Decision Support System for Microclimate Control at Large Industrial Enterprises

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Abstract. The structure and mathematical support for the climate control system for large enterprises is proposed. The developed air conditioning control algorithms and multifunctional software are used at the middle level of an enterprise management using decision-making system. Criteria are defined and algorithms for optimization and adaptation of control systems for industrial air conditioners are proposed. The use of the proposed decision-making system can improve efficiency of the functioning of the microclimate systems of industrial premises when changing their operating conditions. The developed models, methods and control algorithms are recommended for use at the stage of design, commissioning and operation of industrial air conditioners at the middle level of operational production management.

Keywords: integrated enterprise management system, manufacturing execution system, automatic control system, industrial air conditioning, decision-making system, mathematical model.

1 Introduction

Modern production processes place high demands on industrial air conditioning systems. The quality of the product and the reduction in its cost [1] depend to a large extent on the microclimate of industrial premises. The maximum effect of the industrial air conditioners automation is achieved by integrating the air conditioning control system into the enterprise management system.

The world practice of introducing integrated enterprise management systems shows a significant increase in the efficiency of their work by reducing: energy costs, production downtime, optimal distribution of material and energy flows, the use of hidden reserves. Modern automation systems are integrated and include control subsystems interconnected by functions and levels. The architecture of the modern integrated enterprise management system is shown in Fig. 1. The functions of the first three levels are implemented by the automatic control system (ACS) of technological processes, which ensures optimal flow of the technological process in the workshop or on a separate production area. At the fourth level of enterprise management, a manufacturing execution system (MES) is used, which plays the role of an information bridge between the supervisory control and data acquisition (SCADA) and the enterprise resource planning (ERP) system in a single information space of the enterprise.

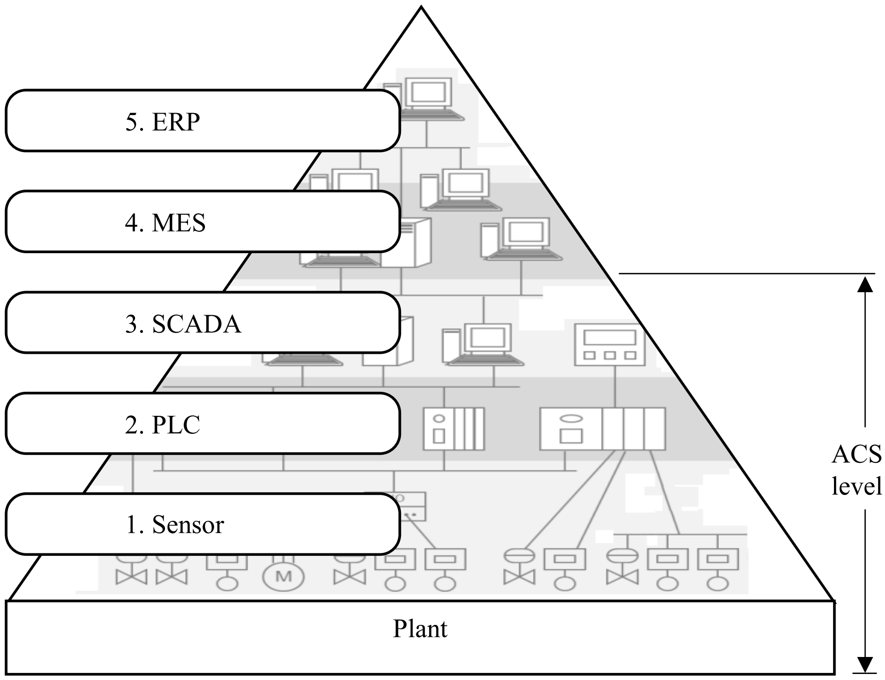

Fig. 1. Integrated enterprise management system hierarchical architecture

At most enterprises, SCADA and ERP are implemented and operated. The next step in improving the quality of products while reducing their cost is the introduction of the MES for operational management of production. MES were first proposed by the Manufacturing Enterprise Solutions Association (MESA) International in 1994. MESA International has established a basic set of functions for MES, which has subsequently been repeatedly adjusted. These results are published in a large number of articles and manuals [2–4]. The most advanced ideas of integrated production were approved by International Society of Automation (ISA) in the international standards ISA – 88, ISA – 95, ISA – 106 [5–7]. The listed standards are the most significant for the development of integrated enterprise management systems.

The developed international standards describe the basic rules for the operation of MES, but do not disclose the mathematical support for the operation of specific systems, in particular for the climate control systems of industrial premises, which are discussed here. In publication [8], a new concept for the automation of industrial air conditioners was proposed. In [9], the principles of automation of industrial air conditioners are considered, which provide an increase in the efficiency of the operation of

HVAC equipment through the use of control algorithms for air conditioners and multifunctional mathematical models of climatic equipment [8–12]. A literature review of industrial air conditioning automation systems confirms that all the prerequisites for integrating industrial air conditioning control systems into the enterprise management system have been created.

2 Problem Statement

At all levels of integrated enterprise management, operator jobs are used in which dispatching decision support system (DSS) are used [13]. The purpose of this research is to develop the structure, software and functioning algorithms of the DSS to support the microclimate in large industrial enterprises. The developed system will improve the overall production efficiency when changing the operating conditions of industrial rooms.

3 Decision Support System for Control the Microclimate

According to Fig. 1, DSS for the industrial air conditioners operational management is realize at the MES level of enterprise management. The block diagram of the developed DSS is shown in Fig. 2.

The proposed DSS is designed and implemented using the following system analysis principles [14]: the hierarchy principle; optimal solutions principles; mathematical models' adaptability; identification and minimization of the uncertainties influence that appear in the control system; the functional orthogonality principle and others. So, the integrated enterprise management system architecture is built according to the hierarchical principle, which assumes the management of several levels plant, united by information links. The operational control system assumes the optimization control actions, which ensures the air conditioning system optimization necessary to determine the acceptable temperature and humidity limits in an industrial room and of the recirculation coefficient, which affects the economical use of energy resources by the microclimate system. DSS provides the functions implementation providing for the structural and parametric adaptation of mathematical models, thereby achieving their high degree of adequacy to the object. Stochastic uncertainties in the form of random external disturbances and measurement errors are minimized by using optimal filtering methods for measurements at the stage of preparing data for modeling. The existing parametric uncertainty of the models is minimized by using alternative methods for estimating the mathematical models' parameters of the studied objects. The functional orthogonality principle ensures the rational implementation of all the control system basic functions and the elimination of their duplication. Thus, the use the system analysis principles in the design of DSS makes it possible to improve quality of the intermediate computation results, and the management quality in general.

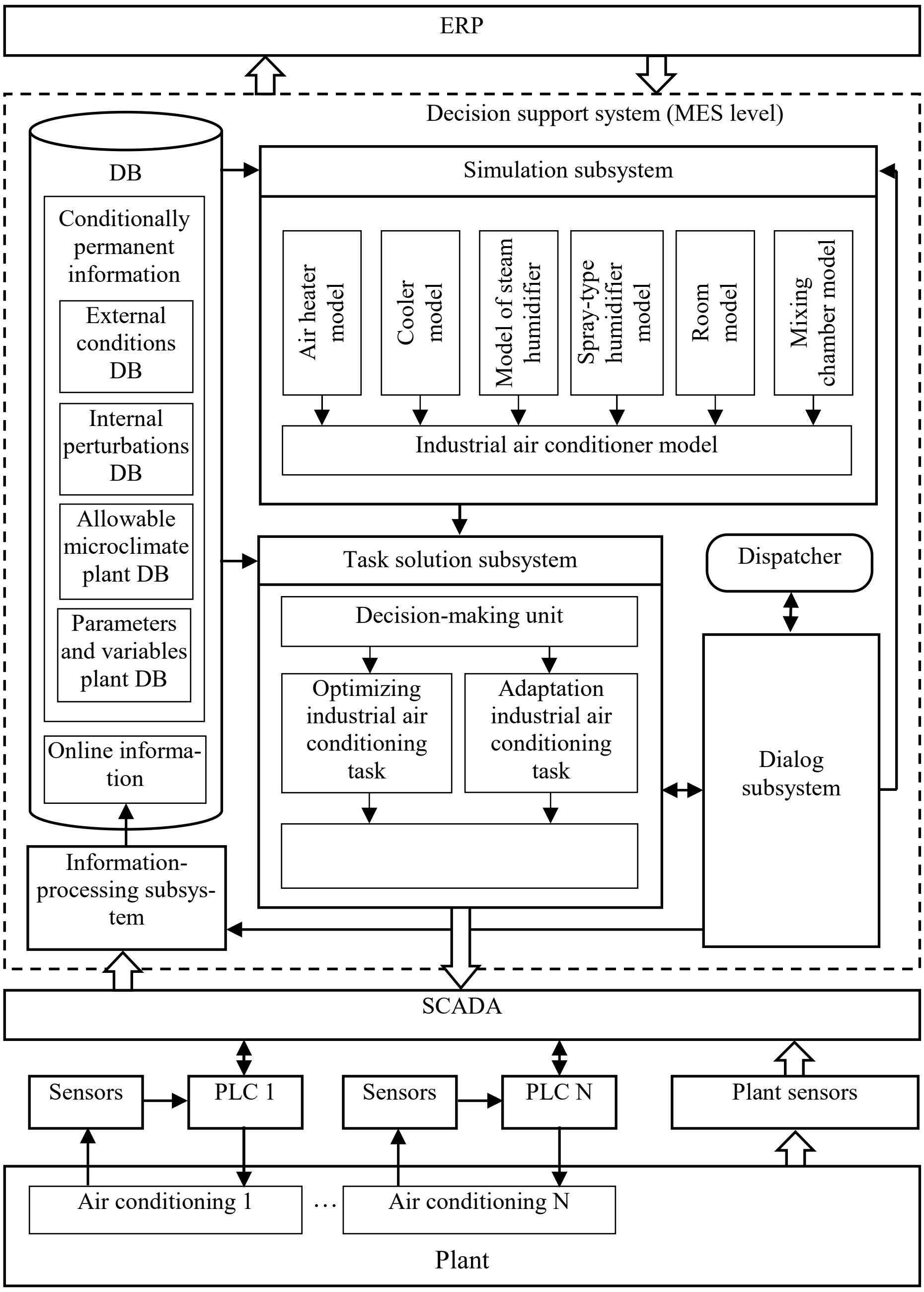

Fig. 2. DSS block diagram for microclimate management

At the lower level, local air conditioning control systems are implemented on program logic controllers (PLC). The SCADA performs cyclical measurements of all current process variables, including the microclimate of industrial premises. The information-processing subsystem DSS performs analysis of input information, replenishes the database (DB) with new information and provides operational information about the condition of industrial air conditioners: the disturbing effects magnitude; operating modes of mixing chambers, water heaters, coolers, steam humidifiers, and industrial rooms.

Using models of climatic equipment, the simulation subsystem implements a model of an industrial air conditioner. The task of control solving subsystem offers the operator a set of possible scenarios for optimization and adaptive control of industrial air conditioners that are used in production. The effectiveness of the proposed solutions is evaluated according to the criteria chosen by the operator. The decisions made by the operator in the form of PLC settings are transferred to the lower hierarchical system control level for execution.

3.1 Mathematical model of industrial air conditioning

The methodology for implementing the air conditioner model was considered in [10, 11]. In general, it is proposed to implement a model of an industrial air conditioner in a state space

$$\begin{cases} \mathbf{X}' = \mathbf{A}\mathbf{X} + \mathbf{B}\mathbf{U} + \mathbf{W}, \\ \mathbf{Y} = \mathbf{C}\,\mathbf{X} + \mathbf{V}. \end{cases} \tag{1}$$

The vectors of the variable statistical perturbations model **W** and **V** are determined in the DSS using the Kalman filtering methods considered in [14, 15]. The matrices content of deterministic component model (**A**, **B**, and **C**) depends on the technological scheme for processing air by an industrial air conditioner. For example, the state matrix **A** is determined by for:

- a direct-flow conditioning system

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}^{\mathrm{P}1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{C}_{\mathrm{P}1} & \vdots & \vdots & \mathbf{0} & \vdots & \vdots \\ \mathbf{0} & \cdots & \mathbf{A}^{\mathrm{P}i} & \cdots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \vdots & \mathbf{C}_{\mathrm{P}i} & \cdots & \mathbf{A}^{\mathrm{P}N-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{C}_{\mathrm{P}N-1} & \mathbf{A}^{\mathrm{P}N} \end{bmatrix},$$

  where $\mathbf{A}^{\mathrm{P}i}$ is the state matrix of the *i*-th equipment, *N* is the number of devices in the technological chain;

- a system with recirculation or heat recovery

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}^{\mathrm{P}1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{C}_{\mathrm{P}N} \\ \mathbf{C}_{\mathrm{P}1} & \mathbf{A}^{\mathrm{P}2} & \vdots & \vdots & \vdots & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_{\mathrm{P}2} & \mathbf{A}^{\mathrm{P}i} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{C}_{\mathrm{P}i} & \mathbf{A}^{\mathrm{P}i+1} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \vdots & \mathbf{C}_{\mathrm{P}i+1} & \mathbf{A}^{\mathrm{P}N-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{C}_{\mathrm{P}N-1} & \mathbf{A}^{\mathrm{P}N} \end{bmatrix};$$

- multi-zone conditioning systems, the filling of matrix A must be analyzed additionally, since it depends on the number of rooms with a microclimate system.

The control matrix **B** is formed on the basis of the existing climate equipment that is involved in controlling the air conditioning. The observation matrix **C** is formed based on the number of state variables that take part in controlling the air conditioning. Among the state variables that are necessarily involved in the management of mandatory are temperature and humidity at the outlet of the air conditioner (or indoors).

A more detailed acquaintance with the methodology for the synthesis of industrial air conditioners complex dynamic models can be found in [10, 11]. For control systems for industrial air conditioners, a synthesis procedure has been developed for a multidimensional linear-quadratic digital controller (LQDC) [10], which takes into account the logical switching of the climate equipment and allows the ACS of industrial air conditioner to adapt to changing of dynamic properties plant. At the ASC-level, direct digital control algorithms are used [9–11]. On a PLC, the control system can be implemented using one-dimensional digital controllers (DC), or using multidimensional LQDC. The use of ACS with LQDC improves the integral quality indicators by 1.2 – 2.3 times in comparison with ACS where one-dimensional DC are used [12].

Consider the tasks of operational management to optimize and adapt the ACS of industrial air conditioners, which are implemented by the task solution sub-system.

3.2 Operational management for the optimization ACS air conditioning

The task of operational management to optimize the air conditioning system is necessary to determine the acceptable boundaries of temperature and humidity in an industrial room, as well as the recirculation coefficient (for air conditioners with recirculation), which affects the economical use of microclimate system energy.

As an example, consider an air conditioner with a steam humidifier and recirculation. For this air conditioner, see Fig. 3 shows a $h - d$ diagram of the preparation of outdoor air with an inlet temperature $\theta_{A0}^{\min} \ldots \theta_{A0}^{\max}$, and moisture content $d_{A0}^{\min} \ldots d_{A0}^{\max}$. Region V characterizes the permissible microclimate in an industrial room with a range of a given temperature $\theta_{ref}^{\min} \ldots \theta_{ref}^{\max}$ and moisture content, $d_{ref}^{\min} \ldots d_{ref}^{\max}$. The smaller is the area V, the higher are the production requirements for the indoor microclimate.

When processing outdoor air (point A or A^*) to a predetermined value (point D or D^*), the minimum energy consumption of the air conditioner will be at the edges of the area V boundary. Therefore, the larger is the area V, the less energy is needed to prepare the outdoor air. Region V, on the other hand, is limited by production requirements for indoor microclimate. To optimize the area of permissible microclimate, the DB of the DSS should contain information on the permissible microclimate parameters for all plants of production.

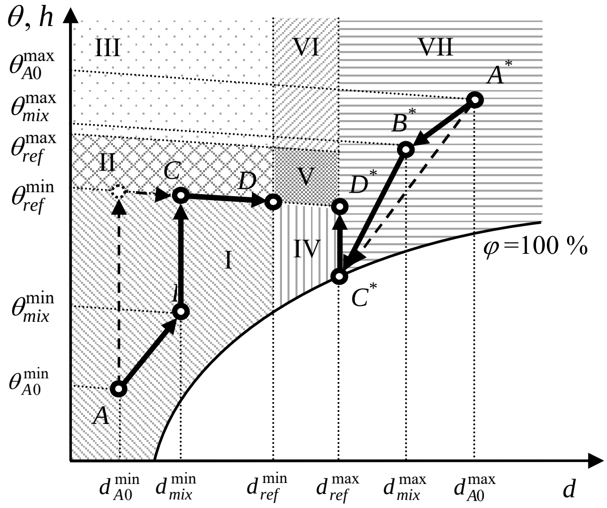

Fig. 3. $H - d$ preparation diagram air

Optimization of the permissible microclimate in industrial premises of production is carried out during the transition of the technological line to the manufacture of new products and consists of the following steps:

1) the decision-making unit initiates a dialogue with the operator and offers acceptable microclimate limits in the room for manufacturing of new products;

2) the simulation model of an industrial air conditioner is formed according to the methodology given in [10];

3) the simulation subsystem performs the ambient air preparation quantitative modeling: the transition from point A (A^*) to point D (D^*);

4) then, the assessment is made of the industrial air conditioner the efficiency of which is based on the criterion of minimizing energy consumption:

$$\sum_{i=1}^{N} Q_i \to \min \tag{2}$$

where, Q_i is the i-th apparatus power consumption; for the water heat-transfer agent $Q_i = G_i\, c_i(\theta_{i0} - \theta_i)$, where G_i, c_i are respectively the flow rate and the coolant heat capacity; θ_{i0}, θ_i are the heat-transfer agent temperatures at the inlet and the apparatus outlet;

5) the operator analyzes the accumulated statistical information and decides to change the specified reference microclimate zone;

6) the laboratory section analyzes influence of the microclimate of the industrial premise on the product quality; if necessary, the range of the boundaries permissible region V is modify by the operator according to steps 1 – 6; thus, statistical information is collected that allows one optimize the energy consumption of the air conditioner due to the permissible range parameters of microclimate in the room.

A significant reduction in energy consumption of the air conditioner is possible through the use of up-take air recirculation. Utilization of the exhaust air heat makes it possible to bring the parameters of the microclimate ambient air from point A to point B for the winter season, and from point A^* to point B^* for the summer season (see Fig. 3). At the same time, the energy consumption for air processing is significantly reduced (transition from point B / B^* to point D / D^*). At 100% recirculation, the energy efficiency air conditioner is maximum. However, according to sanitary norms and rules, there are standards for air exchange with the external environment, which must be maintained in the production premises if there are workers in the room. To optimize the recirculation coefficient of an industrial air conditioner, an air conditioning system database should contain regulatory information on air exchange for industrial premises with employees.

The air conditioner recirculation coefficient is optimized during the transition of the artificial microclimate system from winter to summer mode and vice versa, as well as when the number of workers in the industrial premises changes and consists of the following steps:

1) decision making unit initiates a dialogue with the operator and offers permissible recirculation value for the number of employees in the room;
2) the simulation model of an industrial air conditioner is formed according to the methodology given in the studies [10];
3) the simulation subsystem performs an ambient air preparation quantitative modeling: this is the transition from point A (A^*) to point D (D^*);
4) the assessment of the effectiveness of the operation air conditioner based on minimizing the criterion of energy consumption (1);
5) the operator changes the recirculation coefficient for the air conditioner model based on the experience and DSS statistics:
6) an analysis is performed of the energy efficiency air conditioner; when changing the number of employees or the operation mode air conditioner, steps 1 – 6 are repeated to optimize the recirculation coefficient.

Thus, the DSS helps the operator to optimize the energy efficiency of industrial air conditioning equipment without loss of product quality in production.

3.3 Operational management for the adaptation ACS air conditioning

The operational management task under adaptation is necessary for the correction of ACS settings when changing the dynamic properties of an industrial air conditioner. Any adaptive control system has two loops: internal – a direct-digital control circuit; external – the circuit for evaluating the parameters of plant and calculating the parameters of the controller. The internal adaptive control loop is implemented on the PLC, and the external one in the frames of the constructed DSS (see Fig. 2).

The ACS adaptation of an air conditioner is carried out during the transition of the artificial microclimate system from winter to the summer mode and vice versa. The operational control algorithm for adaptation includes of the following steps:

1) the decision-making unit initiates a dialogue with the operator and offers to evaluate the parameters of mathematical models of HVAC equipment; for models, heat- and mass- transfer coefficients are estimated, which depend on many factors; to eval-

uate the parameters, one can use the scanning or gradient search methods; as a reference model, the accumulated information of measured data of the operated air conditioning systems, which are contained in the DB of the DSS, is used;
2) an industrial air conditioner simulation model is formed according to the method given in the study [10];
3) the LQDC feedback matrix is computed for the diagram regions $h - d$ [10];
4) the assessment is made of the simulation ACS effectiveness functioning with LQDC using a quadratic criterion for all areas of the $h - d$ diagram:

$$I = \int \left[\mathbf{X}^{\mathrm{T}} \mathbf{Q} \mathbf{X} + \mathbf{U}^{\mathrm{T}} \mathbf{R} \mathbf{U} \right] dt , \quad (3)$$

where **Q**, **R,** are weighting coefficient matrices for elements of state and control vectors; **X** is state vector, which includes variable temperatures θ and moisture content d; **U** is the control vector;
5) the operator changes the LQDC parameters if the air conditioner ACS efficiency with the calculated parameters is higher than the existing one;
6) the steps 1 – 5, aiming to adapt LQDC are repeated when the industrial air conditioner changes its operating mode.

4 Conclusions

The DSS structure for the integrating industrial air conditioners ACS into the integrated enterprise management system is proposed. It was proposed to use mathematical models and control algorithms developed in the previous developments [8–12] at the enterprise management (MES) level in the decision support system proposed, which is implemented to improve the industrial air conditioners operation efficiency under changing operating conditions. As a result of applying the system analysis methodology, the multifunctional mathematical and algorithmic software was developed for integrating an industrial air conditioning control system into computer-integrated production management system. The developed models, methods and algorithms are recommended to be used at the stage of design, commissioning and operation at middle level of operational production management. The proposed mathematical models, methods and algorithms for controlling air conditioners are brought to practical implementation and theirs are proposed to be implemented in DSS. The industrial implementations results have confirmed the high efficiency of automatic control systems developed on the basis of the systemic approach to building conceptually integrated industrial control systems discussed above.

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