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The probabilistic-statistical modeling of the external climate in the cooling period

Вероятностно-статистическое моделирование наружного климата в охладительный период

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Key words: probabilistic-statistical model; climate; typical year; safety index; Monte-Carlo procedure; temperature; the cooling period

Ключевые слова: вероятностно-статистическая модель; климат; типовой год; коэффициент обеспеченности; метод Монте-Карло; температура; охладительный период

Abstract. Currently, the successful development of construction industry depends on the improved energy performance of buildings, structures and facilities, as well on the quality estimation of the outdoor climate. The problem of feasibly more accurate determination of energy consumption by climatic systems in buildings is a very high-priority task now because of decrease of energy and fuel sources and because of actualization of building standards in many countries. That is why it is very important to find simple but enough accurate dependences between climatic parameters in the heating as well as in the cooling seasons of a year. In the paper the modern principles accepted in different countries for the selection of the design climate information for the design of building envelopes and systems to ensure building microclimate are considered. Main shortcomings of the methods, including the concept of "typical year", are shown and the advantages of generating climate data arrays programmatically with the use of a pseudorandom number generator are described. Some results of the calculation of current temperature of the external air during the warm period of the year with different safety are presented using numerical modeling with Monte-Carlo procedure. The possibility of practical implementation of probabilistic-statistical principle of climatic data for some calculations relating to climatic systems and thermal regime of the building are shown. The comparison of the obtained values with the analytical expression for the normal distribution of random variables is presented and relationships for the selection of its main parameters according to the existing climatic manuals are proposed.

Аннотация. В настоящее время успешное развитие строительной отрасли зависит от повышения энергетической эффективности зданий, строений и сооружений и в то же время от качественной оценки параметров наружного климата. Задача возможно более точного определения энергопотребления климатическими системами зданий имеет очень большое значение в связи с исчерпанием запасов органического топлива и других ресурсов, а также в связи с актуализацией нормативной базы многих стран в области строительства. Поэтому очень важно располагать простыми, но одновременно достаточно точными зависимостями между климатическими параметрами как в отопительный, так и в охладительный периоды года. В работе рассмотрены принятые в настоящее время в различных странах принципы выбора расчетной климатической информации для проектирования ограждающих конструкций и систем обеспечения микроклимата зданий. Отмечены основные недостатки методик, включающих понятие «типового года», и описаны преимущества генерации массивов климатических данных программным способом с применением датчиков псевдослучайных чисел. Приведены некоторые результаты расчета срочной температуры наружного воздуха в теплый период года с различной обеспеченностью при помощи численного моделирования методом Монте-Карло. Показана возможность практической реализации вероятностно-статистического принципа формирования климатических данных для некоторых расчетов, касающихся систем климатизации и теплового режима здания. Представлено сопоставление полученных значений с аналитическим выражением для нормального закона распределения случайной величины и предложены соотношения для подбора ее основных параметров по имеющимся нормативным данным в области строительной климатологии.

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Introduction

One of the main approaches to determination of design parameters of external climate for designing external enclosures and climatic system of buildings is based on using factor k_h (so called safety index), which represents the likelihood that actual value of considered parameter upon operation of the building will not exceed set thresholds i.e. it will not exceed this threshold in hot period of the year and will not be lower in cold period. The expression for k_h should have the following view [1]:

$$k_h = 1 - \frac{\Delta N}{N} \text{ or } k_h = 1 - \frac{\Delta z}{z}, \quad (1)$$

where N is a total number of supervision events when the parameter exceeds established threshold; z is general time of supervisions; Δz is a duration of time interval when the parameters exceeds threshold value. The first variant is used for evaluation of discrete events k_h, for example, the coldest five days or days, and the second variant is used for determination of the level of general climatic parameters for hot and cold period. However, definite conditions may require parameters under other value k_h that differs from those, for which the values are represented in the source. Especially, this relates to significant and responsible facilities when customer requires high reliability and, respectively, value k_h.

Therefore, in this paper, the object of study is the design outdoor temperature for design of the microclimate systems during the cooling period of the year with a specified safety index. Probabilistic-statistical model of external climate allows determination of scientifically grounded level for this temperature. It can be shown that this model efficiently describes basic ratio between different parameters [2–3] regardless the availability of two main factors that affect formation of these parameters, i.e. regular seasonal trend and fluctuations against this trend that are actually close to random ones.

This method has definite benefits over so-called “typical year” [4–10] that is accepted in many cases and described in details in the last versions of recommendations ASHRAE [11–12]. Eventually, they provide for the selection of so-called “typical meteorological months” chosen from long-time data base (the last variant for the period from 1982 to 2006). Moreover, the data for each day and hour of each month of the year can be selected from different years of considered period, i.e. they are real, so that resultant deviation from the average temperature for this period doesn’t exceed 0.1 °C. Then the massive is analyzed for the respective parameters (in particular, temperature) with necessary reliability. In [13–14] some elements of probabilistic-statistical models were presented, but, again, it is not aimed at obtaining in-depth evaluation of dependencies. So, the benefits of probability/statistical method relate to the absence of the need in the search for accumulation of the large volume of climatic data and their special selection so that these data correspond to the requirements applied to their representatively. Moreover, there is no need in loading of such large amount of data to software. Finally, the method based on ‘typical year’ is less oriented at obtaining any point estimates, including determination of certain external air temperatures t_{ex} with set reliability. The latter is necessary for the correct selection of processes of the supply air treatment in the cooling period and for calculation of installed power of air-conditioning equipment. In the practice of building regulation in several countries, including the Russian Federation and some others, that the safety index of climate parameters forms the basis of their definition, therefore, the application of probabilistic-statistical modeling will allow the most simple way to solve the problem of selection of HVAC equipment within design conditions of the cooling period with any k_h required by the customer.

Generally speaking, the recommendations of the ASHRAE, especially [12], also provide for the regulation of temperatures t_{ex} using a certain analogue of k_h, namely the indication of temperature values the ambient air dry bulb temperature corresponding to 0.4, 1.0, or 2.0 % annual cumulative frequency of occurrence (warm conditions). Unlike the k_h's is that at use of formula (1) in the denominator will be the duration of the cooling period only and not the whole year. However, here the frequency is fixed, and for intermediate values, the corresponding data do not exist.

A slightly different approach is proposed in [15], where t_{ex} is associated with the characteristics of the thermal resistance of the premises and solutions for automatic control of climate systems, but in spite of the physical validity, it is difficult to apply at the stage of making preliminary decisions due to the lack of reliable data on the characteristics of the object of regulation.

Thus, the purpose of this study is to determine key design parameters of external climate in warm season with arbitrary safety index with the help of probabilistic-statistical model. Objectives of the study are to build an algorithm that implements this model, and obtaining analytical dependences for the calculated outside temperature according to the results of approximation results software generation.

Methods

Probabilistic-statistical model is based on determination of urgent ambient air temperature and associated correlation enthalpy as a random value distributed under normal law and characterized by certain expected mean *M(t)* and mean-square deviation σ_t. It should be noted that regular and stochastic factors that determine the behavior of urgent temperature can be tracked separately without significant complication of the algorithm upon computer-based calculations. In studies case, seasonal trend was simulated by the input of float mean that varied within the year under sinusoidal law within the amplitude A_t that corresponds to the half of the difference of average temperatures of the hottest and the coldest month with the maximum near July 31, i.e. on 210th day from the beginning of the year. Then stochastic component with corresponding value σ_t was applied to resultant value. This was performed by means of quasi-random number counter that generates values that are subject to normal distribution law. Considered approach is one of the variants of Monte-Carlo procedure. In variant of ECM program, realized by the author, the generated was performed for the period of 100 years. Then obtained temperatures were ranked in ascending order. This allows building unknown dependency of t_{ex} from k_h.

Results and Discussion

On figure 1, red line indicates results for climatic conditions of Moscow. In this case, mean annual temperature t_{mean} that is equal to +5.4 °C was taken as expected mean. Value A_t of 13.25 °C was considered and the value of amplitude of daily rate of urgent temperatures in hot period, i.e. 9.6 °C was taken as σ_t. It should be noted that in climatic terms the amplitude is considered as the difference between maximum and minimum value within a day since half size value of mathematic amplitude should be used as σ_t for modeling the behavior of not urgent but mean daily temperatures. Moreover, not directly k_h but the probability of contrary event (urgent temperature exceeds its current value, i.e. $1 - k_h$) is taken as independent variable. This is not fundamental importance but it will simplify obtained approximate relationships.

Black line on figure 1 shows approximation of disclosed dependency in the following form (2):

$$t_{ex} = a\ln\left(1-k_h\right) + b \qquad (2)$$

Acceding to the results of regression analysis a = –4.51, b = 9.1 and correlation ratio r = 0.996. Obviously, this expression ensures rather high degree of approximation, considering its simplicity and statistical nature of used initial data that inevitably have variation.

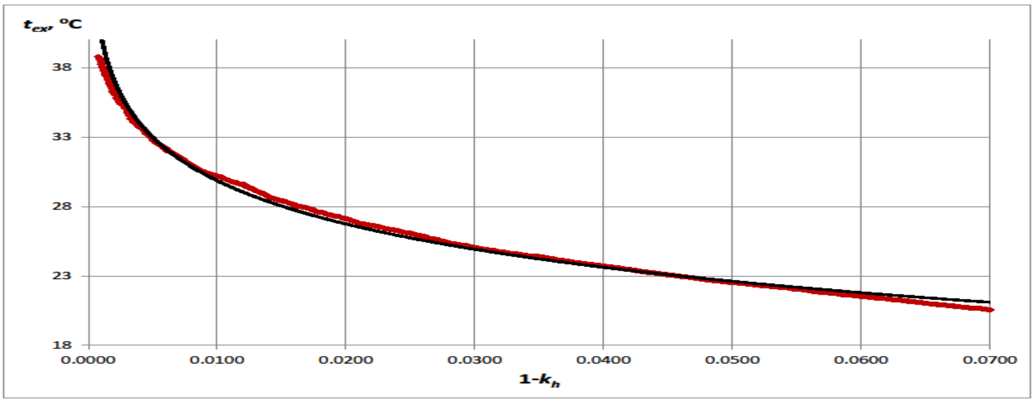

Figure 1. Results of software generation t_{ex} depending on $1 - k_h$ and their approximation (2)

It should be noted that the use of theoretical dependency that directly derives from main probabilistic-statistical model gives higher deviation as we can see on the Figure 2 where red continuous line indicates calculation results by program and black dotted line indicates calculation by formula (3):

$$t_{ex} = t_{mean} + \sigma_t\sqrt{-1.592\ln\left[1-\left(1-2k_h\right)^2\right]} \qquad (3)$$

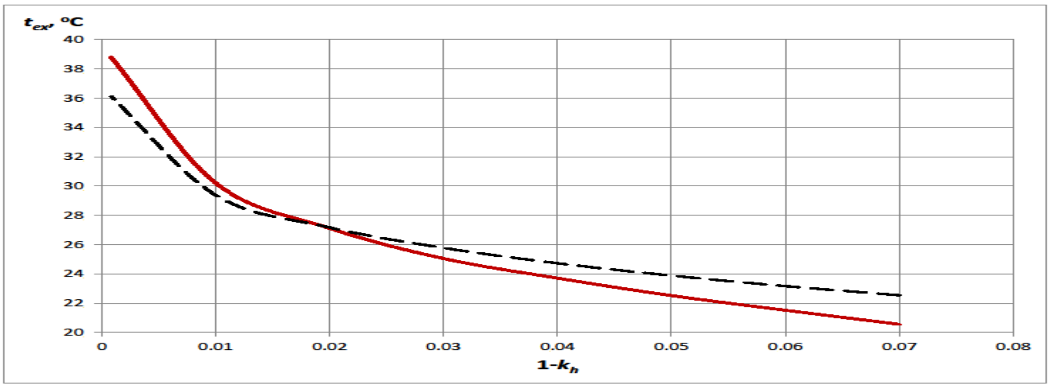

Figure 2. The results of software generation t_{ex} depending on $1 – k_h$ and their comparison with data (3)

This formula is built, considering known approximate expression for error function *erf* at large values of the argument since the model based on normal distribution law provides the dependency in the following from [2–3]:

$$k_h = \frac{1}{2}\left(1 + erf\left[\frac{t_{ex} - t_{mean}}{\sigma_t \sqrt{2}}\right]\right) \qquad (4)$$

It can be assumed that revealed difference is associated with model refinement that is realized in the software and relates to tracking of seasonal nature of the change of external temperature.

Since probabilistic-statistical model provides for the unity of the mechanism for formation of urgent temperature regardless definite construction area and, respectively, the generality of corresponding dependencies, there are solid grounds for stating that the expression in the form (2) is true for all cases and differs only in *a* and *b* values. Therefore, the main task of probabilistic-statistical modeling was to find common type of control $t_{ex} = f(k_h)$, and definite level of numerical radios may be selected by identification of the model, considering available fixed points.

Considering arbitrary probability of fixed temperature values from (2), we find:

$$a = \frac{t_{ex1} - t_{ex2}}{\ln\left(\frac{1-k_{h1}}{1-k_{h2}}\right)}; \qquad (5)$$
$$b = t_{ex1} - a\ln\left(1-k_{h1}\right) = t_{ex2} - a\ln\left(1-k_{h2}\right),$$

where t_{ex1} и t_{ex2} are design external air temperatures basing on the data of this or that source with respective reliability k_{h1} and k_{h2}. For instance, for Moscow t_{ex1} = +23 °C and t_{ex2} = +26 °C at k_{h1} = 0.95 and k_{h2} = 0.98, respectively, where we find *a* = –3.3, *b* = 13.1. These values differ from values obtained from the results of approximation of software generation data but, as it was mentioned above, the purpose of this generation was to disclose dependency form (2). However, the nature of the curves on Figure 1, especially approximating dependency, suggests that their difference from normative values is not very high and does not exceed one degree.

The accuracy and reliability of the results obtained by using dependence (2) with the coefficients calculated by the expressions (5), can be seen from the graphs in figures 3 and 3a. Here, the solid line shows the results of calculations by the proposed method, and dotted line – data from existing observations [13]. In the figure 3, lines 1 refer to the conditions of Moscow; the lines 2 represent the city with substantially more hot and dry climate – Samara. The graph in the Figure 3a refers to the intermediate parameters of Khabarovsk. It is easy to see that the agreement is pretty good, noticeable discrepancies arise only at very high $k_h \rightarrow 1$, which can be explained by the presence of a minimum time interval of averaging measurement results ambient temperature (typically one hour), so that its extreme values in hourly aggregates do not fall. The red lines show the data of ASHRAE [12] with the appropriate conversion. As it can be seen, here the similarity is also quite satisfactory.

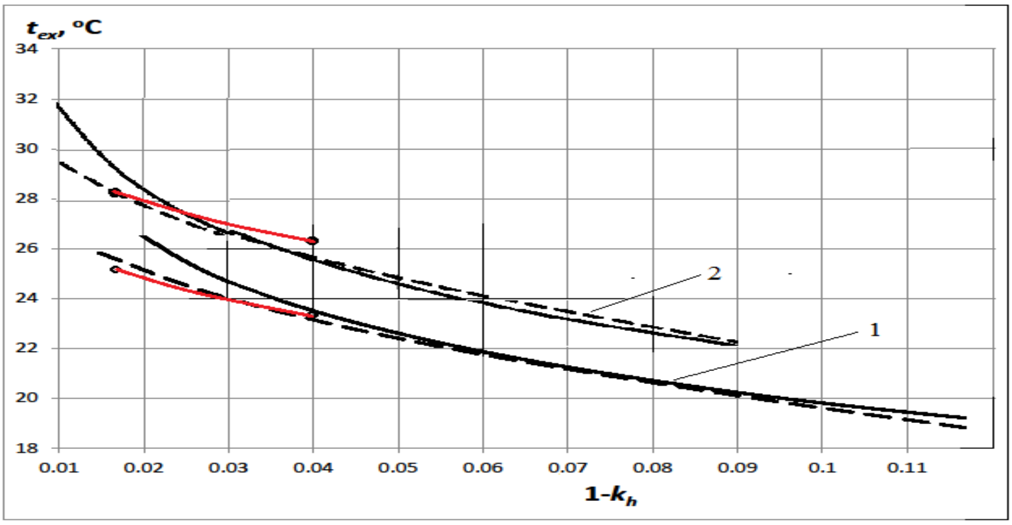

Figure 3. Comparison of calculations by formulas (2), (5) with climate data for Moscow and Samara

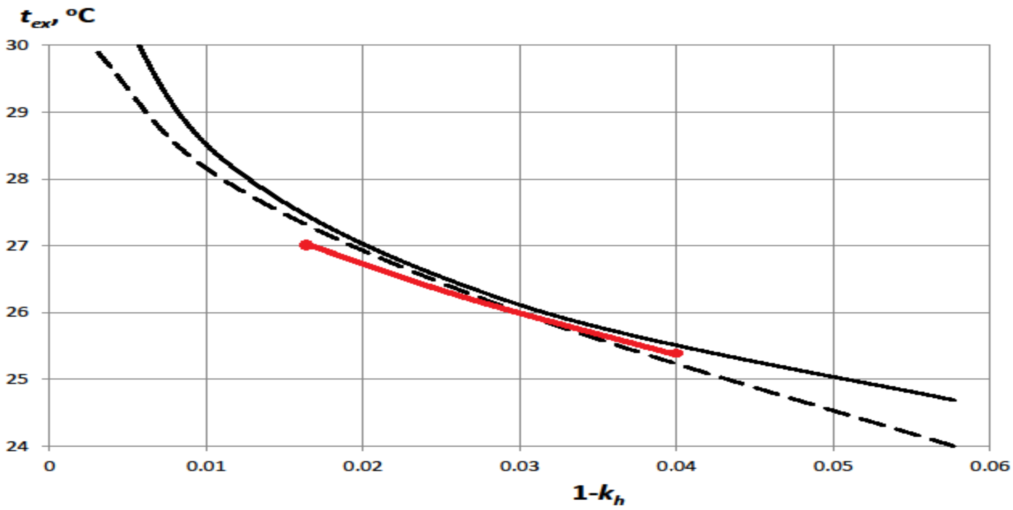

Figure 3a. Comparison of calculations by formulas (2), (5) with climate data for Khabarovsk

If you conduct additional calculations on above-mentioned ECM program at different A_t within the limits from 10 to 15 °C, which is peculiar for most countries of Central and Eastern Europe, it is possible to obtain ratios for parameters *a* and *b* in the following forms through further regressive analysis:

$$a = -0.325A_t\ ;\ b = 0.275A_t + t_{mean}, \tag{6}$$

where $A_t = \frac{t_{hm} - t_{cm}}{2}$.

Correlation ratio is not less than 0.99. t_{hm} and t_{cm} are temperatures of the hottest and the coldest month in considered region, i.e. A_t value is nothing else but the amplitude of annual cycle of mean monthly temperatures [2–3]. Moreover, it was understood that there is correlation ratio between σ_t and A_t in considered target area:

$$\sigma_t = (0.67 \pm 0.13)A_t\ . \tag{7}$$

Thus, the most probable change of σ_t after A_t is considered in (6) automatically. Since values t_{hm}, t_{cm} and t_{mean} for any rather large settlement can be taken from normative and reference documents that are valid in this or that country, it is possible to conclude that the ratio (2), considering (6), is easy-to-use since it requires maximum quantity of accessible initial data.

In this respect, the data offered by ASHRAE [11, 12], is less convenient because, first, does not contain the necessary analytical dependences, but only discrete values of temperatures and other parameters, and secondly, forcing users to resort to self-selecting the required values from the available array. The same applies to more recent studies [4–10], as they support the same methodological approach. Analytical relations are given for example in [7], but they refer to average temperatures, without considering the stochastic component, and [14, 16], despite the elements of probability and statistical consideration, are not aimed at providing analytical assessments.

It should also be noted that models using probabilistic-statistical approach are especially suitable for calculation of annual power consumption of the building upon estimation of energy saving class that is very critical today in the context of depletion of the reserves of organic fuel and increased attention to energy conservation that is observed in most European and other countries [17–22]. Although discussed in the present work a variant of probabilistic-statistical modeling aimed, as mentioned, primarily on the calculation of climatic parameters for estimating installed capacity of HVAC equipment with the required security, in principle it can be used to calculate annual energy consumption. It is enough to integrate the product of the expression containing the difference between t_{ex} (2) and the corresponding temperature of supply or internal air t_{in} for the value $1 - k_h$, because from (1) the difference $1 - k_h$ shows the relative number of hours standing t_{ex}, which is greater than the current value. Then, for example, by expressing additionally the required value $1 - k_h$ from (2) using the set value t_{in}, the degree-days of cooling period can be calculated to determine the total cold consumption by the expression:

$$D_d = 24\exp\left(\frac{t_{in} - b}{a}\right)\left(t_{in} - a\right). \quad (8)$$

Taking by the requirements of ASHRAE [13] the boundary value t_{in} = +15.11 °C (65 °F) and the values of a and b, obtained when plotting figure 3, we can calculate for Moscow D_d = 116 K•day, for Samara 215 K•day. The actual values in [12] are, respectively, 107 and 199 K•day, i.e. the divergence is of only about 8 percent, which is sufficient for engineering calculations considering the simplicity of the obtained relationships.

Conclusion

1. It is confirmed that the probability/statistical modeling can be used for creation of climatic data array upon definite calculations associated with thermal mode of rooms and environmental control systems and selection of design parameters of external climate with required reliability;
2. It has been shown that probability/statistical modeling is suitable for development of simplified models, aimed at determining integral characteristics of the building, enclosures and engineering systems for definite time;
3. It is proved that the results of the probabilistic-statistical modeling reliably and with acceptable accuracy for practice reflect the real data of climate observations from different sources for a significant number of construction areas;
4. Using the probabilistic-statistical model, the formulas are obtained for calculating the design temperature of external air in cooling period for the design of cooling systems and the degree-days of cooling period to determine the total energy consumption with any required safety index;
5. Accessible results are represented in engineering form with use of only basic values that are available from existing sources and can be used in design practice.

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