow measurement area, a flow straightener, a static pressure measurement section and a duct confuser to match the dimensions of the fan impeller to the diameter of the test duct (Figure 1a). The second method (B), performed in accordance with ANSI/AMCA 240-15, is a flow chamber equipped with measuring nozzles, static pressure measuring sections, flow straighteners, an auxiliary fan and an opening selected to form a door on the surface of which a jet of the fan being tested is blown (open flow). The effect of the test conditions for the individual measurement methods (A and B) on the parameters of the mobile fan drive unit was carried out by measuring speed, torque and power at the motor drive shaft, between the motor shaft and the impeller (Figure 2). A torque meter (Electronic Workshop Roman Pomianowski, Poznań, Poland) with a speed measurement function was used in this test (uncertainties of the measurements ±0.1 Nm). A detailed description of torque measurement methods in real-life drive units and working mechanisms is described in Warguła et al., 2020 [14] (Figure 1c).

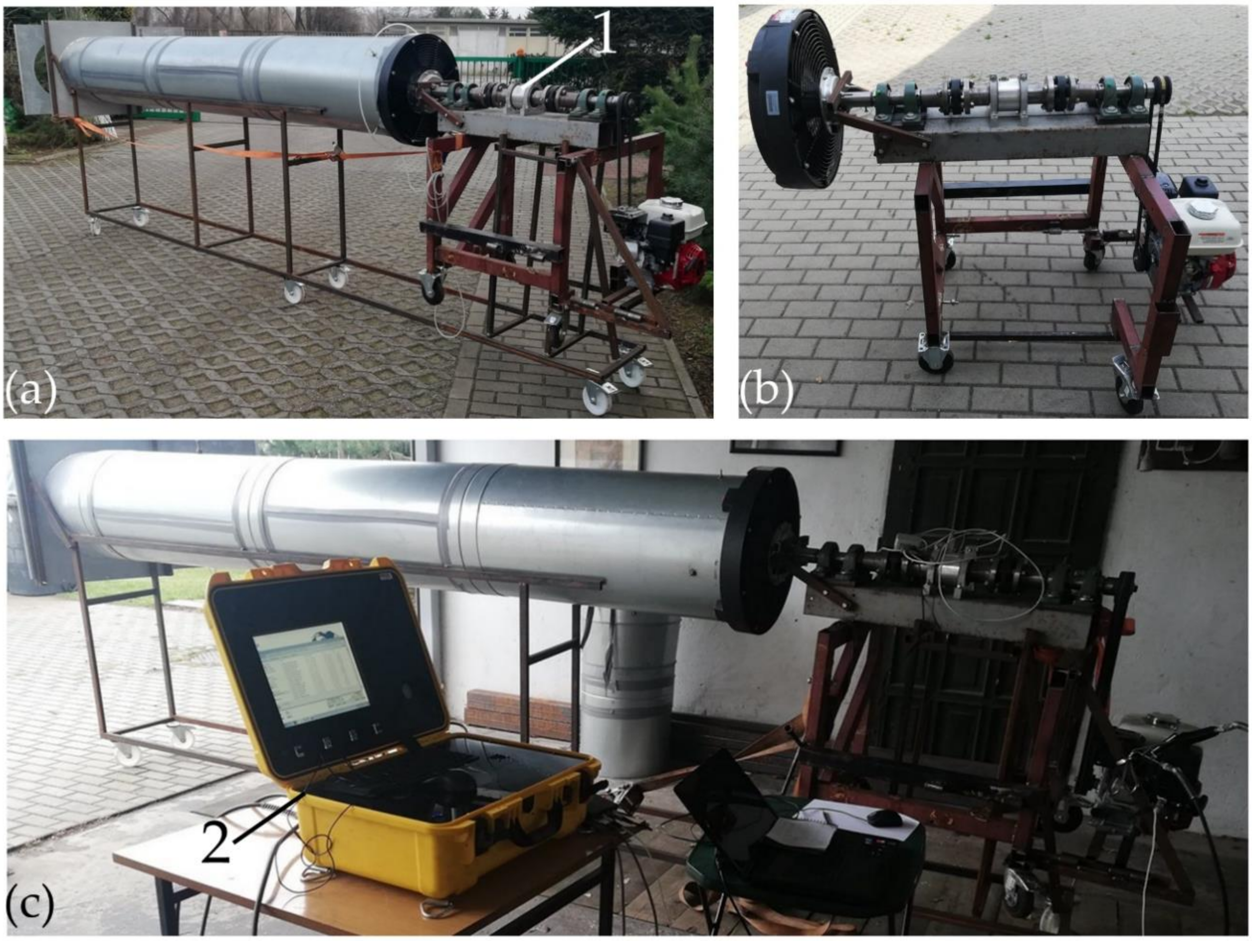

Figure 1. Test stand during measurement of the emissions of harmful exhaust gases and energy consumption: (**a**) measurement during duct flow test (Method A); (**b**) measurement during open flow test (Method B); (**c**) PEMS measuring apparatus, where 1—torque meter, 2—PEMS.

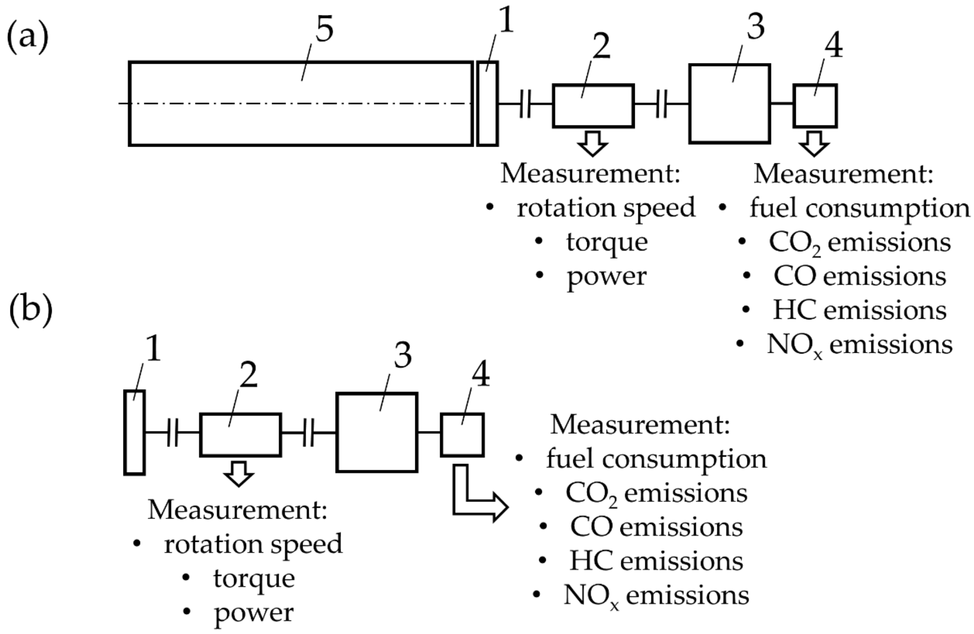

Figure 2. Diagram of the test stand: (**a**) measurement during duct flow test (Method A); (**b**) measurement during open flow test (Method B), where 1—fan impeller, 2—torque meter with speed measurement function, 3—combustion engine, 4—PEMS, and 5—air flow measurement channel.

The Axion RS+, a typical portable emissions measurement system (PEMS) from Global MRV, was used for the emissions test. In the emissions tests, levels of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NO_x) were analysed (Table 1). Fuel consumption was determined based on a carbon balance. The measuring device used in the experiments measured concentrations expressed in vol.% or ppmv. As a result, more measurable emissions were identified. Emissions were calculated on the basis of the measured concentrations of the test compounds and the measurement of the mass of air supplied to the combustion chamber by measuring the pressure in the intake manifold (Figure 1c).

Table 1. Specifications of the Axion RS portable exhaust emissions analyser [15].

Gas	Measurement Range	Sensitivity	Specifications
HC Propane	0–4000 ppm	±3%	1 ppm
CO	0–10%	±3%	0.01 vol.%
CO_2	0–16%	±3%	0.01 vol.%
NO_x	0–4000 ppm	±4%	1 ppm
O_2	0–25%	±3%	0.01 vol.%

Mobile fans commonly used in rescue and firefighting operations were tested. The first is a conventional MW22 (W1) fan (Fogo Sp. z o.o., Wilkowice, Poland), with a Briggs & Stratton 750 engine of 4.4 kW and a displacement of 163 cm^3 (fan performance parameters according to AMCA 240 are 30,000 m^3/h). The second is a GX350 (W2) turbo fan (Ramfan, Spring Valley, NY, USA), with a Honda GX 200 engine of 4.1 kW and a displacement of 196 cm^3 (fan performance parameters according to AMCA 240 are 31,799 m^3/h). The devices are characterised by internal combustion power units, classified in the European Union as non-road machines covered by the legal provisions described in Regulation 2016/1628/E [16,17]. A common feature of the fans is the similar power range of the drive units. Properties of the fuel used during the test, gasoline, with the following parameters: density under reference conditions (liquid phase), 720–775 kg/m^3; density under reference conditions (gas phase), 0.74 kg/m^3; fuel calorific value, 42.6 MJ/kg; boiling temperature, 40–210 °C; excess air coefficient λ up to the ignitability boundaries, 0.4–1.4; motor octane number (MON), 85, and research octane number (RON), 95; and air–fuel ratio (AFR) for stoichiometric mixture (mass), 14.7:1 [18].

In the analysis of the measurement error, the arithmetic mean was taken as the estimator of the desired value, for which the confidence interval was calculated for the confidence interval $p = 0.05$. Statistical analysis was performed in accordance with the procedures appropriate for the normal distribution of the measured measurement points.

3. Results and Discussion

Tests measuring speed, torque, power, fuel consumption and emissions of CO_2, CO, HC and NO_x were carried out as a function of time (Figure 3). The test results for a conventional fan (W1) and a turbo fan (W2) depending on the method of measuring aerodynamic efficiency (A and B) are shown in Figure 4 for speed and Figure 5 for torque; and, from these parameters, the power was determined (Figure 6), according to Equation (1):

$$P = \frac{M \cdot n}{9549.3}, \text{ (kW)} \tag{1}$$

where:

P—power, kW;
M—torque, Nm;
n—rotational speed, rpm.

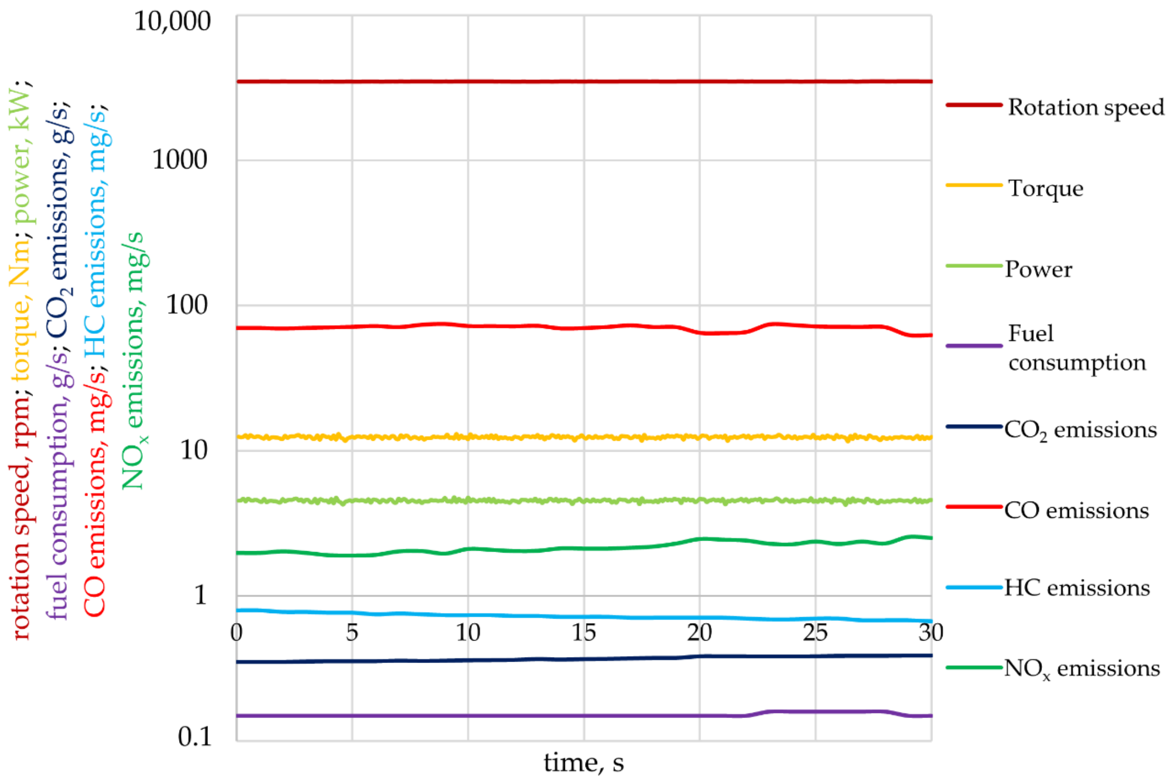

Figure 3. Example of characteristics of the tested parameters as a function of time for fan W1 during open flow measurement (Method B).

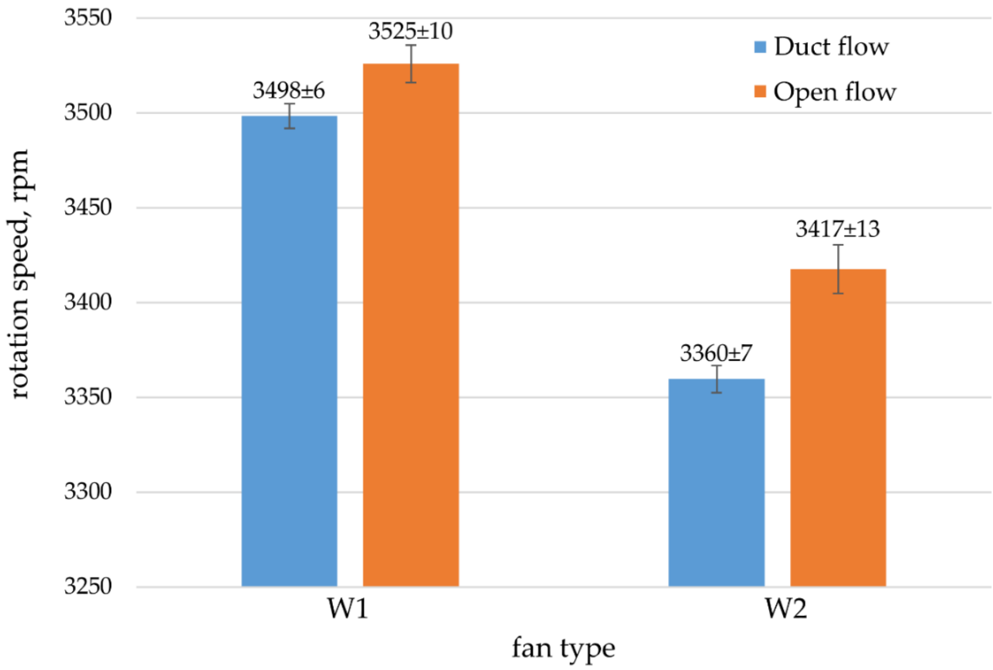

Figure 4. Mean speed during tests with Methods A (duct flow) and B (open flow), where W1—fan with conventional impeller, W2—fan with turbo impeller. All mean values were determined at a 95% confidence interval (p = 0.05).

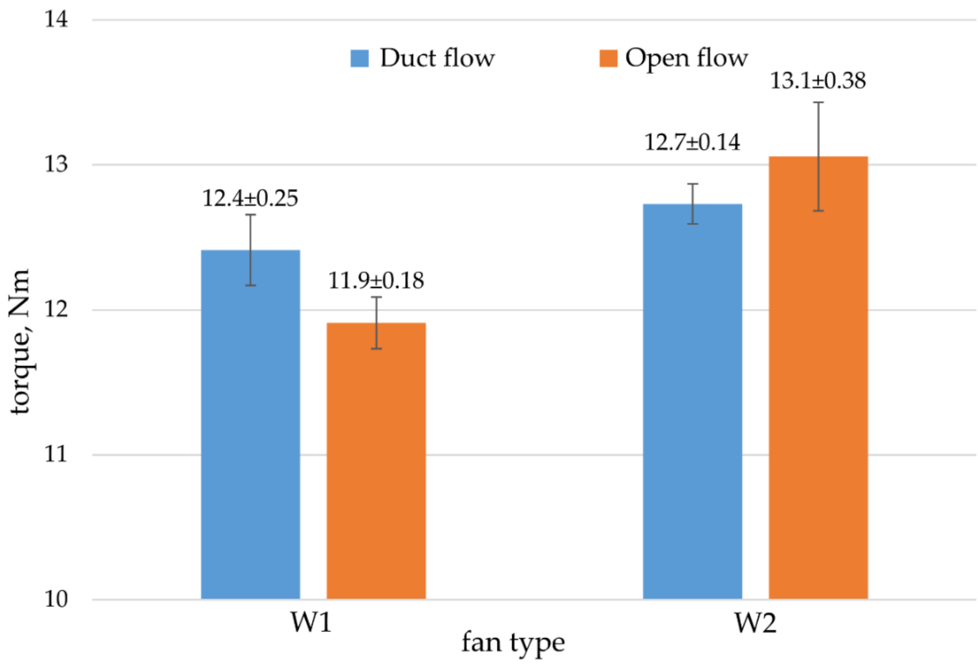

Figure 5. Mean torque during tests with Methods A (duct flow) and B (open flow), where W1—fan with conventional impeller, W2—fan with turbo impeller. All mean values were determined at a 95% confidence interval (p = 0.05).

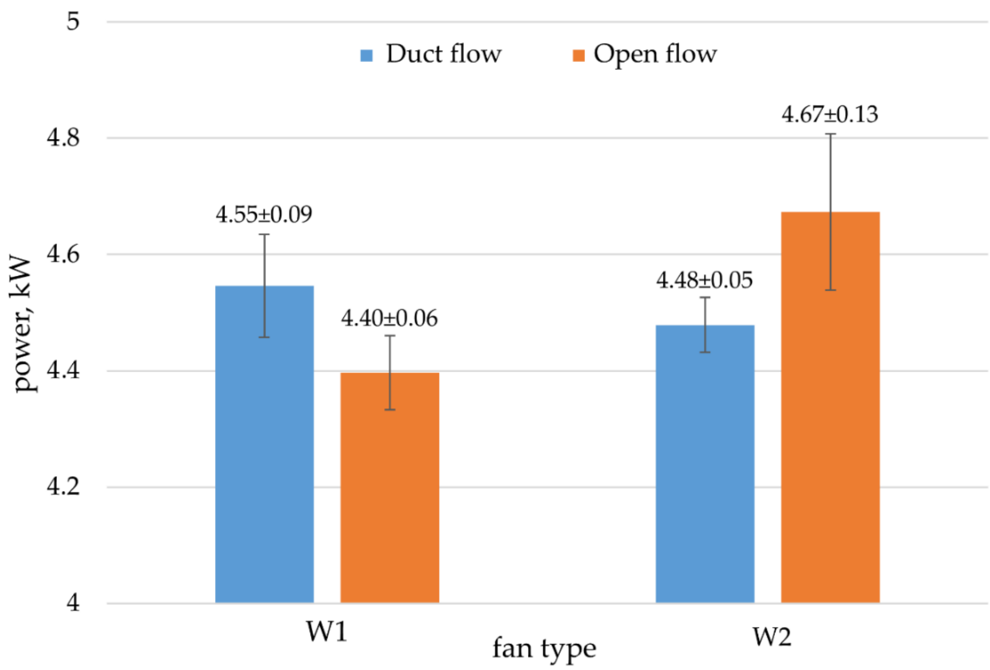

Figure 6. Mean power during tests with Methods A (duct flow) and B (open flow), where W1—fan with conventional impeller, W2—fan with turbo impeller. All mean values were determined at a 95% confidence interval (p = 0.05).

Based on the calculation algorithms built into the PEMS software, mean fuel consumption (Figure 7) and emissions of CO_2 (Figure 8), CO (Figure 9), HC (Figure 10) and NO_x (Figure 11) were determined.

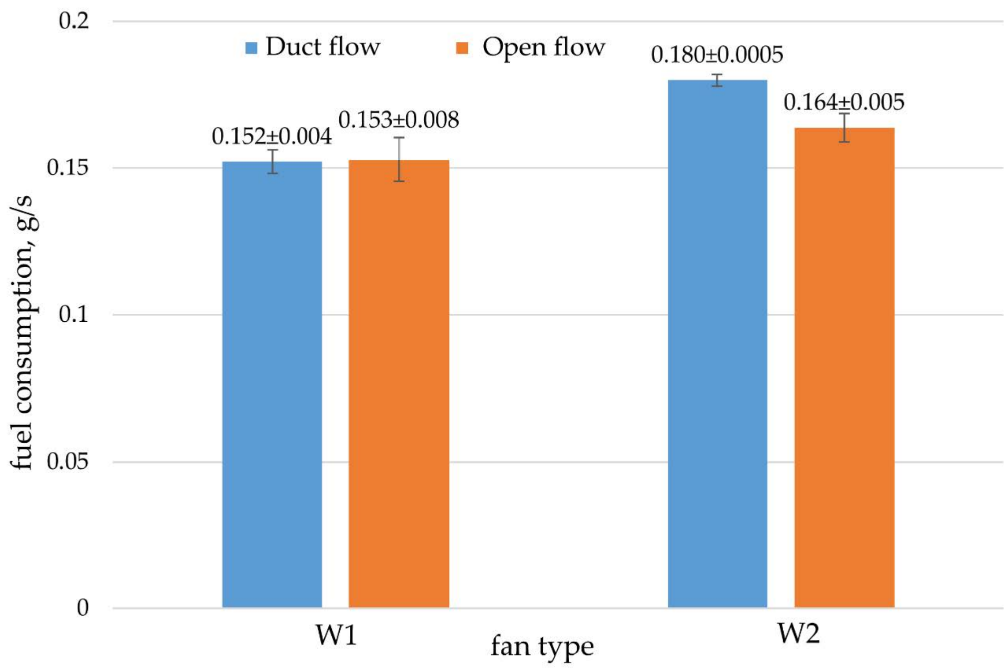

Figure 7. Mean fuel consumption during tests with Methods A (duct flow) and B (open flow), where W1—fan with conventional impeller, W2—fan with turbo impeller. All mean values were determined at a 95% confidence interval (p = 0.05).

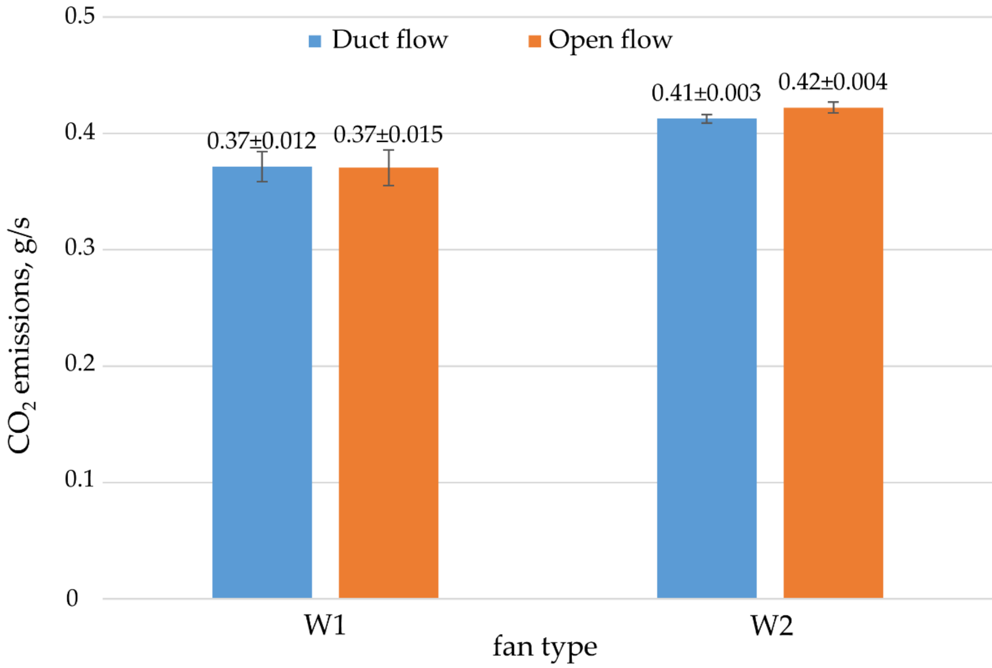

Figure 8. Mean CO_2 emissions during tests with Methods A (duct flow) and B (open flow), where W1—fan with conventional impeller, W2—fan with turbo impeller. All mean values were determined at a 95% confidence interval (p = 0.05).

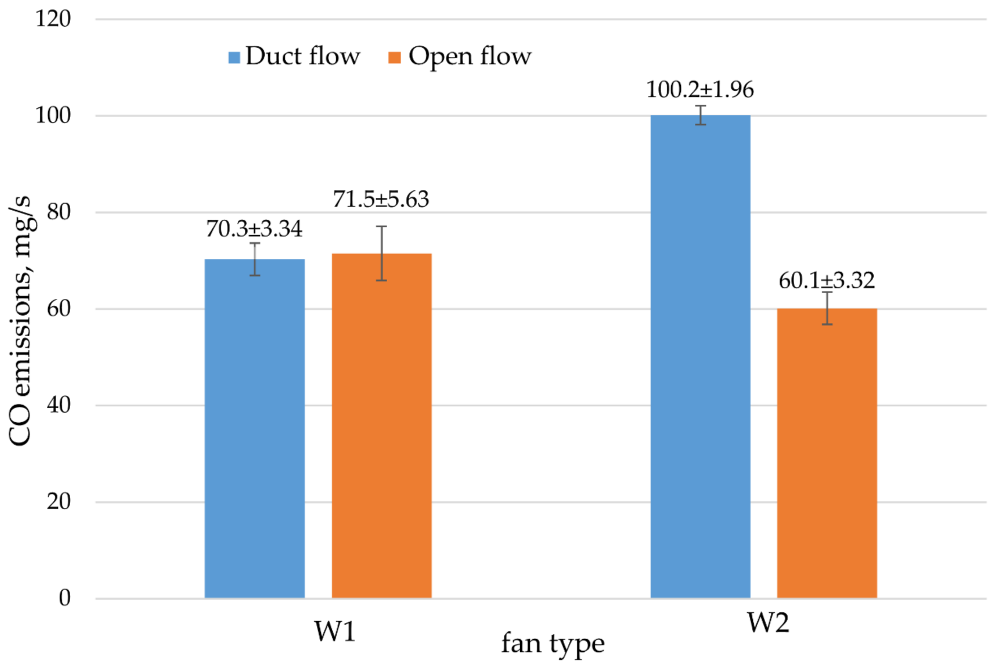

Figure 9. Mean CO emissions during tests with Methods A (duct flow) and B (open flow), where W1—fan with conventional impeller, W2—fan with turbo impeller. All mean values were determined at a 95% confidence interval (p = 0.05).

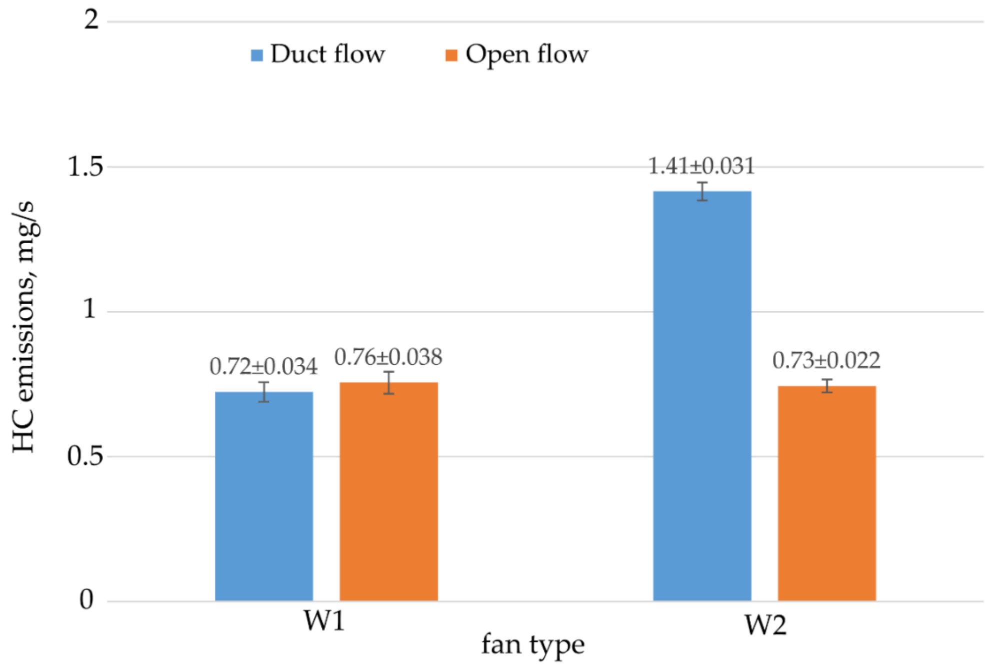

Figure 10. Mean HC emissions during tests with Methods A (duct flow) and B (open flow), where W1—fan with conventional impeller, W2—fan with turbo impeller. All mean values were determined at a 95% confidence interval ($p = 0.05$).

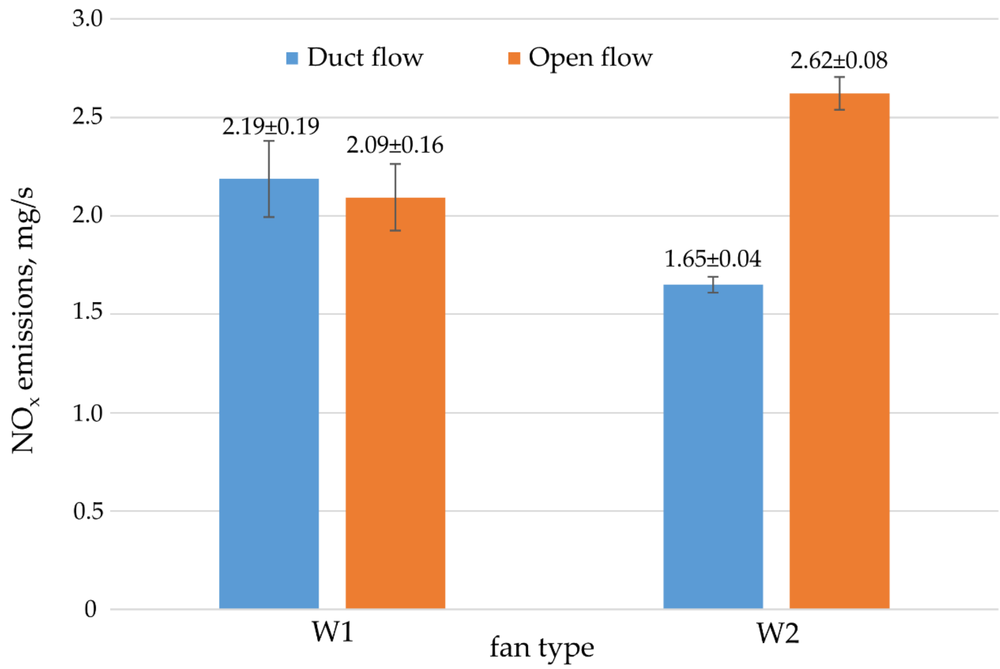

Figure 11. Mean NO_x emissions during tests with Methods A (duct flow) and B (open flow), where W1—fan with conventional impeller, W2—fan with turbo impeller. All mean values were determined at a 95% confidence interval ($p = 0.05$).

Measurement using Method A results in fans operating at a lower speed for both conventional (W1) and turbo (W2) fans. This is due to the fact that in Method B, the generated flux is dynamically dispersed in the surroundings and turbulently mixed with the air collected in the open space [19]. In Method A, on the other hand, the impeller must additionally overcome the pressure loss associated with the flow through the duct. This value is lower than in Method B by between 0.7% and 1.7%, depending on the type of fan tested (Figure 5).

For torque measurement, aerodynamic flow measurement methods affect fans differently depending on the type of fan impeller. Method A results in a torque increase of 4.2% for the conventional fan (W1) and a torque reduction of 3.1% for the turbo fan (W2). This indicates that turbo type fans (W2) are suitable for use in ventilation systems and have lower vapours when conveying air in ducts than fans with conventional impellers.

Variations in rotational speed (Figure 4) and torque (Figure 5) values affect the power value (Figure 6). The nature of the power variation depending on the aerodynamic flow measurement method is the same as for torque measurement. Method A results in a 3.2% increase in drive power for the conventional fan (W1) and a 4.1% reduction in power for the turbo fan (W2). This is also related to the reduction in resistance when the air is pumped in ducts by the turbo fans (W2).

Changes in the operating conditions of the drive unit (speed, torque and power) induced by the aerodynamic flow measurement method are observed in terms of fuel consumption and emissions. Fuel consumption for fans with a conventional impeller (W1) is identical, regardless of the method of measuring the aerodynamic flow (a difference in results of approximately 0.65%). In contrast, turbo fans during Method A tests had higher fuel consumption by 9.8% (Figure 7). This is consistent with the characteristics of internal combustion engines, which are characterised by higher fuel consumption as the load increases or as they operate at higher power levels [20–22]. Such performance characteristics of small non-road spark-ignition engines are also seen in other applications [23].

CO_2 emissions are strongly dependent on fuel consumption, as they arise from the combustion of hydrocarbon fuels and only occur when the mixture is completely burned. These emissions can be reduced by decreasing fuel consumption or using low-emission fuels [24]. For a fan with a conventional impeller (W1), the measurement method has no effect on the CO_2 emissions value, and for a turbo fan (W2), Method A results in a reduction in CO_2 emissions of approximately 2.4% (Figure 8). This coincides with the results for fuel consumption and drive unit load, which indicate that turbo fans (W2), when measured in duct flow (Method A), have a lower load and, thus, lower fuel consumption and CO_2 emissions. Due to the analysis in terms of greenhouse gas emissions, of which carbon dioxide (CO_2) is one of the main ones, Method A is preferable for turbo fans (W2). However, in terms of CO_2 emissions, there is little evaluation of the operational parameters and changes in this value due to the measurement method used.

CO emissions, on the other hand, are the result of incomplete combustion of the fuel. For the fans tested, the aerodynamic flow measurement methods result in a 1.7% reduction in CO for W1 fans during Method A tests and a 67% increase for W2 fans (Figure 9). This indicates that disturbing the fan impeller load (W2) in duct flow (unloading) causes a disturbance in the control of the fuel–air mixture, contributing to a significant increase in CO emissions. CO emissions are unavoidable in internal combustion engines because the combustion chamber never allows the carbon to burn completely. By also observing the increase in HC emissions and the reduction in NO_x, it can be assumed that the mixture is rich. The result is that the engine operating conditions are relieved, and the air–fuel mixture control process does not take this parameter into account, dosing the fuel according to a higher load assumption for the set speed. It can be assumed that the process of adjusting the composition of the fuel–air mixture for a turbo and conventional fan engine takes place under conditions close to real life, i.e., according to the open flow method (Method B).

HC emissions are caused by the presence of unburned fuel particles in the exhaust gas and indicate operation with a rich mixture. For fan W1, Method A results in a 5.2% reduction in HC emissions, while for fan W2, it results in an increase of 93.2% (Figure 10). These results confirm the analysis of the fuel–air mixture control problem during operation of the W2 fan under test A conditions; and also the results of the NO_x emissions, which are the result of the high combustion temperature and free oxygen particles characteristic of lean mixtures, i.e., with an excess of air over fuel relative to the stoichiometric mixture. For fan W1, Method A results in a 4.8% increase in NO_x emissions, while for fan W2, it results in a 37% reduction (Figure 11). In the case of fans with a conventional W1 rotor, Method A causes the drive unit to run on slightly depleted mixtures.

It can be observed that fans with a conventional impeller (W1) have less impact on the drive unit during Methods A and B tests than turbo fans (W2). This means less disturbance to the fuel–air mixture control process. Fans with a turbo rotor (W2) have a problem with controlling the fuel–air mixture during Method A tests. Emissions of harmful exhaust compounds in the tested engines of about 4.2 kW are, for CO_2 levels, from 0.37 g/s to 0.42 g/s; CO, from 60.1 mg/s to 100.2 mg/s; HC, from 0.72 mg/s to 1.41 mg/s; and NO_x, from 1.65 mg/s to 2.62 mg/s, which is in line with the results of other research on engines of similar power outputs [25,26].

Observations of the exhaust emissions, and the demonstration that the turbo fan (W2) exhibits significant fuel–air mixture disturbances (rich-mix operation) during Method A tests, allow us to conclude that, despite lower aerodynamic drag on the rotor, the maladaptive fuel supply system results in operation with increased air pollution parameters. In addition, an inappropriate choice of fuel–air mixture under these conditions can contribute to the drive unit achieving less power, and thus the aerodynamic characteristics of the fan can also be lower. This is a further conclusion that Method A, a poorer representation of actual operating conditions compared to Method B, may not be objective in assessing the aerodynamic and operational performance of mobile fans. The operation of the turbo fans in aerodynamic performance measurement conditions using Method A can be improved by the fuel supply system of the power unit. Currently, the European market is dominated by small spark-ignition (SI) non-road engines, whose fuel supply systems are based on carburettors [16] and whose precision in controlling the fuel dose and its selection is severely limited [17].

Another equally important aspect of determining the characteristics of the operating conditions of the fans tested is the European approval tests for internal combustion engines. Determining the operating conditions of the power unit, mainly speed and torque, is important for the selection of the test during EU power unit approval tests [17,27]. The test procedures for small non-road spark-ignition (SI) engines provide for the selection of an approval test for the operating conditions under which the equipment will generally operate. In case of portable fans, it can be assumed that they will operate at full capacity, as confirmed by the test results.

The tested engines, according to European Union approval regulations (Regulation (EU) 1628/2016), are classified in the category NRS-vr/vi-1b, which applies to small SI non-handheld engines with a power of less than 19 kW and a displacement of up to 225 cm^3. According to Stage V, which has been in force since 2019, the emission limits for this type of engine are CO 610 g/kWh and HC + NO_x 8 g/kWh [16,17,27]. The tested engines, according to Figure 6, were characterised during the tests with power ranging from 4.40 to 4.67 kW. Assuming the operation of these machines in such conditions for one hour of operation, the value of consumed energy can be assumed to be at a level of 4.40 to 4.67 kWh. This means the assumed admissible CO emissions are equal to 60.1 $\pm$ 12 gkW/h, which are lower than the admissible limits by 90.1%. On the other hand, the mean emissions of HC + NO_x are equal to 2.4 $\pm$ 0.2 g/kWh, which means that they are lower than the permissible limits by 70%. The research is consistent with the results of other scientists who studied the engines of mobile non-road machines in real working conditions; e.g., Mayer et al., in 1999, showed CO emissions at a level of 180 g/kWh and HC + NO_x at a level of 12.6 g/kWh [28]. Mitianiec and Rodak, in 2012, tested a 4.5 kW (two-stroke) engine, showing CO_2 emissions at a similar level of 100 g/kWh. On the other hand, HC + NO_x emissions were significantly higher, at about 60 g/kWh, confirming the problems in controlling the fuel–air mixture for two-stroke engines [29]. The research is based on the current trend of testing the emissions of harmful exhaust gases from machines and vehicles in real working conditions [30–32].

4. Conclusions

The methods for measuring the flow characteristics of positive pressure ventilators used in rescue operations affect the performance of the drive units of these devices. Depending on the type of fan impeller and test method, the motor drive power required to drive the fan impeller can vary by 7.7%. The methods for measuring flow parameters affect drive power oscillations, which contributes to disturbances in the control of the fuel–air mixture composition. During testing, it was observed that fans with a conventional impeller (W1) had a reduction in CO of 1.7%, HC of 5.2%, an increase in NO_x of 4.8% and no effect on CO_2 emissions or fuel consumption during Method A tests relative to the open flow method (Method B). In the case of fans with a turbo impeller (W2), greater differences can be observed: a reduction in CO_2 of 2.4% and NO_x of 37%, an increase in CO of 67% and HC of 93.2%, and a slight impact on fuel consumption. Fans with turbo impellers (W2) are more susceptible to the influence of the flow rate test method. When tested using the duct flow method (Method A), they had higher emissions of harmful exhaust gases. Fan drive units of the conventional type (W1) are less influenced by the test method for evaluating flow parameters and have less variation in operating parameters such as fuel consumption or harmful exhaust gas emissions. The research also showed that, depending on the research test, fans may have problems with controlling the composition of the air–fuel mixture. Future research can be expanded to include a larger group of fans and drive unit types. The results presented here indicate that it is important to consider the operating conditions, e.g., the type of test (duct flow according to EN ISO 5801 or open flow according to ANSI/AMCA 240-15), when assessing the performance of mobile fans, such as fuel consumption or emissions of harmful compounds in the exhaust gas. The research conducted is in line with the contemporary scientific trend, testing machines under real working conditions or in terms of the influence of laboratory conditions on discrepancies in test results under real conditions.

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