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Impact of temperature variation on energy consumption and productivity of the occupants in office buildings

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Heating and cooling equipment in office buildings is usually controlled according to external air temperature. However, due to sudden outdoor air temperature variations, indoor climate may not always be adjusted to fit into the comfort range. Despite the modern facilities, occupants may be exposed to a temporary thermal discomfort that affects their performance. The aim of this study was to outline the influence of indoor air temperature variation on office work performance and energy consumption. During the experiment in the real office, indoor and outdoor climate parameters as well as energy consumption were observed. Employees were asked to fill questionnaires by indicating their thermal sensation, perception of air quality and humidity. The results of the study showed that indoor climate changes may cause dissatisfaction of participants, which could lead to their lower productivity. The effects of intermittent indoor climate parameters on energy consumption were outlined as well.

Key words: energy performance, unsteady air temperature, thermal sensation, work performance

INTRODUCTION

Modern people spend most of their lifetime indoors. Therefore alongside air quality, thermal environment is one of the most important parameters of indoor climate [1]. Nevertheless, in many buildings thermal conditions are not well-controlled due to insufficient heating or cooling capacity, high internal or external loads, large thermal zones, improper control or operation of heating, ventilation and air conditioning (HVAC) equipment as well as other factors.

The comfort air temperature range in Lithuania is regulated by the standards of hygiene [2]. It may vary from +22 °C to +24 °C in case of performing sedentary job in the fixed workstation during the cold season, and from +23 °C to +25 °C during the warm season. Relative humidity should be in the range of 40–60%, air velocity should not exceed 0.1–0.15 m/s accordingly. No probable variations of parameters time-wise are given.

Seppänen et al. [3] outlined a relation between human performance and air temperature based on various productivity studies. It showed that performance increases when air temperature rises up to +21–+22 °C and decreases by approximately 2% per 1 °C increase of air temperature in the range of +23 –+35 °C. The maximum performance is achieved at +21.6 °C (Fig. 1).

Lan et al. [4] outlined the correlation between indoor air temperature, human performance and different clothing insulation (0.86, 1.0 and 1.19 clo) levels during the winter season. It showed that the maximum performance was achieved at 21.9 °C with the clothing insulation equal to 0.86 clo and at 19.7 °C with the clothing insulation equal to 1.19 clo.

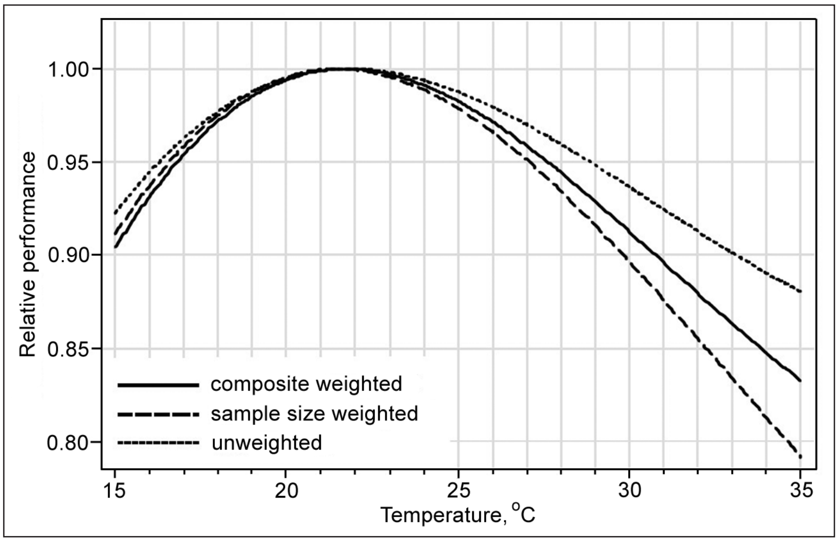

Fig. 1. Normalized relation between performance and air temperature in rooms (Seppänen et al., 2006)

The results of the study performed by Valancius and Jurelionis (2011) showed that short-term temperature drop from 22 °C to 18 °C increased general employee productivity by 4.1%. Moreover, tasks requiring concentration and focus were performed at 10% higher productivity [6].

Pupeikis et al. [7] defined that in order to efficiently increase energy savings in buildings by means of air temperature reduction, heating power should be enlarged by approximately 50% in most cases. The simulation has showed that for buildings with a medium thermal inertia (time constant τ = 144 h) the expenses by employing the intermittent heating (reduced temperature period: 12 h on working days and 48 h at weekends) pay back after one year. When designing the heating system, attention should be paid to the thermal inertia of a particular building. Research showed that considering various thermal inertias of buildings, the adequate modes of intermittent heating must be chosen.

Rimkus et al. [8] presented the climate forecast for Lithuania for the 21th century according to which the annual air temperature is expected to be higher by 2.3–5.7 °C till 2080. The extreme alteration is expected in February (mean temperature would rise by 3–9 °C). Similar trends are observed in most parts of the Baltic Region [5]. According to the forecast, day temperature range splay out, inrush of brief strong winter frosts will be more frequent. In other study the author prognosticated longer duration of the high sun spine during the average season [9]. This would be extremely perceptible during May to September. On the other hand, there would be less direct sunlight in the winter.

K. Stankevica [10] presented the cooling degree day and hour data in the tabular format for Riga (Latvia) calculated with various base temperatures and using outdoor air temperature data for the last 10 years. The actual mean outdoor temperature measured during the last 10 years is significantly higher (e. g. about 2 °C for July and August months) compared to the normative values given in the climatology norms, indicating the necessity for their update.

The outdoor climate change in the future will have more significant effect on indoor air temperatures as the heating and cooling power of HVAC systems will not be sufficient to handle the processes.

In this article, the study of the influence of the temperature swings on building energy consumption and human performance is discussed. The results and conclusions were based on the findings of the experimental research.

METHODOLOGY

In order to evaluate the influence of temperature variations during the winter period on general energy consumption and performance of the employers the real building was selected (Fig. 2). The building was built in Kaunas in 1950 and was refurbished in 2000. The energy class of the building is E. The evaluated general energy consumption of the building is 240.75 kWh per square meter of the net floor area [12] per year. The building represents a typical construction of Lithuanian buildings built during the 80's [11].

Offices are heated by two natural gas boilers, 40 kW of heating power each. Indoor air temperature is controlled according to external air temperature by either compensating the heating controller or adjustment of the thermostatic radiator valves.

Indoor air temperature during weekends and after working hours is reduced by 4 degrees. During working days, air temperature is decreased in the period from 5.30 pm to 7.00 am, on Saturdays air temperature is set back to optimal from 9 am till 2 pm because some offices in the building are also used in Saturdays.

Fig. 2. The view of the case study building used as an objective of the research

Natural ventilation is installed in the building. Basic data of the analyzed building are presented in Table 1.

The second floor offices A, B, C and D were selected for the analysis of air temperature swings and the calculation of energy consumption (Fig. 3). Rooms A, B, C are oriented to North–East, there are nine persons performing sedentary work in these rooms. The room D is orientated to South–West and it is used as an archive and a storage room. There are no people working consistently in the room D.

Air temperature and relative humidity sensors with data loggers HOBO were used (in A, B, C and D rooms) to measure external and internal air temperature variation during the observed period. Heat meters Kamstrup Multical 601 (class 2) were installed (one meter for A, B, C areas, the second one for D room, the third meter for the second floor) in order to record energy consumption. The period of the measurement was one month from 7 January 2012 to 7 February 2012 with values recorded every 30 minutes. At the end of this period, the employees were asked to fulfill questionnaires about thermal sensation and indoor climate in the office during this month (Table 2).

Persons working in the rooms A, B and C were allowed to adjust thermostatic valves on the radiators according to their thermal comfort needs. A supplementary heating device was used in the room C on 19th, 20th, 23rd of January ant 7th of February. In the room D the thermostatic valves on the radiators were set to 18 °C during the whole investigative period. Blinds were used in rooms A, B, C in order to avoid direct solar radiation.

In the following calculation the physical activity level of the occupants was considered equal to 1.2 met (69.6 W/m^2) and the average clothing level was considered as invariable – 0.75–1.0 clo (0.116–0.160 m^2 °C W^{-1}).

The relative humidity indoors was 30–50%, air velocity was lower than 0.10 m/s.

Taking into account that the office building was heated with the gas boilers, energy charges were estimated 0.06 €/kWh. For further calculations assumption on the average employer profit was estimated equal to 20% of each employee's monthly average salary which was approximately equal to 1 000 € excluding taxes. It was considered that the profit was 9 € per day per person, having in mind that the employees work 8 hours a day, 22 days per month.

Table 1. **Basic data of the case study building used as an objective of the research**

Shape, area	Rectangular, 461 m^2
Number of floors	2 and garret
Number of employees	34
Construction	Walls: heavy construction without insulation, U = 1.12 W/m^{2}K, windows (glass, PVC frame) U = 1.60 W/m^{2}K
Glazing	13% of the total wall area
Work schedule	8 a. m. – 5 p. m.; no occupancy on Sundays and holidays

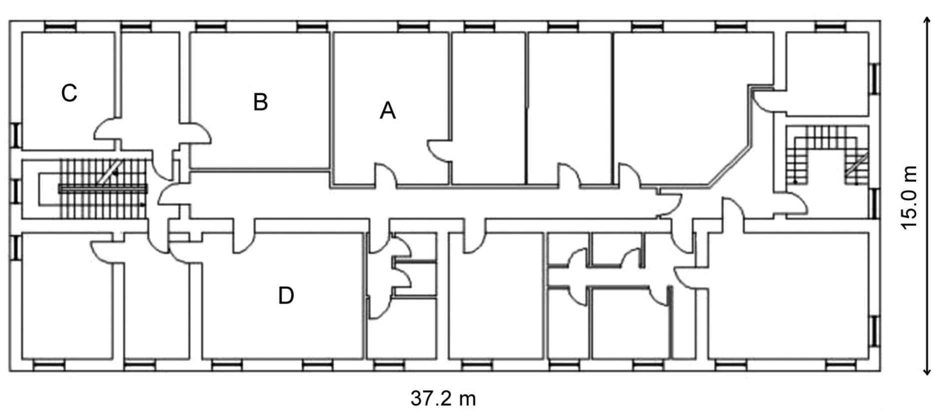

Fig. 3. The plan of the second floor of the case study building

RESULTS

The questionnaire survey of the office employees showed that 11% of the personnel evaluated the thermal conditions as very good, 54% as good and 35% as moderate. There were no respondents who described the conditions as bad and very bad. Other results of the questionnaires are presented in Table 2. The values in Table 2 are in%, where 0% means the statement is totally untrue, and 100% mean the statement is totally true. Participants were mostly dissatisfied with intermittent air temperature, too low air temperature as well as stuffy and dry air.

During the analyzed period (01.07.2012–02.07.2012), the average air temperature during the day was –6.5 °C, the lowest observed temperature was –24.7 °C, the highest recorded temperature 5.4 °C (Fig. 3). In the rooms A, B and C 4 134 kWh or 34 kWh/m^2 of thermal energy were consumed and in the room D 542 kWh or 14.5 kWh/m^2, respectively. Expenses for heating of rooms A, B and C were 2.04 €/m^2 and 0.87 €/m^2 for the room D.

Figure 4 shows that similar swings of air temperature are repeated at all selected dates, except the days between 28th of January and 7th of February. At these days, temperature changed during the day by 15.6 °C, the average temperature was –15.4 °C and the lowest recorded temperature was –24.3 °C.

Two periods from 9th to 13th of January and from 30th of January to 3rd of February were compared. As the subject for further analysis, the exponentials of the room A were selected. In the following figures, the temperature of the room A and the optimal air temperature (Fig. 5), outdoor air temperature and instantaneous power of heating system (Fig. 6) are presented.

The optimal air temperature curve presented in Fig. 5 was established to maximize productivity of the occupants. From the point of view of long-term performance, indoor air temperature should be fixed at +21.6 °C from the moment when the work starts at the office. On the other hand, air temperature should be gradually decreased to +18 °C one hour before the end of the working day in order to use the effect of productivity rise due to temporarily lowered air temperature.

It is important to outline that personal adaptation to thermal conditions of each individual are not taken into account

Table 2. **Results of the questionnaire survey performed during the experiment**

How often have you felt thermal discomfort because of the following reasons last month?				
	Never	**Few times**	**Several times a week**	**Every day**
Draught	53.9	34.6	7.7	3.9
Too-high temperature	73.1	23.1	3.9	0.0
Changeable temperature	23.1	42.3	23.1	11.5
Too-low temperature	15.4	53.9	19.2	11.5
Stuffy air	23.1	30.8	30.8	15.4
Dry air	42.3	30.8	19.2	7.7

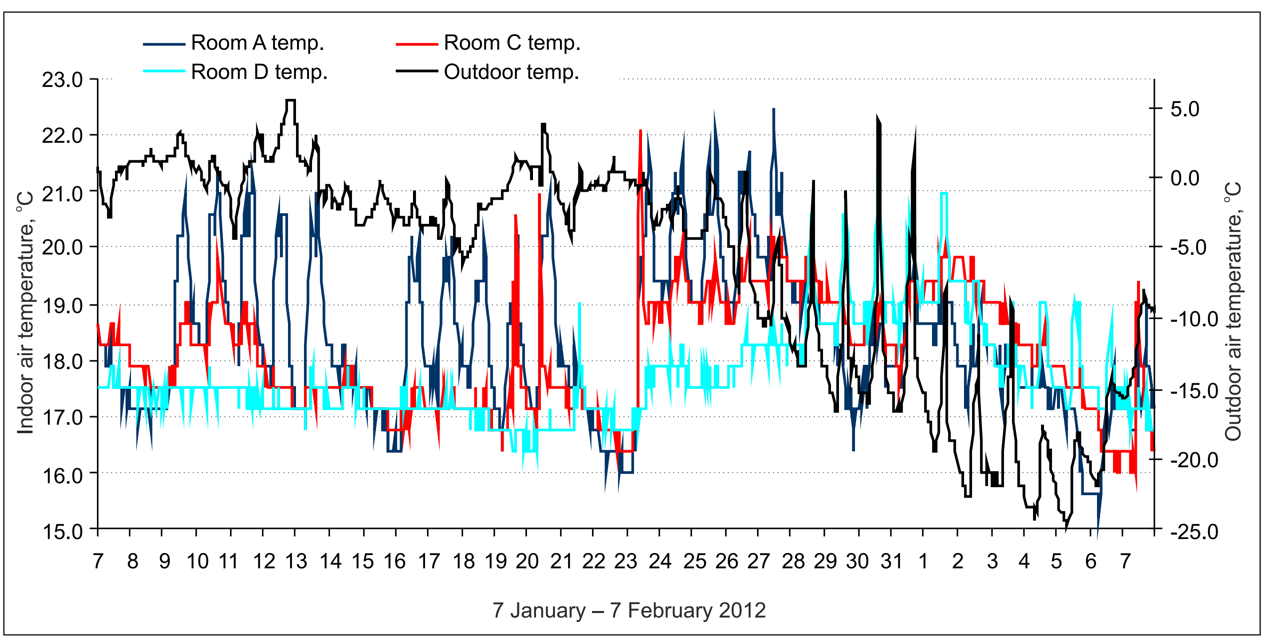

Fig. 4. Variation of external and internal air temperature during the experiment

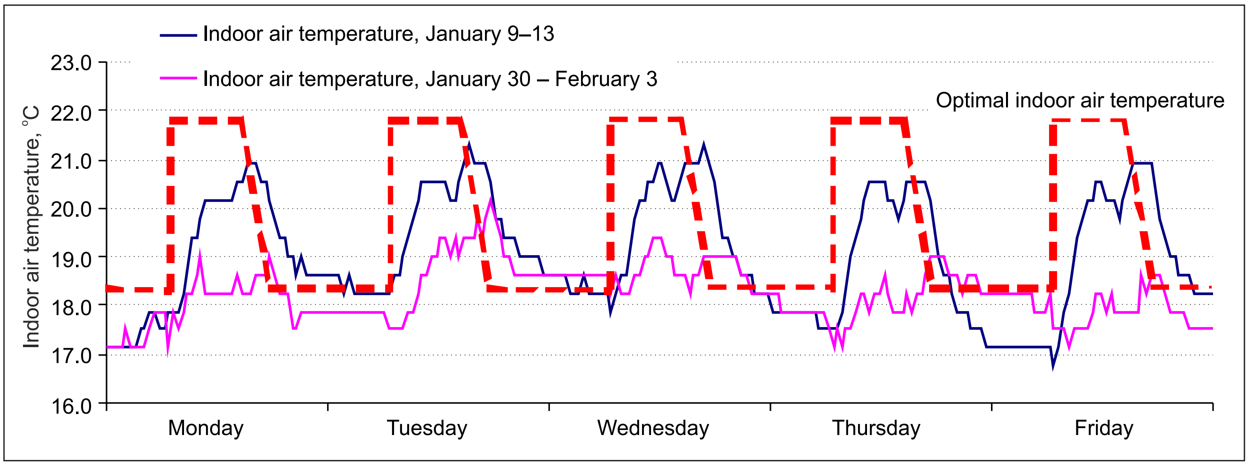

Fig. 5. The optimal air temperature curve and indoor air temperatures in the room A

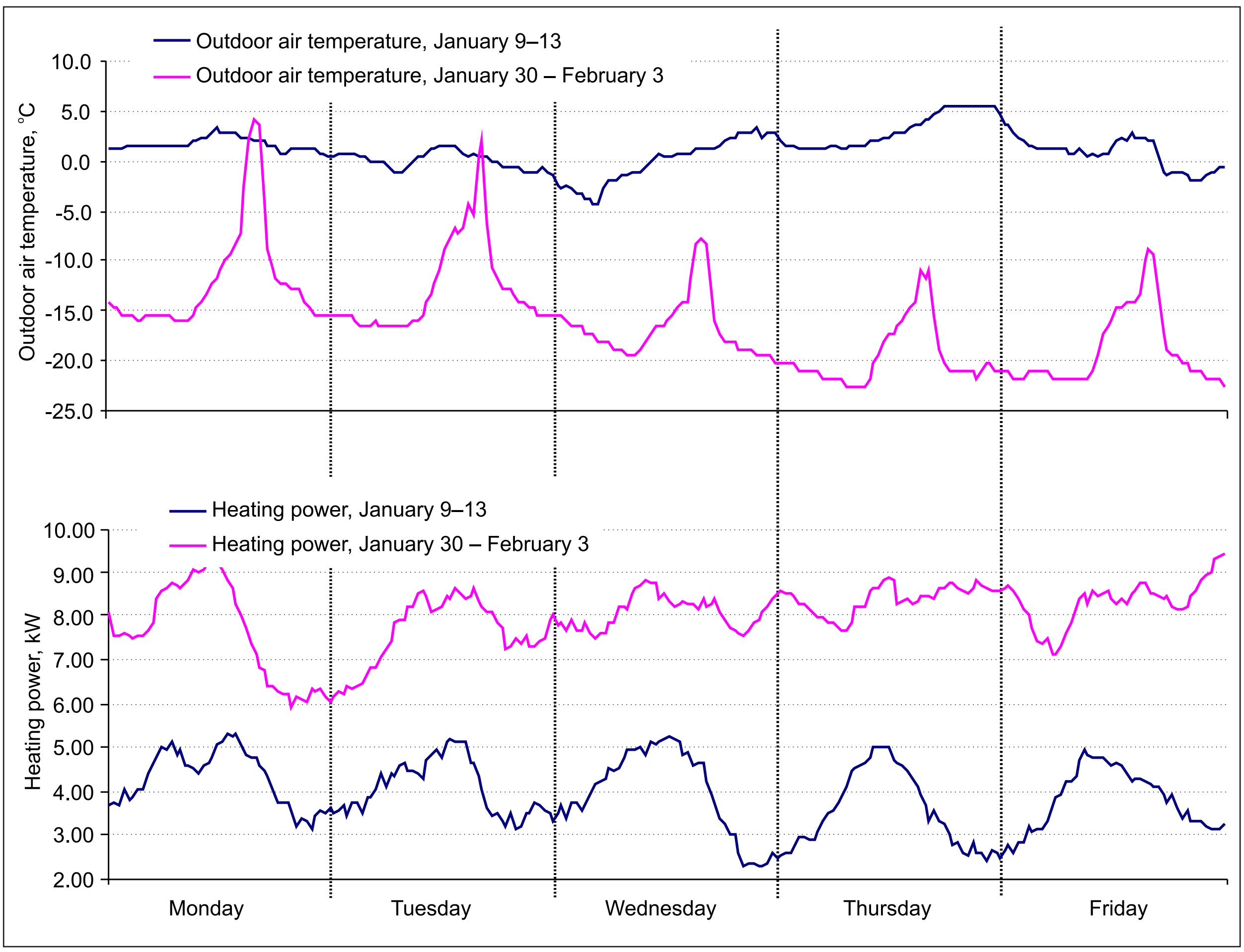

Fig. 6. Variation of outdoor air temperature and instantaneous heating power in the rooms A, B and C during the following periods: 9th to 13th of January and 30th of January to 3rd of February 2012

in this study. Results of the research performed with larger groups of individuals were used in order to draw the optimal curve; therefore there is a chance of complaints due to too-low temperature in the rooms from certain individuals.

Measurements in the case study building showed that the optimal air temperature drop during the off-work time is not possible to achieve due to imperfection of the heating system control as well as thermal inertia of the building. Moreover, the long-term measurements in the offices showed that during the working hours the internal air temperature is too low, especially at the morning hours. At the end of the day the rooms are usually overheated (Fig. 5).

According to the results of the study reported by Seppänen et al. [3], a reliable loss of productivity of the occupants would be approximately 5.2% in the analyzed building rooms A, B and C. The average value of the PMV index [2] would be 0.78.

The loss of productivity of the occupants was calculated and converted to the monetary value. Thermal discomfort of the occupants working in the rooms A, B and C would result in a loss of performance by proximally 93.6 € from 7th of January to 7th of February.

In order to compensate the loss of productivity the rooms A, B and C would need 212 kWh of additional energy for the analyzed building. For that reason, higher heat consumption equal to 12.7 € would be needed at the period from 7th of January to 7th of February.

However, the occupation density in the particular building was lower than 0.1 person per square meter, which is the standard value outlined in the standards [13]. Therefore, in the typical office buildings the productivity of the office work would result in a higher monetary value.

CONCLUSIONS

1. The main complaints received by performing the questionnaire survey of the occupants of the case study building were stuffy air, too-low air temperature and too-high variation of the temperature during the day.

2. The results of the study showed that the control of the heating system does not ensure the optimal temperature in the analyzed building. According to long-term and short-term productivity studies, the air temperature should be fixed to 21.6 °C and should be reduced to 18 °C until the end of the work hours.

3. In order to ensure the optimal air temperature control from the point of view of energy saving as well as the maximized productivity of the office work, the power of the heating system should be increased by 18%. In case the power of the heating system would remain unchanged, the temperature control curve should be adjusted to advance the temperature rise in the morning and the temperature drop in the afternoon.

4. The financial losses due to decrement of office work performance are 7.4 times higher comparing to additional expenses for increased energy demand evoked by ensuring higher air temperature in the rooms.

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TEMPERATŪROS SVYRAVIMŲ ĮTAKA ENERGIJOS SĄNAUDOMS IR ŽMONIŲ DARBINGUMUI BIURUOSE

Santrauka

Šildymo ir oro kondicionavimo įranga biuruose įprastai reguliuojama pagal išorės oro temperatūrą. Tačiau dėl didelių išorės oro temperatūros svyravimų patalpų mikroklimatas gali kisti komfortinių parametrų ribose. Nors naujuose biuruose yra šiuolaikinė įranga, darbuotojai vis tiek gali jausti laikiną diskomfortą, o tai tiesiogiai veikia jų darbingumą. Šio tyrimo tikslas buvo ištirti temperatūros svyravimų įtaką pastatų energijos sąnaudoms ir darbingumui realiame biure.

Tyrimo objektu buvo pasirinktas realus pastatas, kuriame buvo stebima oro temperatūra, momentinė šildymo sistemos galia. Darbuotojai dalyvavo apklausoje, kurios tikslas – identifikuoti pastato mikroklimato problemas. Gauti rezultatai parodė, kad vidaus oro temperatūros svyravimai ir nuokrypiai nuo projektinių verčių neigiamai veikia darbuotojų savijautą, mažina jų darbingumą. Nustatyta, kad norint užtikrinti optimalų oro temperatūros valdymą patalpose, šildymo sistemos galia turėtų būti padidinta 18 %.

Raktažodžiai: energijos parametrai, kintanti temperatūra, šilumos komfortas, darbingumas

Рокас Валанчюс, Андрюс Юрелёнис

ВЛИЯНИЕ УСЛОВИЙ ПЕРЕМЕНЧИВОЙ ТЕМПЕРАТУРЫ НА РАСХОДЫ ЭНЕРГИИ И РАБОТОСПАСОБНОСТЬ СЛУЖАЩИХ

Резюме

Оборудование отопления и кондиционирования воздуха в помещениях обычно регулируется по температуре наружного воздуха. Однако, из-за резких изменений наружней температуры, способность систем микроклимата помещений часто бывает недостаточно поддержать проектный температурный режим внутри здания. Отклонения температуры от нормы может вызвать ухудшение самочувствия людей и влиять на их работоспособность. Целью эксперимента было исследовано влияния резко меняющегося микроклимата помещений на потребление энергии и работоспособность служащих.

В качестве объекта исследования было выбрано здание бюро, в котором были измеряемы параметры: температура воздуха, мгновенная мощность системы отопления, а также сотрудники участвовали в опросе, целью которого было определение проблем микроклимата.

Результаты показали, что резко изменяющиеся параметры микроклимата помещений негативно действуют на самочувствие и работоспособность служащих. В целях обеспечения оптимального контроля температуры воздуха, мощность системы отопления должна быть увеличена на 18 %.

Ключевые слова: энергетические параметры, переменчивая температура, тепловой комфорт, работоспособность служащих