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THE IMPACT OF BUILDING PARAMETERS AND WAY OF OPERATION ON THE OPERATIVE TEMPERATURE IN ROOMS

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Abstract
The control of the thermal environment and the assessment of the quality of rooms in terms of thermal comfort of users is often based solely on the measurement of the air temperature. Proper assessment should, however, be based on an analysis of the operative temperature, which, in many cases, differs from the air temperature in the room. The operative temperature takes into account also the influence of surrounding building partitions on building occupants due to thermal radiation. The paper analyzes the impact of building elements such as the construction of the building walls, the size of the glazing, building orientation, as well as the way the building is operated on the differences between the air temperature and the operating temperature. Multivariate simulation analyzes were carried out for an exemplary office room using the IDA Indoor Climate and Energy (IDA ICE) program.

Streszczenie
Kontrola środowiska cieplnego i ocena jakości pomieszczeń pod kątem komfortu cieplnego użytkowników jest często oparta wyłącznie na pomiarze temperatury powietrza. Właściwa ocena powinna jednak zawierać analizę temperatury operatywnej, która, w wielu przypadkach, różni się od temperatury powietrza w pomieszczeniu. Temperatura operatywna uwzględnia także oddziaływanie otaczających przegród budowlanych na użytkowników wskutek promieniowania cieplnego. W artykule przeanalizowano wpływ takich elementów budynku jak konstrukcja ścian budynku, wielkość oszklenia, orientacja względem stron świata, a także sposób eksploatacji budynku na różnice między temperaturą powietrza a temperaturą operatywną. Wielowariantowe analizy symulacyjne przeprowadzono dla przykładowego pomieszczenia biurowego wykorzystując program IDA Indoor Climate and Energy (IDA ICE).

Keywords: **Thermal comfort; Assessment of indoor environment; Simulation methods; Operative temperature.**

1. INTRODUCTION

Thermal environment in buildings is one of the most important aspects for occupants' comfort [1]. Thermal comfort, i.e. satisfaction with the environment depends on the occupants' thermal sensation. The thermal sensation is a function of four physical variables of indoor environment in the room (air temperature, mean radiant temperature, relative air humidity and air velocity) and two variables related to people (activity level and clothing). Knowledge of these parameters allow to predict the mean thermal sensation (PMV) of a group of people staying in the room with particular thermal environment. The PMV index and the related PPD index (predicted percentage of dissatisfied) are currently used in standards [2–4] to prescribe the thermal environment conditions in buildings with mechanical ventilation. The PMV and PPD indexes, due to the numerous input parameters and the complexity of their determination, are not suitable for controlling of

HVAC systems operation. The HVAC systems are typically controlled by the room thermostats, which measure air temperature. Analysis performed by Kontes et al. [5] have shown that relying on the thermostat temperature indication and neglecting other thermal environment parameters can lead to improper thermal sensation estimation.

A better indicator of thermal environment than air temperature is operative temperature. It is defined as a uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. The operative temperature thus takes into account both convective and radiant heat exchange between occupants and the environment while air temperature affects only convective heat exchange. The determination of operative temperature is, however, more complex than relatively simple measurement of air temperature. Most often the operative temperature is calculated, from formula (1), based on measurements of air temperature and mean radiant temperature [4].

$$t_o = A \cdot t_a + (1 - A) \cdot t_{mr} \tag{1}$$

where:

t_a – air temperature,

t_{mr} – mean radiant temperature,

A – function of the air velocity.

In cases, when the difference between t_{mr} and t_a does not exceed 4 K and the air velocity in the room is small, i.e. <0.2 m/s, the operative temperature may be determined by equation (2).

$$t_o = (t_a + t_{mr})/2 \tag{2}$$

The methods for mean radiant temperature and operative temperature determination are described in details in ISO 7726:1998 standard [6]. The direct measurement of operative temperature requires specially designed sensor [7] and is performed less frequently, mainly in thermal comfort research [8].

For buildings with mechanical ventilation and/or mechanical cooling the standards [2, 3] prescribe the optimum ranges of operative temperature during summer and winter for standardized clothing of 0.5 clo or 1.0 clo during respective season and for the given activity level. For buildings with natural ventilation the adaptive model [2, 4] should be used instead. Adaptive thermal model assumes that occupants can freely adjust their clothing insulation and may open windows, and relates indoor operative temperature to the changes in the outdoor temperature [9]. According to EN 15251:2007 standard [3], the assessment of thermal environment quality category in occupied building may be based on temporal and spatial variability of operative temperature in the examined premises. In practice, long-term measurements are often limited to measurements of air temperature only. Assuming arbitrarily their equality is improper as it may negatively affect occupants' thermal comfort and energy used by systems in buildings. In such case the standard suggests correction of the recorded air temperature for the radiation effect of large, warm or cool surfaces (expressed by mean radiant temperature). The informative supplement to ASHRAE 55 standard [4] defines the conditions under which the operative temperature can be replaced with air temperature in premises as: heat transfer coefficients through windows and external walls as well as window solar heat gain coefficient should be small and there should be no radiant panel heating, cooling systems or devices generating significant heat gains in premises. There are, however, no detailed guidelines under which conditions the air temperature should be adjusted for the effect of mean radiant temperature. There is lack of systematic analysis of the effect of different building characteristics and little data is available on the differences between air temperature and operative temperature occurring in buildings in moderate climate.

The input signal for control of HVAC system determines not only the thermal comfort of occupants, but also affects the energy consumption. Simulation results of the energy consumption in buildings with high glazing fraction in hot climate differ significantly depending on whether indoor environment control was based on air temperature or operative temperature [10]. Thus the combination of two goals – maintaining good quality thermal environment and minimizing the energy consumption in a building requires application of optimization procedures and introduction of reliable input thermal parameters affecting the thermal behavior of the building [11–13]. Therefore measurements of indoor environment quality in real buildings and the indication of the correct measurement methodology are particularly valuable [14, 15].

The purpose of the paper is to demonstrate the relationship between the operative temperature and the air temperature in office room for different constructions of external walls, window size and orientation, as well as diverse internal heat gains in the premises. The relationship is determined based on analyzes of the multivariate simulation results carried out by IDA Indoor Climate and Energy (IDA ICE) program.

2. METHODOLOGY

Numerical analysis has been carried out with the IDA ICE 4.22 simulation program [16], which is a tool for conducting dynamic simulations of energy consumption in a building. The software allows building and solving equations of heat balance of declared calculation zones. The simulation takes into account heat fluxes resulting from operation of heating/cooling equipment, transferred with ventilation air flows and coming from the effect of solar radiation, internal heat gains, and also resulting from the accumulation of heat in building structures and in equipment of analyzed areas. Moreover, it is possible to calculate mean air temperature and operative temperature in analyzed zones, as well as thermal comfort indices (PMV and PPD) and detailed settlement of energy consumption for heating/cooling purposes.

The office room was simulated in the form of a macroscale single zone model as an idealized zone with constant parameters of air within it.

The analysis covered two office units with dimensions 6×6×3 m (width×depth×height), identical in construction, but differing in window location: one room has a north-facing window, whereas the other has a window facing south. It was assumed that heat losses occur only through the external walls; the remaining walls in the premises were taken as adiabatic. In thermal model, besides heat fluxes penetrating through the external walls, also solar radiation and heat generated by people and equipment (including lighting) were taken into account.

3. SIMULATION VARIANTS

Three types of external walls, differing in heat transfer coefficients, were modeled for the purpose of the analysis:

- brick walls, $U=1.43\ W/m^2K$;
- reinforced concrete walls, $U=0.76\ W/m^2K$;
- reinforced concrete walls with thermal insulation, $U=0.28\ W/m^2K$.

Typical double-glazed windows, considering two size options: with an area of 50% and 70% of the external wall area (lack of sun visors), were modeled for both premises.

The following assumptions respecting the operation of offices were made:

- indoor temperature: 24°C – cooling (summer), 20°C – heating (winter);
- natural ventilation – infiltration: air change rate $ACH = 0.5\ h^{-1}$ (previously identified average value of air change rate in buildings with natural (gravitational) ventilation in Polish climate conditions [17–19]).

The room is occupied according to three variants:

- from 8 a.m. to 5 p.m. (the most popular case);
- all day (less frequent case, for example in 24-hour monitoring offices);
- no occupants (lack of internal gains).

Internal heat gains during occupations hours [20]:

- 2 people – activity 1 met (about 108 W); clothes: 0.5 in summer, 1 clo in winter;
- equipment (2 computers) – the sensible heat flux per unit: 133 W;
- lighting – the sensible heat flux per unit: $15\ W/m^2$ (50% convection, 50% radiation).

The outdoor conditions: consistent with available meteorological data (typical meteorological years – one of the Polish cities – Krakow): air temperature and relative humidity, wind speed and direction, total and diffuse solar radiation. One-hour time step data were used.

The series of computer simulations were performed for the whole year (with one-hour time step), which allowed receiving instantaneous values of mean air temperature, operative temperature and temperature of individual walls surfaces. Structure of external walls, size of the windows and internal heat gains were changed in particular series.

The analyses were performed according to the recommendations of the standard [3] for three coolest months (December–February) and three warmest months (June–August). Since operative temperature is a function of mean radiant temperature, its value depends on the point of the room it is measured at. It was assumed in all simulations that the operative temperature was appointed in the middle of the room, at a height of 0.6 m above the floor, which corresponds to the height of sitting person's torso, as recommended by ISO 7726:1998 standard [6].

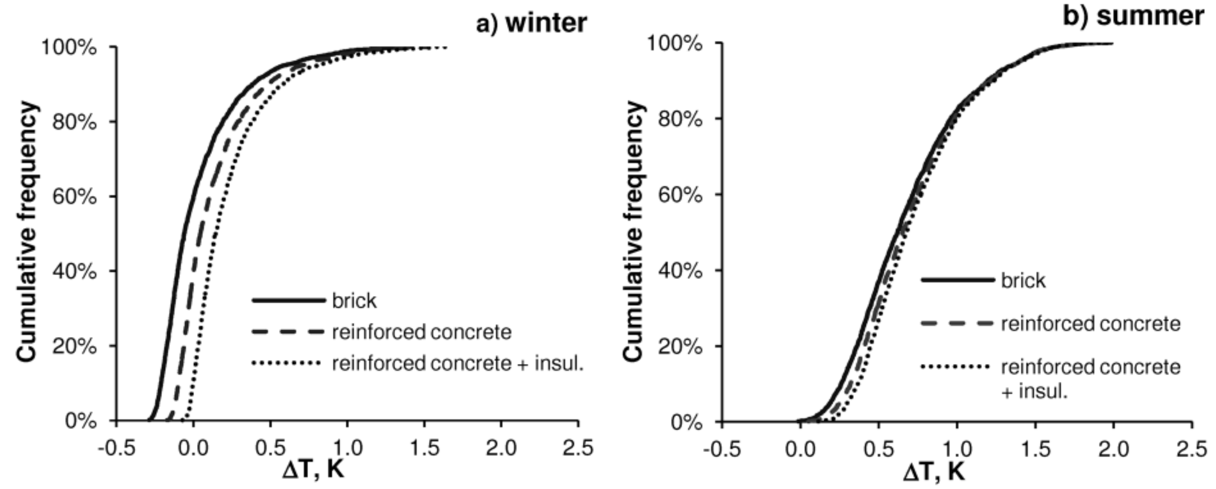

Figure 1.
Cumulative distribution of difference between operative temperature and air temperature for three types of external walls for case with small window south-facing, heat gains from 8 a.m. to 5 p.m.

4. RESULTS

According to the assumptions of the research, the analysis of the results concerns comparison of differences between operative temperature and air temperature ($\Delta T = t_o - t_a$) for different constructional and operational variants of modeled premises. Data in the figures correspond to 24 hours during each analyzed three-month period.

The influence of the following factors on studied temperature difference ΔT was analyzed:

- construction of partitions;
- window location in relation to cardinal directions and a degree of glazing;
- internal heat gains.

4.1. The impact of external walls construction

The structure of partitions' construction determines the amount of heat flow between room and environment. Thermal characteristics of individual walls (e.g. accumulation resulting from differences in density and specific heat of particular materials forming the partitions) affect temperature of their surfaces, and consequently radiant temperature. Fig. 1 presents cumulative distributions of differences between operative temperature and air temperature for winter and summer when using walls with different structures.

The differences between operative and air temperature were smaller in winter than in summer. The largest temperature difference is nearly 2 K in summer, whereas in winter it reaches at most about 1.4 K. On average, the calculated differences in temperature smaller than 0.5 K occur for 90% of the time in the winter and only 30% of the time during summer. Temperature difference ΔT in winter is the smallest for the wall with the highest heat transfer coefficient, and increases with increasing wall insulation. In summer, curves of differences between operative temperature and air temperature for different walls almost overlap, however, relationship between temperature difference and wall insulation is maintained. Such result for the summer – minor influence of wall insulation – results from a small heat flow through the external wall, whereas temperature difference between the building interior and the environment is small.

4.2. The impact of location and size of the windows

The obvious effect of solar radiation on heat balance of premises becomes exposed also in relationship between operative temperature and air temperature. Comparison of temperature difference ΔT for the cases of south-facing windows (S) and north-facing windows (N) is presented in the Fig. 2. The figures contain curves of cumulative values of ΔT for winter and summer for two types of partitions: with small insulation (brick) and with low heat transfer coefficient (reinforced concrete with thermal insulation).

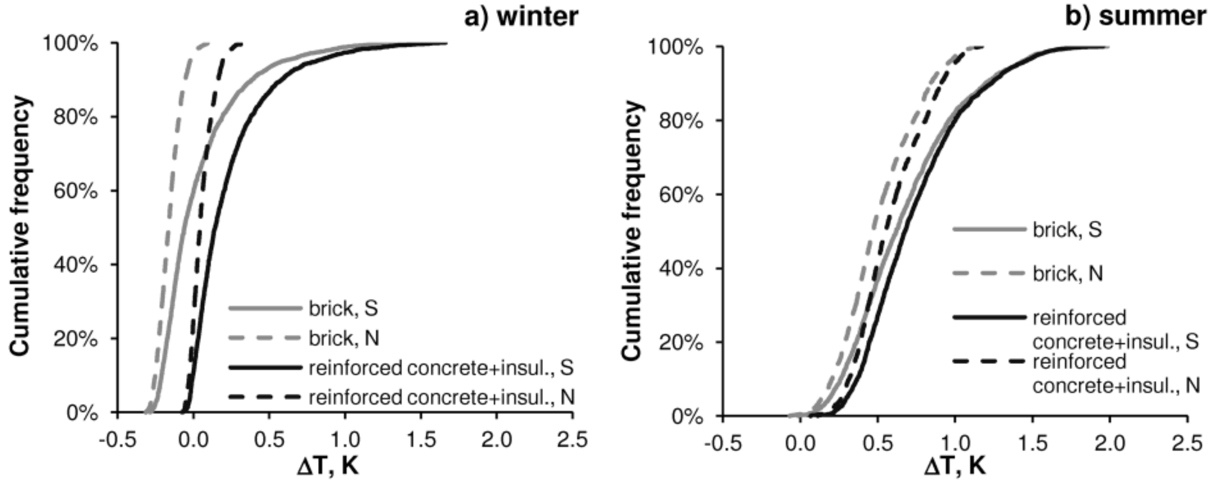

Figure 2.
Cumulative distribution of difference between operative temperature and air temperature for cases with small window facing south (S) or north (N), heat gains from 8 a.m. to 5 p.m.

Data in the figures allow simultaneous assessment of the impact of structure of walls and direction of window location (south-north). When the windows are located on the wall facing south it results in the increase of temperature difference ΔT, both in summer and in winter. In summer, the influence of walls' insulation is small, thus ΔT is almost comparable; in winter the impact of heat transfer on the wall temperature increases, thus ΔT is greater, both for south- and north- facing windows. In the case of windows facing south, both in summer and winter, maximum differences between operative temperature and air temperature are comparable – in summer they reach nearly 2 K and in winter 1.7 K (for means from three months: 0.7 K in summer and in winter). For the windows facing north, the largest ΔT in winter reaches only 0.4 K (for mean from three winter months it is about 0.1 K).

The effect of window size is different in winter and summer. Windows in studied model (and in actual objects) are characterized by much greater values of heat transfer coefficient than the walls they are built in. The external wall is being cooled in winter, since heat gains from solar radiation do not compensate heat losses through transfer; therefore ΔT is lower than for the smaller window. In summer, when temperature differences inside and outside are small, heat gains from solar radiation determine temperature of the walls, thus the greater glazing, the larger ΔT. Fig. 3 presents these comparisons, and additionally shows the impact of internal heat gains. Both for summer and winter, heat gains in the premises significantly increase the difference between operative temperature and air temperature (in summer by about 0.5 K and in winter by about 0.2 K). In the summer, in case of heat gains constantly present in the room, the value of ΔT practically do not drop below 0.5 K. For more than 60% of time the deference exceeds 1 K.

4.3. The impact of internal heat gains

This factor is the most problematic to predict, but it is also important component of heat balance of a premises. Heat gains resulting from office room operation also significantly affect analyzed difference between operative temperature and air temperature. According to assumed variants, three series of simulations were performed by changing profiles of internal heat gains. As presented above, the greatest studied temperature difference was observed for the wall with good insulation. The results concerning the difference between operative temperature and air temperature in office units are presented in Fig. 4, and show the data for external wall with thermal parameters consistent with current requirements (reinforced concrete wall with thermal insulation). Heat gains generated round the clock cause significant increase in operative temperature compared to the absence of internal gains or to the case when gains occur during the working hours of the office (8 a.m. to 5 p.m.). As before, ΔT is higher in summer compared to winter, which is an effect of solar radiation that is greater in summer. ΔT reaches between 0.6 and 2.3 K in the summer for round the clock gains, and between 0.1

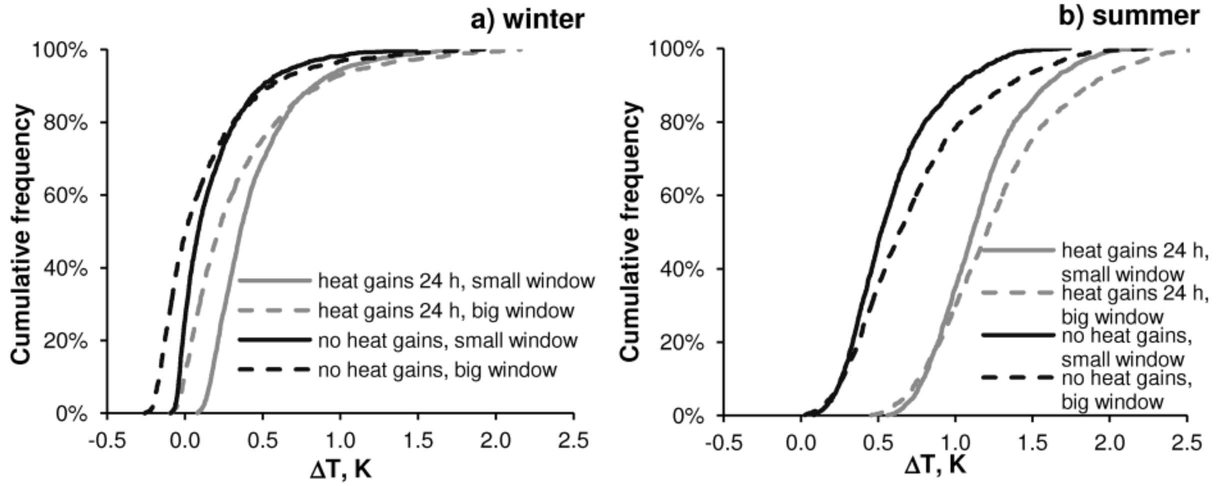

Figure 3.
Cumulative distribution of difference between operative temperature and air temperature for two sizes of windows and different internal gains for case with external walls modelled as reinforced concrete with thermal insulation

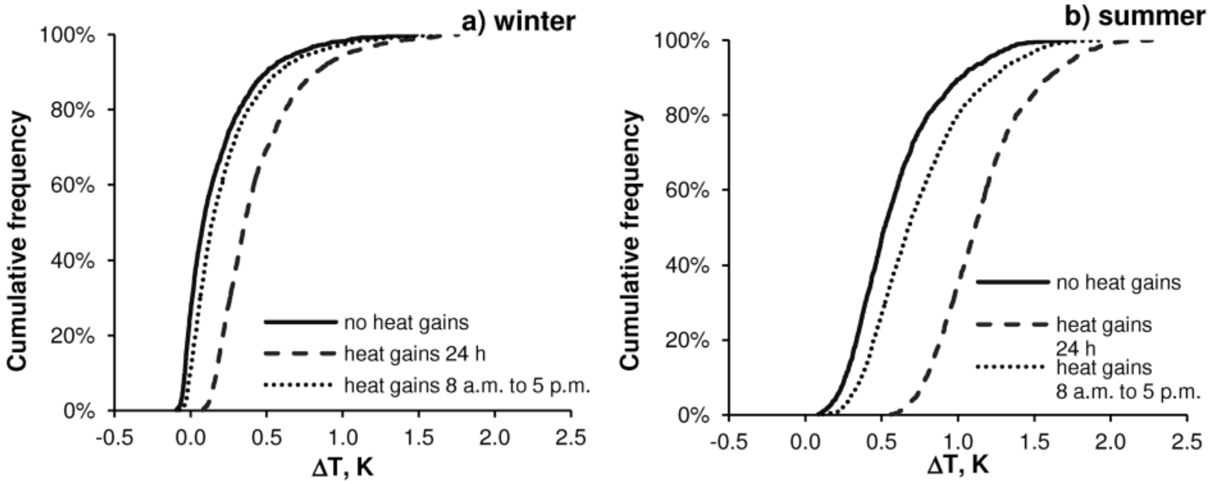

Figure 4.
Cumulative distribution of difference between operative temperature and air temperature for three patterns of internal gains occurrence for case with external walls modelled as reinforced concrete with thermal insulation, south-facing

and 1.7 K in the absence of internal heat gains – mean from three months in the absence of gains reaches 0.6 K in the summer and 0.2 K in the winter, and for round the clock gains respectively: 1.2 and 0.4 K.

5. SUMMARY AND CONCLUSIONS

Conducted series of simulations indicated that in the typical office room – in terms of construction and operation – air temperature differs from operative temperature for almost the entire analyzed period, both in winter and summer. This fact carries certain consequences as to reliability of thermal comfort assessment based only on air temperature. The assumption of the equality of both temperatures' values may distort the assessment of studied building category due to thermal comfort.

Performed series of simulations concerned only a limited number of combinations of parameters, which determine the operation of a building, i.e. the glazing of buildings facades, only variation of windows area was taken into account, while the whole range of possibilities of complex technical solutions for restriction of solar radiation effects was not considered. Nevertheless, the presented data provides an input for the control and evaluation of the thermal environment.

From the point of view of HVAC system operation, air temperature in the premises is a parameter far easier to use, as it can be directly measured. In case of operative temperature determination of either a special sensor or additional measurement of mean radiant temperature is necessary. Presented results of the simulations demonstrate also the committed error, if HVAC system is controlled based on air temperature. The difference in operative and air temperature may reach even 2 K. Such difference will affect the thermal comfort of occupants.

Thus the assumption of equality of the air temperature and the operative temperature can also carry implications for the erroneous measurement assessment of thermal comfort conditions. According to ISO 7726:1998 standard [6], required accuracy of air temperature sensor should be ±0.5°C. The results of the calculations show that the measured air temperature may exceed this value for substantial amount of time, which in consequence leads to incorrect assessment of thermal comfort indices.

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