Analysis of the energy efficiency of air conditioning systems based on the outdoor climate statistical model

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Abstract. The analysis of outdoor climate normative information, given in the form of calculated parameters of outdoor air for warm and cold periods of the year, is given. The requirements to the form of presentation of climatic information and to its content are formulated. The information is presented in the form of tables of recurrence of outdoor parameters in two-dimensional intervals for different cities of the Russian Federation and the capital of Iraq, Baghdad. It is shown that the information in the form of these tables can be used for the tasks indicated in the article at the stage of conceptual design of air conditioning system. The results of approbation of the considered form of climate information implemented at practical tasks are demonstrated. Among these results, we should pay special attention to dependence of installation capacities of subsystems on the time of non-availability of the rated parameters of the air environment in a room. Moreover, it is shown by the example that information about heat, cold, air, and water consumption by heat and humidity treatment in air conditioning systems can be determined for various calculated periods of time. The results were obtained using an applied computer program that executes the recommended form of presentation of climate information for the design of air conditioning systems.

1. Introduction
To implement the method of energy-saving modes of operation of air conditioning systems (AC) [1], information about the outdoor climate (as well as internal loads [2]), based on statistical data on climatic parameters over a long period of time, which includes the characteristic of climatic regions by combinations of climatic factors, is necessary. Climatic conditions determine the need for energy consumption, so the form of their presentation should reflect the actual and current probability of observation of meteorological parameters and be convenient for use in calculations of consumption of heat, cold, air, and water, which determine the total energy consumption of AC [3].

Regulatory information about outdoor climate, presented in the form of calculated parameters for warm and cold periods of the year, does not provide the solution of the problem of AC optimal management operation [4]. The method of energy-saving modes of AC, implemented in the form of appropriate software, allows one to organize the management of functioning in the operation of air conditioning systems.
The purpose of this study is to formulate requirements for the content and form of climatic information for the preliminary stage of design (conceptual design), based on the need to achieve the optimal (energy-saving) control of AC operation.

2. Object and method of research
First of all, information about outdoor climate is necessary for justification of energy-saving technology of thermal and humid air treatment in AC [1]. Information about outdoor climate is also necessary to solve the problem of determining the installed capacity of AC subsystems. In general case these are heating, cooling, humidification, first and second recirculation subsystems [5]. At a reasonable value of setting capacity of equipment of AC subsystems, time of «insecurity» \( \tau_{\text{ins}} \), that is «violation» of air parameters in a room should not exceed its permissible value \( \tau_{\text{ins}}^{\text{add}} \). Under \( \tau_{\text{ins}}^{\text{add}} \) this value means the continuous time of «insecurity» of air parameters in the room. This value is taken into account including the peculiarities of the intended use of the room. The absence in the code of rules on building climatology of data on unavailability for values of design enthalpies of outdoor air does not allow one to establish a relationship between the time of unavailability \( \tau_{\text{ins}} \) of standardized indoor air parameters and the setting capacities of AC subsystems.

Estimation of the quantity of consumed resources (technological parameters), namely, - the costs of heat, cold, air, and water for the accepted design time period of system functioning also requires availability of information about outdoor climate [1]. Thus, normative information about climate, presented in a set of rules on building climatology, does not provide the solution of the above tasks. Their solution requires information that includes characteristics of climatic areas by combinations of climatic factors [6].

Such information is presented in various sources (including reference sources) [7] in the form of \( (t-\phi) \)-tables, which provide data on the duration (not continuous) of the combination of temperature with an interval \( \Delta t \), equal to 5°C and relative humidity with an interval \( \Delta \phi \), equal to 5% for a year, according to the results of long-term observations at different geographical locations. In the climatic guidebook [8] \( (t-\phi) \)-tables are presented with smaller temperature intervals (\( \Delta t = 2 \) °C), and the values of repeatability of combinations of temperature and relative humidity are given both for a year and by months. Information on climate in the form of \( (t-\phi) \)-tables generally allows us to solve the above problems.

On the \( (I-d) \)-diagram of humid air, the area of outdoor climate parameters can be visually represented by «elementary areas» with intervals of specific enthalpy \( \Delta I \) and moisture content of outdoor air \( \Delta d \) [1].

Elementary sites of the outdoor climate area can be represented by values of two temperatures: dry thermometer temperature \( t \) and wet thermometer temperature \( t_{\text{M}} \) in \( (t - t_{\text{M}}) \)-tables [9, 10]. For automatic calculations, information about climate from tabular \( (t-d) \)-tables is converted into electronic form, where each table is represented in «Notepad» editor as a separate file.

Operation of AC, using energy-saving technologies, should not be limited only to information about design parameters of outside air for warm and cold periods of the year, but also include data about climate for the whole design period of time. When assessing the energy efficiency of a building, the consumption of heat, cold, air, and water for outdoor air treatment plays an important role, which can only be calculated based on the probabilistic distribution of outdoor climate parameters in the construction zone [11].

An example of a climate map in the form of dry and wet thermometer temperatures is given in Fig. 1 [8]. Information in the form of these tables can be used for solving the above-mentioned tasks at the stage of conceptual design of AC. However, these tables have certain drawbacks, which can be eliminated by using the recommended form for presenting climatic information in the form of \( (t-d) \)-tables in electronic form. Such information is presented by climatic statistical data based on actual measurements of thermodynamic parameters of outdoor air in real time mode in the form of tables with «cells» containing repeatability of outdoor air temperature with 5°C step, relative humidity with 5% step and moisture content with 1 g/kg step (Table 1). Columns contain average values of humidity intervals \( d_{\text{av}} \), rows contain average values of temperature intervals \( t_{\text{av}} \). Text file formula tables (t-d)
consist of 45 columns and 20 rows of five zero digits; temperature range is from $-60 \, ^\circ C$ to $+60 \, ^\circ C$ with total intervals $(5 \times 45) = 225$.

Figure 1. Initial climatic thermodynamic scheme (Dry-Bulb Temperature Hours for an Average Year July-ST. PETERSBURG 722116)

| July | Average values of moisture content $d_{av}$ in each of the intervals, g / (kg dry. air.) |
|------|--------------------------------------------------------------------------------------------------|
|      | 5       | 6       | 7       | 8       | 9       | 10      | 11      | 12      | 13      | 14      | 15      | Sum. h |
| 6    | 1       |         |         |         |         |         |         |         |         |         |         |         |
| 9    | 2       | 6       | 2       |         |         |         |         |         |         |         |         |         |
| 12   | 4       | 12      | 13      | 2       |         |         |         |         |         |         |         |         |
| 15   | 5       | 13      | 26      | 30      | 8       |         |         |         |         |         |         |         |
| 18   | 4       | 12      | 25      | 43      | 42      | 15      |         |         |         |         |         |         |
| 21   | 1       | 5       | 10      | 20      | 30      | 34      | 35      | 14      | 1       |         |         | 150     |
| 24   | 3       | 11      | 16      | 23      | 23      | 25      | 17      | 11      | 2       |         |         | 131     |
| 27   | 1       | 2       | 7       | 11      | 15      | 18      | 13      | 11      | 8       | 3       |         | 89      |
| 30   | 1       | 4       | 6       | 11      | 10      | 9       | 7       | 6       | 3       |         |         | 57      |
| 33   | 1       | 3       | 5       | 5       | 4       | 6       | 4       | 3       |         |         |         | 31      |
| 36   | 1       | 1       | 2       | 3       | 3       | 2       | 2       | 1       | 1       |         |         | 16      |
| 39   |         |         |         |         |         |         |         |         |         |         |         |         |
| Σ The total for month, h | 2       | 27      | 77      | 123     | 162     | 144     | 104     | 58      | 33      | 13      | 1       | 744     |
3. Results
On the (I-d)-diagram of humid air, climatic information for the selected calculated time period is represented graphically by points with coordinates \( t_{av} \) and \( d_{av} \). For each calculated climatic «point» the time of complete recurrence of combinations of temperature and relative humidity within elementary sites is calculated. Climatic information in the form of (t-d)-tables was developed for four Russian cities: Arkhangelsk, St. Petersburg, Moscow, and Rostov-on-Don (based on statistical data for the period from 1966 to 2000). The calculated values of technological parameters are given in Table 2.

In this table:
- in the numerator there are AC values for adiabatic humidification, in the denominator for saturated steam humidification;
- figures without brackets mean heat or cold costs; figures in brackets mean duration of modes as a percentage of year;

Analysis of the data in Table 2 and Fig. 2 shows that the heat consumption in steam humidification is increased 1.5 times for Arkhangelsk. For St. Petersburg, Moscow and for Rostov-on-Don - 2.1 times. The excess of cold consumption for Moscow was 2.1 times, for Rostov-on-Don 1.8 times; for St. Petersburg 2.4 times; for Arkhangelsk 1.7 times. The duration of operation without heat and cold consumption decreased 1.6 to 1.9 times.

| Mode Groups                  | Climate region          |
|------------------------------|-------------------------|
|                              | Arkhangelsk | St. Petersburg | Moscow | Rostov-on-Don |
| Heat consumption \( q_T \)   | \( \sum q_T \) | 233.6          | 237    | 291.13        | 86.8        |
| (kW/m²)                      | \( \sum \tau_T \) | (13 %)         | (12.4 %) | (14.8 %)      | (6.3 %)     |
| Cold consumption \( q_c \)   | \( \sum q_c \) | 547            | 274.3  | 430.7         | 1301        |
| (kW/m²)                      | \( \sum \tau_c \) | (11.3 %)       | (7.2 %) | (9.7 %)       | (21.1 %)    |
| Without consumption \( q_T \) and \( q_c \) | \( \sum \sigma \) | 0              | 0      | 0             | 0           |
|                              | \( \sum \sigma \tau \) | (75.7 %)       | (80.4 %) | (75.5 %)     | (72.6 %)    |
|                              | \( \sum \sigma \tau \) | (48.9 %)       | (51.5 %) | (45.6 %)     | (37.8 %)    |

The data in Fig. 2 show that with the second class of loads the periods without heat and cold consumption increase at the expense of reducing the periods with heat consumption. Other changes are...
not obvious, as they require calculations, taking into account the standing time of the outdoor air parameters on the elementary sites of the (I-d)-diagram.

Based on the results of the analysis of the presented materials, the following should be noted.

1. Heat consumption for all cities is practically the same under the second-class load (except for Rostov-on-Don); under the first-class load, heat consumption increases 25-30 times for Arkhangelsk, St. Petersburg, and Moscow, and 50 times for Rostov-on-Don.

2. Cold consumption for the first and second load classes almost coincide: for Arkhangelsk, these indicators are higher than for Moscow and St. Petersburg, but less by half than for Rostov-on-Don.

3. Duration of periods without heat and cold consumption are as follows: for the second-class of load, it reaches 7,000 hours per year; for the first class of load, it is within 2,000 hours, i.e. with a difference of almost 4 times for the three cities, and 2.7 times for Rostov-on-Don.

Similar calculation results can also be presented for water consumption for humidification, air consumption in air conditioner on inflow and on first and second recirculation.

Figure 2. Annual values of technological parameters for various load classes:
(a) – energy consumption, (b) – duration of energy consumption
Figure 3. Annual energy consumption by months of the year: (a) - for the first class of loads; (b) - for the second class of loads

Fig. 3 shows the specific annual expenditures of the AC for different load classes by months of the year. We noted the peculiarities of AC functioning for separate months for each city, in particular:
- there are significant differences in heat consumption for the first and second load classes, with some cities consuming heat during the warm period of the year when district heating is turned off;
- while the average annual consumption of cold is close, its consumption varies 3 - 4 times in different cities. In Arkhangelsk, cold consumption is higher than that in St. Petersburg and Moscow, but lower than that in Rostov-on-Don in July - 2 times, and in June - 1.5 times.
4. Discussion
The purpose of the climate model is to justify the requirements to the content of climatic information for the conceptual design phase of the AC, based on the task of providing energy-efficient management of the AC functioning, and - consideration of the presentation of such information and demonstration of the results of its testing.

The climate model in the form of t-d-tables provides information on the repeatability of combinations of temperature and relative humidity of the outside air for different time intervals of the day and, depending on its basis, - a quantitative assessment of heat, cold, air, and water consumption.

A probabilistic-statistical climate model is the basis for a more accurate estimate of the multiyear average consumption of heat, cold, air, and water by various AC.

The economic evaluation of the performance of various AC under current economic conditions using total discounted costs shows that accounting for capital costs can change the system ranking of heat, cold, air, and water operating costs.

Experimental studies have shown that energy consumption calculations using the developed climate model provide a sufficient degree of convergence of the results.

5. Conclusions
As a result of the performed research, the proposed methodology of presentation of climatic information in combination with the methodology of justification of energy-saving modes allows one to provide selection of the technological scheme of heat and humidity air treatment, selection of setting capacities of AC subsystem equipment, calculation of consumption of heat, cold, and water in different periods of time.

Based on the results of AC operation of different supply air preparation schemes, it will be possible to determine a rational volume for each of these schemes and adopt an energy-efficient composition, as well as to determine a program for automating its operation depending on the current weather conditions in the climatic region of the object construction.

The actual tasks that cause the need to change the traditional approaches to the creation of AC for premises with different types of loads have been identified. The development of appropriate methodologies deserves serious attention, since their application makes it possible to achieve not only reduction of capital costs due to centralization of outdoor air processing, but also to significantly increase the efficiency of consumed energy resources [12].

6. Summary
The most complex system in the structure of the of microclimate support systems is the air conditioning system. The system approach is used for the development of a technical solution of AC, in which the main attention is paid to the modeling of modes and technological processes of air conditioning systems.

Thus, the proposed form of presentation of climatic information makes it possible to realize three interrelated problems. Firstly, we choose the optimal solutions for the technological schemes and the modes of functioning of air conditioning systems implemented in them. Secondly, we determine the setting capacities of subsystems with allowance for various degrees of nonavailability of the rated air parameters in premises. Thirdly, we calculate the technological parameters: the consumption of heat, cold, air, and water consumed, for different rated time periods.

7. References
[1] Rymkevich A A 2003 System analysis of optimization of general ventilation and air conditioning.
[2] Ryabova T V, Sulin A B, Nikitin A A, Emelyanov A L, Bordashev K A 2019 Equivalent parameters of thermal comfort of the room. In IOP Conference Series: Materials Science and Engineering 656 012045)
[3] Kuvshinov Y J 2006 Calculation of annual energy consumption by ventilation and air conditioning systems AVOK: Ventilation, heating, air conditioning, heat supply and construction thermal physics 7 15-8

[4] Shvetsov I V, Vankov Y V, Zagretdinov A R 2018 Control of rotary equipment unbalance with using statistical criteria comparison of vibration spectrum. In IOP Conference Series: Materials Science and Engineering 441 012051

[5] Kochenkov N V 2016 Adaptive control of air steam treatment in air-conditioning systems. Journal of Computer and Systems Sciences International 55(5) 767-76

[6] Malyavina E G, Ivanov D S, Frolova A A 2013 Presentation of climate information as “reference year”. Promyshlennoe i grazhdanskie stroitelstvo [Industrial and civil engineering] 9 27-9

[7] WMO No 722116 Dry-Bulb Temperature Hours for An Average Year July-ST. PETERSBURG.

[8] Malyavina E, Malikova O 2018 The Impact of the Climate Model Details on the Accuracy of Power Consumption Calculation of Air Conditioning Units. In IOP Conference Series: Materials Science and Engineering 463 022065

[9] Gvozdkov A, Suslova O 2017 Some Aspects of Improving the Efficiency of Air Treatment in the Contact Units of HVAC Systems. In Environmental Engineering. Proceedings of the International Conference on Environmental Engineering. ICEE 2017 10 pp 1-8 (Vilnius Gediminas Technical University, Department of Construction Economics & Property)

[10] Samarin O D 2017 The probabilistic-statistical modeling of the external climate in the cooling period. Magazine of Civil Engineering 73(5)

[11] Muraveinikov S S, Sulin A B, Baranov I V, Nikitin A A 2019 Average annual efficiency evaluation in the design of life support systems. In AIP Conference Proceedings 2141 030019