





Article

Airflow Fluctuation from Linear Diffusers in an Office Building: The Thermal Comfort Analysis

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Abstract: In buildings, the HVAC systems are responsible for a major part of the energy consumption. Incorrect design or selection of the system and improper installation, operation, and maintenance of the systems' elements may result in increased energy consumption. It is worth remembering that the main aim of the appropriate system is to maintain the high quality of the indoor environment. Appropriate selection of the HVAC solution ensures both thermal and quality parameters of the air, independently of the internal and external heat loads. The microclimate of a room is affected not only by air temperature, humidity, and purity, but also by air velocity in the occupied zone. The proper air velocity distribution prevents discomfort, particularly at workstations. Based on the measurements in the office building, an analysis of velocity profiles of air supplying two different types of linear diffusers was carried out. The analysis was made based on the results of measurements performed with thermoanemometers in the actual facility. During the study, temperature of the supply air was lower than the air in the room. Analysis was focused on the airflow fluctuation and its impact on the users' comfort. This is an obvious topic but extremely rarely mentioned in publications related to air diffusers. The results show the importance of air fluctuation and its influence on the users' comfort. During the measurements, the instantaneous air velocity for one of the analyzed types of the diffuser was up to 0.34 m/s, while the average value from the period of 240 s for the same measuring point was relatively low: it was 0.19 m/s. Only including the airflow variability over time allowed for choosing the type of diffuser, which ensures the comfort of users. The measurements carried out for two linear diffusers showed differences in the operation of these diffusers. The velocity in the occupied zone was much higher for one type (0.36 m/s, 3.00 m from diffusers) than for another one (0.22 m/s, 5.00 m from diffusers). The improper selection of the diffuser's type and its location may increase the risk of the draft in the occupied zone.

Keywords: ventilation and cooling systems; linear diffuser; indoor environment; air flow distribution



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1. Introduction and Literature Review

Nowadays, we spend most of our time indoors, including homes, apartments, offices, and shopping centers. In conjunction with the increasing living standards, more and more attention is focused on indoor conditions and air quality. The environmental conditions directly affect our satisfaction and, consequently, the quality of our work or the possibility of focus and rest. Therefore, the comfort of users of buildings must be at the highest level, regardless of the purpose of a given facility [1,2]. Many factors directly affect the comfort of users. Besides the individual parameters related to users' activities, metabolism, and the work performed, the parameters of the air surrounding the user, including temperature, humidity, and air velocity, are crucial. At the same time, it is important to remember that buildings account for a substantial proportion of global energy consumption and significantly contribute to CO₂ emissions. The operation of the HVAC systems consumes a large amount of energy. It often accounts for the majority of the building's energy use.

High energy demand may be associated with inappropriate system design and incorrect installation or maintenance. Therefore, highly efficient innovative HVAC systems are increasingly often applied. These solutions, at the same time, should ensure appropriate indoor conditions and reduce maintenance costs. The combination of those two aspects, both economic and quality factors, is a great challenge for the designers. At the design stage, the facility's functions, workplace locations, and general characteristics of the building should be considered.

In ventilating and air-conditioning systems, the most popular group of supply air diffusers used are ceiling diffusers. The advantage of this type of supply components arises from the popularity of overhead mixing ventilation. Easy access to the ceiling space as well as available space and easy installation of ventilation increase the popularity of this type of solutions. Ceiling diffusers can generate a limited or semilimited, attached to the ceiling, airflow. Depending on the type and structure of the supply air diffuser, the airflow can be swirling (with adjustable or nonadjustable blades), formed in a given direction (one-way, two-way, three-way, or four-way air discharge) [3]. Slot diffusers, perforated ceilings or, in tall structures, long-range nozzles are often used in addition to typical supply air diffusers. The stability of the supply airflow moving in the room depends on the supply air diffuser's structure. From the point of view of proper air distribution in the room, the range of influence of the supply airflow and its parameters (temperature differential, velocity) at the input into the occupied zone are of great importance.

In recent years, a great interest in air-conditioned office rooms of a higher standard has been observed. Unfortunately, their users often express their dissatisfaction with the quality of internal environment. Among the facilities assessed negatively, there are also those in which investors, designers, and contractors tried to comply with all the recommendations and standards. Designing the air-conditioning installation for facilities intended for public use is particularly difficult due to the presence of many users with different requirements. Thermal requirements are the basic criterion for proper microclimate of a given room. However, the air-flow velocity in the occupied zone also affects thermal sensation. The air supplied to the rooms is very often cooler than the air in the room, which causes local discomfort due to the increase in the cooling capacity of air, as its flow velocity increases. When organizing an air exchange in the office premises, the airflow from the supply ventilation should not be directed toward the workstation in a direct way and should not cause draughts, chills, and overheating/overcooling of the workstation.

The appropriate operation of the ventilation system is not possible without the proper choice of supply air diffusers. Depending on the purpose of a facility, supply air diffusers have to maintain the velocity below the maximum in the occupied zone, even with variable air flow [4]. Convective and evaporative heat transfer to and from the body are sensitive to air velocity [5]. Unfortunately, the draft is one of the most common causes of complaint in ventilated spaces. The appropriate value of air velocity may be determined primarily on thermal conditions and the metabolism of users. ASHRAE Standard 55 [6] defines the comfort zone as the range of thermal environmental conditions which the majority of people find acceptable. Determining the appropriate configuration of parameters inside the room is crucial, and the permissible ranges of individual values depend on each other. The air velocity limit depends mainly on the air temperature and humidity as well as on the clothing insulation and physical activity of the users. Air velocity is a crucial factor in thermal comfort. Even small values of air velocity by low temperature may be perceived as a draught. On the other hand, the still air in indoor environments may cause users to feel stuffy and decrease heat loss through convection. For mixed air systems at standard conditions, the comfort could be improved by maintaining air velocities of less than 0.25 m/s in the occupied zone [7]. The value of 0.20 m/s is often assumed as the maximal air velocity, which provided a comfort condition in the occupied zone. This may be because the use of the predicted mean vote (PMV) model is limited to air velocity below 0.20 m/s [6]. PMV model is one of the most popular thermal comfort models. Figure 1 shows the acceptable combinations of temperature and air velocity, assuming that the

humidity ratio equals 0.010 kg H₂O/kg dry air and metabolic rate is in the range from 1.0 to 1.3 met. The graph may be used lightly clothed person where clothing insulation equals 0.5 or 0.7 clo. Analyzing the permitted values of air velocity, it could be noted that at temperatures ranging from 21 to 28 °C, a speed of 0.20 m/s is an acceptable value.

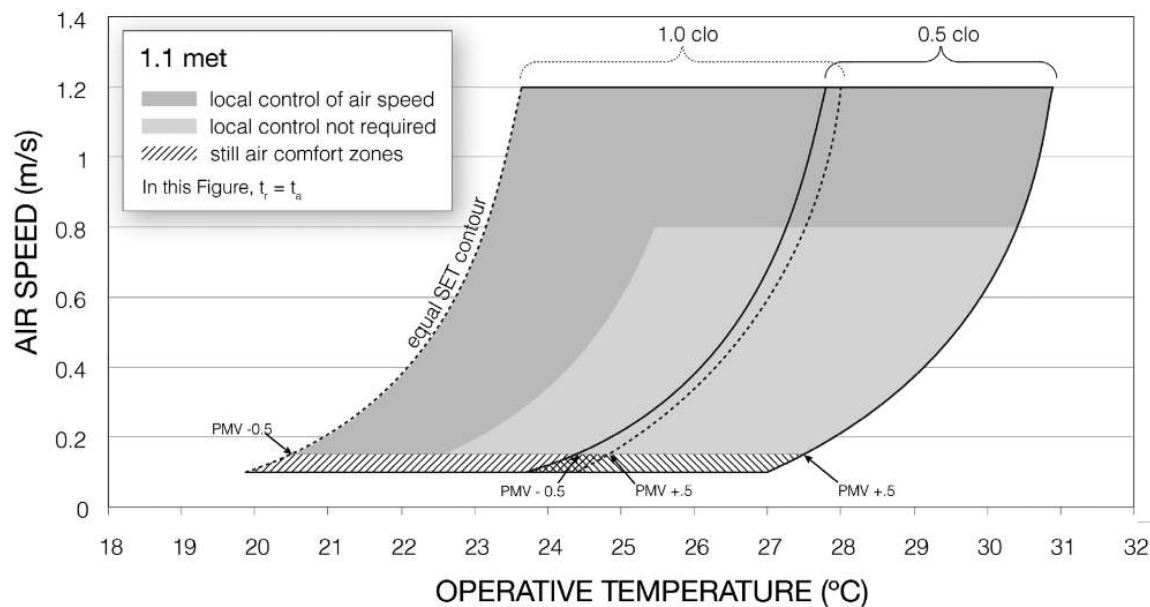


Figure 1. Acceptable range of operative temperature and air speeds for the comfort zone at humidity ratio 0.010 kg H₂O/kg dry air. Adapted from [6].

It happens very often on designed buildings that the air velocity exceeds the recommended values in the occupied zone. It is particularly problematic in residential and public buildings, e.g., in offices. Guidance on methods for the selection of ceiling-based air diffusion equipment was provided by ASHRAE in the Designer's Guide [8]. This document helps engineers and designers to design effective HVAC systems. The main aim is to ensure parameters of thermal comfort and indoor air quality. The guidance on several methods of air distribution is also provided in chapter Space air diffusion of the ASHRAE Fundamentals Handbook [9]. Besides the classification of air diffusion methods, the airflow patterns of different diffusers were described in the guidelines. The efficiency of air exchange directly depends on the design, construction, and operations parameters of the air distribution system. Hence, it is advisable to thoroughly investigate the method of operation of a given type of system and the possibilities of their application.

The experience of specialists in the HVAC industry shows that, in many cases, it is necessary to study the air velocity distribution on real facilities. In normal operating conditions, it is possible to individually set the diffusers so that the velocity profile does not cause local discomfort. The behavior of the airflow can be determined from the data provided by manufacturers of supply air diffusers. The information contained in specifications should include the characteristics taking into account the profiles of the supply stream of air, its range, often the critical range (distance between the separation of the stream of air from the ceiling), and efficiency of the supply air diffuser. From these data, it is possible to precisely determine the conditions for stable operation of supply air diffusers and to calculate velocity and temperature of the airflow in the occupied zone. The information provided by the manufacturers of supply components is very often insufficient. In many cases, information on the supply airflow profile is missing. The lack of such information results in an incorrect selection of diffusers or incorrect assembly. It translates into discomfort for the users of the room in which the given supply or exhaust elements are installed.

There are many works on thermal comfort inside buildings [10,11]. Many authors focus in particular on the influence of the applied ventilation system and air velocity on the comfort of users [12,13]. Currently, solutions are being sought that combine the energy-saving features of an air-conditioning system with the provision of thermal comfort conditions in the occupied zone. The functioning of fabric diffusers in layered ventilation in eight different configurations was analyzed by Yao et al. [14]. The tested parameters were compared with a supply grille containing two rows of moving blades. The analyses showed that fabric diffusers operate better for larger streams of air. In comparison to the supply grille, fabric diffusers were able to provide a relatively regular velocity and temperature distribution for most areas in the room as well as more comfortable thermal conditions in the room. Currently, design solutions are being developed for supply air diffusers, which reduce energy consumption, e.g., supply air diffusers with recirculation [15]. They use local heat gains in the room to heat up the supply air. New air-conditioning systems based on a combination of natural ventilation and thermally activated building systems (TABS) [16–18] are being analyzed. Diffuse air supply systems have recently attracted great interest. Reference [19] presents the results of experimental and theoretical research on the diffuse ceiling ventilation system for office usage. Both analyzed scenarios (for air changes per hour 3.5 and 5.1) showed good air mixing in the occupied zone and no formation of draughts, even for large streams of air. The assessment of thermal comfort gave the results of PPD index (predicted percentage of dissatisfied) of 5% and 8%. The subject of the article by Liu et al. [20] is the air diffusion performance index (ADPI) method, which is adapted in ASHRAE Handbook. This method combines local airspeed and local dry-bulb temperature into an effective draft temperature, which reflects the subjective sensation of coldness. This article presents new experimental results to update the ADPI-based guideline with 15 diffuser types at low loads. IAQ assessment was also discussed in the paper by Piasecki and Kostyrko [21]. This article provides an overview of IAQ methodology and attempts to systematize the approach. In addition, the article presents a method of correcting the weights of individual components and a practical case study in which the implementation of the IAQ and IEQ model for the assessment of a large office building (with a BREEAM rating at the Excellent level) was presented.

Hurnik et al. [22] presented the results of the velocity distributions from the radial wall jets. The authors analyzed two ceiling diffusers of different constructions and at three airflow rates. Based on the results, a method for calculating velocity distributions in radial wall jets was developed. Another paper [23] presented an experimental study concerning the effect of a chilled ceiling on the indoor air distribution with a mixing ventilation when the internal and external cooling loads changed. The chilled ceiling had a slight impact on air distribution in a room with mixing ventilation. It is interestingly found that the small vertical air temperature difference coincided with the large turbulence intensity and contaminant removal effectiveness with different internal or external cooling loads. Abdullah and Alibaba [24] focused on air quality and thermal comfort in naturally ventilated office buildings. The authors noticed an influence of the direction, speed, and turbulence of the wind on the ventilation efficiency. In addition, it was noted that, for example, the floor of the analyzed room, the orientation, and the sunlight of the windows are important. The topic of ventilation efficiency, including the influence of the geometry of both space and furniture and their arrangement in the room, was discussed in their article by Hormigos-Jimenez et al. [25]. The authors presented a numerical analysis confirmed by experimental research. In Reference [26], the authors measured the air velocity profiles from slot diffusers on a laboratory test, using thermoanemometry and the measurement methodology contained in EN 12238:2001 [27]. The experimental studies were conducted [28,29] to identify the variation characteristics in jet behavior for ceiling slot diffusers. Nine cases, covering different aspect ratios, were measured under isothermal conditions in two test rooms using traversing measurement systems. The results confirmed that the coefficient of jet maximum velocity decay depends on the details of the diffuser and thus should be identified for different products. The selection of the jet model should be determined by

the aspect ratio of the jet slot to predict the maximum velocity decay. Direct air distribution measurement could provide quantitative information of local air velocity [30] and the whole field airflow pattern, which is correlated with the air exchange rate between the fresh supply air and the room air, and the pollutant transportation. Reference [31] summarizes modern methods for airflow measurement and characterization, specifically, focus on the measurement technologies, their applications, and limitations. Song et al. [32] presented studies of thermal comfort for the nonuniform thermal environment in a hot environment, where air temperature and radiant temperature differential are noticeable. The results showed that increasing the air velocity from 0.00 to 1.20 m/s can improve thermal comfort and reduce thermal discomfort caused by the difference between radiation temperature and air temperature. An interesting case is also air movement in hot humid climates. Buildings in this climate are usually naturally ventilated. Air exchange for buildings in this climate is usually provided by natural ventilation. Candino et al. [33] identify acceptability levels of the air movement inside naturally ventilated buildings in Brazil. The results show that for a temperature of 26 °C, the minimum required air velocity was 0.40 m/s, while for a temperature of 30 °C, it was already 0.90 m/s. In such a climate, users prefer much higher air velocities than indicated by the general guidelines. The high air velocities may be desirable to improve the thermal comfort of the facility.

The results presented in the article concern the comfort of users in an office space, with particular emphasis on air velocity. The measurements were carried out due to the problem of discomfort in the office space reported by users. It is particularly important because the feeling of discomfort affects the quality and efficiency of work. The purpose of the article is to show differences in the operation of linear diffusers. In the study, commonly known measurement methods were used. Two linear diffusers with different design solutions were compared. The catalog cards of these devices do not present their characteristics for the working conditions that occur in the analyzed building. Nevertheless, the supplied air was within the operating range declared by the manufacturers for each of the compared devices. Theoretically, both of these diffusers should ensure appropriate conditions for the users of the room. Although linear diffusers are commonly used, especially in office buildings, this topic is rarely considered in the literature. It should be added that most of the publications devoted to this subject present the results of measurements for isothermal conditions. The results presented in the article were carried out for the supply of air cooler than the air in the room. The tests concern the often-overlooked issue in the measurement of the velocity of air flowing out of the diffuser, which is the variability of this velocity over time. Consideration of the airflow fluctuation has a significant impact on the assessment of the diffuser action. The performed measurements confirmed that the velocity profile created by one of the analyzed types of the diffuser did not provide comfort conditions. The air velocity distribution tests were carried out for another construction of the diffuser. Finally, the second type of diffuser was selected to be used in the analyzed building because it provided better air distribution.

The paper is divided into four chapters. The first chapter is an introduction to the subject matter of the article. It contains a literature review on measurements in the field of ventilation, with particular emphasis on diffusers' impact on the comfort of users. Chapter 2 describes the methodological approach during the experiment in the office space. The next chapter presents the obtained results and their analysis. The final chapter covers the main conclusions.

2. Methodology

The subject of the paper is a new, open space office building. The facility is part of a service complex. The analyzed office is located in the center of Krakow (southern Poland). In order to determine the parameters of air distribution from the supply air diffuser, tests were carried out on two linear diffusers of different types, with adjustable nozzles and slots, used in the air-conditioning system in an open space office building. Figure 2 shows the location of the linear diffusers in the open space office and detailed

construction. Figure 2a shows Type I of the linear diffusers, and Figure 2b shows Type II of diffusers. Diffusers for testing characterized by the same external dimensions of the panel (length and width). Air diffusers were installed onto an air duct using a plenum box with a side connection. The tested diffusers differed significantly in design. Type I consisted of two rows of individually adjustable nozzles. Type II consisted of six rows of steering wheels, individually adjustable rollers. Each row was composed of individually set up 0.10 m modules. Both types of diffusers were characterized by manual change of the position of the blades. The measurements were carried out for one, selected as optimal for the analyzed space of the room, diffuser blade settings.



Figure 2. Linear diffuser: (a) Type I; (b) Type II.

The measurements were carried out in two stages for each of the analyzed types of diffusers. Firstly, the profile of the air stream supplied from the linear diffusers was determined. In the next stage, the air parameters directly at the workstations, including the temperature, relative humidity, and velocity of the air, were measured. The measurements were made using AirDistSys 5000—a measurement system for velocity and temperature. This system is applicable for multi-point measurements and is used for the assessment of thermal conditions and room velocity distribution. The measuring system used consists of four SensoAnemo 5100LSF transmitters with SF3 probe, enabling simultaneous measurement of velocity and temperature at 4 measurement points, with an accuracy

of $\pm 0.02 \text{ m/s} \pm 1.5\%$ of a measured value and $\pm 0.2 \text{ }^\circ\text{C}$ for temperature. The system is additionally accompanied by SensoBaro 5301—a barometric pressure transmitter. The system also includes AirDistSys 5000 software which enables the determination of: the average air velocity and temperature; velocity standard deviation; intensity of turbulent flow; and draught risk level at all measurement points. The program also enables you to the recording all parameters on a computer. This system meets the requirements of standard EN 12238:2001 [27]. The measurements were carried out continuously over the period of 3 min for each type. The presented averaged values results were calculated based on values over this time.

The location of the measuring probes to measurements of the velocity of the air stream supplied from linear diffusers in the space of an office building is shown in Figure 3. Since the room height was 2.70 m, measurements for the supply air point diffuser Type I and II were taken in three planes/heights: 2.50 m from the floor (0.20 m from the ceiling); 2.10 m, and at the height of 1.70 m (Figure 3a,c). The last height, i.e., 1.70 m, is treated as the occupied zone, where the air velocity should not exceed $v = 0.20 \text{ m/s}$. Four probes were used in the measurements, which were located in parallel to the length of diffusers. The distance among the probes was 0.30 m, and subsequent measuring points were shifted from the first one by 0.30 m. The measuring grid was located between desks marked as D1-D2-D3 and D4-D5-D6. Figure 3b shows the desk arrangement. Desks were marked with the letter D and subsequent numbers from 1 to 6. For further analysis, it was assumed that the X-axis runs along the lines of the desks, Y-axis runs parallel to the wall line. The origin of the coordinate system was assumed at the intersection middle line between the desks with the outside edge of the diffuser and the height of the floor ($Z = 0 \text{ m}$). The measuring points were located at the distance of 0.15, 0.45, -0.15 , and -0.45 m in the direction of the Y-axis. This measurement line was set at the distance of 1.00, 2.00, 3.00, 4.00, and 5.00 m at a distance from the analyzed diffusers.

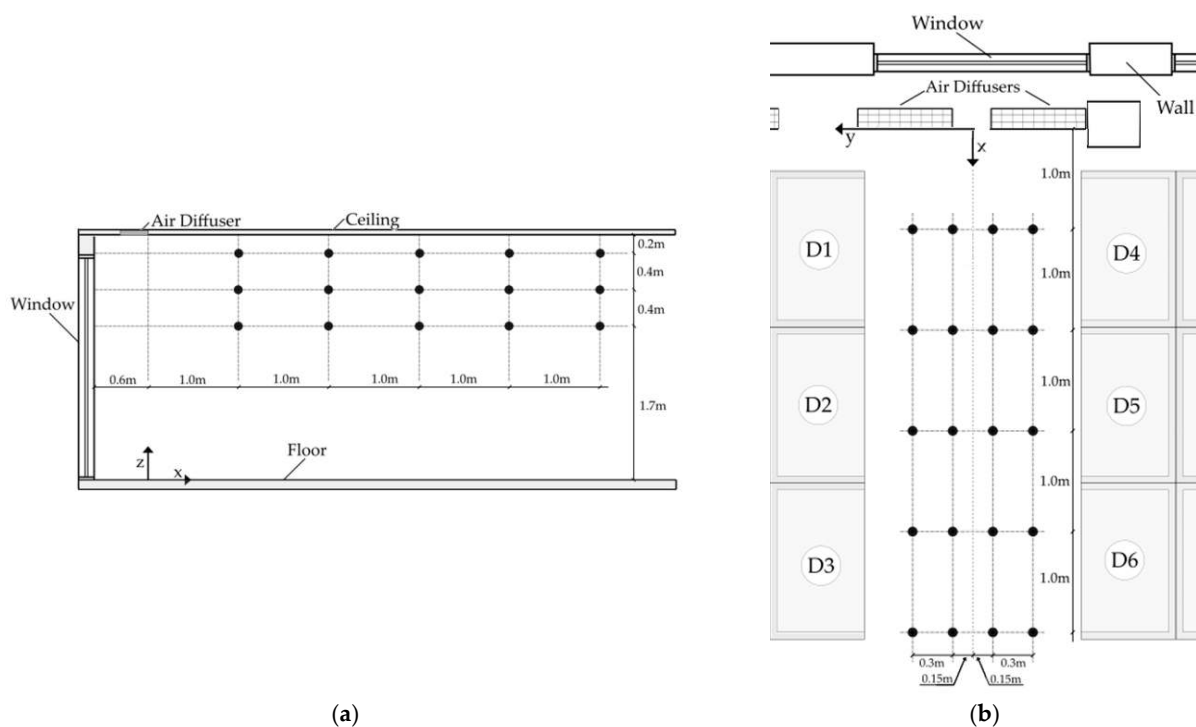


Figure 3. Cont.

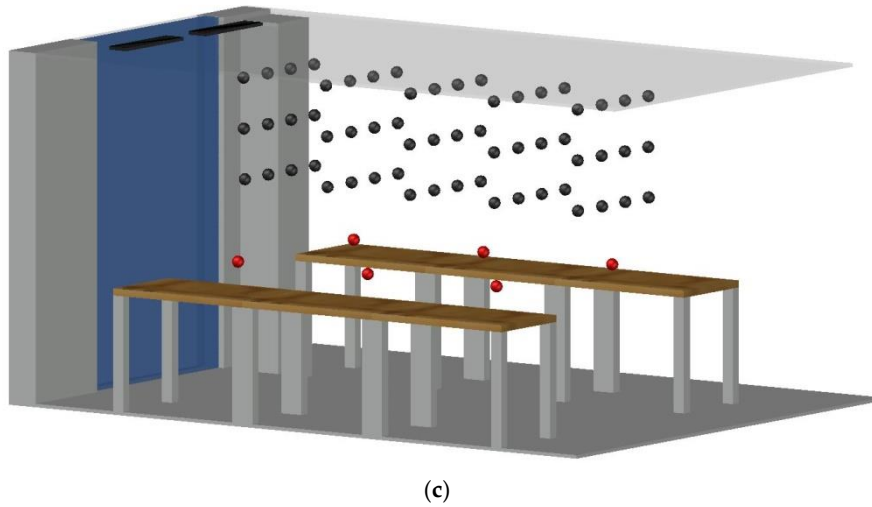


Figure 3. The location of the measuring probes: (a) vertical section; (b) horizontal section; (c) three-dimensional view: black points—AirDistSys 5000; red points—microclimate meter.

Figure 4 shows the measuring set in open space office in building. The velocity of air in the occupied zone directly affects the microclimate conditions in the room and can cause a feeling of the draft. Therefore, in addition to measuring the air velocity above the aisle between desks, the ambient parameters at workplaces were also measured using the EHA MM101 microclimate meter (Figure 4b). The meter consists of a central unit, a set of temperature sensors, i.e., actual air temperature, blackened sphere temperature (heat radiation meter), natural wet-bulb temperature, sensor relative air humidity, a probe for measuring air velocity, and a tripod with handles for mounting measuring sensors at different heights. The meter meets the requirements of PN-EN ISO 7726 [34]. The sensors of the meter were placed at the height of the human head in a sitting position, i.e., at the height of 1.20 m (Figure 3c).



(a)



(b)

Figure 4. View of measuring probes in open space office in building: (a) velocity transmitters; (b) microclimate meter.

The article focuses on the comparison of air distribution from two different types of linear diffusers and their influence on the air movement in open-space offices. The article presents the results of velocity distribution of the supplied air stream from the supply air diffusers built in a suspended ceiling at a height of 2.70 m and at a distance of 0.60 m from the outer wall (southern orientation). The analysis was concentrated on the change of supply air velocity, for which exceeding the value of 0.20 m/s in the occupied zone causes discomfort to users of the facility.

Firstly, the measurements were carried out for a linear diffuser marked as Type I. The measurements began with the determination of the microclimate at workstations, i.e., at the employees' desks. Air temperature, humidity, and air velocity were measured. The next step was to determine the instantaneous speed in points as shown in Figure 3a,b using the Air-DistSys 5000. After carrying out the tests at all measuring points, the second type of diffuser was installed (marked as diffuser Type II). Similarly, the measurements procedure was repeated for diffuser Type II by determining the microclimate at workstations and then measuring the air velocity in the selected measuring grid.

3. Results and Discussion

3.1. Preliminary Indoor Quality Assessment

During measurements, an air stream of about 270 m³/h was supplied through a single diffuser. Table 1 shows averaged values of temperature and air velocity at a height of 1.2 m at workstations. The recording time of the measurement was 4 min. The temperature oscillated around 22 °C for diffuser Type I and around 20 °C for diffuser Type II, while the relative humidity at the workstations oscillated between 53–56% during both measurements for the diffuser Type I and Type II.

Table 1. Results of the measurements for air parameters on selected desks for air diffuser Type I and Type II.

Desk	Diffuser Type I		Diffuser Type II	
	Temperature, °C	Average Velocity, m/s	Temperature, °C	Average Velocity, m/s
D1	22.1	0.13	20.0	0.12
D2	22.0	0.18	19.8	0.18
D3	21.9	0.21	19.8	0.22
D4	22.0	0.14	20.1	0.11
D5	21.9	0.19	20.1	0.19
D6	21.9	0.19	20.3	0.22

In the case of the diffuser Type I, the velocity limit of 0.20 m/s was exceeded only at the desk marked as D3, and the exceedance was only 5% of the permissible value. In the case of the diffuser Type II, the highest velocity was also obtained at the D3 workstation, while the air velocity was higher than for Type I and was 0.22 m/s (10%). For the diffuser Type II, the velocity was also exceeded at the D6 desk by 10% concerning the velocity recognized as the limiting. Although the air velocity did not significantly exceed the limit values, the analysis of the variability of this parameter during the 4 min of the measurements was also carried out. Figure 5 shows the variation in velocity at each of the six analyzed desks (D1–D6).

Although the air velocity did not significantly exceed the limit values, the analysis of the variability of this parameter during the 4 min of the measurements was also carried out. Figure 5 shows the variation in velocity at each of the six analyzed desks. These measurements confirmed local problems with incorrect distribution of air in the room then the people felt discomfort. The airflow fluctuation can cause a draft feeling for the occupants of the room. This is especially noticeable with the diffuser Type I. Comparing the recorded velocity measurements during the 4 min measurement, the flow from the Type I diffuser was characterized by greater variability. Pulsations of air flowing out of this type of diffuser reached the velocity of 0.34 m/s for the D5 workstation. It is worth emphasizing that the averaged velocity at this desk, for measurements with the diffuser Type I, did not

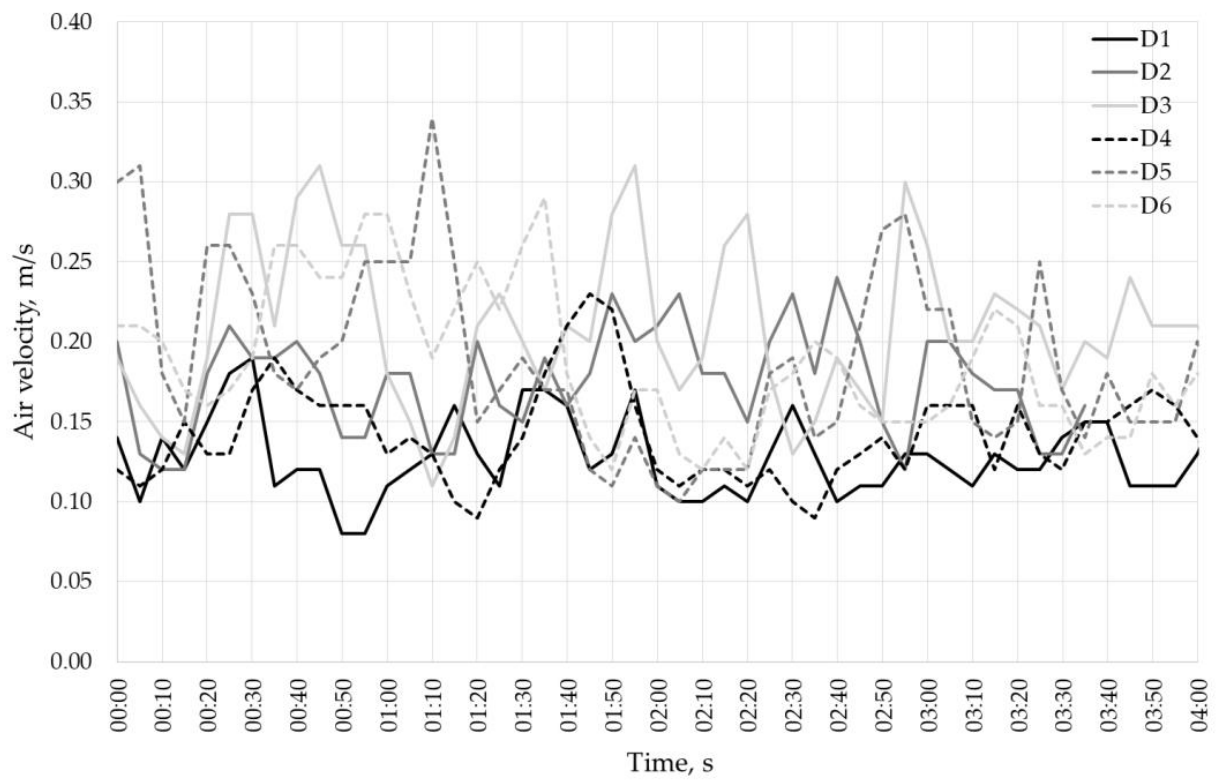
exceed the limit value and amounted to 0.19 m/s. The air outflow from diffuser Type I near the D5 desk was characterized by the greatest variability. The minimum air velocity was 0.10 m/s, which means that the differential between maximal and minimal measurements equals 0.24 m/s. Exceeding the instantaneous velocity above 0.30 m/s also occurred at the D3 desk, i.e., the workstation with the highest average velocity. The Type II of the diffuser was characterized by a much lower velocity variation during the measurements period. The maximal differential between the recording values was 0.15 m/s. The maximum instantaneous velocity of 0.27 m/s was noted at the D3 and D6 desks, i.e., the most distant desks from the analyzed diffusers. The analysis of airflow velocity variability over time at workstations provides an explanation of the feeling of the draft by the users of the facility with the use of the Type I diffuser. The performed measurements, taking into account the variability of air velocity over time, confirm better operation of the diffuser Type II. It is worth noting that considering only the averaged velocity, the Type I diffuser presents better results. These measurements show how crucial a detailed analysis of velocity variability is. Averaging the results hides air fluctuations, which, as the results showed, are a key aspect. Noticeable variability of the velocity and air pulsations cause a local discomfort to the users.

3.2. Analysis of the Air Distribution

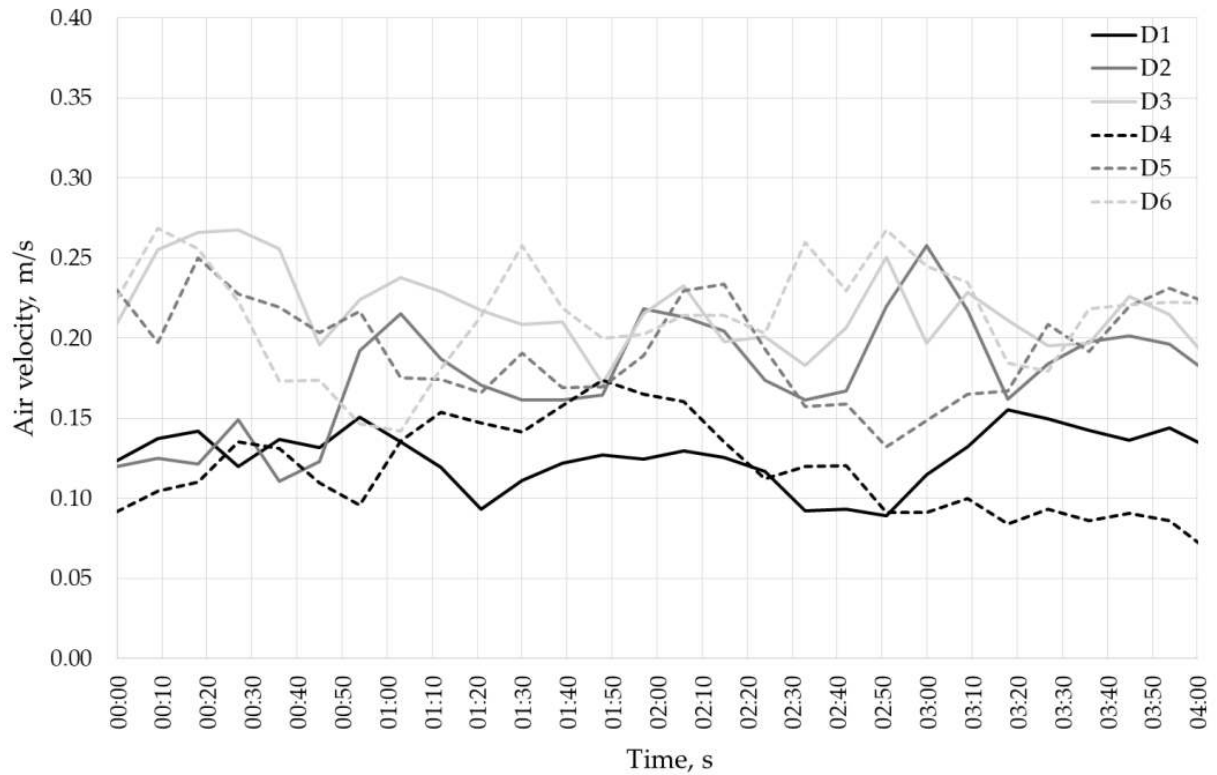
The next stage of measurements was to determine the velocity in the occupied zone between two rows of desks. Instantaneous measurements were carried out using AirDistSys 5000. Results from a 3 min period were averaged. Airstream supplied to the room by each of the diffusers amounted to about 270 m³/h. The supply air temperature was in the range of 12–14 °C (depending on the tested type of diffuser). This means the temperature differential between the ambient and the supplied air temperature amounted to 8 K. Table 2 shows the results obtained during the measurements. The distance along the airflow from the linear diffuser was marked with X, whereas the perpendicular direction was marked with Y (according to the axes in Figure 3). The table includes results for both types of diffusers.

Table 2. Results of the measurements for velocity of the air flowing out of the supply air diffuser Type I and Type II.

Height Z m	Distance X m	Type I Distance Y, m				Type II Distance Y, m			
		0.45	0.15	−0.15	−0.45	0.45	0.15	−0.15	−0.45
1.70	1.00	0.12	0.13	0.14	0.14	0.13	0.12	0.11	0.11
	2.00	0.17	0.22	0.17	0.12	0.10	0.10	0.12	0.13
	3.00	0.16	0.26	0.36	0.24	0.15	0.15	0.15	0.18
	4.00	0.16	0.25	0.29	0.29	0.20	0.19	0.21	0.22
	5.00	0.19	0.21	0.20	0.24	0.20	0.20	0.22	0.21
2.10	1.00	0.16	0.18	0.16	0.14	0.10	0.10	0.09	0.10
	2.00	0.31	0.45	0.34	0.18	0.13	0.11	0.11	0.14
	3.00	0.16	0.38	0.42	0.25	0.22	0.16	0.15	0.16
	4.00	0.14	0.16	0.19	0.20	0.21	0.19	0.18	0.24
	5.00	0.13	0.14	0.14	0.15	0.22	0.18	0.15	0.32
2.50	1.00	1.01	0.38	0.34	0.12	0.34	0.15	0.20	0.25
	2.00	0.45	0.75	0.35	0.20	0.55	0.38	0.47	0.90
	3.00	0.27	0.39	0.30	0.27	0.68	0.58	0.76	0.97
	4.00	0.23	0.20	0.21	0.18	0.47	0.54	0.78	0.86
	5.00	0.25	0.24	0.21	0.20	0.39	0.44	0.66	0.82



(a)



(b)

Figure 5. The air velocity on selected desks in time 4 min (a) for diffuser Type I; (b) for diffuser Type II.

For both diffusers, the maximal air velocity usually occurred at a distance of about 2.00–3.00 m from the diffuser in the X-axis. This tendency was observed at each of the analyzed heights and for both of the diffusers. Upon reaching its maximum value, the airstream began to descend to the occupied zone. However, for the diffuser Type I at the height of $Z = 2.50$ m, i.e., at a distance of 0.20 m from the ceiling, the highest velocity was achieved at a distance of 1.00 m from the diffuser. This velocity equals over 1.00 m/s and was recorded at a distance of $Y = 0.45$ m. For Type II, the highest recorded velocity was slightly lower and amounted to 0.97 m/s. This value was also determined for the height $Z = 2.50$ m but at a distance of 3.00 m from the diffuser. Comparing the results in terms of variability of the outflow profile from the diffuser along its length, it can be observed that, for $Z = 1.70$ m and $Z = 2.10$ m, diffuser Type II was characterized by more even airflow. Although at the distance higher than 3.0 m in the X-axis for $Z = 2.50$ m, the more even airflow is notable for diffuser Type I.

To determine the trend of air velocity changes with the distance away from the diffuser, line graphs were developed, as shown in Figure 6. A separate graph was developed for each analyzed measurement height. The presented results include two planes along the Y-axis. Black lines show the results for the Type I diffuser and the gray ones for the Type II diffuser. The solid lines refer to the results at the plane $Y = \pm 0.45$ m, and the dashed lines for $Y = \pm 0.15$ m.

For the selected planes, the highest velocity values were recorded for diffuser Type II near the ceiling ($Z = 2.50$ m). For diffuser Type I, the higher velocity occurred at the height of $Z = 2.10$ m. At the height of $Z = 1.70$ m, i.e., in the occupied zone, the limit velocity of 0.20 m/s is exceeded at a distance of about 2.25 m from the diffuser Type I ($Y = -0.15$ m). For the same height, the exceeding of 0.20 m/s in the case of the analysis for the Type II diffuser takes place by more than 1.00 m further from the diffuser. It is worth emphasizing that for the Type I diffuser, the velocity in the zone where people are present is higher (0.36 m/s, 3.00 m from diffusers) than for the Type II diffuser (0.22 m/s, 5.00 m from diffusers). For the compared diffusers, the differences in the value of the maximum air velocity and the distance at which they occur are significant. The type II diffuser obtained better performance.

Measurements at workstations were made in the place of the user's chair, assuming that it is in the symmetry axis of the desk. This means that for D1 and D4 desks, the measurement was made at the distance from the diffuser approximately $X = 1.25$ m, for D2 and D5 desks $X = 1.75$ m, and for the D3 and D6 desks $X = 4.25$ m. For D1–D3 desks, the closest measurement line using to determine the air distribution was $Y = 0.45$ m, and for D4–D6 desks, the $Y = -0.45$ m line. Figure 7 summarizes the results of measurements at workstations (D1–D6) for $Z = 1.20$ m and the velocity of the air flowing out of the supply air diffuser for the height of $Z = 1.70$ m.

Comparison of the averaged velocity results from both measurement series shows the similarity between the results, especially for the Type II diffuser. The biggest differences for this type were observed at the desks marked as D2 and D5. At that distance, the air velocity tested at the workstations was higher but did not exceed 0.20 m/s. Larger differences between the measurements for the Type I diffuser can be explained by significant fluctuations and the variability of the outflow profile from this diffuser along its length, as shown in Table 2.

3.3. Comparison of the Air Distribution

Besides the abovementioned comparisons, the assessment of air distribution was based on the comparison of velocity fields. Measurements carried out in the $Y = -0.15$ m plane were used to prepare the velocity fields for both types of diffusers. Velocity fields were performed using the Surfer software [35]. Figure 8 shows the isolines of air velocity, expressed in m/s, at the height range from 1.20 to 2.70 m.

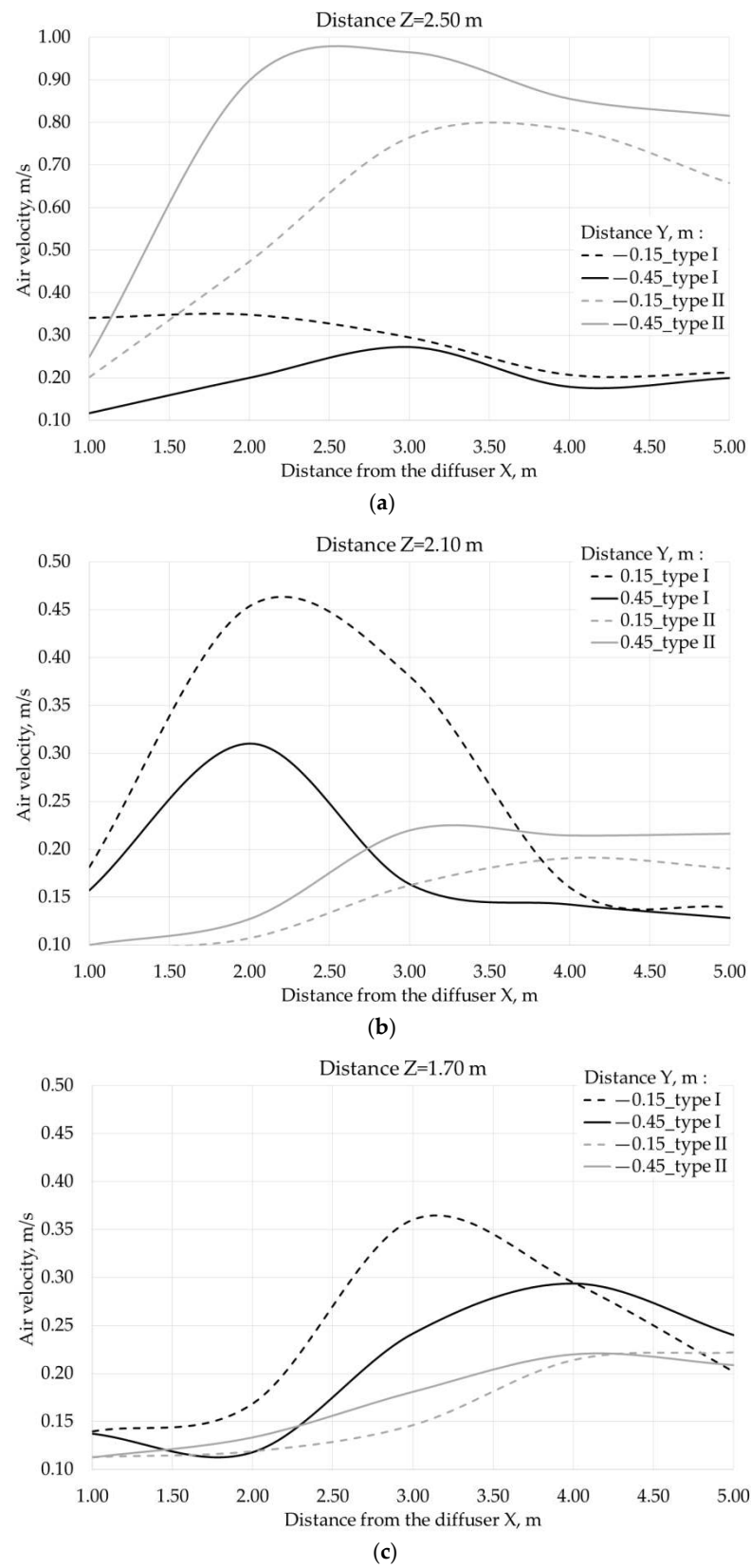


Figure 6. Results of air velocity measurements as a function of the distance from the diffuser Type I and Type II for height from the floor: (a) $Z = 2.50$ m; (b) $Z = 2.10$ m; and (c) $Z = 1.70$ m.

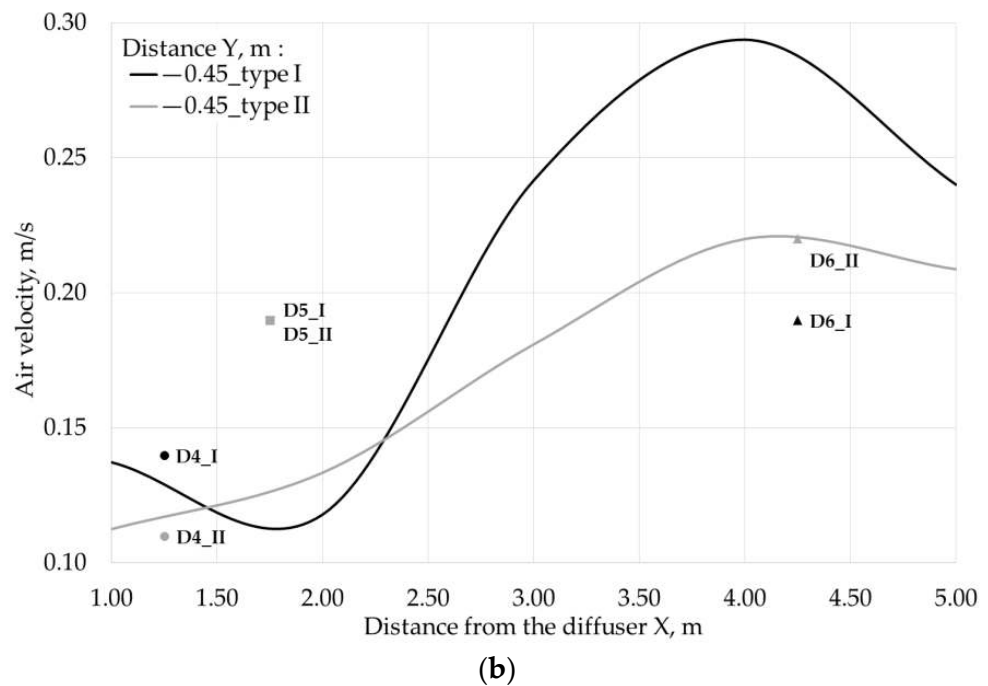
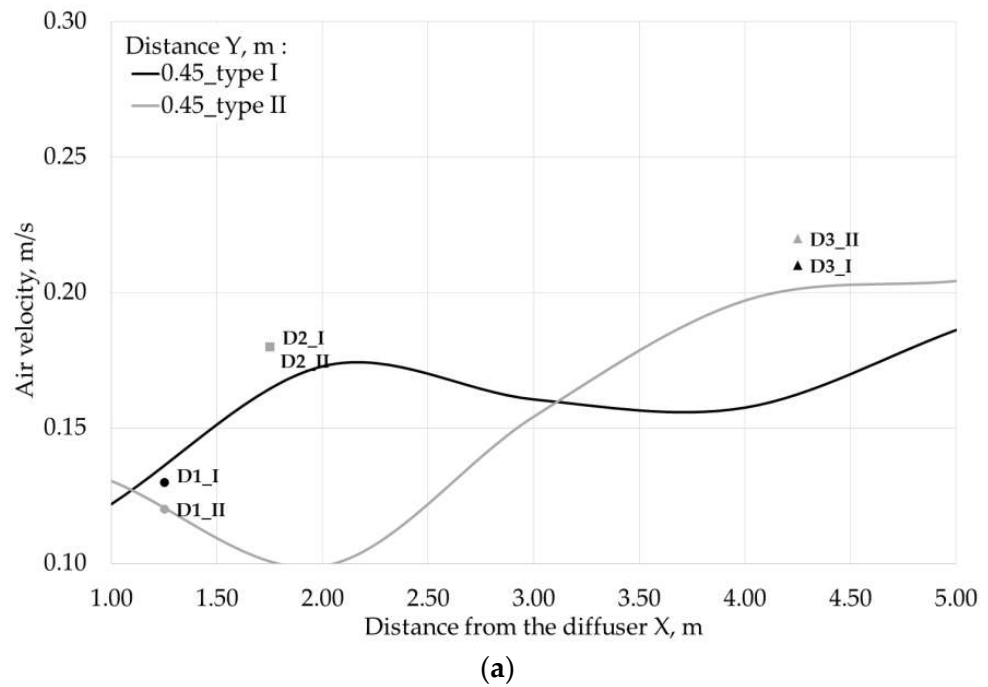


Figure 7. Distribution of the air velocity with the distance from the diffuser for Type I and Type II at the height of $Z = 1.70$ m (for lines) and $Z = 1.20$ m (for points) for: (a) $Y = 0.45$ m and desk D1–D3; (b) $Y = -0.45$ m and desk D4–D6.

As can be seen, the differences in the velocity range are significant between the diffusers. In the case of the Type I diffuser, the airstream clearly descends into the occupied zone ($Z = 1.80$ m), while for the Type II diffuser, high velocity are maintained at the ceiling. Similarly, control planes for $Y = 0.15$ m were prepared, as shown in Figure 9.

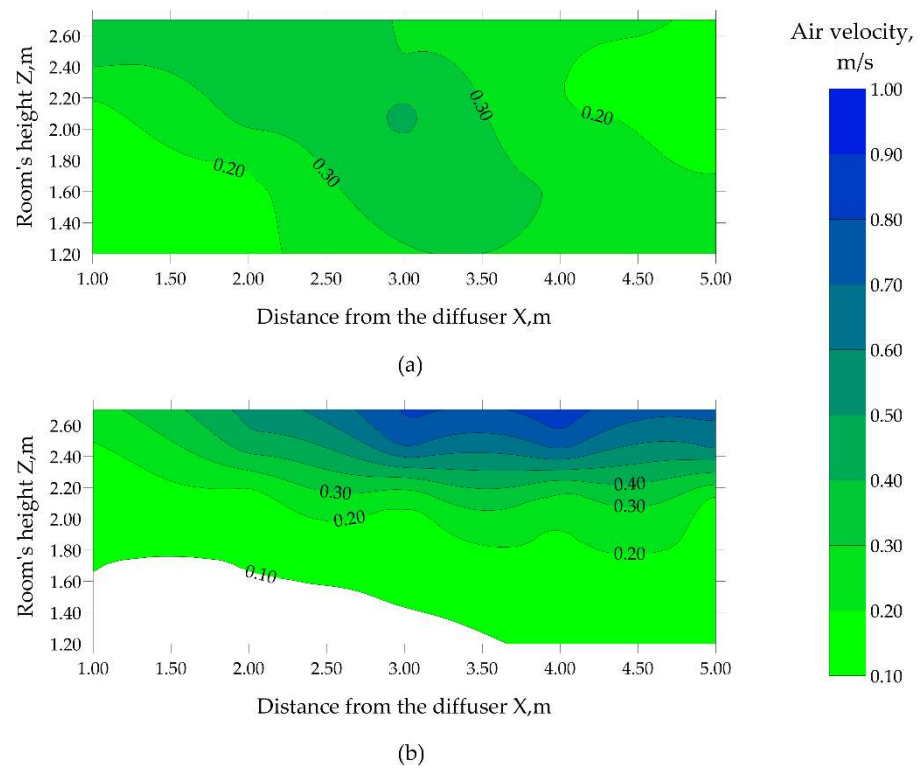


Figure 8. Isolines of air velocity distribution from the supply air for $Y = -0.15$ m: (a) diffuser Type I; (b) diffuser Type II.

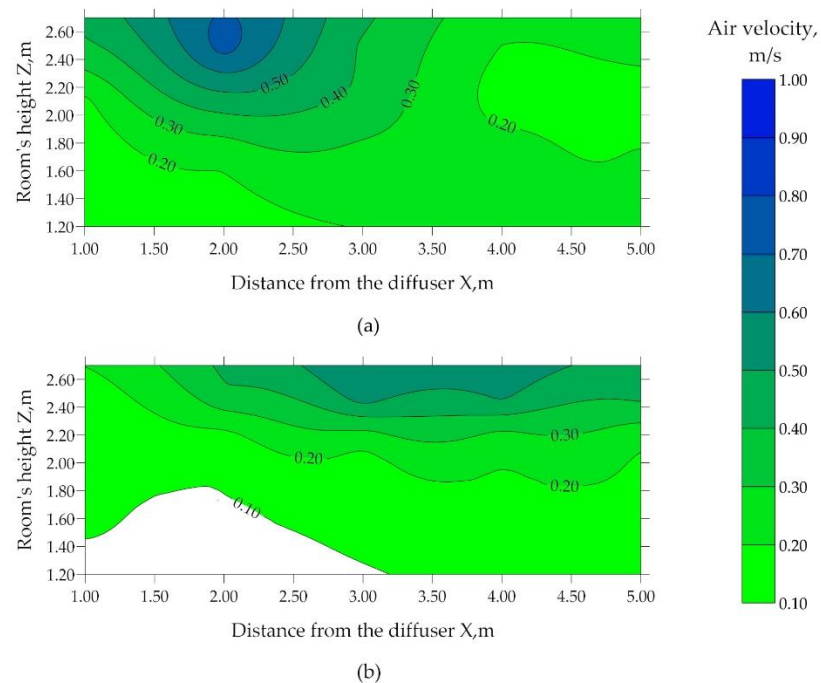


Figure 9. Isolines of air velocity distribution from the supply air for $Y = 0.15$ m: (a) diffuser Type I; (b) diffuser Type II.

Based on the measurement results taken and developed for air velocity in the office building, it should be stated that the linear diffuser Type I does not provide the required velocities in the occupied zone and at workstations; therefore, the comfort conditions are not met. In the occupied zone, the air velocity at a distance of 2.50 m from the diffuser Type I exceeds 0.30 m/s, both for the plan at $Y = -0.15$ m and $Y = 0.15$ m. Such a situation

is unacceptable from the point of view of proper use of the room, and it contributes to the creation of a zone where a user of the room feels discomfort. The diffuser Type I directs the air to the occupied zone. On the other hand, the measurements taken for the supply air linear diffuser Type II show that the supply air diffuser directs air under the room ceiling and ensures proper air distribution velocity in the room and in the occupied zone. For diffuser Type II, the air velocity in the occupied zone shows a value near the limit of 0.20 m/s. Only for single measuring points was this velocity limit slightly exceeded (maximum value 0.22 m/s).

Based on the velocity fields present in Figure 8; Figure 9, it is noticeable that diffuser Type II was characterized by a more even airflow from the diffuser along its length than the Type I. This can be explained by the design of the diffuser. The geometry of diffuser Type I is not a typical linear outlet because air is supplied by several nozzles. It causes significant differences in the measurement results for the analyzed planes. The linear outlet from diffuser Type II provides an even airflow at different distances in the Y-axis.

The determined velocity fields in the space between the desks confirm, similarly to the measurements at the desks, a better operation of the Type II diffuser. The design of this diffuser ensures air velocity within the acceptable range in the occupied zone. The air flows from the diffuser Type II, for the analyzed position of the blades, is directed toward the ceiling of the room. It ensures that the cool airstream does not fall into the occupied zone with excessive velocity. The setting of nozzles in the Type I diffuser does not allow one to obtain a similar result. Using this type of diffuser, the acceptable values of the air velocity are not obtained in the occupied zone.

3.4. Discussion of the Results

The microclimate of a given room and comfort conditions present in it depend not only on temperature and humidity values but also on the velocity of the air in a room, especially in the occupied zone. Improper type selection or location of the air-conditioning system's supply components in a facility may contribute to local discomfort for users of the building.

One of the most important aspects of proper air distribution in the room is the selection of the elements of the ventilation system, especially air diffusers. Users' comfort connected with airflow in the room has a crucial influence on efficiency and quality of work. The research was carried out for the most difficult working conditions for diffusers, i.e., the cooling variant. The cool airstream dropping into the occupied space may cause a draught feeling. For heating mode or isothermal conditions, the higher velocity of the air may obtain acceptable conditions. The results showed how important it is to control the variability of the air velocity flowing from the diffusers. The proposed analysis allows assessing the comfort of the users at the workplaces. The average velocity values at workplaces did not confirm the legitimacy of the discomfort experienced by users. Only a thorough analysis of the air velocity fluctuation in time allowed one to assess the scale of the problem in the analyzed object. Using the Type I diffuser, significant exceedances of the acceptable velocity of 0.20 m/s were noted. The instantaneous velocity was up to 0.34 m/s (desk D5), while the average value over the duration of the measurement was relatively low (for the desk D5 to 0.19 m/s). For diffuser Type II, the velocity variability over measurement time was also noticed, but the deviations were much smaller. According only to the averaged velocity from the measurement time, the Type I diffuser was characterized by the lower velocity at workplaces. Only including the airflow fluctuation of velocity over time to the analysis allowed for the assessment of the diffusers' operation. Based on the results, Diffuser II was selected as the one which ensures the comfort of users.

The location of the measuring grid was selected to allow for the evaluation of outflow along the length of the diffusers. The data presented in Table 2 show that the Type II diffuser was characterized by a more uniform profile along its length for the results from the measurement plane $Z = 1.70$ m and $Z = 2.10$ m. Only at the height $Z = 2.50$ m from the distance of 3.00 m from the diffuser did Type I display more even airflow.

The presented velocity fields for Type I (Figure 8) and Type II (Figure 9) most accurately illustrate the differences in air distribution between these two types of diffusers. The results of air distribution measurements confirm that the design of the diffuser is significant for the shape of the stream flowing out of the diffuser. In a diffuser consisting of nozzles (Type I), the cool air stream detaches from the ceiling at a short distance from the diffuser and falls into the occupied zone. At a distance of 2.50 m from the diffuser Type I, velocity in the occupied zone exceeds 0.30 m/s. For the same operating parameters, diffuser Type II allows for the supply of air horizontally, under the ceiling. It reduces the risk of the draft in the occupied zone. For diffuser Type II, the air velocity in the occupied zone reaches the values near the limit of 0.20 m/s. In the analyzed building, the solution to the issue of users' discomfort and the perceived feeling of the draft was to replace the installed air supply elements. The tested diffuser consisting of two rows of nozzles did not make it possible to propose such an air distribution that would ensure both low air velocities in the occupied zone and a low level of turbulence. Only the replacement of the elements with the Type II diffusers ensured optimal conditions.

4. Conclusions

The selection of diffusers should be based on the assessment of air flow from the diffusers, pressure drop and the sound generated by them. It should be noted that the characteristics given in the catalogs of diffuser manufacturers very often result from averaged measurements over time, which are performed under isothermal conditions.

The most common mistake is the selection of the air diffuser based on the dimension and general type of the element without a solid assessment of their operation in analyzed conditions. Often, inappropriate elements are replaced with the same type of diffuser provided by other manufacturers. Such a solution may result in continuous discomfort for the users. Evaluation of operating parameters of diffusers should be done at least for the most difficult working conditions for diffusers.

The knowledge of the air stream profile by the selection of the elements of the ventilation and air-conditioning system is crucial. The detailed analysis helps avoid problems with the air velocity distribution in the room. The appropriate selection of the diffusers and the proper air distribution in the room allow for the maintaining of the proper microclimate parameters in the facility. The selection process of the device requires including the operating parameters for which the device ultimately works. For cooling mode, it is important to consider this temperature difference. It is worth emphasizing that the considerations made based on the performed measurements are valid for all types of diffusers, not only linear diffusers for which the tests presented in the article were carried out.

A good practice for designing HVAC installations from the point of view of air distribution through diffusers is their proper placement. Using more diffusers helps to maintain thermal comfort conditions more effectively. Designing the installation to operate for smaller differences in the supply air temperature and the room also allows for improving these conditions. Nonetheless, this approach requires an increase in the supplied air stream. According to the authors, a good practice is to use diffusers because their design allows for the modifying of the shape of the air stream flowing. Many factors may affect the operation of the air diffusers. At the design stage, it is difficult to predict all the aspects which may occur in the facility. The possibility of diffusers' adjusting at the stage of commissioning the installation in the facility often allows for solving many problems with air distribution. By consequence, it could be a crucial activity that provides comfort parameters for users.

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Abbreviations

AirDistSys 5000	Measurement System—Velocity and Temperature
HVAC	Heating, Ventilation, and Air Conditioning
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
TABS	Thermally Activated Building Systems

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