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Field study of thermal comfort in dwelling during the winter, mid-season and summer

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Abstract. This research focused on adaptive thermal comfort in dwelling in the cold winter and hot summer climate zone of Russia. A field study was conducted throughout the three seasons (winter, mid-season and summer) beginning in September 2019 and ending in June 2020 in Volgograd (48°43.164′N, 44°30.108′E), Russia. The survey included simultaneous measurements of outdoor and indoor environmental parameters and an assessment of the participants' sensations using questionnaires. The living room and bedroom of an apartment building for a family with a child were chosen as the research environment for indoor physical parameters and for administering the questionnaires. Only free-running thermal environments were considered in this research. The sensation ratings were analyzed, and thermal comfort temperature was calculated using regression methods. Results showed that in winter there were deviations in the thermal sensation, satisfaction, expectation of residents, and that they preferred a neutral cold environment. There were differences between the mid-season results and those of winter and summer. The thermal comfort assessment in premises under continental climate conditions should be based on thermal adaptation models. We calculated that the acceptable temperature range for residents in winter was 17.5–22.5 °C, 20–25 °C (with acceptable deviation of 2.5 °C) in mid-season and 22.5–27.5 °C in summer. The actual indoor relative humidity was almost within the applicable ranges (30–60 %) as well. The ASHRAE55-2013 and EN15251-2007 adaptive thermal comfort models are suitable for premises in mid-season and summer. The predictions of both mid-season and summer models were reliable. The main solutions to improve the indoor temperature conditions include heat flux control in heaters within the apartment in accordance with the adaptation thermal comfort model, as well as control of natural ventilation in winter. In this case it is predicted, that the reduction of total heating load is 24.2 %. Indoor thermal neutral temperature at the small energy demand in premises can be obtained by implementing the smart home concept. These results can be used to assess indoor thermal comfort in dwelling and help create friendly and energy efficiency building environments in Russia.

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1. Introduction

Indoor thermal environments significantly influence human health and comfort, since most of the time people are indoors [1]. Thermal comfort and adaptation are considered important issues in the interior design of buildings [2]. Also, energy consumption is required to ensure comfortable indoor conditions [3–5]. Therefore, the main task of designers is to obtain the comfortable conditions in the premises using minimum energy consumption [6, 7].

The first human comfort model was developed by Fanger in 1967. Fanger used the seven-point form of a thermal sensation scale along with numerous experiments involving human subjects in various environments [8, 9]. He related the subject's response to various variables which influence the condition of thermal comfort. This mathematical model is probably the most well-known and is the easiest to use because it has been put in both chart and graph form.

Bogoslovsky developed the original theory of thermal comfort in the premises and proposed two conditions of comfort, as shown in paper [10].

Later, the Pierce Model was developed at the John B. Pierce Foundation [11]. This model considers the human body as two isothermal, concentric compartments, one representing the internal section or core and the other representing the skin. This allows the passive heat conduction from the core compartment to the skin to be taken into account.

The LSTM model is quite similar to that of the Pierce Foundation. The main difference between the two models is that the LSTM model predicts thermal sensation differently for warm and cold environment [12].

Tabunshchikov developed the theory of buildings as single energy systems [13]. Currently, some adaptive thermal comfort models have been included in ASHRAE 55-2013 and EN 15251-2007 standards.

The paper [14] provides a comparison of the country's requirements for building energy efficiency and how the application of different standards in combination with ventilation alternatives in each analyzed city affects annual energy consumption in the Saint Petersburg region. IDA Indoor Climate and Energy (ICE) 4.7 dynamic simulation software was used to evaluate normative requirement effect on building energy consumption in different areas of the Baltic Sea region.

The research method [15] is based on a review of technical parameters; in well ventilated buildings all CO_2 sensors showed similar results and the difference between sensors located in different zones was minimal.

The paper [16] analyses typology of Latvian fire stations and their energy consumption. Standardized IFC model was developed to evaluate effect of implementation of energy efficiency measures in a selected building.

The focus of the paper [17] is to develop a verified simulation model for a cooling panel with integrated phase-change materials (PCMs).

The PMV measurements in a temporary shelter showed that the thermal comfort is very low as the PMV values were outside the range of –1 to +1 for 57 % of the time [18].

Many researches have been exploring ways to predict the thermal sensation of people in their environment based on the personal, environmental and physiological variables that influence thermal comfort [19–22]. From the research done, some mathematical models that simulate occupants thermal response to their environment have been developed.

Adaptive comfort theory considers that the optimal indoor operative temperature for occupants who can interact with the building and its devices relates primarily to the outdoor environmental conditions, and the application conditions differ among building types and outdoor temperatures [23]. For buildings located in a tropical climate, several field studies have estimated the thermal comfort and adaptability using adaptation theory. The studies usually report the thermal adaptability, adaptive thermal comfort model, and deviations between proposed models with reference cases [24]. In recent years, researchers have conducted extensive field studies in different climatic regions (mainly in cold and warm environments), but most of them focused on residential [25, 26], office [27], educational buildings [28], churches [29, 30], long-distance trains [31], etc.

It is important to note that the actual data illustrating occupants' adaptability to thermal environment in the premises during the winter (heating), mid-season and summer are not detailed in the scientific literature.

The research objectives were as follows:

1. To investigate the thermal environment and comfort of premises based on the field tests.
2. To determine the neutral, comfort, and acceptable temperature ranges of premises in different seasons, using different adaptive comfort models.
3. To conduct a comparative analysis of this models.

2. Methods

The field study included simultaneous instrumentation measurements of indoor environment parameters (air temperature, relative humidity), including analyses of outdoor environment parameters, and the assessment of the thermal comfort conditions in the rooms of the apartment building (Fig. 1).

a.


b.


Figure 1. Location of the study object: master plan (a) and Google photography (b) (Volgograd, Russia).

The field study began in September 2019 and ended in June 2020. Data were collected in winter, summer, and mid-season (spring and autumn). Winter (heating) included a season with average daily outdoor air temperatures less or equal to 8 °C, summer was June through August, mid-season was autumn (from September to the start of the heating season) and spring (from the completion of the heating season to May).

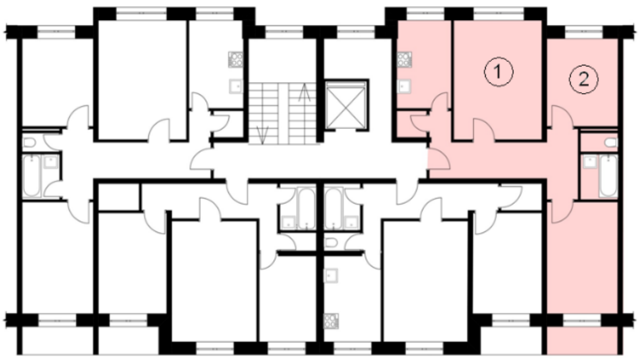
2.1. Climatic conditions

Volgograd (48°43.164′N, 44°30.108′E) experiences a continental climate. Volgograd is in the cold winter and hot summer zone of the Russian building-climate zone. It is one of the hottest summer cities in Russia. The average air temperature in February ranges from –21.9 to 1.3 °C; in July it ranges from 19.8 to 28.9 °C. The average annual temperature is 8.8 °C. The amount of precipitation is 267 mm. The total average annual cloudiness is 6.1 points. The average annual wind speed is 5.0 m/s. The average annual relative humidity is 70 %. The average temperature of the heating season is –2.2 °C; its duration is 177 days.

The outdoor meteorological data were collected from the Russian Meteorological Data Center, including the hourly values of outdoor air temperature. These data were used in the adaptive comfort models.

2.2. Surveyed building

The living room (1) and bedroom (2) (Fig. 2, a) of an apartment building for a family with a child were chosen as the research environment for indoor physical parameters and for administering the questionnaires.



a

b

Figure 2. Plan of the block-section (a) and instrumentation (b) (1 – head unit, 2 – air temperature sensors, 3 – relative humidity sensors, 4 – window/door opening sensors).

An assessment of the field conditions revealed that the rooms had air conditioners (AC), but most residents did not use them. Therefore, only free-running thermal environments were considered in this research. The main characteristics of the subject of inquiry are given in Table 1.

Table 1. Characteristics of the subject of inquiry.

Name	Characteristic	Name	Characteristic
Type	Apartment building	R-value	1.21 $m^2\ K{\cdot}W^{-1}$ (wall)
			0.56 $m^2\ K{\cdot}W^{-1}$ (window)
Configuration	Rectangular	Internal heat gains	80 W (person)
			20 W (electric devices)
Number of block sections	4	Air exchange rate in winter	$1.6{\cdot}h^{-1}$ (window is open)
			$1.1{\cdot}h^{-1}$ (window is closed)
Number of storeys	9	Natural ventilation	Yes
Basement	Yes	Smart sensors	Yes
Attic	Yes	District heating	Yes

Note: The walls are made of prefabricated reinforced concrete panels (PRCP), windows are made of single-chamber double-glazed units, the average air flow rate in winter as well as the heat gain are given according to expert assessment.

Instruments listed in Table 2 were utilized to measure indoor air temperature, relative humidity (RH), and windows opening monitoring (see Fig. 2, b).

Table 2. Instrumentation measurement range and accuracy.

Parameter	Instrumentation	Accuracy	Accuracy requirements in GOST 30494–2011 (National Standard)
Air temperature	AT sensor	±0.3 °C, range: –20…60 °C	Minimum: ±0.5 °C, ideal: ±0.1 °C
Relative humidity	RH sensor	±3.0 % RH, range: 0…99 %	±5.0 % RH
Air exchange	Window/door opening (WDO) sensor	Qualities analysis only	No requirements

Note: The data specified in the table are given in: https://osensorax.ru/klimat/datchik-temperatury-i-vlazhnosti-xiaomi.

The evaluation process of the indoor thermal environment was based on the ASHRAE 55-2013 and EN 15251-2007 standards. The main radiant temperature (MRT) was determined according to the method specified in Interstate Standard GOST 30494–2011, using the surface temperature of building components. In this case, the standard MRT can be calculated approximately using the equation summed over all zone surfaces [9]. Then the operative temperature was derived from the air temperature and mean radiant temperature. The obtained values of operative temperature were used in evaluation of thermal comfort in rooms.

2.3. Determining the indoor thermal comfort zone in the living room

At present, the main standards for determining the indoor thermal comfort zone of a free-running environment when using the thermal adaptation model are the ASHRAE 55-2013 and European Standard (EN 15251-2007). The estimate of indoor thermal comfort zone in the room using these standards is below.

The model of ASHRAE 55-2013 defines two comfort zones: 80 % acceptability, and 90 % acceptability. If the prevailing mean outdoor temperature is not within the specified domain of 10.0 °C to 33.5 °C, the model is not applicable.

The model of EN 15251-2007 also accounts for people's clothing adaptation in naturally conditioned spaces by relating the acceptable range of indoor temperatures to the outdoor climate, so it is not necessary to estimate the clothing values for the space. No humidity or air-speed limits are required when this option is used. The model defines three comfort zones: category I (90% acceptability), category II (80 % acceptability), category III (65 % acceptability). If the prevailing mean outdoor temperature is not within the specified domain of 10.0 °C to 30.0 °C, the model is not applicable.

The comfort zone boundaries in this model can be calculated by following formulas (see Table 3).

Table 3. Indoor temperature conditions for the thermal adaptation models according to Standard ASHRAE 55-2013 and Standard EN 15251-2007.

ASHRAE 55-2013		EN 15251-2007	
Category	Formula	Category	Formula
Comfort temperature	T_{ot} = 0.31T_o + 17.8	Comfort temperature	T_{ot} = 0.33T_o + 18.8
90% acceptability limit	T_{ot} = 0.31T_o + 17.8 ± 2.5	I – 90 % acceptability limit	T_{ot} = 0.33T_o + 18.8 ± 2.0
80% acceptability limit	T_{ot} = 0.31T_o + 17.8 ± 3.5	II – 80 % acceptability limit	T_{ot} = 0.33T_o + 18.8 ± 3.0
		III – 65 % acceptability limit	T_{ot} = 0.33T_o + 18.8 ± 4.0

Note: T_{ot} is the operative temperature (°C), calculated as the average of the indoor air dry-bulb temperature and the mean radiant temperature of zone inside surface; T_o is the prevailing mean outdoor air dry-bulb temperature (°C).

The explanations of categories for European Standard EN 15251-2007 are listed in Table 4.

Table 4. Categories for European Standard EN 15251-2007.

Category	Explanation
I	High level of expectation recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation, should be used for new buildings and renovations
III	An acceptable, moderate level of expectation, may be used for existing buildings
(IV)	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

In Russia basic requirements for the thermal protection of enclosing structures and optimal/permissible air parameters of living rooms are defined by Interstate Standard (GOST 30494-2011) “Residential and public buildings: Microclimate parameters for indoor enclosures” (Table 5).

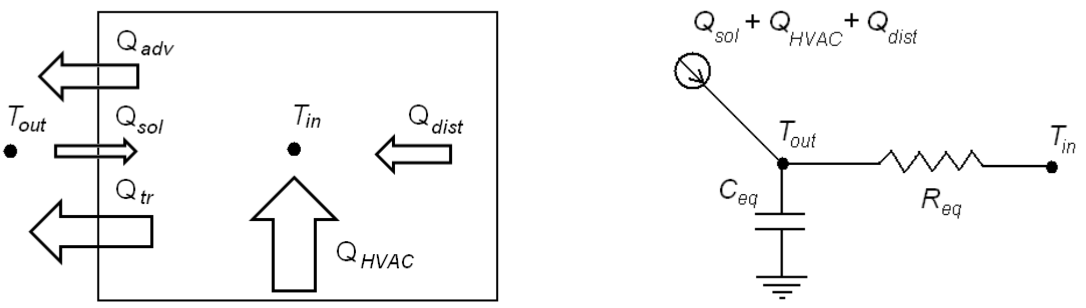
Table 5. Optimal and acceptable air parameters of living room according to Interstate Standard (GOST 30494-2011).

Time of the year	Air parameters (optimal/acceptable)			
	Temperature T_i, °C	Operative temperature T_{ot}, °C	RH, %	Speed v_i, m·s^{-1}
Cold period	20–22	19–20	30–45	0.15
	18–24	17–23	60	0.2
Non-cold period	22–25	22–24	30–60	0.2
	20–28	18–27	65	0.3

In addition to the above, a questionnaire was offered to the residents. The questionnaire was compiled through an interview. The questionnaire included the following options: thermal sensation (range from cold to hot), preference (should be cooler or warmer), and acceptability (acceptable or unacceptable).

2.4. Heating consumption

Simple models can be used to determine the heat flow rate for a room during the heating period, as shown in Fig. 3*a*. By reducing the circuit to the simplest possible dynamic process, 1R1C model is built (Fig. 3*b*).



a b

Figure 3. Thermal system for the room (a) and 1R1C electrical circuit (b) with two nodes of air temperatures (indoor T_{in} and outdoor T_{out}).

The model uses the available input and output data [32]. The equivalent thermal resistance R_{eq} of building components (wall and window) can be calculated like the electrical circuit taking into account the transmission $\left(Q_{tr}\right)$ and advection $\left(Q_{adv}\right)$ heat loss (through infiltration and ventilation). Similarly, the global equivalent thermal capacitance C_{eq} represents the building components of the total equivalent thermal mass, demonstrated the dynamic ability of the system to accumulate heat $\left(Q_{st}\right)$. It is important to note that this thermal capacitance is not the air capacitance, but it reflects the behavior of the building, including building components and air. Other heat sources such as solar heat gains through window $\left(Q_{sol}\right)$, heating load $\left(Q_{HVAC}\right)$, and internal heat gains from electric devises $\left(Q_{dist}\right)$ can be accounted for in the model.

The state equation based on energy conservation is as follows:

$$\left(Q_{tr}+Q_{adv}\right)+Q_{HVAC}+Q_{dist}+Q_{sol}-Q_{st}=0. \tag{1}$$

Taking a global equivalent thermal resistance between indoor and outdoor air, and a global capacitance which stores and releases the heat from/to the air and the building components, Eq. (1) can be transformed to the following:

$$R_{eq}^{-1}\left(T_{in}-T_{out}\right)+Q_{HVAC}+Q_{dist}+Q_{sol}-C_{eq}\frac{\partial T_{in}}{\partial t}=0. \tag{2}$$

In Eq. (2), we use the symbol (t) to indicate time.

It is expected that indoor air temperature varies slightly with time, so the thermal model (2) can be simplified $\left(Q_{st}=C_{eq}\frac{\partial T_{in}}{\partial t}=0\right)$.

The windows for all surveyed rooms occupied by the participants are oriented to north-eastern (see Fig. 1), which practically prevents the direct sunlight from entering the surveyed rooms during the heating season.

3. Results and Discussion

According to the results of the questionnaire, all residents noted a warm sensation in the heating season. At the same time, residents noted low air humidity. The main preference of residents was decrease in air temperature. Some residents noted unacceptable conditions. To improve temperature and humidity conditions, residents used frequent ventilation and humidification of air in rooms and other adaptation solutions.

3.1. Thermal and humidity parameters

The field test data in the representative room (living room) are presented in Fig. 4. The hourly indoor air temperature and relative humidity were obtained from the actual values. The hourly outdoor air temperature is calculated from a full annual weather file that must be specified for the simulation.

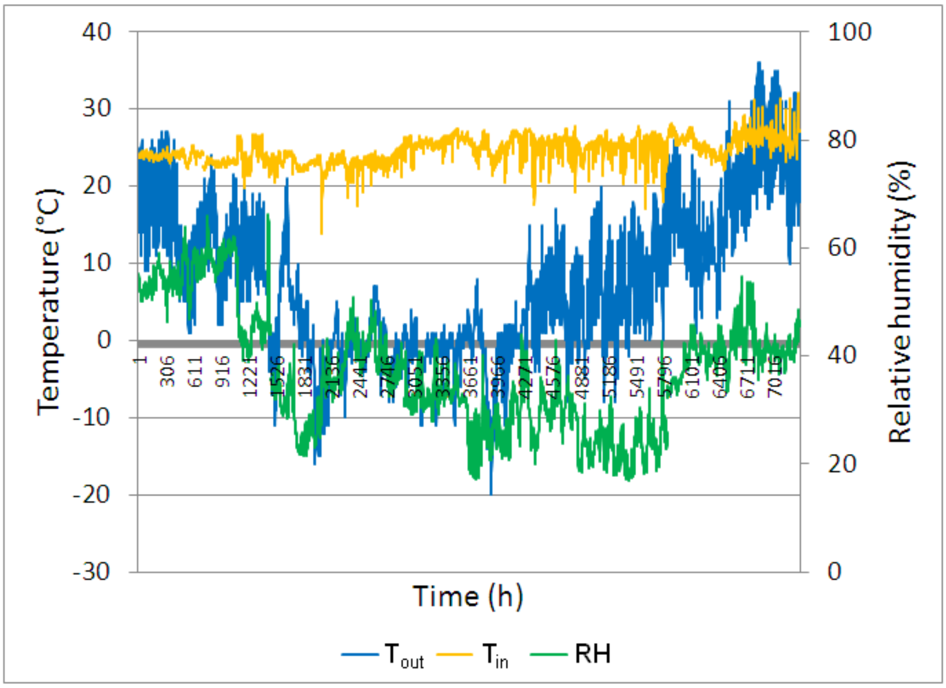


Figure 4. Outdoor, indoor air temperatures (left scale) and relative humidity (right scale) for the observed period (hourly values) in representative room.

The window opening status during the winter is 15.6 % (open) and 84.4 % (closed). Uniform ventilation of the room degrades its temperature and humidity parameters. The field test results are correlated with the questionnaire data. The peaks of temperature and relative air humidity (see Fig. 4) corresponded to the instances when the windows were open.

Overviews of the indoor and outdoor thermal environment parameters are given in Table 6. These thermal environment parameters clearly vary by season. The fluctuation of indoor air temperatures in all seasons of the year is relatively small. The fluctuation of outdoor air temperatures in winter is at the maximum. The fluctuation of indoor relative humidity in winter is the largest. The observed phenomenon is due to the residents periodically opening the windows.

Table 6. Indoor and outdoor average thermal physical parameters.

Season	Statistical information	Outdoor air temperature (°C)	Indoor air temperature (°C)	Relative humidity (%)
Winter	Minimum	–20.0	13.8	16.9
	Maximum	21.0	27.7	66.1
	Mean	1.3	24.5	30.7
	Standard deviation	13.7	1.9	17.6
Summer	Minimum	10.0	22.9	35.6
	Maximum	36.0	32.0	54.8
	Mean	24.0	26.5	42.7
	Standard deviation	11.7	2.4	5.5
Mid-season	Minimum	0.0	17.9	18.8
	Maximum	31.0	28.4	66.0
	Mean	13.7	24.4	46.7
	Standard deviation	5.5	1.6	10.2

In Table 6, the standard deviations of the observed characteristics were calculated by formula (3):

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}, \tag{3}$$

where n is the sample size, x_i is *i*-th fetch item, $\overline{x}$ is the arithmetic mean sample.

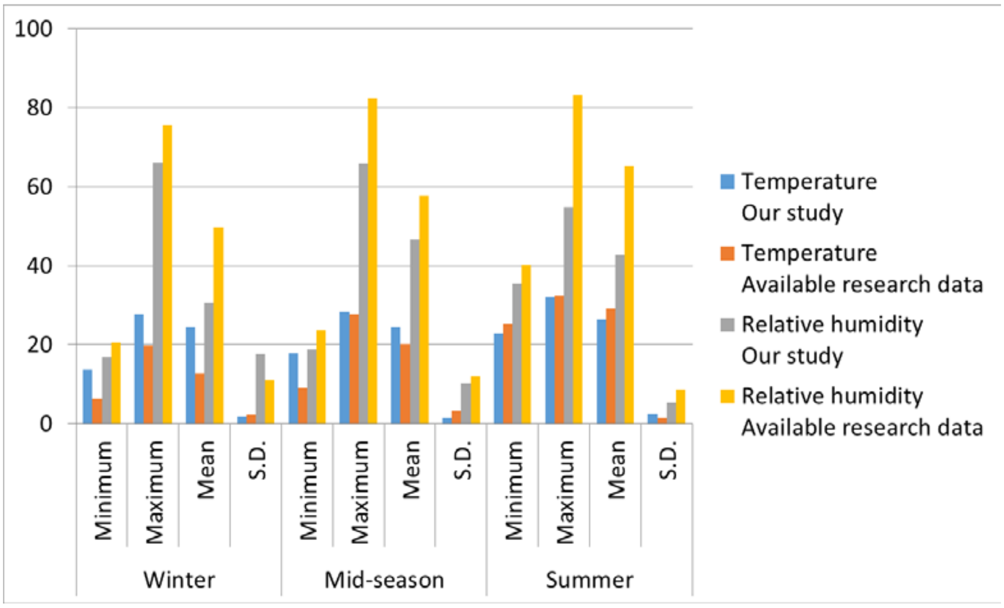


Figure 5. Comparison of the obtained field test data with the available research data [25].

Comparison of the obtained field test data with the available research data [25] demonstrated that our data are agrees well with those of other researchers in the mid-season (Fig. 5). However, our investigations showed that in winter and summer, there were deviations due to the features of the environment and buildings.

3.2. Indoor thermal and humidity conditions and heating load analysis

The indoor thermal conditions analyses when using ASHRAE 55-2013 and EN 15251-2007 standards are derived in Fig. 6 (actual results indicated as points). In order to increase accuracy, the analysis of the results was performed using the average daily values of meteorological parameters.

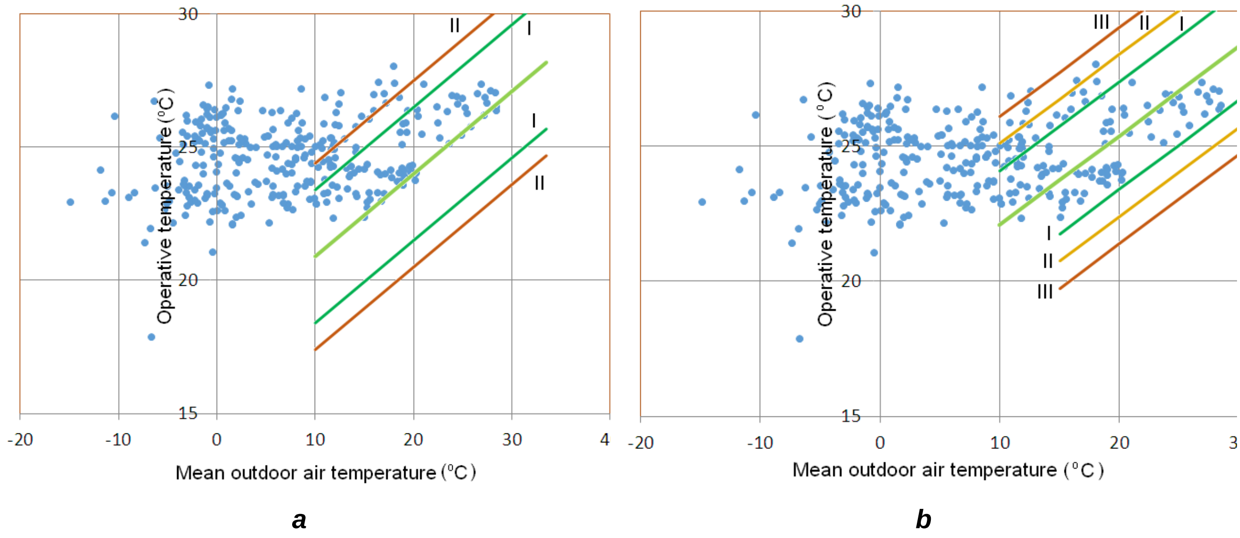


Figure 6. Thermal conditions analysis in representative room according to thermal adaptation models in ASHRAE 55-2013 (a) and EN 15251-2007 (b) standards.

As can be seen from these figures, the suitable outdoor temperature conditions for the thermal adaptation model ranged within 10–33.5 °C in ASHRAE 55-2013 and 10–30.0 °C in EN 15251-2007. In our study, the mean outdoor air temperature was within –15.2–8.0 °C in winter, 22.3–28.7 °C in summer, and 8.1–22.2 °C in mid-season. Therefore, in winter, 98.5 % of data points exceed the applicable range of the model for ASHRAE 55-2013, while 97.6 % exceed the applicable range of the model for EN 15251-2007. In the summer and mid-season, the actual indoor operative temperatures were almost within the applicable ranges for these models.

The actual indoor relative humidity was almost within the applicable ranges as well (Fig. 7).

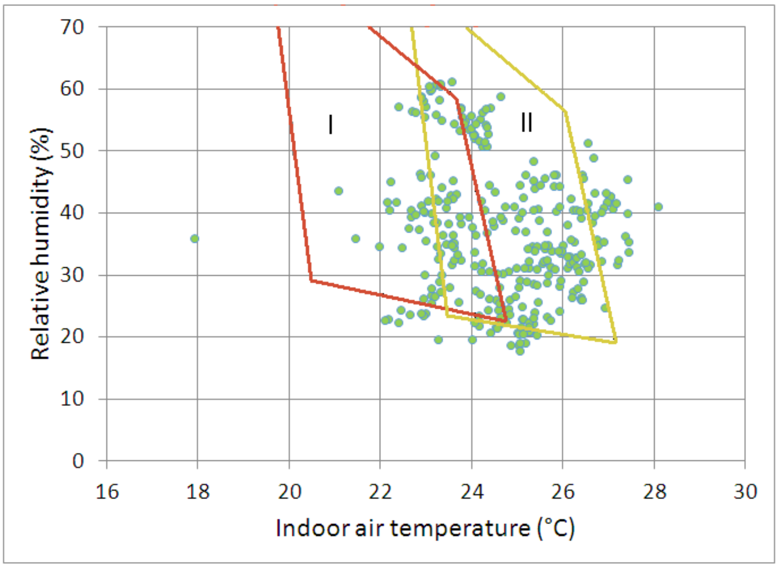


Figure 7. Humidity conditions analysis in representative room according to thermal adaptation model in ASHRAE 55 (I – winter, II – summer).

The indoor thermal and humidity conditions analysis when using International Standard (GOST 30494-2011) is demonstrated in Fig. 8 (actual results indicated as points, available ranges indicated as red lines).

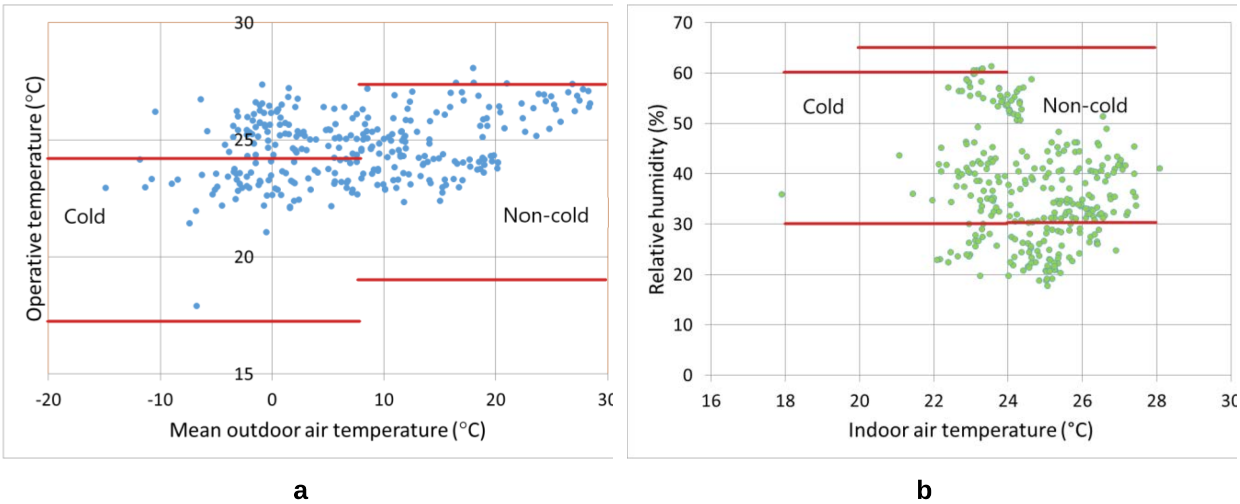
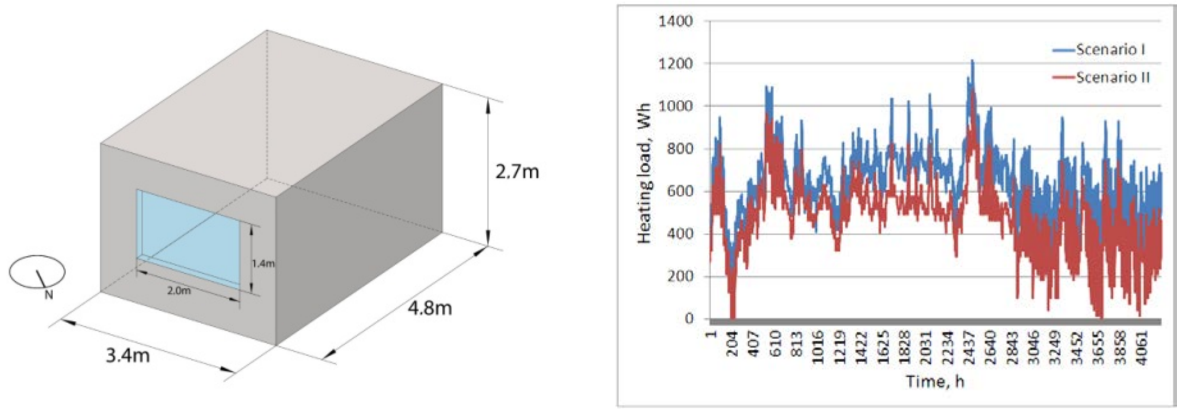


Figure 8. Thermal (a) and humidity (b) conditions analysis in representative room according to the National Standard model (GOST 30494-2011).

As can be seen from these figures, in winter, most data points correspond to the applicable range of the model for Interstate Standard GOST 30494-2011. In the summer, the actual indoor operative temperatures were also almost within the applicable ranges of this model (Fig. 8, a).

The actual indoor relative humidity also was almost within the applicable ranges of the model for Interstate Standard GOST 30494-2011 (Fig. 8, b).

The heating load analyses for 3D model of the representative room when using hourly values of meteorological parameters are derived in Fig. 9.



a b

Figure 9. 3D model of the representative room (a) and its heating load (b).

The heating loads were obtained based on actual (1) and modified (2) calculation scenarios. The first calculation scenario used the actual thermal and humidity parameters listed in Table 1 (at the actual air temperature range and average air exchange rate in the room in winter of 1.2 h^{-1}). The second calculation scenario used optimal thermal and humidity parameters in this room (at the air temperature of 20 °C and average air exchange rate in the room in winter of 1.1 h^{-1}).

Analysis of the calculation results shows that according to the first scenario, the largest heating load is 1.22 kWh; the smallest heating load is 0.05 kWh. In the second scenario, the largest heating load is 1.08 kWh; the smallest heating load is –0.068 kWh. The total heating load in the first scenario is 2704 kWh, in the second scenario – 2049 kWh. Consequently, the reduction of total heating load is 24.2 %.

Thus, the actual temperatures were significantly different from the indoor temperature conditions for the thermal adaptation models according to ASHRAE 55-2013 and EN 15251-2007 Standards in winter (room overheating effect), as plotted in Fig. 6. The results indicate that it is necessary to improve the indoor temperature conditions using the adaptive comfort models. The main solutions are the heat flux control in heaters within the apartment in accordance with the thermal adaptation model of thermal comfort, as well as improvement of indoor environment quality with controlled natural ventilation in winter. Indoor thermal neutral temperature at the small energy demand in premises can be obtained using the smart home concept [33]. The choice of the best scenario is based on the use of a self-learning computer program in interactive user mode (Fig. 10).

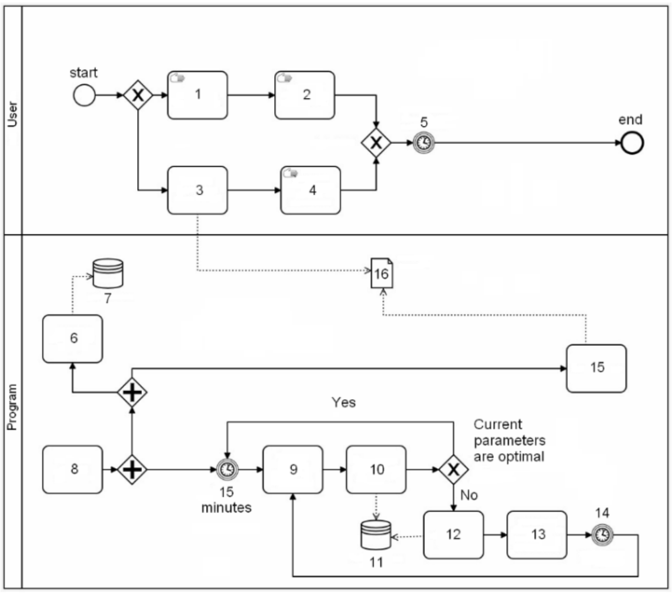


Figure 10. Schematic block diagram for indoor environment optimization: 1 – indoor environment assessment; 2 – turning on the equipment, opening the window; 3 – indoor environment control; 4 – turning on the equipment through the application; 5 – time of equipment operation/ventilation; 6 – sending readings to the server; 7 – Xiaomi server; 8 – sensor readings received; 9 – sensor activation, parameter measurement; 10 – comparison with optimal scenario; 11 – HUB built-in memory; 12 – selecting the optimal scenario; 13 – turn on the equipment according to the scenario; 14 – equipment operation time; 15 – display; 16 – sensor readings.

4. Conclusions

Objective physical measurements of the indoor thermal environments in premises and subjective assessments of the thermal sensation and adaptive thermal comfort of participants in winter, mid-season and summer under continental climate conditions (on the example of Volgograd, Russia) were conducted. The conclusions drawn from our detailed analyses and discussions are as follows:

1. Our investigations showed that in winter there were deviations in the thermal sensation, satisfaction, expectation of residents, and that they preferred a neutral cold environment. There were differences between the mid-season results and those of winter and summer.

2. The thermal comfort assessment in premises under continental climate conditions should be based on thermal adaptation models. We calculated that the acceptable temperature range for residents in winter was 17.5–22.5 °C, 20–25 °C (with acceptable deviation of $\pm$ 2.5 °C) in mid-season and 22.5–27.5 °C in summer. The actual indoor relative humidity was almost within the applicable ranges (30–60 %) as well.

3. The ASHRAE55-2013 and EN15251-2007 adaptive thermal comfort models are suitable for premises in mid-season and summer. The predictions of both mid-season and summer models were reliable.

4. The main solutions to improve the indoor temperature conditions include heat flux control in heaters within the apartment in accordance with the thermal adaptation model of thermal comfort, as well as control of natural ventilation in winter. In this case it is predicted, that the reduction of total heating load is 24.2 %. Indoor thermal neutral temperature at the small energy demand in premises can be obtained by implementing the smart home concept.

5. These results can be used to assess indoor thermal comfort in dwelling and help create friendly and energy efficiency building environments in Russia.

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