LIFE CYCLE MANAGEMENT OF CONSTRUCTION FACILITIES

УПРАВЛЕНИЕ ЖИЗНЕННЫМ ЦИКЛОМ ОБЪЕКТОВ СТРОИТЕЛЬСТВА

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Original Empirical Research

Digital Approach to Lifecycle Management of a Low-Rise Capital Construction Facility with Heat and Air Exchange

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Abstract

Introduction. The relevance of using applying air-source heat pumps (ASHPs) in Russia’s moderately cold climate conditions is restrained by a sharp decline in their efficiency at low outdoor air temperatures. The aim of this study is to present a digital approach to lifecycle management of low-rise capital construction facilities based on a combined heat pump system with optimized heat and air exchange.

Materials and Methods. A technical solution is set forth incorporating a patented mixing chamber installed in the boiler room to supply an air mixture with a calculated temperature gradient to the ASHP evaporator. The system is integrated with a cross-stream supply and exhaust ventilation (efficiency of 40–60%) and controlled by a digital module based on a microprocessor and PWM regulator. Mathematical modeling of streams was performed using the Bernoulli and continuity equations. For monitoring and automatic control, a set of temperature and pressure sensors was employed to ensure adaptive operation of the compressor, fans, and backup electric boiler.

Research Results. Experimental data have confirmed that the joint operation of the ASHPs with a heat recuperator and mixing chamber allows maintaining a high coefficient of performance (COP) of the system. It was found that the threshold of economic feasibility remains at an outdoor air temperature of down to –15°C and heat carrier temperatures of +30…+45 °C. The developed digital control algorithm optimizes the ratio of outdoor to recirculating air minimizing heat losses and electrical loads.

Discussion and Conclusion. Implementation of the suggested digital modular and functional control scheme ensures rational heat and air exchange, reduces the size and cost of engineering utilities, and enhances the energy efficiency of low-rise buildings. The developed solution can be scaled for a broad range of climatic conditions nationwide contributing to resource conservation and extension of the lifecycle of capital construction facilities.

Keywords: lifecycle management; capital construction facilities; heat pump systems; digital twin; simulation modeling

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Оригинальное эмпирическое исследование

Цифровой подход к управлению жизненным циклом малоэтажного объекта капитального строительства с тепло- и воздухообменом

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Аннотация

Введение. Актуальность применения воздушных тепловых насосов (ВТН) в условиях умеренно холодного климата России ограничена резким снижением их эффективности при низких температурах наружного воздуха. Цель статьи — представить цифровой подход к управлению жизненным циклом малоэтажных объектов капитального строительства на основе комбинированной теплонасосной системы с оптимизированным тепловоздухообменом.

Материалы и методы. Предложено техническое решение, включающее запатентованную камеру смешения, устанавливаемую в помещении котельной, которая обеспечивает подачу на испаритель ВТН воздушной смеси с расчетным температурным градиентом. Система интегрирована с приточно-вытяжной вентиляцией перекрестного типа (КПД 40–60 %) и управляется цифровым модулем на базе микропроцессора и ШИМ-регулятора. Математическое моделирование потоков выполнено с применением уравнений Бернулли и неразрывности. Для мониторинга и автоматического регулирования использован комплекс датчиков температуры и давления, обеспечивающий адаптивную работу компрессора, вентиляторов и резервного электрокотла.

Результаты исследования. Экспериментальные данные подтвердили, что совместная работа ВТН с рекуператором и смесительной камерой позволяет поддерживать высокий коэффициент эффективности (COP) системы. Установлено, что порог экономической целесообразности сохраняется при температуре наружного воздуха до –15 °C и температуре теплоносителя +30…+45 °C. Разработанный алгоритм цифрового управления оптимизирует соотношение уличного и рециркуляционного воздуха, минимизируя теплопотери и электрические нагрузки.

Обсуждение и заключение. Внедрение предложенной цифровой модульно-функциональной схемы управления обеспечивает рациональный тепловоздухообмен, снижает габариты и стоимость инженерных коммуникаций, а также повышает энергоэффективность малоэтажных зданий. Разработанное решение может быть масштабировано для широкого диапазона климатических условий РФ, способствуя ресурсосбережению и продлению жизненного цикла объектов капитального строительства.

Ключевые слова: управление жизненным циклом; объекты капитального строительства; теплонасосные системы; цифровой двойник; имитационное моделирование

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Introduction. Over the recent years, the proportion of demand in the market of air-source heat pumps (ASHPs) has risen tenfold in European and Scandinavian countries that can be called moderately cold. Russia is at the top of the official ranking of the relatively cold countries. Thus possible and effective use of air-source heat pumps of most of the country's climatic conditions remains relevant [1].

It is to be noted that well-known scientists from Russia [2–7] and the West [8–14] have dealt with the issues pertaining to the life cycle of capital construction facilities.

In the modern conditions, continuing on the tradition of resource and energy conservation, development and practical solutions for using (ASHPs) based on digital computer control are becoming increasingly important.

Materials and Methods. A distinct feature of application of ASHPs is that ambient air is used as a source of low-potential heat. If installed outdoors, it might be not effective, particularly at low outdoor temperatures. The authors set forth using a mixing chamber device built into a boiler room [15] to supply the pressure of the air mixture to a heat exchanger evaporator with a calculated temperature gradient (Fig. 1).

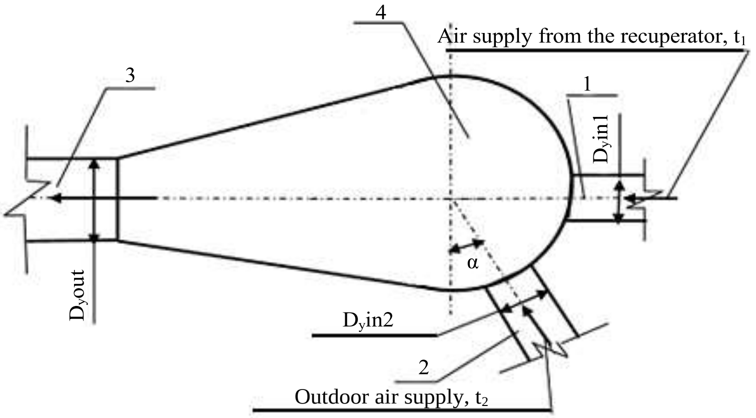

Fig. 1. Device for mixing gas streams

It is to be noted that the operation of the ASHPs mixing chamber is an essential link for recycled air mixing in the evaporator.

The air-stream mixing device itself contains an inlet pipe of an air duct, a pipe for supplying additional stream, and a section of a mixed stream. The nozzle for supplying additional stream 2 is located at an angle within 0 ° ≤ α ≤ 90 ° to the vertical (Fig. 1).

The inlet pipe of the duct is connected to a chamber made in the form of a capsule shaped like a hemisphere connected to a large base of a truncated cone. The diameters of the inlet pipe of the duct and the pipe for supplying additional air stream are equal, with each referring to the diameter of the outlet pipe of the duct directed to the evaporator of the ASHPs ($d_{inlet1} = d_{\text{вх}2} = 0.7d_{outlet}$).

This technology of air mixing organization enables an increase in the intensity of equilibrium mixing thus improving the heat exchange conditions. The greatest mixing intensity of the mixed stream occurs once it enters the zone of the truncated cone and chamber, and once it enters the cylindrical part of the outlet pipe of the duct 3, the homogenized stream transitions into a laminar stream. The velocity of the homogenized stream before it enters the cylindrical part of the outlet pipe of the duct 3 increases to the initial velocity of the main stream of the duct 1, equal to the stream velocity before it enters the hemisphere 4 according to the Bernoulli equation:

$$\frac{pv^2}{2} + pgh + p = const,$$

where $\frac{pv^2}{2}$ is the dynamic pressure; pgh is the hydrostatic pressure; p is the static pressure.

Given the cross section of the inlet pipe of the duct 1, the branch pipe for supplying additional stream 2 and the outlet pipe of the flue 3 using the Bernoulli equation, let us write:

$$\left(\frac{pv_{inlet1}^2}{2} + p_{inlet1}gh_{inlet1} + p_{inlet1}\right) + \left(\frac{pv_{inlet2}^2}{2} + p_{inlet2}gh_{inlet2} + p_{inlet2}\right) = \frac{pv_{outlet}^2}{2} + p_{outlet}gh_{outlet} + p_{outlet}$$

As the pressure $p_{\text{вх}1}$, $p_{\text{вх}2}$and $p_{\text{вых}}$ at the cross-sectional levels of the inlet pipe of the duct 1, the branch pipe for supplying additional stream 2 and the outlet pipe of the duct 3 are equal to the atmospheric one, i.e., $p_{\text{вх}1} = p_{\text{вх}2} = p_{\text{вых}}$, the equation takes the form:

$$\left(\frac{pv_{inlet1}^2}{2} + p_{inlet1}gh_{inlet1}\right) + \left(\frac{pv_{inlet2}^2}{2} + p_{inlet2}gh_{inlet2}\right) = \frac{pv_{outlet}^2}{2} + p_{outlet}gh_{outlet}$$

Based on the continuity equation:

$$\frac{v_{inlet}}{v_{outlet}} = \frac{s_{inlet1} + s_{inlet2}}{s_{outlet}},$$

where $s_{inlet1}, s_{inlet2}, s_{outlet}$ are the areas of the transverse sections and $v_{inlet} = v_{outlet}$.

Then $s_{inlet1} + s_{inlet2} = s_{outlet}$. Expressing the parameters $\frac{\pi d_{inlet1}^2 + \pi d_{inlet2}^2}{4} = \frac{\pi d_{outlet}^2}{4}$, we get:

$$d_{inlet1}^2 + d_{inlet1}^2 = d_{outlet}^2$$

According to the specified conditions, d_{inlet1} and d_{inlet2} are equal, as an example let us denote: $d_{inlet1} = d_{inlet2} = 0{,}2m$.

Then:

$$d_{outlet} = \sqrt{d_{inlet1}^2 + d_{inlet2}^2} = \sqrt{0.2^2 + 0.2^2} = 0.28m.$$

Then we get the ratio $\frac{d_{inlet}}{d_{outlet}} = \frac{0.2}{0.28} = 0.7$.

Then

$$d_{inlet1} = d_{inlet2} = 0.7d_{outlet}.$$

The suggested tool enables an increase in the equilibrium mixing intensity improving the heat exchange conditions.

In the studies of the air exchange process, the authors have developed a combined heat pump heat supply system including a mixing chamber, an air exchange circuit with a recuperation element and an additional tubular heating exchanger (THE) controlled by a pulse width modulation regulator (PWM regulator) (Fig. 2).

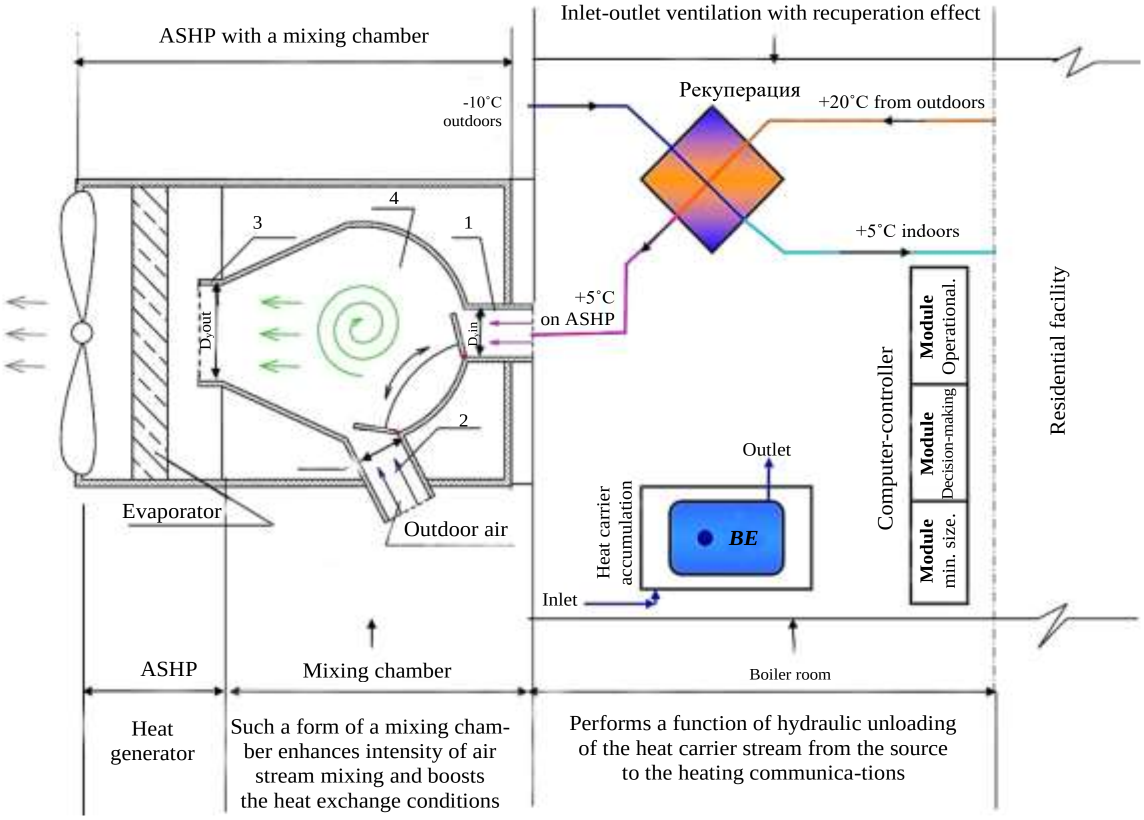

Fig. 2. Combined heat pump heat supply system with mixing chamber, air exchange circuit with recuperation elements

In this case, the ASHP operating mode in a moderately cold climate tends to consistently retain a sufficiently high coefficient of performance (COP) receiving a signal from the digital heat exchange control model of the heat supply system.

Given the specifics of the ASHP air exchange mode with a recovery element, the functionality of the heat exchange system operating through the boiler room and the air ducts of the facility is identified. The existing traditional natural exhaust ventilation found in private homes, apartments, and modern buildings these days is not effective, as while installing sealed plastic double-glazed windows and using highly insulating materials, the air supply is considerably reduced, resulting in an inefficient exhaust system.

Research Results. The central idea of the study is to propose that supply and exhaust ventilation system should be used that employs the principle of heat recuperation, i.e., a process where some of the heat is returned from the exhaust air.

Leaving the facility, the warm air partially heats the counter-cold air stream in the heat exchange system and, according to the configuration, becomes an exhaust at the outlet through the duct guides into the mixing chamber to the evaporator and then through the exhaust air outlet outdoors, and partially heated recuperated air enters the facility.

In such conditions, based on the main goal of creating energy-efficient heating, an air exchange system is obtained that is economically advantageous for the ASHP heat generator.

I.e., as an example, selecting a heat exchanger with an efficiency of η = 50%, the temperature of the mixed air stream supplied to the evaporator is obtained (Fig. 3).

For practical calculation of the effective temperature of the supplied mixed air to the heat pump evaporator, an engineering calculation method based on the influence of the percentage of temperatures according to the "outdoor-indoor" formula is employed. Let us make use of the solution for a special case from the heat balance conservation equation to identify the temperature relative to the warm air stream removed from the facility and supplied to the ASHP evaporator (Fig. 3).

Entering information to the mixing chamber operation control module, the microprocessor programmatically provides the appropriate current solution.

$$\frac{\eta \cdot t_1 + \eta \cdot t_2}{100} = \frac{50 \cdot 24^{\circ}\mathrm{C} + 50 \cdot (-10^{\circ}\mathrm{C})}{100} = \frac{(1200 - 500)^{\circ}\mathrm{C}}{100} = 7\ ^{\circ}\mathrm{C}$$

where t_1 = 24 °C is the temperature in the facility, t_2 = –10 °C is the outdoor temperature.

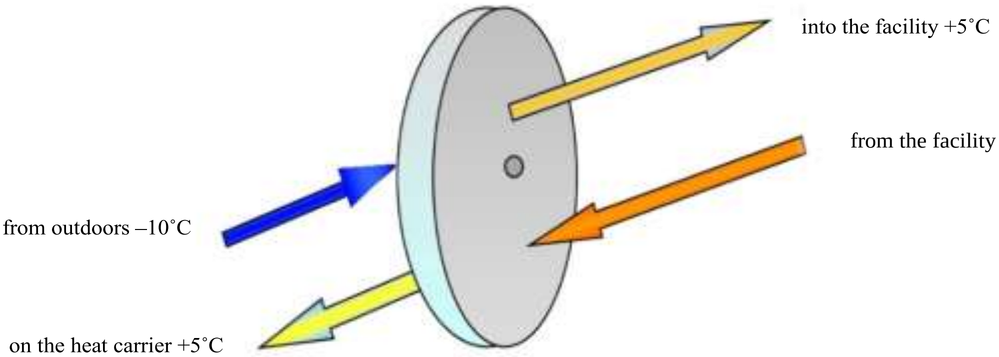

Fig. 3. Change in the temperature of air streams in air ducts with recuperation

In Finland, e.g., prior to commissioning an air duct with recuperation following testing, an annual regeneration coefficient is employed that is retained for Helsinki and Lapland.

When ASHPs and supply and exhaust ventilation work jointly with integrated heat recovery elements, the technical parameters of the system must comply with the following:

1. The diameter of the connected duct used for the above conditions is 125 mm.
2. The number of connected air ducts with ASHP is 4.
3. The heat recuperation efficiency (η) ranges from 40 % to 60 %.
4. Cross type recuperation.
5. The recuperation plate material is polymerized cellulose.

Structurally, the recuperator is located in a confined facility of a thermal unit (boiler room) with air ducts connected on one side to the exhaust air supply to the evaporator, on the other, it provides a facility with slightly heated fresh air through the air ducts (Fig. 4).

The technology of employing such a configuration of air ducts with recuperation allows for an effective increase in the heating capacity of high-pressure vessels in the heating mode of facilities with a moderately cold climate.

According to the tests, the graph (Fig. 5) shows how much more efficiently a recirculating heat pump with a recuperation element and an integrated mixing chamber operates. The "threshold" of savings (losses) is not attained until the outdoor air temperature reaches –15° C at a temperature of the coolant (water) from +30° C to +45° C.

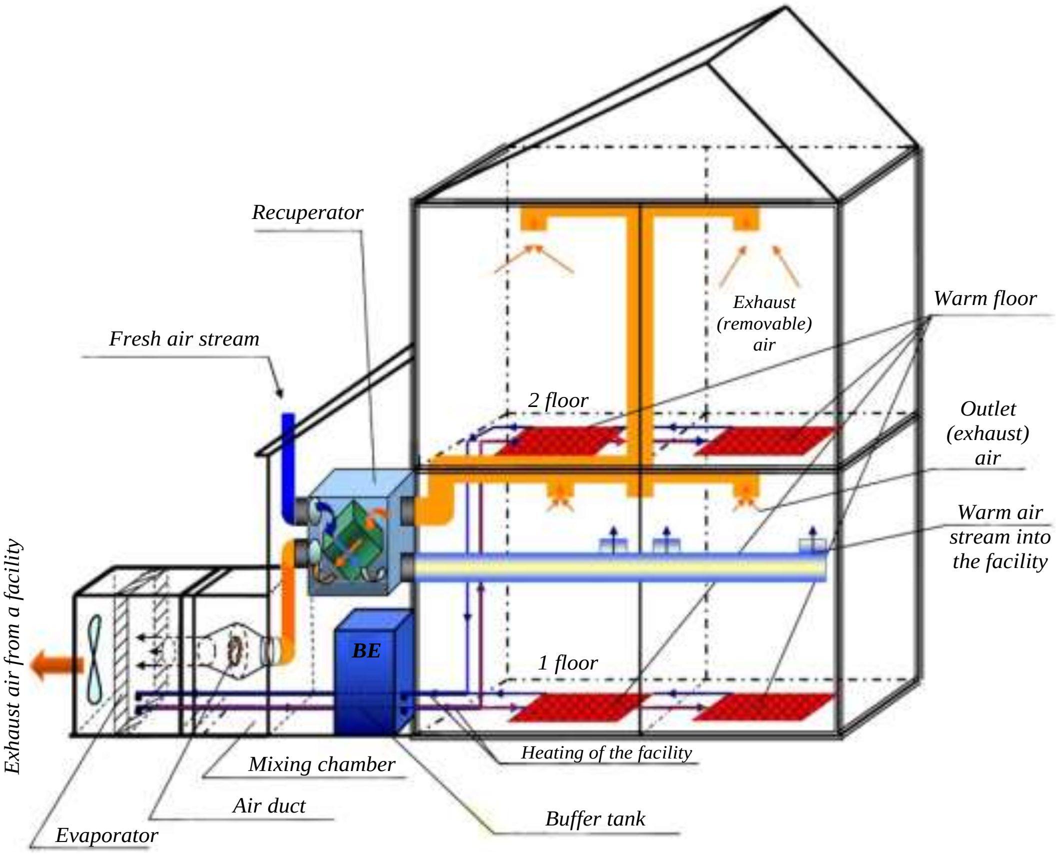

Fig. 4. Effective air exchange system of ASHP

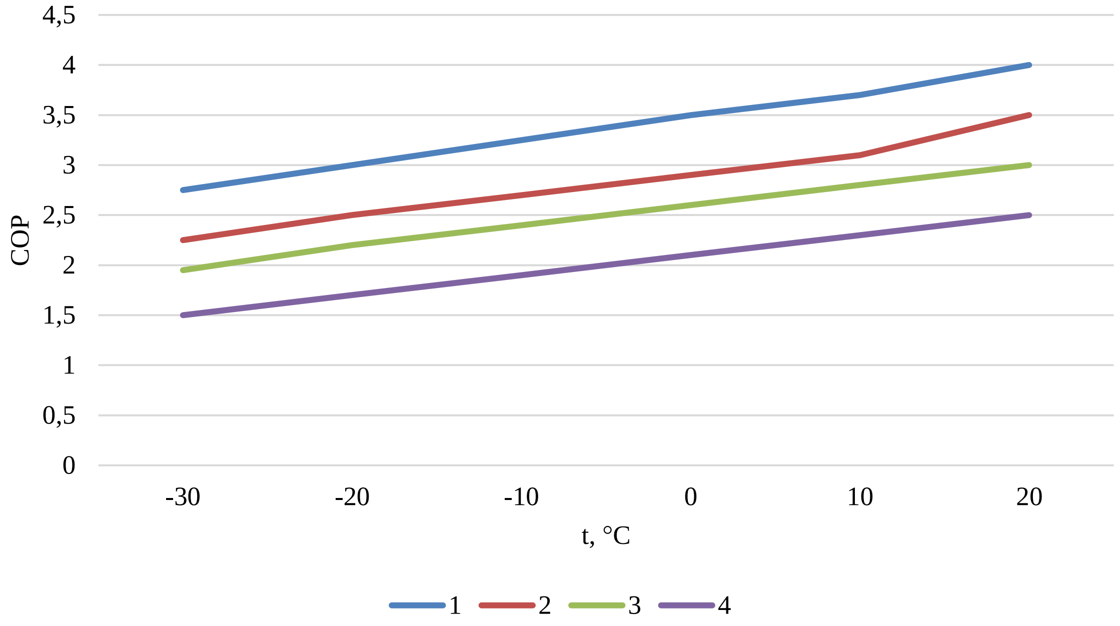

Fig. 5. Graph of the result of the operation of the heat exchange heat pump system of the experimental facility at the outdoor temperatures: 1 — 30 °C; 2 —35 °C; 3 — 40 °C; 4 — 45 °C

The buffer storage tank in such a combined heating system performs the function of hydraulic decoupling of the volumetric streams of the heat source and heating, equalizes the moment of the electric energy on/off switch, compensating for the heating capacity of the heat generator and heat consumer, and at the same time partially covers the tariff periods of electricity.

In the actual experimental conditions (Fig. 6), long-term extensive studies were performed on digital processing of this technological process. The resulting data made it possible to develop an experimental circuit solution (algorithm) for a broad range of various climatic conditions.

Fig. 6. Air mixing chamber [15] and an ASHP installed in a low-rise residential building in the Ivanovo region

It is suggested that a digital technological model is developed for controlling heat exchange through an air heat pump for low-rise and cottage buildings (Fig. 7). This scheme is detailed in Table 1.

Table 1

Regulator sensor description

Sensor 1 — *D/t*$_1$	Installed in a buffer tank. The signal is sent to the a pulse width modulation regulator (PWM) when the boundary values of the set temperature and the output heat output are changed. ASHP is on or off.
Sensor 2 — *D/t*$_2$	Installed on the evaporator. The signal is sent to the PWM when the set parameter values change. The fan blowing the evaporator changes the rotation speed according to the parameters.
P_1, P_2, P_3	Compressor protection sensors. In normal operation, the contacts are closed. When the set parameters are exceeded or lowered, the sensor contacts open, which causes the compressor to stop.
Sensor 2 — *D/t*$_3$	Installed outdoors and gives a temperature status signal to the PWM controller module of the electric boiler. The PWM controller module has its own program — setting the electric boiler control.
Sensor 2 — *D/t*$_4$	Installed in a volumetric mixing chamber and sends a signal to the mixing chamber operation control module. A software setting that is wired for 10°C by reacting to temperature changes inside the mixing chamber. The aim of the damper mechanism is to respond to changes in the proportion of the incoming air from outdoors and from the facility, ensuring that the desired temperature is obtained on the evaporator.

The power modules provide the necessary electrical power to loads. Loads include: PWS compressor, evaporator fan, defrost solenoid, circulation pump, electric boiler heating elements, damper drive mechanism. The module of power (MP) ensures the operation of the entire circuit.

Digital technological model of regulating heat exchange through the air-source heat pump in a low-rise building

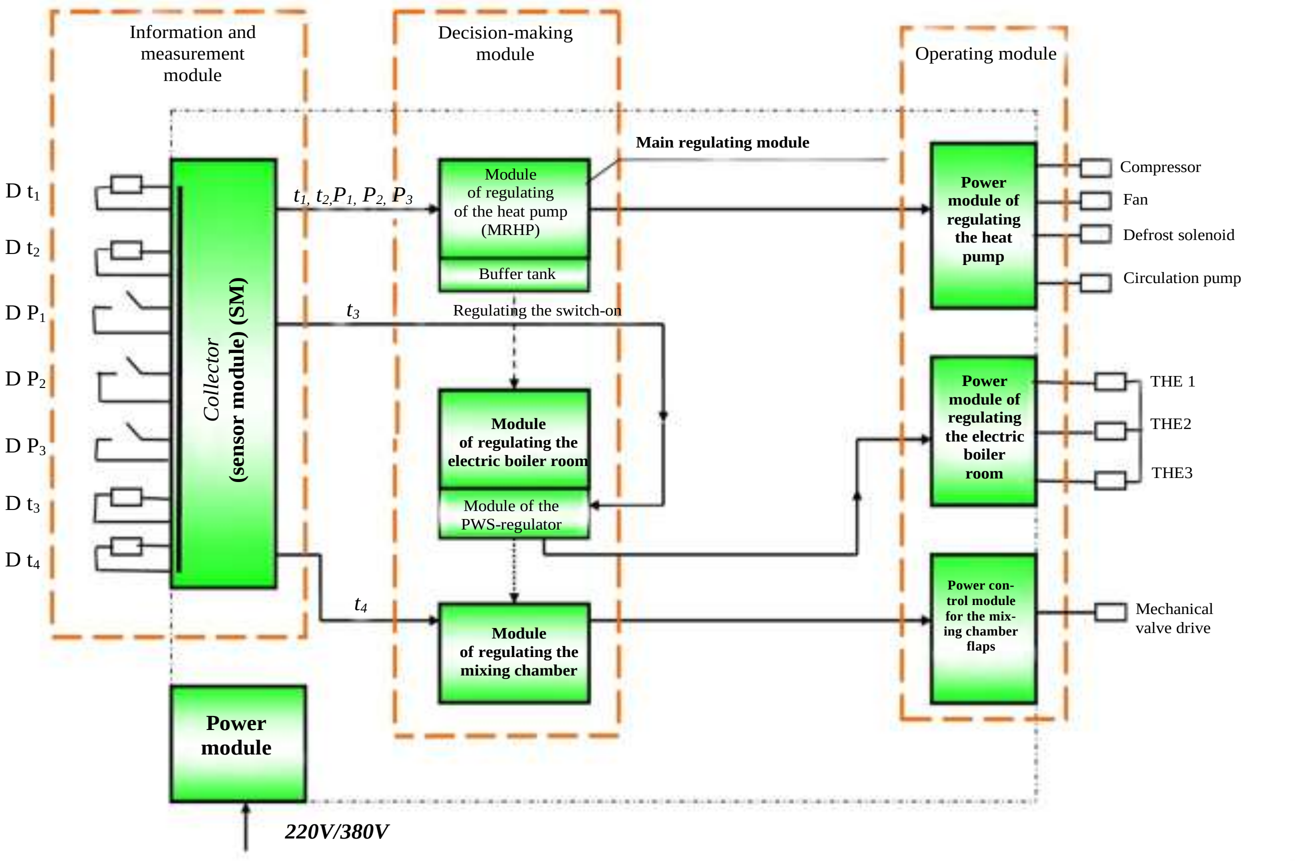

Fig. 7. Digital combined ASHP regulator module (computer controller)

Discussion and Conclusion. The use of information and digital solutions opens up a broad range of functionality for technological control and regulation of the temperature and humidity state in a facility, outdoor temperature gradient along with the collector module of the Dt_1 — Dt_4 sensors. The digital module for recognizing the parameters of this technological process enables ASHPs to regulate an alternating stream of warm and cold air, implementing this process through a computer controller on the operating mechanisms of the an exchange system. Such digitalization allows for a reduction in excessive heat and electrical load, as well as minimization of the volume, area of the boiler room and air exchange communications. As a result of using these solutions, costs and sizes of facilities are cut down.

Having set forth a digital modular functional structural scheme of heat generation from the environment, i.e., relying on the energy efficiency of a circuit solution with an electric boiler, buffer tank and a patented mixing chamber [15], we have attained a rationally controlled heat and air exchange of a combined heat pump system.

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Claimed contributorship:

SV Fedosov: scientific supervision, formation of the basic concept, aims of the study.

VN Fedoseev: formation of the basic concept, revision of the manuscript, correction of the conclusions.

VA Voronov: carrying out the calculations, analysis of the research results, preparation of the manuscript, formation of the conclusions.

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All authors have read and approved the final version of manuscript.

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