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DATAWARE AND SOFTWARE OF THE AUTOMATED TECHNOLOGY FOR COMPUTER- INTEGRATED CONTROL OF HEAT PUMP SYSTEMS

The paper has solved a scientific and applied problem as for substantiating requirements to technical and functional characteristics of the automated technologies of computer-integrated control of heat pump systems in the heating and cooling modes owing to its dataware and software developing and testing.

Following functional procedures have been taken into consideration during the dataware and software development of the computer-integrated subsystem for heating of buildings: monitoring of ambient air temperature, ground temperature, and operating modes of functional elements of the heat pump system as well as zonal monitoring of indoor air temperature; computer-integrated processing of the monitoring data; automated control of the heat pump as well as modes of zonal thermal medium supply to the building; and analysis of energy efficiency as for implementation of the proposed computer-integrated method to control systems of thermodynamic heating. It has been identified that thermal capacity of a heat pump is rather sensitive to indicators of the total heat losses of a building. If the total heat losses increase from 0.2°C/hour up to 0.5°C/hour then constant value of the thermal capacity increases by 48%. Moreover, thermal capacity of a heat pump is quite sensitive to ambient air temperature dynamics: if temperature variation is 12°C (i.e. 3°C-9 °C) then average increase in thermal capacity is 58 %.

Following functional procedures have been involved during the dataware and software development of the computer-integrated subsystem for cooling of buildings: monitoring of ambient air temperature and operating modes of functional elements of the heat pump system; zonal computer-integrated monitoring of indoor air temperature; computer-integrated the monitoring data processing based upon microcontrollers; automated control of the thermal pump operating modes (i.e. heat energy outfeed and release to the main intercooler unit); and analysis of energy efficiency as for implementation of the proposed computer-integrated method to control systems of thermodynamic cooling of buildings. The abovementioned has helped identify that thermal capacity of a heat pump is rather sensitive to indicator of heat exchange with surrounding air: four times increase in heat-exchange coefficient (i.e. from 1°C/hour up to 4°C/hour) results in 20% growth of thermal capacity of the cooling subsystem system at similar ambient air temperature (it varies from 30°C up to 36 °C) if the maintained target indoor temperature is 22°C.

Keywords: dataware and software, automated technology, cooling, heating, heat pump.

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ІНФОРМАЦІЙНЕ ТА ПРОГРАМНЕ ЗАБЕЗПЕЧЕННЯ АВТОМАТИЗОВАНОЇ ТЕХНОЛОГІЇ КОМП'ЮТЕРНО-ІНТЕГРОВАНОГО КЕРУВАННЯ ТЕПЛОНАСОСНИМИ СИСТЕМАМИ

В статті вирішено науково-прикладну задачу обґрунтування вимог до техніко-функціональних характеристик автоматизованих технологій комп'ютерно-інтегрованого керування теплонасосними системами у режимах опалення та кондиціонування завдяки розробці та тестуванню її інформаційного та програмного забезпечення.

Під час розробки інформаційного та програмного забезпечення комп'ютерно-інтегрованої підсистеми опалення будівель було враховано наступні функціональні процедури: моніторинг температури повітря навколишнього середовища, температури ґрунту та режимів роботи функціональних елементів теплонасосної системи, а також зональний моніторинг температури повітря в будівлі; комп'ютерно-інтегрована обробка даних моніторингу; автоматизоване керування тепловим насосом та режимами зональної подачі теплоносія до будівлі; аналіз енергоефективності реалізації запропонованого комп'ютерно-інтегрованого методу керування системами теплонасосного опалення. Встановлено, що теплова потужність теплового насосу є значно чутливим параметром до показників сумарних теплових втрат будівлі. За умови підвищення сумарних теплових втрат будівлі з 0,2 °С/год. до 0,5 °С/год. стале значення теплової потужності зростає на 48 %. Теплова потужність теплового насосу є значно чутливою характеристикою до динаміки температури повітря навколишнього середовища: при зміні температури на 12 °С (у діапазоні від –3 °С до 9 °С) теплова потужність зростає у середньому на 58 %.

Під час розробки інформаційного та програмного забезпечення комп'ютерно-інтегрованої підсистеми кондиціонування будівель було враховано наступні функціональні процедури: моніторинг температури повітря навколишнього середовища та режимів роботи функціональних елементів теплонасосної системи, а також зональний комп'ютерно-інтегрований моніторинг температури повітря в будівлі; комп'ютерно-інтегрована обробка даних моніторингу на основі мікроконтролерних засобів; автоматизоване керування режимами роботи теплового насосу (відбирання та скидання теплової енергії до головного теплообмінника); аналіз енергоефективності реалізації запропонованого комп'ютерно-інтегрованого методу керування системами теплонасосного кондиціонування будівель. У результаті цього було встановлено, що теплова потужність теплового насосу є значно чутливим параметром до показника теплообміну з навколишнім середовищем: збільшення коефіцієнту теплообміну в 4 рази (з 1 °С/год. до 4 °С/год.) призводить до зростання теплової потужності підсистеми кондиціонування на 20 % за однакових температур повітря навколишнього середовища (змінюється в діапазоні від 30 °С до 36 °С) під час підтримання цільової температури повітря в будівлі на рівні 22 °С.

Ключові слова: інформаційне та програмне забезпечення, автоматизовані технології, охолодження, опалення, тепловий насос.

1. Introduction

Development and implementation of the automated technologies controlling heat pump systems, including computer-integrated control of heating and cooling processes of buildings, make it possible to optimize considerably the use of energy and resources. In turn, dataware and software of such systems helps provide accurate zonal control and regulation in premises and buildings optimizing energy losses and minimizing heating losses respectively [1, 2].

Online precision automated control of temperature behaviour enables provision of both stable and comfortable microclimate in residential units and administrative facilities. The automated indoor temperature control under heating and cooling modes, based upon computer-integrated methods and means with further energy accumulation in the thermal storage, makes it possible to provide both stable and comfortable microclimate of buildings and structures taking into consideration indicators of energy consumption and energy loss. Dataware and software of computer-integrated subsystems of the automated heating and cooling control help involve various destabilizing factors and such informative parameters as meteorological conditions, building structures, physiochemical properties of the building materials etc. Consequently, the scientific and applied problem as for substantiation of requirements to technical and functional characteristics of the automated technologies of computer-integrated control of heat pump systems under heating and cooling modes is both promising and topical today owing to its dataware and software developing and testing.

The paper aim is to improve energy efficiency of indoor heating and cooling through the development and use of software and data support of the automated technology of computer-integrated control of heat pump systems. The research object is processes of the automated control of heat pump systems. The research subject involves methods, models, and means to develop the automated technologies of computer-integrated control of heat pump systems.

2. Dataware of computer-integrated subsystem for the automated control of indoor heating

A model, which includes following procedures and functions, has become the developed dataware of the technology for the automated control of indoor heating: monitoring of ambient air temperature, ground temperature, and operating modes of functional elements of a heat pump system; and zonal monitoring of indoor temperature; online computer-integrated processing of the monitoring data; automated control of a heat pump as well as the modes of zonal thermal medium delivery to the building; and analysis of energy efficiency as for implementation of the proposed computer-integrated method to control systems of thermodynamic heating. Fig. 1 shows the generalized graphical interpretation of the proposed dataware of computer-integrated subsystem of the automated control of building heating in the form of a functional scheme taking into consideration the known findings [3, 4].

The key goal to solve the scientific and research problem of information support development for computer-integrated subsystem indoor heating is substantiation of the requirements to intrinsic program component of the automated control of the subsystem. Hence, relying upon the fact, the necessity arises to perform mathematical description of the main stages of data gathering and processing with following generation of controlling and regulating impacts in accordance with the abovementioned information model (see Fig. 1).

The proposed mathematical formulation is based upon a heat-balance equation of a building [3, 5]:

$$T_{in}(t+1) = T_{in}(t) + \left(P_{HP}(t) - Q_{SUM}(t)\right) \cdot \Delta t, \tag{1}$$

where T_{in} is indoor air temperature; P_{HP} is capacity of a heat pump; Q_{SUM} is total thermal loss; t is current time interval; and Δt is time interval being analyzed.

Parameter of equation (1), corresponding to the total thermal loss (Q_{SUM}), can be calculated based upon the equation [5, 6] taking into account components of the heat losses through walls, roof, windows, and floor:

$$Q_{SUM}(t) = k_{AIR}(T_{in}(t) - T_{out\ air}(t)) + k_{GROUND}(T_{in}(t) - T_{out\ ground}(t)), \tag{2}$$

where Q_{SUM} is total thermal loss; T_{in} is indoor air temperature; $T_{out\ air}$ is ambient air temperature; $T_{out\ ground}$ is ground temperature; k_{AIR} is coefficient of the total thermal losses through windows, roof, and walls of the building; k_{GROUND} is coefficient of heat losses of the building through its floor; and t is current time interval.

Thermal capacity parameter of a heat pump (P_{HP}) within equation (1) is the controlled parameter. Consequently, controlling rule should be selected. Analysis of prior information as for synthesis of temperature controllers of different building types [7–9] has helped identify that *PI* regulating devices are characterized as satisfactory. In turn, while controlling indoor temperature, the regulator is described using the equation:

$$P_{HP}(t) = K_p e(t) + K_I \int e(t)dt, \tag{3}$$

where P_{HP} is heat pump capacity; e is control error being calculated as a difference between the target and current indoor temperatures; K_P is proportional gain; K_I is integral factor; and t is current time interval.

Relying upon the PI rule, air control error in formula (3) is calculated at discrete time intervals by means of a program block of the subsystem based upon indoor air measurement monitoring data as a difference between the target indoor temperature and the current one with the help of the formula:

$$e(t) = T_{in\ target} - T_{in}(t), \quad (4)$$

where e is control error of indoor air temperature; $T_{in\ target}$ is target indoor air temperature; T_{in} is current indoor temperature; and t is current time interval.

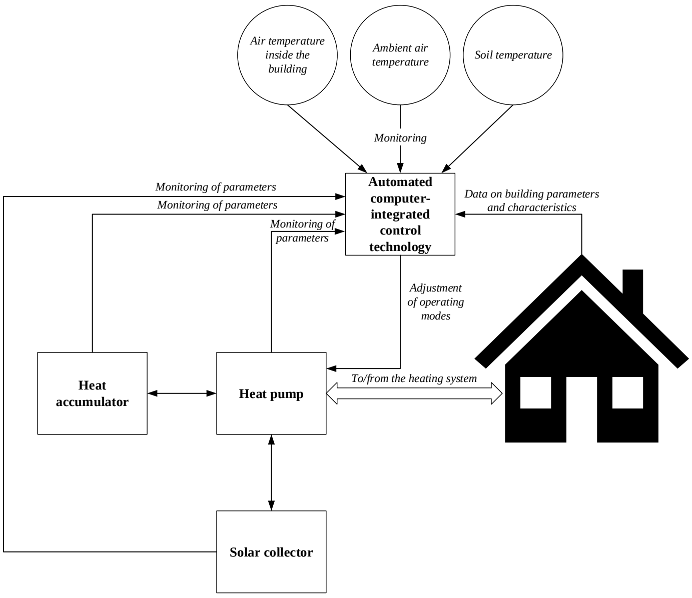

Fig. 1. Functional implementation scheme of information model of the computer-integrated subsystem of the automated control for indoor heating

As it has been abovementioned, the designed information support of computer-integrated subsystem of the automated control of building heating involves zonal regulation of indoor temperature. In such a way, during the development of the subsystem program block, formula (4) involves its cyclic use for each zone of the building with future averaged and gradient analysis.

Taking into consideration the monitoring data processing as well as further automated control of indoor temperature based upon the heat pump control through digital procedures, integral component of the error, being a component of formula (3), should be computed relying upon the equation:

$$\int e(t)dt = \sum_{i=0}^{t} e_i \Delta t, \quad (5)$$

where e is control error of indoor air temperature; i is serial number of discrete timing; and Δt is time interval being analyzed.

Thus, as it has been abovementioned, the development results of information support of computer-integrated subsystem of the automated control of building heating may be applied as the algorithmic basis while synthesizing and testing software of the designed subsystem of the automated control of building heating.

3. Software of computer-integrated subsystem of the automated control for building heating

The designed software, being functionally algorithmic basis to substantiate requirements to thermal pump system for building heating, is based upon following functional chain being developed cyclically online: determination of target indoor air temperature value; assessment and consideration of a dynamic range of change in such destabilizing factors as ambient air temperature, and ground temperature; measuring online monitoring of indoor temperature; determination of indoor air regulation at each time step of the simulation; computation of the integral component of a regulation error; assessment of the output value of PI regulator signal based upon the data on a current error taking into consideration the integral component; calculation of the heat pump capacity based

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upon the output value of PI regulator signal; introduction of restrictions on a capacity parameter of the heat pump to avoid initiation of negative values; evaluation of the total thermal losses through walls, roof, windows, and floor of the building; and computation of the updated current indoor temperature value relying upon the data on heat pump capacity and total thermal losses.

Single-storey building with the internal volume of 450 m^3 and overall dimensions of 15x12x2.5 m, which corresponds to the requirements for standard structures of such a type, has been selected as the basis to develop the software. Light concrete is a construction material for the bearing stratum of a protective structure. Mineral cotton is a thermal insulation material being popular today owing to its satisfactory thermal characteristics making it possible to maintain comfortable indoor temperature for a full year decreasing heat looses in winter and heat input in summer. Statistical data as for ambient air temperature dynamics have been selected for climatic conditions of Dnipropetrovsk Region. While developing program component of computer-integrated subsystem to control indoor heating, PI regulator was adjusted in such a way to maintain target indoor temperature at the level of 21°C ambient air temperature varied from –3°C up to 9°C and ground temperature varied from 6°C up to 10°C.

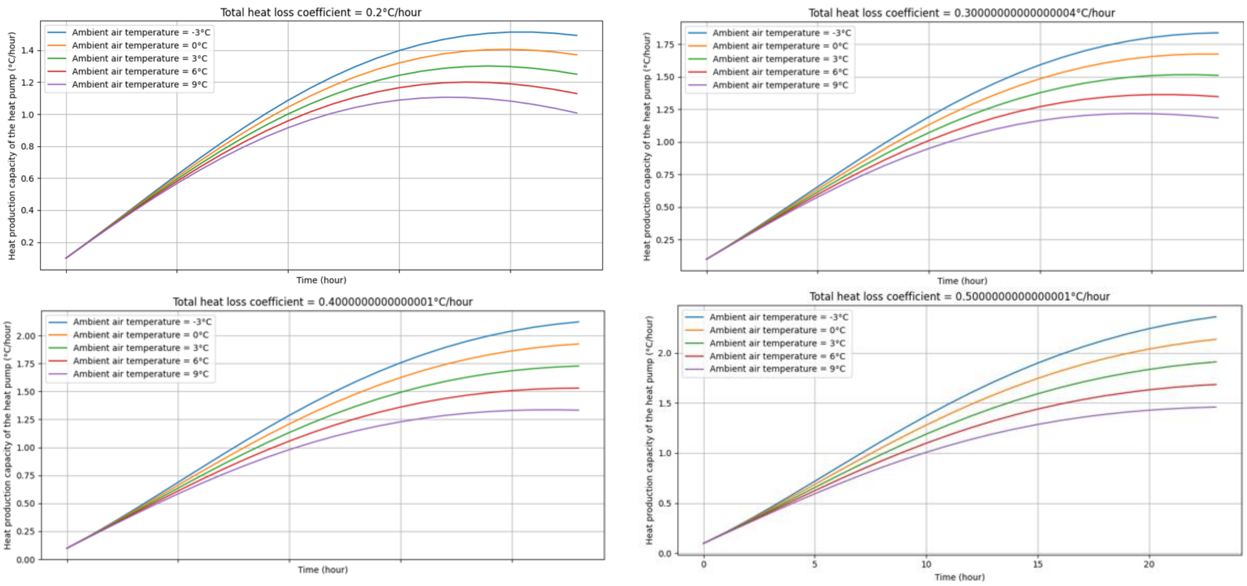

Fig. 2. Heat pump capacity dynamics during indoor heating

Relying upon the implementation of a program component of the analyzed computer-integrated subsystem of heating control, using Python language in the JupyterLite online environment [10, 11], graphical dependencies have been obtained (see Fig. 2) which helped substantiate requirements for the technical and functional parameters as well as for the characteristics of heat pump equipment.

capacity during indoor heating. Consequently, more rapid heating and maintenance of adequate target temperature should involve ranging of a pump thermal capacity indicated along ordinate axis according to the corresponding ambient conditions while multiplying by $k=Time$.

Relying upon the analysis of the findings of a program component of a computer-integrated subsystem of the automated control of indoor heating, it is possible to conclude the following:

– thermal capacity of a heat pump is rather sensitive to indicators of the total thermal losses of a building: if the total thermal losses of a building increase from 0.2°C/hour up to 0.5°C/hour then constant value of the thermal capacity grows from 1.25°C/hour (when the average ambient air temperature is 3°C) to 1.85°C/hour (when the average ambient air temperature is 3°C) to be 48% of the initial thermal capacity;

– heat capacity of a thermal pump is rather sensitive to dynamics of ambient air temperature: if temperature changes within the dynamic range of –3°C to 9° then thermal capacity increases from 1.0°C/hour to 1.5°C/hour (in terms of the minimal total heat losses being 0.2°C/hour), and from 1.45°C/hour to 2.4°C/hour (in terms of the total thermal losses being 0.5°C/hour). It is 50%-65% per unit; and

– the abovementioned numerical characteristics of the dynamics of heat pump equipment thermal capacity during indoor heating are based upon calculation of the target temperature (i.e. 21°C) from its initial value (i.e. 12°C) per day.

The carried out research, aimed at the development of software for computer-integrated subsystem of the automated control to heat buildings, has helped substantiate the requirements for technical and functional characteristics of a thermal pump being, in turn, the central structural element of the subsystem for the automated control of indoor heating.

4. Dataware of computer-integrated subsystem for the automated control of indoor cooling

Analogously with a heating process, the designed dataware for the automated control of indoor cooling (heat utilization) is based upon a model which includes and implements various procedures, operations, and functions:

– ambient air temperature monitoring as well as operating modes of functional elements of a heat pump system, and zonal computer-integrated monitoring of indoor air temperature;

– computer-integrated processing of the monitoring data using microcontrollers;

– computer-integrated automated control of the thermal pump operating modes (i.e. heat energy removal and release to the main intercooler unit); and

– analysis of energy efficiency as for implementation of the proposed computer-integrated method to control the systems of thermodynamic indoor cooling.

Fig. 3 shows the proposed generalized graphical interpretation of the designed dataware of a computer-integrated subsystem of the automated control of indoor cooling in the form of a functional scheme taking into consideration the known findings [12, 13].

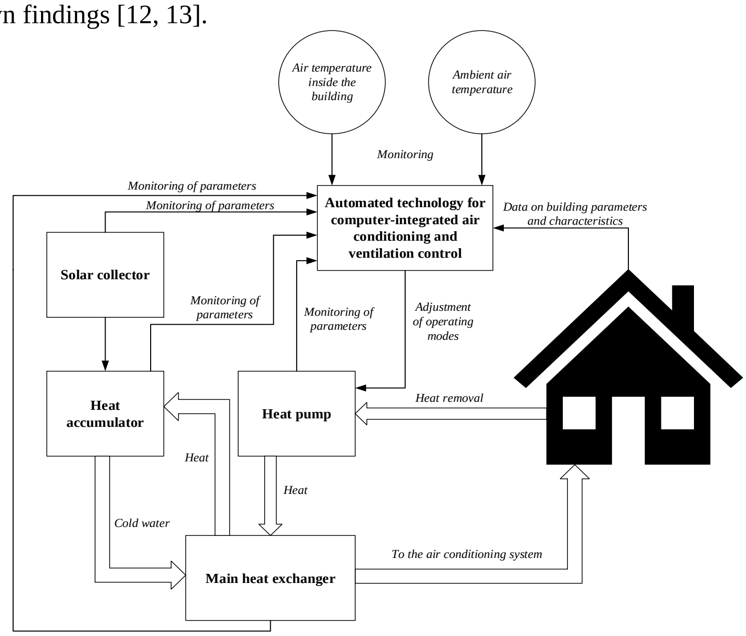

Fig. 3. Functional implementation scheme of an information model of the computer-integrated subsystem of the automated control for indoor cooling (heat utilization)

The proposed mathematical formulation of the automated control for indoor conditioning and ventilating subsystem with the possibility to accumulate heat in the thermal storage is based upon a model of thermal balance of a building taking into consideration control actions [14, 15]:

$$T_{in}(t+1) = T_{in}(t) + \frac{\alpha\left(T_{out}(t) - T_{in}(t)\right) + \beta \cdot u(t)}{S_{area}}, \quad (6)$$

where T_{in} indoor air temperature; T_{out} is ambient air temperature; α is thermal structure-environment conductivity; β is coefficient taking into consideration the environmental conditions; u is control signal; S_{area} is total area of the building involving following surfaces: ceiling, floor, windows, and walls; and t is current time interval.

It should be mentioned that equation (6) takes into consideration the competitive heat-exchange processes, namely indoor heating at the expense of higher ambient temperature to compare with the target indoor temperature $\alpha\left(T_{out}(t) - T_{in}(t)\right)$, and the total heat losses through walls, windows, ceiling, and floor $\beta \cdot u(t)$.

The parameter (u) in equation (6) is the regulated value. Hence, selection of a regulating rule is required. Analysis of prior information as for synthesis of temperature controllers of different building types [7–9] during their cooling has helped identified that PI regulating devices are characterized as satisfactory. Following equation can describe the regulator type while indoor temperature controlling under conditioning mode:

$$u(t) = K_P \cdot e(t) + K_I \sum_{i=0}^{t} e_i \Delta t, \quad (7)$$

where u is control signal for a heat pump system; K_P is proportional gain; K_I is integral factor; e is control error; t is current time interval; i is serial number of discrete timing; and Δt time interval being analyzed.

Relying upon the PI rule, formula (7) calculates a temperature control error under conditioning mode within the discrete time intervals. The computation is performed using the subsystem block based upon the temperature measurement monitoring data as a difference between the target indoor temperature and the current one similarly to a heating process where formula (4) is applied.

Thermal capacity of the conditioning system (heat utilization), relying upon the idea represented by a functional implementation scheme of an information model of a computer-integrated subsystem of indoor conditioning, can be calculated through the formula [17, 18]:

$$P_C = S_{area} \cdot \left| u(t) \right| , \quad (8)$$

where P_C is thermal capacity of the conditioning system (heat utilization); u is control signal for heat pump system; S_{area} is total area of the building taking into consideration following surfaces: ceiling, floor, windows, and walls; and t is current time interval.

In formula (8), signal module for the heat pump system control ($\left| u(t) \right|$) shows a direction of thermal energy movement; namely, its removal to cool the building.

In such a way, the research, intended to design dataware of a computer-integrated conditioning and ventilating subsystem for buildings at the expense of heat utilization (removal), which were implemented through synthesis of functional scheme of information model of computer-integrated subsystem to control indoor conditioning as well as through mathematical formulation of the main stages of data collecting and processing as for monitoring of parameters of processes and objects for ventilation of buildings with future generation of control signals by thermal pump to achieve and maintain target indoor air temperature, are the algorithmic basis for software of a subsystem controlling indoor conditioning.

5. Software for computer-integrated subsystem of the automated control of indoor conditioning

Following set of procedures, functions, and operations, developed by microcontroller block online, are the functional and algorithmic basis for the designed software of the automated control subsystem for indoor conditioning:

– definition of the target indoor air temperature to be achieved and maintained;
– parallel computer-integrated monitoring of both ambient air temperature and indoor air temperature;
– assessment of the indoor air temperature deviation from its target value using formula (4);
– identification of the required control value for conditioning subsystem using formula (7);
– assessment of a heat indicator increase and its loss at the expense of heat-exchange with the environment, and impact on the system of the automated conditioning control;
– calculation of the updated indoor temperature value; and
– computation of the thermal capacity of indoor conditioning subsystem.

While developing a program component of the computer-integrated subsystem to control indoor conditioning, PI regulator was adjusted for the target temperature maintenance (i.e. 22°C). At the same time, the ambient air temperature varies from 30°C up to 36°C correlating with the statistical data as for ambient air temperature dynamics for climatic conditions of Dnipropetrovsk Region in warm season. Based upon the implementation of a program component of the analyzed computer-integrated subsystem for indoor conditioning using thermal pump for heat utilization, Python language in the JupyterLite online environment [10, 11] was applied to obtain graphical dependencies (see Fig. 4). That helped substantiate the requirements for technical and functional parameters as well as for characteristics of heat pump equipment used for indoor conditioning and ventilating.

It should be mentioned that the graphical dependencies in Fig. 4 characterize daily dynamics of thermal capacity during indoor conditioning (negative values of heat capacity within the graphical dependencies show direction of the thermal energy movement, i.e. heat removal from the building. Moreover, more rapid cooling (i.e. heat utilization) and the target temperature maintenance while conditioning and ventilating need scaling of the thermal pump capacity along the ordinate axis (cooling capacity is the parameter) according to the corresponding ambient conditions while multiplying by $k = Time$. Analysis of the obtained results has made it possible to identify that thermal capacity of a heat pump is rather sensitive to the indicator of heat exchange with environment. The four-time increase in a heat-exchange coefficient (i.e. from 1°C/hour up to 4°C/hour) results in 20% (25 kW-30 kW) growth of thermal capacity of the conditioning subsystem system provided the ambient air temperature is equal.

Consequently, the research to design the software for a computer-integrated subsystem of the automated control of indoor conditioning has helped substantiate requirements to technical and functional characteristics of heat pump equipment (see Fig.4) being, in turn, the central structural element of a subsystem for the automated control of indoor conditioning and ventilating.

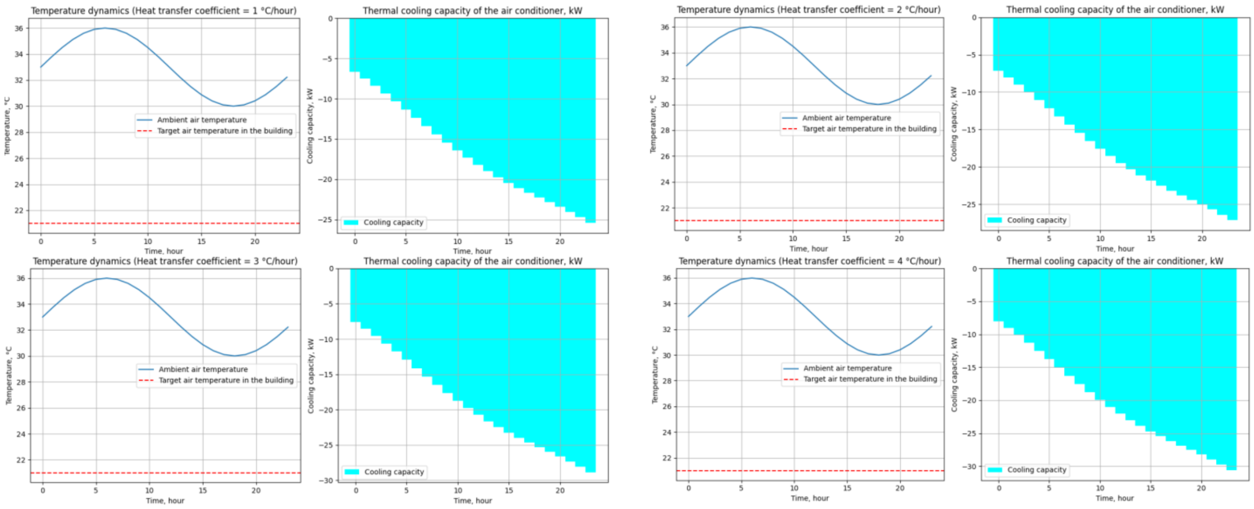

Fig. 4. Capacity dynamics of a thermal pump while indoor conditioning (heat utilization)

6. Conclusions

Resulting from the research, the topical scientific and applied problem has been solved which concerned dataware and software development for the automated technology controlling thermal pump systems operating for heating and conditioning. The key findings are as follows:

1. Dataware for computer-integrated control of indoor heating has been developed. It involves such functional procedures as: monitoring of ambient air temperature, ground temperature, operating modes of functional elements of thermal-pump system as well as zonal monitoring of indoor air temperature; computer-integrated processing of the monitoring data; automated control of a heat pump, and modes of zonal thermal medium delivery to a building; and analysis of energy efficiency as for implementation of the proposed computer-integrated method to control systems of thermal pump heating.

2. Software of the computer-integrated subsystem of the automated control to heat buildings has been implemented and tested using computer experiment methods. As a result, it has been identified that thermal capacity of a heat pump is rather sensitive to indicators of the total thermal losses of a building (if the total thermal losses increase from 0.2°C/hour to 0.5°C/hour then constant value of the heat capacity increases by 48%); thermal capacity of a heat pump is rather sensitive to the ambient air temperature dynamics (if temperature varies within the -3°C-9 °C dynamic range then thermal capacity experiences 58% increase on the average).

3. Information support for a computer-integrated subsystem of the automated control of indoor conditioning has been developed. It takes into consideration following functional procedures: monitoring of the ambient air temperature and operating modes of the functional elements of the system as well as zonal computer-integrated monitoring of the indoor air temperature; computer-integrated processing of the monitoring data based upon microcontrollers; automated control of the heat pump operations (i.e. heat energy removal and release to the main intercooler unit); and analysis of energy efficiency of the proposed computer-integrated method implementation to control systems of the heat pump indoor conditioning.

4. Software of the computer-integrated subsystem of the automated control of indoor conditioning and ventilating has been implemented and tested using computer experiment methods. As a result, it has been identified that thermal capacity of a heat pump is rather sensitive to indicator of heat exchange with environment: a four-time increase in heat-exchange coefficient (i.e. from 1°C/hour up to 4°C/hour) results in 20% growth of thermal capacity of the conditioning subsystem system provided the ambient air temperature is equal (it varies from 30°C up to 36 °C); a four-time increase in heat-exchange coefficient (i.e. from 1°C/hour up to 4°C/hour) results in 20% growth of thermal capacity of the conditioning subsystem system at similar ambient air temperature if the maintained target indoor temperature is 22°C.

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