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ANALYTICAL DETERMINATION AND INTERPRETATION OF THERMAL COMFORT

Semko O. V., Filonenko O. I., Yurin O. I., Mahas N. M., Norka A. R.

INTRODUCTION

The energy consumption of buildings depends significantly on the criteria of the microclimate of the premises (temperature, ventilation and lighting) and buildings (including systems) used in the design and operation. The microclimate of the room also affects the health, productivity and comfort of the people in the room. The cost of the impact of an unsatisfactory microclimate on the premises, the building owner and society as a whole often far exceeds the cost of energy used by the same building. It has also been shown that the high quality of the indoor microclimate can increase productivity and learning ability and reduce absenteeism.

1. Certification of the thermal environment of the premises as part of the assessment of the overall energy efficiency of the building

Insufficient thermal insulation of the elements of enclosing structures leads to thermal discomfort caused by unwanted local cooling or heating of the body. The most common local factors of discomfort are asymmetry radiation temperature (cold or warm surface), draft (defined as local cooling of the body caused by air movement), vertical temperature drop and cold or warm floors.

When developing thermal modernization projects as part of the reconstruction or overhaul of buildings, the customer often insists on insulation of the outer shell. Example:

– in case of thermal modernization of the school, do not include in the project the replacement of windows with energy-efficient ones, as the existing ones are new, although they have low heat transfer resistance;

– during the thermal modernization of the university building, which is an architectural monument, the installation of facade insulation and finishing systems is unacceptable, and the internal insulation of the walls leads to a reduction in the area of educational premises and their re-repair;

– at thermal modernization of a sports hall there is no possibility to carry out warming in a design of already existing floor on soil, and effective vertical warming of a peri-foundation zone on external perimeter of the building is impossible because of the base of glass type.

The design standards allowed the use of individual structural elements of the thermal insulation shell with reduced values of heat transfer resistance to the level 75% of R_{qmin} for opaque parts of external walls and up to 80% of R_{qmin} for other enclosing structures in accordance with the condition according to the formula (4) DBN V.2.6-31:2016[1] with mandatory compliance with the conditions for these elements of the insulating shell according to formulas (5) and (6) DBN V.2.6-31:2016.

Estimated or actual specific annual energy consumption of the building must be at least the maximum allowable value of the annual energy consumption of the building (p. 5.1 DBN V.2.6-31:2016).

In the cases listed above, the energy efficiency class of buildings not lower than C was achieved by increasing the heat transfer resistance of other enclosing structures in determining the reduced heat transfer coefficient of the insulating shell.

According to paragraph 2 of section II «Methods for determining the energy efficiency of buildings»[2] in the reconstruction, overhaul of buildings in general or their separate parts, the minimum requirement is to meet the condition:

$$EP_{use} \leq 1{,}2 \times EP_p, \tag{1}$$

where EP_{use} – total specific energy consumption for heating and cooling, kW×h/m^2, (kW×h/m^3), calculated for «Methods for determining the energy efficiency of buildings»;

EP_p – the limit value of specific energy consumption for heating and cooling of residential and public buildings, kW×h/m^2, (kW×h/m^3), which is given in the appendix to the «Minimum requirements for energy efficiency of buildings»[3].

In Europe and America, the assessment of thermal comfort in thermally asymmetric environments is a mandatory part of the energy audit.

The University of California at Berkeley has developed a model of thermal comfort (UC Berkeley Comfort Model), which provides local comfort for different parts of the body and integrates local comfort levels to provide thermal comfort for the whole body. The model is based on a large number of human tests in different asymmetric and transient thermal media. The model divides the surface of the human body into more than five thousand polygons to calculate the radiative heat exchange between the body and the environment (Fig. 1).

[1] ДБН В.2.6–31:2016 Теплова ізоляція будівель. – Мінбуд України. – К.: Укрархбудінформ, 2016. – 33 с. – (Державні будівельні норми України).

[2] Методика визначення енергетичної ефективності будівель – Наказ Мінрегіону від 11 липня 2018 року № 169 (Зі змінами – Наказ Мінрегіону від 27.10.2020 № 261)

[3] Мінімальні вимоги до енергетичної ефективності будівель – Наказ Міністерства розвитку громад та територій України 27 жовтня 2020 року № 260.

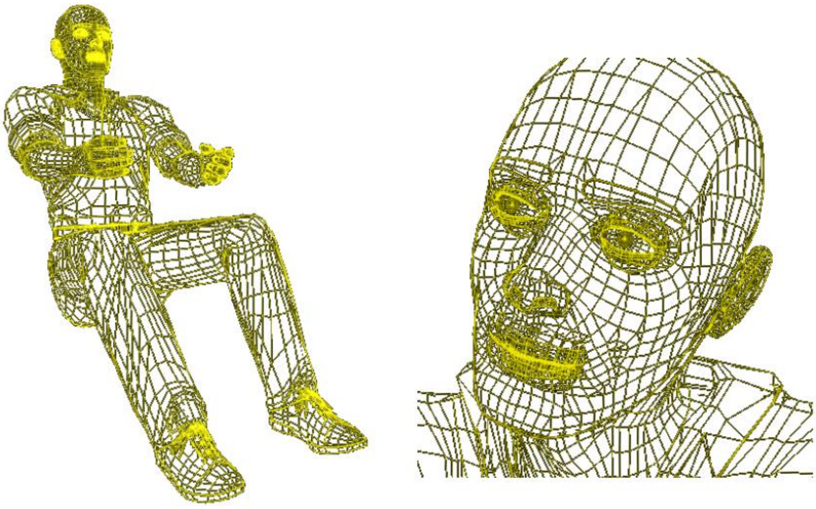

Fig. 1. Human body model used to calculate radiant heat transfer in the UCB comfort model

Therefore, the heat transfers between the housing and the thermally asymmetric surfaces can be calculated in great detail. In Fanger, P.O.[4,5,6,7], Olesen, B.W.[8,9,10], and Nilsson, H. O.[11,12] presented models for predicting human thermal comfort, developed on the basis of human tests. Models provide sensation and comfort in transient and asymmetric thermal conditions.

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That is, in the above domestic methods when assessing the overall energy efficiency of buildings does not pay attention to the comfort of the premises. Underestimation of requirements to thermal characteristics of designs is allowed. A non-complex approach to thermal modernization of public buildings leads to a deterioration of the microclimate of the premises. Aspects of certification of the thermal environment of premises, which is based on indices of thermal comfort, as one of the parameters for assessing the overall energy efficiency of the building should be explored.

In Ukraine, normative documents on ergonomics of the thermal environment (DSTU B EN ISO 7730: 2011[13], DSTU B EN 15251: 2011[14], etc.) have been introduced, but they are not harmonized with current methods and are practically not used in thermal calculations.

2. Methods for determining the calculated parameters of the thermal environment by category of premises

With the introduction of DSTU B EN 15251: 2011 introduces the concept of certification of the thermal environment of the premises, which is based on thermal comfort indices PMV-PPD (estimated average expectation – the estimated percentage of dissatisfied) with predictions of activity levels and thermal insulation of clothing (summer and winter). The standard introduces the concept of categories of the internal environment.

Temperature (thermal comfort) is a state of satisfaction with the thermal conditions of the environment. Dissatisfaction can be caused by discomfort from overheating or cooling of the body as a whole, which is assessed by PMV and PPD, or unwanted cooling (overheating) of one specific part of the body.

When designing the thermal performance of the elements of the thermal insulation of the house according to DBN B.2.6-31: 2016 it is necessary to use methods to predict the overall thermal sensation and the degree of discomfort (thermal dissatisfaction) of people exposed to moderate thermal environments. Analytical determination and interpretation of thermal comfort using PMV (predicted average air quality assessment) and PPD (projected percentage of dissatisfied with ambient temperature), as well as local thermal comfort criteria helps to assess the acceptability of environmental conditions for human thermal comfort. PMV can be used to set requirements for the thermal environment.

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[13] ДСТУ Б EN ISO 7730: 2011 Ергономіка теплового середовища. Аналітичне визначення та інтерпретація теплового комфорту на основі розрахунків показників PMV і PPD і критеріїв локального теплового комфорту (EN ISO 7730: 2005, IDT).

[14] ДСТУ Б EN 15251:2011 Розрахункові параметри мікроклімату приміщень для проектування та оцінки енергетичних характеристик будівель по відношенню до якості повітря, теплового комфорту, освітлення та акустики (EN 15251:2007, IDT).

By setting PMV = 0, we obtain equations for predicting combinations of activity, clothing, and environmental parameters that typically provide neutral temperature sensitivity. Due to individual differences, it is impossible to establish a thermal state of the environment that would satisfy everyone. There will always be a percentage of dissatisfied people. But you can set up environments that are acceptable to a certain percentage of people.

1. At the design stage, the verification of microclimate parameters can be carried out on the indices of thermal comfort, determining the category of the internal environment at the stage of input data according to the following recommendations (Table 1).

The choice of category is a feature of the building and the needs of special groups of residents, such as the elderly (low metabolism and impaired body temperature control).

Table 1

Recommended description of the categories of premises

Requirements for the thermal environment of the premises	**Category**
High expectations recommended for rooms occupied by people with special needs, such as the disabled, the sick, young children and the elderly	A
Normal expectations should be used for new buildings and renovations	B
The allowable average level of expectations can be used for existing buildings	C
Values outside the criteria of the above categories. This category should be accepted for a limited period of the year	D

2. After determining the category of the thermal environment of the premises it is necessary to determine the characteristics of the categories of the thermal environment in accordance with Table. 2 (DSTU B EN ISO 7730: 2011). All criteria must be met simultaneously for each category.

Each category assigns the maximum percentage of dissatisfied for the body as a whole PPD and PD for each of the four types of local discomfort. The three categories presented in Table 1 apply to rooms where there are people who are exposed to the same thermal environment.

3. The next step is to determine the characteristics of clothing for the season (winter/summer). Clothing modification can also help reduce individual differences in environmental assessment. The influence of the optimal equivalent temperature on the addition or removal of various items of clothing is given in table C.2 DSTU B EN ISO 7730: 2011, and its fragment – Table 3.

Table 2

Characteristics of thermal environment categories

Categories	Temperature sensations of the body as a whole		Local discomfort			
	PPD, %	PMV	DR, %	PD, % conditioned		
				the difference in air temperature vertically	warm or cold floor	asymmetry of radiative thermal radiation
A	< 6	-0,2 < PMV < +0,2	< 10	< 3	< 10	< 5
B	< 10	-0,5 < PMV < +0,5	< 20	< 5	< 10	< 5
C	< 15	-0,7 < PMV < +0,7	< 30	< 10	< 15	<10

Table 3

Thermal resistance of typical clothing combinations

Clothes	I_{cl}	
	clo	m^2K/W
Pants, overalls, socks, boots	0,70	0,110
Panties, shirt, suit, socks, shoes	0,80	0,125
Briefs, T-shirts, shorts, light socks, sandals	0,30	0,050
Briefs, short-sleeved shirt, light pants, light socks, boots	0,50	0,080

4. Determine the motor activity according to the purpose of the house for the selected category. Metabolic rate depends on physical activity and posture. It is recommended to determine them at the stage of initial data on the purpose of the main function room according to table B.1 of DSTU B EN ISO 7730: 2011, a fragment of which is given below.

Table 4

Metabolic rate

Motor activity, outside	Metabolic rate	
	W/m^2	met
Semi-recumbent	46	0,8
Sitting relaxed	58	1,0
Work (office, home, school, laboratory)	70	1,2

The algorithm for determining the calculated parameters of the thermal environment by categories of premises is shown in Figure 2.

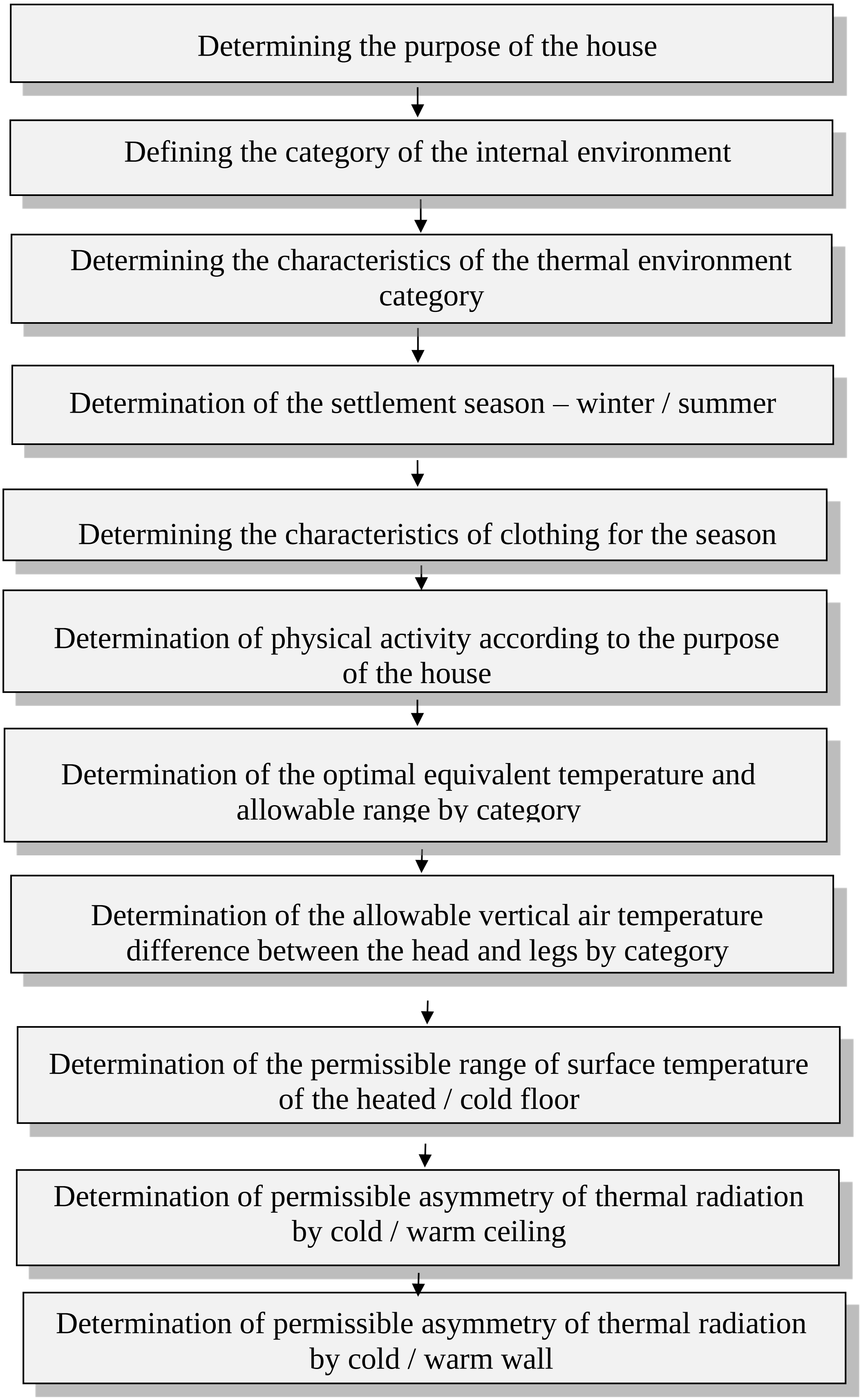


Fig. 2. Block diagram of the method of determining the parameters of the microclimate

3. Estimated parameters of thermal comfort for different categories of environments and types of space

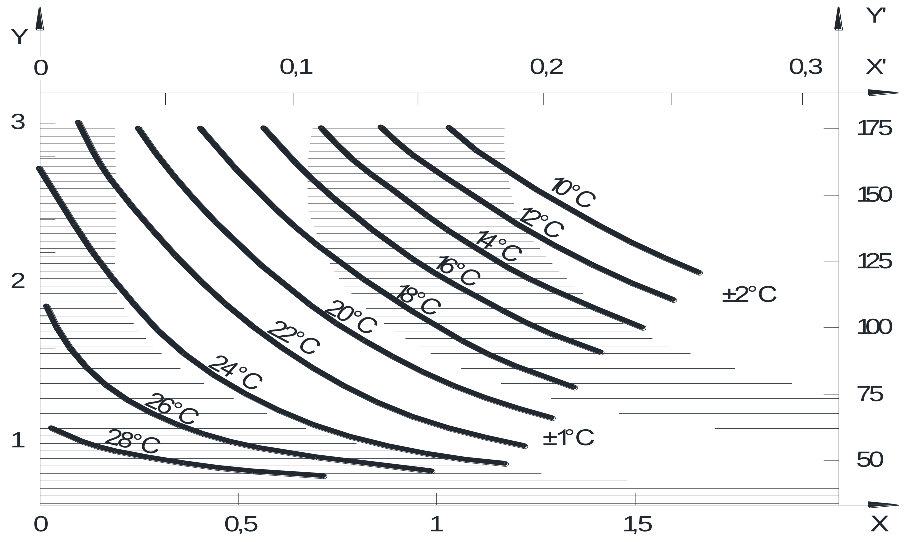
Determining the range of equivalent temperature

To determine the space, there is an optimal equivalent temperature, which corresponds to PMV = 0, depending on the activity and clothing of people. Figures 3 and 4 show the optimal equivalent temperature and allowable temperature range as a function of clothing and activity for each of the three categories.

Equivalent temperature is a uniform temperature of an imaginary enclosed space in which a person loses the same amount of heat by radiation and convection as in a real environment (with uneven temperature).

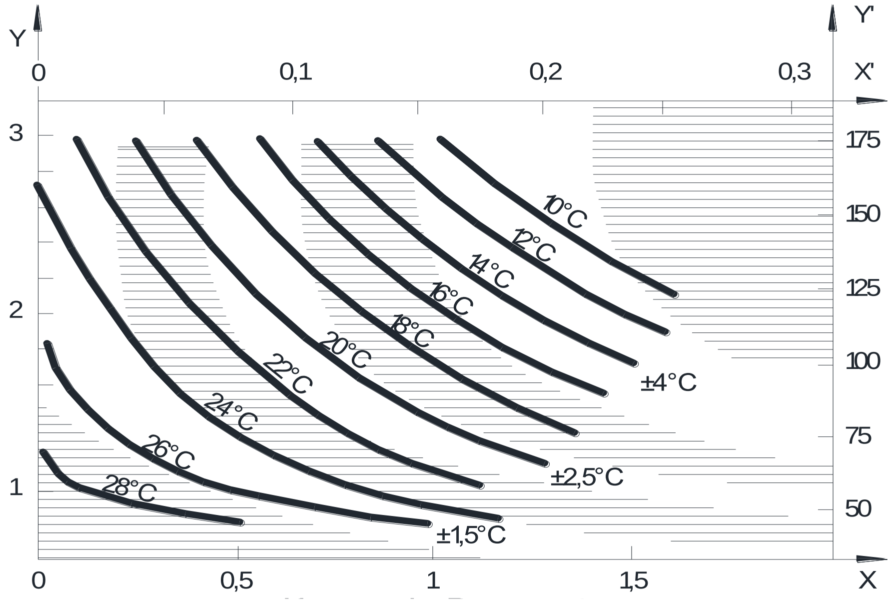
The optimum equivalent temperature is the same for the three categories, while the allowable range around the optimum temperature varies.

Figures 3 and 4 refer to a relative humidity of 50%; however, in temperate thermal environments, humidity has little effect on temperature sensitivity. Diagram of the optimal equivalent temperature depending on clothing and physical activity for the three categories.

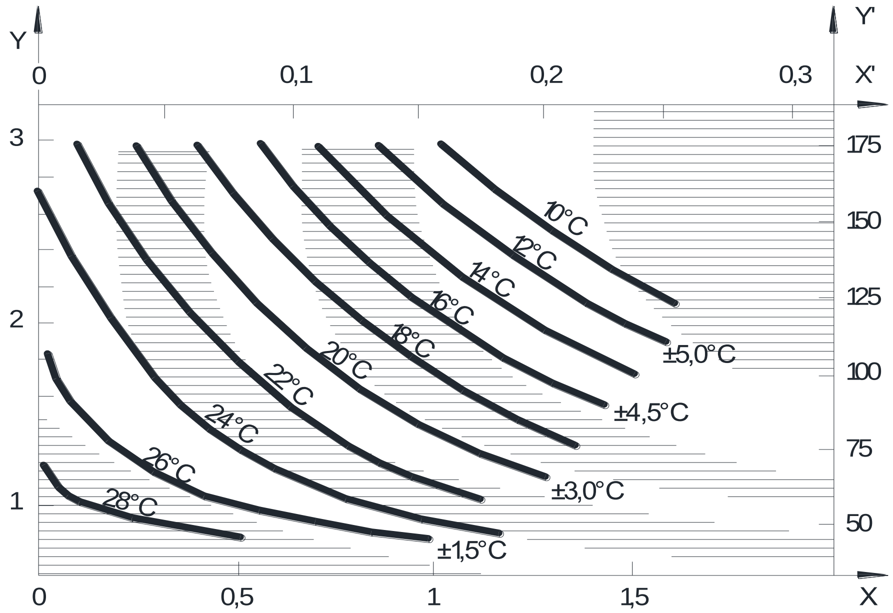


Category A: PPD < 6%

Fig. 3. Optimal temperature as a function of clothing and activity – category A



Category B: PPD < 10%



Category C: PPD < 15%

Fig. 4. Optimal temperature as a function of clothing and activity – category V and S.

Notation: PPD – projected percentage of dissatisfied;

X – the main insulation of clothing, clo;

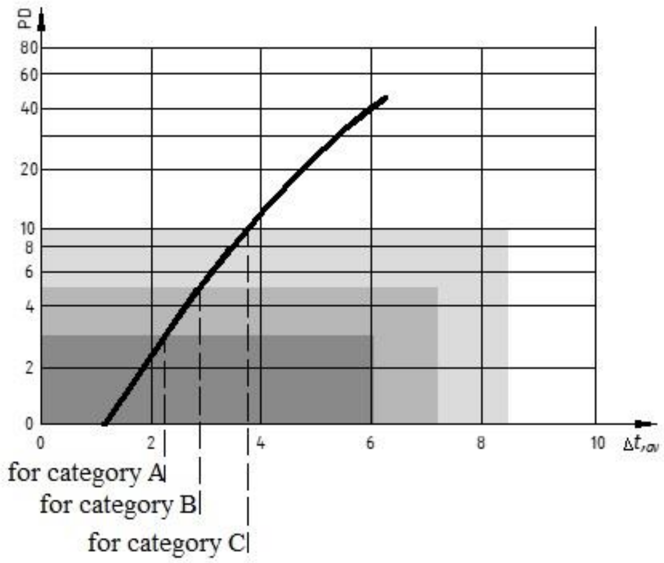
X^I – basic clothing insulation, $m^2 \cdot °C / W$;

Y – metabolic rate, met;

Y^I – metabolic rate, W / m^2.

Determining the allowable difference in vertical air temperature by the percentage of dissatisfied.

A significant difference in air temperature vertically between the head and ankles can cause discomfort. Figure 5 shows the percentage of dissatisfied PD as a function of the difference in air temperature in the head and legs. The figure is used when the temperature is higher from above. For people, the lower temperature is less noticeable.



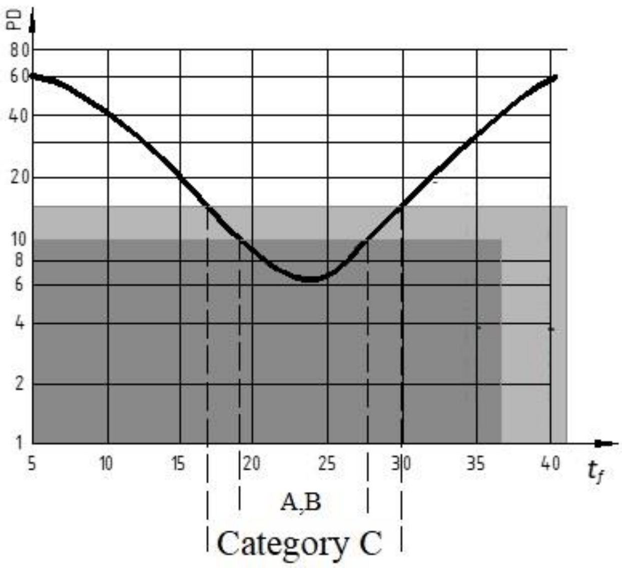
Category A: PD < 3%; Category B: PD < 5%; Category C: PD < 10%

Fig. 5. Proposed areas for determining the allowable vertical temperature difference by the percentage of dissatisfied

Notation: PD – the percentage of dissatisfied;
$\Delta t_{a,v}$ – the difference in air temperature vertically between the head and legs, °C.

Determining the allowable range of floor surface temperatures by the percentage of dissatisfied.

If the floor is too warm or too cold, people feel discomfort due to the thermal sensations of their feet. For people wearing light (home) shoes, comfort is first and foremost the floor temperature, not the floor covering material. Figure 6 shows the percentage of dissatisfied as a function of floor temperature for people sitting, standing or lying on the floor.



Category A: PD < 10%; Category B: PD < 10%; Category C: PD < 5%

Fig. 6. Proposed areas for determining the allowable range of floor surface temperature by the percentage of dissatisfied

Notation: PD – the percentage of dissatisfied;
t_f – floor temperature,°C.

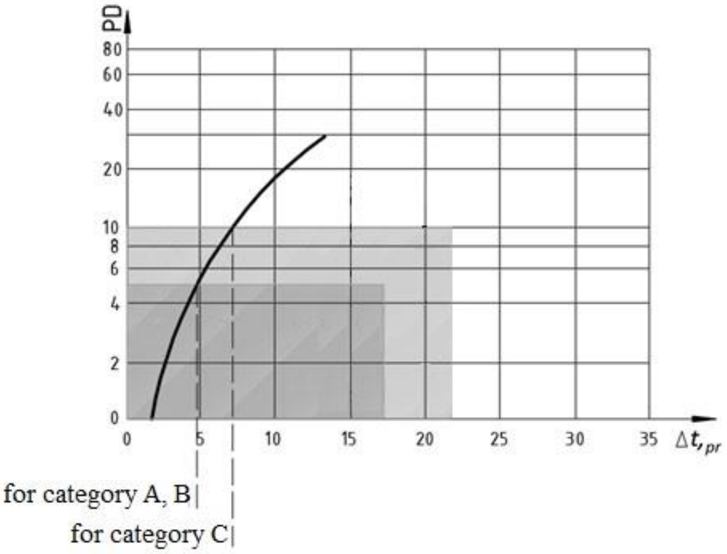
The results do not apply to electric underfloor heating during a long stay on the floor. For floor surfaces where people walk barefoot, see ISO / TS 13732-2.

Determination of the permissible range of asymmetry of radiation radiation

Asymmetry of radiation Δt_{pr} can also cause discomfort. People are most sensitive to temperature asymmetry due to warm or cold ceilings, walls (windows). Figures 7-10 show the percentage of dissatisfied as a function of radiation asymmetry due to a warm ceiling, a cool wall, a cool ceiling, and a warm wall. Figures 7-10 refer to the estimation of radiation asymmetry from side to side (left / right or right / left); other body positions relative to the surface (eg, front / back) do not increase discomfort.

Figures 7-8 show the allowable range of asymmetry of radiation radiation from cold and warm ceilings by the percentage of dissatisfied, which is determined by the selected category of indoor environment.

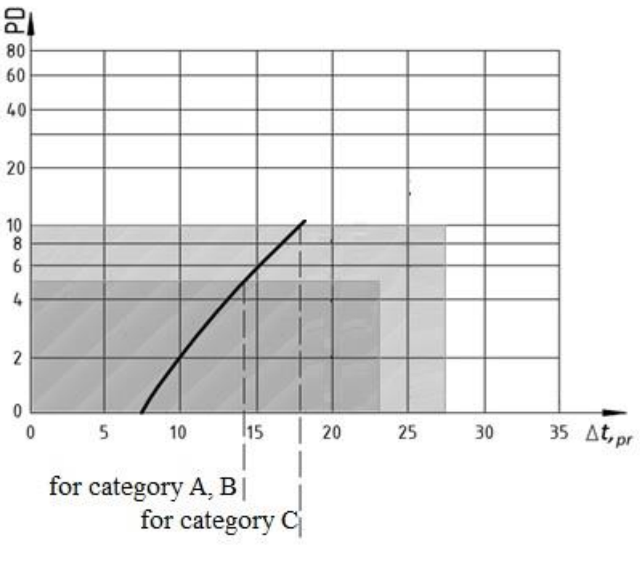
Figures 9-10 show the allowable range of asymmetry of radiation of cold and warm walls by the percentage of dissatisfied, which is determined by the selected category of indoor environment.



Category A: PD < 5%; Category B: PD < 5%; Category C: PD < 10%

Fig. 7. Proposed areas for determining the allowable range of asymmetry of radiation from a warm ceiling

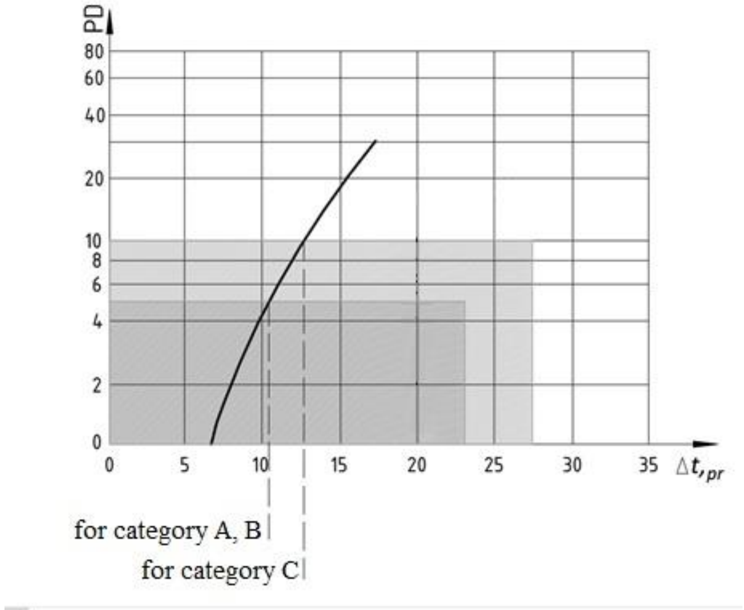
Notation: PD – the percentage of dissatisfied;
Δt_{pr} – asymmetry of thermal radiation,°C;



Category A: PD < 5%; Category B: PD < 5%; Category C: PD < 10%

Fig. 8. Graph to determine the allowable range of asymmetry of radiation from the cold ceiling

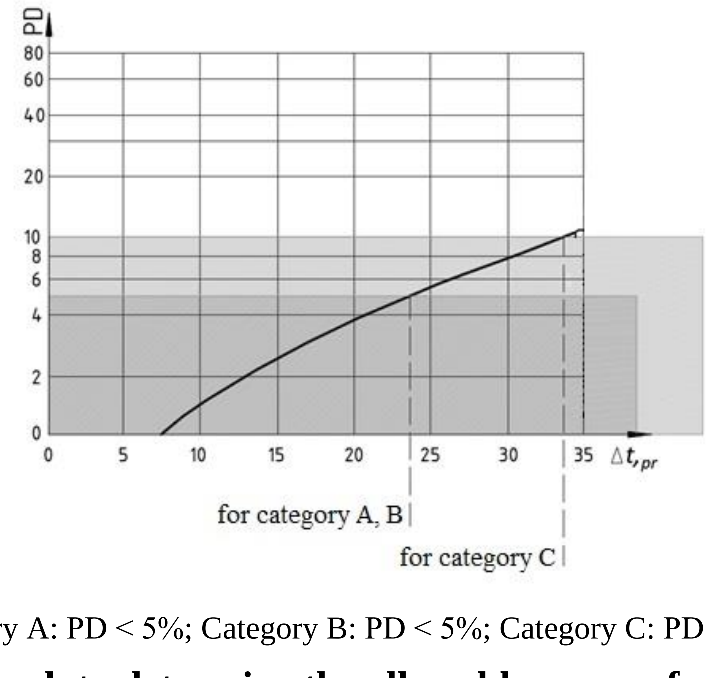
Notation: PD – the percentage of dissatisfied;
Δt_{pr} – asymmetry of thermal radiation,°C;



Category A: PD < 5%; Category B: PD < 5%; Category C: PD < 10%

Fig. 9. Graph to determine the allowable range of asymmetry of cold wall radiation

Notation: PD – the percentage of dissatisfied;
Δt_{pr} – asymmetry of thermal radiation,°C;



Category A: PD < 5%; Category B: PD < 5%; Category C: PD < 10%

Fig. 10. Graph to determine the allowable range of asymmetry of radiation by a warm wall

Notation: PD – the percentage of dissatisfied;
Δt_{pr} – asymmetry of thermal radiation, ° C;

Often one person is more sensitive to different types of local discomfort. For example, a person sensitive to drafts may also be sensitive to local cooling caused by asymmetry of radiation or cold floors. Such a cold-sensitive person may experience discomfort for the body as a whole. Therefore, PPDs, DRs, or PDs calculated for different types of local discomfort cannot be combined (added / added).

4. Examples of determining the calculated parameters of the microclimate

The object is a hospital, summer period of operation.

Determine the category of the internal environment according to Table 1 – A.

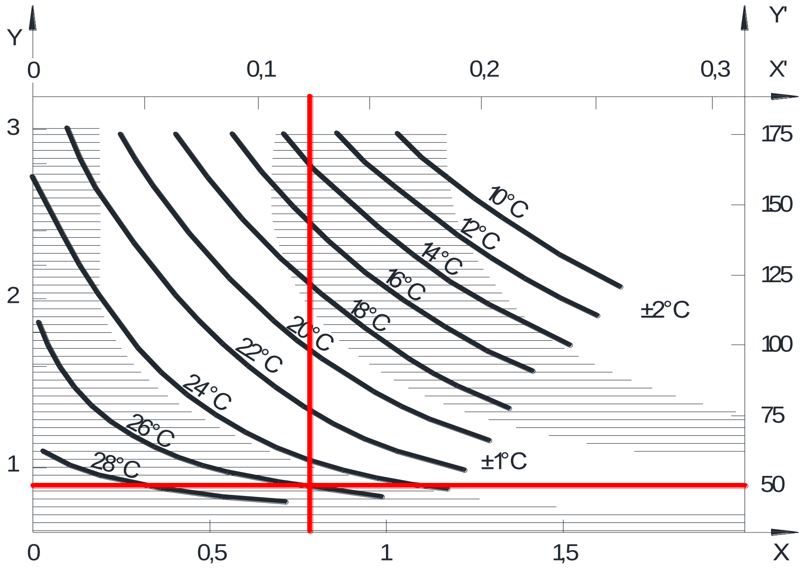
Determine the characteristics of the categories of thermal environment in accordance with table 2 for category A:

PPD, %	< 6
PMV	-0,2 < PMV < +0,2
PD, %, conditioned:	
the difference in air temperature vertically	< 3
warm or cold floor	< 10
asymmetry of radiative thermal radiation	< 5

Determine the characteristics of clothing for the season (summer) according to Table C.2 DSTU B EN ISO 7730: 2011 – 0.7 clo (0,110 $м^2$K/W).

Determine the mobile activity according to the purpose of the house for the selected category A according to table B.1 DSTU B EN ISO 7730: 2011– 46 W / m^2 (0.8 met).

Determine the optimal temperature as a function of clothing and activity for category A on the Figure 3 – 26°C.



Category A : PPD < 6%

Fig. 11. Scheme for determining the optimal temperature

Determine the allowable difference in air temperature vertically by the percentage of dissatisfied in Figure 5 – 2.1°C.

Determine the allowable range of floor surface temperatures according to the percentage of dissatisfied – according to the Figure 6 – 19 – 25°C.

Determine the allowable range of asymmetry of radiation radiation from a warm ceiling on a Figure 7 – 5°C.

Determine the allowable range of asymmetry of radiation radiation by a warm wall on a Figure 10 – 23°C.

As the load of each building changes in space and time, the designed systems may not meet the design intentions in all rooms at all times. Therefore, there is a need to assess the long-term characteristics of the building in relation to the internal environment. This assessment is mandatory to reflect the microclimate (internal environment) in the energy certificate.

Assessment of the internal environment of the building is performed by assessing the environment of typical rooms representing different areas of the building. The assessment may be based on a design, calculations, measurements or survey.

Design criteria for different types of space. Examples

The design criteria listed in Table 5 are derived for the following conditions. Criteria for equivalent temperature are based on typical levels of activity, clothing with an index of 0.5 clo during the summer («warm season») and with an indicator – 1.0 clo in the winter («cold, heating season») . Criteria for the average air velocity assume a turbulence intensity of approximately 40% (mixed ventilation).

Table 5

Examples of design criteria for premises in different types of buildings

Types of buildings / spaces	Activity, W / m^2	Categories	Equivalent temperature,°C		Amplitude of fluctuations of equivalent temperature,°C	
			Summer (warm season)	Winter (cold season)	Summer (warm season)	Winter (cold season)
Open space Premises with partitions Concert hall Audience Cafe Class	70	A	24,5	22,0	±1,0	±1,0
		B	24,5	22,0	±1,5	±2,0
		C	24,5	22,0	±2,5	±3,0
Kindergarten	81	A	23,5	20,0	±1,0	±1,0
		B	23,5	22,0	±2,0	±2,5
		C	23,5	22,0	±2,5	±3,5
Department store	93	A	23,0	19,0	±1,0	±1,5
		B	23,0	19,0	±2,0	±3,0
		C	23,0	19,0	±3,0	±4,0

The given design criteria are also valid for other types of spaces with similar parameters.

CONCLUSIONS

A non-complex approach to thermal modernization of public buildings leads to a deterioration of the microclimate of the premises. Aspects of certification of the thermal environment of premises, which is based on indices of thermal comfort, are investigated. The need to include in the energy certificate of the building information about the internal environment of the building as one of the parameters for assessing its overall energy efficiency.

Information about the internal environment of the building should be included in the energy certificate of the building to assess the general characteristics of the building.

When designing the thermal performance of the elements of the thermal insulation of the house according to DBN V.2.6-31: 2016 it is necessary to use methods to predict the overall thermal sensation and the degree of discomfort (thermal dissatisfaction) of people exposed to moderate thermal environments.

A method for determining the calculated parameters of the microclimate according to the criteria of local thermal comfort has been developed, which allows to design rooms with high air quality according to the categories.

Analytical determination and interpretation of thermal comfort using PMV (predicted average air quality assessment) and PPD (projected percentage of dissatisfied with ambient temperature), as well as local thermal comfort criteria helps to assess the acceptability of environmental conditions for human thermal comfort.

SUMMARY

In the domestic methods when assessing the overall energy efficiency of buildings does not pay attention to the comfort of the premises. Underestimation of requirements to thermal characteristics of designs is allowed. A non-complex approach to thermal modernization of public buildings leads to a deterioration of the microclimate of the premises. In Ukraine, normative documents on ergonomics of the thermal environment (DSTU B EN ISO 7730: 2011, DSTU B EN 15251: 2011, etc.) have been introduced, but they are not harmonized with current methods and are practically not used in thermal calculations. Aspects of certification of the thermal environment of premises, which is based on indices of thermal comfort, as one of the parameters for assessing the overall energy efficiency of the building be explored. A method for determining the calculated parameters of the microclimate according to the criteria of local thermal comfort has been developed, which allows to design rooms with high air quality according to the categories. Analytical determination and interpretation of thermal comfort using PMV (predicted average air quality assessment) and PPD (projected percentage of dissatisfied with ambient temperature), as well as local thermal comfort criteria helps to assess the acceptability of environmental conditions for human thermal comfort.

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Information about the authors:
Semko Oleksandr Volodymyrovych,
Doctor of Technical Sciences,
Head ot the Department of Construction and Civil Engineering
National University «Yuri Kondratyuk Poltava Polytechnic»
24, Pershotravnevyj ave., Poltava, 36011, Ukraine

Filonenko Olena Ivanivna,
Doctor of Technical Sciences,
Professor at the Department of Construction and Civil Engineering
National University «Yuri Kondratyuk Poltava Polytechnic»
24, Pershotravnevyj ave., Poltava, 36011, Ukraine

Yurin Oleg Ivanovych,
Candidate of Technical Sciences,
Associate Professor at the Department of Construction and Civil Engineering
National University «Yuri Kondratyuk Poltava Polytechnic»
24, Pershotravnevyj ave., Poltava, 36011, Ukraine

Mahas Nataliia Mykolaivna,
Candidate of Technical Sciences,
Associate Professor at the Department of Construction and Civil Engineering
National University «Yuri Kondratyuk Poltava Polytechnic»
24, Pershotravnevyj ave., Poltava, 36011, Ukraine

Norka Anastasiia Ruslanivna,
Student at the Scientific and Research Institute of Architecture, Construction and Land Management
National University «Yuri Kondratyuk Poltava Polytechnic»
24, Pershotravnevyj ave., Poltava, 36011, Ukraine