Ing. Kateřina ROŠKOTOVÁ
Ing. Daniel ADAMOVSKÝ, Ph.D.
CTU in Prague, Faculty of Civil Engineering, Department of Indoor Environmental and Building Services Engineering

Thermal Comfort in Cleanrooms: Findings from Cleanroom Experiments

Tepelná pohoda v čistých prostorách: Poznatky z experimentů v čistých prostorách

In the majority of cleanroom applications, the thermal environment is overshadowed by the contamination control as a priority. As a consequence, the cleanroom users are likely to experience a lower thermal comfort. This study investigated the thermal environment of six research laboratories designed and operated as cleanrooms with the class of cleanliness ISO 5 or ISO 7. A comparison of the various classes of cleanliness and the different air distribution systems enabled the complex analysis in order to determine the issues of the thermal environment. Apart from the calculation of the PMV and PPD indexes, the vertical air temperature difference, risk of draught and homogeneity of the local conditions were also examined. Based on the results, cleanroom users are often exposed to conditions unsuitable for their well-being. The specific requirements of cleanrooms frequently result in high air velocities and inconvenient temperatures that are not tied to the activity and clothing levels of the users.
Keywords: *cleanrooms, indoor environment, thermal comfort, draught*

U většiny aplikací čistých prostor je tepelně-vlhkostní prostředí zastíněno řízením kontaminace, protože dosažení požadované čistoty je zde prioritou. Důsledkem je potom pravděpodobnější výskyt snížené tepelné pohody uživatelů těchto prostor. V této studii bylo analyzováno tepelně-vlhkostní prostředí v šesti výzkumných laboratořích, které jsou navrženy i provozovány jako čisté prostředí třídy čistoty ISO 5 nebo ISO 7. Porovnání laboratoří s různou třídou čistoty a s různými systémy distribuce vzduchu umožnilo komplexně nahlédnout na tuto problematiku za účelem definování možných problémů v souvislosti s tepelně-vlhkostním prostředím. Kromě výpočtu ukazatelů PMV a PPD byl dale stanoven také vertikální rozdíl teplot, riziko průvanu a homogenita lokálních podmínek v laboratoři. Z výsledků vyplývá, že uživatelé čistých prostor jsou často vystaveni podmínkám, které nejsou vhodné pro zajištění jejich spokojenosti. Specifické požadavky čistého prostředí způsobují vysoké rychlosti proudění vzduchu nebo nevhodně zvolené teploty, které nezohledňují stupeň aktivity nebo použitý oděv uživatelů.
Klíčová slova: *čisté prostory, vnitřní prostředí, tepelný komfort, průvan*

INTRODUCTION

Nowadays, the application of cleanrooms is much wider than just in the healthcare sector or space industry that are very well-known from history. High-tech laboratories using the most advanced methods, semiconductor and pharmaceutical industries or food processing are the great examples of cleanroom designs. Generally, a clean environment is required in applications where airborne particles or microbes could affect the ongoing processes, the manufacturing process and the quality of the final product or research and its results.

According to the international standard ISO 14644-1, *"cleanrooms are a specific environment, where the concentration of airborne particles is controlled and classified, and which is designed, constructed and operated in a manner to control the introduction, generation and retention of particles inside the room"* [14]. However, not only the level of cleanliness is controlled, but so too are other variables, such as the air pressure, temperature and relative humidity. Indoor environmental conditions are fundamentally influenced by the required level of cleanliness and the associated air distribution system designed to reduce the airborne and microbial concentrations below the levels required by ISO 14644-1 and the Good Manufacturing Practice Annex 1 (GMP Annex 1).

In the majority of cleanroom applications, the thermal environment is overshadowed by the contamination control system. In some applications, the installed technologies or ongoing processes are temperature and humidity sensitive, therefore, the actual levels of these variables are tightly controlled by precise air-conditioning. Unfortunately, these maintained conditions are, very often, unsuitable for cleanroom users as their level of activity and clothing requirements are not considered, thus, their thermal dissatisfaction is more likely. Unsuitable thermal conditions are a frequently occurring phenomenon, even in applications without strictly determined temperatures, due to the primary focus on the achievement of the desired class of cleanliness and not on the well-being of the users. According to the GMP Annex 1, the temperature and relative humidity are dependent on the product and the type of the ongoing operations [10]. Nevertheless, the cleanliness should not be affected by these variables.

Given the situation and considering the likelihood of the possible inappropriate behaviour of the users, the cleanliness in these applications can be easily endangered.

THERMAL ENVIRONMENT OF CLEANROOMS

Undoubtedly, cleanrooms represent a greater challenge to provide the desired environment than other applications. Due to the primary focus on the cleanliness, the air velocities or temperatures are frequently not tied to the needs of the cleanroom users. However, an indoor environment suitable for the occupants should be ensured whenever possible. Generally, most information about the indoor environment of cleanrooms is available for operating theatres, while, in a majority of other applications, there is a lack of information and or recommendations. Thus, the indoor environmental design and cleanroom operation are even more difficult to set up.

Table 1 Parameters of the analysed cleanrooms

Cleanroom no.	Class of cleanliness	Floor area [m²]	Air change [h⁻¹]	Type of supply/ exhaust outlets	Clothing insulation [clo]	Number of workplaces
1-5	5	35	180	Laminar flow ceiling (70 % coverage) / Perforated wall diffusers, floor height	0.9	3
2-5	5	5	343	Laminar flow ceiling (90 % coverage) / Perforated wall diffusers, floor height	0.9	1
3-7	7	450	17	Perforated laminar diffusers / Perforated wall diffusers, floor height	1	6
4-7	7	550	15	Perforated laminar diffusers / Perforated wall diffusers, floor height	1.1	4
5-7	7	35	25	Swirl diffusers / Perforated wall diffusers, floor height	1.1	3
6-7	7	26	20	Swirl diffusers / Perforated ceiling diffusers	1.1	3

Note: 1-5 represents cleanroom 1 and an ISO 5 class of cleanliness

In the clean environment of operating theatres, as Mora et al. have stated, the thermal comfort is more closely monitored to ensure the best possible conditions for a successful surgery, while among other cleanroom applications, the thermal comfort is hardly considered [6]. As various studies including the study conducted by Mazzacane et al. have pointed out, difficulties in ensuring thermal satisfaction of all the occupants within the operating theatre have been found as a result of the different activities and clothing levels of the users as well as their personal preferences [4]. Rarely, all participants in the surgery are fully satisfied with the current conditions. For example, surgeons require lower temperatures during the surgery than anaesthesiologists and nurses due to the higher activity level and higher clothing insulation.

Another study conducted by Balaras et al. showed that while surgeons evaluate the thermal perception at 21 °C as slightly warm to warm, anaesthesiologists and nurses perceive the same environment as slightly cool to cool as a result of the different clothing and activity levels [1]. The heavier gowns with higher thermal insulation used by surgeons for special surgeries require even lower temperatures down to 18 °C [1]. Murphy has revealed that surgeons expect lower temperatures than the values suggested in the guidelines for operating theatres [7]. Although the thermal comfort of surgeons is important for the concentration and, thus, the success of the surgery, Melhado et al. pointed out that the thermal environment is maintained to achieve suitable conditions for the patient as a priority [5]. As Melhado et al. summarised other studies, temperatures lower than 21 °C may cause hypothermia to the patient, while temperatures above 23 °C are not tolerated by surgeons and other operating staff [5]. Balaras et al. have noted that higher temperatures lower the users' comfort while creating a favourable environment for bacterial growth and their transfer [1]. In particular, the environmental conditions in operating theatres also depend on the type of surgery as some procedures may require a different temperature or illuminance, the equipment used or the number of people, their activity and clothing [5].

A suitable indoor environment, as Hwang et al. have remarked, fundamentally affects the physical and mental state of the patient and shortens the recovery time from the surgery [2]. However, as Khodakarami and Nasrollahi mentioned in their review of thermal comfort in hospitals, not only are the patients affected by the poor environment, but also the indoor environment affects the working conditions, well-being, safety and health of the medical personnel [3]. Due to the diversity of the applications outside the healthcare sector, there are no general requirements with regards to the room temperature. Thus, designers and cleanroom operators are responsible for the actual levels based on the requirements of each individual application and installation. Unfortunately, the occupants' lower thermal satisfaction is expected.

Based on the aforementioned findings and the lack of thermal comfort assessment outside the healthcare sector, this study analysed the issues of the thermal environment of research laboratories designed and operated as cleanrooms. A comparison of various classes of cleanliness and different air distribution systems enabled the complex analysis, in order to determine the fundamental issues of the thermal environment.

EXPERIMENTS

Analysed cleanrooms

In total, the thermal conditions in six research laboratories in two buildings located in the outskirts of Prague were analysed in this study. The experiments mainly focused on the environment of occupied laboratories rather than on the adjacent rooms such, as utility rooms or transfer areas essential for the cleanroom operation. All laboratories were designed and operated as ISO 5 or ISO 7 cleanrooms according to ISO 14644-1 [14]. The cleanrooms differ not only in the maintained class of cleanliness, but also in other design parameters, such as the floor area, number of air changes per hour or in the types and positions of the supply and exhaust outlets. Although the laboratories serve various research purposes, the similarities in the schedule and operation allowed the comparison of the indoor environmental conditions. The level of clothing was determined based on ISO 7730 and a study conducted by Mora et al. [6, 12]. The activity level was assessed as a light activity of a standing person in a laboratory (1.6 met = 93 W/m²) that corresponds best to the real situation. The parameters of each laboratory are listed in Table 1.

Methodology

All the experiments were carried out during a standard weekday cleanroom operation with the technologies in service and with occupants in attendance. However, the operation of the technologies in each laboratory might be highly variable each day, as well as the presence and movement of the users. In each laboratory, the thermal comfort assessment was carried out following the ISO 7730 standard and was complemented by a subjective evaluation. Questionnaires for the subjective evaluation were created with the guidance of the ANSI/ASHRAE 55 standard [9] and consisted of both general questions regarding the overall perception of the indoor environment, as well as the specific questions aimed at determining the local sources of discomfort and the possible consequent actions of the users.

An Ahlborn thermal comfort set with additional temperature and humidity sensors and omnidirectional thermo-anemometers were used for this experiment. The measurement of the thermal comfort variables was carried out in all the workplaces in each cleanroom at three different heights (0.1, 1.1 and 1.7 m) representing the various points on body of a standing person. Each position was measured in stable conditions for 30 minutes with an average cycle of 1 minute. Besides the calculation of *PMV* (predicted mean vote) and *PPD* (predicted percent dissatisfied) indexes to express the thermal comfort of the users, the local thermal discomfort (vertical air temperature difference and draught) was also assessed. Unfortunately, the widely used estimation of the turbulence intensity as 40 % for a draught assessment was not applicable for these applications due to the different airflow patterns in each cleanroom. To enable the assessment of the predicted draught ratio, the turbulence intensity (T_u) was calculated by the following Equation (1) from ISO 7726 [11]:

$$T_u = 100 \frac{SD}{v_a} \ [\%] \quad (1)$$

where
SD is the standard deviation of the local air velocity [m/s]
v_a is the local mean air velocity [m/s]

Moreover, the homogeneity of the environmental conditions across the workplaces in the two largest laboratories (3-7 and 4-7) was examined. For the plot of the spatial variations in the conditions, the Inverse Distance Weighted Interpolation (IDW) in MATLAB software was used to predict the conditions based on the scattered set of points from the actual results in each workplace.

RESULTS AND DISCUSSION

Thermal comfort

In general, the thermal comfort in the analysed cleanrooms was assessed as a neutral to slightly warm thermal sensation (Table 2). Therefore, the overall thermal satisfaction of the cleanroom users can be expected, however, any incorrectly determined predicted values of the activity and or clothing levels may result in vague results. Firstly, the estimation of the activity level of the cleanroom occupants is difficult as the activity can frequently change during the working day depending on their assigned tasks and, thus, also differs with the occupants. Secondly, the clothing level and related thermal insulation can be hardly estimated as the thermal characteristics of a specific cleanroom's clothing requirement cannot be found in the widely used standards ISO 7730 and ISO 9920 [12, 13]. Clearly, the use of values for casual clothing instead is unreliable. The mistakes in the identification of the clothing and activity levels, as a reason for misleading results, were pointed out in the study of the thermal environment in hospitals conducted by Skoog et al. [8].

According to the results, the average relative humidity met the recommended range of 30 to 70 %, however, the humidity level in 3-7 is close to the bottom value and the need for this low level should be considered. In general, a low relative humidity reduces the comfort of the users in the form of drying their skin, eyes, nose and throat and, thus, increases the likelihood of respiratory problems [3]. Although a lower humidity level is frequently required for special technologies in cleanrooms, the lower amount of moisture vapour in the air can significantly increase the risk of the electrostatic discharge (ESD) that should always be prevented. It may not cause any serious injuries to the occupants, but it can damage sensitive technologies, computer components, etc.

Table 2 Thermal comfort in the cleanrooms

Cleanroom no.	Air velocity		Air temperature		Rel. humidity		PMV	PPD
	Avg.	SD	Avg.	SD	Avg.	SD		
	[m/s]	[m/s]	[°C]	[°C]	[%]	[%]	[-]	[%]
1-5	0.195	0.075	19.76	0.93	57.73	3.47	0.03	5.73
2-5	0.256	N/A	23.73	N/A	43.92	N/A	0.61	12.90
3-7	0.253	0.142	20.52	0.43	33.29	1.39	0.17	6.08
4-7	0.158	0.033	18.37	0.52	44.90	2.08	0.07	5.30
5-7	0.186	0.030	20.61	0.06	47.48	0.32	0.38	7.93
6-7	0.140	0.003	22.77	0.15	46.48	0.32	0.78	17.70

Note: SD represents the standard deviation of the results between workplaces in one cleanroom. The SD in cleanroom 2-5 was not applicable (N/A) due to only one workplace in this room.

Local thermal discomfort

As can be seen from Figure 1 below, the average vertical air temperature difference between the head and ankles in all the cleanrooms was found below 1 °C, and, thus, a very low number of percentage dissatisfied (*PD*) can be expected. The very low values in the cleanrooms with swirl diffusers (5-7 and 6-7) confirmed the ability of these outlets to provide homogenous conditions.

A draught is a frequently occurring phenomenon in cleanrooms due to high amount of air changes, and, thus, high air velocities essential for achieving low concentrations of airborne particles. However, the actual level of the draught is dependent not only on the air velocities, but also on the temperature and turbulence intensity. Thus, the prediction of the draught rate based on the velocity only is not accurate. With higher temperatures, the effect of high air velocities is lowered. Similarly, lower turbulences result in a lower percentage of people predicted to be dissatisfied by a draught (Table 3). In cleanrooms, the effect of a draught might be overestimated as people with higher levels of activity than the light sedentary ones determined in ISO 7730 are less sensitive to draughts and the risk of discomfort is lower. Furthermore, this was confirmed by the respondents who rarely evaluated a draught as an issue despite the high air velocities.

Regardless of the highest air velocity, a low draught can be expected at workplace 2-5.1 in the cleanroom with the laminar ceiling due to the lowest turbulence. Despite the lower air velocities, the risk of a draught was similar at higher levels for the workplace with the perforated laminar diffusers (4-7.1) due to the much lower temperatures and higher turbulences emphasising the effect of the air velocity. Given the results, the position of the exhaust outlets and the value of the overpressure to the adjacent areas influenced the air velocity at a height of 0.1 m. Especially in a colder environment, the lower part of the body can be exposed to a much colder thermal sensation and the risk of a draught. In cleanrooms, the most important aspects that should be monitored are the conditions at the working height. High velocities with significant turbulences at this level may often cause some disruptions to the conducted experiments. One of the examples is the inability to weigh a low amount of bulk materials in these conditions.

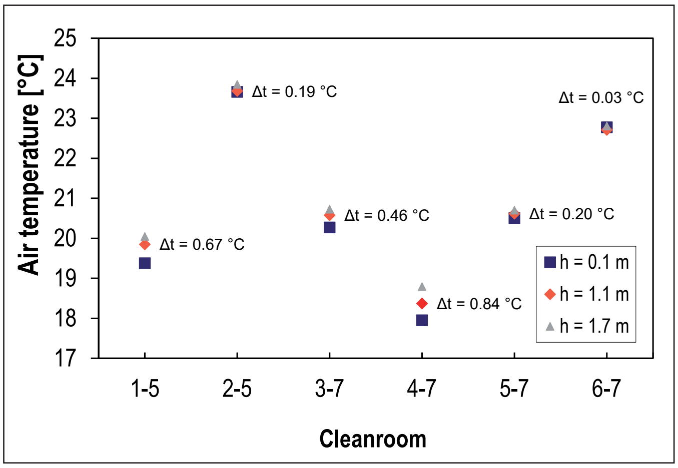

Figure 1 Average vertical air temperature differences in the cleanrooms

Table 3 Comparison of the local conditions at three workplaces in different cleanrooms

Workplace	Air velocity [m/s]			Air temperature [°C]		
	Height of measurement			Height of measurement		
	0.1 m	1.1 m	1.7 m	0.1 m	1.1 m	1.7 m
2-5.1	0.372	0.245	0.152	23.66	23.68	23.85
4-7.1	0.241	0.125	0.070	18.15	18.62	19.14
6-7.1	0.120	0.164	0.139	22.81	22.81	22.97
Workplace	Turbulence intensity [%]			Draught [%]		
	Height of measurement			Height of measurement		
	0.1 m	1.1 m	1.7 m	0.1 m	1.1 m	1.7 m
2-5.1	2.84	4.42	7.22	18.07	13.28	8.76
4-7.1	29.28	33.51	55.74	32.73	14.45	6.05
6-7.1	42.59	33.02	37.18	10.86	14.92	12.50

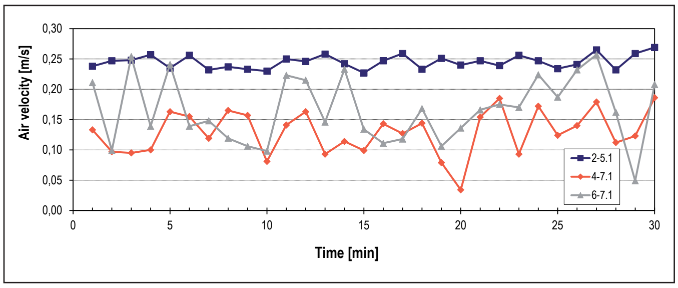

Figure 2 Comparison of the air velocity fluctuations at 1.1 m in height for the different workplaces

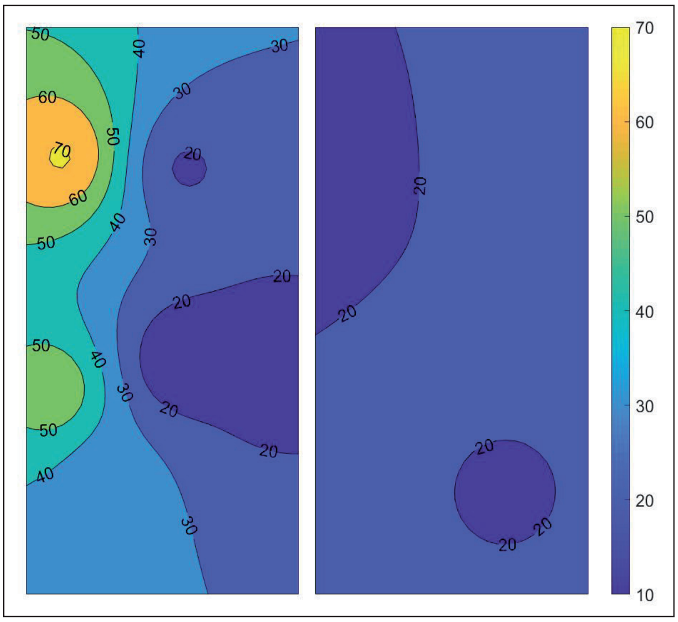

Figure 3 Expected draught homogeneity across cleanrooms 4-7 (left) and 3-7 (right) at the working height of 1.1 m

As can be seen from Figure 2, the velocity at the working height of 1.1 m at workplace 2-5.1 is very stable compared with the other two cases. Simply, this can be explained by the difference in the air distribution system and, thus, in the turbulence intensity (Table 3). The unidirectional airflow applied in cleanroom 2-5 results in low turbulences to minimise the risk of contamination and to avoid any particle retention within the space. On the contrary, the non-unidirectional airflow pattern used in cleanrooms 4-7 and 6-7 (and in cleanrooms with an ISO 6 class and lower, in general) is responsible for high turbulences to enable the reduction in the particle concentration in the environment by mixing the supply air with the indoor air.

Homogeneity of indoor conditions

The uniformity of indoor conditions is affected by the type of the air distribution system and the position of the supply inlets and outlets. Frequently, the stability and uniformity of the indoor conditions are demanded by researchers and a close control of the environment is essential. Concerning the standard deviations mentioned in Table 2, the most uniform indoor conditions are maintained in cleanrooms with swirl diffusers. In spite of their great impact on the thermal environment, the mixed airflow pattern, as a result of these outlets, is usually not suitable enough for the removal of airborne particles and the installation is appropriate in special cases only.

According to the comparison of the homogeneity of the indoor environment in similar cleanrooms, 3-7 and 4-7, with the same type of air distribution system, a different level of the free area ratio was partially responsible for the exposure to the different local conditions in both laboratories. While in cleanroom 3-7, the actual layout corresponded with the original design and the free area ratio was not reduced (21.3 % of the floor area was used), in cleanroom 4-7, the reality was different. Besides the higher use of the space (33.4 % of the floor area was used), almost half of the exhaust outlets (47 %) were blocked with additional installations. As a result, higher draught rates with local peaks occurred in cleanroom 4-7. Given the situation, the increased risk of contamination in cleanroom 4-7 can be expected as the airborne particles may not be eliminated in some areas and, thus, retained within the laboratory. These facts affect not only the cleanliness, but also the temperature distribution or draught differences across the cleanroom, as the whole concept of the air distribution is changed. As a result, together with the existence of local heat gains, the thermal satisfaction of the cleanroom users can be reduced at some workplaces as the conditions can differ.

Especially in large cleanrooms, the achievement of suitable indoor conditions in all the workplaces is difficult and there are always some individuals who will be dissatisfied. Often, the thermal comfort is highly dependent on the actual position of the workplace, whether it is located directly under the supply outlet, as these positions expose workers to a higher draught ratio.

Subjective evaluation

A total of twenty-seven respondents participated in the survey to determine the subjective evaluation of the indoor environment of the clean laboratories. Such a number of respondents is not high enough for a deep statistical analysis; however, it is still beneficial in terms of finding the sources of discomfort for the consequent actions and improvements. Based on the results from the questionnaires, the real perception of the thermal comfort was generally warmer than predicted. The main reason for the differences is given by the personal factors which cannot be measured. Regarding the aforementioned information, a higher thermal sensation can be also associated with increased activity or clothing levels.

Besides, the general evaluation of the thermal comfort, the questionnaires pointed out the local issues and sources of discomfort. With a view to the higher thermal satisfaction, more than 90 % of the cleanroom users responded that they have to make some behavioural adjustments as a change in the optimal room temperature is usually not possible. However, some of their actions are not suitable for a clean environment. The most common action was a change in the amount of the clothing layers or the type of clothing (51.9 % of the respondents) and the need to drink more water (48.1 % of respondents).

Unfortunately, their selection of clothing materials rarely corresponded to the clothing policy, and the cleanrooms might end up with a higher risk of contamination. As a remark from the onsite investigation, the choice of a cotton hoodie due to the perception of a draught and cold environment is far from an ideal solution to enhance the thermal comfort regarding the contamination control. Obviously, this may further result in a higher energy consumption, operational costs and delays in the performed research or manufacturing. Higher classes of cleanliness require different sets of cleanroom clothing with various impacts on the user's thermal satisfaction. However, this fact is very often not taken into account when designing and operating a cleanroom and suitable clothing or thermal conditions are not ensured.

CONCLUSION

As this study highlighted, cleanrooms represent an example of the environment that is not designed to provide an optimal working environment for the occupants as a priority. Thus, a lower thermal comfort is likely. Hardly any studies are focused on the thermal comfort of cleanroom users besides the studies conducted in operating theatres; however, other applications are no less important. Nonetheless, the suitability of the thermal environment should be considered when designing and operating these places, as poor thermal conditions may result in a higher risk of contamination and lower cleanliness. Consequently, cleanroom users take adaptive actions to increase their thermal satisfaction that do not always correspond with the cleanroom operational guidelines, and, thus, the desired cleanliness may be threatened. As a result, the expenses for the cleanroom operation are much higher. When possible, the room temperature should reflect the activity levels and clothing requirements that differ in each cleanroom and the class of cleanliness, while also considering the requirements of the ongoing processes and energy consumption. Admittedly, the temperature optimisation is frequently not possible, and the best option to increase the thermal comfort of the occupants is to offer clothing alternatives with various thermal insulation properties.

Undoubtedly, cleanrooms are among the special applications whose demanding indoor environmental conditions present a challenge for both the designers and cleanroom operators. Any changes in the cleanrooms, especially in the class of the cleanliness or the air distribution, should be carefully discussed from various perspectives before implementation, as these changes affect not only the indoor environmental conditions and required clothing, but also the operating costs. Besides, the reckless installation of equipment or the blockage of exhaust outlets to create additional storage space should be avoided as they may change the airflow patterns and endanger the desired cleanliness.

As can be seen from the current situation around COVID-19, the importance of the use of these special environments cannot be questioned. The rapid development and trend of using the latest high-tech technologies in many sectors show that the need for cleanrooms will continue to rise and their design and operation will be subject to even higher technological demands and a greater emphasis on energy efficiency. In the majority of cleanrooms, ISO 5 to ISO 8, despite the wide use of automatisation, people are still necessary in cleanrooms and unfortunately, present the major source of contaminants. Therefore, the well-being of occupants should receive more attention as their behaviour is not only responsible for the efficient manufacturing of high-quality products due to their productivity, but can also influence the level of contamination.

Acknowledgment: This paper was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS20/098/OHK1/2T/11.

Contact: katerina.roskotova@fsv.cvut.cz

References

[1] BALARAS, Constantinos, Elena DASCALAKI a Althina GAGLIA. HVAC and indoor thermal conditions in hospital operating rooms. *Energy and Buildings*. 2007, Vol. 39, Issue 4, pp. 454-470. ISSN 0378-7788

[2] HWANG, Ruey-Lung, Tzu-Ping LIN, Ming-Jen CHENG a Jui-Hung CHIEN. Patient thermal comfort requirement for hospital environments in Taiwan. *Building and Environment*. 2007, Vol. 42, Issue 8, pp. 2980-2987. ISSN 0360-1323.

[3] KHODAKARAMI, Jamal a Nazanin NASROLLAHI. Thermal comfort in hospitals - A literature review. *Renewable and Sustainable Energy Reviews*. 2012, Vol. 16, Issue 6, pp. 4071-4077 ISSN 1364-0321.

[4] MAZZACANE, Sante, Carlo GIACONA a Silvia COSTANZO. A Survey on the Thermal Conditions Experienced by a Surgical Team. *Indoor Built Environment*. 2007, Vol. 16, Issue 2, pp. 99-109. ISSN 1423-0070

[5] MELHADO, M.A., J.L.M. HENSEN a M. LOOMANS. Literature Review of Staff Thermal Comfort and Patient "Thermal Risks" in Operating Rooms. In: *Proceedings of the 8th Int. Healthy Buildings conference, 4 – 8 June*. International Society of Indoor Air Quality and Climate. 2006, pp. 11-14

[6] MORA, Rodrigo, Michael J.M. ENGLISH a Andreas K. ATHIENITIS. Assessment of Thermal Comfort During Surgical Operations. *ASHRAE Transactions: Research*. 2001, Vol. 107, pp. 65-74. ISSN 0001-2505

[7] MURPHY, John. Temperature & Humidity Control In Surgery Rooms. *RX for Health-Care HVAC A supplement to ASHRAE Journal. ASHRAE Journal*. 2006, Vol. 48, pp. 18-25.

[8] SKOOG, Jennie, Niklas FRANSSON a Lennart JAGEMAR. Thermal environment in Swedish hospitals: Summer and winter measurements. *Energy and Buildings*. 2004, Vol. 37, pp. 872-877. ISSN 0378-7788.

[9] ANSI/ASHRAE Standard 55:2017. *Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers

[10] EU GMP Annex 1:2008. *Manufacture of Sterile Medicinal Products.* Brussels, Belgium: European Commission

[11] ISO 7726:2002. *Ergonomics of the thermal environment – Instruments for measuring physical quantities.* Geneva: International Organization for Standardization

[12] ISO 7730: 2005. *Ergonomics of the thermal Environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.* Geneva: International Organization for Standardization

[13] ISO 9920: 2007. Ergonomics of the thermal environment – estimation of thermal insulation and water vapour resistance of a clothing ensemble. Geneva, Switzerland: International Organization for Standardization

[14 ISO 14644-1:2015. *Cleanrooms and associated controlled environments – Part 1: Classification of air cleanliness by particle concentration.* Geneva, Switzerland: International Organization for Standardization