

SMART PNEUMATIC AIRBAG-TYPE ENERGY ABSORBER – DESIGN AND DEVELOPMENT

**BLAZEJ POPLAWSKI, JAN STOPPEL, MARIUSZ OSTROWSKI, RAFAŁ
WISZOWATY AND RAMI FARAJ**

Institute of Fundamental Technological Research
Polish Academy of Sciences
Pawinskiego 5B, 02-106 Warsaw, Poland
e-mail: bpop@ippt.pan.pl

Abstract. Large pneumatic airbag-type energy absorbers, such as rescue air cushions, are inherently passive structures. Large size, low stiffness, high displacements during the impact as well as large gas volume enclosed inside the airbag – these are, among others, the biggest obstacles preventing the development of adaptation strategies for these devices. Therefore, their ability to actively adjust their mechanical properties in real-time, based on detected impact parameters, is highly limited. Real-time adaptation seems impossible or extremely challenging to be implemented for such devices. Nevertheless, adaptation of their properties, based on the impact parameters estimations taken before its occurrence, yields promising results.

This study explores the challenges in developing an adaptive pneumatic airbag-type energy absorber. Key aspects include designing an adaptation strategy, implementing the physical adaptation system within the airbag, conducting numerical simulations, experimentally testing the system, and advancing toward full autonomy. Achieving autonomous operation requires several critical steps, primarily the accurate estimation of impact parameters for a falling object. To accomplish this, various methods capable of detecting, tracking, and estimating the object's trajectory must be evaluated, implemented, tested, and compared from multiple perspectives. Promising approaches include radar, lidar, and computer vision, with computational cost being the most crucial factor, as it directly affects processing time. Once an effective impact parameter estimation system is established, it will be integrated with the control system responsible for executing the adaptation strategy, ultimately enabling fully autonomous operation.

Key words: Adaptive Rescue Cushion, Adaptive Airbag, Pneumatic Energy Absorber, Adaptive Impact Absorption, Impact Parameters Estimation

1 INTRODUCTION

Rescue air cushions are intended to safeguard individuals who jump or fall from significant heights. Although their initial use dates back to the 20th century, they represent one of the most recent developments in fall protection systems to gain widespread acceptance among regulatory

authorities. Despite their long presence, their design has not changed much since the first devices of this type. Their operational principle relies on generating a pneumatic force – similar to that employed in automotive airbags – to decelerate the falling person as gently as possible upon impact. However, practical applications indicate that achieving satisfactory levels of load attenuation and operational safety remains a significant challenge. They are most commonly used in emergency situations, such as evacuation from a burning building or assisting during suicide attempts by jumping from height.

For such a device to be approved for use by qualified safety personnel, such as firefighters, it must undergo a formal certification procedure as stipulated in national standards (e.g. DIN 14151 [1]) or special regulations issued by authorized public administration authorities (e.g. the Polish regulations outlined in [2]). Despite undergoing formal certification procedures, rescue cushions are still regarded as relatively hazardous devices. Consequently, their deployment is recommended only as a last resort, with ladder trucks remaining the preferred method for assisting individuals at risk of falling.

Rescue cushions demonstrate substantially diminished effectiveness when subjected to fall parameters outside their designated operational conditions. This inherent performance degradation justifies their classification as a last-resort intervention in emergency situations. This is also supported by the fact that documented fatalities have occurred during training exercises, where a firefighter died while jumping onto a rescue cushion from relatively low height.

Integration of smart technologies into such structures could significantly improve shock absorption efficiency across diverse impact conditions, representing an important societal benefit. However, all currently available devices of this type remain entirely passive in design. Notably, neither academic nor industrial sectors have demonstrated meaningful progress in this area, leaving the problem of their low efficiency unsolved. Our research so far proved that integrating adaptation mechanisms into these devices is possible and effective [3, 4]. This paper presents a general overview of the impact absorption efficiency of rescue cushions, outlines our findings on potential improvements through the adaptation of their characteristics, and explores the integration of smart functionalities enabling autonomous adjustment of the device.

2 OPERATION PRINCIPLE AND PERFORMANCE IMPROVEMENT

Rescue cushions are, in essence, large-scale airbags whose operating principle relies on the generation of a pneumatic counterforce. This force arises from the rapid compression of air within the cushion upon impact, effectively opposing and dissipating the kinetic energy of a falling individual. Improvement of its energy dissipation effectiveness results in reduction of peak forces transmitted to the body, thereby mitigating the risk of injury. This issue has been acknowledged by German regulatory authorities, who, in the standard specifying the approval criteria for rescue cushions intended for the German market, have stipulated that the maximum accelerative loads transmitted to a person during impact must not exceed 80 g for the head and 60 g for the thorax and pelvis, with these limits applying to durations exceeding 3 ms [1].

Figure 1 illustrates a comparison between the theoretical time profiles of impact force experienced by a falling individual when landing on a conventional rescue air cushion and on

a cushion with improved energy dissipation efficiency. A corresponding comparison in the force–displacement domain is shown in Figure 2.

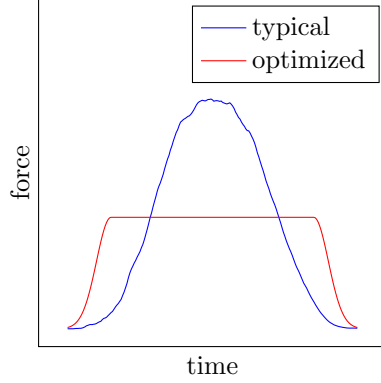


Figure 1: Typical and improved force-time curve during impact

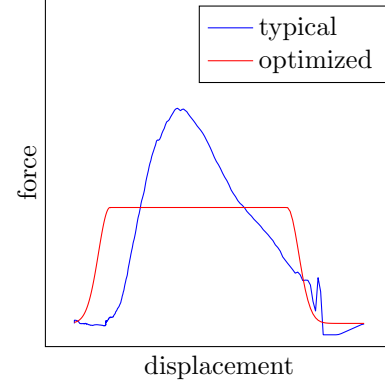


Figure 2: Typical and improved force-displacement curve during impact

The force profiles resulting from impact on a standard rescue cushion typically exhibits a bell-shaped curves, characterized by a pronounced peak. Any proposed improvements should aim to reshape these profiles to more closely resemble the curves labelled ‘optimized’ in the figures, thereby reducing the peak force transmitted to the body. In both cases, the optimized cushion design demonstrates a significant reduction in peak impact force and a broader distribution of force over time or displacement, indicating more effective energy absorption. These characteristics are critical for minimizing injury risk and enhancing the overall safety performance of rescue cushions. Lowering the peak force is critical for minimizing the risk of injury, as it directly decreases the maximum stress experienced by different parts of the human body during deceleration. Ideally, the initial phase of impact would involve the compression of the gas within the airbag without any leakage, allowing for the efficient build-up of internal pressure. Once the force exerted on the falling individual reaches a predefined threshold, a controlled release of gas would commence to maintain a near-constant force plateau, thereby extending the deceleration duration while limiting peak force. Following the completion of the deceleration process – prior to ground contact – the reaction force would rapidly diminish to zero, indicating a safe and complete energy dissipation.

Several factors inherent to the impact dynamics of rescue cushions hinder the achievement of an optimal force-time distribution. The large physical dimensions of the cushion entails a substantial internal gas volume, which in turn requires extensive venting areas to facilitate adequate gas expulsion during impact. This imposes the need for a significant variation in out-flow area between the initial pressure build-up phase and the subsequent force plateau phase. Achieving precise real-time control of this gas release would demand highly responsive actuators capable of maintaining accuracy across a wide operational range. Additionally, the use of flexible membrane materials in the construction of the cushion further complicates the continuous control of gas discharge, as such materials may deform unpredictably under dynamic

loading. Compounding these challenges is the short duration of the impact event – typically in the range of 100 to 200 milliseconds – which necessitates extremely rapid and coordinated system response. These constraints significantly limit the feasibility of implementing real-time control mechanisms, as the required precision and response speed are difficult to achieve under the given conditions. Consequently, a more viable approach involves enhancing energy dissipation efficiency through passive means or by pre-adjusting the performance characteristics of the cushion based on estimated impact parameters obtained prior to the event.

3 RESCUE CUSHION DESIGN

Rescue air cushions are conventionally categorized into two principal types: (1) pneumatic-frame systems, which employ an inflated structural frame to maintain cushion shape, and (2) fan-inflated systems, which utilize high-capacity fans to continuously supply air for shape preservation. The typical configurations of both types of rescue cushions are shown in Figure 3. Specifically, the pneumatic-frame variant is depicted in Figure 3a, while the fan-inflated version is illustrated in Figure 3b.



Figure 3: Exemplary rescue air cushions (AI generated)

3.1 PNEUMATIC-FRAME CUSHION

This type of rescue air cushion incorporates a deformable frame structure inflated with compressed air (airtight pneumatic frame), over which a membrane is tensioned to form the airbag. Prior to impact, the internal pressure within the cushion is equal to atmospheric pressure. The

membrane is equipped with discharge orifices/vents that allow air to escape during compression. These orifices are dimensioned to induce choked flow conditions, thereby generating a desirable pressure increase as the cushion deforms. Simultaneously, they are sufficiently large to limit the back-bounce effect from the air cushion. One of the earliest documented references to this type of rescue cushion appears in a patent application by Peter Lorsbach [5]. Since its introduction, the fundamental design has remained largely unchanged.

An advantage of using a pneumatic frame to maintain the shape of the air cushion prior to impact is the possibility of transporting the deployed device, along with the ease and speed of its deployment. The cushion is deployed by filling the frame with compressed gas from a cylinder, after this relatively low time consuming process, the device is ready to absorb a fall. Due to the airtightness of the frame, the device does not require continuous gas supply, which allows for its free relocation within the boundaries of the rescue operation area.

The primary limitation of this design lies in the relatively small top surface area of such rescue cushions. Scaling up the cushion is constrained by the increasing structural demands placed on the frame, as larger dimensions require proportionally greater rigidity to maintain stability. One way to achieve the necessary rigidity is by increasing the internal pressure within the airframe; however, this may exceed the mechanical limits of the materials typically used, potentially necessitating a change to stronger, and often heavier or more expensive, materials. Additionally, enlarging the cushion and its supporting frame leads to a significant rise in the volume of compressed air required for deployment, complicating both storage and operational logistics, as the cylinder with compressed gas, used for filling the pneumatic frame, would be much bigger and heavier. This increase in volume not only extends the deployment time but also adds to the overall weight of the system, thereby reducing portability and limiting its practicality for rapid-response scenarios.

3.2 FAN-INFLATED CUSHION

In fan-inflated rescue cushions, a slight internal overpressure – maintained by the continuous inflow of air from external fans and the regulated outflow through orifices or vents (similar to those used in pneumatic-frame cushions) – allows the structure to retain its shape. This approach facilitates the construction of rescue cushions in virtually any size and reduces the requirement for airtightness, as only a minimal overpressure is needed to maintain its shape. Larger cushion heights significantly enhance impact absorption from higher falls, while increasing the top surface area has been shown to positively influence the psychological comfort of individuals preparing to jump. Consequently, the scalability of fan-inflated systems represents a major advantage over pneumatic-frame designs. However, their primary drawback lies in their stationary nature, due to the necessity of a continuous connection to the air supply system and much greater weight.

As with pneumatic-frame rescue cushions, the fundamental design of fan-inflated systems has remained largely unchanged since their initial development, as documented in John Scurlock's patent application [6].

4 ENERGY ABSORPTION IMPROVEMENT METHODS

As mentioned earlier, passive rescue cushion systems typically produce force-time (force-displacement) profiles with a bell-shaped curve during impact (see Figures 1 and 2). Achieving a force distribution that more closely approximates the optimal profile necessitates the incorporation of adaptive or intelligent/smart features. Such enhancements would enable the system to modify its response characteristics based on pre-estimated impact parameters.

Rescue cushions of pneumatic-frame type may incorporate passive design features aimed at enhancing their energy absorption performance. For instance, one of the earliest patents for such rescue cushions proposed the inclusion of a horizontal bulkhead positioned at mid-height within the cushion, intended to be nearly impermeable to air flow [5]. This internal partition was designed to equalize pressure distribution within the device during impact. In contemporary designs, such bulkheads are still present; however, they typically include large openings that prevent the establishment of significant pressure differences between the upper and lower chambers, thereby limiting their intended function.

In the case of pneumatic-frame rescue cushions, regulating the venting area through adjustable orifices appears to be the most viable approach for achieving adaptive behaviour. The effectiveness of this method has been demonstrated in laboratory-scale experiments [3, 4]. Using this technique, the venting area can be tailored to manually estimated impact parameters by referencing predetermined "choice surfaces" – surfaces that define the optimal venting area as a function of key parameters, such as impact velocity and the mass of the falling individual, taking into account possible errors in estimates. However, manual estimation of these parameters is prone to significant inaccuracies. To mitigate this, the choice surfaces must incorporate safety margins, which inherently reduces the system's potential for optimal energy absorption. Moreover, reliance on manual estimation is often viewed by potential operators as risky, as it places a high degree of responsibility on human judgment in critical situations.

Fan-inflated rescue cushions, owing to their operating principle, offer potential for enhancement through the integration of at least two intelligent control features. As with pneumatic-frame systems, one possibility is to regulate the venting area of the outflow orifices ("breathers") based on estimated impact parameters. Alternatively, the volumetric airflow supplied by the attached fan could be actively controlled to adjust the internal pressure within the airbag. However, this latter approach faces significant limitations. Standard large-scale fan-inflated rescue cushions are certified for use in falls from heights of up to 60 meters. Free-fall duration from such height lasts approximately 3.5 seconds. This time frame is generally insufficient for conventional industrial fans – typically constructed from steel and characterized by high rotational inertia – to achieve meaningful changes in rotational speed, generated airflow and, consequently, built overpressure. Figure 4 illustrates this phenomenon: preliminary tests revealed that the fan supplying gas to the rescue cushion requires approximately 30 seconds to transition from zero to maximum volumetric flow rate, with pressure stabilization occurring after an additional 10-second delay (~40 seconds total from initiation). This observation further challenges the feasibility of implementing real-time adaptability through fan control. Moreover, the limited

pressure difference achievable by the tested fan presents an additional constraint. Specifically, the fan under investigation was capable of generating an overpressure of approximately 150 Pa (see Figure 5). Range of pressure variation such fans can produce is relatively limited compared to the rapid and substantial pressure changes induced by impact events (see Figure 6 for comparison of pressure levels generated by the fan supplying the airflow and the impact in standard conditions). These limitations favour the use of controllable outflow vents over the regulation of fan operation as a means of adapting the cushion’s performance. One possible advantage of fan-inflated rescue cushions is the possibility of placing the venting elements within the duct connecting the fan to the cushion. Since this duct maintains a relatively stable shape during impact, it may offer improved consistency between numerical simulations and experimental results, compared to vents mounted directly on the deformable sidewalls of the cushion.

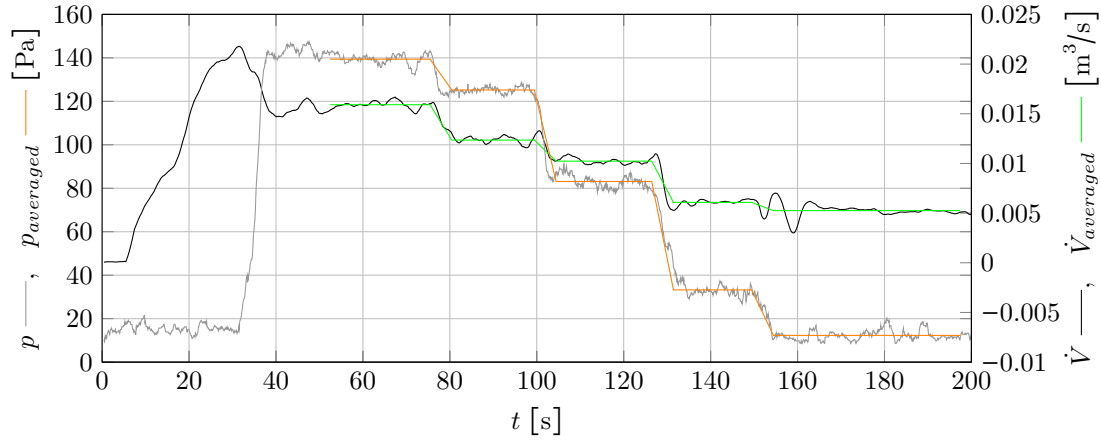


Figure 4: Time histories of internal pressure within the rescue cushion and the volumetric air-flow rate generated by the supply fan

5 IMPACT PARAMETERS ESTIMATION SYSTEMS

A remote impact parameters estimation system represents a critical component of an intelligent rescue cushion. It enables the automatic adaptation of the system’s performance characteristics, irrespective of the cushion type – whether pneumatic-frame or fan-inflated – as it functions as an independent module. This system can be integrated with adaptive cushions, currently operated manually, by allowing for automatic recognition of impact parameters, thereby eliminating the need for operator input.

Two fundamentally distinct methodological approaches can be identified for remote impact recognition: vision-based and wave-based systems.

Vision-based techniques have gained significant attention in recent years. Numerous methods have been developed for estimating the distance to observed objects, ranging from traditional stereo vision algorithms [7, 8] to more recent monocular vision approaches [9]. A principal limitation of these methods is that depth estimation remains inherently indirect – no

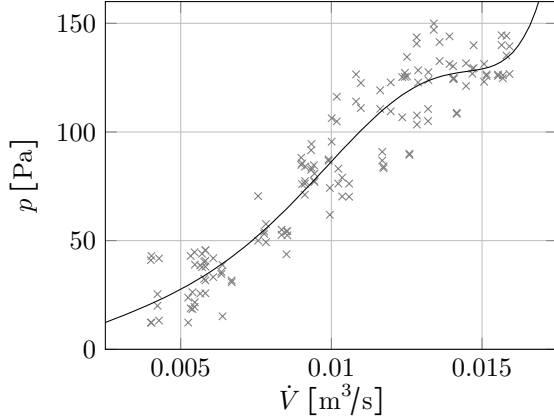


Figure 5: Pressure in the cushion obtained by various volumetric flow rates of the air

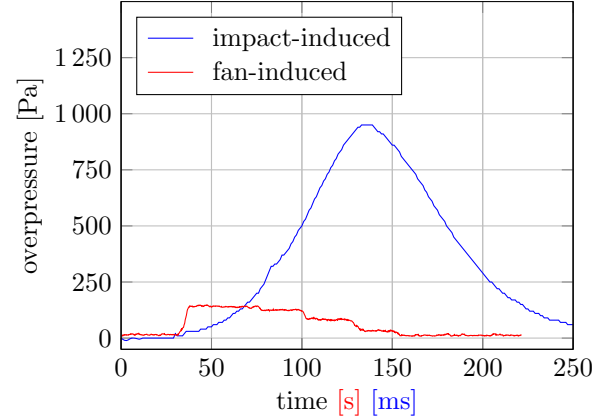


Figure 6: Pressure in the cushion as a result of maximal fan power (red) and impact (blue)

vision-based system can directly measure distance, as the estimation relies on geometric inference or learning-based approximations.

In addition to depth estimation, accurately detecting, classifying, and tracking the object of interest is essential for effective impact parameter recognition. A wide variety of techniques have been developed for this purpose, with deep neural network-based methods currently dominating the field. These can be categorized into two primary classes: single-stage detectors, such as the Single Shot Multibox Detector (SSD) [10], and two-stage detectors, such as Region-based Convolutional Neural Networks (R-CNN) [11]. Historically, two-stage methods offered superior accuracy at the cost of significantly greater computational complexity. However, recent advances in single-stage models have led to notable improvements in both computational efficiency and detection accuracy. Among these, the YOLOv8 framework has demonstrated state-of-the-art performance in object detection and tracking tasks [12].

An alternative class of methodologies, capable of directly measuring the distance to an object of interest, involves the use of wave-based systems comprising wave emitters and receivers. Depending on the nature of the wave employed, these systems can be categorized as ultrasonic, radar, or LiDAR. Ultrasonic devices operate using sound waves, while radar and LiDAR systems utilize electromagnetic waves at differing frequency ranges. Due to the relatively low frequency – and consequently long wavelength – of ultrasound, such systems are generally unsuitable for accurately detecting objects with dimensions comparable to the human body. In contrast, high-frequency radar and LiDAR sensors are highly effective for this application, offering the spatial resolution necessary for precise detection and tracking of human-sized targets.

Both wave-based methodologies – LiDAR and radar – offer distinct advantages and limitations in the context of human body recognition and tracking. The very high frequency of LiDAR, typically in the hundreds of terahertz, enables the detection of small objects due to the inverse relationship between wavelength and object resolution; shorter wavelengths allow for finer spatial discrimination. However, this high frequency also makes LiDAR signals more sus-

ceptible to atmospheric attenuation. Substances such as fog, rain, water vapour, or smoke can significantly absorb or scatter the signal, thereby degrading performance in adverse environmental conditions. In such scenarios, high-frequency radar systems – operating at 24 GHz, 77 GHz, or 79 GHz – present a more robust alternative. Although they offer lower spatial resolution compared to LiDAR, their longer wavelengths enable greater penetration through atmospheric obscurants, making them better suited for reliable operation in challenging environments.

Regardless of the selected approach, these methods offer distinct advantages over computer vision techniques by enabling direct distance measurements and permitting volume estimation of falling objects through methods such as voxelization.

The optimal performance of both methods can be achieved through the application of data fusion techniques.

6 TESTING EQUIPMENT

To reliably evaluate potential enhancements in the energy dissipation performance of rescue cushions, several experimental setups were developed.

The primary and most essential apparatus is the drop tower (see Figure 7a), which enables the simulation of vertical falls from heights of up to 6 meters. Planned modifications to the tower include a mechanism capable of imparting an initial vertical velocity to the falling object, thereby replicating the conditions of falls from greater heights. Additionally, the system will be equipped to introduce horizontal velocity components, enabling the simulation of parabolic trajectories representative of real-world jumping scenarios.

Currently, the test objects being dropped consist of plates and spheres, in accordance with the certification procedures outlined in the DIN standard [1] and relevant Polish regulatory documentation [2]. However, to more accurately replicate the biomechanical response of a human body during impact, a manikin with limited joint mobility is being developed (see Figure 7b). This manikin will be outfitted with a data acquisition system designed to measure accelerations in three critical regions: the head, thorax, and pelvis.

An additional experimental setup was developed for laboratory-scale testing of axial fans. This system was designed in accordance with the ISO standard specifying test methods for industrial fans [13]. It enables the evaluation of fan-inflated rescue cushions constructed at laboratory scale (see Figure 8).

7 CONCLUSIONS

Rescue air cushions play a vital role in public safety; however, they have received limited attention from both academic and industrial communities. Their current energy dissipation capabilities could be significantly enhanced through the integration of intelligent features. An independent system for estimating impact parameters would enable the full automation of adaptive mechanisms incorporated into rescue cushions. This system could be optimized through the fusion of data obtained from computer vision techniques and wave-based sensors such as LiDAR or radar.



(a) Drop tower for testing purposes

(b) Dummy imitating a falling person

Figure 7: Drop testing equipment

Although current certification procedures do not require the use of manikins that replicate the biomechanical behaviour of the human body, incorporating such test devices into both experimental and computational studies would be highly advantageous. This is particularly important given that the effectiveness of energy dissipation in rescue cushions is strongly influenced by the specific characteristics of each impact event.

The research campaign undertaken to enhance the energy dissipation characteristics of rescue cushions holds considerable promise for advancing the state of the art in impact mitigation technologies. By improving the performance of these devices, particularly in terms of reducing peak impact forces and adapting to a wider range of fall conditions, the safety and survivability of individuals in emergency scenarios can be significantly increased. In turn, this could lead to meaningful societal benefits, including the reduction of injury severity and fatalities in high-risk situations such as building evacuations or rescue operations. Moreover, from an economic perspective, the widespread deployment of more effective rescue cushions may reduce health-care costs associated with fall-related injuries and lower the liability risks faced by emergency service providers and building operators.

Continued research and development in this area not only addresses a critical gap in safety technology but also contributes to broader public health and emergency preparedness goals.

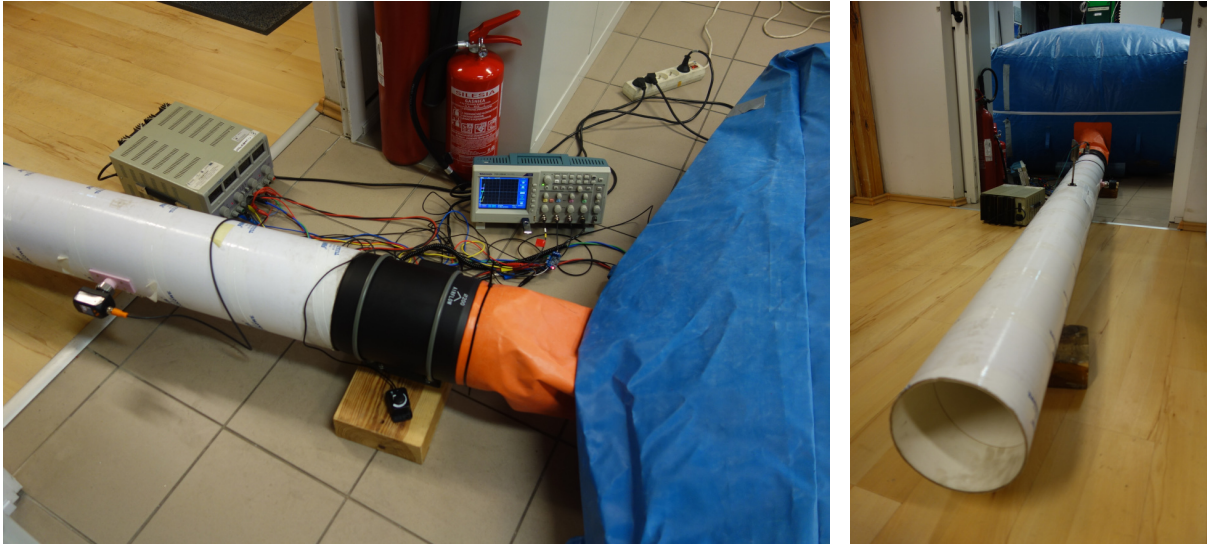


Figure 8: Fan testing equipment

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL, Google Translate and LLMs in order to correct language, grammar, and punctuation of the text. After using these tools, the authors reviewed and edited the content and take full responsibility for the content of publication.

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