Current approaches to studying the level of pedestrian comfort in urban development

Victoria Meshkova[1*], *Alexander* Dekterev[1,2], *Kirill* Litvintsev[2], and *Sergei* A. Filimonov[1]

[1]Siberian Federal University, 79/10 Svobodny pr., 660041 Krasnoyarsk, Russia
[2]Kutateladze Institute of Thermal Physics, SB RAS, 1 Akademika Lavrentiev Avenue, 630090 Novosibirsk, Russia

Abstract. The paper presents the results of a numerical forecast of the pedestrian comfort level in the territory of urban development. The research uses the microscale numerical model of the atmosphere in the urban environment, into which the equations of temperature and seasonal indices are integrated. These equations are used to simulate and analyse pedestrian comfort conditions. The paper presents the results of the proposed model approbation in the real environment of the residential neighbourhoods of Krasnoyarsk city. External conditions, typical for summer and winter seasons, were simulated. The results produced are presented as distribution fields of the considered indices. During the analysis, comfortable/discomfort areas for humans staying in the environment of studied urban development were revealed.

Key words: Microscale numerical model; Pedestrian comfort level; Urban environment; Hydrodynamics; Heat and mass transfer.

1 Introduction

The current urbanization level in Russia is about 74%. The main contribution to urbanization is made by major regions, such as Moscow, St. Petersburg, Samara, and Ekaterinburg [1]. It is worth noting, however, that when considering Russian cities individually, one can note a trend toward their growth and development [2]. In this case, development refers to the active construction of new residential neighborhoods necessary to form a housing stock for the population.

The expansion of the city boundaries is carried out through the construction of new residential microdistricts. And modern approaches in urban planning are aimed precisely at the compacted location of high-rise buildings, which makes it possible to place a larger number of residential places in small areas [3]. These approaches, as a rule, contribute to intensive reducing wind conditions of built-up areas, as well as lead to forming areas with critically low wind speeds, at which the diffusion processes are practically impossible [4]. The presence of pollutant emission sources in these areas leads to the accumulation of health-hazardous fine particles and gaseous substances [4-5].

* Corresponding author: vredel@sfu-kras.ru

https://doi.org/10.1051/e3sconf/202343505004

Particular attention should be paid to the building materials of structures, roadways, etc., since the concerned pavement surfaces lead to a significant change in the natural thermal balance of the Earth through the accumulation of a large proportion of incident solar energy, forming an urban heat island effect. Integrating with various anthropogenic heat sources, the noted negative effect is enhanced [6], which in hot climate conditions and low wind speeds negatively affects the human body's increasing risk of heat stroke.

The above interaction mechanisms between natural and anthropogenic factors lead to forming specific external conditions in the city that form the microclimate of the environment. External conditions are very important for the population's life since they determine the human health condition. In this regard, the conducted study is focused to the human condition in the pedestrian area of the built-up developments in summer and winter seasons.

For several decades, various microscale numerical atmospheric models have been used to address this class of problems [7-9]. The results of a numerical study, presented in the form of velocity fields, make it possible to determine the wind regime of development, taking into account heat and mass transfer. Literature analysis of recent works has shown that the assessments were carried out mainly for pedestrian comfort. That is, only the wind characteristic was considered [10-13]. The results obtained in the form of a velocity field are compared with the wind comfort criteria [14]. A numerical tool for predicting the comfort of pedestrians based on a set of parameters of aerodynamic characteristics, heat transfer, and the effect of temperature and seasonal comfort indices on the system has not been developed before.

Currently, to address this class of problems, the research team of the Siberian Federal University together with the Kutateladze Institute of Thermophysics SB RAS have developed the «SigmaEco» software module based on previously developed «SigmaFlow» software package [15]. «SigmaEco» software module allows calculating multicomponent unsteady turbulent flows with dispersed phase considering heat transfer in an urban environment. The present work demonstrates the capabilities of the suggested numerical model by simulating external environment conditions of the real object, namely, the urban development in Krasnoyarsk city (coordinates: 56.043349, 92.903846), taken as an example.

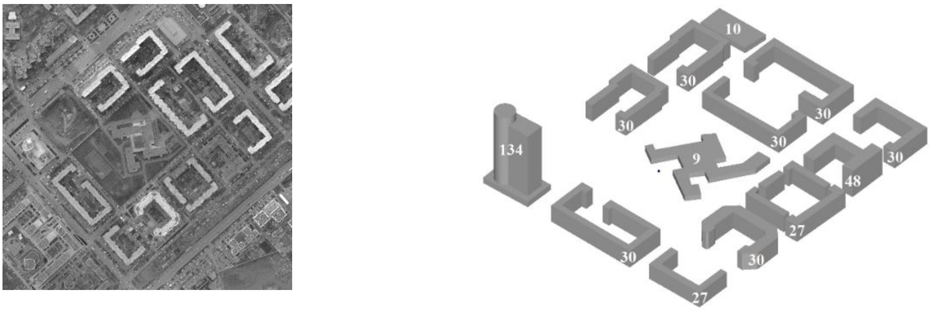
1.1 Setting the problem

A residential neighbourhood in the city of Krasnoyarsk was considerred as the model problem (Fig. 1a). The peculiarity of this development is that it consists of a combination of geometrically different buildings with different number of storeys in a building (Fig. 1b). The chosen development type reflects modern approaches, used currently when considering architectural and planning concept for the urban development [16].

Pedestrian comfort conditions were evaluated for simulated conditions, typical of summer and winter seasons. The following initial conditions were defined for the numerical simulation:

- clear cloudless weather;
- inlet velocity profile was set according to the logarithmic law, and $v_{h_{10}}$ = 3 m/s (velocity at a height of 10 m)
- linear distribution of potential temperature was considered with the rate of temperature increase along the height θ_h = 3 K/km;
- T_B = 293 K, T_E = 263 K in winter season;
- T_B = 293 K, T_E = 293 K in summer season;
- $\alpha_{u.s} = 0.45$ (ground surface albedo), $\alpha_B =$ 0.3 (building surface albedo);
- $\alpha_{u.s} > \alpha_B$, in winter season;
- $\alpha_{u.s} < \alpha_B$ in summer season.

 https://doi.org/10.1051/e3sconf/202343505004



a) b)

Fig. 1. Schematic map of residential development in an urban environment (a); geometry of the concerned area indicating characteristic building heights, m (b).

Evaluation of the level of pedestrian comfort within residential development will be carried out on the basis of temperature and seasonal criteria of comfort, which are integrated into a microscale numerical model for predicting comfort conditions. The numerical model used allows us to jointly study the patterns of interaction between the air flow and the obstacle that the buildings themselves act as, and also take into account heat transfer processes in the environment.

2 Methods

The microscale numerical model of atmosphere in urban environment is based on the Reynolds averaged Navier-Stokes equations for incompressible flows with variable density. The basic equations (1), (2), and (3) are given below.

The continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0, \tag{1}$$

The motion equation:

$$\frac{dU}{dt} = -\nabla p + g \cdot \rho_{ref} \cdot {(\theta_{ref} - \theta)}/{\theta_{ref}} + \nabla[\mu(\nabla U + \nabla U^T)], \tag{2}$$

The energy conservation equation is written using the potential temperature:

$$\rho C_p \frac{d\theta}{dt} = \nabla \cdot \left[\left(\lambda + \frac{\mu_t C_p}{\mathrm{Pr}_t} \right) \nabla \theta \right] + S_\theta, \tag{3}$$

The relation between potential temperature, temperature, and static pressure is described as follows

$$\theta_h = T \left(\frac{P_0}{P_h} \right)^k, \tag{4}$$

where $k=R_{м}/C_p$.

The diffusion-inertial model of low-inertia particle motion is used to simulate the transport of the dispersed phase. The radiation fields are calculated for shortwave solar radiation, as well as longwave atmospheric and terrestrial radiation based on the finite volume method [17].

The mathematical model was previously validated and showed a good comparison of the results of numerical simulation with the results of experimental and numerical studies [18].

The equations of temperature and seasonal indices were integrated into the developed software module to simulate comfort conditions (Table 1).

Table 1. Temperature and seasonal comfort indices [19-21].

Temperature indices
Effective temperature (*ET*, °C) $$\boldsymbol{ET = t - 0.4 \cdot (t - 10) \cdot \left(1 - \frac{f}{100}\right)}$$
Equivalent-effective temperature, B.A. Eisenstat (*EET*, °C) $$\boldsymbol{EET = t \cdot [1 - 0.003 \cdot (100 - f)] - 0{,}38v^{0{,}59} \cdot [(36.6 - t) + 0.622 \cdot (v - 1)] + [(0.0015v + 0.008) \cdot (36.6 - t) - 0.0167] \cdot (100 - f)}$$
Radiation-equivalent-effective temperature, E.G. Golovina, V.I. Rusanov (*REET*, °C) $$\boldsymbol{REET = 0{,}83 \cdot \text{ЭЭТ} + 12}$$
Normal-effective air temperature, I.V. Butieva (*NEET*, °C) $$\boldsymbol{NEET = 0.83 \cdot EET + 7}$$
Biologically active air temperature, E.V. Tsitsenko (*BAT*, °C) $$BAT = 0{,}8 \cdot \boldsymbol{NEET} + 9$$
Seasonal indices
Wind chill index, Siple and Passel ($\boldsymbol{WCIs}$, kcal/m^2 · h) $$\boldsymbol{WCIs = \left(10.45 + 10v^{0{,}5} - v\right) \cdot (33 - t)}$$
Wind (humidity) chill index, M. Hill ($\boldsymbol{WCIh}$, $\boldsymbol{W}$/m^2) $$\boldsymbol{WCIh = H_c + (0.085 + 0.102v^{0{,}3}) \cdot (61.1 - e)^{0{,}75}}$$ Wind chill index ($\boldsymbol{H_c}$): $$\boldsymbol{H_c = (0.13 + v^{0{,}5}) \cdot (36.6 - t)}$$
Weather hardness index, S. Bodman (S) $$\boldsymbol{S = (1 - 0.04 \cdot t) \cdot (1 + 0.272 \cdot v)}$$

It is possible to evaluate how a person perceives the external environment through heat sensation. The effective temperature (ET) just allows to evaluate how a person feels when combined with such parameters as temperature and humidity. The equivalent effective temperature (EET) makes it possible to perform estimates considering the wind characteristic, which is correct. Since the wind factor is decisive in determining the conditions of comfort. Radiation equivalent effective temperature (REET) allows you to determine how solar radiation affects heat sensations when a person is fully dressed. Normally equivalent effective temperature (NEET) considers the effect of solar radiation on the heat sensation of a person dressed to the waist.

Such an indicator as biologically active temperature (BAT) links the indicators of EET and NEET. It is this indicator that can be used for a comprehensive assessment. Considers in aggregate all the main parameters that form the conditions of the external environment - total and long-wave radiation, anthropogenic heat, through temperature, wind speed. To assess the perception of a cold period of time by a person, seasonal indices can be used for assessment, which determine the severity and «continentality» of the climate. In the aggregate, the definition of the load on the human body that a person experiences is determined through temperature. Table 2 shows the temperature gradation according to heat sensations. The Siple-Passel severity criteria are shown in Table 3. Table 4-5 presents the Hill wind chill criteria and the winter severity criteria.

Table 2. Sensation of warm and stress experienced by humans [19-21].

ET; EET, ºC	REET, ºC	NEET, ºC	BAT, ºC	Sensation of warm
$> +30$	×	×	×	Very hot, heavy thermal stress, discomfort conditions
+30…+24	×	>+22	> +23,9	Hot weather, heavy thermal stress, conditional discomfort
+24…+18	+32…+27	+22…+17	+23,9…+21	Warm, comfortable thermal stress, comfortable conditions
+18…+12	+27…+21		+20,9…+10	Moderately warm, comfortable thermal stress, conditional comfort
+12…+6	+21…+17	+16…+8	+9,9…+6	Cool, conditional comfort
+6…0	+17…+12	<+8	<+6	Moderately cool, conditional comfort
0…-12	×	×	×	Cold, moderate stress, discomfort conditions
-12…-24	+7…+2	×	×	Very cold, severe stress, discomfort conditions
-24…-30	+2…-3	×	×	Extremely cold, extremely high stress, extreme discomfort
< -30	-3…-8	×	×	Extremely cold, extremely high risk of frostbite, extreme discomfort

Table 3. Severity criteria according to the Siple-Passel scale [19].

Interval	Conditions
$WCIs \leq 50$	hot
$50 < WCIs \geq 1000$	very cold
$1000 < WCIs \geq 2500$	unbearably cold

Table 4. Criteria for wind (moist) cooling according to Hill [20].

Interval	Conditions
$WCIh \geq 90$	very discomfort conditions
71≤WCIh ≥90	discomfort conditions
$51 \leq WCIh \geq 70$	relatively discomfort conditions
$31 \leq WCIh \geq 50$	relatively comfortable conditions
$11 \leq WCIh \geq 30$	moderately comfortable conditions
$WCIh < 10$	comfortable conditions

Table 5. Characteristics of the winter period, Bodman scoring system [21].

Interval	Conditions
$0 \leq S > 1$	mild conditions
$1 \leq S > 2$	soft conditions
$2 \leq S > 3$	slightly severe conditions
$3 \leq S > 4$	moderately severe conditions
$4 \leq S > 5$	severe conditions
$5 \leq S > 6$	strongly severe conditions
$S > 6$	extremely severe conditions

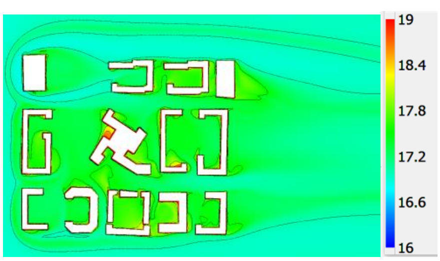
3 Results

The results of a numerical study of the microdistrict under consideration made it possible to determine what kind of external environment forms climatic parameters and what kind of load a person experience. The assessment was carried out through heat sensations using the considered temperature and seasonal comfort indices.

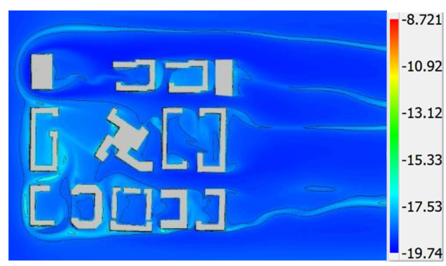
First, consider what conditions are formed in the summer period. Figure 2a shows the effective temperature distribution field. The numerical results made it possible to determine that, in the aggregate, the conditions of «moderate heat» with an acceptable load level are formed. It should be noted that an increase in the indicator is observed near the walls of buildings by about 1-2 °C. But even in these places, under the considered conditions, the load on the human body is acceptable. Considering the winter period, the reverse situation is observed. Conditions near the walls of buildings are formed more favorable for a person than on the territory of the building itself. The person perceives conditions as very cold (Fig. 2b).

Considering the indicator of equivalent effective temperature (EET), which takes into account the wind load, allows us to clearly demonstrate how the wind affects the formation of external conditions. Depending on the formation of various wind zones (zones with low wind speeds and zones with local acceleration), it leads to a gradation of the temperature field. In the zones of local wind acceleration, conditions of «conditional comfort» are formed, and the external environment is perceived by a person as cool. In the semi-enclosed spaces between houses, where the force of the wind is reduced, there is a change in perception. Conditions of moderate heat are formed (Fig. 2c).

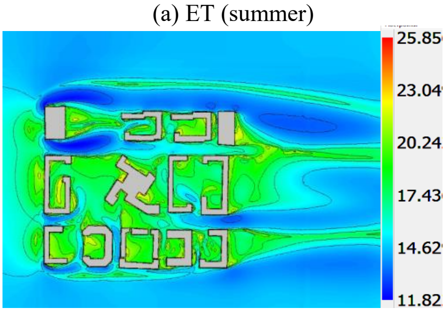
Considering the winter period of time, uncomfortable conditions are formed in the building under consideration, which are accompanied by a dangerous cold load. Comfort conditions increase with increasing temperature, which is observed near the walls of buildings. Due to the heat losses of the buildings themselves, as they are sources of anthropogenic heat during the heating season (Fig. 2d).



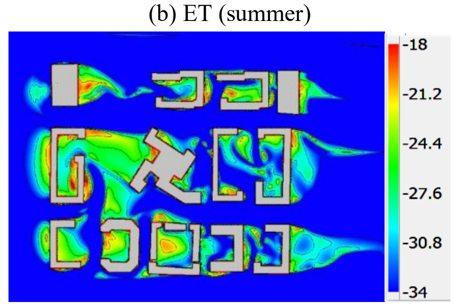
(a) ET (summer)



(b) ET (summer)



(c) EET (summer)



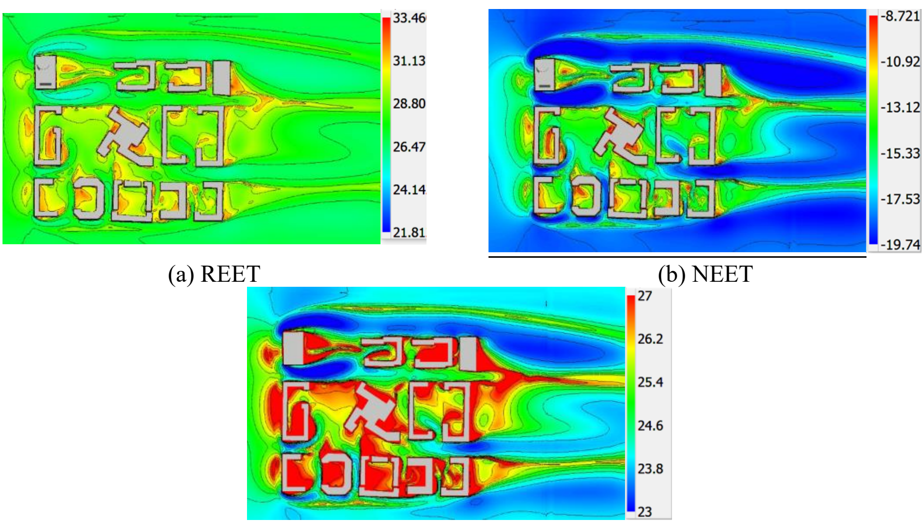
(d) EET (summer)

Fig. 2. Distributions of the effective temperature field, ^{o}C (a; b), and equivalent-effective temperature field, B.A. Eisenstat, ^{o}C (c; b).

The criterion of radiation-equivalent-effective temperature (REET), which considers the effect of solar radiation on human sensation of warm, is considered next. This parameter is considered for summer season only. According to the results (Fig. 3a), formed conditions are «comfortable» with an acceptable level of warm.

Below are the results of those criteria that are considered only in the warm period of time. The radiation-equivalent-effective temperature makes it possible to take into account the influence of solar radiation of a fully dressed person. The results of the numerical study made it possible to determine that, in the aggregate, comfort conditions with an acceptable level of heat are formed (Fig. 3a). Analyzing the distribution fields of normal-effective temperature in the building area, conditions of moderate heat are formed, but uncomfortable conditions are observed in areas where the maximum values of the NEET indicator are recorded. It is possible to obtain a thermal shock, due to a decrease in the aeration regime (Fig. 3b).

The main characteristic of the external conditions in the warm period of time can be done through the biologically active temperature (BAP). Considering courtyard areas that have «closed» and «semi-closed» courtyards, as a result of the geometric features of buildings, conditions of strong thermal load are formed, a person perceives external conditions as «heat», which is uncomfortable for him. These conditions are formed due to the fact that the natural ventilation mode is reduced to a minimum (Fig. 3c).



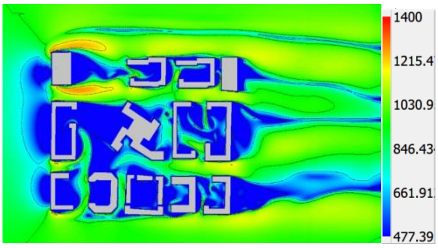
(a) REET (b) NEET

(c) BAT

Fig. 3. Distributions of the radiation-equivalent-effective temperature field (a), normal-equivalent-effective temperature field (b), and biologically active temperature field (c), ºC.

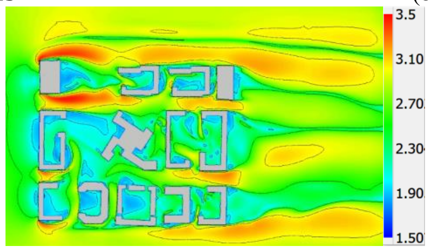
Seasonal indices were used to determine comfort conditions in winter. An assessment of how the aeration mode of development is perceived was performed using the Siple-Passel equation. The results of the numerical study showed that very cold conditions are formed (Fig. 4a).

Considering the index of wind (wet) cooling according to Hill, the conditions of relative comfort are mainly formed in the territory under consideration. In places where the wind speed has the highest values, the level of comfort changes to relatively uncomfortable (Fig. 4b). An assessment of the severity of the winter period showed that there are conditions characteristic of mild and moderately severe winters (Fig. 4c).



(a) WCIs

(b) WCIh



(c) S

Fig. 4. Distributions of Siple-Passel wind chill index field, kcal/m^2·h (a), Hill wind (humidity) chill index, W/m^2·h (b), and rating of winter severity conditions, score (c).

4 Discussion

Numerical study resulted in producing temperature and seasonal indices distribution fields, which were used to estimate the level of pedestrian comfort in summer and winter seasons in a modern development in Krasnoyarsk city.

The implementation of the presented numerical methods will allow a different approach to the planning of modern cities. The software module «SigmaEco» allows to perform a comprehensive analysis of the interaction of aerodynamics and thermophysical characteristics in a complex urban system. And to reveal what conditions develop in the masses of the constant stay of people outside the walls of buildings. The use of this tool at the planning stage of residential areas allows assessing it from the point of view of environmental safety and comfort, identifying unfavorable places for their further minimization or elimination.

Nomenclature

H	Building height, m
h	Height above underlying surface, m
$v, \mathbf{U}$	Speed, m/s
$v_{h_{10}}$	Wind speed at 10 metres above ground, m/s
θ	Potential temperature, K
θ_h	Potential temperature at a height h, K
θ_E	Potential temperature at the surface, K
T_B	Temperature inside buildings, K
$\alpha_{u.s}, \alpha_B$	Albedo of underlying surface and building surface
$R_м$	Gas constant for air, J/(kg·K)
P_0, P_h	Atmospheric pressure, equal to 101 kPa, and the pressure at height h, respectively
C_p	Specific heat capacity, J/(kg·K)

p	Average pressure, Pa
μ	Dynamic viscosity, Pa
S_θ	Heat source, W/m^3
T, t	Temperature in K and °C, respectively
f	Relative humidity, %
$e\ (E)$	Elasticity of water vapor, hPa

Funding

The study was funded by the grant 22-61-00098 from the Russian Science Foundation.

References

1. Statistics and indicators. Regional and federal. https://rosinfostat.ru/urbanizatsiya-v-rossii/. Accessed 10 May 2023
2. B.I. Giyasov, R.B. Giyasov. J. Engineering Bulletin **1** (2022) ivdon.ru/ru/magazine/archive/n1y2022/7395
3. S.E. Bibri, J. Krogsty, M. Karholm, Events in the Built Environment (2020) https://doi.org/10.1016/j.dibe.2020.100021
4. G. Ulpiani, Sci Total Environ **751**, 141727 (2021) 10.1016/j.scitotenv.2020.141727
5. M. Wu, G. Zhang, L. Wang, X. Liu, Z. Wu, Int J Environ Res Public Health (2022) 10.3390/ijerph191912895
6. S.A. Filimonov, V.D. Meshkova, A.A. Dekterev, A.A. Gavrilov, S.V. Shebelev, Journal of Physics: Conf. ser. 2057, 012134 (2021) 10.1088/1742-6596/2057/1/012134
7. J. Toarlar, B. Blocken, P. Vos, G.J.F. van Heist, V.D. Janssen, T. van Hoff, H. Montazeri, H.J.P. Timmermans, Building & Environment (2015) 1016/j.buildenv.2014.08.004
8. M. Gu, J. Wind Eng. Ind. Aerodyn. (2020) 10.1016/j.jweia.2020.104305
9. K. Du, B. Chen, Appl. Sci. (2022) https://doi.org/10.3390/app12042254
10. S. Jia, Y. Wang, Build. Environ. (2021) https://doi.org/10.1016/j.buildenv.2021.107988
11. M. Mohammadi, P.W. Tien, J. Kaiser Calautit, BUILD SIMUL (2023) https://doi.org/10.1007/s12273-022-0943-7
12. J. Liu, J. Niu, Q. Xia, Build. Environ. (2016) https://doi.org/10.1016/j.buildenv.2016.05.038
13. M. Taleghani, D. Sailor, G.A. Ban-Weiss, Environ. Res. Lett. (2016) 10.1088/1748-9326/11/2/024003
14. P.W. Thien, J.K. Kaloutit, J. Build. Eng. (2019) 10.1016/j.jobe.2019.100735
15. V.D. Meshkova, A.A. Dekterev, S.A. Filimonov, K.Yu. Litvintsev, Journal of Siberian Federal University. Technics and Technology **15**, 4 (2022) 10.17516/1999-494X-0398
16. A.Yu. Lipovka, I.G. Fedchenko, Urbanistka 3 (2021)
17. G.D. Wrightby, E.H.J. Chui, Heat transfer (1990) https://doi.org/10.1289/ehp.7938
18. V. Meshkova, A. Dekterev, Journal of Physics: Conference Series 1675, 012119 (2020) 10.1088/1742-6596/1675/1/012119

19. P.A. Saipl, Measurements of Dry Atmospheric Cooling at Negative Temperatures. Reports on the scientific results of the expedition of the US Antarctic Survey. In P.A. Saipl, S.F. Passel, Tr. Amer. Philos. **89**, 177 (1945)
20. E.G. Golovina, M.A. Trubina, *Method for calculating biometeorological parameters (indices)* (Saint Petersburg, 1997)
21. L.E. Hill, T.S. Angus, E.M. Newbold, Further experimental observations to determine the dependence of catacooling capacity on atmospheric conditions, J. Ind. Hyg. **10**, 391 (1958)