Mathematical modeling of the fire within the premise equipped by the system of antismoke ventilation

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Abstract. Results of mathematical modeling for the fire parameters within a premise are presented with the account of characteristics of the antismoke ventilations system. The effect of the fire loading kind in the premise on the value of the average-volume temperature of the gaseous medium was studied in case of the work of antismoke ventilation. Mathematical model allowing to evaluate dynamics of the fire temperature in the premise equipped with a system of antismoke ventilation was developed. This modeling was shown to considerably simplify the problem of determination for the parameters of emergency ventilation system already at the design stage. It also enables to estimate the efficiency of ventilation systems in the buildings in the fire conditions.

1. Introduction

Current objects of construction represent complexes consisting of a great number of premises for different purposes, engineering systems and equipment. Note that the premises and engineering systems are quite different, and the differences are in the functional assignment of these premises. When developing and implementing of the fire safety events it is required to consider the structural features of the premises – their geometry and shape, their functional assignment and configuration of the engineering systems.

Since the study of the fire dynamics parameters with the use of physical model seems to be inefficient and economically inappropriate because of the impossibility to develop the experimental unit considering the individual specific features of every real object. At the same time, it is unreal to perform fire tests at each facility. Therefore, it appears a necessity to obtain the system of mathematical relationships corresponding to the simulated processes taking place in the conditions of non-controlled combustion [1-10].

The purpose of mathematical simulation is to obtain, to process, to represent and utilize information on the fire parameters, which interact between themselves and the environment. As a result, the model should provide not only the obtaining of the quantitative values of these parameters but it must be used as a mean for cognition of the regularities in the interaction of these parameters.

Effective mathematical model enables not only to determine the dynamics of the fire parameters to be interested but also to define the most effective fire protection facilities of the buildings and constructions already at the design stage.
Basing on the fact that the main task of all the dire safety measures is the protection of life and health of the people a special attention should be paid to the dangerous fire factors, which are as follows [11-14]:

- flame and sparks;
- increased temperature of environment;
- lack of oxygen;
- toxic combustion products;
- loss of visibility as a result of smoke formation.

Taking into account the dangerous fire factors it should be considered that the most dangerous is the impact of increased temperature of the environment. The effect of this factor can result in a death of asphyxiation due to getting burned by breathing; skin burn as well as injuring from collapse of structures as a result of loss of fire resistance.

2. Decomposition of the processes

Air flows within a premise can have a considerable effect on the fire spread. It is connected with the fact that convective streams uprising over a seat of fire heat the flammable materials and thus facilitate its spread. In addition, air intake enriches combustion zone with the required portion of oxygen therefore considerably increasing combustion zone and the amount of the radiated radiant heat.

In order to study the influence of the systems of antismoke ventilation on the dynamics of temperature conditions in the fire we have considered and analyzed the equation of energy conservation in the case of fire.

\[
\frac{1}{(K-1)} \frac{d}{dt} (p_m V) = \eta Q_{H}^p \psi + i_g \psi + c_p T_b G_b - c_p T_m m G_g - Q_w
\]

(1)

This equation demonstrates the dependence of the rate of changes for the internal heat energy of the gas medium inside the premium per time unit on the total amount of heat turning round within the premise [14].

Considering this task, we selected parameters that have a significant influence on the temperature of the fire separating them from a set of insignificant ones and they were represented in the form of a function:

\[
T_m = f (\eta, Q_{H}^p, \psi, Q_w, F, p_m, G_b, G_g, \rho_m, V, \tau)
\]

(2)

where \( \eta \) – is the coefficient of combustion completeness, a dimensionless quantity;

\( Q_{H}^p \) – combustion heat of a substance/material, J/kg;

\( \psi \) – rate of burnout of a substance/material, kg/(m²s). Since middle-volumetric values of parameters are taken into account than the value of rate is more convenient to use as specific a rate \( \psi_{spec} \);

\( Q_w \) – is a heat flow into the barriers. Let us assume that the premise is not a hermetic one and thus the middle-volumetric pressure in this case will be approximately equal to the atmospheric one. It means that \( p_m = \text{const} \) and the flow of heat into the barriers is equal to:

\[
Q_w = \alpha F_w (T_m - T_w)
\]

(3)

where \( \alpha \) – is the coefficient of heat transfer of the internal premise surface and it characterize the amount of heat escaping through the barriers.

The most significant influence on the heat flow into the barriers is exerted by the parameters of the heat transfer and losses of heat through the barriers; hence, it is required to account for the coefficient characterizing heat losses through the barriers and specific mass heat capacity of gas medium. In order
to connect these two characteristics, let us consider the functional dependence of the heat flow into the barriers on those parameters.

\[ Q_w = f(\alpha, c_p) \]  \hspace{1cm} (4)

It is also necessary to account for the geometrical sizes and shape of the fire seat. In this form of the problem statement it is adopted that the flame spreads in a circle.

\[ d_{\psi}(t) = v \cdot t \]  \hspace{1cm} (5)

where \( v \) – is a linear rate of the flame spreads by the fire load, m/s.

Since the purpose of mathematical simulation is to determine the influence of the ventilation equipment on the dynamics of the temperature behavior of the fire then it is required to take into account fan delivery of the antismoke ventilation system. This enables to estimate in full the amount of gas ejected into the atmosphere and the amount of the air entering into premise.

It is also necessary to account for that under the change of temperature gas medium changes its own characteristics, particularly, the value of its density changes. Therefore, one can state that this parameter can influence on the gas exchange in the premise as well [11-13].

Thus, when considering the statement of the problem it seems possible to adopt the following boundary conditions and assumptions.

**Boundary conditions:**

- Premise is not hermetic;
- Spread of the flame over the fire load occurs in a circle;
- Temperature of the gas medium in the premise is within the range of 293 K to 343 K;
- Specific mass heat of the gas medium is constant and is determined for the value characteristic for the air.

**Assumptions:**

- flow of the energy into the premise entering along with the products of gasification (pyrolysis, evaporation) of the flammable material is insignificant;
- rate of the burning-out of a substance/material is not changed, this specific value of the rate is adopted;
- middle-volumetric pressure is equal to the atmospheric one.

In order to determine the interactions of the parameters it is reasonable to define functional dependence of (2) in the form of the power law.

After making certain transformations, the following equation was obtained:

\[ \frac{T_m}{Q_{w}^p \psi_{y,0}^2} = \left( \frac{1}{c_p \psi_{y,0}} \cdot \alpha \right) \cdot \exp\left(1 - \frac{1}{\rho_m \cdot \sqrt{Q_{w}^p}} \cdot \frac{1}{\psi_{y,0}^2} \cdot d_{\psi} \cdot \frac{1}{\tau \cdot [Q_{w}^p]^{3/2}} \cdot \frac{1}{W_{hom}} \cdot \frac{1}{\tau^3 \cdot [Q_{w}^p]^{3/2}} \cdot V_{hom} \right)^{\eta} \]  \hspace{1cm} (6)

where \( T_m \) – is a middle-volumetric temperature of gaseous medium in the premise, K;  
\( \eta \) – is the coefficient of combustion completeness, a dimensionless quantity;  
\( Q_{w}^p \) – combustion heat of a substance/material, J/kg;  
\( \psi_{y,0} \) – rate of burnout of a substance/material, kg/(m²s);
\( \alpha \) – is the coefficient of heat transfer of the internal premise surface, W/(m²K);

\( c_p \) – specific mass heat capacity of the gaseous medium for \( p=\text{const} \), J/(kgK);

\( d_{\text{mean}} \) – mean diameter of the liquid spillage spot, m;

\( W_{\text{exhaust}} \) – exhaust emergency ventilation performance, m³/sec.;

\( \rho_m \) – is middle-volumetric density of the gaseous medium in the premise, kg/m³;

\( V_{\text{prem}} \) – volume of the premise (\( V_{\text{prem}}=\text{const} \), m³;

\( \tau \) – time, sec.

Equation (6) describes interaction of the middle-volumetric temperature of the gas medium and its physics-technical characteristics with some kind of the fire load in a premise during the work of antismoke ventilation. In order to obtain quantitative dependences between the values, describing the process of the fire, it is necessary to perform the calculated experiment.

Approbation of the model implied obtaining of the analytical solution of the equation (6) for the special case of combustion of the wood in a typical premise.

As a result, the equation was derived describing the process of the changes in the environment state filling the premise which takes the form:

\[
\frac{T_{\text{m}}}{Q_{\text{ϕ}}^\alpha} = A \left( \frac{\alpha}{c_p \Psi_{\alpha}} \right)^{-\exp(1)} \cdot \left( \frac{\Psi_{\alpha}^\alpha}{\rho_m (Q_{\text{ϕ}}^\alpha)^{1/2}} \right)^{-0.78} \cdot \left( \frac{d_{\text{mean}}}{\tau (Q_{\text{ϕ}}^\alpha)^{1/2}} \right)^{2.29} \cdot \left( \frac{W_{\text{exhaust}}}{\tau^2 (Q_{\text{ϕ}}^\alpha)^{3/2}} \right) \cdot \left( \frac{V_{\text{prem}}}{\tau^2 (Q_{\text{ϕ}}^\alpha)^{3/2}} \right)
\]

(7)

3. Conclusions

The proposed mathematical model enables to obtain the analytical solution of the problem which is concerned with the determination of dynamics of the fire temperature behavior in the premise equipped with antismoke ventilation.

This will substantially simplify the problem of determination of the exhausting emergency ventilation at the stage of designing and also allows the estimation of efficiency of the ventilation systems in the buildings in case of the fire occurrence.

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