Technologia i Automatyzacja Montażu

Volume 125, Issue 3/2024, Pages 12-20
https://doi.org/10.7862/tiam.2024.3.2

Original Research

HORIZONTAL LAMINAR FLOW CABINET WITH A LOW BACKGROUND AND CLEAN AIR

POZIOMA KOMORA LAMINARNA Z NISKIM TŁEM I CZYSTYM POWIETRZEM

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Abstract

The publication presents the design, construction of a prototype, and the course of verification tests of a special horizontal laminar flow cabinet made entirely of plastics. In the cabinet design process, numerical simulations and airflow analyses were used to achieve a laminar, uniform flow in the device's workspace. A prototype was built and subjected to verification tests regarding the intensity and nature of airflow as well as air cleanliness. The cabinet is equipped with its own filtration-ventilation module providing clean air to the workspace and removing used air to the external ventilation system. It ensures an increased level of protection for workers dealing with microorganisms and hazardous airborne chemicals, as well as complete corrosion resistance inside the workspace. A particular area of application for the cabinet is research involving radionuclides, volatile, toxic chemical compounds for which air-recirculating devices cannot be used in the room where they are placed. The developed solution has been protected by industrial property rights and used to implement a contract for the supply of a set of equipment to the laboratory of the Institute of Nuclear Physics of the Polish Academy of Sciences.

Keywords: laminar flow cabinet, prototype, airflow testing

Streszczenie

Publikacja przedstawia projekt, budowę prototypu oraz przebieg badań weryfikacyjnych specjalnej komory laminarnej o poziomym przepływie powietrza wykonanej w całości z tworzyw sztucznych. W procesie projektowania komory wykorzystano symulacje numeryczne i analizy ruchu powietrza w celu uzyskania laminarnego ujednoliconego przepływu w przestrzeni roboczej urządzenia. Zbudowano prototyp i poddano badaniom weryfikacyjnym pod względem intensywności i charakteru przepływu oraz czystości powietrza. Komora jest wyposażona we własny moduł filtracyjno-wentylacyjny dostarczający czyste powietrze do przestrzeni roboczej oraz usuwający powietrze zużyte do systemu wentylacji zewnętrznej. Zapewnia zwiększony stopień ochrony pracowników zajmujących się pracą z drobnoustrojami oraz niebezpiecznymi lotnymi substancjami chemicznymi, a także całkowitą odporność na korozję wewnątrz przestrzeni roboczej. Szczególny obszar zastosowania komory stanowią badania z udziałem radionuklidów, lotnych, toksycznych związków chemicznych, w przypadku których nie wolno stosować urządzeń z recyrkulacją powietrza do pomieszczenia, w którym są ustawione. Opracowane rozwiązanie zostało objęte ochroną własności przemysłowej i wykorzystane do realizacji kontraktu na dostawę zestawu aparatury do laboratorium Instytutu Fizyki Jądrowej PAN.

Słowa kluczowe: komora laminarna, prototyp, badania przepływu powietrza

1. Introduction

Laminar flow cabinets are devices used in laboratory work requiring a sterile environment (Miring'u et al., 2017, Vellutato, 2021). In the designated space of the cabinet, a unidirectional, laminar flow of sterile air occurs, with constant velocity and approximately parallel streamlines. The air is pre-filtered through a pre-filter and a HEPA filter. The purified air exits the cabinet in a continuous, uniform stream, forming a barrier that impedes the entry of bacterial spores or fungal spores, which are constantly present in the air outside the cabinet (Barbosa et al., 2017, Parks et al., 2022). This allows for the maintenance of sterile conditions required for work, including with bacteria or cell cultures (Pawar et al., 2021). Another application of laminar flow cabinets is to protect research personnel from the harmful effects of substances used during laboratory work conducted inside the cabinet. In terms of construction, there are cabinets with horizontal or vertical airflow (Fig. 1).

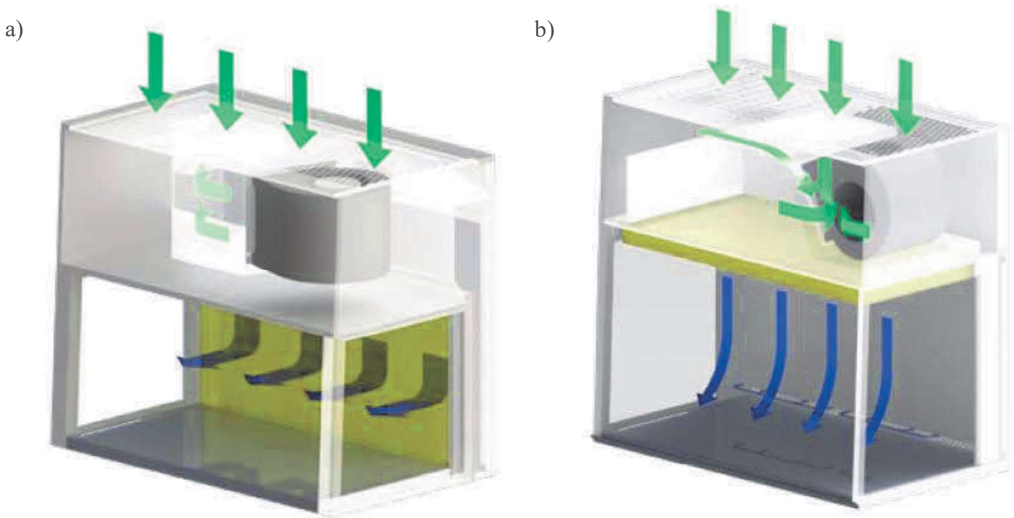

Fig. 1. Diagrams showing a) horizontal and b) vertical airflow in a laminar flow cabinet (Guide, 2024)

The criteria for the operation and classification of laminar flow cabinets intended for safe microbiological work are contained in the standard PN-EN 12469:2002. The standard distinguishes three classes of cabinets for safe microbiological work.

A class I cabinet with a large window in the front wall, through which the person working can perform tasks inside it, protects the worker and prevents the escape of contaminants generated inside the cabinet through the airflow, thanks to forced inward flow into the chamber and exhaust air filtration. It is suitable for work involving low or moderate-risk toxic agents where product (sample) protection is not required.

A Class II cabinet, with a similar construction, has additional air filtration circuits inside the chamber and exhaust air filtration. It provides protection for personnel, the environment, and the sample (Lapamnouysup et al., 2022, Jones et al., 2001). In a Class II cabinet, an internal unidirectional downward laminar airflow and an air curtain at the cabinet opening are used.

In a Class III cabinet, the workspace is completely enclosed. The person working is isolated from the workspace by a physical barrier (e.g., gloves). Filtered air is continuously supplied to the cabinet, and exhaust air is treated to prevent the release of microorganisms and chemical contaminants. In the workspace, a negative pressure of approximately 120 Pa is maintained, and airflow is forced by an external ventilation system.

Laminar flow cabinets are most commonly constructed from stainless steel with a front shield (glass or plastic), which either opens completely or allows the user's hands to be inserted into the workspace. Typical equipment in cabinets includes air/gas valves, electrical sockets, a sink, and a water tap (Vellutato, 2021).

The Łukasiewicz Institute for Sustainable Technologies has extensive experience in designing and manufacturing research equipment capable of achieving specific atmospheric parameters required for test environments (Kozioł, et al., 2019, Kozioł, et al., 2021, Samborski et al., 2022). Examples of such equipment include sets for testing volatile organic compound (VOC) emissions from building materials and wood, climate chambers with wide ranges of temperature and humidity changes, dust, aging, rain, corrosion, condensation, and calorimetric chambers. The experience and expertise gained during the execution of these projects enabled the achievement of the goal described in this work, which was the development and construction of a set of special laminar flow cabinets made entirely of plastics, following the requirements of the Institute of Nuclear Physics of the Polish Academy of Sciences. The most important requirements of the purchaser were to achieve laminar, horizontal airflow and air cleanliness delivered to the chamber in ISO6 class.

2. Laminar Flow Cabinet Design

The developed acid-resistant laminar flow cabinet with horizontal airflow direction in non-metallic execution is a niche product not offered on the market. Its unique design, characterized by the complete elimination of metallic elements from the workspace, prevents corrosion and increases the cabinet's operational durability. A specially designed laminarizer with appropriately distributed outlet holes organizes airflow and ensures a uniform horizontal flow. The possibility of collaboration with an exhaust system ensures the removal of hazardous vapors from the room while maintaining clean room requirements.

Figure 2 depicts a virtual 3D model of the constructed cabinet with horizontal laminar flow.

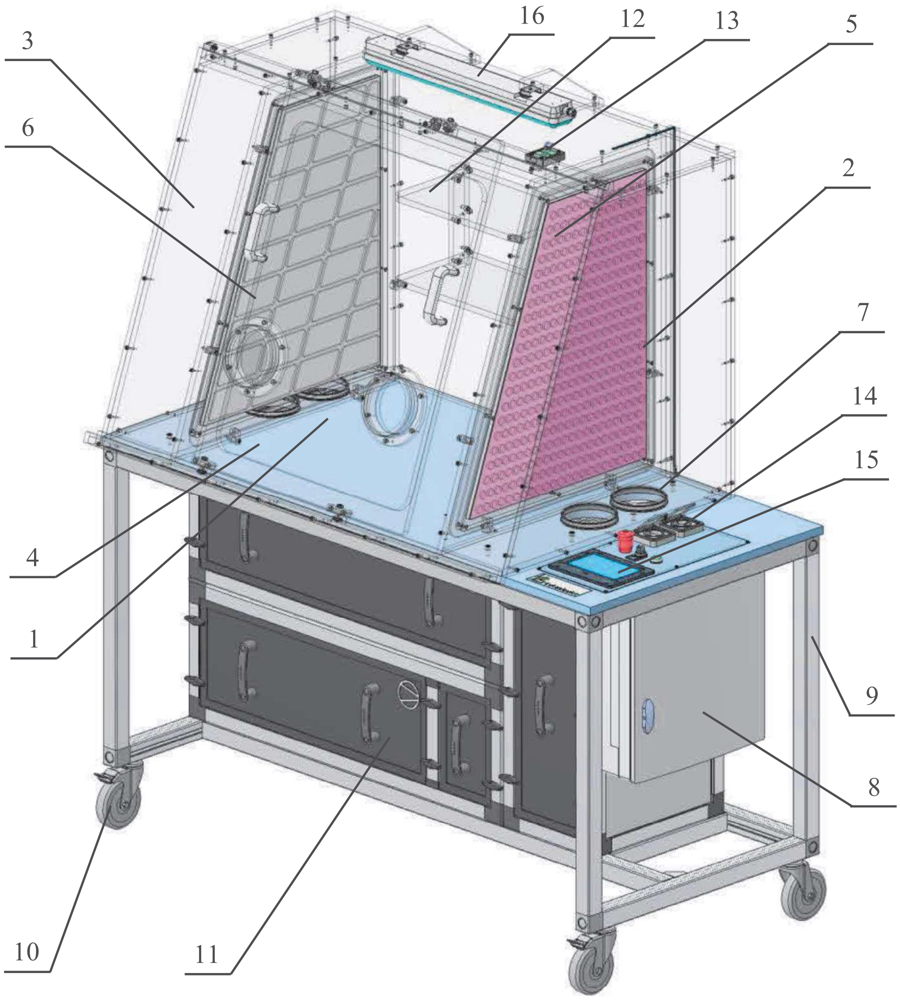

Fig. 2. 3D virtual model of the laminar flow cabinet (front view): 1 - workspace, 2 - inlet chamber, 3 - outlet chamber, 4 - sliding doors, 5 - inlet partition (right), 6 - outlet partition (left), 7 - inlet channels, 8 - control system cabinet, 9 - frame, 10 - caster wheel with lock, 11 - ventilation module, 12 - shelves, 13 - cable gland, 14 - power sockets, 15 - control panel, 16 - LED lighting

The laminar flow cabinet, constructed from PMMA panels, consists of three spaces:

- the central workspace 1, where laminar, horizontal airflow is achieved,
- the inlet chamber 2, supplied with filtered air from the ventilation module 11 through ducts 7,
- the outlet chamber 3, from which the air flows into the ventilation module and then to the discharge, where it is expelled outside (Fig. 3).

Between chambers 1, 2, and 3, there are partitions 5 and 6 made of perforated PMMA panels and appropriately selected filter mats. The damping properties of the mats, perforation of the partitions, and the pressure and flow rate of the airflow are selected so that a laminar, orderly flow occurs horizontally in the workspace 1. Access to the interior of the cabinet is provided through sliding doors 4, which are designed with sockets for glove attachment. The lower wall of the airtight cabinet is the workbench. Inside the cabinet, there are two shelves 12, and a cable gland 13 is located in its upper wall. The cabinet, along with the workbench, is placed on a mobile frame 9, housing the ventilation module 11 that implements the airflow circuit depicted in Figure 3. The electronic control system console 8 contains the device's control system with software, operated using the control panel 15. The workspace of the cabinet is illuminated by an external LED lamp 16. Next to the control panel, electrical power sockets are installed for the optional powering of additional equipment used during experiments.

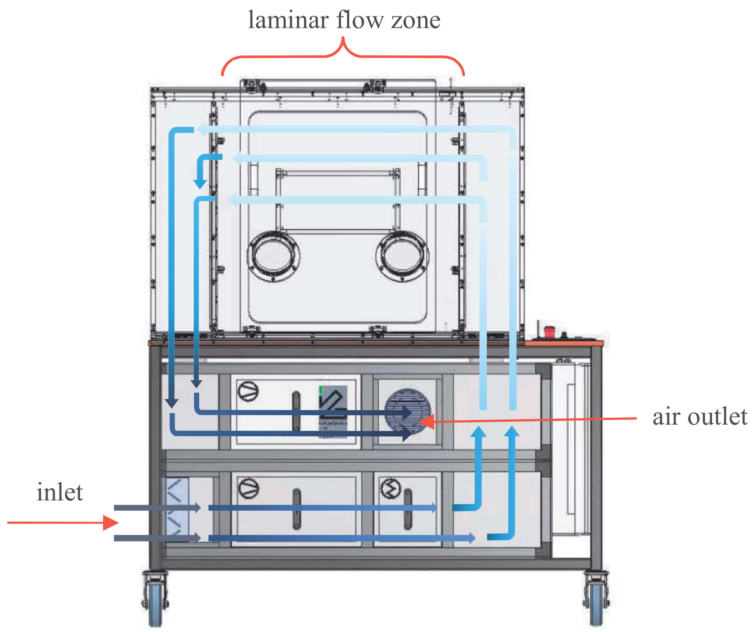

Fig. 3. Air circulation in the laminar flow cabinet

3. Airflow Simulations and Analyses

During the construction and refinement stages of the virtual spatial model and the development of the device's construction documentation, numerical simulations and airflow analyses were conducted. The aim was to preliminarily select airflow parameters and verify the model. The following parameters were adopted for the numerical calculations:

- Total airflow capacity through the device ranging from 100 to 300 m^3/h.
- Flow with a capacity above 200 m^3/h is used for intensive ventilation of the workspace and does not need to be laminar.
- The construction of partitions between the inlet, workspace, and outlet chambers can be modified (filling degree, shape of openings, type of filter mat) to optimize the flow distribution through the workspace.
- It is possible to divide the airflow streams supplied from the ventilation module to the inlet chamber and extracted from the outlet chamber (two flow channels each) and adjust the flow velocity in individual channels (typically achieved through the use of interchangeable baffles).

During the simulations, the flow resistance through the partitions, division of airflow streams, and flow velocities in the channels connecting the chambers to the ventilation module were varied.

The calculations were performed using computational fluid dynamics (CFD) software - Autodesk® CFD, which is a tool used to solve equations describing fluid flow using numerical methods. The use of such tools provides extensive capabilities for analyzing flow phenomena and processes, enables a better understanding of them, and thus allows for the optimization of existing solutions. During the development of new products, CFD is used as a tool to shorten the product development time.

During the simulation process, constant volumetric flow conditions at the inlet and outlet of the chamber were assumed as boundary conditions. The analysis concerned calculations excluding the temperature change and impact to achieve a steady-state flow condition. The model was meshed using adaptive technology, starting with default settings for the density of finite element mesh with initial three wall-adjacent layers and a gradation factor of 0.45. A modified Petrov-Galerkin method was used as a computational model (advection scheme) to ensure stability of calculations. Air with constant parameters was used as an agent (Table 1).

Table 1. Air parameters used in the CFD analysis

Material Environment

Fixed Variable

Use scenario environment

Properties for Air (fixed)

Environment: 101325 Pa, 19.85 Celsius (from scenario)

Property	Value	Units	Underlying variation
Density	1,20473e-06	g/mm3	Equation of State
Viscosity	1,817e-05	Pa-s	Constant
Conductivity	2,563e-05	W/mm-K	Constant
Specific heat	1,004	J/g-K	Constant
Cp/Cv	1,4	none	Constant
Emissivity	1	none	Constant
Wall roughness	0	millimeter	Constant
Phase	0		Vapor Pressure

OK Cancel

Figures 4 and 5 show the results of the calculations in graphical form showing the flow velocity distributions, directions and distribution of air flows for a total flow through the cabinet equal to 150 m^3/h. An ordered flow through the workspace in a horizontal direction with a constant velocity distribution across the entire cross-section of the cabinet, excluding the wall areas, is visible.

From Figure 4b, it can be inferred that the expected airflow pattern was achieved by supplying the inlet chamber from one of the two ducts connecting it to the ventilation module and by extracting air from the outlet chamber through both modeled ducts. The results of the numerical calculations were used to develop the design of the partitions and to select the interaction mode of the cabinet with the ventilation module. The results were verified during prototype testing.

a)

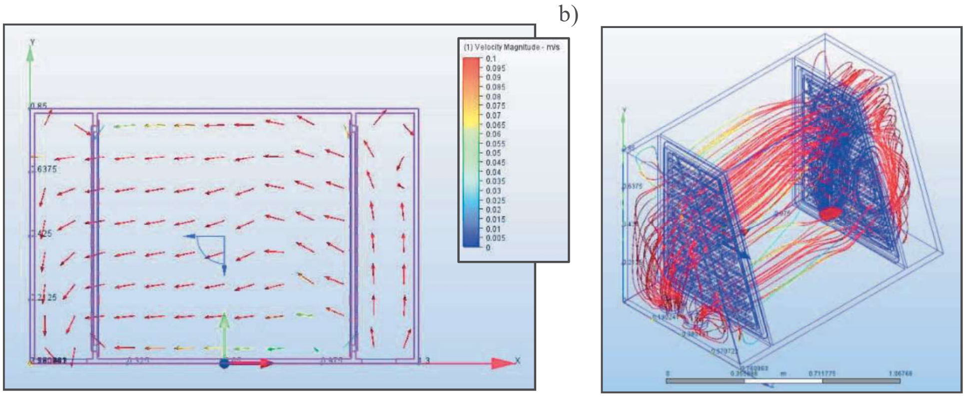

Fig. 4. The result of the airflow simulation in the cabinet: a) velocity distribution in the inlet, workspace, and outlet chambers, b) airflow distribution (view from the outlet chamber side)

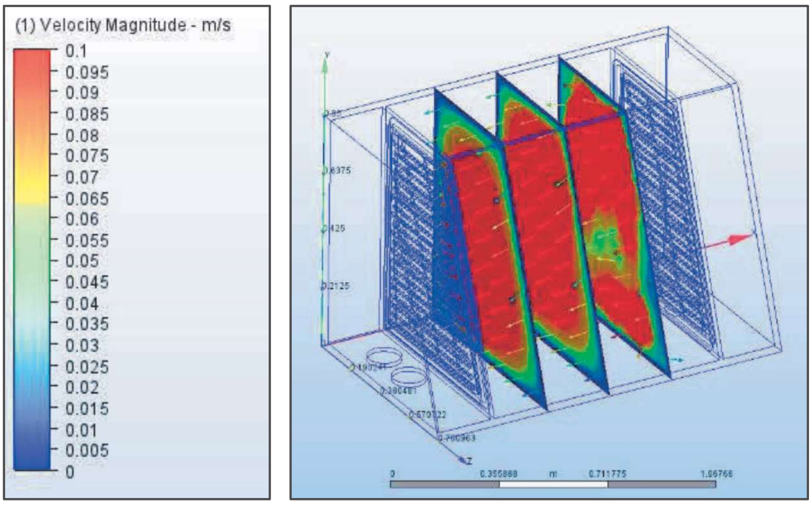

Fig. 5. Result of airflow simulation in the cabinet – velocity distribution in the workspace in selected vertical planes

4. Prototype and Verification Testing of the Special Laminar Flow Cabinet

The prototype of the special laminar flow cabinet was manufactured at the Łukasiewicz – ITEE Prototyping Center based on the developed technical documentation. Most of the structural elements in contact with the internal experimental environment were made of polymethyl methacrylate (PMMA) sheets joined by polyamide screw connectors. Such a design, according to the assumptions, prevents corrosive processes that may occur during work with aggressive chemical environments. Figure 6 shows a photograph of the prototype cabinet.

Fig. 6. Prototype laminar flow cabinet made of plastic

The control of all functions of the complete device is performed using the operator's panel. Most control functions are accessible from the touch control panel equipped with user software (Fig. 7). The operator menu allows for adjustment and displays values of the airflow rate through the cabinet and the pressure difference relative to the surroundings. It is used to stabilize device operating parameters and signal warning and failure states, such as filter clogging or fan damage.

The constructed prototype of the cabinet was started up and tested to perform all manual and automatic operational activities.

The prototype underwent verification testing to ensure that the technical parameters of the device met the customer's requirements. The tests included the following:

- measurement of the airflow rate through the cabinet,
- examination of the airflow velocity distribution,
- examination of air cleanliness,

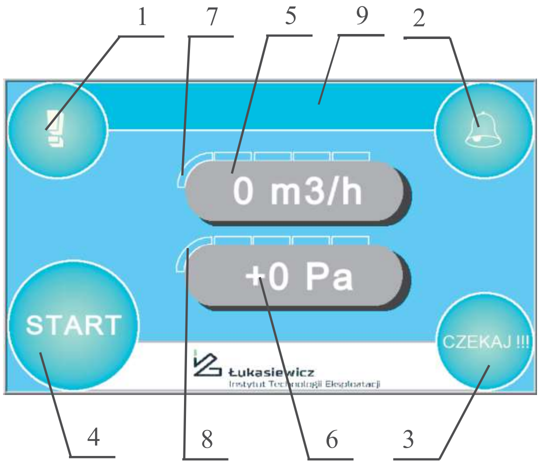

Fig. 7. View of the control panel: 1 - warning icon, 2 - alarm icon, 3 - ready-to-operate icon, 4 - device activation icon, 5 - information about current airflow rate, 6 - information about current pressure difference between the cabinet and the surroundings, 7 - barograph of the percentage efficiency of the supply fan, 8 - barograph of the percentage efficiency of the exhaust fan, 9 - field with information about alarms, warnings, and current events

The airflow rate through the cabinet ranging from 100 to 400 m^3/h was measured under normal conditions using a balometer, with a measurement uncertainty of ±3% of the measured value, and compared with the indications on the operator panel calculated based on the measured pressure difference at the fan and its characteristic. In the range of airflow rates up to 200 m^3/h, the relative measurement error was up to 7%, while above this range, it did not exceed 4%. The exact value of the airflow rate through the cabinet is not a critical parameter of the process being carried out and serves to assess the intensity of its ventilation. Therefore, the achieved measurement accuracy is sufficient.

Local airflow velocity measurements inside the chamber were conducted at nodes defined by a grid of measurement points evenly distributed across the transverse middle section of the workspace. Table 2 shows the coordinates of each measurement point and the measured airflow velocity values at those points.

Table 2. Airflow velocity distribution in m/s in the central plane of the chamber for an airflow rate of 300 m^3/h

Y-coordinate of the measurement point [mm] \ X-coordinate of the measurement point [mm]	107	169	230	290	351	412	472	533	595
727	0.08	0.14	0.17	0.26	0.17				
666	0.00	0.16	0.24	0.23	0.23	0.10			
604	0.02	0.07	0.14	0.22	0.25	0.19			
533	0.00	0.19	0.25	0.23	0.37	0.23			
462	0.17	0.19	0.22	0.21	0.32	0.16	0.10		
373	0.19	0.23	0.31	0.20	0.20	0.26	0.23		
302	0.23	0.30	0.33	0.19	0.21	0.23	0.21	0.17	
231	0.24	0.20	0.25	0.18	0.21	0.30	0.30	0.05	
169	0.21	0.16	0.16	0.27	0.20	0.18	0.33	0.19	
108	0.19	0.28	0.22	0.29	0.24	0.21	0.35	0.23	0.31

The Y-coordinate of the measurement point represents its distance from the chamber's bottom surface (table), while the X-coordinate represents its distance from the rear wall. Measurements were performed using a thermo-anemometer probe with a measurement uncertainty of ± 0.015 m/s. The measurement results indicate a sufficiently uniform velocity distribution in the central transverse plane of the chamber, except for the wall areas where the velocity is lower than the average value. In Table 3, the average values of laminar airflow velocity are shown for several selected total airflow rates.

Table 3. Average values of laminar airflow velocity in the cabinet for selected total airflow rates

Airflow rate through the cabinet [m^3/h]	150	200	300
Average value of air velocity in the working chamber [m/s]	0.09 ±0.048	0.13 ±0.055	0.21 ±0.076

The laminar airflow character in the working chamber was also confirmed using a smoke test according to the method described in the PN-EN ISO 14644-3 standard, section B.3 – the introduction of a marker (smoke generated from test tubes containing smoldering sulfuric acid) into the air stream (Fig. 8).

Air cleanliness in the working chamber was assessed using the particle counter Met One 3423 (Fig. 9a) (flow rate of the counter: 50 l/min., measurement channels from 0.3 to 10 μm, measurement uncertainty ISO-21501-4 Calibration). The test was conducted under the same conditions as the other verification tests.

Figure 9b shows the particle counter during measurements in the cabinet and the test report with a total airflow rate of 300 m^3/h.

Fig. 8. Airflow smoke test

a)

b)

----- ISO 14644-1:2015 ------
---------- REPORT -----------
AVERAGE PARTICLES/CUBIC METER
S/N: 2010532001
LOCATIONS: 001
LOCATION ID: 000
LOCATION NAME:
Location1
AREA NAME:
Area1
2020-11-17 02:55:51
FLOWRATE: 49.6 LPM
VOLUME: 71.3 L
SAMPLES: 1

SIZE(um)	CUMUL.	DIFF.
0.3	54789.9	50345.6
0.5	4444.3	4065.8
1.0	378.5	322.5
3.0	56.1	0.0
5.0	56.1	14.0
10.0	42.1	42.1

ISO Class 6; At Rest;
1 m^2;

SIZE(um)	CRITERIA	PASS/FAIL
0.5	35200	Pass
1.0	8320	Pass
5.0	293	Pass

Fig. 9. Air cleanliness test in the working chamber using the particle counter Met One 3423 (a), and the test report for a total airflow rate of 300 m^3/h (b)

The functional tests of the prototype laminar flow cabinet and the results of the verification tests confirmed that the constructed device meets the technical and functional requirements formulated during the conceptualization and technical design stage.

5. Summary

At Łukasiewicz – ITEE in Radom, a prototype laminar flow cabinet with horizontal airflow, entirely made of plastics, was developed and constructed. The concept and operation of the device were developed in cooperation with and commissioned by the Institute of Nuclear Physics of the Polish Academy of Sciences. During the device's design, numerical simulations and airflow analyses were utilized to achieve the required laminar horizontal airflow throughout the working chamber's volume. A fully functional prototype chamber equipped with apurification and ventilation module was built and subjected to comprehensive verification testing within a complete laboratory setup. The developed chamber allows for collaboration with an external exhaust system and provides complete corrosion resistance inside the working space. The combination of these features makes it a unique product not previously available on the market. A set of four chambers was manufactured and installed in the laboratory of the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków. The original design solutions developed at Łukasiewicz – ITEE have been protected by industrial design registration (Rp.27206, 2021).

Further work is planned to increase the functionality of the device. This includes equipping the chamber with a water supply and sewerage system (sink, eye wash station), and consequently modifying the structure of the ventilation module.

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