IMPROVEMENT OF MICROCLIMATE CONTROL ENERGY-SAVING SYSTEMS AT INDOOR SPORTS FACILITIES IN RURAL AREAS

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Abstract. The paper considers and substantiates the algorithm based on the maintenance of the desired discomfort index using the fuzzy logic controller (fuzzy-controller) for systems of energy-efficient management of microclimate of premises of sports complexes in rural areas (such as, for example, as physical fitness centres). The existing methods of complex energy-efficient management of microclimate of premises in sports facilities from the point of view of regulation methods are investigated. The approach to determining the discomfort index is analysed. The values of the discomfort index (for a person being in a room for physical training and recreational activities, sports) are divided into ranges depending on the average perceptions of comfort conditions for a person, equipment and the room itself of the above-mentioned functional purpose. A database of rules based on the calculated values of the discomfort index was developed. An intelligent system of automatic support of comfortable microclimatic conditions in the premises of a sports complex located in rural areas for all components of the system “premises of the sports complex - inventory - person” has been theoretically designed. On the basis of the calculated values of the discomfort index for all possible variants of dry and wet bulb temperature values, a rule base for fuzzy controller was built. The results of mathematical modelling show the efficiency of using the proposed control algorithm, which provides minimum power consumption of available resources. According to the results of modelling it is possible to note the compliance with the requirements of the obtained energy-efficient control system regarding the maintenance of the desired level of the discomfort index in the room of the sports facility, as well as the minimum number of activations of the executive mechanism (fuzzy - regulator and controller) of the air conditioning system, the absence of over-regulation and energy saving.

Keywords: fuzzy logic controller, energy efficiency, discomfort index, microclimate, air conditioning, temperature, humidity.

Introduction

Reducing the negative impact of the microclimate in the premises of indoor sports facilities can be achieved by using the following measures: introduction of rational energy-saving technologies for their operation; protection of people engaged in physical culture or competitive sports, educational and training activities, various types of screens, partitions, mechanization and automation of processes that provide the appropriate parameters of the microclimate in the premises; rational thermal insulation of sports equipment, tools, shells, etc.; rational placement of sports equipment and auxiliary equipment (trainers, bars, dumbbells, medicine balls, etc.); implementation of automated systems for ensuring the optimal microclimate of premises, in particular sports facilities, using intelligent control systems based, for example, on the use of fuzzy logic tools, methods and algorithms and, in particular, fuzzy logic controllers (FLC) of the NLR, the so-called “fuzzy-controllers” [1-3].

The introduction of intelligent control and automation systems for maintaining the optimal microclimate of indoor sports facilities in rural areas that function on the basis of the appropriate NLR software in “fuzzy-controllers” [4-6], which constantly monitor, using stationary sensors, air parameters, and monitor its condition according to a complex of air mass characteristics in real time, will allow controlling and regulating changes in microclimate parameters (as well as the behaviour of air masses in general) in such premises, improving their management, the management process itself, by incorporating modern mechatronic systems/complexes into it [7; 8].

For the control of modern air conditioning systems of indoor sports facilities (ISF) fundamentally new laws of regulation are actively used, which are called “neurotechnology and fuzzy logic” (Neuro & Fuzzy logic) [9; 10]. The criterion of functioning and the purpose of control in them is a set of parameters that determine the comfort of the environment for a person (a visitor of the indoor sports facility), sports equipment (equipment located in the ISF) and the room itself, in which visitors and the specified sports equipment are located, according to the value of the discomfort index D_n [3; 9]. The system evaluates the microclimate parameters of ISF and automatically selects the operating mode. The selection is based on practical analysis - the average wishes of people who use the system, the conditions (comfortable) for storing sports equipment and the standards of operation of the premises themselves are taken as a benchmark. The values, D_m (m = 1,2,3), where the number denotes, respectively, sports equipment (training complex, sports shell, sports equipment and other) (m = 1), the human body (m = 2), the actual room of the indoor sports facility (m = 3), operated in accordance with sanitary and other norms, will be further considered according to the level of significance (from the highest to the lowest). The values D_m represent the levels of various factors, the values of which depend on: 1) comfort of the visitor to ISF; 2) safe keeping of the sports equipment placed in the room; 3) various norms of ISF operation – these are, first of all, temperature, humidity, intensity (speed of movement) of air flows and other.

The main advantage of the fuzzy logic controller (fuzzy-controller), compared to traditional control approaches, is that the design of the controller does not require a mathematical model of the control object [4; 11]. The results of research of such systems are presented in [11; 12]. Another advantage of fuzzy logic controllers is their robustness to changes in the parameters of the control object, which is explained by the nonlinear nature of such controllers [5; 6; 12].

Another approach is proposed by the authors [13-15]. These works propose a methodology for developing a complex mathematical model of an industrial air conditioner in the state space. The methodology allows to obtain a complex model of an industrial air conditioner as a single multidimensional control object. In contrast to the existing systems that stabilise the temperature and relative humidity of the air, a method of regulating the temperature and humidity of the air is proposed, which allows to reduce, and in some modes to exclude, the relationship between the parameters of temperature and humidity.

This paper partially uses the results of the authors' research [13-15], but the basis of microclimate control of ISF is a different idea, converging to the maintenance in these rooms of a constant value of air pressure, depending on the temperature of air humidity, as well as the velocity of the air mass flow. However, none of the authors under review have dealt with the problems of microclimate management in sports buildings.

In order to assess the impact of the ISF environment on a person, on the sports equipment/inventory located in it, as well as on the very room where this expensive modern equipment (training system and others) is located, it is necessary to determine not only the quantitative value of individual microclimate parameters, but also the results of their overall impact on the human body, on the sports equipment and on the room where they are located. It is not difficult to calculate the influence of one factor on a single person, it is much more difficult to calculate the influence of several factors. In order to formulate a qualitative comfort index, such evaluation systems as the environmental heat load (WBGT) [16] and the discomfort index D_i [17; 18] were previously introduced. According to the discomfort index, the environment changes from comfortable to slightly annoying and then to intolerable. This is the approach that will be used in this study in relation to the three main components of the system, the microclimate to be regulated, namely: 1) to the visitors of the premises of ISF who are in it at a given time; 2) to sports equipment displayed in the premises of ISF; 3) to the ISF itself, where visitors and sports equipment are accommodated.

Materials and methods

The research methods used in the work are: 1) mathematical and physical-mechanical modelling; 2) geometric control theory; 3) fuzzy logic; 4) method of setting the priority of local criteria; 5) Mamdanis algorithm or 'minimax inference' algorithm; 6) computer modelling of the system of microclimate regulation; 7) method of determining a generalised discomfort index for room.

Firstly, let us consider the procedure of the algorithm for taking into account the influence of humidity on the human condition. To assess the joint influence of temperature and humidity on the feeling of discomfort, an index was introduced

$$D_n^{(1)} = 0{,}72_1 \cdot (t_d - t_w) + 40{,}6, \tag{1}$$

where t_d – temperature of the "dry" thermometer, °C;

t_w – wet bulb temperature, °C (both thermometers are part of the classical hygrometer present in most sports halls).

An index can be introduced to assess the effect of the airflow velocity on the sensation of discomfort:

$$D_n^{(2)} = 37{,}5 \cdot v_a + 66{,}25, \tag{2}$$

where v_a – air mass flow velocity, m·s^{-1}.

Fuzzy logic has its advantages over the use of PID-regulators when processing very complex processes, nonlinear processes, when processing expert data [7, 9, 19]. Below in Table 1 are presented the degrees of discomfort for a person defined by parameters (1) and (2), which take into account the joint influence on the human organism of three leading factors that determine the comfort of staying in a given room: temperature, humidity and air mass flow rate (at the same time the air pressure in the given room remains unchanged).

Table 1

Degrees of discomfort for the human visitor to ISF

Discomfort Index $D_n^{(1)}$, $D_n^{(2)}$	Degree of discomfort
< 70	Comfortable
70...75	Some visitors to ISF feel uncomfortable
75...80	50 per cent of people in ISF feel uncomfortable
80...85	All of the people in ISF feel uncomfortable
> 85	Intolerable discomfort

We will further denote: 1.) index i_1 – discomfort index for visitors; 2.) index i_2 – discomfort index for sports equipment and equipment located in the premises; 3.) index i_3 – discomfort index for the operation of the premises itself. The generalised discomfort index of such a complex system, formed on the basis of three indices (temperature, humidity, air mass flow rate in the room), as shown below, also takes into account the weight ("influence") of each of the individual indices. The weight of a particular discomfort index is determined by the existing specialists of ISF and the equipment of the training equipment placed in them.

Given the difficulty of unambiguously determining the optimal set of indoor climate parameters of ISF in real time for the system "visitors – sports equipment/inventory – room", which complicates the procedure of setting tasks for automatic controllers, a promising approach to control is using fuzzy logic [2; 10; 20]. The structure of the fuzzy input system is induced in [3-7].

Results and discussion

Let us see further the procedure of synthesis of FLC for the system of air-conditioning of ISF. For this purpose at the beginning we will consider the principle of air-conditioner control to maintain the discomfort index D_{ni}, $i = \overline{(1{,}3)}$ within the available limits.

Firstly, the capacity with which the air conditioner should work to cool the air in the air conditioning centre is determined by the desired temperature that we would like to have in this room (of course, it is necessary to take into account all "interests" of all parties of components of the system). The temperature in ISF is the first linguistic variable of FLC and can take the values "small", "medium", "large". These values are assigned to the temperature based on the intersection of the boundaries of small average and large temperatures of all components of the system and only then the generalisation "small", "average ", "large" occurs. These values are assigned to the temperature on the basis of the intersection of the boundaries of small average and large temperatures of all components of the system and only then generalised "small", "average", "large" room temperature arises, which is already applied as a concept for all aggregate components of the system. Let us conditionally assume a range of changes in the readings of a dry thermometer for a fitness room from 16° C to 30° C.

Secondly, comfortable climatic conditions in ISF are determined not only by the air temperature, but also by its relative/absolute humidity, as well as by the velocity of the air mass movement. With regard to the latter, all distributions are similar to those given above for the indoor temperature of ISF. Therefore, the velocity of the air mass movement is the second linguistic variable, note that for a comfortable stay of people in the room, the velocity of the air mass movement according to (2) should lie within the range v_a = 0,1... 0,5 m·s^{-1}.

The third linguistic variable of FLC is humidity or the wet bulb temperature of the hygrometer, which appears in formula (1) and together with the readings of the dry thermometer unambiguously determines the humidity in ISF. The range of temperature changes of the wet bulb is larger than the range of changes of the "dry" thermometer, so there will be more linguistic variables of the third type of humidity: "very low", "low", "satisfactorily low", "satisfactorily high", "high", "very high".

To determine the weight and priority in the assessment of the generalised discomfort index of the system, we will use the approaches and results of [19-22] in which a method of setting the priority of local criteria is proposed. In this case we will be guided by the existing expert assessments of priority characteristics for the case studied in this paper (the system "visitors" - "sports equipment/inventory" – "premises"). The main priority features include the following three: 1) priority row - I; 2) priority vector – V; 3) weighting vector – Λ.

According to expert estimates, in the studied case for this sports hall we have: I = (1,2,3), V = (4,2,1). Components of the vector $V = (v_1, v_2, v_3) = (4,2,1)$, and components of the weight vector $\Lambda = (\lambda_1, \lambda_2, \lambda_3)$can be calculated [19] by the formula

$$\lambda_q = \frac{\prod_{i=q}^{k} \gamma_i}{\sum_{q=1}^{k} \prod_{i=q}^{k} \gamma_i}, q = \overline{(1,3)} \tag{3}$$

so the weight vector Λ has the following component values: $\lambda_1 = 0{,}7272$, $\lambda_2 = 0{,}1818$, $\lambda_3 = 0{,}0909$.

Further we define for calculation of the generalised discomfort index of the system "visitors - sports equipment/inventory - premises (premises of ISF) $D_n^{(gen)}$:

$$D_{nj}^{(gen)} = \sum_{i=1}^{3} \lambda_i \cdot D_{ni}^{(j)}, i = \overline{(1,3)}, j = (1,2), \tag{4}$$

where $D_{ni}^{(j)}, i = \overline{(1,3)}$ discomfort indices are indicated for visitors, sports equipment/inventory, sports hall room, respectively.

Each of the discomfort indices in turn is determined either by formula (1) (j = 1), or by formula (2) (j = 2), i.e. for temperature and humidity indices (j = 1) or for the air flow velocity index (j = 2). Therefore, the result is

$$D_{ni}^{(1)} = A_1 \cdot (t_d - t_h) + B_i, i = \overline{(1,3)} \tag{5}$$

where the empirical coefficients, A_i, B_i are defined for each component of the system under consideration separately and integrated many other dependencies, which ultimately determine the discomfort index of a particular component of the system. Here we present the conceptual basis for the development of algorithms of fuzzy logic regulator functioning.

For the discomfort index $D_{ni}^{(2)}$ we have the following relationship:

$$D_{ni}^{(2)} = E_i \cdot v_a + F_i, i = \overline{(1,3)}, \tag{6}$$

where the empirical coefficients, E_i, F_i are determined for each component considering the system separately, and the algorithm for their determination is similar to the one given above for the coefficients, A_i, B_i.

Having the value $D_{nj}^{(gen)}$ for j = (1,2), we can find the value of the discomfort index for all three linguistic variables using the disjunction operation (intersection) of the sets D_{nj} with each other, i.e.:

$$D_n^{(gen)} = D_{n1}^{(gen)} \cap D_{n2}^{(gen)} \tag{7}$$

the initial value of FLC is the control action on the refrigerant compressor, which is assigned the following terms: "large negative" (NB), "negative" (N), "zero" (ZE), "positive" (P), "large positive" (PB). That is, under comfortable conditions, there is no control action and the compressor operates in the gymnasium at the set capacity. In the presence of deviations from comfortable conditions, the FLC produces a control action in the direction of increasing or decreasing the compressor capacity until the negative perturbation of the microclimate of the room and the whole system are compensated.

Table 2 summarises the rule base of FLC for maintaining indoor climate of ISF. Mamdani's algorithm [18; 19] or "minimax inference" algorithm is used here as a fuzzy inference algorithm. To calculate the resulting odd set of the output variable, this algorithm uses the operation of logical minimum (min) at the fuzzy inference stage and the operation of logical maximum (max) at the composition stage.

Table 2

Rule base of fuzzy logic controller

$\begin{Bmatrix} t_d, °C; \\ v_a, m \cdot s^{-1} \end{Bmatrix}$	**Temperature of "wet" thermometer, °C**					
	Very small (6-11)	**Small (12-14)**	**Satisfactorily small (15-18)**	**Satisfactory (19-21)**	**Big (22-25)**	**Extra large (26-29)**
Small $\begin{Bmatrix} 16-21; \\ 0.10-0.20 \end{Bmatrix}$	N	N	ZE	ZE	-	-
Medium $\begin{Bmatrix} 22-25; \\ 0.21-0.40 \end{Bmatrix}$	N	ZE	ZE	P	P	-
Large $\begin{Bmatrix} 26-30; \\ 0.41-0.50 \end{Bmatrix}$	ZE	ZE	P	P	P	PB

In this paper, the method of determining the 'centre of gravity' is used to obtain a clear conclusion, in which a clear numerical value is determined according to the formula:

$$u_c = \frac{\int_{u_1}^{u_2} u \cdot \mu_c(u)du}{\int_{u_1}^{u_2} \mu_c(u)du}, \tag{8}$$

where u_c – result of defuzzification;
u_1, u_2– boundaries of changes in the linguistic variable u;
$\mu_c(u)$ – resulting adjacency function (AF).

The most common adjacency functions of linguistic variables in practice are triangular AF, whose mathematical description is given in the form [3, 7]:

$$\mu_1(u) = (1 - u),\ \mu_2(u) = \text{u},\ 0 \le u \le 1. \tag{9}$$

Regulation of microclimate in the premises of ISF with the help of intelligent control systems based on mechatronics, fuzzy logic controllers according to the algorithm described above was used as a design solution to improve the energy efficiency of microclimate control systems of sports halls in the sports complex KNUCA. The functional scheme of the systems of automated provision of optimal microclimate of premises, taking into account the functional requirements, consists of two modules: design and the system itself. The design module is designed to select the number of air conditioners that should be used in the room at a given current time, based on the specific conditions in the room. The following 3 blocks lead to the system module: 1 - measuring, 2 - control block, 3 - execution block.

To assess the quality of the synthesized control system, it is necessary to specify the actual models of the control objects [4]. The temperature (and humidity) models, which are the input parameters of FCL, are described by 1st-order differential equations with delay, which are based on those given in [7]:

- dry bulb temperature

$$186 \cdot \frac{d}{dt}\{t_d(t)\} + t_d = 0{,}1 \cdot u(t-160); \tag{10}$$

- wet bulb temperature

$$405 \cdot \frac{d}{dt}\{t_w(t)\} + t_w = 0{,}28 \cdot u(t-184). \tag{11}$$

Dry bulb temperature transfer function:

$$W_d(s) = \frac{0{,}11}{186 \cdot s + 1} \cdot \exp(-160s) \tag{12}$$

Wet bulb temperature transfer function:

$$W_w(s) = \frac{0{,}28}{405 \cdot s + 1} \cdot \exp(-184s) \tag{13}$$

In (12) and (13) s is a symbolic variable (differentiation operator), which is related to time t using the Laplace transform for $t_d(t)$ and $t_w(t)$.

The modelling of the microclimate control system in the premises of ISF was carried out in two ways: 1) for the intelligent control system in the Simulink MATLAB environment using the Fuzzy Logic Controller with Rule Viewer block (for the implementation of the designed FLC); 2) for information processing, its collection and integration with fuzzy logic tools in the control system of the dispatch point, the Delphi 7 environment was selected.

To keep constant the partial pressure (its static and dynamic components) of the main components of the air mass (nitrogen, oxygen and water vapor), the relations and laws of the molecular-kinetic theory of gases are used in the work. Thus, for i-th air mass components ($i = \overline{(1,3)}$) (random) change in its characteristics (Δm_i – mass, ΔT – temperature, ΔV – velocity) should be controlled and regulated (until this parameter becomes comfortable for the athlete in the building) by special control sensors (temperature, humidity, velocity of air masses).

In this case, based on the basics and principles of geometric control theory, the specified changes in the main characteristics of the building air masses and their reduction to comfortable (for athletes) values are as follows, (m_i^K, T^K, V^K) should be determined and promptly eliminated using the following relationship:

$$\frac{\Delta m_i}{\left\{\dfrac{\mu_i \cdot \tilde{V}}{R \cdot T^K}\right\}} + \frac{\Delta T}{\left\{\dfrac{\mu_i \cdot \tilde{V}}{m_i^K \cdot R}\right\}} + \frac{\Delta V}{\left\{\dfrac{1}{\rho_i \cdot V^K}\right\}} = 0 \tag{14}$$

where μ_i – mass of 1 kg-mole of component, kg·mol^{-1};
R – universal gaseous constant, 8.314 J·(mol·K)$^{-1}$;
ρ_i – compression of i - component;
$\tilde{V}$ – full internal volume of an indoor sports facility for artificial hypoxic training.

It should be noted that the geometrical image of relation (14) is a plane in the three-dimensional parameter variation space (Δm_i, ΔT, ΔV), that passes through the point (0; 0; 0), with orthonormal vector with components:

$$\tilde{n} = \left\{\frac{\mu_i \cdot \tilde{V}}{R \cdot T^K}; \frac{\mu_i \cdot \tilde{V}}{m_i^K \cdot R}; \frac{1}{\rho_i \cdot V^K}\right\} \tag{15}$$

In swimming pools for sports swimming: 1) the air temperature is (25…29) °C, that is T^K = (298…302) °K; 2) water temperature – (25…27) °C; 3) relative humidity (denoted m_{H2O}^K) constitutes (50…60)%; 4) velocity of air masses does not exceed 0.3 m·s^{-1} (that is $V^K \leq 0.3$ m·s^{-1}).

Table 3 shows the calculations of $\frac{\Delta m_i}{m_i^K}, \frac{\Delta T}{T^K}, \frac{\Delta V}{V^K}$ changes for $\tilde{V}$ = 10^5 m^3.

The presence of such technology for regulating the movement of air masses in a sports facility can also significantly reduce energy costs for the functioning of a forced ventilation system in it. In computer comparative analysis of the effectiveness of microclimate management of such premises using intelligent control systems based on fuzzy logic controllers and modern mechatronic systems, in contrast to the classical approach existing in the fitness halls of the KNUBA sports complex (with forced ventilation), in which all air conditioning systems operate in stationary mode (or are turned off or turned on once and at the same time), monthly energy savings amount to 12.2% (about 200 kWh), and 2400 kWh per year.

Table 3

Calculations of $\frac{\Delta m_i}{m_i^K}, \frac{\Delta T}{T^K}, \frac{\Delta V}{V^K}$ changes for $\widetilde{V}$ = 10^5 m^3

$\frac{\Delta m_i}{m_i^K}$	$\frac{\Delta T}{T^K}$	$\Delta V = 0$	$\frac{\Delta V}{V^K}$
+ 1%	-1%	0	-
+ 2%	-2%	0	-
+ 3%	-3%	0	-
+ 5%	-5%	0	-
0%	+ 1%	-	-2,6%
0%	+ 2%	-	-5,2%
0%	+ 3%	-	-7,8%
0%	+ 5%	-	-13%

Conclusions

1. Maintaining the minimum permissible generalised discomfort index of sports facilities provides a reduction in overall energy consumption and eliminates unnecessary regulatory actions for small deviations of the measured parameters, which are temperature, humidity, air mass movement velocity, pressure of air and water vapour in sports facilities.
2. The considered system of microclimate regulation of ISF premises on the basis of determination of a generalised discomfort index provides comfortable conditions of stay of a person, sports equipment/inventory with the help of which it is possible to carry out training activity of people simultaneously staying in the given place and at the given moment of time, and also satisfying all norms of operation of ISF premises stated in instructional documents.
3. Although the above system provides coarser regulation (robust) with respect to direct parameter changes, it is still able to provide comfortable microclimatic conditions for ISF due to the rule base embedded in FLC. In this system there is no specific setting of the temperature of "dry" and "wet" thermometers, the speed of air mass flow, and the parameters that are regulated, in fact, there is a generalised discomfort index $\mathrm{D_n^{(gen)}}$ which is an indirect index and is calculated on the basis of both temperatures for a given air velocity.
4. In computer comparative analysis of the effectiveness of microclimate management of such premises using intelligent control systems based on FLC and modern mechatronic systems, in contrast to the classical approach existing in the fitness halls of the KNUBA sports complex (with forced ventilation), in which all air conditioning systems operate in stationary mode (or are turned off or turned on once and at the same time), monthly energy savings amount to 12.2% (about 200 kWh), and 2400 kWh per year. Such an economic effect of energy savings during the operation of the specified KNUBA sports complex is due to the following: a) when the comfort parameters of the microclimate in the premises change, adaptive regulation of active air conditioners occurs without unnecessary switching on/off; b) at the current moment, depending on the situation that has arisen in the microclimate of the premises (of specific dimensions), only the required number of air conditioners is operating, and not all of them installed in one room.

Author contributions

Conceptualization, Y.C.; methodology, A.M. and S.R.; software, Y.C.; validation, S.R. and O.S.; formal analysis, Y.C., A.M. and S.R..; investigation, Y.C., A.M., S.R. and O.K.; data curation, O.S., and O.K.; writing – original draft preparation, Y.C.; writing – review and editing, A.M. and S.R.; visualization, S.R. and O.K.; project administration, A.M.; funding acquisition, S.R. All authors have read and agreed to the published version of the manuscript.

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