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ENERGY EFFICIENCY OPTIMIZATION OF THE OPERATING ROOM DUE TO THE DISPOSITIONAL LOCATION

OPTYMALIZACJA EFEKTYWNOŚCI ENERGETYCZNEJ W SALI OPERACYJNEJ ZWIĄZANA Z LOKALIZACJĄ SYSTEMU WENTYLACJI

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Abstract

Clean rooms, including operating rooms, are energy-intensive. During their operation, the concentration of particles in the air, air temperature and humidity are strictly monitored. HVAC systems in the operating room are subject to high demands on maintaining a stable heat and humidity microclimate, as well as particle concentrations within the permitted range. To cover heat losses and heat loads of the building, it is necessary to dimension ventilation equipment with high outputs and high energy consumption. By suitable optimization of the dispositional location of the operating tract in the building and the use of suitable thicknesses of insulating material, it is possible to reduce the performance requirements for the HVAC system, which significantly reduces energy consumption. Heat loss and heat load of the operating tract were evaluated using TechCon software. The performance values of the heaters and coolers for the HVAC units were calculated in the VentiCad design software. The optimization indicates a significant reduction in heat loss and heat load, as well as a reduction in the required temperature of the air supplied to the room by more than 10°C.

Keywords: energy efficiency, HVAC systems, energy consumption optimization

Streszczenie

Pomieszczenia czyste, łącznie z salami operacyjnymi wymagają dużo energii. Podczas ich pracy dokładnie monitoruje się stężenie cząstek stałych w powietrzu, jego temperaturę i wilgotność. Systemy grzewcze, wentylacji i klimatyzacji (HVAC) w salach operacyjnych podlegają wysokim wymaganiom związanym z utrzymaniem stabilnego mikroklimatu cieplno-wilgotnościowego, jak również stężenia cząstek w dozwolonym zakresie. Pokrycie strat i zysków ciepła budynku wymaga projektowania systemów wentylacyjnych o wysokim zużyciu energii. Poprzez odpowiednią optymalizację lokalizacji przewodów w budynku i zastosowanie właściwej grubości materiału izolacyjnego możliwe jest odgraniczenie wymagań układów HVAC, co znacząco zmniejsza zużycie energii. Straty i zyski ciepła określono przy użyciu programu TechCon. Parametry nagrzewnic i chłodnic w układzie HVAC wyznaczono w programie VentiCad. Optymalizacja wskazuje na znaczącą redukcję strat i zysków ciepła, jak również zmniejszenie temperatury powietrza dostarczanego do pomieszczenia o więcej niż 10°C.

Słowa kluczowe: efektywność energetyczna, systemy HVAC, optymalizacja zużycia energii

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1. INTRODUCTION

Clean room is defined as the space in which the concentration of particulates in the air is controlled and monitored [1]. Rules for the design and use of such spaces prescribe the use of construction materials, equipment of the space but also the operation with an emphasis on minimizing the emission of particles that could contaminate the space. The construction materials and equipment used must meet strict requirements for surface treatment. Personnel must wear the prescribed clothing and uniforms, depending on the cleanliness class in which the room is classified. According to the standard of operation of the clean room and the need for its cleanliness, based on the EN-ISO 14 644-1 standard, clean rooms are divided into eight categories, where the highest cleanliness class is marked EN-ISO 1 and the lowest clean class is EN-ISO 8. EN-ISO classes 1-5 are typical of the most accurate manufacturing, laser technology, pharmaceutical laboratories and others. Classes EN-ISO 5-8 are used for premises in medical facilities. Aseptic operating rooms for routine surgery fall into category EN-ISO 7 and rooms adjacent to the operating room (operating room background: filter, patient preparation, clean cloakroom and washroom) fall into category EN-ISO 8. The lower cleanliness class compared to the operating room guarantees controlled flow of air particles from a cleaner room to a less clean one, thus reducing the risk of contamination of the operating room.

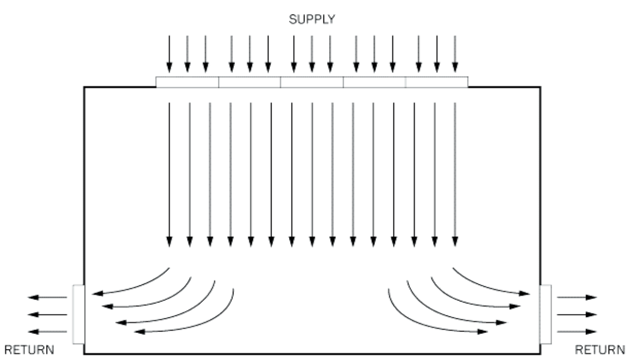

Fig. 1. Laminar air flow in a clean room [2]

The principle of reducing the concentration of particles in the clean room air consists in controlled forced ventilation of the room at high air exchange intensities and the use of supply air filtration with high efficiency of air particle capture. The nature of the air flow in a ventilated clean room is for operating theaters in the form of a laminar field around the operating table on which the patient lies [3]. Air is supplied through a ceiling distribution element located above the operating table. The filtered air flows downwards at flow speeds of 0.15-0.25 $m \cdot s^{-1}$, creating an imaginary air piston which expels air particles around the patient, as shown in Figure 1. The removal of contaminated and polluted air is ensured by diffusers located in the corners of the room, most often in the lower part of the wall.

The size of the air supply distribution element is determined by the size of the clean zone it must overlap. In the clean zone, the operating table must be covered with the patient, but also the medical staff performing the operation. To maintain the required flow rate to create a laminar air stream that also has sufficient kinetic energy to expel air particles in the patient bed area, a high power HVAC device is required for forced clean room ventilation. The operating tract, which consists of an operating room and the necessary facilities (filter, patient preparation, cloakroom and washroom), needs air volume flows of 2500-3500 m^3/h for their proper functioning. In clean rooms, it is not possible to use circulating devices to ensure the required indoor microclimate and thermal comfort. The airflow from the circulator could disrupt the laminar airflow in the patient area, leading to contamination and infectious disease. The total heat loads of clean rooms must therefore be covered by the HVAC device for forced ventilation of the room. Wall-mounted and cassette units for refrigerant or fan-coil units are unsuitable for this purpose. The same ventilation device can then be used to cover heat losses. A popular way of heating operating theaters is radiant floor heating or its combination with hot air heating using a forced ventilation device. Conversely, the use of convectors or heaters is undesirable due to their complicated cleaning and the risk of affecting the controlled air flow [4, 5].

2. OPTIMIZATION OF ARCHITECTURAL DESIGN OF CLEAN ROOMS

The problem that occurs when cooling a room using an HVAC system is the supply air temperature. Air with a low temperature difference from the room temperature should be supplied to the room. If an internal temperature in the range of 24 ±2°C is required, it would be optimal to supply cooling air with a temperature of at least 20°C from the point of view of thermal comfort and comfort in the room. In extreme cases, which occur a few days a year, it would be possible to supply air at a lower temperature. However, the temperature difference should not exceed 6°C compared to the indoor temperature. With such a relatively low temperature drop and specific heat capacity of the air, higher air flows are required. The required amount of supplied air expresses the relation (1).

$$\dot{V}_{C/H} = \frac{Q_{HL} \cdot 3600}{\left(t_{sa} - t_{ra\,r}\right) \cdot c_{sa} \cdot \rho_{sa}} \tag{1}$$

$\dot{V}_{C/H}$ – calculated air volume flow required for cooling/heating, $m^3 \cdot h^{-1}$;
Q_{HL} – heat load/heat loss, W;
t_{sa} – supply air temperature, °C;
$t_{ra\,r}$ – required room air temperature, °C,
c_{sa} – specific heat capacity of the supplied air, $J \cdot kg^{-1} \cdot K^{-1}$;
ρ_{sa} – supply air density, $kg \cdot m^{-3}$.

The specific heat capacity of the supplied air with the temperature change in the interval of 6°C hardly changes and therefore we can use the table value 1010 $J \cdot kg^{-1} \cdot K^{-1}$ for the calculation. However, a more substantial change occurs in air density. The density of the supplied air is a function of the external atmospheric pressure and its temperature. It is expressed by relation (2):

$$\rho_{sa} = \frac{p_a}{287 \cdot \left(273.15 + t_{sa}\right)} \tag{2}$$

p_a – atmospheric pressure, Pa.

From the previous relationships, we can conclude that the higher the heat load of the room, the greater the amount of cooling air at the desired temperature must be supplied to the room.

3. REDUCING ENERGY CONSUMPTION

Clean rooms consume high amounts of energy [6-8]. By ensuring minimum performance requirements with regard to air quality (i.e. J. Concentration of Contaminants), intensively energy-intensive clean rooms provide an opportunity to save large amounts of energy [9]. The size of heat loss and load is affected by the quality and thickness of construction materials, quantity, size and orientation of glazed surfaces, as well as the layout within the floor plan. The current state of many medical facilities is shown in Figure 2.

Many medical facilities have not yet been renovated at all. The perimeter walls are not insulated and in many cases the room with the highest requirements for the heating and ventilation system is in the corners of the floor plan and thus has up to two cooled walls in winter. Some buildings have already been renovated, but the thickness of the thermal insulation often does not exceed 100 mm. Such rooms have high heat losses and even higher heat loads, mainly due to windows, which in most cases do not have effective shading. In the figure of Figure 3 we can see the first two stages of optimization of the architectural design of a medical facility.

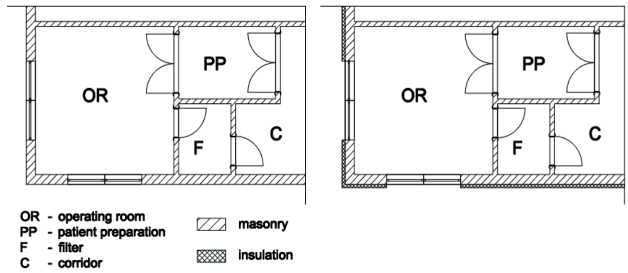

Fig. 2. Typical current state of medical facilities

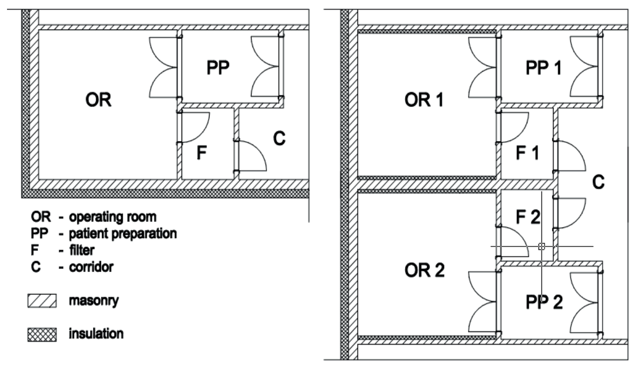

Fig. 3. I. stage (left) and II. stage (right) of architectural optimization

The first stage of optimization of the architectural design consists in the removal of glazed areas from the perimeter walls of the building. Windows in the room are not necessary, as the operating room must be equipped with a number of lamps with the prescribed brightness. These luminaires are often integrated in the ceiling laminar field, or on adjustable arms mounted on the ceiling of the room. This step will reduce the heat loss of the room, but in particular will reduce the heat load depending on the orientation of the building. The thickness of the insulation should correspond to the thickness used for passive houses. The second stage of optimization reduces the heat loss and the load on the building by reducing the number of perimeter walls. The mirror layout of the two operating theaters and their facilities is also complemented by internal insulation against the mutual influence of the climate between the operating theaters.

The third stage of architectural optimization is shown in Figure 4. By horizontal and vertical mirroring of the operating room with the background, we have achieved the creation of the so-called "Cores" without a vertical perimeter wall causing heat stress or loss through heat transfer through the structure. It is advisable to place such halls on the floor so that under the floor is heated, respectively, refrigerated space. From the point of view of savings, it is best to set up an air-conditioning engine room above the operating theaters. The short distance between the air handling unit and the ventilated room will reduce the acquisition costs for the air handling unit, the response time when the required temperature changes, but also the loss of energy through the insulation transmitted by the supply air to the room.

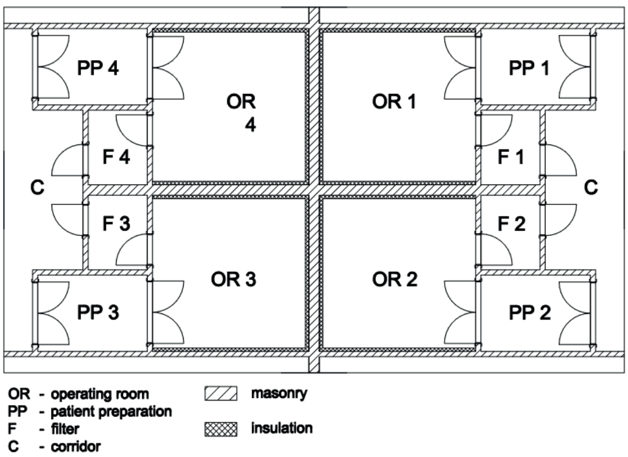

Fig. 4. III. degree of architectural optimization

In rooms with insufficient thickness of thermal insulation or a larger area of glazed structures, there may be a requirement for an even higher flow of supplied air than prescribed by the hygienic minimum. From an economic point of view, such ventilation is unsuitable and therefore it is necessary to eliminate the heat load and loss through the structure as much as possible, which directly results in reducing the required flow to a hygienic minimum.

To evaluate the required temperature of the air supplied to the room, we can use the modified relation (1), which is expressed by relation (3).

$$t_{sa} = t_{ra\,r} + \frac{Q_{HL} \cdot 3600}{\dot{V} \cdot c_{sa} \cdot \rho_{sa}}, °C \qquad (3)$$

It is clear from the previous relationship that in order to influence the temperature of the supplied air, it is possible to vary only with the required heat output of the ventilation system, which is given by the heat loss of the ventilated object or the amount of air supplied to the room. Due to the legislative determination of the minimum required air volume flow for clean room ventilation in terms of maintaining a low concentration of aerosol particles in the room, it is possible to reduce only the heat output of the air handling unit, which must depend proportionally on reducing heat loss of the ventilated object. By suitable optimization of the layout and location of the operating tract in the building, it is possible to achieve different heat losses. These were expressed on a model operating tract using TechCon software.

4. REDUCING ENERGY CONSUMPTION FOR CLEAN ROOM HEATING

The horizontal location of the operating tract, thermal-technical properties of building structures as well as architectural-dispositional optimizations have a fundamental impact on the heat loss of the operating room and on the overall heat loss of the operating tract. Table 1 describes the individual variants. A comparison of the decrease in heat load for the whole tract is shown in Figure 5 and Table 2.

Table 1. Description of variants for calculation of heat loss of the operating tract

Variant	Variant description
1A	Influence of the most unfavorable horizontal location of the operating tract (on the 1st floor with a roof above). Figure 1 left
1E = 2A	Influence of the most favorable horizontal location of the operating tract (between heated rooms). Figure 1 left
2B	Use of insulation with a thickness of 50 mm on the perimeter walls and double glazing of windows ($U = 1.3\ W{\cdot}m^{-2}{\cdot}K^{-1}$). Figure 1 right
2C	Use of insulation with a thickness of 100 mm on the perimeter walls and triple glazing of windows ($U = 0.8\ W{\cdot}m^{-2}{\cdot}K^{-1}$). Figure 1 right
2E	II. Degree of optimization – use of insulation with a thickness of 250 mm on the perimeter walls and removal of windows. Figure 2 left
3A	II. Degree of optimization – reduction of the area of the perimeter walls behind which the exterior is. Figure 2 right
3B	III. Degree of optimization – the absence of perimeter walls behind which is the exterior. Figure 3

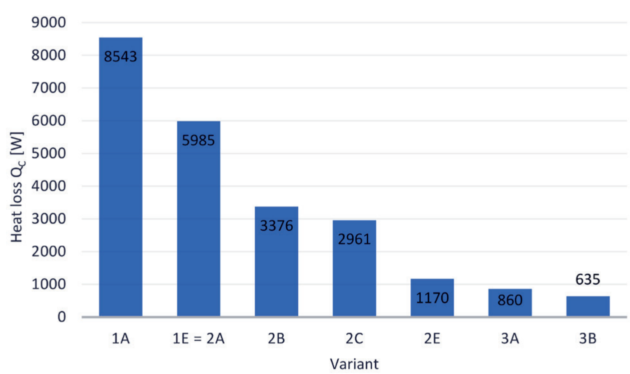

Fig. 5. Comparison of heat loss of the operating tract for different variants

Table 2. Comparison of heat loss of the operating tract for different variants

Variant	Heat loss Q_c, W	t_{sa}, °C	Heater power Q_o, W	Savings over variant 1A, %	Savings over previous variant, %
1A	8 543	35.6	12.8	0.00%	0.00%
1E = 2A	5 985	32.1	10.0	29.96%	29.96%
2B	3 376	28.6	7.1	60.49%	43.58%
2C	2 961	28.0	6.6	65.34%	12.27%
2E	1 170	25.6	4.6	86.31%	60.49%
3A	860	25.2	4.3	89.94%	26.56%
3B	635	24.9	4.1	92.58%	26.24%

5. REDUCING ENERGY CONSUMPTION FOR CLEAN ROOM COOLING

Horizontal and vertical location of the operating tract, thermal-technical properties of building structures as well as architectural-dispositional optimizations have a fundamental impact on the thermal load of the operating room and the overall thermal load of the operating tract. Table 3 describes the individual variants. A comparison of the heat load decrease for the operating tract is shown in Figure 6 and Table 4.

Table 3. Description of variants for calculation of thermal load of the operating tract

Variant	Variant description
1A	Influence of the most unfavorable horizontal location of the operating tract (on the 1st floor with a roof above). Figure 1 left
1D = NW	Influence of the most favorable horizontal location of the operating tract (between heated rooms) + orientation of the windows to the north-west. Figure 1 left
2A = SE	Influence of the most favorable horizontal location of the operating tract (between heated rooms) + orientation of the windows to the south-east. Figure 1 left
2B	Use of insulation with a thickness of 50 mm on the perimeter walls and double glazing of windows ($U = 1.3\ W{\cdot}m^{-2}{\cdot}K^{-1}$). Figure 1 right
2C	Use of insulation with a thickness of 100 mm on the perimeter walls and triple glazing of windows ($U = 0.8\ W{\cdot}m^{-2}{\cdot}K^{-1}$). Figure 1 right
2E	I. Degree of optimization – use of insulation with a thickness of 250 mm on the perimeter walls and removal of windows. Figure 2 left
3A	II. Degree of optimization – reduction of the area of the perimeter walls behind which the exterior is. Figure 2 right
3B	III. Degree of optimization – the absence of perimeter walls behind which is the exterior. Figure 3

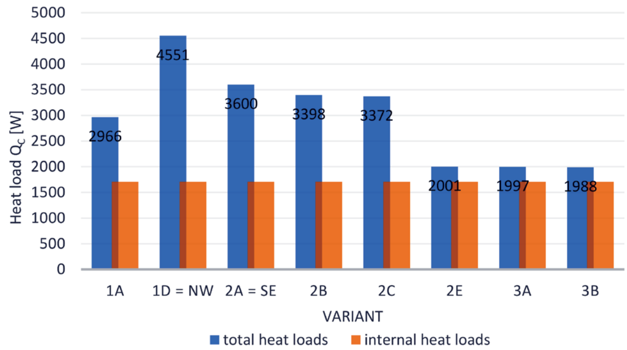

Fig. 6. Comparison of thermal load of the operating tract for different variants

Table 4. Comparison of heat load of the operating tract for different variants

Variant	Heat load Q_c, W	t_{sa}, °C	Cooler power Q_{CH}, kW	Savings over variant 1A, %	Savings over previous variant, %
1A	2 966	20.0	8.8	48.66%	48.66%
1D = NW	4 551	17.8	13.1	0.00%	0.00%
2A = SE	3 600	19.1	10.1	14.06%	14.06%
2B	3 398	19.4	9.6	16.93%	3.34%
2C	3 372	19.4	9.6	25.25%	10.02%
2E	2 001	21.3	6.7	56.52%	41.83%
3A	1 997	21.3	6.7	56.61%	0.21%
3B	1 988	21.3	6.7	57.08%	1.07%

6. CONCLUSION

By suitable vertical and horizontal location, orientation and choice of operating room construction materials, it is possible to achieve up to 92% reduction in annual heat demand due to heat loss through perimeter structures compared to the normal state of existing operating rooms. The annual cooling demand is 57% lower with the same optimization. The optimization of the architectural design will ensure the thermal neutrality of the operating room, which has a positive effect on its energy intensity and undesirable variability of air velocity in the clean room due to the temperature gradient between room air temperature and the temperature of air supplied through the laminar field. Although the total heat loss or heat load of the building is not reduced, the lower required heat and cold source power in the ventilation unit is achieved, which has a positive effect on reducing the risk of laminar flow being affected by natural convection and different vertical temperature gradients in the ventilated room. At the same time, it is possible to dimension lower power lines for the heat and cold source, which reduces the acquisition costs of the system.

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