Запропоновано вирішення проблеми створення системи автоматичного регулювання температури у середовищі більше ніж одним промисловим кондиціонером. Розроблена схема, що моделює поведінку системи управління. Особливістю схеми є наявність об'єкту «аналізатор температур», що вибирає потрібний режим роботи та формує початкові дані для обраного режиму, та блок перевірки виходу на усталений рівень, що може змінюватися шляхом задання допустимої похибки. Висвітлено особливості створеної схеми керування та проаналізовано її переваги над уже існуючими схемами

Ключові слова: промисловий кондиціонер, система автоматичного регулювання, схема керування, аналізатор температур

Предложено решение проблемы создания системы автоматического регулирования температуры в среде более чем одним промышленным кондиционером. Разработана схема, моделирующая поведение системы управления. Особенностью схемы является наличие объекта «анализатор температур», который выбирает нужный режим работы и формирует исходные данные для выбранного режима, и блок проверки выхода на устойчивый уровень, который может изменяться путем задания допустимой погрешности. Освещены особенности созданной схемы управления и проанализированы ее преимущества над уже существующими схемами

Ключевые слова: промышленный кондиционер, система автоматического регулирования, схема управления, анализатор температур

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CREATING AN AUTOMATIC CONTROL SYSTEM FOR INDUSTRIAL AIR CONDITIONERS

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1. Introduction

It is difficult to find any modern industrial building or residential apartment without an organized system of air conditioning. Given that industrial buildings may be of large sizes, it is necessary to equip each of them with two or more air conditioners. Therefore, the study focuses on creating a control system for more than one air conditioner. The topic is relevant since brands such as Daikin, Panasonic and Mitsubishi Electric are interested in resolving the problem of air conditioning in buildings of any shape and size.

Introduction of new standards for managing the process of air conditioning, engineering of innovative sensors and creation of control systems for individual processes in air conditioners result in adapting the established air conditioner to suit customer requirements. However, air conditioning is mainly improved via increasing the number of air conditioners and installing additional auxiliary appliances.

The technology of air conditioning can be improved and developed via creating automatic control systems for more than one industrial air conditioning unit or separate blocks of air conditioning systems.

2. Analysing the previous studies and formulating the problem

Using more than one air conditioner reduces delays in the control system, i.e. changes in the latter affect air temperature quicker than changes in the operation mode of a single air conditioner.

Moreover, a large number of air conditioners help to reduce the risk of heat exhaustion, improve the state of employees, improve the quality and efficiency of production, and prevent product defects (via eliminating distortion and condensation that may result from excessive heat or dampness).

The authors of [1] proposed a fuzzy control system for air conditioners based on the PID controller, although failed to analyse its use for controlling more than one apparatus. The control system presented in [2] is based on the heat island effect that is expected in an urban microclimate; thus, it is not appropriate for managing industrial air conditioners.

An intellectual control system presented in [3] is designed for flexible adjustment of temperature in residential apartments. Given that sensors are placed on people, information from them can be used to adjust air conditioning in advance in accordance with the people's intentions. Thus, this system is not appropriate for temperature control in those industrial buildings where personnel is absent.

In [4], the authors present a way to manage a group of air conditioners whose mathematical model can not be described by means of the conventional thermodynamic model as each air-conditioned room is a dynamic system. This control method can not be used in control systems for industrial air conditioners since the model does not fully consider the device behaviour when some parameters change.

In [5], the researchers present an air conditioning system based on "local radian temperatures". However, in some specific cases, i.e. in large open spaces such as industrial plants, descriptors that determine indoor comfort conditions based on mean values do not provide optimal values that are necessary at the design stage of control systems for industrial air conditioners.

The authors of [6] propose using a fuzzy logic controller to create a control system with a mode of unpredictable change in air conditioning parameters. However, the suggested system can not be applied since there is no analysis of its possible use in an air conditioning system for more than one air conditioner. In [7], the researchers propose a control system for indoor air conditioning that is based on individual approach to analyzing the user's lifestyle. This system is meant for residential apartments and can not be used in control systems in industrial areas.

Analyzing the above listed sources, we can conclude that the suggested air conditioning systems are based on the use of one air conditioner and, thus, can be applied as subsystems of an air conditioning system that comprises more than one air conditioner.

Studying the operation of conditioning complexes [8] for facilities such as "hospital building", "office building with individual rooms", "hotel building" and "school building" indicates that the main task of air conditioning systems in this case is supplying the required amount of fresh air and providing the necessary temperature independently in separate rooms. In these complexes, each room is equipped with a separate individual room temperature controller, which ensures temperature control in facilities with a large number of separate and independent rooms. For this reason, these complexes are inapplicable in air conditioning systems for industrial bildings.

PACi [9], with the configuration of indoor units such as Twin, Triple, and Double-Twin, whose external unit is capable of distributing the operating capacity among several (up to 4) zones inside the building simultenuously and providing a possibility to connect up to four indoor units to one external. Such solutions are particularly relevant and successfully applied in public areas.

In [9], the research focuses on commercial applications with small loads such as Mini ECOi: Panasonic has specially designed small 2-pipe heat pump systems for the most demanding commercial applications. The proposed systems allow connecting up to 9 indoor units, and Mini ECOi is the standard of flexibility and productivity in its class. Mitsubishi Electric has suggested similar systems [10]: household multisystems MXZ-2D/3D/4D/5D allow connecting from 2 to 6 indoor units of various designs, whereas semi-industrial MXZ-8B140/160 – up to 2–8 indoor units.

A comparative analysis of the existing systems from the world leaders shows that the analysed systems intensify air conditioning by means of increasing the number of structural blocks rather than air conditioners themselves, which indicates the feasibility of further research in this direction. In particular, the process of air conditioning can be intensified via designing a system of automatic control of more than one air conditioner that will ensure: firstly, a smooth technological equipment operation in the power save mode and, secondly, shorter delays in the operation. The problem can be resolved via studying temperature control systems and air-conditioning with more than one air conditioner in the mode of normal operation. Further study will allow making conclusions about the effectiveness of the proposed control system in terms of reducing energy consumption by reducing delays in the control system.

3. The purpose and objectives of the study

The aim of the study is to create a mathematical software for temperature control by industrial air conditioners and devise a scheme that would simulate the behaviour of control systems for industrial air conditioners. To achieve the purpose, we set the following objectives:

(1) to choose a mathematical model that reflects the real nature of changes in the parameters of air,

(2) to formulate the problem for the control system and implement it in the Simulink package, and

(3) to model the created control system and analyse the findings.

4. Devise the scheme of control for industrial conditioners

4. 1. A mathematical modelling of a water cooler of an industrial air conditioner

The authors of [11] provide a heat and mass transfer model for a water cooler of an industrial air conditioner that is described with sufficient accuracy by transfer functions of the second order without delay.

A design model of the suggested water cooler is shown in Fig. 1. The coolant is water with a flow rate of $G_w(t)$, the coolant temperature at the inlet of the cooler is $\Theta_{w0}(t)$, and at the outlet – $\Theta_w(t)$. The water cools heat exchange tubes, the average temperature of which is $\Theta_M(t)$. An air mixture with an expenditure of $G_A(t)$ that is supplied to the water cooler crossflows the traffic of the coolant. The input air temperature is $\Theta_{A0}(t)$, the initial moisture content – d_{A0}, the output air temperature – $\Theta_A(t)$, and the moisture content in the output air is d_A. The physical dimensions of the heat exchanger are: L, C, H – the depth, width and height of the cooler, respectively.

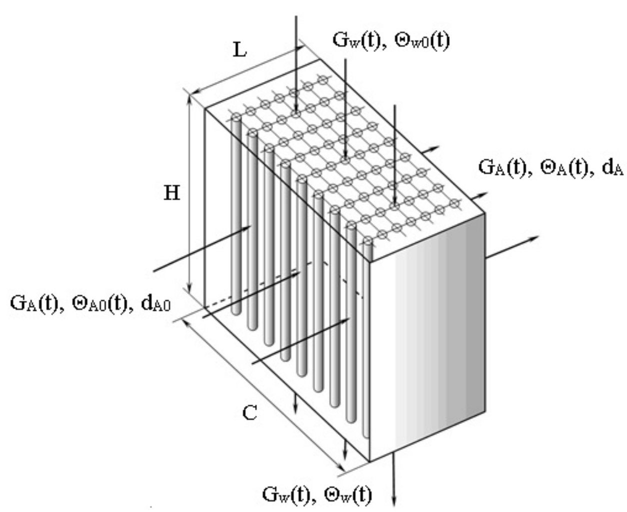

Fig. 1. A design model of a water cooler

The dynamic model of heat and mass transfer in a water cooler can be presented as a system of ordinary differential equations:

$$\begin{cases} T_W \dfrac{d\Delta\Theta_W}{dt} + \Delta\Theta_W = k_0\Delta\Theta_{W0} + k_1\Delta\Theta_W + k_2\Delta G_W, \\ T_M \dfrac{d\Delta\Theta_M}{dt} + \Delta\Theta_M = k_3\Delta\Theta_W + k_3\Delta\Theta_A, \\ T_A \dfrac{d\Delta\Theta_A}{dt} + \Delta\Theta_A = k_5\Delta\Theta_{A0} + k_6\Delta\Theta_M + k_7\Delta G_A + k_8\Delta d_{A0} + k_9\Delta d_A, \\ T_d \dfrac{d\Delta d_A}{dt} + \Delta d_A = k_{10}\Delta d_{A0} + k_{11}\Delta G_A + k_{12}\Delta\Theta_M. \end{cases} \quad (1)$$

After appropriate mathematical transformations, the dynamic model of a water cooler can be presented as transfer functions:

$$A(p) = 0.32p^4 + 4.85p^3 + 19.63p^2 + 13.42p + 1, \quad (2)$$

$$W_{1,1} = (0.76p^3 + 6.15p^2 + 5.71p + 0.55)/A(p), \quad (3)$$

$$W_{1,2} = (1.69p^3 + 1.78p^2 + 0.18p)/A(p), \quad (4)$$

$$W_{1,3} = (16.69p^3 + 79.84p^2 + 67.24p + 6.45)/A(p), \quad (5)$$

$$W_{1,4} = (0.14p + 0.45)/A(p), \quad (6)$$

$$W_{1,5} = (-4.05p - 12.46)/A(p), \quad (7)$$

$$W_{2,1} = (0.72p + 0.13)/A(p), \quad (8)$$

$$W_{2,2} = (0.75p^3 + 6.14p^2 + 4.47p + 0.33)/A(p), \quad (9)$$

$$W_{2,3} = (3.48p^3 + 28.57p^2 + 29.17p + 3)/A(p), \quad (10)$$

$$W_{2,4} = (0.036p + 0.56)/A(p), \quad (11)$$

$$W_{2,5} = (-1.01p - 7.23)/A(p). \quad (12)$$

The obtained mathematical model of a water cooler and the research findings on its dynamics reflect the real nature of changes in the parameters of air and can be used in designing and operating devices that would provide a high-quality automatic mode of air temperature regulation.

4. 2. Simulink implementation of the suggested control system

This study considers a control system for two air conditioners, although the number of air conditioners is not restricted. The scheme of this control system is implemented in the Simulink package, in MATLAB [12–15].

The task of the control system that is suggested by the technologist must provide the work of two air conditioners so that the room employee might set any temperature of the operating range and air conditioners could bring the room temperature to the specified constant level. The operating temperature range for the considered system is 25–35 °C. If the temperature is specified within 25–28 °C, only the first air conditioner is operating, 28–32 °C – only the second one, 32–35 °C – two air conditioners are operating, over 35 °C – an accident (fire) may happen.

The initial data are set as follows: the temperature that we want to obtain is Setting and an excessive temperature (that must be eliminated) is Perturbation. The initial conditions in Simulink will be set as constants (Commonly Used Blocks > Constants).

Thus, if the room temperature is 29 °C, and the desired constant temperature that we want to obtain is 25 °C, the excess of 4 °C is perturbation. To set the above initial data, we assign a value of 25 to the Setting constant and 4 – to Perturbation.

Given that each of the air conditioners operates within its own temperature range and brings the temperature to a constant level only within this range, there is a need to form the values of Setting and Perturbation for each air conditioner separately.

The above problem is resolvable with a special temperature analyser (Fig. 2). The work of the analyser is to verify a temperature range for the sum of the values of a constant level and perturbation of the room temperature as well as form new values of a constant level and perturbation for each operating mode (temperature range).

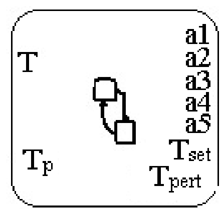

Fig. 2. The exterior of the software implementation of the temperature analyser

The analyser is a chart facility (Stateflow [16–18]> >Chart) that includes 2 inlets and 7 outlets. The temperature analyser logic is shown in Fig. 3.

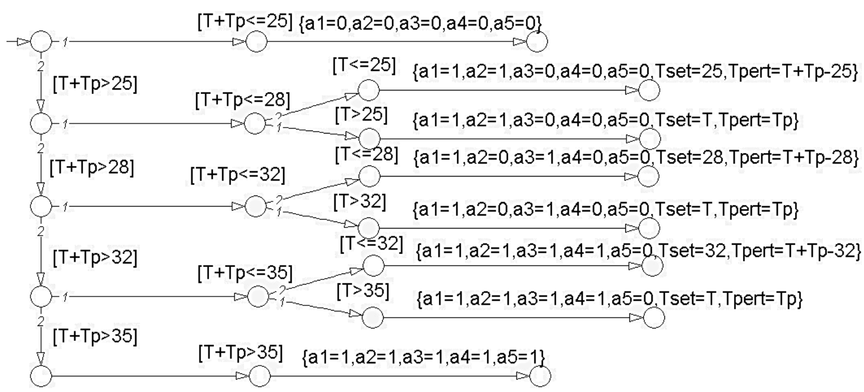

Fig. 3. The logic of the temperature analyser

Consider two options of operation of the suggested analyser.

In the first option, the input data acquire values T=25 and T_p =2. In this case, the constant temperature level is 25 and the perturbation that must be eliminated is 2, T+T_p=27. When the temperature values are verified, value 27 falls into the range of the first air conditioner. The output generated signals are as follows: a new constant level (T_{set}), a new perturbation value (T_{pert}), power (a1=1), the 1st air conditioner is activated (a2=1), the 2nd air conditioner is non-activated (a3=0), both air conditioners are non-activated (a4=0), and an accident (a5=0).

In the next option, T=25 and T_p=5. In this case, the constant level is 25, the perturbation that must be eliminated is 5, and $T+T_p$=30. When the temperature values are verified, value 30 appears in the range of the first air conditioner. The output generated signals are as follows: a new constant level for this air conditioner (T_{set}), a new perturbation value (T_{pert}), power (a1=1), the 1st air conditioner is non-activated (a2=0), the 2nd air conditioner is activated (a3=1), both air conditioners are non-activated (a4=0), and an accident (a5=0).

Fig. 4 shows the analyser operation in the above described options.

The analyser gives us all necessary data for operation of the required air conditioner. The air conditioner operation is presented by means of transfer functions W(p) that reflect the relationship of input and output parameters of individual components and the entire system.

The contour of the air conditioner in this case includes a PID controller, the air conditioner transient response, and feedback. The scheme versatility allows changing the controller or the transient response. The control contour is presented in Fig. 5.

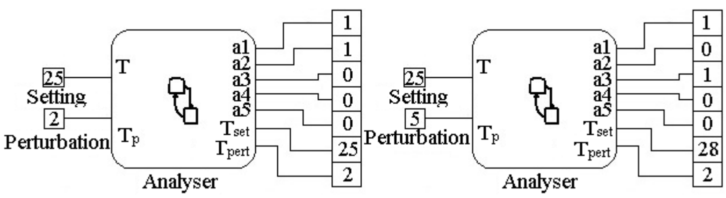

Fig. 4. An example of the analyser operation

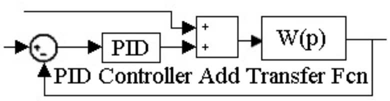

Fig. 5. Control contour in Simulink

The controller parameters are determined with the help of the controller setting function in MATLAB. Having built a model circuit (Fig. 6) of control (Fig. 8) and specified the type of transition in the Signal Constraint block, we obtain the controller setting parameters.

After the air conditioner operation, we select the values and analyse whether the temperature has been brought to the desired constant level. Provided the temperature falls into the permitted sustainable range, it is concluded that the air conditioner has solved the problem and brought the temperature to the specified level. It is necessary to compare the perturbation feedback value (the value of perturbation that has been eliminated by the air conditioner) to the one that was set initially. Fig. 7 shows an algorithm to verify bringing temperature to a constant level.

After transfering the perturbation feedback signal to an adder, we obtain either a new perturbation value that must be eliminated by the other air conditioner or the set constant temperature.

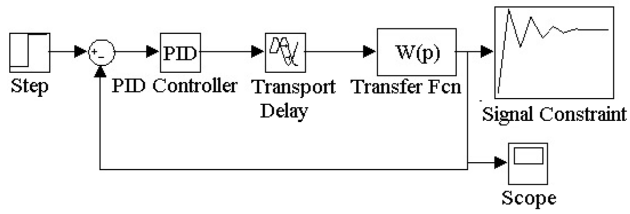

Fig. 6. A model circuit of setting the controller parameters

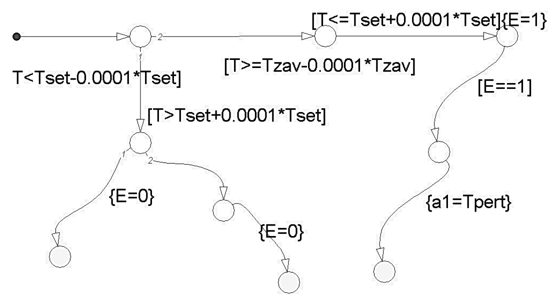

Fig. 7. An algorithm to verify bringing temperature to a constant level

5. The research findings on the automatic temperature control system for more than one industrial air conditioner

The research result is a designed scheme that simulates the behaviour of a three-mode control system for two industrial air conditioners. Fig. 8 shows the entire scheme.

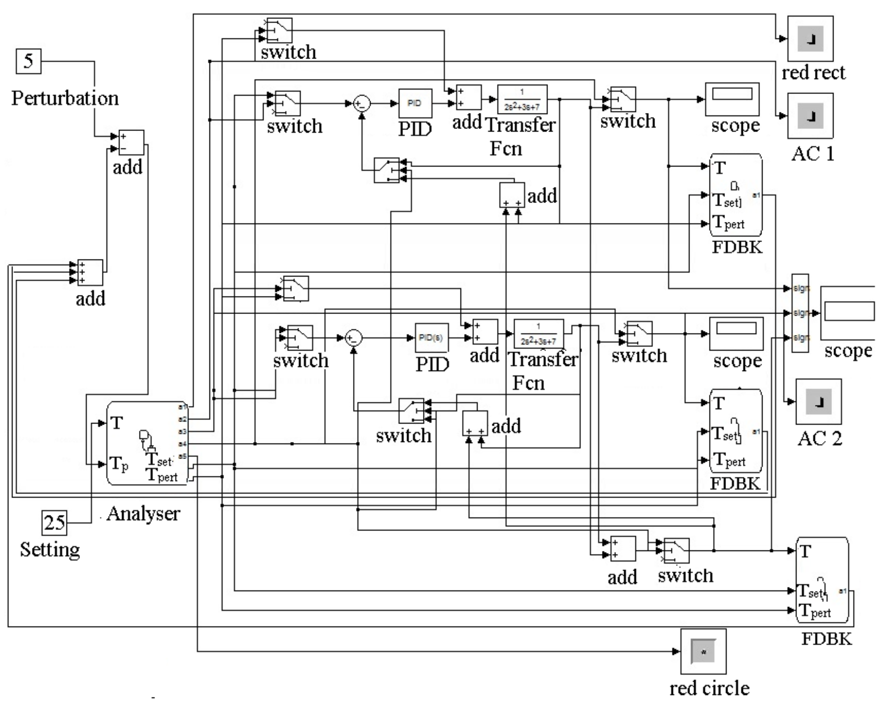

Fig. 8. A scheme of the control system for two industrial air conditioners

The system operation is exemplified with the research findings (Fig. 9) based on initial parameter values of T=25 and T_p=9.

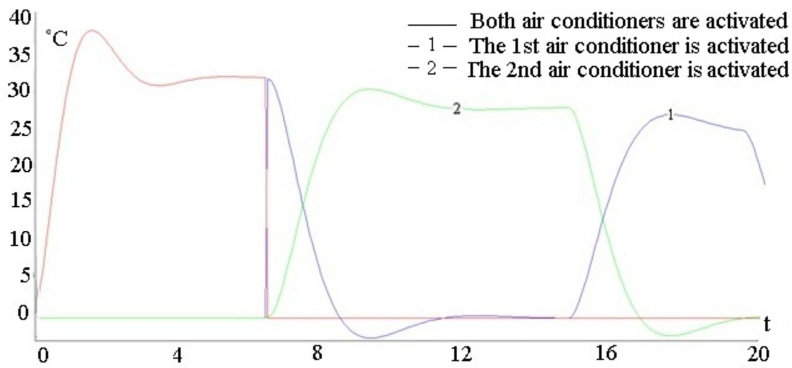

Fig. 9. A chart of temperature changes, °C/min

The above specified input data create a situation that was not considered in the previous examples. As Fig. 9 shows, if the indoor air temperature reaches 34 °C, two air conditioners become activated simultaneously. The work of two air conditioners in 6 min lowers the temperature to 32 °C, which provides transition to the operating mode of the 2nd air conditioner alone. Further lowering of the temperature is provided by the 1st air conditioner. According to the chart, the total operation time of the system is 20 min.

6. Discussing the automatic temperature control system for more than one industrial air conditioner

The study presents a simulated control system for two air conditioners, although their number is not limited. The research reveals operational features of the automatic control system for two industrial air conditioners, reflecting the nature of changes in the air temperature and experimental values of the system operation time.

The versatile nature of the new system distinguishes it among other automatic control systems and makes it valuable for further research in this area. The possibility to control any desired number of air conditioners and set the required operating modes allow developing and creating new control systems based on this one. The system provides control of more than one air conditioner due to the "temperature analyser" that is capable of setting the required number of operating modes, specifying their peculiarities, and forming initial data for the corresponding mode.

Unlike an intellectual controller that was designed for flexible temperature control in a residential apartment or an air conditioning control system that affects air quality via analysing the user's lifestyle, the new system is capable of setting the required number of operating modes with the help of the "temperature analyser".

The existing control systems that, for example, use fuzzy logic of the controller for unpredictable changes in air conditioning parameters or a fuzzy control system for air conditioning that is based on a PID controller can provide a better control law but can not change the range of constant temperatures by setting an allowable error, which is implemented in the new system as a special block to verify bringing temperature to a constant level. The possibility of adjustment to air conditioning peculiarities allows creating an improved control system that would resolve the problem and ensure an effective control of air conditioners.

The research findings can be used in further individual projects on air conditioning of industrial buildings, which is likely to provide high-quality automatic air temperature control modes. We consider a perspective further research with account of such factors as a room size and placement of an air conditioner in it, which requires devising models of indoor heat exchange under various conditions.

7. Conclusions

1. After analyzing the existing mathematical models, we selected the model of a water cooler of an industrial air conditioner. Experimentally obtained transfer functions for liquid heat exchangers that are quite accurately described by transfer functions laid the basis for the newly devised mathematical model with focused parameters for water cooling. This reflects the real nature of changes in air parameters and can be used in designing and operating devices that provide high-quality automatic modes of air temperature control.

2. The devised scheme that simulates the behaviour of a control system for two industrial air conditioners has three operating modes. The scheme comprises three main components: (1) a "temperature analyser" that forms the operating modes and their initial data, (2) a verifying block that checks bringing air temperature to a constant level and controls the task performance, and (3) a contour that, in this case, includes a PID controller, the air conditioner transient response, and feedback.

3. The experimental findings reflect the operation of an automatic temperature control system for two industrial air conditioners. The system operation reduces an initial indoor temperature of 34 °C by 9 °C bringing it to a set constant level of 25 °C in 20 min. During this experiment, the system worked in all the three operating modes, namely: (1) two air conditioners were activated simultenuously within 6 min, (2) only the 2nd air conditioner was activated within 9 min, and (3) only the 1st air conditioner was activated within about 5 min.

Thus, the research shows that the devised scheme that simulates the system behaviour can be used in working out individual projects of air conditioning in industrial buildings.

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