Energy performance analysis of the temperature control system of an object with a random principle of thermal perturbations

A B Sulin¹, A L Timofeevskiy¹, T V Ryabova¹, A A Nikitin¹, S S Muraveinikov¹ and S I Arendateleva²,³

¹Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics, ul. Lomonosova, 9 191002 St. Petersburg, Russia
²Yaroslav-the-Wise Novgorod State University, ul. B. St. Petersburgskaya, 41 173003 Veliky Novgorod, Russia
³E-mail: Svetlana.Arendateleva@novsu.ru

Abstract. The application of simulation modeling to the development of a temperature control system for an object with a random nature of thermal loads is considered. The object under study is a facility with enclosing structures made of fiberglass, inside of which there is heat-generating equipment. Thermostatic control of the object is carried out by a fully recirculating ventilation system that provides even blowing of the inner walls of the object with fresh air. To create a simulation model that is closest to real conditions, based on statistical meteorological data for the city of St. Petersburg, a model of meteorological conditions was created, suggesting every three hours the following parameters: ambient temperature, wind speed, solar radiation intensity, cloudiness. Heat generating equipment located inside the serviced facility does not operate continuously. The turning-on of this equipment occurs at random, the duration of work and the amount of heat dissipation also vary. To take into account this circumstance, the specified parameters are selected by the program in accordance with the Simpson distribution. The article presents graphs of changes in temperature and energy characteristics of the system for the three cold and three warm days of the considered annual period of the system operation. Conclusions are drawn about the feasibility of using the simulation method in the design and development of such systems, on the possible increase in their energy efficiency, as well as on the reduction of capital and operating costs.

1. Introduction
Modern high-tech equipment, which includes components subject to the action of the atmosphere, usually should work in a certain range of environmental parameters, the proper choice and implementation of which depends on the ability of equipment to function normally and ensure its design performance, as well as uptime [1, 2]. Among such requirements, one can single out the requirements for the quality of the surrounding air, its humidity, temperature, mobility and other parameters. In some cases, to ensure the required parameters of the ambient air, it is necessary to develop a temperature control system that is complex and saturated with equipment, which should operate year-round, quickly responding not only to changes in ambient temperature, solar radiation, but also to fluctuations in internal heat generation from the equipment itself. An important factor...

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
is to ensure maximum energy efficiency of the temperature control system, the maintenance of which is often very expensive [3].

2. Results and Discussions

The development and calculation of such a system is a labor-intensive process that requires taking into account a significant number of factors affecting its behavior, as well as taking into account their mutual influence [4, 5, 6], since it is the summation and superposition of peak loads on each other that is most often taken for the main design mode of operation of the temperature control system. To study complex systems with a large number of variables, it is advisable to use simulation. Further, using an example of a simulation model of an object’s temperature control system with a large number of unsteady external and internal parameters created in the AnyLogic program [7, 8], we will consider the annual cycle of its operation closest to reality. In the framework of this model, the system is considered as a system with lumped parameters. The combined action of various kinds of factors affecting the operation of the temperature control system sometimes poses quite unexpected tasks for it, which cannot always be taken into account with traditional design methods, but it is their consideration that makes it possible to obtain the most balanced and stable operating system.

The object under consideration represents a confined volume, inside of which there is periodically switched on equipment that releases a significant amount of heat (20–30 kW) during operation. The shell of the object consists of fiberglass with a thickness of about 30 mm. The facility is located in the open air in the city of St. Petersburg. Permissible environmental parameters inside the shell for the normal functioning of the equipment: air temperature from +5 to +45 °С, relative humidity not more than 70%, complete absence of drip moisture, which necessitates temperature control. The air thermostatic control system of the internal volume of the object is organized according to the principle of 100% recirculation. The air preparation system that processes it before being fed into the serviced volume allows first draining it to a dew point of about +5 °C and then heating it to the required temperature. The schematic diagram of the object under consideration is shown in figure 1.

![Figure 1. Scheme of the research object.](image)

To develop the most accurate model of the impact of the atmosphere on the object, we used statistical climatic data for the city of St. Petersburg, which were recorded daily for a year in increments of 3 hours. From the entire array of meteorological data, the following outdoor parameters were used to develop a simulation model, which have the greatest impact on the temperature control system:

- outdoor temperature – for calculating heat influx from the environment;
- wind speed – for calculating the heat transfer coefficient from fences to the outside air;
- cloud cover – for calculating solar radiation on the wall of an object.

In addition to these data, to calculate the heat input to the object from solar radiation, a parameter was added for the total (direct and scattered) daily average solar radiation flux density for each month of the year, taking into account the duration of daylight hours [9].

As noted earlier, under the shell of the object there is the equipment that during operation emits a time-varying thermal power. Due to the periodic nature of the heat in the serviced volume and the impossibility to determine their magnitude accurately, to calculate the heat balance of the room we used the distribution of its values according to the triangular law (Simpson’s law), which is often used when there is insufficient information about the parameters of the object. In this case, to specify a triangular distribution, it is necessary to know three quantities:
- is the minimum value of the parameter (min);
- is the maximum value of the parameter (max);
- the most probable value of the parameter (mode).

In accordance with the Simpson distribution, the following parameters were changed:
- frequency of turning the equipment on: it is accepted that the equipment is turned on from 1 to 2 times a month, most likely 1 time per month;
- duration of operation of the equipment: if it is turned on, the duration ranges from 24 to 48 hours, most likely 24 hours;
- heat from the equipment ranges from 20 to 30 kW, most likely 25 kW.

The algorithm of the temperature control system involves four modes of its functioning: two for the warm season (when the outdoor temperature is more than +15 °C) and two for the cold season (the outside temperature is less than +15 °C). Of the two modes possible in a certain period of the year, one is realized when the equipment inside the facility is turned off, and the other when it is turned on. An enlarged version of the algorithm is presented in figure 2.

![Figure 2](image_url)

**Figure 2.** The enlarged algorithm of the temperature control system. \( T_{\text{out}} \) is the outdoor temperature, \( Q_{\text{ob}} \) is the heat dissipation from the equipment, \( t_{\text{vent}} \) is the supply air temperature, \( t_{\text{in}} \) is the exhaust air temperature, \( t_{\text{w}} \) is the temperature of the inner surface of the wall.

Each operating mode is described in more detail below. Due to the impossibility of presenting, within the framework of this article, annual graphs of the temperature and energy characteristics of the system (due to their large size and saturation), graphs for three days of the warm and three days of the cold period of the year are presented to demonstrate the operation of the simulation model.

Modeling the system in the cold season. The two main tasks that the developed algorithm of the temperature control system had to solve in the cold season were to ensure the complete absence of drip moisture in the internal volume of the facility and increase its energy efficiency. Since the air preparation system for the object (not considered in this article) involves drying it to a dew point of +5 °C followed by heating it to the required temperature, in order to realize the condition of complete absence of moisture condensation in the object, it is necessary to maintain the temperature of all its surfaces at a level above +5 °C. The coldest surface of an object, on which droplet moisture...
from air can form, is the inner surface of its shell; therefore, in the cold season it is necessary to maintain the temperature of this surface above the dew point of the air blowing at it. Air supply to the inner surface of the shell of the object cannot always be ensured with sufficient uniformity [10], therefore, to ensure prevention of moisture condensation, the temperature of the inner surface of the shell of the object was set to $+15^\circ C$, i.e., $10^\circ C$ above the dew point of the supply air. In addition to the non-uniformity of the blowing of the inner surface of the shell with the supply air, it became possible to level out the influence of such factors as the unevenness of the wind load acting on the object from the outside and the non-isothermal supply air stream propagating along the internal wall of the object.

When the equipment located in the simulation facility was suddenly turned on, the generated heat causes significant heating of the internal volume. This circumstance allows using the excess heat to heat it and not to spend additional energy on heating the supply air [11]. In this case, it is advisable to transfer the temperature control system from the mode of maintaining the wall temperature at $+15^\circ C$ to the mode of maintaining the maximum allowable air temperature in the internal volume of the object, which, according to the terms of reference, should not be higher than $+45^\circ C$. Due to the non-uniformity of the inside temperature field, an air temperature of $+40^\circ C$ is accepted. The above described system operation algorithm is used at the outdoor temperature below $+15^\circ C$.

At higher outdoor temperatures, the discussed below algorithm of the system for the warm period of the year is used. Graphs of temperature changes in the temperature control system of the facility for three days of the cold period of the year, during which the equipment is turned on, are shown in figure 3. The beginning of the experiment was the time point 00 hours 00 minutes 01 second January 01. Further, the countdown of model time was carried out in minutes.

Figure 3. Graph of the change in the main temperatures of the temperature control system for three days of the cold season (December).

The graph of changes in the energy characteristics of the object for the same three days of the cold period of the year is shown in figure 4. The equipment was turned on in the time interval from 19,200 min to 22,000 min.
Figure 4. Graph of changes in the energy characteristics of the temperature control system for three days of the cold season (December).

As can be seen from figure 3, at low outdoor temperatures, the supply air temperature and the air temperature inside the serviced volume do not go beyond the required limits (+5 °C ... +45 °C) both when the heat-generating equipment is turned on and off. In the cold season, during operation of the heat-generating equipment, the recirculation air is cooled before it is supplied to the serviced volume by using the external temperature potential and does not entail significant energy costs [12].

Modeling the system in the warm season. With the unconditional need to keep the temperature of the internal volume within the specified limits, the control of the operation of the temperature control system of the facility in the warm season is aimed, inter alia, at minimizing energy costs to maintain the required parameters. Maintaining the temperature of the shell wall, which was emphasized in the algorithm of the system during the cold season, in this case does not matter, since the inclusion of the algorithm of the system for the warm period of the year occurs only if the ambient temperature reaches +15 °C and more. In normal mode, when the heat generating equipment is turned off, the supply air temperature is taken equal to the ambient air temperature. This condition can significantly reduce the heat transfer of the internal volume of the object with the environment, and minimize the amount of artificially obtained cold required for cooling the supply air before its subsequent supply to the serviced volume (the system is considered as a fully recirculation one).

When the heat generating equipment is turned on, the temperature control system in any period of the year maintains a temperature of +40 °C in the internal volume of the facility. This circumstance makes it possible to increase the outflow of excess heat into the environment by maintaining the maximum possible temperature difference outside and inside the object, as well as to minimize the power spent on cooling the recirculated air before its subsequent supply to the serviced volume while maintaining the required initial temperature data. A graph of temperature changes over time for three days of the warm period of the year (August), which also includes the period of activation of the heat-generating equipment, is shown in figure 5. In the period from 311000 minutes to 313100 minutes, the equipment is turned on.
Figure 5. Graph of changes in the main temperatures of the temperature control system for three days of the warm period of the year (August).

The graph of changes in the energy characteristics of the temperature control system for the same three days of the warm period of the year (August) is shown in figure 6.

Figure 6. Graph of changes in the basic energy characteristics of the temperature control system for three days of the warm period of the year (August).
3. Conclusion
The graphs for the warm and cold periods of the year clearly show that the simulated system in the entire range of outdoor temperatures, under the influence of solar radiation, as well as internal thermal loads, the occurrence of which is random, provides the required thermal regime inside the object, while maintaining high level energy efficiency [13, 14].

In the cold season, when the heat generating equipment is turned off, the cost of heating the supply air is minimized by maintaining its temperature at the minimum acceptable level, which helps prevent moisture condensation on the inner surface of the shell.

In the warm season, when the heat generating equipment is turned off, the cost of cooling the supply air is minimized by maintaining its temperature at the level of the outdoor temperature. As can be seen from the graph in figure 6, the level of total heat input to the object in this case is maintained at around 13 kW, which is insignificant for such an object.

In the event of a sudden turning on of the heat generating equipment in the cold season, the need for heating the supply air with a temperature control system completely disappears, and, conversely, there is a need for cooling it, which is relatively easy to do by using the low-temperature potential of outdoor air.

When the heat generating equipment is suddenly turned on during the warm season, a controlled increase in air temperature inside the facility to a maximum of +40 °C allows maximizing the outflow of excess heat into the environment and reducing the load on the air conditioning system.

The developed algorithm allows for research and experiments to optimize the operating modes of ventilation and heat exchange equipment, while minimizing capital and operating costs for the functioning of the temperature control system.

References
[1] Bykov V J and Ilyin G N 2010 Mnogokanal’naya cifrovaya sistema termostatirovaniya ehlementov radiometricheskogo bloka. [Multichannel digital temperature control system for radiometric unit elements Proceedings of the Institute of Applied Astronomy RAN 21 288–293 [In Russ.]
[2] Kravchenko A V, Plaksin S V and Sokolovskij I I 2005 Aktivnoe termostatirovanie poluprovodnikovyh SVCH-generatorov [Active temperature control of semiconductor microwave generators] Technology and design in electronic equipment [In Russ.]
[3] Kobeleva S A 2011 Metodicheskie podhody proektirovaniya resurso- i ehnergoehffektivnyh zdaniij [Methodological approaches to the design of resource and energy efficient buildings. Construction and reconstruction] Stroitel’stvo i rekonstrukciya 5(37) 18–20 [In Russ.]
[4] Mar’yasin O YU and Ogarkov A A 2017 Imitacionnoe modelirovanie i optimizaciya ehnergopotrebleniya ofisnogo zdaniya [Simulation and energy optimization of an office building] Simulation modeling. Theory and practice pp 480–4 [In Russ.]
[5] Shon D et al. 2017 CFD modelling of air temperature reduction and airflow induced by the use of chilled wall panels based on the biological principles of zebra stripes Architectural Science Review vol 60 6 507–515
[6] Bastani M S and Asadi S 2015 Simulating the impact of feedback on energy consumption and emission production in commercial buildings using agent-based approach AEI 2015: Birth and Life of the Integrated Building pp. 78–90
[7] Borschchev A 2013 The big book of simulation modeling: multimethod modeling with AnyLogic 6 (Chicago: AnyLogic North America) p 614
[8] Borschchev A, Karpov Y and Kharitonov V 2002 Distributed simulation of hybrid systems with AnyLogic and HLA Future Generation Computer Systems vol 18 6 pp 829–839
[9] 2012 Svod pravil SP131.13330.2012: Stroitel’naya klimatologiya. Aktualizirovannaya redakciya [Construction climatology. Updated edition] SNiP 23-01-99 (Moscow: NIISF RAASN)
[10] Lepesh G V, Sproge G A and Odnodvorec Yu V 2015 Imitacionnoe modelirovanie
дифференцированного обогрева вентиляируемого помещения комплексом современных отопительных приборов [Simulation of differentiated heating of a ventilated room with a complex of modern heating devices] TTPS 1(31) 31–37 [In Russ.]

[11] Szász C 2014 Intelligent building development and LabView-based modelling of a net zero-energy strategy International Review of Applied Sciences and Engineering vol 5 2 157–166

[12] Hesselbach J et al. 2008 Energy efficiency through optimized coordination of production and technical building services LCE 2008: 15th CIRP Int. Conf. on Life Cycle Engineering: Conf. Proc. CIRP p 624

[13] Baranska M, Fütterer J and Müller D 2017 Development of a generic model-assisted control algorithm for buildings HVAC systems

[14] Menassa C C et al. 2013 Conceptual framework to optimize building energy consumption by coupling distributed energy simulation and occupancy models J. of Computing in Civil Eng. vol 28 1 50–62