TECHNOLOGY, CREATIVITY, IMPLEMENTATION

MODERN APROACH TO MICROCLIMATE CONTROL ON BOARD SHIPS

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Summary

Ambient and indoor air pollution have high impact on public health. Safety of indoor air is crucial for well-being and stress tolerance of seafarers due to their prolonged stay in the environment characterized by adjacency of work and leisure premises. Flaws in ventilation and air distribution systems may lead to infiltration and accumulation of pollutants in air of living and recreation premises. However, available onboard HVAC systems designs are not fit to ensure cleanliness and quality of the indoor air of ships accommodation.

In this study a new approach for indoor air quality management on board merchant ships is proposed. Air quality standards and requirements analyzed and formal representation formulated. Approximation techniques for thermal comfort index PMV reviewed and computationally efficient polynomial representation proposed. Unified dynamic model of microclimate, thermal comfort and gas composition of air is developed. Model performance was studied in simulation environment with superstructure microclimate model of a real ship. As a proof of the hypothesis a preliminary prototype developed and tested on board of gas carrier vessel.

A proposed control optimization problem statement allows implementation of a wide range of indoor air quality and comfort management systems at scale. Prototype multiparameter controller based on microprocessor technology showed potential of performance improvement and scalability for development of distributed control systems.

Keywords: indoor air quality, safety, living premises, automation control, distributed control system.

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1. Introduction

Growing competition and cost cutting in maritime transportation business are key factors in reduction of onboard crews down to the minimum with perspective of replacing traditional ships by unmanned alternatives or retrofitting existing ships with autonomous technologies. As a result, workload and stress of seafarers rises which has a direct impact on vessel safety (*Elspeth et al.,2021)*. Ensuring safe and comfort environment in working and living premises is basis for seafarer's recovery from exposure to harmful factors, fatigue reduction and avoiding of chronic fatigue syndrome. Studies have shown insufficient level of air cleanliness and quality on board of some types of merchant vessels *(Webster et al., 2005, Kim et al., 2008,* *Kim et al, 2010, Kennedy, 2019)*. Fuel type and chemical composition along with ventilation system design flaws have serious impact on indoor air contamination from exhaust gases and hydrocarbon vapors infiltration *(Langer, 2020)*. Indoor air quality as a measure of its cleanliness along with thermal comfort influence occupant productivity *(Alhorr, 2016).* which especially important for maintaining situational awareness of watchkeeping personnel.

Depending on the type of vessel and the purpose of the premises, they are divided into classes according to the degree of accommodation: without presence, with partial periodic presence and with round-the-clock presence. Depending on the class of accommodation, there is a need to consider the human element and the associated social aspect of safety of the crew and ship, as it is necessary to create living conditions for people of the appropriate level of safety and comfort.

2. Purpose and methods of research

The article focuses on formalization of indoor air quality requirements and development of a combined mathematical model of the microclimate, thermal comfort and gas composition. Such model allows to find the optimal structure of a control system develop algorithms for effective management of indoor air quality and study its efficiency.

3. Indoor Air Quality

Air quality is a characteristic of its purity and suitability for human breathing. There are two approaches to assessing air quality: comparing the concentrations of pollutants with the maximum allowable and using air quality indices.

With first approach the maximum allowable concentrations set at the international, national or sectoral level are used *(Zhang, 2020)*. Maximum permissible concentrations may be mandatory and recommended, apply only to open air, industrial air or residential air.

Mandatory concentration limits are set at the state level in the following countries: Australia, USA (US EPA and OSHA), Germany (Deutsche Forschungs Gemeinschaft), South Korea.

The recommended concentration limits can be used by national and sectoral agencies in case of need to establish control of air pollution of the environment, work area or living quarters, non-industrial outdoor environment and indoor air. Such limits set by Federal Commission of the Canadian Government, World Health Organization (WHO), National Institute of Safety and Health (NIOSH), American Conference of Governmental Industrial Hygienists (ACGIH), American Society of Heating, Cooling and Air Conditioning Engineers (ASHRAE).

With second approach Air quality index is used as a quantitative measure of air quality. Generally, with increase of air quality index the risks to human health increase. Currently, the various air quality indexes are used in England, South Korea, the European Union, Mexico, Singapore, India, Canada, China, Hong Kong and the United States. In most of these countries, regional agencies and affiliates are required to report an air quality index on a daily basis, which allows them to assess the dynamics of air pollution at the state level and take appropriate measures to reduce it.

The air quality index indicates on some scale the level of pollution from low to heavy, or the level of breathability from suitable to dangerous. Index scales from 0 to 10, from 0 to 100 and from 0 to 500 are used, where smaller values correspond to cleaner and safer air, and larger values correspond to higher concentrations of pollutants.

The world's leading countries have developed their own air quality indices and national air quality standards. ISO has developed a number of standards ISO16000-1 – ISO16000-38, which regulates the methods of measuring air quality parameters and the latest standard ISO / FDIS 16000-40 Indoor air quality management system (Indoor air quality management system).

Most countries use concentrations of ozone, sulfur dioxide, carbon monoxide, particulate matter and nitrogen dioxide to determine the Air Quality Index. For each of the pollutants, calculate the corresponding partial index AQI_i by the ratio of the short-term average value of its concentration, usually eight or twenty hours, with the corresponding maximum allowable concentration. The air quality index is taken equal to the value of the largest of the partial indices of pollutants:

$$AQI = MAX\left(AQI_i\right)$$

To calculate the partial indices for each of the pollutants the following formula is used:

$$AQI_i = \frac{I_j - I_{j-1}}{C_{ji} - C_{(j-1)i}}\left(c_i - C_{(j-1)i}\right) + I_{j-1}$$

where AQI_i is the partial index of the pollutant i; c_i is the concentration of the pollutant i; C_{ji} is the upper limit of the concentration range in which c_i falls; $C_{(j-1)i}$ is the lower limit of the concentration range in which c_i falls; I_{j+1} – AQI value corresponding to C_{ji}; I_j is the value of AQI corresponding to $C_{(j-1)i}$.

Dependences of partial quality indices on pollutant concentrations are continuous piecewise linear functions and can be represented analytically in the form:

$$AQI_i = a_i c_i + b_i + \sum_{j=1}^{n} w_{ji}\left|c_i - C_{(j-1)i}\right|, \tag{1}$$

$$w_{ji} = \frac{k_{ji} - k_{(j-1)i}}{2},$$

$$k_{ji} = \frac{I_j - I_{j-1}}{C_{ji} - C_{(j-1)i}},$$

$$a_i = \frac{k_{i0} + k_{in}}{2},$$

where c_i is the concentration of the i-th pollutant; k_{ji} is the angle of inclination of the segment j of a piecewise linear function with index i.

4. Thermal comfort

In order to ensure proper working and rest conditions, the air of office and residential premises, in addition to safety, must meet the requirements of comfort. The ISO7730 standard for the assessment of comfort accepts the analytical dependence of the integrated comfort indicator PMV on the parameters of air, metabolism and human clothing.

According to the standard, the algorithm for calculating the PMV at the stage of determining the surface temperature of clothing requires a numerical solution of the equation of the fourth degree, which involves the use of an iterative algorithm. To synthesize and study automatic comfort control systems, it was proposed to use the approximation of PMV by algebraic expressions with exponential terms *(Holykov, 2000)* or polynomial dependences of the form $PMV_{MET} = f_{MET}(PT)$ for several values of MET metabolism and fixed temperature range PT *(Khodaryna, 2013)*. Note that the calculation of the PMV by the latter method for intermediate values of MET requires additional interpolation.

A promising approach to the calculation of the integrated comfort index is its approximation by a multidimensional polynomial, for the efficient calculation of which Horner scheme can be used. To assess the accuracy of the approximation, a computational experiment was performed using the method of multidimensional polynomial regression, which was implemented using the Python programming language and the SKIKIT-LEARN software library. The results of the experiment showed satisfactory accuracy of approximation of PMV by multivariable polynomials of degree 3 and above:

$$PMV\left(t,t_r,v,\varphi,MET,CLO,W\right)\approx p^n\left(t,t_r,v,\varphi,MET,CLO,W\right) \qquad (2)$$

where t is the air temperature, t_r – average radiation temperature, v – air velocity, φ – relative humidity, MET – metabolic rate, CLO – indicator of clothing thermal insulation, W – external work, n is the degree of the polynomial.

5. Mathematical model of microclimate

The dynamics of indoor air absolute humidity is defined as:

$$\frac{d\alpha}{dt}V+\alpha q_{out}=\alpha_s q_s+\dot{m} \qquad (3)$$

where α – absolute humidity of the room, g/m^3; α_s – absolute humidity of supply air, g/m^3; $\dot{m}$ – mass flow of water vapor from internal sources, g/s.

The relationship between indoor air mass balance and dynamics of its temperature and pressure is described by the following expression:

$$\left(\frac{1}{p}\frac{dp}{dt}-\frac{1}{T}\frac{dT}{dt}\right)\rho V+10^{-3}\cdot\frac{R_{dry}-R_w}{R}\left(\alpha_s q_s+\dot{m}-\alpha q_{out}\right)+$$

$$+10^{-3}\sum_{i=1}^{N}\frac{R_{dry}-R_i}{R}\left(c_s^i q_s-c^i q_{out}\right)=\rho_s q_s-\rho q_{out}+10^{-3}\dot{m} \qquad (4)$$

where p is the room air pressure, Pa; T – room temperature, K; ρ – density of room air, kg/m^3; R_{dry}, R_w and R_i – individual gas steels of dry air, water vapor and pollutant i, J/(kg•K), respectively; ρ_s – density of supply air, kg/m^3.

The energy balance of the cabin can be represented as:

$$\rho C_v V\frac{dT}{dt}=u_s\rho_s q_s-u\rho q_o+Q_f+Q \qquad (5)$$

where C_v – specific heat capacity of the room air at a constant volume J/kg•K; u and us – respectively, the specific internal energy of indoor and supply air, J/kg; Q_f – heat flux from the fences, J/s; Q – heat flux from internal sources, J/s;

Mathematical model of the cabin indoor microclimate based on equations (1) – (5) allows to consider it as a multidimensional multiconnected control object (Fig. 1) with five control inputs (t_s, φ_s, C_s, q_s, q_{out}), five control parameters (t, φ, **C**, PMV, **AQI**) and six perturbances (Q_f, Q, MET, W, $\dot{m}$, CLO).

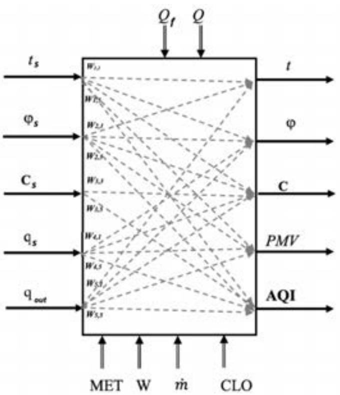

Fig. 1. Multidimensional multiconnected control object

6. Multiparametric microclimate control

Multidimensional representation of indoor microclimate allows to propose a design of multiparametric control system (Fig. 2).

The system must provide optimal control

$$\mathbf{u} = argmin\, J,$$

$$\mathbf{u} = \left(t_s, {}_s, c_s^1, \ldots, c_s^M, q_s\right),$$

with objective function

$$J = \sum_{j \in N} C^j \cdot \left(c^j\right)^2 + \sum_{i \in N} Q_a^i \cdot \left(AQI^i\right)^2 + C_t \cdot PMV^2 + T \cdot \left(t - t_{set}\right)^2 +$$

$$+ H \cdot \left(\varphi - \varphi_{set}\right)^2 + V \cdot v^2 + E \cdot c_a q_s \left(t - t_s\right)^2, \quad (6)$$

and restrictions

$$c^j \le c_{max}^j$$

$$AQI^i \le AQI_{max}^i$$

$$t_{min} \le t \le t_{max}$$

$$\varphi_{min} \le \varphi \le \varphi_{max}$$

$$v \le v_{max}$$

where t, φ, v – respectively temperature, relative humidity and velocity of indoor air; c_j – concentration of the j-th pollutant; t_s, φ_s, cj_s – respectively temperature, relative humidity and concentration of the j-th pollutant of supply air; N is the number of controlled pollutants; q_s – mass flow rate of supply air; C^j, Q_{ia}, C_t, T, H, V, E – objective function coefficients.

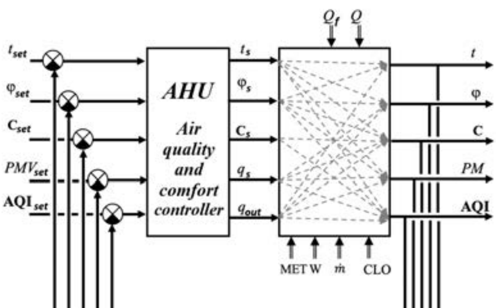

Fig. 2. Multiparametric microclimate control

Structure of the objective function ensures versatility of optimization problem statement and allows adjustment of the optimization strategy using weight coefficients. For example, compliance with air quality standards and maintaining comfort with the lowest priority of energy saving are ensured by weight coefficients that satisfy condition:

$$C^j > Q_a^i >> C_t > T > H > V > E.$$

If optimization strategy aims minimizing of energy consumption and allows overshoot of thermal comfort index value, other set of weight coefficient values may be used:

$$C^j > Q^i_a > E >> C_t > T > H > V.$$

In any formulation of the optimization problem, it is important that values of concentrations and air quality weight coefficients ensure the priority of air cleanliness over other indicators.

Model Predictive Control is one of the promising methods of optimal multiparametric control. The core idea behind this method is determining optimimum control by a finite time-horizon prediction of a system state based on its dynamic model.

The efficiency of microclimate control system with MPC controller and objective function (6) has been studied in Matlab-Simulink environment using simulation model of real ship's superstructure *(Bily, 2021)*. Obtained results showed promising performance of proposed system design for managing safety and comfort of indoor air on board ships.

6. Multiparametric control system prototype

Based on proposed mathematical model (1)-(5) and objective function (6) an experimental indoor air quality management system prototype (Fig. 3) was developed and tested on board of a gas carrier vessel.

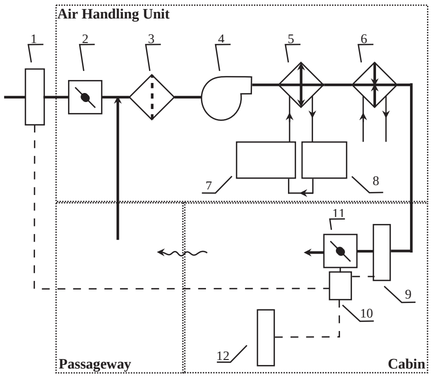

Fig. 3. Schematic diagram of onboard air quality and comfort controller: 1 – outdoor air analyzer; 2 – mixing damper; 3 – filter; 4 – fan; 5 – cooler; 6 – heater; 7 – freon condenser; 8 – freon compressor; 9 – supply air analyzer; 10 – quality regulator, 11 – supply air damper; 12 – indoor air analyser

Due to limited computational power of air quality controller the following reduced objective function was used:

$$J(\mathbf{u}) = C^{C3H6} \cdot \left(c^{C3H6}\right)^2 + C^{CO2} \cdot \left(c^{CO2}\right)^2 + T \cdot \left(t - t_{set}\right)^2 + H \cdot \left(\varphi - \varphi_{set}\right)^2,$$

$$\mathbf{u} = (q_s),$$

$$c^j \le c^j_{max}$$

$$t_{min} \le t \le t_{max}$$

$$\varphi_{min} \le \varphi \le \varphi_{max}$$

with optimization strategy $C^{C3H6} > C^{CO2} >> T > H$.

A discretized form of the equations (1) – (5) was used by MPC controller with sample time of 1 second and prediction horizon of 10 seconds to generate control value of supply air damper opening angle.

During the experiment the following have been discovered:

• Air quality controller prototype allows to keep the content of harmful substances below TLV most of the time and with a slight excess during emergencies

• During degassing of tanks, the maximum content of propylene in the outside air reached 2250 ppm, which is 4.5 times higher than TLV. At the same time, the concentration of the pollutant in the indoor air did not exceed 700 ppm

• At all times temperature and relative humidity in the control cabin retained at comfort levels as per regulatory requirements.

7. Conclusions

In this work the requirements for the safe gas composition of the air were formalized, analytical dependences were obtained. The mathematical model of indoor microclimate, comfort and air composition dynamics developed.

A general approach for indoor air comfort and quality and the structural scheme of the automatic control system proposed. The objective of automatic control is formulated in the form of multiparameter optimization. Prototype multiparameter controller based on microprocessor technology developed. The proposed design of multiparametric control of the ship's microclimate allows to control the gas composition of the air in terms of its quality or in accordance with the maximum allowable concentrations set at the sectoral and national levels.

Practical implementation of automatic control systems for air quality and comfort of ship premises requires the following further research: scaling of prototype up to distributed air quality control system, development and testing of control algorithms for air distribution, handling and filtration and study of their efficiency.

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