Heat-mass exchange processes dynamics forecasting in fires in typical multistorey apartment buildings

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Abstract. Heat-mass exchange dynamics forecasting in fires in typical multistorey buildings allows to prove the need and determine organizational and technical solutions parameters aimed to increasing such buildings residents safe evacuation probability, which is an urgent problem according to statistics on the deceased persons number of this population category as a result of fires. On the numerical studies results basis, the characteristic time changes regularities of critically dangerous fire factors for humans are established; the most dangerous factor according to the people safe evacuation possibility from these buildings is the optical smoke concentration level. A method for determining the critical smoke time for safe evacuation has been proposed. It is proposed to equip mass construction 5–9 storey apartment buildings with early fire detection and warning systems.

1. Introduction

In accordance with the state policy in the fire safety field, one of the main tasks for the governing bodies and persons authorized to solve problems in the fire safety field is to ensure the safe people evacuation in case of fires in residential buildings [1], [2]. Safe people evacuation during fire in buildings is possible if the time from start of ignition to the emergency exits blocking moment due to a critical for human life so-called dangerous fire factors (DFF) values (increased temperature and toxic combustion products concentration values, decreased oxygen concentration and visibility values because of the smoke) will not exceed the total evacuation time, which consists of the evacuation beginning time (the time from the fire beginning until the person receives information about the fire) and the people movement time from their residence places to the building exit or in another safe area.

According to statistics [1], [2], [3] in the Russian Federation, more than 90% of people total number deceased in fires die in apartment buildings. This number vast majority die in apartment buildings up to 9 floors. Just these typical 5 and 9 storey buildings form the mass housing construction basis of all major Russian cities.

The reasons for this are, firstly, increased high-rise buildings fire hazard compared with low-rise buildings due to the relatively high DFF velocity in the vertical buildings spaces, along with the evacuation routes length and their fast enough blocking, largely caused by intense smoke, significantly reduces the successful residents evacuation probability.

Secondly, according to the current domestic regulatory requirements fire detection system should be equipped with only apartment buildings higher than 28 meters (buildings above 9 floors). In addition, apartment buildings with a height less than 10 floors do not need to provide for fire warning system and evacuation management installation. Therefore, in the fire case in an apartment, in a stairwell or in a basement of a 5-9 storey building, the question arises: how can the house residents, being in their apartments, can independently learn about the fire presence and take action to save.

The situation is exacerbated by the modern apartments furnishing seal doorways characteristic leading into the stairwell, which significantly increases for residents the possible signs definition time of smoke and gas in the entrance. These signs independent determination usually occurs too late, when the only evacuation way through the stairwell had already cut by supercritical for human life DFF values, especially supercritical smoke value (optical smoke concentration). The fire detection system absence, in addition, leads to a delay in fire units warning, in their rapid arrival to the fire site and the rescue operations implementation.

Thirdly, typical for modern life flats filling by synthetic construction and finishing materials, furniture and household equipment with a high flammability degree, toxicity and smoke-producing ability promotes the potential fire probability in residential buildings, and its consequences.

Thus there is a serious problem in ensuring the safe people evacuation in fire cases in typical apartment 5-9 storey buildings and in multistorey buildings in general around the world [4], [5], [6], [7], [8].

The problem predetermined the study purpose. It is to predict the fire development and its dangerous factors in apartment high-rise building.

The study purpose determines the need to solve the following problem - to perform numerical experiments to determine the changes dynamics in the fire spatio-temporal parameters as it develops and to identify this change patterns in relation to a multistorey apartment building. As a result of this study, it is necessary to estimate the time available to residents for the safe evacuation possibility from apartments by stairwells. The data obtained should be the theoretical basis for the organizational and technical decisions adoption, which implementation will improve people safety evacuation in case of fires in multi-storey apartment buildings.

2. Materials and Methods

The fire development thermo-gas dynamics and mass transfer processes can be described by the following partial differential equations system expressing spatio-temporal distribution of temperature, pressure, density, velocities and concentrations of gas mixture components, including oxygen concentrations critical for human viability and toxic combustion products.

Mass conservation equation:

$$\frac{\partial \rho}{\partial \tau} + \nabla \cdot \rho \boldsymbol{u} = 0\,, \tag{1}$$

where τ is time; ρ is gas mixture density; ∇ is nabla operator (Hamilton operator); u is gas mixture velocity.

Momentum conservation equation:

$$\frac{\partial}{\partial \tau}(\rho \boldsymbol{u}) + \nabla \cdot \rho \boldsymbol{u}\boldsymbol{u} + \nabla P = \rho g + \nabla \cdot \delta_{ij} + \boldsymbol{f}_{\textit{в}}\,, \tag{2}$$

where P is gas mixture pressure; g is acceleration of gravity; $f_{в}$ is external force; δ_{ij} is tensor of viscous stresses. These stresses are determined by dependence

$$\delta_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu \beta_{ij}(\nabla \cdot \boldsymbol{u}), \tag{3}$$

Where μ is the dynamic viscosity; x is coordinate; $\beta_{ij} = 1$ for $i = j$; $\beta_{ij} = 0$ for $i \neq j$; $i, j = 1,2,3$.

Energy conservation equation:

$$\frac{\partial}{\partial \tau}(\rho h) + \nabla \cdot \rho h\, \boldsymbol{u} = \frac{\partial P}{\partial \tau} + \nabla \cdot \left(\frac{\lambda}{c_p}\nabla \cdot h\right) - \nabla \cdot \boldsymbol{q}\,, \tag{4}$$

where h is gas mixture static enthalpy; λ is gas mixture thermal conductivity coefficient; c_p is gas mixture heat-capacity at constant pressure; q is energy flow due to heat transfer.

Ideal gases mixture state equation:

$$P = \rho R_0 T \sum_{\kappa} \frac{Y_\kappa}{M_\kappa}, \tag{5}$$

where T is the absolute temperature of the gas mixture; R_0 is the universal gas constant; M_K is the k–th chemical component molar mass of the gas mixture; Y_κ is the k-th chemical component mass concentration of the gas mixture.

K-th chemical component mass conservation equation of a gas mixture:

$$\frac{\partial}{\partial \tau}(\rho Y_\kappa) + \nabla \cdot \rho \; \boldsymbol{u} \; Y_\kappa = \nabla \cdot \left(\rho D_\kappa (\nabla \cdot Y_\kappa) \right), \tag{6}$$

where D_κ is the k-th chemical component diffusivity of the gas mixture.

The dynamics of fire parameters is determined by the combustion area development taking into account the combustible materials complex real composition and mass (the so-called fire load), their location and combustion completeness, the fire occurrence place.

The smoke amount emitted during the fire load combustion is determined taking into account the smoke-producing ability and combustible materials combustion rate.

3. Experimental Section

Numerical experimentation was carried out on the FDS software complex basis [9], [10], which most accurately implements the above mathematical fire model according to the conclusion of well-known authoritative sources.

The study object is the DFF distribution processes in a typical entrance of a multi-storey apartment building.

As a result of numerical experiments, the gas-smoke medium parameters current values for the entrance well area and height, depending on the time elapsed since the fire beginning. Most dangerous for evacuated people is smoke, a which critical value occurs before the critical values of other DFF [7]. The smoke degree, and therefore the visibility range of in the smoke, is characterized by the optical density (concentration) of smoke. Since people during evacuation a natural way in considered buildings types must overcome the fire floor stairwell, just it the smoke degree of this floor is the key parameter determining the safe evacuation possibility. The gas-smoke medium extends up the staircase and blocks primarily the upper floors, so the lower fire floor is, the worse evacuation conditions are. Obviously, the most dangerous conditions for the people evacuation are the fire on the first floor.

In fig. 1 for the ground floor area, which must be overcome by all evacuating entrance residents, the smoke optical density dependence of from the time elapsed since the fire beginning is presented. These dependencies nature, and accordingly the critical evacuation time, which people have, are determined primarily by the physical and burning materials chemical parameters (the so-called fire load), the premises geometric parameters and a number of other factors. The critical smoke optical density value established by normative documents is μ_{cr} = 0.12 Np / m.

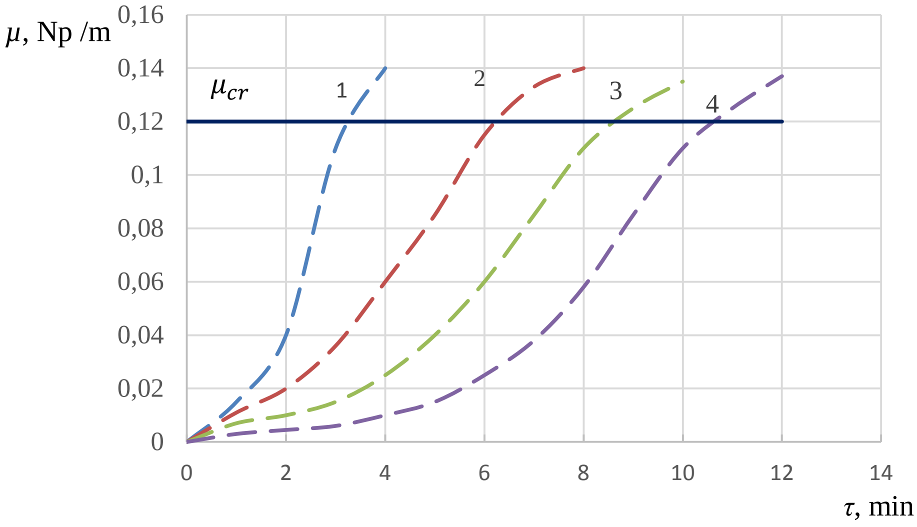

Figure 1. Optical smoke density dependences on the time elapsed since the fire beginning: 1, 2, 3, 4 – are four alternatives of fire load and the room geometry.

The use of labor-intensive computer programs and sufficiently productive computer equipment to calculate the available time of people evacuation is not always affordable and is more expensive economically. The study results allow proposing a simplified "manual" method of predicting the critical smoke time. It is based on the following assumptions. If we consider the nature of the optical smoke density dependence on time (see fig. 1) in the region close to the critical values, with sufficiently for practical purposes, this dependence can be approximated by the logarithmic dependence (see fig. 2) in the form of

$$\mu = K \cdot ln\,\tau \,, \tag{7}$$

where μ is the optical smoke density, Np / m; τ is the time counted from the ignition moment, min; K is the coefficient of the fire load and the geometry of the premises, coinciding in dimension with μ.

Dependences shown in fig.1 are fire parameters calculations for different variants of fire load and the space geometry.

Fig. 2 illustrates the dependence comparison μ from τ (obtained by calculation) with the approximating logarithmic dependence obtained when K=0.05, which is typical for the most common "average" version of the fire load and the geometry of space for this buildings type. An increase in this coefficient indicates the increased fire load presence (with unchanged building premises geometry), for example, additional combustible materials in apartments, on entryway or in the basement. Accordingly, the safe evacuation critical time, which is available to entrance residents, is significantly reduced. A decrease in this ratio indicates a reduced fire load, for example, apartments free of furniture and things. At the same time the safe evacuation critical time increases.

Formula (7) can be reduced to the form

$$\tau = \exp\left(\frac{\mu_{кр}}{K}\right), \tag{8}$$

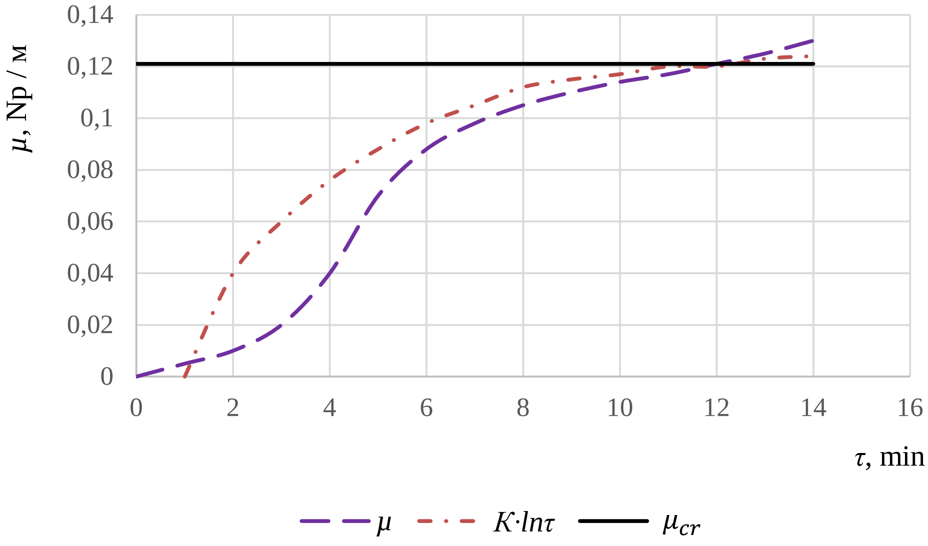

Figure 2. The dependence μ from τ with a value K=0,05

Taking into account that μ_{cr} = 0.12 Np / m, the safe evacuation critical time can be calculated by simple formula

$$\tau_{\kappa p} = \exp\left(\frac{0{,}12}{K_i}\right), \tag{9}$$

where K_i is the coefficient corresponding to the i-th type of fire load and premises geometry.

The K_i coefficients values should be pre-calculated for possible the most common fire load and the space geometry, but they are not so many and error values when rating the critical time for safe evacuation are not significant taking into account many uncertainties introduced into the real dynamics of the fire by several other occurring factors.

4. Discussion

The use of modern software [7], [9], [10], modeling the heat and mass transfer processes dynamics in case of fire, allows to calculate the current gas-smoke medium parameters values in the house entrance well area and the height depending on the time elapsed from the ignition start. Thus it becomes possible to determine the time when a particular DFF reaches its critical value for human life. The numerical studies results have shown that for typical high-rise apartment buildings the most dangerous factor is smoke, as the critical value of the smoke optical density on the evacuation routes comes before other factors. This leads to a significant reduction in the visibility range and people orientation loss when moving to the building exit, that is, blocks the escape route. It should be noted that the smoke has a special negative impact on people. Toxic gases condense on the smoke particles, which are unburned carbon particles. For example, the carbon monoxide toxicity, which has the highest concentration among all gaseous combustion products, increases in the presence of smoke. That is, there is a synergistic effect from the joint influence of several DFF, which increases their negative impact on human health.

The main calculations result is numerical time values that a person has in order to safely evacuate.

The proposed method for determining the critical smoke time allows conduct an approximate assessment of the available time for safe evacuation in typical multi-storey mass construction houses.

5. Conclusion

Just the late fire detection is the main problem of timely and safe people evacuation in typical 5-9 storey mass construction apartment buildings. The only effective solution to the residents evacuation problem in such houses is the entrances equipping by floor (ideally also by apartment) early fire detection and warning systems (for example, in the simplest case, an entrance siren). These systems permissible inertia can be determined using the presented tools and similarly presented results. It should be taken into account, firstly, the time delay value for the residents evacuation after the appropriate signal about the fire, including contingent type and evacuate mobility level (children, older persons, people with disabilities, etc.), and secondly, the people movement from their residence places exit out of the building or other safe area. The last parameter can be obtained not only by calculation, but also evaluated in practice as a result of training evacuations.

The performed calculations confirmed the widespread statement that the spread of smoke inside multi-storey buildings should be the primary problem of designers and specialists in fire safety.

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