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Validation of Enclosure Fire Model in Integral form Using an Inverse Approach

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

This paper presents a new methodology of estimating the mass flow rate of gases flowing outward from room, the mass flow rate of the outer air entering a room and the rate of combustible1material gasification in building based on solving the problem of inverse enclosure fire dynamics in an integral form and validation of this model. The approach is based on an approximation of dependence on the combustion completeness of the mass flow rate of the outer air entering room and of the rate of combustible material gasification and then on solving a quadratic equation with respect to the mass flow rate of the outer air entering a room. The simulation results of the problem of inverse fire dynamics in integral form are cited. As an example of the practical application of the proposed approach, the problem of identification of a combustible material is considered. The obtained results are an important step towards the development of fire reconnaissance systems, which, for example, are able to lead the robotic reconnaissance.

Keywords: Fire simulation; inverse enclosure fire dynamics problem; fire model in an integral form; fire reconnaissance system.

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1. INTRODUCTION

Fire, which is conventionally defined as uncontrolled flame spread, is arguably one of the most complex phenomena considered in combustion science. Fluid dynamics, combustion kinetics, radiation and in many cases multi-phase flow effects are linked together to provide an extremely complex physical and chemical phenomenon [1]. Also, this phenomenon has various hazards to humans, property and environment. The number of people's deaths caused by fires is not decreasing today. Using fire-fighting mobile robots is a subject of research interest in terms of fire safety science because of the complexity of problems, which need to be solved. At the same time, a decrease in the level of risk facing the fire fighter is attained using mobile robots. The fire fighting strategy is currently known to be based mostly on the experience and the intuition of the commanding officers on duty [2]. Therefore, there are two main tasks for these robots. One of them is to search for a fire source in a group of rooms in low visibility conditions [3]. The another problem is the estimation of the main characteristics of fire, for example, a fire area, a type of combustion material and gas exchange parameters, to support the decision of the commanding officers, if a visibility is limited and a robot is not able to drive up close to a source of fire. One way to solve this problem is to forecast a fire dynamics using an inverse modeling approach. This approach, which is based on assimilation of temperature sensor observation, has previously been used to forecast a fire growth [1,4]. To do this, the authors used the two-zone fire model and the computational fluid dynamics (CFD) model, what makes this approach for a fire-fighting reconnaissance robot complex is the need to distribute a network of sensors in space. Thus, an integral model is considered prospective of fire-fighting reconnaissance applications due to a smaller number of necessary sensors located on the robot to estimate the main characteristics of a fire by the inverse fire dynamics problem. For example, the inverse heat transfer analysis [5,6] is applied for estimation the eight pyrolysis properties, such as heat of pyrolysis, virgin thermal conductivity and other, by using surface temperature and mass loss rate histories obtained from all the calculated experiments. We propose to use a gaseous atmosphere in the room to estimate some of the characteristics of pyrolysis using the inverse fire dynamics problem.

The integral theory of an enclosure fire in a compartment has been widely discussed, for example, in papers [7-14]. This paper develops an approach for modeling the fire in integral form and its applied aspects in the exploration of fire. Therefore, the paper is organized as follows. Section 2 is devoted to describing of the fire integral model. In Section 3, a solution of inverse enclosure fire dynamics problem in an integral form is given. In Section 4, the solution is analyzed mathematically for the individual states of enclosure fire. Section 5 contains the simulation results of the inverse fire dynamics problem's solution in integral form. In Section 6, we consider a fire classification method based on fuzzy logic, which supports the use of stoichiometric coefficients for determining the type of combustion material. This method explains the practical application of the solving of inverse dynamics problem. In Section 7, we discuss the results of solving the problem. The final section contains the conclusions. An Appendix contains explanations of how to calculate mean-volume gases concentrations and to use the methodology for the mobile robot.

2. INTEGRAL MODEL OF ENCLOSURE FIRE

The integral theory of a compartment fire is commonly used for the expert estimation of the value of dangerous factors of fire at its initial state [7]. The gas medium of a building is an open thermodynamic system between the building and the environment in which there occurs a mass and an energy exchange through open openings and fencing constructions of a building. In modeling of heat and mass transfer, the following assumptions and simplifications of the thermogas dynamic pattern of a fire are introduced [8,9]:

1. It is assumed that the characteristics of gas exchange between the building and the environment through an open opening of the building are uniquely determined at each instant of time using the mean-volume parameters of the gas medium inside the building;
2. There is a good mixing of the combustion products within the entering air over the entire volume of the room;
3. Combustion occurs within the entire volume of the compartment;
4. The character of development of the fire is a quasi steady (without sharp pressure jumps);

5. The gaseous atmosphere in the compartment (room) is assumed to be an ideal gas with constant thermophysical properties, since the difference of the isobaric specific heat, the mean gas constant and specific gas ratio of the gaseous atmosphere between the combustion products and pure air is small in the temperature range usually observed in fire.

Additionally, the geometric position of a fire load within the building is assumed to have no effect on the parameters of the heat and the mass exchange between the building and the environment through open openings of the building and on the heat removal into fencing constructions. This assumption is true in cases where combustible material is positioned in the so-called zone of reciprocal "insensibility" of the opening [8]. This zone is characterized by the fact that, at any position of the fire load within it, the parameters of heat and mass exchange (mean-volume parameters, mass flow rates of the gases flowing outward and of the air flowing inward, heat flows to the fencing constructions, etc.) remain practically unchanged [8].

Taking into account the above assumptions, the process of enclosure fire is convenient described as a block diagram form (Fig. 1).

The change rates of state variables of block "Fire dynamics" are determined by the mass flow rate of the outer air entering the room G_{IN}, the mass flow rate of gases flowing outward from the room G_{OUT} and the gasification rate ψ of a combustible material. The mass flow rate of gases G_{IN} and G_{OUT} are dependent on the coordinates of openings relative to the floor, on a difference of outer air density ρ_a entering the room and density of gases ρ_m flowing outward from the room, on a position neutral plane y^* [9,10,14].

The position of the neutral plane is defined by ρ_a and ρ_m, the mean-volume pressure in room P_m and an atmospheric pressure P_a. An oxygen mass concentration in the outer air entering the room $x_{O_{2IN}}$, a mean-volume mass concentration of oxygen x_{O_2} , a specific gasification rate of the combustible material ψ_{spec} and a fire area $F_{combustion}$ define a combustion regime and a gasification rate of combustible material ψ.

The integral model of enclosure fire as the block "Fire dynamics" in Fig. 1, which is given in the papers [7-13] has the next form (1)-(7):

- The mass conservation law

$$V\frac{d\rho_m}{dt} = \psi + G_{IN} - G_{OUT} \,, \tag{1}$$

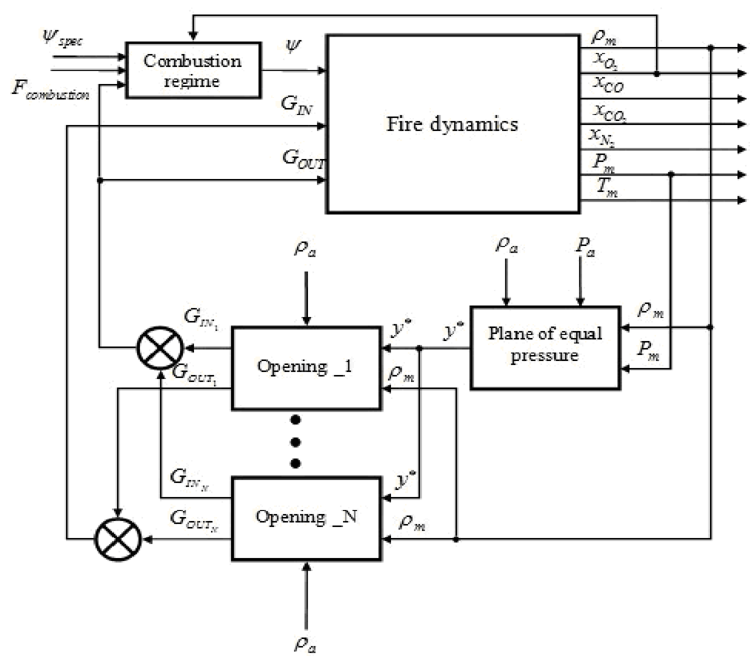


Fig. 1. A block diagram of the integral fire dynamics model for a room

Where V – the volume of a room, ρ_m – the gas density in the room, ψ – the gasification rate of combustible material, G_{IN} – the mass flow rate of outer air entering the room, G_{OUT} – the mass flow rate of gases flowing outward from the room;

- The equation of the oxygen mass conservation

$$V\frac{d\left(\rho_m x_{O_2}\right)}{dt} = G_{IN}\cdot x_{O_{2IN}} - G_{OUT}\cdot n_1\cdot x_{O_2} - \psi\cdot\eta\cdot L_{O_2}\,, \qquad (2)$$

Where x_{O_2} – the mean-volume mass concentration of oxygen, $x_{O_{2IN}}$ – the mean-mass concentration of oxygen in the outer air entering the room, n_1 – the irregularity of oxygen mass concentration in room, η – the completeness of combustion, L_{O_2} – the stoichiometric coefficient of combustion reaction (a specific consumption of oxygen);

- The equation of the carbon-dioxide gas mass conservation

$$V\frac{d\left(\rho_m x_{CO_2}\right)}{dt} = \eta\cdot\psi\cdot L_{CO_2} + G_{IN}\cdot x_{CO_{2IN}} - G_{OUT}\cdot n_2\cdot x_{CO_2}\,, \qquad (3)$$

Where x_{CO_2} – the mean-volume mass concentration of carbon-dioxide, $x_{CO_{IN}}$ – the mean-mass concentration of carbon-dioxide in the outer air entering the room, n_2 – the irregularity of combustion products distribution in room, L_{CO_2} – the stoichiometric coefficient of combustion reaction (a specific consumption of carbon-dioxide);

- The equation of the carbon-dioxide gas mass conservation

$$V\frac{d\left(\rho_m x_{CO}\right)}{dt} = \eta\cdot\psi\cdot L_{CO} + G_{IN}\cdot x_{C_{IN}} - G_{OUT}\cdot n_2\cdot x_{CO}\,, \qquad (4)$$

Where x_{CO} – the mean-volume mass concentration of carbon monoxide, $x_{CO_{2IN}}$ – the mean-mass concentration of carbon monoxide in the outer air entering the room, L_{CO} – the stoichiometric coefficient of combustion reaction (a specific consumption of carbon monoxide);

- The equation of the inert gas (nitrogen) mass conservation

$$V\frac{d\left(\rho_m x_{N_2}\right)}{dt} = G_{IN}\cdot x_{N_{2IN}} - G_{OUT}\cdot n_3\cdot x_{N_2}\,, \qquad (5)$$

Where x_{N_2} – the mean-volume mass concentration of nitrogen, $x_{N_{2IN}}$ – the mean-mass concentration of nitrogen in the outer air entering in the room, n_3 – the irregularity of nitrogen concentration distribution in room;

- The energy conservation law

$$V\frac{d}{dt}\left(\frac{P_m}{k-1}\right) = \eta\cdot Q_H^P\cdot\psi + c_{pIN}\cdot T_{IN}\cdot G_{IN} - c_{pm}\cdot T_m - Q_s - Q_m\,, \qquad (6)$$

Where k – the mean-volume adiabatic value, Q_H^P – the net calorific value of combustion material, c_{pIN}, c_{pm} – the specific isobaric heat capacity of air and gases, respectively; T_{IN}, T_m – the outer air temperature and mean-volume temperature, respectively, Q_s – the total heat flow into the building envelope, Q_m – the heat flux emitted through the aperture;

- The constraint equation

$$P_m = \rho_m\cdot R_m\cdot T_m\,, \qquad (7)$$

Where P_m – the mean-volume pressure, ρ_m – the mean-volume density, R_m – the mean gas constant.

3. A SOLUTION TO THE INVERSE ENCLOSURE FIRE DYNAMICS PROBLEM

A practical aim of the solution is to validate the integral model of enclosure compartment fire and to determine the informative vector of stoichiometric coefficients by which we will determine the type of combustible material (see Section 6).

The coordinates of stoichiometric vector $\vec{L} = \left(L_{O_2}, L_{CO}, L_{CO_2}\right)$ are expressed of formulas (2)-(4):

$$\vec{L} = \begin{pmatrix} L_{O_2} \\ L_{CO} \\ L_{CO_2} \end{pmatrix} = \frac{1}{\eta\psi}\cdot\begin{pmatrix} G_{IN}x_{O_{2B}} - G_{OUT}n_1 x_{O_2} - V\dfrac{d\left(\rho_m x_{O_2}\right)}{dt} \\ V\dfrac{d\left(\rho_m x_{CO}\right)}{dt} + G_{OUT}n_2 x_{CO} - G_{IN}x_{CO_B} \\ V\dfrac{d\left(\rho_m x_{CO_2}\right)}{dt} + G_{OUT}n_2 x_{CO_2} - G_{IN}x_{CO_{2B}} \end{pmatrix} \qquad (8)$$

From the resulting Expr. (8), it is clear that, in order to find the vector $\vec{L}$ it is necessary to determine mean-volume concentrations of CO, CO_2, O_2, N_2, the mean-volume density and to calculate the mean-volume values G_{IN}, G_{OUT}, ψ by means of the estimated mean-volume of gases to solve the inverse fire dynamic problem. An approach to determining mean-volume concentration of CO, CO_2, O_2, N_2 and mean-volume density is considered in the Appendix. This approach can be used for the mobile robot with a telescopic rod, which has sensors.

A computation of G_{IN}, G_{OUT} and ψ is associated with certain difficulties: To determine the mass flow rate G_{IN} and G_{OUT} is difficult directly, for it is necessary to know the number of openings, their condition (open or closed) and a positional relationship relative to the floor [11]. Direct measurement of the gasification rate of the combustible material ψ is impossible. Also, there is always not enough detailed prior information about the firefighting object. Therefore, it is necessary to restrain the additional relationship on input variables G_{IN}, G_{OUT}, ψ. As such, in terms of the relationship it is proposed to use the relation of non-linear feedback $\psi\left(x_{O_2}\right)$ with $G_{IN}\left(\rho_m, P_m\right)$ (the block "Combustion regime", Fig. 1). Two limiting behaviors in room [11,15], namely the fuel-controlled burning and ventilation-controlled burning, determine the gasification rate of the combustible material $\psi\left(x_{O_2}\right)$.

In the first case, the oxygen concentration is near its value in outdoor air and reaction conditions correspond to the combustion outdoors. In the second mode, the oxygen concentration is reduced, with the reaction rate limited by the rate of oxygen entering indoor from the outside air. In a real fire the transition of limited behavior, each other is observed. The formula for the calculation of the completeness of combustion on these cases is given in the paper [12]:

$$\eta = \eta_0 K + \frac{x_{O_{2IN}} G_{IN}}{L_{O_2} \psi}\left(1-K\right), \qquad (9)$$

Where η_0 is the completeness of combustion on an open air, $K = K(x_{O_2})$ – the function defining the fire regime.

This function has the next form [12]:

$$K\left(x_{O_2}\right) = \begin{cases} 1, if\ z \geq 1 \\ z^B e^{B(z-1)}, if\ 0 \leq z < 1 \\ 0, if\ z < 0 \end{cases},$$

Where $z = \frac{x_{O_2} - x^{**}}{x^* - x^{**}}, B = \left(\frac{x_a}{x_a - 0.12}\right)^2$, $x^{**}=0$, $x^*=0.9x_a$, $B=2$, x_a=0.23 – the oxygen mass concentration in the atmosphere.

The graphic form of function $K\left(x_{O_2}\right)$ is presented in Fig. 2.

On the other hand, the experimental dependence for a determination of the combustion completeness which is valid for the mean-volume oxygen concentration range from 0.105 to 0.23 is obtained as follows [9]:

$$\eta = 0.63 + 0.2x_{O_2} + 1500x_{O_2}^6 . \qquad (10)$$

When two graphs are plotted (Fig. 3), $f_2 = \eta\left(x_{O_2}\right)$ is the experimental characteristic (Expr. (10), Graph 2) and $f_1=\eta_0 \cdot K$ is the first summand in the right part of the Expr. (9) (Graph 1).

As can be seen from Fig. 3, firstly, the inequality $\eta_0 \cdot K > \eta$ works throughout the oxygen concentration range $x_{O_2} \in$ [0.105; 0.23], which contradicts the Expr. (10), considering that all summands of Expr. 9 are positive. Secondly, if the oxygen concentration less than 10%, the burning stops, but Fig. 3 (Graph 1) shows that fire regime is still ventilation-controlled burning. Therefore, the function $K(x_{O_2})$ for the correctly description of the combustion completeness must have the form (11).

In this case, the authors received the corrected form of the dependence $f_3=\eta_0 \cdot K$ (Fig. 3, Graph 3), where

$$K\left(x_{O_2}\right) = \begin{cases} \left(\frac{x_{O_2} - 0.117}{0.9 \cdot x_{O_{2IN}} - 0.082}\right)^C \cdot \exp\left[C \cdot \left(1 - \frac{x_{O_2} - 0.117}{0.9 \cdot x_{O_{2IN}} - 0.082}\right)\right], if\ x_{O_2} \leq 0.216 \\ \frac{1}{\eta_0}\left(44.048 \cdot x_{O_2}^2 - 13.958 \cdot x_{O_2} + 1.7777\right),\ if\ 0.216 < x_{O_2} \leq 0.23 \end{cases}, \qquad (11)$$

$$C = \left(\frac{x_{O_{2IN}}}{x_{O_{2IN}} - 0.12}\right)^2 .$$

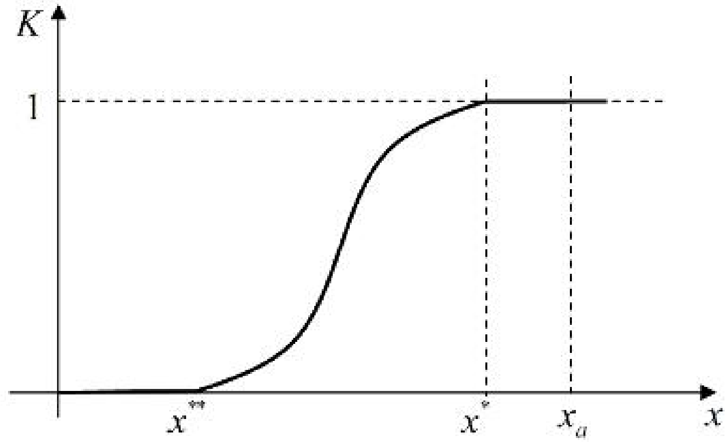


Fig. 2. The function of the fire regime

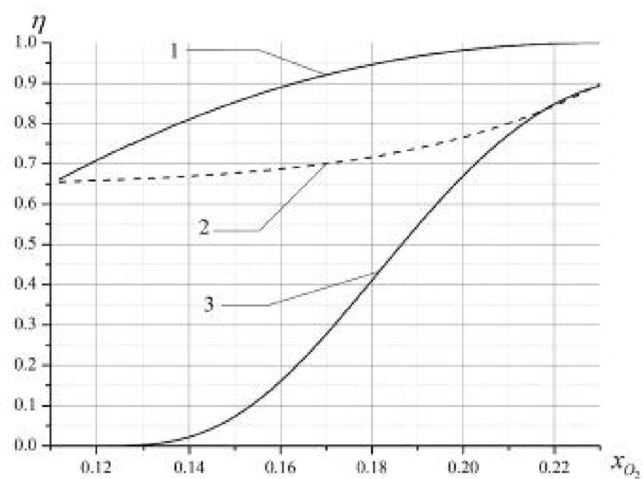


Fig. 3. The combustion completeness dependence of a oxygen concentration (1 – the summand $\eta_0 K$ of Expression (12), 2 – the experimental characteristic (13), 3 – the refined form of dependence $\eta_0 K$)

Thus, having determined the form of function $K\left(x_{O_2}\right)$, we must turn to the decision of the inverse fire dynamics problem in integral form. If we express ψL_{O_2} from (9) and multiply both sides of the equation on η:

$$\eta \psi L_{O_2} = \frac{\eta\left(\eta - \eta_0 K\right)}{x_{O_{2IN}} G_{IN}\left(1 - K\right)}$$

Substituting this expression into the Eq. (2):

$$V\frac{d\left(\rho_m x_{O_2}\right)}{dt} = x_{O_{2IN}} \cdot G_{IN} - x_{O_2} \cdot n_1 \cdot G_{OUT} - \frac{\eta\left(\eta - \eta_0 K\right)}{x_{O_{2IN}} \cdot G_{IN} \cdot \left(1 - K\right)} \quad . \tag{12}$$

And multiplying both sides of the Eq. (12) by G_{IN}:

$$x_{O_{2IN}} \cdot G_{IN}^2 - x_{O_2} \cdot n_1 \cdot G_{IN} \cdot G_{OUT} - \frac{\eta(\eta-\eta_0 K)}{x_{O_{2IN}}(1-K)} - V \cdot G_{IN} \cdot \frac{d(\rho_m x_{O_2})}{dt} = 0 . \qquad (13)$$

We can then express the variable G_{OUT} from the Eq. (5):

$$G_{OUT} = \frac{x_{N_{2IN}} \cdot G_{IN}}{n_3 \cdot x_{N_2}} - \frac{V}{n_3 \cdot x_{N_2}} \cdot \frac{d(\rho_m x_{N_2})}{dt} . \qquad (14)$$

And substituting the Expr. (14) in the Eq. (13), we get the quadratic Eq. (15):

$$G_{IN}{}^2 \left(x_{O_{2IN}} - \frac{x_{O_2} \cdot n_1 \cdot x_{N_{2IN}}}{n_3 \cdot x_{N_2}} \right) - G_{IN} \cdot V \cdot \left(\frac{x_{O_2} \cdot n_1}{x_{N_2} \cdot n_3} \cdot \frac{d(\rho_m x_{N_2})}{dt} + \frac{d(\rho_m x_{O_2})}{dt} \right) - \frac{\eta(\eta-\eta_0 K)}{x_{O_{2IN}}(1-K)} = 0. \qquad (15)$$

If we define the value of ψ from the Eq. (1) substituting G_{OUT} by the Expr. (14):

$$\psi = V \frac{d\rho_m}{dt} + G_{OUT} - G_{IN} ,$$

$$\psi = V \frac{d\rho_m}{dt} + \frac{x_{N_{2IN}} \cdot G_{IN}}{n_3 \cdot x_{N_2}} - \frac{V}{n_3 \cdot x_{N_2}} \cdot \frac{d(\rho_m x_{N_2})}{dt} - G_{IN} ,$$

$$\psi = V \left(\frac{d\rho_m}{dt} - \frac{1}{n_3 \cdot x_{N_2}} \cdot \frac{d(\rho_m x_{N_2})}{dt} \right) + \left(\frac{x_{N_{2IN}}}{n_3 \cdot x_{N_2}} - 1 \right) \cdot G_{IN} . \qquad (16)$$

And combine Expr. (14)-(16), we write the solution of inverse fire dynamics problem as (17):

$$\begin{cases} G_{IN}^2 \left(x_{O_2IN} - \frac{x_{O_2} n_1 x_{N_{2IN}}}{n_3 x_{N_2}} \right) - G_{IN} \cdot V \left(\frac{x_{O_2} n_1}{x_{N_2} n_3} \cdot \frac{d(\rho_m x_{N_2})}{dt} + \frac{d(\rho_m x_{O_2})}{dt} \right) - \frac{\eta \cdot (\eta-\eta_0 K)}{x_{O_{2IN}} \cdot (1-K)} = 0, \\ G_{\Gamma} = \frac{1}{n_3 x_{N_2}} \cdot \left(x_{N_{2IN}} G_{IN} - V \frac{d(\rho_m x_{N_2})}{dt} \right), \\ \psi = V \left(\frac{d\rho_m}{dt} - \frac{1}{n_3 x_{N_2}} \frac{d(\rho_m x_{N_2})}{dt} \right) + \left(\frac{x_{N_{2IN}}}{n_3 x_{N_2}} - 1 \right) \cdot G_{IN}, \end{cases} \qquad (17)$$

4. ANALYSIS OF THE INVERSE SOLUTION

We can analyze the quadratic equation of the system (17) to determine the existence of domain feasible solutions. Let us introduce into the Eq. (15) the following notation: G_{IN}=g,

$$x_{O_{2IN}} - \frac{x_{O_2} \cdot n_1 \cdot x_{N_{2IN}}}{n_3 \cdot x_{N_2}} = a , \; V \left(\frac{x_{O_2} n_1}{x_{N_2} n_3} \cdot \frac{d(\rho_m x_{N_2})}{dt} + \frac{d(\rho_m x_{O_2})}{dt} \right) = b , \; \frac{\eta \cdot (\eta-\eta_0 K)}{x_{O_{2IN}} \cdot (1-K)} = c .$$

Thus, the Eq. (15) takes the form $ag^2-bg-c=0$. We can investigate the increase in fire intensity, i.e. $\frac{d\left(\rho_m x_{N_2}\right)}{dt}<0$ and $\frac{d\left(\rho_m x_{O_2}\right)}{dt}<0$ – the nitrogen mass concentration and the oxygen mass concentration which decrease.

In addition, it is known that $n_1 \le 1$ and $n_3 \approx 1$ [7,15], therefore, $n_1/n_3 \le 1$ and condition $\frac{x_{O_2} \cdot n_1 \cdot x_{N_2IN}}{n_3 \cdot x_{N_2}} \le x_{O_2IN}$ is met. The coefficient *a* is always positive for $x_{O_2} < 0.23$. If $x_{O_2} = x_a = 0.23$ the quadratic equation transforms in an identity for any G_{IN}, which corresponds to the steady state, i.e. there is no fire. From Expr. (9) it follows that $\eta\text{-}\eta_0 \cdot K>0$ and with a view to $K \in [0;1]$, the coefficient *c* is positive (*c*>0) and quadratic Eq. (15) becomes $ag^2+bg-c=0$ and has roots $g_{1,2} = \frac{-b \pm \sqrt{b^2+4ac}}{2a}$.

From the last equation it can be seen that the root $g^* = \frac{-b+\sqrt{b^2+4ac}}{2a}$ is the solution ($\exists g>0$) satisfying conditions $\forall\left(a>0, b>0, c>0\right)$.

For the fire stabilization mode the quadratic equation becomes $ag^2-c=0$, having the root $g^* = \sqrt{c/a}$. For combustion attenuation, the equation has form $ag^2-bg-c=0$, with the root being $g^* = \frac{b+\sqrt{b^2+4ac}}{2a}$.

Thus, one can conclude that there is an inverse dynamics fire solution in any stage of fire up growth, excluding the beginning of a fire. The obtained estimations G_{IN}, G_{OUT} and ψ (17) are substituted into the Expr. (8) to determine the coordinates of the unknown vector $\vec{L}^*$.

5. SIMULATION SOLUTION TO THE PROBLEM OF THE INVERSE FIRE DYNAMICS IN INTEGRAL FORM

An experimental verification of the inverse fire dynamics problem in the integral form was based on a computer simulation in FDSv5 [16]. The combustion of ethanol was simulated (test fire TF6 from the EN 54 Fire detection and fire alarm systems), the burning area was 0.2x0.2 m^2 in the test compartment with dimensions 10x7x4 m^3 (Fig. 4(a)).

The results exported from FDS mean-volume values are presented in Figs. 4(b)-Fig. 4(f). These values were substituted into Exprs. (14) and (15) which were implemented on Excel spreadsheets. A calculation of derivatives held for the two-point method. The function $K\left(x_{O_2}\right)$ was calculated by the Expr. (11) for a range of oxygen concentration 0.12–0.216 and the coefficient $(\eta\text{-}\eta_0 K)/(1\text{-}K)$ is approximated by the relationship: $-0.6117 \cdot x_{O_2}^2 - 6.8999 \cdot x_{O_2} + 1.6374$ for a range of oxygen concentration 0.216–0.232, giving a more accurate description of the function of fire regime in the specified range of the oxygen concentration.

The calculated estimates of the quadratic equation's coefficients, the estimates of mass flow rates of gases of the outer air entering into a room, the mass flow rates of gases flowing outward from the room and the gasification rate of the combustible material are presented in Fig. 5.

The estimates of stoichiometric coefficients in Eq. (8) were defined by calculated values and were shown in Fig. 6. For trends in 10 seconds, fixed by a period of 100 seconds, mean values and mean-square deviations are given in Table 1. The tabulated values are L_{CO}=0.269, L_{O_2} =2.362, L_{CO_2} =1.937.

It should be noted that there is good agreement between the tabulated results L_{O_2} L_{CO_2}, L_{CO} and the results of solving the inverse fire dynamics problem, although the estimation of stoichiometric coefficients was carried out without the use of filtering methods. As we see the coefficient *B* of quadratic equation (see Fig. 5(a)) is noisy as it contains the calculated derivatives. Fig. 6 shows that there is a deviation in estimated values of coefficients, at the same time, the greatest discrepancy between the results is observed in the time interval to 200 seconds, i.e. in the initial state of a fire. As we can see, the approximated Expr. (11) has the greatest deviation from the true function $K(x_{O_2})$ on this time interval.

While solving inverse fire dynamics, it has been found that a strong impact on the accuracy of the coefficient inhomogeneity has a nitrogen environment. The best agreement between the tabulated results and the estimations of L_{O_2} and L_{CO_2} was obtained with n_3= 0.998. It has been although established that the solution has the highest sensitivity of the value n_3. In general, the simulation results correspond to the results of analytical solution of inverse fire dynamics problem in integral form.

6. FIRE CLASSIFICATION USING INVERSE FIRE DYNAMIC PROBLEM IN INTEGRAL FORM

One of the practical applications of the obtained solution is to determine stoichiometric coefficients to identify a class of fire when carrying out exploration of a mobile robot. The classification problem involves the need to correlate a fire with one of the classes $\{d_1, d_2, \ldots, d_m\}$ by received reconnaissance data, which is quantified using the informative vector $\vec{L} = (l_1, l_2, \ldots, l_n)$. According to Russian safety standards, fires which depend on the type of combustible load are classified *qualitatively* as follows:

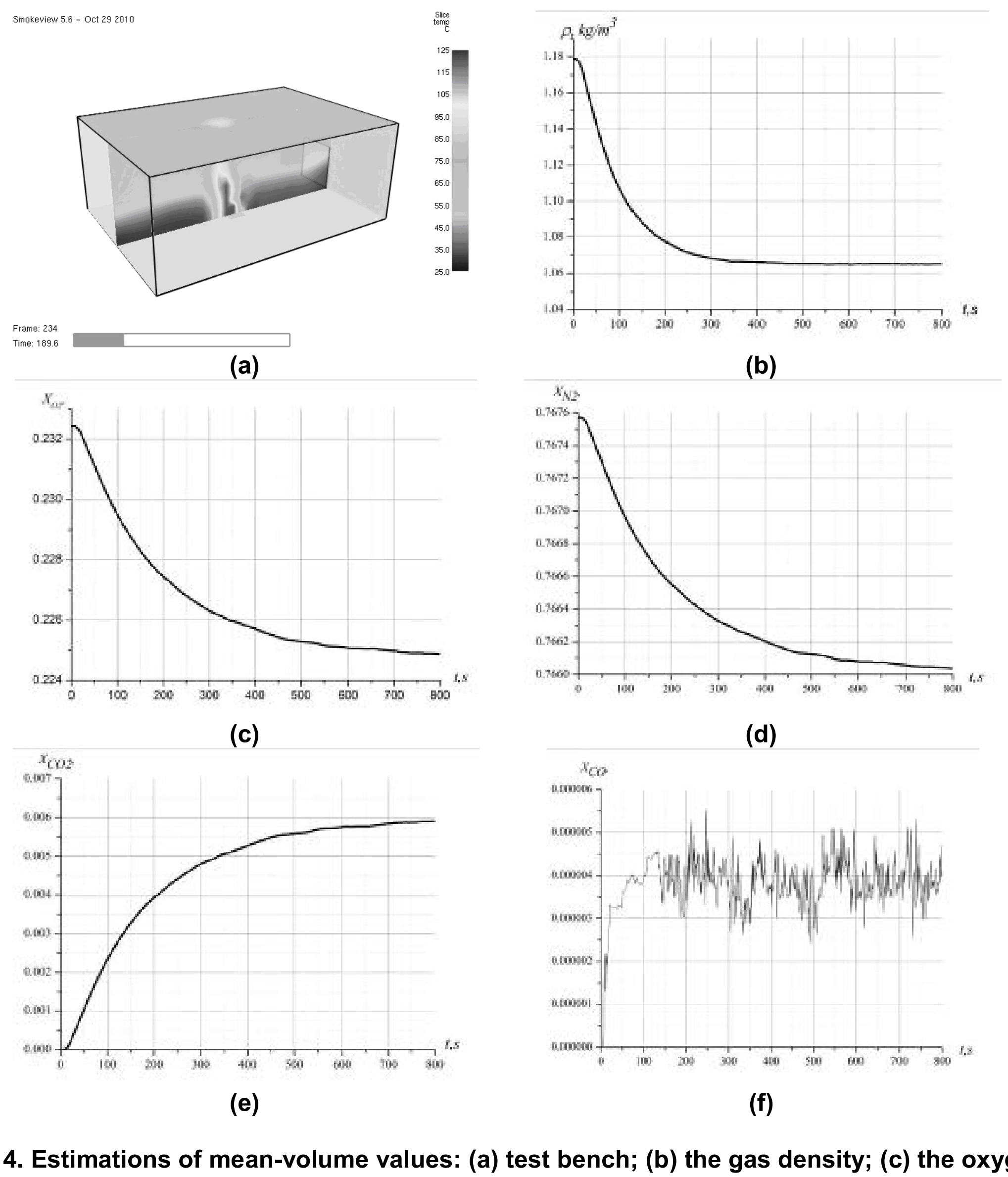
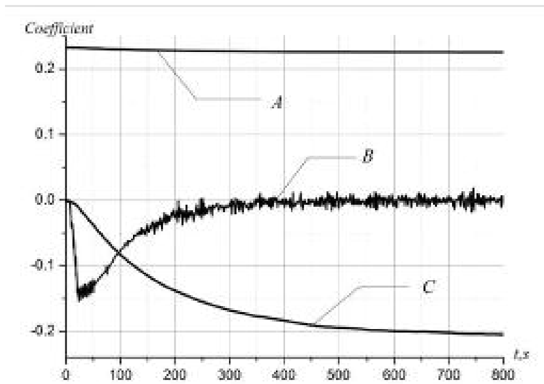
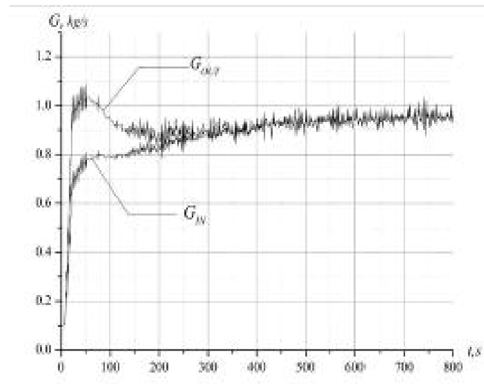


Fig. 4. Estimations of mean-volume values: (a) test bench; (b) the gas density; (c) the oxygen (O_2) mass concentration; (d) the nitrogen (N_2) mass concentration; (e) the carbon-dioxide (CO_2) mass concentration; (f) the monoxide (CO) mass concentration



(a)



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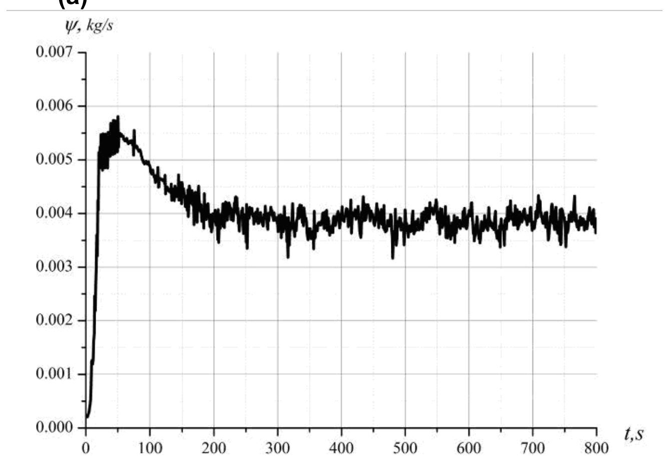


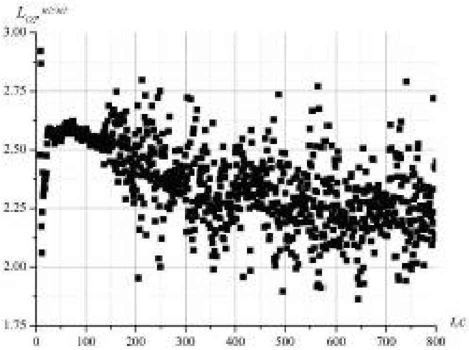
(c)

Fig. 5. The solving of inverse fire dynamics problem in integral form: (a) estimation coefficients of quadratic equation when finding G_{IN}; (b) estimation mass flow rates of gases of the outer air entering G_{IN} and flowing outward G_{OUT} from the room; (c) the gasification rate of the combustible material ψ

- A class A1 fire is a burning of solids followed by smoldering (paper, wood, textiles, etc.);
- A class A2 fire is a burning of solids, which are not accompanied by smoldering (for example, plastic);
- A class B1 fire is a burning of liquids insoluble in water (benzene, ether, petroleum) and of incompressible solids (paraffin);
- A class B2 fire is a burning of water-soluble liquids (alcohol, glycerol);
- A class C fire is a burning of gases;
- A class D fire is a burning of metals;
- A class E fire is an electrical fire.

It should be noted that when using mobile robots in fire-fighting operations we encounter usually only the first four of them A1, A2, B1, B2.

Therefore, a set of classes can be written as $d=\{d_1,d_2,d_3,d_4\}$. As already noted above, the classes are defined qualitatively. To solve the same problem of classification, the quantitative characteristics that define different types of combustion materials are required. According to analysis of the database of typical fire loads [7] we propose to choose the vector species $\vec{L} = \left(L_{O_2}, L_{CO}, L_{CO_2}\right)$ as a vector of informative characteristics, where L_{O_2} is a stoichiometric coefficient of combustion reaction (a specific consumption of oxygen), L_{CO} is a specific consumption of carbon monoxide, L_{CO_2} is a specific consumption of carbon-dioxide, or in other words, the stoichiometric coefficient vector. Selection of these coefficients is because the stoichiometric coefficients characterize a flow of



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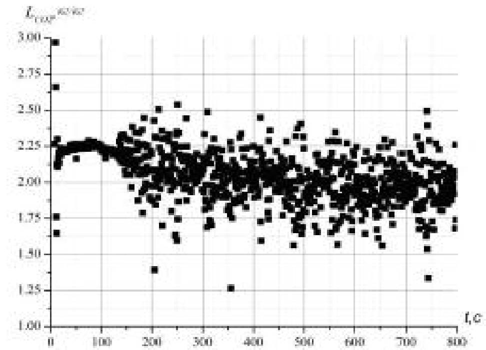

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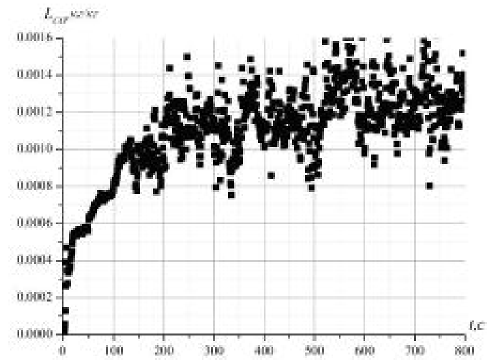


(c)

Fig. 6. The estimates of stoichiometric coefficients obtained in the course of computational experiment: (a) the stoichiometric coefficient of combustion reaction (specific consumption of oxygen); (b) the stoichiometric coefficient of combustion reaction (specific consumption of carbon-dioxide); (c) the stoichiometric coefficient of combustion reaction (specific consumption of carbon monoxide)

Table 1. A deviation of $\vec{L}$ - vector coordinates

Time, s	L_{O_2}		L_{CO_2}		L_{CO}	
	Mean-value	Mean-square deviation	Mean-value	Mean-square deviation	Mean-value	Mean-square deviation
50-60	2.583	.006	2.243	.007	6.51E-4	5.62E-6
150-160	2.54	.0235	2.168	.0233	9.7E-4	1.037E-5
250-260	2.34	.0334	2.114	.052	1.13E-3	2.31E-5
350-360	2.21	.047	1.94	.0735	1.15E-3	4.51E-5
450-460	2.358	.028	2.037	.03	1.2E-3	2.13E-5
550-560	2.27	.0487	1.992	.0495	1.3E-3	2.01E-5

chemical combustion reactions underlying the fire as a physicochemical process. A summary of typical fire loads in the form of two-dimensional projections of multivariate cluster corresponding class d_i ($i = \overline{1,4}$) is shown in Fig. 7. Every type of fire load is defined by three values $\{L_{O_2}, L_{CO}, L_{CO_2}\}$ in the feature space $L_{O_2}' \times L_{CO}' \times L_{CO_2}'$.

Fig. 7 shows that boundaries between the classes are fuzziness and two points belonging to the class B1 are greatly removed from the center of the same name set. These points characterize the turbine and industrial oils, respectively. Given the fuzzyfied boundaries between the classes, we propose to use the fuzzy classification, which is a development of expert systems. The main advantage of fuzzy classification is possible to formulate reliable classification conclusions based on incomplete and not entirely reliable input preconditions. In this case, a fuzzy knowledge base can be represented as the next production rules:

IF $L_{O_2} = a_{1,j1}$ AND $L_{CO_2} = a_{2,j1}$ AND $L_{CO} = a_{3,j1}$

OR $L_{O_2} = a_{1,j2}$ AND $L_{CO_2} = a_{2,j2}$ AND $L_{CO} = a_{3,j2}$

OR $L_{O_2} = a_{1,jk_j}$ AND $L_{CO_2} = a_{2,jk_j}$ AND $L_{CO} = a_{3,jk_j}$

THEN $y = d_j$, $j = \overline{1,4}$,

Where $a_{j,jp}$ is a fuzzy term whereby the variable L_i in a rule with number jp is estimated, $p = \overline{1,k_j}$, k_j is a number of rules describing the class d_j.

Grades of membership $\overrightarrow{L^*} = \left(L_{O_2}, L_{CO_2}, L_{CO}\right)$ to classes d_j are calculated by the next formula:

$$\mu_{d_j}\left(L^*\right) = \max_{p=\overline{1,k_j}} \min_{i=\overline{1,n}} \left(\mu_{jp}\left(l_i^*\right)\right), \quad j = \overline{1,4}.$$

An inference is performed by the modified Takagi-Sugeno method. This method, unlike the Mamdani method has several advantages: firstly, an output fuzzy set is defined on the set of real number, secondly, there is no summation of the same rules in defuzzification and thirdly, it allows the inference in hierarchical fuzzy systems without fuzzification/defuzzification intermediate variables passed to the fuzzy system the next level of the hierarchy. Consequently, its application is considered most appropriate in a fuzzy classifier.

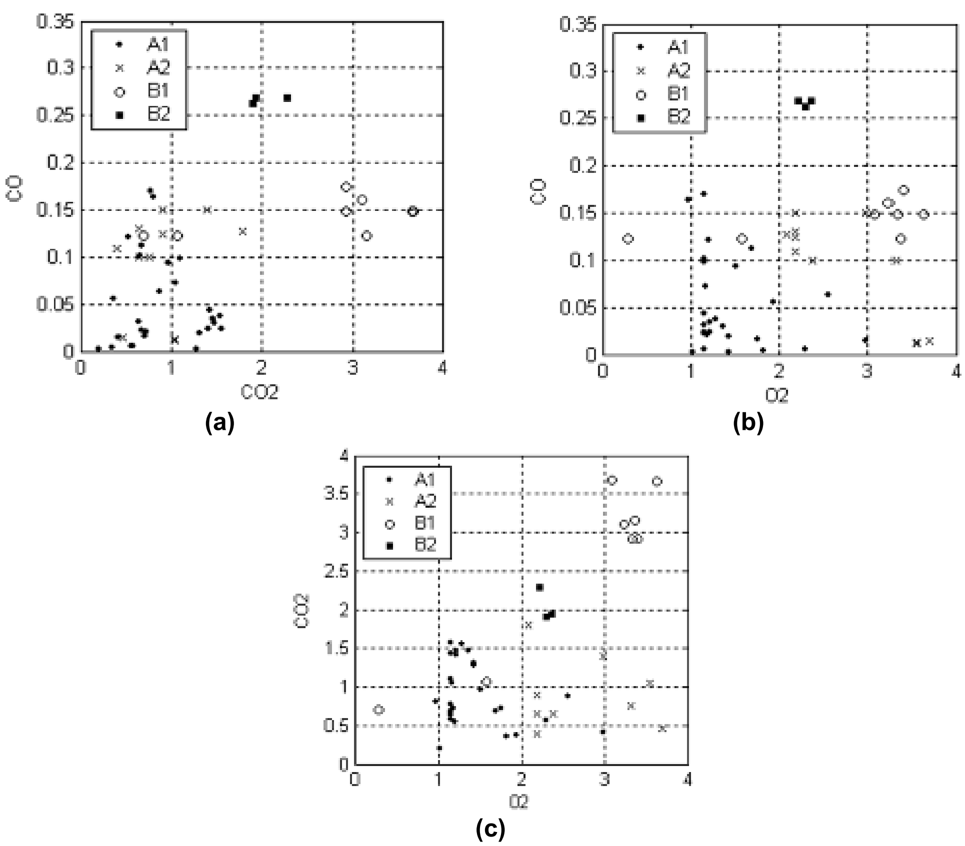


Fig. 7. A distribution of classes of typical combustible loads: (a) projection $L_{CO}' \times L_{CO_2}'$, (b) projection $L_{O_2}' \times L_{CO}'$, (c) projection $L_{O_2}' \times L_{CO_2}'$

The input variables of the classifier are the specific consumption of oxygen L_{O_2}, specific consumption of carbon monoxide L_{CO}, specific consumption of carbon-dioxide L_{CO_2} and the output variable is a "class of fire". The fuzzy terms "small", "middle" and "big" are encouraged to use for a linguistic evaluation for signs of fire. The fuzzy knowledge base has the next form:

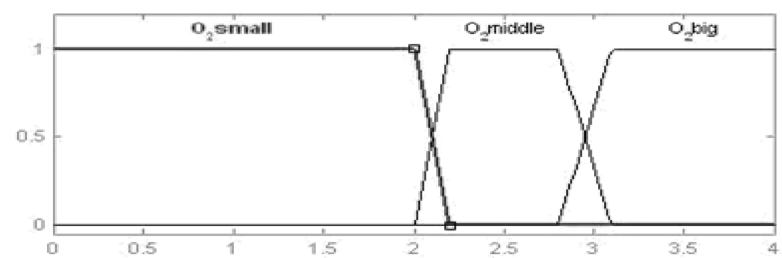
1. IF "L_{CO} is big" THEN "class is B2"
2. IF "L_{O_2} is big" AND "L_{CO_2} is big" AND "L_{CO} is middle" THEN "class is B1"
3. IF "L_{O_2} is small" AND "L_{CO} is middle" THEN "class is A1"
4. IF "L_{O_2} is middle" AND "L_{CO} is small" THEN "class is A1"
5. IF "L_{O_2} is small" AND "L_{CO} is small" THEN "class is A1"
6. IF "L_{O_2} is middle" AND "L_{CO} is middle" THEN "class is A2"
7. IF "L_{O_2} is big" AND "L_{CO} is small" THEN "class is A2".

The membership functions of input variables obtained after processing the sample data from a database of typical fire loads and used in the system recognition rules are shown in Fig. 8.

The membership functions of output variable "class of fire" are singletons. For example, the function $\mu_{A_1} = \{1/0\}$ corresponds to the class A1, the function $\mu_{A_2} = \{1/0.333\}$ corresponds to the class A2, the function $\mu_{B_1} = \{1/0.667\}$ corresponds to the class B1 and $\mu_{B_2} = \{1/1\}$ corresponds to the class B2.

Below there are two examples of fuzzy classifier. The examples illustrate the characteristic feature on the Sugeno fuzzy method.

Example 1. Assume, a piece of plywood is burning and that the class of fire is A1: L_{O_2} =1.205; L_{co}=0.121; L_{CO_2}=0.54. The above knowledge base is used. The vector (1.205; 0.54; 0.121) is input to the classifier. A process interpretation of fuzzy inference in Fuzzy Toolbox of Matlab is shown in Fig. 9. The figure shows that for a given input vector (1.205; 0.54; 0.121) the rules numbered 2, 3, 5 and 7 are activated. In this case, all logical premises are activated in rule 3 and this rule defines a class A1 of combustible load ($\mu_{A_1} = \{1/0\}$).



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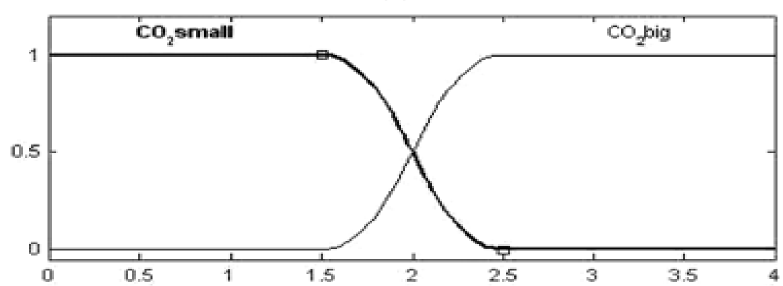

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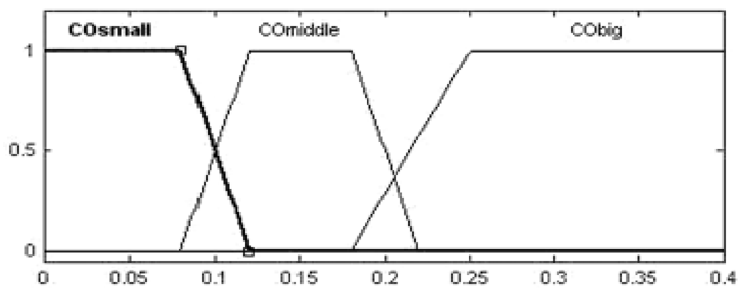

(c)

Fig. 8. The membership functions of input variables of fuzzy classifier: (a) the specific consumption of oxygen; (b) the specific consumption of carbon-dioxide; (c) the specific consumption of carbon monoxide

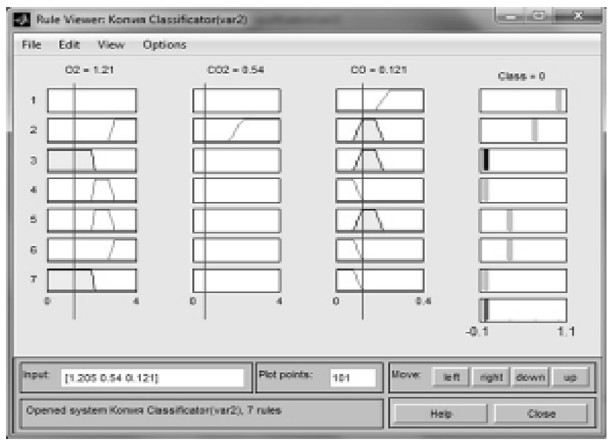

Fig. 9. A fuzzy inference for the classification process of a piece of plywood burning (a class of fire A1)

Example 2. Assume that nylon and cotton are burning, where the class of fire is A2: L_{O_2} =3.55; L_{co}=0.013; L_{CO_2} =1.045. The vector (3.55; 1.045; 0.013) is input to the classifier. Fig. 10 shows that for a given input vector (3.55; 1.045; 0.013), the rules numbered 2, 4, 6 and 7 are activated. All logical premises are activated in rule 6 and this rule defines a class A2 of combustible load ($\mu_{A_2} = \{1/0.033\}$).

Therefore, the above examples clearly demonstrate the process of performing inference on a combustible load on the coordinates of the vector of stoichiometric coefficients $\overrightarrow{L^*} = \left(L_{O_2}, L_{CO_2}, L_{CO}\right)$.

7. DISCUSSIONS

The problem discussed in this work is more theoretical than practical, but still has a practical application. From a theoretical point of view the inverse enclosure fire dynamics problem is solved and integral model of enclosure fire is validated. A mathematical analysis shows that a solution exists on all states of an enclosure fire, except for its start time. The obtained solution allows for an express analysis of a fire including estimations of a gasification rate of combustible material, mass flow rates of gases of the outer air entering and flowing outward from a room. As a result of solving the inverse fire dynamics problem, a corrected form of function $K\left(x_{O_2}\right)$ was obtained. This function enables the dependence of the gasification rate of the mean-volume oxygen mass concentration, which provides clarification of the theoretical and experimental results, to be obtained.

The resulting solution is close in meaning to the works [17,18,15] in terms of solving the basic problem of the integral theory of fire in a room to analyze a gas exchange between the building and the environment through open openings of the building. The results can be used in the development of paper [17] for practical problem of the replacement of a complicated system of openings by a single rectangular opening without diminishing of the level of the fire danger taking into account a non-linear feedback, which has relation between burning rate and ventilation rate.

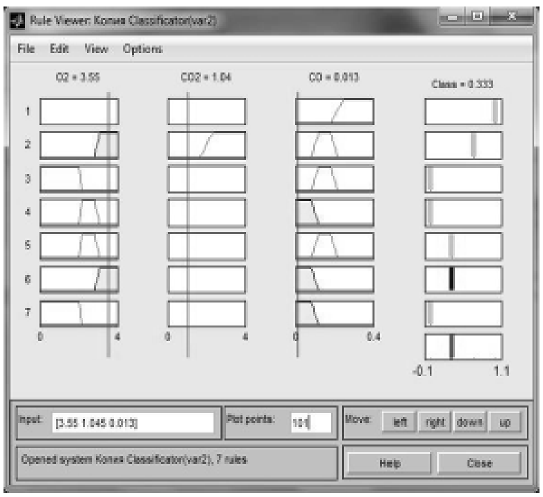

Fig. 10. A fuzzy inference for the classification process for nylon and cotton burning (a class of fire A2)

Another practical application of the solution is to determine stoichiometric coefficients to identify a class of fire when carrying out exploration of a mobile robot. A comparison of numerical experiment results for the solution of inverse fire dynamics problem with tabular data on the example of the ethanol burning allows us to conclude that the error in determining the stoichiometric coefficients is within the error of fire integral model (15-20%). Note that the values of these errors are obtained without the use of filtering methods for calculating derivatives.

8. CONCLUSIONS

The advantage of using the integral model compared to the zone approach and CFD is a smaller number of sensors placed on a robot. Thus, there is no need to place the sensors near the ceiling, but only in the doorway, through which the reconnaissance robot explores. The lack of practical application of the inverse problem means that there is a need to know the volume of space (room) that narrows the field reconnaissance, which takes place in conditions of great uncertainty. At the same time, the solution is sensitive to the parameter of irregularity of nitrogen concentration distribution in a room, which is difficult to calculate in advance.

In general, we note that the results of the solution can be used to create fire reconnaissance assets in the premises, as well as for the development of advanced algorithms for fire detection systems, fire alarm systems. Our future research will focus on the development of this area, which we believe is quite promising.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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APPENDIX

Mean-volume gases concentrations entering in expression (8) may be determine from the expression [8], describing vertical gases concentration distributions for assumptions and simplifications of the thermogasdynamic pattern of fire introduced in Section 2:

$$x_i = x_{0i} + \frac{x_{zi} - x_{0i}}{Z}, \quad Z = \frac{y}{H} \cdot e^{1,4 \cdot \frac{y}{H}},$$

where x_{0i}, x_i – the mean-volume concentration of *i*-gas (CO, CO_2, O_2, N_2) in the room before a fire, and during the fire, respectively, x_{zi} – the mean-volume concentration of *i*-gas at a *y*-meters above a floor, *Z* – a dimensionless parameter of uneven distribution of fire hazards on a *y*-height of room, *H* – the ceiling height.

It is worth considering the method of determining the mean-volume density of the gaseous medium and position of the neutral plane in the room. Two differential manometers, measuring a difference of pressure in a few heights indoors and outdoors [7] determine a mean-volume overpressure. For each fixed time the graph of the overpressure $\Delta P = P_{IN} - P_{OUT}$ (Fig. A.1) on the coordinate *y* is plotted.

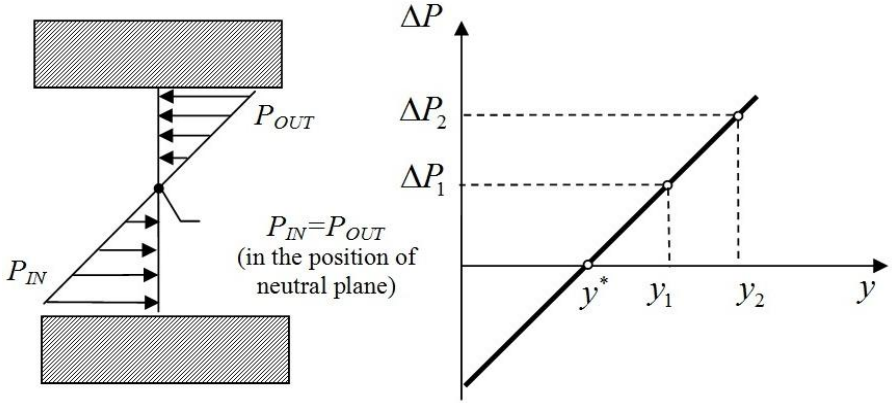

Fig. A1. The dependence of overpressure ΔP on the coordinate y, counted in height from the floor level

For plotting, the linear interpolation is used, since the vertical pressure distribution indoors and outdoors $\Delta P = f(y)$ in a first approximation near linear. Then,

$$\Delta P_m = P_m - P_a = \frac{1}{H} \int_0^H \Delta P(y)\, dy.$$

The neutral plane position y^* may be calculated from the formula (A.1):

$$y^* = \frac{H}{2} - \frac{P_m - P_a}{g(\rho_a - \rho_m)}. \tag{A.1}$$

The position y^* is easily determined from the functionally dependence of $\Delta P = f(y)$ by taking $\Delta P = 0$. From the expression (A.1), the mean-volume density of the gaseous medium indoors is determined by the next expression:

$$\rho_m = \rho_a + \frac{\Delta P_m}{g\left(y^* - \frac{H}{2}\right)}.$$

Thus, the mobile robot must be equipped with minimal set of sensors to determine the mean-volume parameters of gas environment in the room. Herewith, tactics of the robot is the following. The robot drives up to the room of fire, pushes out the telescopic rod and places the sensors in the doorway to explore the compartment fire. All the necessary measurements can be made at only two points in space of room unlike the CFD-method. Measurements at two points are required to calculate the neutral plane position y^*.

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