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The Effect of Airflow Velocity through a Laminar Airflow Ceiling (LAFC) on the Assessment of Thermal Comfort in the Operating Room

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Abstract: Forced ventilation is applied in clean rooms, specifically operating rooms, to ensure the health of both the patient and the medical staff. Ventilation reduces the risk of patient contamination, and its parameters are legally prescribed. In addition to preventing contamination, the ventilation system also ensures the creation of a comfortable environment for personnel who spend a large amount of working time in the operating room. This research focuses on the appropriate design of the air flow rate from the distribution element to the operating room. The PMV and PPD indexes were used to evaluate thermal comfort for human beings. The measurements of parameters determining thermal comfort took place in a laboratory with an accurate model of the operating room, including equipment and HVAC system, during the summer months, in cooling mode. Discharge speeds in the range of 0.15–0.175 m/s were evaluated as the most comfortable, with the PPD index ranging up to 22%. There was a significant increase in user dissatisfaction up to the limit of 70% at higher discharge speeds.

Keywords: indoor air quality; health care; occupational health; built environment; thermal comfort; HVAC; special environment; predicted mean vote (PMV); predicted percentage of dissatisfied (PPD); clean room; operating room; airflow velocity

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1. Introduction

Operating rooms (OR) are legislatively classified as clean rooms according to standard EN 14 644-1 [1]. The first mentions of clean rooms come from the middle of the 19th century. However, their greatest development occurred only after World War II. Legislation determines the conditions of use and the quality of the internal environment of operating rooms [1–9]. One of the most important components of clean rooms is the HVAC system, which provides controlled and forced ventilation with air filtration. The HVAC system serves to achieve a low concentration of airborne particles using two mechanisms. The first mechanism works on the principle of diluting the particle concentration by supplying a large amount of clean and filtered air to the OR. The second mechanism consists of pushing particles out of the space around the operating table using laminar air flow [10]. These mechanisms ensure a healthy environment, which is required in the OR for both the patient and the medical staff [11,12]. The concentration of airborne particles and the quality of the indoor environment are monitored to minimize the occurrence of infection during surgery [13]. Infection occurs when an open wound is contaminated with viruses or bacteria that enter the wound through direct contact or are secondarily transmitted by airborne particles [14,15]. Secondary contamination can be prevented by creating a clean zone in the OR. It is an area covered by a laminar airflow ceiling (LAFC), where filtered air is supplied [16,17]. Air flow in the clean zone prevents the dispersion of pathogenic airborne particles [14,18]. Common air flow velocities from LAFC are from 0.1 to 0.5 m/s [1,5–9,19,20], which can result in decreased thermal comfort for staff and patients in clean zone.

The HVAC system defines not only the air flow in the operating room but also the thermal conditions [21], which are specified by legislation and standards [1,2,5–9]. These standards also prescribe the use of LAFC in operating rooms. In addition to infection prevention, HVAC technical standards state that thermal comfort must be achieved in the OR for all members of the surgical staff as well as for the patient [13,21]. Thermal comfort is defined as a state when the thermoregulatory member of the human body is minimally stressed or as a state of mind that expresses satisfaction with the internal microclimate [3,22–26]. The perception of the thermal environment by people is evaluated by the international standard ISO 7730, standard EN 15 251 and standard ASHRAE 55 [3,4,18,27]. Various models and assessment indices have been created to assess the quality of the indoor environment and thermal comfort. Among the first is the "Two-node model", which compares the temperature of the core of the body and the surface of the body for the analysis of energy exchanges between the human body and the surrounding environment [28]. In the publication "Determining lines of equal comfort" [29], the concept of thermal comfort was empirically expressed using the effective temperature. Subsequently, these studies were improved, and the "Standard Effective Temperature" [30] was introduced. Currently, the most used model is according to Fanger, which represents the PMV (Predicted Mean Vote) and the PPD (Percentage People Dissatisfied) indices for predicting a person's thermal sensation [31]. In these models, thermal comfort is a function of subjective parameters, including thermal resistance of clothing and heat flow from the body due to metabolism, and objective parameters, including mean radiant temperature, air temperature, air flow velocity and air humidity in the room [31–33].

Several studies on thermal comfort in clean rooms, and specifically in the OR, have reported that achieving thermal comfort during LAFC operation is problematic [6–9,16,17,21,34,35]. Different feelings of comfort and perception of air temperature result in different subjective parameters of thermal well-being. Persons in the operating room differ in the thermal resistance of clothing (CLO) but also in the heat flow from the body due to metabolism (MET). In addition to these parameters, the position of the person in the OR has a fundamental influence on the overall feeling of thermal well-being. By default, the medical staff stands during the procedure in the OR, though some participants can also sit, e.g., anesthesiologist doctor and anesthesiologist nurse. In most cases, the patient is in a horizontal position on the operating table. The mentioned studies state that due to these differences, it is impossible to simultaneously achieve thermophysiological comfort within 10% of the patient's PPD in terms of the staff, or individual staff in terms of one another. In this study, we will address the reduction of the PPD index for users in the OR by appropriate adjustment of the outlet airflow rate through the LAFC. The novelty of this study is the provision of information for designers on how to appropriately choose the size range and flow rate through LAFC in clean rooms.

2. Materials and Methods

The aim of the study is to improve the thermal comfort in OR spaces by means of the appropriate setting of the flow rate through the LAFC. The PMV and PPD indices were evaluated in an experimental laboratory, which was built as an OR model on a real scale.

2.1. Operating Room Model

The experimental laboratory for the simulation of operating room ventilation was designed and implemented according to the currently valid legislation in the area of the research [1,2]. The dimensions of the laboratory are 5.76 × 5.95 × 2.70 m^3 (Figure 1). The supply distribution element (LAFC) is located slightly asymmetrically from the center of the laboratory floor plan. The structural elements are certified for use in clean rooms and have a low level of airborne particle emission. The floor is made of antistatic material. The walls are composed of metal panels with thermal insulation inside and polyethylene film on the surface. The ceiling is made of metal cassettes with a polyethylene surface to reduce the number of emitted particles. Internal equipment such as electrical sockets, lamps, operating table, operating lamp, instrument tables and others are also certified for use in clean rooms. The equipment of the laboratory can be seen in Figure 2. In a previous study, a CFD model with the same geometry was also created [19].

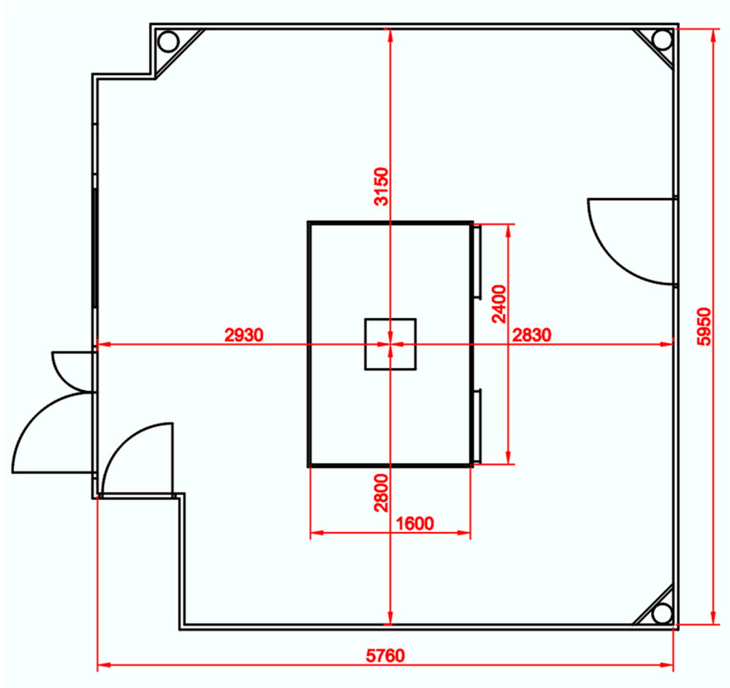


Figure 1. Dimensions of the laboratory and the location of the LAFC.

Figure 2. OR equipment.

The HVAC system is designed to ensure an internal microclimate, achieve thermal comfort, and create a clean environment with a low concentration of airborne particles. Its performance, air flow, internal temperature and relative air humidity are specified by legislation and are compared with the study of R.V. Gaever et al. [21]. This comparison is supplemented by legislative requirements of the country origin (Table 1).

As shown in Table 1, the ventilation system was designed to meet legislative requirements, which include the minimum air exchange rate for cleanliness as specified in ISO EN 6 (typical aseptic operating room with LAFC). According to EN ISO 14 644-1, the air-change rate (ACR) should be 120–300 h^{-1} in the area of the clean zone (floor plan area covered by LAFC, 2.4 × 1.6 m). To fulfill this condition, a volumetric air flow of 1250–3120 m^3/h is required. At the same time, according to Z. z. 259/2012, it is necessary to maintain an ACR in the entire volume of the room of at least 15/h, which represents a volume flow of 1320 m^3/h. The designed ventilation unit with exterior design enables a variable air flow of up to 3200 m^3/h with an external pressure loss of up to 600 Pa in the range of

30–100%. The ventilation unit is equipped with a cross exchanger, two-stage filtration of the supplied air, a heater and cooler in the form of a condenser and evaporator, and a backup electric heater. The backup electric heater serves to prevent the cooling down of air in the OR during defrosting of the heat pump (source of heat and cold for HVAC). An external air humidifier is added to maintain the relative humidity within the permitted range. A schematic representation of the HVAC system is shown in Figure 3. The location of the ventilation unit in the version for clean rooms, as well as the heat pump and air humidifier, are shown in Figure 4; Figure 5 shows a plan view of the HVAC.

Table 1. Comparison of requirements for indoor microclimate in the OR as specified in different international standards.

Standard	Supply Air Temperature t_a (°C)	Relative Humidity (%)	Supply Air Velocity (m/s)
EN ISO 14 644-1 [1]	22–26	40–60	0.1
ZZ 259/2012 [2]	$t_a > 25$	30–70	-
DIN 1946 [7]	19–26	-	$v \geq 0.23$
VDI 2167 [6]	22	30–50	$v \geq 0.23$
ASHRAE 170 [8]	20–24	30–60	0.13–0.18
ASHRAE application handbook [9]	17–27	45–55	1.3–1.8

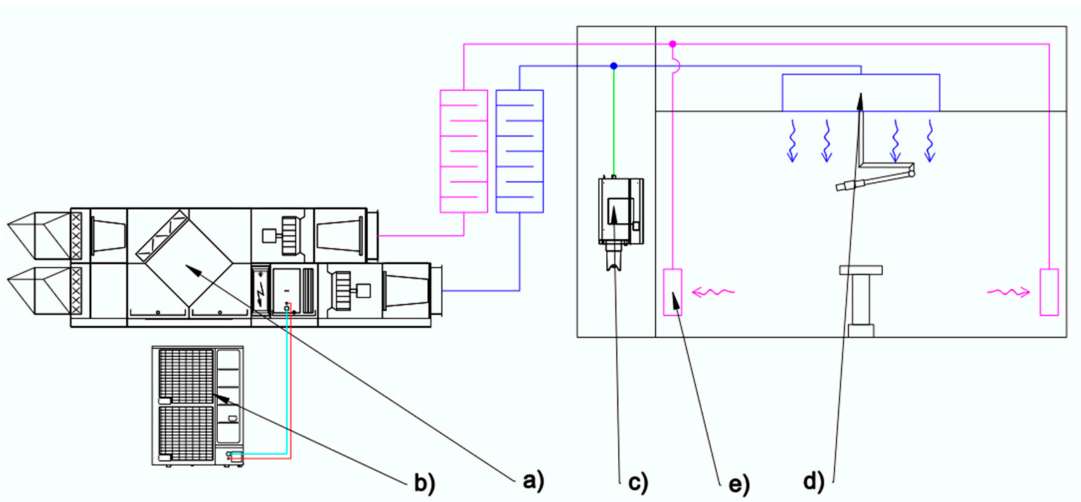
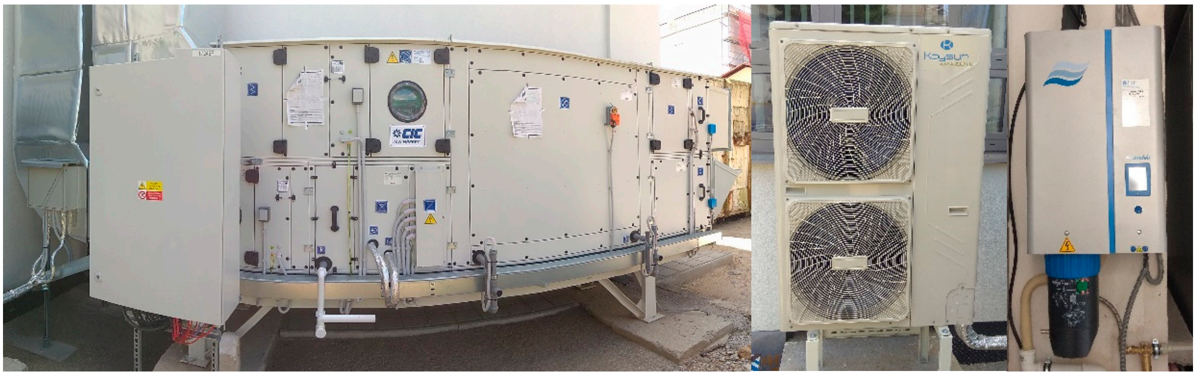


Figure 3. Scheme of HVAC equipment: (a) ventilation unit, (b) heat pump, (c) air humidifier, (d) LAFC, and (e) drainage outlets.



(**a**) (**b**) (**c**)

Figure 4. Location of HVAC equipment: (**a**) ventilation unit, (**b**) heat pump, and (**c**) air humidifier.

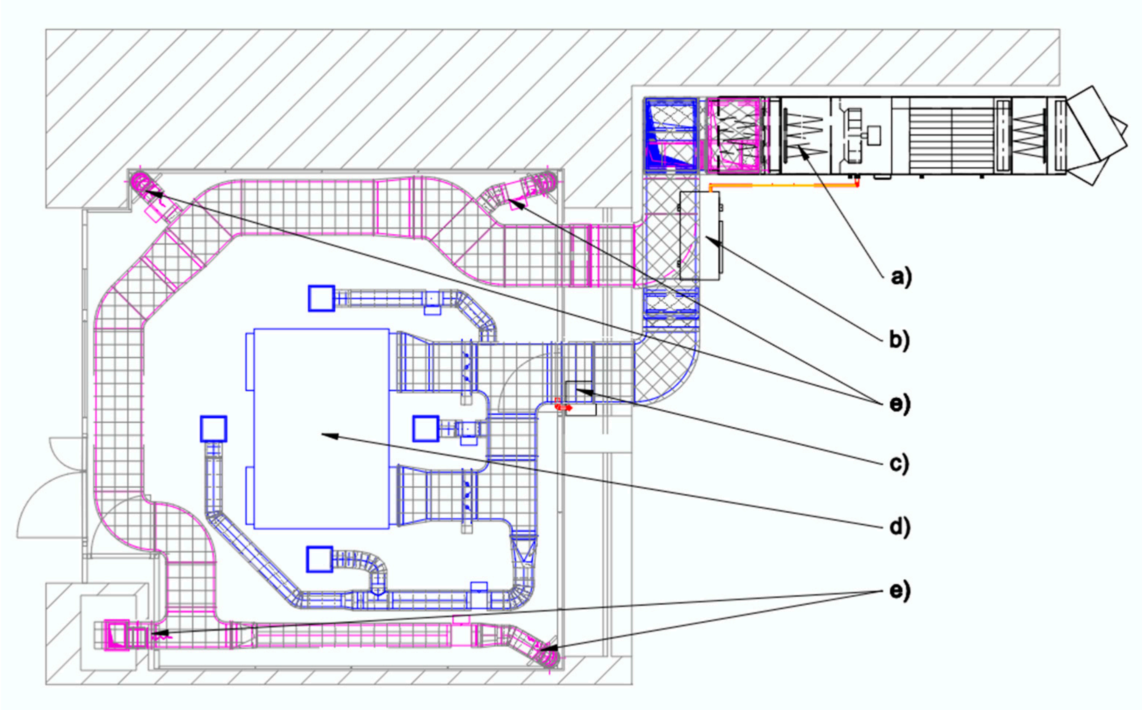


Figure 5. HVAC floor plan drawing: (a) ventilation unit, (b) heat pump, (c) air humidifier, (d) LAFC, and (e) drainage outlets.

The intake square diffusers are also indicated on the HVAC plan drawing. These diffusers are designed for clean spaces and were closed with tight check valves during the measurement. This will avoid affecting the airflow through the LAFC, and only the airflow image formed by the flow through the LAFC will be monitored. In a previous study [20], a difference in the air flow rate gradients in the entire cross-section of the OR was visible, due to the change in the air flow rate through the LAFC. A comparison of the profiles passing through the center of the LAFC for the outflow velocity of 0.15 and 0.25 m/s through the LAFC is shown in Figure 6.

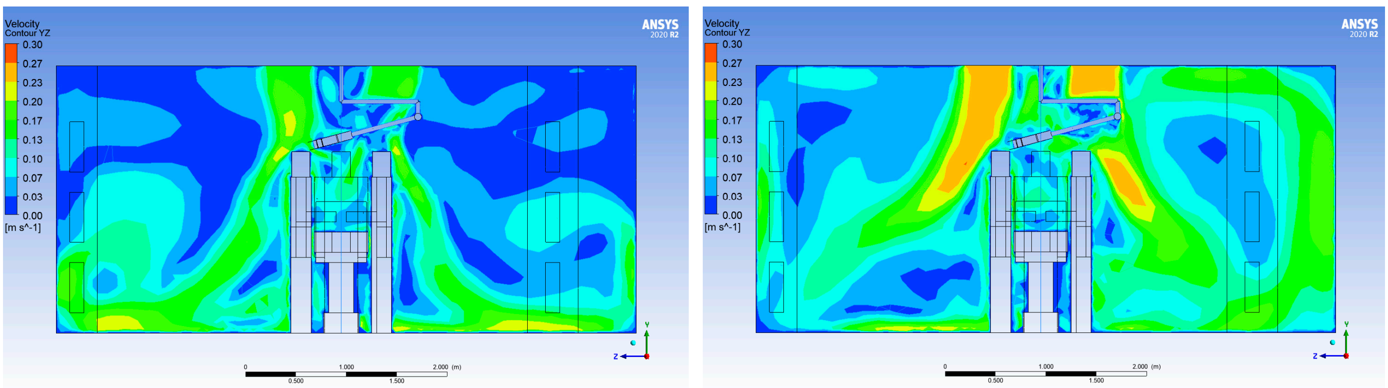


Figure 6. Air velocity profiles for outlet air velocity of 0.15 m/s (**left**) and 0.25 m/s (**right**) over LAFC [19].

2.2. Evaluation of Thermal Comfort

The thermophysiological model defined by Fanger [31] was used to assess the quality of the thermal comfort environment in the OR. The model describes a person's thermal sensation according to the predicted mean voice (PMV). It depends on the parameters of the internal environment and the reaction of the human body to these parameters [13,24]. This is a complicated iterative calculation with several variables; it is explained in more detail in several studies [36,37]. In a simplified way, it can be described as a function of the internal parameters of the environment, according to Equation (1).

$$f\left(q_q, R_{cl}, \theta_i, \varphi, v_i, \theta_u\right) = 0 \quad (1)$$

where

q_q—total density of heat flow from the human body (W/m^2)
R_{cl}—thermal resistance of clothing (CLO) (m^{2}K/W)
θ_i—indoor air temperature (°C)
p_i—partial pressure of the water vapor of the internal air (Pa)
v_i—indoor air flow rate (m/s)
θ_u—average radiant temperature (°C)

The indoor environment is rated on a 7-point scale ranging from −3 (cold) to +3 (hot), with 0 being neutral. Since this scale does not create an adequate idea of the quality of the thermal-humidity microclimate in the environment, the PPD index (predicted percentage of dissatisfied) is also introduced. This index is a function of the PMV index [38]. Optimal thermal comfort is determined as between PMV −0.5 and +0.5 [17,24,31], which represents a range of 5 to 20% PPD.

The ComfortSense Dantec measuring device was used to measure the internal parameters of the thermal-humidity microclimate and evaluate the PMV and PPD indexes. The device is designed for the development and research of heating, cooling and ventilation systems, using multi-point measurement of temperature and air velocity. The device consists of five measuring elements (H1, H2, H3, OT and RH) on a tripod, a measuring unit for the transformation of an analog signal into a digital, cabling and the corresponding NiMax software (https://www.ni.com/en-rs/support/documentation/supplemental/21/what-is-ni-measurement---automation-explorer--ni-max--.html, accessed on 6 April 2023). The designation of measuring elements and measured quantities is given in Table 2. The measuring device and measuring elements are shown in Figure 7. Thermal comfort parameters were measured in the position of the surgeon at the operating table. The measuring station is shown in Figure 8. Stationary measurements were taken for 30 min at each measuring position. The resulting values are averaged over the entire measurement period. The measurement error and the inaccuracy of the measuring members are shown in Table 2.

Table 2. Marking of measuring members, measured quantities and measurement accuracy for the ComfortSense device.

Mark Measuring Element	Measured Quantity	Thermal Comfort Parameter	Accuracy of Measurement	Vertical Position Y (m)
H1 H2 H3	t_a—air temperature	t_a—air temperature	± 0.2 °C	0.1 1.1 1.7
	v_a—indoor air flow rate	v_a—indoor air flow rate	±0.02 m/s	
OT	t_o—operative temperature	t_r—average radiant temperature	±0.2 °C	1.1
RH	φ—relative humidity	p_p—partial pressure of water vapor	±2%	1.8

The measured parameters of the thermal-humidity microclimate at the measuring stand with the surgeon's position differed minimally from the alternative positions; therefore, only the results from the surgeon's position will be presented in this chapter. The advantage of the measuring device and the software used is the evaluation of the profiles of air flow speed and air temperature on the imaging planes. In order to evaluate these, it was necessary to supplement the measurements in the middle of the walls with a rebound of 0.6 m (marginal zone). The measuring positions are indicated in Figure 8e. The plane shown is reduced on both sides by the edge zone (2 × 0.6 m). The disadvantage of the used software is the dynamic scale and the possibility of creating only a simple room in the shape of a cuboid. Atypical shapes, bounces and slopes as compared to the actual shape had to be neglected. Subjective parameters were chosen according to estimation and consultation with medical staff. The value of total metabolism was considered as

1.0 MET, which represents 58 W/m^2. This value represents the total metabolism of a standing person with moderate physical activity. The thermal resistance of clothing depends on its thermal and technical properties and the combination of individual types of clothing. During the preparation of the study and the design of the model of the operating room, several excursions to real operating rooms were completed. The design of the experimental operating room was inspired by the real conditions in the clean rooms. Protective clothing should consist of long trousers and a coat with long sleeves, gloves, a mask and headgear. In the summer months when the measurement took place, almost all participants wore a coat without long sleeves. According to the parameters of protective clothing, the actual thermal resistance of operating room workers was 0.6 CLO, which is 0.093 m^{2}K/W. Thermal resistance was evaluated in a similar range by Bogdan et al. [39] The effect of the thermal resistance of protective clothing on the assessment of thermal comfort of healthcare workers was also addressed in a study by Wang et al. [34].

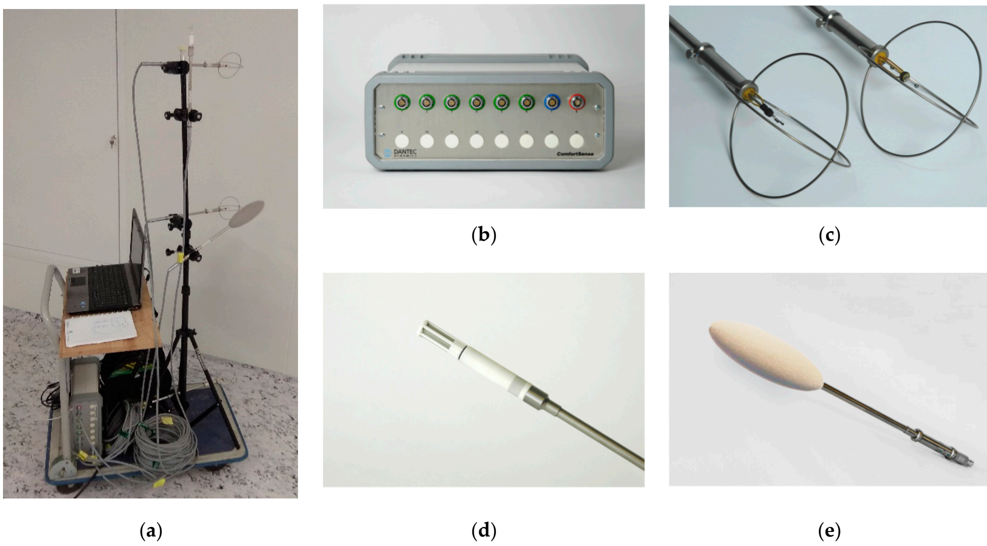


Figure 7. ComfortSense measuring device, (**a**) device during measurement, (**b**) measuring unit, (**c**) measuring elements H1–H3, (**d**) measuring element RH, (**e**) measuring element OT.

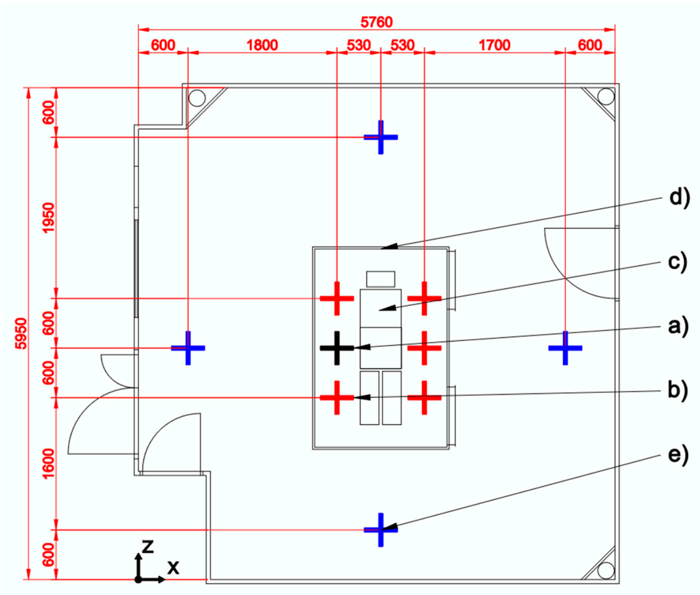


Figure 8. Measurement positions: (a) thermal comfort of the surgeon, (b) thermal comfort of the assistant surgeon (c) operating table, (d) LAFC (e) additional measurement of the thermal-humidity microclimate parameters.

3. Results and Discussion

The effect of air flow speed on the thermal comfort of people in the operating room was monitored during the measurement. The effect of different volumetric flow rates and velocity profiles of air flow on the thermal comfort in the OR was investigated. The higher the speed in the person's residence zone, the higher the feeling of cold. This can create negative feelings for the staff in the operating room and thus degrade the working conditions and the overall performance of the staff. The measurements in the experimental laboratory were made at different speeds of air flow from the laminar field. The recommended outflow velocity of the laminar field is in the range of 0.15–0.25 m/s for most manufacturers. With the known air speed from the laminar field and the known free outlet area (in our case, 3.55 m^2), we can determine the amount of air transported by the distribution element using Equation (2). The amount of air transported at different speeds as well as the designation of variants for these conditions is expressed in Table 3. According to the amount of transported air, five different variants were measured, from a speed of 0.15 m/s to a speed of 0.25 m/s, with graduations of 0.025 m/s. A 10% smaller amount of air is removed from the space, evenly distributed between the four corners of the room through exhaust diffusers of 0.5 × 0.2 m.

$$\dot{V}_{SUP} = v_{SUP} \cdot S_{SUP} \tag{2}$$

$\dot{V}_{SUP}$—air flow of the supply distribution element (m^3/h)
v_{SUP}—speed of the air flowing from the supply distribution element (m/s)
S_{SUP}—free outlet surface of the supply distribution element (m^2)

Table 3. Air flow of the laminar field for individual variants.

Variant	v_{SUP} (m/s)	V_{SUP} (m^3/h)
1	0.150	1916
2	0.175	2235
3	0.200	2555
4	0.225	2874
5	0.250	3194

The parameters determining thermal comfort in the environment are listed in Table 4. At three height levels (0.1, 1.1 and 1.7 m from the floor level), the air temperature and air flow velocity in the room were measured using the "draft probes" shown in Figure 7c. The probe for measuring humidity is shown in Figure 7d, and the probe for measuring the mean radiation temperature, or the operating temperature expressed from it, is shown in Figure 7e. The vertical position of the individual measuring members (Y) is determined by the recommendation for measuring thermal comfort and local discomfort (warm head, cold ankle, etc.).

Table 4. Parameters of thermal-humidity microclimate for individual variants.

Measuring Element	Unit	Variant				
		1	2	3	4	5
H1	t_a (°C)	23.1	22.6	23.5	23.7	23.0
H2	t_a (°C)	23.4	23.5	23.7	24.3	22.5
H3	t_a (°C)	23.8	24.1	23.8	24.8	22.7
H1	v_a (m/s)	0.10	0.14	0.05	0.11	0.09
H2	v_a (m/s)	0.12	0.15	0.20	0.24	0.25
H3	v_a (m/s)	0.03	0.05	0.19	0.19	0.20
OT	t_o (°C)	23.4	23.4	23.5	24.1	22.6
RH	φ (%)	44	44	42	40	45

Figures 9 and 10 show the temperature and air velocity profiles on the imaging planes passing through the center of the LAFC (reference point (x,y,z) = (0,0,0), lower left corner of Figure 8). Lower outflow velocities through the LAFC cause the formation of higher temperature gradients in the vertical direction, and stratification of air with a different temperature occurs. With increasing speed, there was a higher degree of air turbulence and mixing of individual layers, which reduced the vertical temperature gradient. It is also interesting to compare the speed of air flow at different height levels. In all cases, lower velocities were measured at the level of the head than at the level of the body's center of gravity. This can also be seen on the profiles of air flow speed in Figure 10. This phenomenon was discussed in more detail in a previous study, where it was also confirmed by CFD simulation and was created by a combination of the coanda effect, the flow around obstacles and the cumulation of velocity vectors [19].

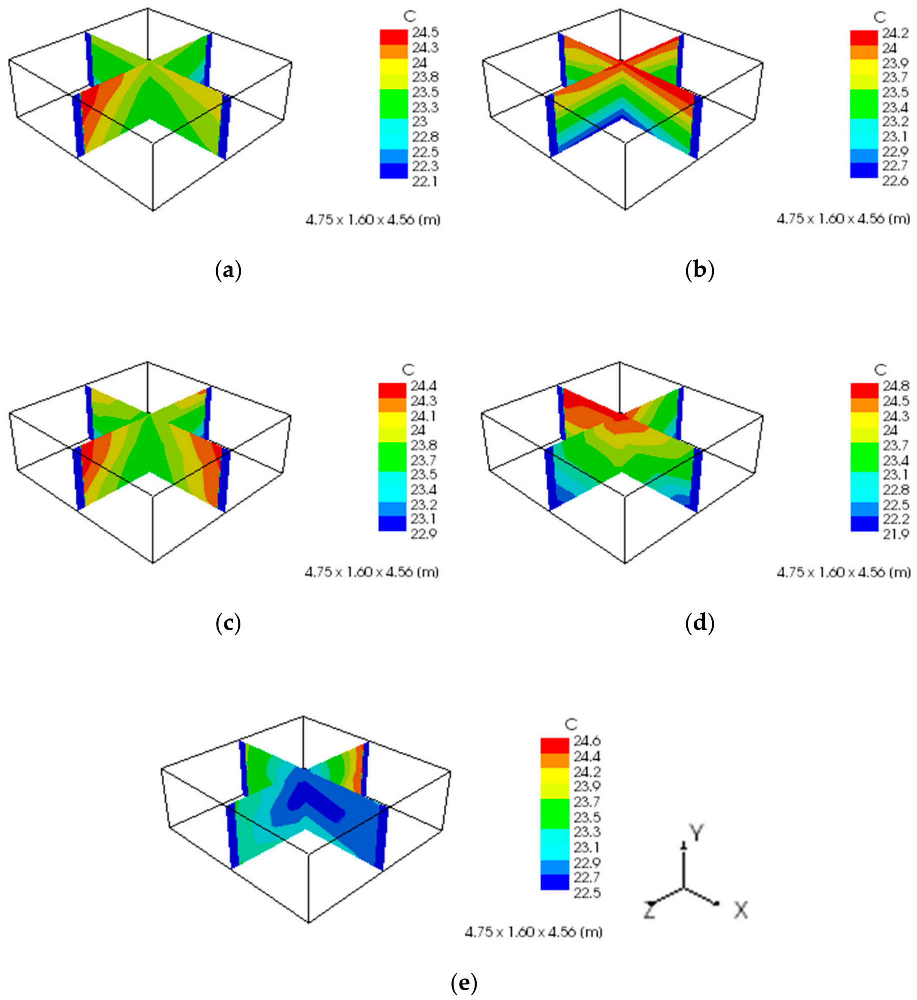


Figure 9. Air temperature profiles in the experimental laboratory for individual variants; (**a**) Variant 1; (**b**) Variant 2; (**c**) Variant 3; (**d**) Variant 4; (**e**) Variant 5.

The PMV and PPD indexes were expressed from the measurable parameters of the thermal-humidity microclimate and from the subjective parameters (thermal resistance of clothing and total metabolism). As indicated in Table 5 and in Figure 11, as the air outlet speed through the LAFC increases, the air flow speed in the residence zone also increases, and people's dissatisfaction with the indoor environment, i.e., the PPD index, increases. We can notice the connection between the increasing speed of the air flow and the increasing PPD index, especially by comparing the height level. For variant 3, at height level H1, the air flow speed is 0.05 m/s and the temperature is 23.5 °C. At altitude level H2, the temperature is 23.7 °C and the air flow speed is 0.20 m/s. Although the temperature is slightly higher at the H2 level, due to the higher air flow speed, there was an increase in user dissatisfaction with the environment (PPD index) due to the cold, from 18.45% to 34.35%. In the area of the legs (H1), there were no significant changes in air flow speed and PPD index between the first and fourth variants. According to the curve of a comfortable and acceptable environment from the point of view of thermal well-being, there is a significant disturbance of comfort from the outflow velocity of 0.2 m/s.

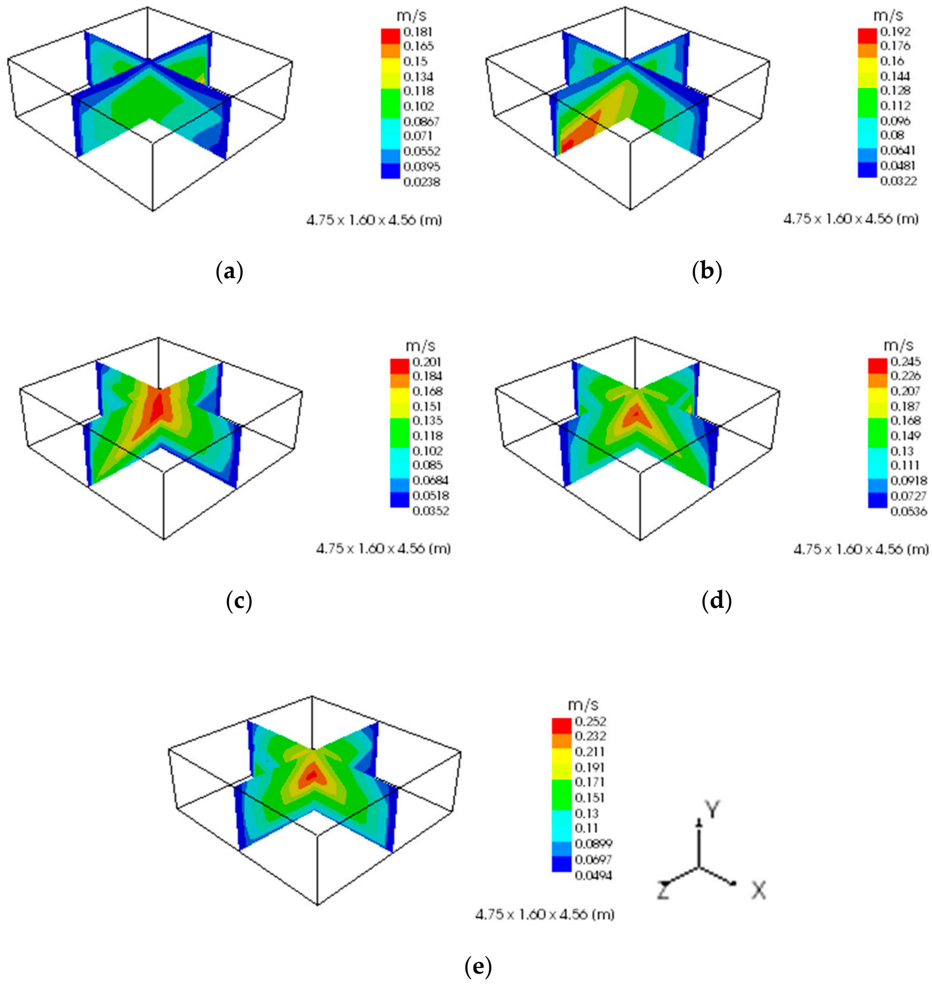


Figure 10. Velocity profiles of air flow in the experimental laboratory for individual variants; (**a**) Variant 1; (**b**) Variant 2; (**c**) Variant 3; (**d**) Variant 4; (**e**) Variant 5.

Table 5. PMV and PPD indexes for individual variants.

PMV Index	**Variant**				
	1	**2**	**3**	**4**	**5**
position H1 [-]	−0.62	−0.90	−0.80	−0.81	−1.25
position H2 [-]	−0.70	−0.91	−1.18	−1.25	−1.86
position H3 [-]	−0.53	−0.62	−1.16	−1.10	−1.71
PPD Index	Variant				
	1	2	3	4	5
position H1 [%]	13.04	21.95	18.45	19.01	37.77
position H2 [%]	15.26	22.47	34.35	37.50	70.20
position H3 [%]	10.79	13.12	33.34	30.31	62.25

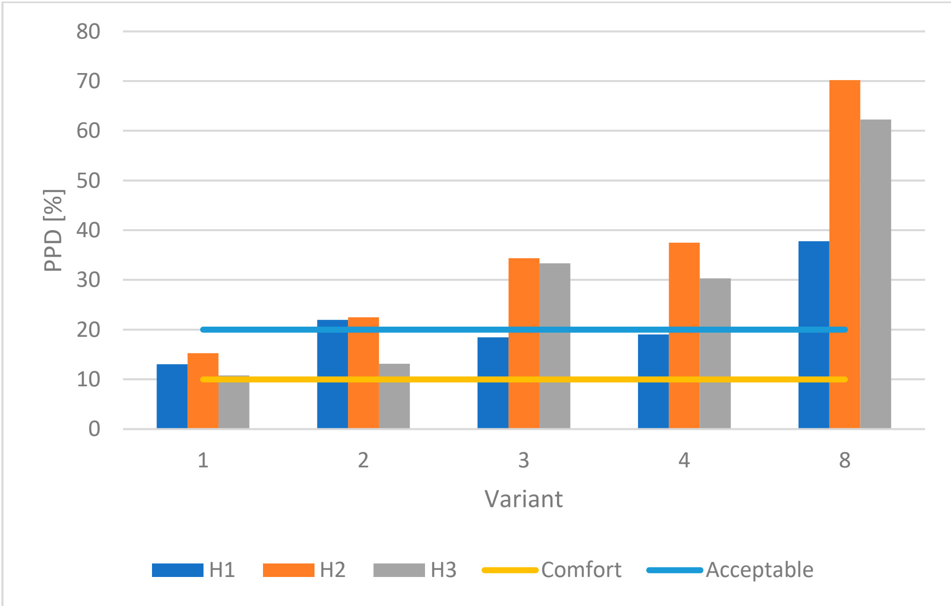


Figure 11. Comparison of PPD indexes for variant 1 to 5.

The measurement of thermal-humidity microclimate parameters took place in laboratory conditions with stabilized air flow. The supplied air was only exterior, and the device was not in circulation mode. This resulted in a slight fluctuation of the air temperature in the interior. The desired temperature in the room was set at 24 ± 2 °C. The outside air temperature was higher than 30 °C, which caused a thermal load on the OR, and at the same time raised the demands for cooling the air behind the recovery exchanger of the HVAC equipment. The temperature supplied through the LAFC must therefore be lower than the required 24 °C [5–8,40]. As mentioned in the description of the HVAC system, the primary source of heat and cold is the heat pump, which is directly connected to the evaporator, or the condenser in the ventilation unit. The disadvantage of this system is a slower response to changes in the desired temperature of the supplied air and a less sensitive power regulation. Therefore, there were slight variations in the air temperature during individual measurements. However, this also applies to normal operating conditions of OR ventilation and reflects sudden local changes in comfort near the LAFC. The lower temperature of the supply air through the LAFC also affected the overall velocity and trajectory of the air flow in the operating table area, due to Newton's law of gravity. If the temperature difference is too large, the area of direct flow may decrease, and the air column may narrow [17]. In addition to the inaccuracy of the measuring device, another limitation of the study, compared to the real situation, is the absence of medical personnel, which partially (200–400 W) reduced the heat load of the OR. Other devices in the OR (lamps, surgical equipment, etc.) that produce heat were turned on.

As already mentioned in several studies, the issue is to find a compromise between the requirements of the OR ventilation legislation and the thermal comfort of medical personnel [6–9,16,17,21,34,35]. Even while maintaining a higher air flow rate, it is possible to achieve a low air outlet velocity through the LAFC by using LAFCs with larger dimensions and a larger outlet area. It is necessary to observe the recommended speeds of legislation, standards and the LAFC manufacturer. Several studies have already indicated that lower discharge velocities reduce the risk of contamination by suppressing unwanted turbulence [19,41,42]. The PMV and PPD indices indicate that in the summer months, when air is supplied to the OR that is cooler than the desired room temperature, it is more advantageous to choose the dimensions of the LAFC so that the outflow velocity is in the range of 0.15–0.175 m/s. The increasing velocity of air flow through the LAFC causes an unpleasant feeling of coldness for the medical staff (surgeon). This can negatively affect the work performance and the success of the surgical procedure [43]. At an air flow speed of 0.2 m/s through the LAFC, the PPD index was higher than 30% in the area of the body's center of gravity (1.1 m) and the head (1.7 m). At a speed of 0.25 m/s, which is commonly used, the PPD index was evaluated at 70% in the area of the center of the body. Wang et al. [34] monitored the airflow velocity through the LAFC in the range of 0.1–0.5 m/s. In this range of speeds, a difference of up to 5 °C was detected on the surface of the protective clothing. Legislation, standards and regulations in different countries do not have the same statement on the appropriate outflow velocity through the LAFC. Standards VDI 2167 [6] and DIN 1946 [7] recommend speeds above 0.23 m/s, while standard ASHRAE 170 [8] recommends speeds in the range of 0.13–0.18 m/s, which was the range identified in our results. The EN ISO 14 644-1 standard recommends, for operating room in cleanliness class ISO 6, outflow velocities in the range of 0.1–0.25 m/s [1]. It can be concluded that during the summer months, the combination of a lower supply temperature and a higher speed of air flow in the area of the operating table results in the local creation of an uncomfortable environment. This conclusion was confirmed, through personal discussion and consultation with several medical professionals (mainly surgeons). Atmaca et al. [44], in his study, also confirmed the different assessment of thermal comfort between body segments caused by different radiant temperatures. Geaver et al. [21] mentioned that decreasing the air flow rate in the OR is one of the options for reducing the feeling of cold in the OR. The results indicate the least comfortable environment is located in the area of the body's center. ASHRAE Standard 55 adopts the P.O. Fanger indexes of PMV and PPD and takes into account the effect of local discomfort by increasing PPD by 10% [45]. However, in the mentioned consultation and discussion, the surgeons mainly complained about the unpleasant blowing on the neck and the subsequent pain in the cervical spine after a longer procedure with a LAFC. Medical staff are often not sufficiently informed about the function of the LAFC and the need for forced ventilation in the OR. Due to the uncomfortable environment, during the operation the LAFC is often in attenuation mode (50% air flow), and in some cases the ventilation system is switched off. This can seriously endanger the patient in aseptic ORs or even the staff in septic ORs. From the point of view of patient and staff safety, it is therefore advisable to design LAFC size series at the lower limit of the recommended outflow velocity range. This also has a favorable effect on the lower pressure loss of the filters in the LAFC and the overall energy consumption by the fans [46]. The unpleasant feeling of cold on other parts of the body can be compensated by a higher thermal resistance of the clothing (CLO) [34]. Unfortunately, some medical facilities have their own protocol for protective clothing, which cannot be varied in order to achieve an optimal feeling of thermal well-being.

4. Conclusions

This study investigated the trade-off between thermal comfort ratings and the conditions of legislation and standards for air flow rates through the LAFC. The measurements took place in a clean room laboratory, in a model operating room, with certified equipment. A ComfortSense Dantec device was used to record data and evaluate PMV and PPD indices. Legislation in different countries recommends different discharge velocities through the LAFC, ranging from 0.1 m/s to 0.45 m/s. This research focused on evaluating the thermal comfort during the summer months, when the LAFC is used for cooling, at discharge velocities from 0.15 m/s to 0.25 m/s. The use of speeds up to 0.175 m/s appears to be the most suitable, when the PPD index fluctuates at a value of 20%. At a speed above 0.2 m/s, the PPD index is above 30%. The combination of subcooled air and air speed through the LAFC of 0.25 m/s increased the PPD index up to 70% in the area of the body's center of gravity. In all cases, the velocities in the area of the center of gravity were higher than in the area of the head. The results of this study should provide valuable information for the design and sizing of LAFCs in ORs and other clean rooms. With the help of the choice of a higher LAFC size series, a lower flow rate will be achieved, which will have a favorable effect on the thermal comfort of healthcare workers in the summer months.

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