Air in industrial premises

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Abstract. The article considers a method for increasing the stability of air parameters in a limited space of the general production process using simulation methods in the environments of SolidWorks Flow Simulation HVAC Module Add-In and Matlab Simulink and Fuzzy Logic Toolbox. To select the simulation method, the models of Boussinesq, Spalart - Almaras, k - ω and k - ε models, Reynolds, and the equations describing these models are considered. It is established that the most effective for the problem is the Navier-Stokes equation averaged by Reynolds. For the calculated ventilation system, as a result of simulation, we obtained the distribution of temperatures, air velocities, and temperatures of enclosing surfaces, floors, and objects. The results obtained were used to create a fuzzy controller. We obtained the set term and membership functions for input and output variables for four zones. The hierarchical structure consisting of three levels was used to implement the control process. Setting the FC parameters to the desired parameters is achieved by changing the dimension of the terms of the sets, the number and type of the membership function. An analytical description of the control method based on fuzzy logic is obtained. The control process is being carried out continuously in tracking mode. The results of experiments are submitted. The simulation showed that it is possible to stabilize the parameters in a given temperature range with a specified error.

1. Introduction

Manufacturing and operation of high-precision equipment of mechanical engineering and instrument-making enterprises in the conditions of increasing requirements for temperature stabilization and reducing air pollution requires strict conditions for the development of ventilation equipment and the effectiveness of its application in industry.

Due to the complexity of the mathematical description of the processes of propagation and transfer of air flows in the production environment, simulation is the most effective. To simulate the process of air flow transfer, among many known mathematical methods, it is necessary to choose a model which describes the processes under study in each specific case the most accurately.

Scientists Poz M.Y., Elterman V.M., Taliev V.N., Kokorin O.Y., Kuvshinov Y.Y., Titov V.P., Polushkin V.I., Polosin I.I., Grimitlin M.I., Logachev I.N. made their contribution to the study of methods of mathematical simulation of air currents [1 - 4].

These scientists in their works proposed a method for constructing a mathematical model of the process of air movement. It was the basis for the equations of motion, the continuity of the medium, thermal conductivity and mass transfer are given.

In some cases, the differential equation is solved for the laminar medium flow, the coefficients of these equations are physical constants. In the case of turbulent flows, the differential equation has
coefficients of turbulent viscosity, turbulent exchange, and thermal conductivity that are not known values. Therefore, existing systems of equations become undiscovered, and their solution requires additional dependencies, which are defined using various turbulence theories.

Simplified systems of differential equations are used to describe individual ventilation processes, and in this case the process is not significantly affected by changes in various variables. These processes include convective and supply jets, which have a significant impact on the formation of air in industrial premises. A large number of research results on turbulent jets are applicable to industrial ventilation problems.

The analysis of the mathematical model of the jet stream was carried out by Bogoslovsky V. N., Tabunschikov Y.A., made during the study of buildings ventilation [5, 6].

Posin G.M. derived an algebraic equation, the solution of which is a matrix form, as close as possible to the mathematical model, which reflects the interaction of the heat flow of air in a room equipped with a ventilation system.

A significant part in the works of scientists Elterman V.M. and Kun M.Y. is devoted to the study of the formation of harmful substances concentrations in a ventilated room [7, 8].

As a result of research, it was found that the air flow formed as a result of ventilation is characterized by a high degree of turbulence, so it is necessary to take into account its influence on the distribution of concentrations of harmful substances.

Based on the differential equation of turbulent exchange in the incoming air flow, a solution was obtained that established the concentration field of gas flow from different types of air flows, close to the characteristics of ventilation technology. However, these results apply only to the case of a fixed process of contamination propagation in a flat parallel stream [9].

The development of information technologies has allowed to reveal regularities of emergence speed and temperature fields in a room with active ventilation based on the solution of a system of equations that also includes the Navier-Stokes equation of motion, energy equation and equation of turbulence models (Poz M.Y., Hanel B., Nielsen P., Baklanev A.I., etc.)

Poz M.Y. developed a solution to the problems of heat transfer and mass transfer in ventilation systems using the method of "gluing" flows and the Navier-Stokes equations, which allow determining the velocity and temperature fields in the volume of the room.

To perform this calculation according to this method, it is necessary to divide the area into zones and perform calculations for each of them using a simpler system of equations than the Navier-Stokes system of differential equations.

The results obtained from the calculations are "glued" at the border of the zones. The "gluing" method can be used only when the nature of circulation and the direction of movement of air flows in the room are known, i.e. there are relevant research results obtained in full-scale conditions or on physical models.

As to gas dynamics, the heat flow of air is turbulent and three-dimensional. For mathematical simulation of these processes, it is necessary to use various mathematical models to fully reveal the mechanism of energy transfer and impulse of turbulent pulsation [10, 11].

To solve the corresponding mathematical problems, effective numerical algorithms were created, they allowed us to obtain accurate results over a certain time. The results obtained using these models were tested on verified known problems and experimental data. The Navier-Stokes equation is a basic mathematical model for describing air flow. The closure hypothesis used for significant turbulent stresses and heat flows, the turbulence parameters can be estimated by solving the Reynolds-averaged Navier-Stokes equations. In the most common turbulence model, the Reynolds averaging method is used to close the Navier-Stokes equations, including the standard k-ω turbulence model.

On the one hand, traditional methods of system design do not lead to satisfactory results as the initial description of the problem to be solved is incomplete. The desire to obtain complete information for accurate mathematical modeling of the system leads to the waste of time and money, due to the structure complexity of real control systems.
In 1965 Zade published a fundamental work on the theory of fuzzy sets, in which he outlined its mathematical apparatus. In 1973 he presented the theory of fuzzy logic, and later he delivered the theory of soft computing and the theory of computing with words and perceptions. This was followed by the development of a new direction in solving many problems in various fields of knowledge. At the same time it was the beginning of the use of fuzzy logic theory in implementation of technical systems [12].

Application of the theory of fuzzy sets in the design of automatic control systems is explained by the fact that fuzzy systems are designed faster, they are obtained easier than clear analogues [13]. Expert knowledge is easily introduced into fuzzy systems that enable to quickly create a system with operating algorithms understandable to an engineer [14]. The training methods developed in the last decade allow to set up a fuzzy system to ensure the required quality of functioning. The use of fuzzy logic in automatic control systems is specific, associated with the essential features of organizational nature, in implementation of structure and operating algorithms [15,16].

The purpose of research is to create algorithms for controlling equipment based on air flow simulation that ensure temperature stability and reduce air pollution using fuzzy logic methods.

2. Air flow simulation

2.1. Modeling Methods

The object of research is a 100 sq.m. spot in a common production room five times larger than the spot under study. There is the equipment with a high level of heat generation on the spot. We consider two cases: when the spot has enclosing surfaces and when it doesn’t. One of the tasks is to ensure temperature stability within ±2 degrees Celsius.

Supply and exhaust systems in the serviced premises are located under the ceiling. Air exchange is carried out according to the "top-up" scheme. The supply air is supplied in such a way as to provide the required microclimate parameters within the serviced area. Supply and removal of air is carried out by means of ventilation air distributors.

Control of the aerodynamic mode of ventilation systems is provided by frequency regulators of fan rotation speed, controlled by throttle valves and air flow valves.

The solution of this problem is associated with the use of mathematical models. In a variety of modern simulation programs with different depths, air exchange processes are represented and calculated. The choice of a particular method depends on the problem being solved. To achieve more reliable data, it is advisable to use several methods. Let's consider some of the simulation methods.

1. Böussinesq’s Model. The Navier-Stokes equation can be modified taking into account the influence of turbulent viscosity. This adjustment affects the number of variables defined during the simulation process.
2. The Spalart - Almaras Model. This model offers a different solution to another additional equation of displacement of the turbulent viscosity coefficient.
3. k - ω Model. The equation of motion changes in the form of fluctuations in the average speed and in the process of reducing these fluctuations due to the viscosity. The model can solve two additional equations for the transfer of turbulent flow energy and the transfer of turbulent scattering.
4. k - ε Model. It is similar to the above model, but the difference is in replacing the solution of the dissipation equation with the solution of the equation for the rate of dissipation of turbulent energy. The model gives good results in the wall area.
5. Reynolds Stress Model. The Reynolds-averaged equation (RANS) defines solutions for seven equations that complement the Reynolds stress transfer.
6. Large Eddy Simulation method (LES). This method occupies an intermediate position between models using the Reynolds average number and the DNS equation. It is used for greater fluid flow. The eddy effect is smaller than the cell size of the computational grid, and it is converted into an empirical model.
7. Direct Numerical Simulation (DNS). There are no additional equations. The unstable Navier-Stokes equation is solved in very small steps on a small spatial grid.

The experts claim that the k-ε turbulence model is most often used for solving engineering problems.

The following calculation methods solve the problems of estimating temperature instability and air transport to a different extent. However, they do not give a generalized assessment.

A.N. Selvestrov’s equation: 

\[ C_i(\tau) = \frac{M_{hs}}{L_{inf}} + C_{inf} + \frac{C_{inf}^2}{k} - e^{-\tau(L_{inf}/V_T)} \]

The equation does not take into account the coordinates of the source, which averages the entire displacement volume at a certain moment. The index of the harmful substance concentration, calculated from the model, is underestimated.

V.M. Elterman’s equation:

\[ \frac{\partial^2}{\partial t^2} (\rho C^a) + \frac{\partial}{\partial x} (\rho u_i C^a) = \frac{\partial}{\partial x} \left( \mu^a \frac{\partial C^a}{\partial x} + \frac{\partial u_j}{\partial x} \right) - 2/3 \left( \frac{\partial}{\partial x} \left( \mu^a \frac{\partial u_j}{\partial x} \right) \right) - 2/3 \left( \frac{\partial}{\partial x} \left( \rho \kappa \right) \right) - \sigma_1 \rho g \]

Equation for the propagation of harmful substances in the oncoming air flow by diffusion (N.F. Titchenko):

\[ C_x = k C_0 e^{-\delta x/\lambda} \]

reflects the spread of harmful substances concentration in the counter-flow of air and causes a large error when the inlet jet directly enters the local suction hole. Preference is given to the Reynolds-averaged Navier-Stokes equation:

\[ \frac{\partial}{\partial t} \left( \rho u_i \right) + \frac{\partial}{\partial x} \left( \rho u_i u_j \right) = \frac{\partial}{\partial x} \left( \frac{\partial u_i}{\partial x} \right) + \frac{\partial}{\partial x} \left( \frac{\partial u_j}{\partial x} \right) - 2/3 \left( \frac{\partial}{\partial x} \left( \mu \frac{\partial u_j}{\partial x} \right) \right) - \sigma_1 \rho g \]

As a result of the simulation, a grid with the size of 4,539 was formed (including in the fluid medium 3, 491, and 1,048 in a solid body). The main results are shown in Figures 1 and 2.

### Table 1. The initial conditions of the simulation

| Entry conditions | Boundary conditions at the input | The boundary conditions at the walls | Boundary conditions at the output |
|------------------|----------------------------------|-------------------------------------|----------------------------------|
| \( u_x = u_y = u_z = 0 \) \( k_0 = 0 \) \( \varepsilon_0 = 0 \) \( h_0 = \text{const} \) \( p_0 = \text{const} \) | \( u_x = \text{const} \) \( u_y = u_z = 0 \) \( k = 3/2 \left( \frac{u_x}{I} \right)^2 \) | \( u_x = u_y = u_z = 0 \) \( k = 0 \) | \( \frac{\partial u_x}{\partial x} = \frac{\partial u_y}{\partial x} = \frac{\partial u_z}{\partial x} = 0 \) |
| \( \rho \) | | | \( \delta k / \delta x = 0, \delta \xi / \delta x = 0 \), \( \delta p / \delta x = 0 \) |

As a result of the simulation, a grid with the size of 4,539 was formed (including in the fluid medium 3, 491, and 1,048 in a solid body)

The main results are shown in Figures 1 and 2.
There is a very convenient function. The model is linked using equations that are placed in separate text documents. Changing one element in an object changes the entire model simultaneously. Previously the ventilation system was calculated and the simulation was performed for the considered room.

As a result of calculations in the Solidworks program, the temperatures of air flows and objects were determined.

The air temperature near the equipment is approximately 27°C - 32°C. The indoor air temperature varies from 25 to 26°C. The supply air temperature in the air ducts is 25°C. The temperature of the removed air in the air ducts is 25°C.

The temperature of the equipment is about 40°C. Figure 2 shows how some of the heat from the equipment is transferred to the floor, as well as to the ventilation systems. The floor temperature reaches 26-27°C. The supply air ducts of the system are heated to 27°C. One part of the elements of the exhaust air ducts is heated to 27°C, and the other part, when the air flows merge, reaches the temperature equal to 25°C.

The main task was to form the term sets needed to create a control algorithm. The results obtained allowed us to find a solution for installing temperature sensors within the study zone.

3. Building a management system

3.1 Building a management system

Building fuzzy controllers is the second task of ensuring the stability of air parameters.

It is not possible to give general recommendations on the choice of solution – it depends on application and specifics of control object operation. For ACS, like any technical system using controllers with fuzzy logic, we can formulate the following steps [19, 20]:

- to set a goal of application and choose the structure of FC;
- Being a universal approximator, FC is able to calculate any function that can be used in its setting. It is possible to recommend the following structures of FC: classic FC, adjustable FC, tunable FC, adaptive FC, a self-adjusting FC, FC with a reference mode.
- organization of the database for controller training, determination of the terms number of input and output variables and conversion of actual data into linguistic variables (fuzzification).
- Organization of the database due to the complexity of the systems and limitations on the measurement of variables is the key prerogative of models.

Calling on experts’ aid to collect data is appropriate, but the data would have a purely linguistic meaning and would need to be ranked according to the technical characteristics of the systems in order
to be used in the real operating procedure. Experts’ opinions are often controversial and require additional approvals, especially for systems with incomplete information on the structure.

- selection of the type of fuzzy variables membership functions.

In practice, any dependencies that approximate the input and output data with the expected accuracy can be used as membership functions. The number of terms in the interval representation is substantial, as well as specifics of superposition of membership functions, the ways of their setting, the final and initial look of the functions and specifically of the output.

- generation of the data base and communication between background space and conclusion space.

Knowledge base is the most essential component in the structure of FC. Data processing is based either on the rules or on fuzzy relations.

Max-Min Inference method of logical solution is the most frequently used. The resulting membership function with the maximum validity value is selected by means of mutual superposition.

It is possible to get a decisive rule (conclusion) using the well-known methods Sugeno, Mamdani, Larsen and Tsukamoto. If these methods do not meet your expectations, develop your original method of implementing the conclusion, but this is not an easy task. Care should be taken to choose the method of logic conclusion and composition rules.

- a method of converting linguistic variables into numerical ones (defuzzification).

There are several methods for converting linguistic variables into numeric variables that differ in accuracy. This is First-of-Maxima – the first maximum, Middle-of-Maxima – the average maximum, Max-Criterion – the maximum criterion, Height Defuzzification - the largest of all \( \alpha \) - levels. The study of the operating capacity of the considered automatic control structure was implemented in the Simulink and Fuzzy Logic Toolbox packages of the MatLab program by the example of a ventilation system equipped with adjustable fan drives and throttle drives. It was assumed that the temperature in space is affected by an external temperature perturbation, which has the form of a low-frequency harmonic function. Studies were conducted to assess the operating capacity and characteristics of the fuzzy system and its ability to compensate for temperature disturbances. The phase and amplitude of periodic signals were set arbitrarily.

The block diagram of the automated control system is shown in Figure 3. It contains three subsystems: drives providing air supply and removal from the working area with a set of control equipment, temperature measurement sensors, and a computer that implements a control algorithm built using fuzzy controllers (FC) combined in a three-level structure [21].

Temperature sensors form four zones, with sensor 1 belonging to all zones, and 2, 3, 4 and 5 belonging to adjoining zones. The sensors of each zone are connected to the corresponding fuzzy controller. The outputs of the FC of the first layer are connected to the inputs of the FC of the second layer. The outputs of all FC are connected to the corresponding drives of the supply and exhaust ventilation mechanisms. The considered structure is designed to reduce the size of the data base. For example, with four input signals with three term sets, the number of entries in the data base will be more than five hundred and twelve. In this case, the time for decision-making and implementation of the outcomes becomes significant.

The algorithm of the scheme is as follows. The universal set \( P \), that characterizes the space of temperature state of the room, has the following subsets:

- Subset \( T^1 \) characterized by the membership function \( \mu_{T^1}(t^1) \) Subset \( T^1 \) is the set of pairs \( \{t^1|\mu_{T^1}(t^1), \forall t^1 \in P\} \) describing the temperature for the first sensor;
- Subset \( T^2 \) characterized by the membership function \( \mu_{T^2}(t^2) \) Subset \( T^2 \) is the set of pairs \( \{t^2|\mu_{T^2}(t^2), \forall t^2 \in P\} \) describing the temperature for the second sensor in the first zone;
- Subset \( T^3 \) characterized by the membership function \( \mu_{T^3}(t^3) \) Subset \( T^3 \) is the set of pairs \( \{t^3|\mu_{T^3}(t^3), \forall t^3 \in P\} \) describing the temperature for the second sensor in the second zone;
Subset $T^4$ characterized by the membership function $\mu_{T^4}(t^4)$ Subset $T^4$ is the set of pairs \[\{t^4|\mu_{T^4}(t^4), \forall t^4 \in P\}\] describing the temperature for the second sensor in the third zone.

![Figure 3. Block diagram of the temperature control system](image)

Subset $T^5$ characterized by the membership function $\mu_{T^5}(t^5)$ Subset $T^5$ is the set of pairs \[\{t^5|\mu_{T^5}(t^5), \forall t^5 \in P\}\] describing the temperature for the second sensor in the forth zone.

The input terms of the set were determined based on the analysis of the actual data obtained from the simulation results (Figure 1, Figure 2). Term sets are represented by three triangular membership functions for each sensor and are described by the linguistic variables SN - below normal, N – normal, and BN – above normal.

The output term set is represented by five linguistic variables S - small, SM - below average, M – average, BM - above average, and B - large.

Controllers of the first level are built on the same type structure, two inputs and one output. The outputs of the first-level FC are connected to the second-level controller. It is represented by four input term sets and two output ones, on the basis of which a conclusion is made about changing the operating mode of the drives of either the supply or exhaust branches of the ventilation device. The output signals of all FC are connected to the control devices of the drives.

Initially, the data base for each first-level FC was represented by nine rules. As a result of the analysis, the conflicting rules were removed, and seven rules were finally used.

The conclusion was made using the Mamdani method. Initially, we find the $\alpha$ - levels for each of the rules using the operation MIN:

\[
\alpha_1 = T^4_1(t^1) \land T^4_2(t^2) \land T^4_3(t^3),
\]

\[
\alpha_2 = T^5_1(t^1) \land T^5_2(t^2) \land T^5_3(t^3),
\]

\[
\alpha_3 = T^4_1(t^4) \land T^5_2(t^2) \land T^5_3(t^3),
\]

and then the corresponding membership functions:

\[
K^1(e) = \alpha_1 \land K^4_1(e), \quad K^2(e) = \alpha_2 \land K^5_2(e), \quad K^1(e) = \alpha_3 \land K^5_1(e).
\]

Output was performed using the MAX operation, combining truncated functions. As a result we get an output variable with the membership function:

\[
\mu_2(e) = (\alpha_1 \land K^4_1(e)) \lor (\alpha_2 \land K^5_2(e)) \lor (\alpha_3 \land K^5_1(e)).
\]

The output of each controller is directly connected to the drives, and it simultaneously transmits information to the second layer. The output set of FC1 and FC2 is the input sets of FC5. The output sets of FC3... FC4 arrive at the inputs of FC7 as well. The final information is collected at the input of the FC6 controller, whose output signals control the fan drives. NC FC5 and FC 7 emit a significant
excess of temperature and transmit this information to the input of the FC6 controller in which a decision is made to increase the fan speed.

3.2 Simulation result

The results of the algorithm are shown in Figure 4.

The temperature level was set as follows: \( T = (0.5...2) \sin((0.1t...0.5t) + \varphi)\) according to the data taken during simulation in Solidworks (Figure 4a). The fuzzy controller FC1 generates control signals to the drive input (Figure 4b) regulating the temperature in the first zone. FC2 – FC4 controllers function similarly. The data base is of the same type, differing only in the range of terms of sets. Initially, the average value of the control voltage was set, relative to which the voltage at the input of the drives is reduced or increased, depending on the temperature level.

The simulation has shown that it is possible to control the temperature within the desired limits with a prescribed accuracy.

![Figure 4. Influence of the amplitude and frequency of the perturbation on the output coordinate: A -
the simulated temperature of the sensors, B - the output signal of the controller FC1.](image)

4. Conclusion

The intervals of sets, the type and number of membership functions providing the desired characteristics of the temperature control process are revealed. The material stated in the article represents a method for constructing a control algorithm using fuzzy controllers. The presented multi-level structure reduces the knowledge base volume requirements.

The study of the model in Solidworks and Fuzzy Logic Toolbox has shown that it is possible to build systems using fuzzy logic for temperature control in industrial premises with high stability requirements. The considered system is functional, and the characteristics of the fuzzy system show the ability to compensate for temperature perturbations. The general data base has thirty-two entries that provide the desired output characteristics. Difficulties are associated with determining the location of sensors and their type. Without simulation the ventilation system, it is not possible to determine the term of the set. The only drawback is the limited capacity to conduct field tests within the production process.

Further work is related to the research of algorithms of controllers self-tuning for the parameters of the controlled environment, with respect to the initial conditions, and predicting possible changes.

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