Heat-mass exchange processes dynamics in fires in multi-apartment buildings and its impact on safe people evacuation probability

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Abstract. The urgency of people safe evacuation problem from small and medium storeys typical residential sectional type multi-apartment buildings, which in accordance with current regulatory requirements are not equipped with technical means of fire detection and notification of residents, are not equipped with active smoke ventilation systems and do not have effective structural evacuation solutions is shown. Based on modern software systems, numerical experimental studies were conducted to assess the dynamics impact (intensity rate impact) of heat and mass exchange combustion processes on the people evacuation parameters and the corresponding rate of increase dangerous factors for human viability in fire. The time intervals available to residents for safe and timely evacuation are calculated, depending on the typical residential premises fire load characteristic quantity. Taking into account the results obtained, practical measures aimed at improving the people safety in fires in residential multi-apartment buildings are proposed for implementation.

I. Introduction
This article presents the research results continuing the authors’ work published, in particular, in the previous article of "Dynamics of systems, mechanisms and machines" [1]. The previously described materials show the topicality of the people safe evacuation problem solving from small and medium storeys typical residential multi-apartment buildings (up to 9 floors inclusive) [2]. This problem is mainly due to the lack of the following fire safety elements in such buildings:
– automatic fire detection system and automatic fire alarm system;
– active smoke ventilation systems working during a fire;
– space-planning and structural evacuation solutions, especially for sectional type residential buildings, in which the only way of evacuation is to descend the standard staircase of the stairwell (in contrast to corridor-type buildings that have emergency internal or external stairs at the ends of the building).

At the same time, it should be noted that small and medium storeys sectional buildings (especially old buildings) make the predominant part of large cities’ housing stock.

The time interval that residents have for timely evacuation is mainly determined by the dynamics (intensity rate) of heat and mass exchange combustion processes and the corresponding rate of increase dangerous factors for human viability in fire that threaten his life and movement safety along evacuation routes. Therefore, it is of significant practical importance to conduct these processes
intensity impact study on the safe evacuation possibility of all residents from an apartment building in fire case.

2. Materials and Methods

In connection with the vital people safe evacuation problem from small and medium storeys buildings, it is interesting to assess such evacuation possibility both in the actual absence and in the presence of technical means and space-planning solutions that ensure the human viability from the fire start moment and throughout the time of movement along the evacuation routes up to the exit from the building.

It is obvious that people evacuation problems full-scale experimental studies in fire case are impossible due to their extreme danger. Therefore, a generally accepted approach is to conduct numerical experimental studies based on computer programs that implement mathematical models of heat and mass exchange and gas dynamic processes occurring during a fire, as well as people evacuation processes.

The results of this study will allow to develop practical proposals for the people safety improving in the fire case in residential multi-apartment buildings.

The condition for timely and safe evacuation of all people in fires in buildings is the following: [3], [4]:

\[ \tau_0 + \tau_e \leq K_s \tau_b, \]  

where \( \tau_e \) is the calculated people evacuation time (time of people movement throughout evacuation routes); \( \tau_0 \) is the evacuation start time, defined as the time interval from the fire start time to the evacuation; \( \tau_b \) is the evacuation routes blocking time, defined as the time interval from the fire start time until the evacuation routes blocking moment due to the distribution of so-called dangerous fire factors (DFF) [3-5], reaching the maximum allowable critical for the human viability values and not allow him to safely evacuate; \( K_s \) is safety coefficient (according to standards of Russian Federation \( K_s = 0.8 [3], [4]. \)

Fire hazards [3], [4], to be calculated include the gas medium temperature, the oxygen concentration, the toxic gaseous products concentration of combustion and thermal decomposition, and the visibility range in the smoke (determined by the optical smoke density).

To determine the blocking time \( \tau_b \), in this paper we use the field (differential) mathematical model of heat and mass exchange and gas dynamic processes in fire (the model field equations system is presented in [1], [3], [6]), which is implemented in software in a computing complex FDS [6-8]. This computing complex allow to calculate geometrically complex multi-story facilities, has sufficient positive evidence to support the acceptable reliability of the obtained results and is widely used in the global design practice [6-9]. To determine the estimated time of evacuation \( \tau_e \), an individual-flow mathematical model of human movement was used, which was implemented in software in the EVATEK computer complex [9-13].

The evacuation start time value choice is associated with considerable uncertainty. This time interval is the sum of two components, called "technical" and "psychophysical" [14], [15].

The "technical" component includes the time period from the moment of fire ignition to its detection and the time spent on fire alert. The fire detection time depends on the settings and sensitivity of technical automatic devices (fire detectors). This parameter can be determined by comparison of the calculated results or full-scale studies of gas environment parameters growth dynamics common to fire and these parameters achievement values operation of fire automatics means with alarm about the fire. For example, in [14], based on a calculations comparison performed using the FDS computing system, data on the fire detection time by a smoke detector in various functional purposes premises, including in a residential two-room apartment, are presented. When the fire center is located in a residential room, and the fire detector is located in the apartment's entrance hall, the fire detection time is about 1 min [14]. The time spent on fire alarm can be considered as the technical means inertia sum in the chain: fire detector, fire receiving and control device, fire alarm voice
evacuation system (FAVES) and the duration of sound or speech notification (depending on the type of FAVES [16]). The time interval determined by the technical means inertia is negligible compared to the notification duration, which for example for speech notification is about 30 seconds [15].

The greatest difficulty is the assessment of the "psychophysical" component, which is usually represented [14], [15] as the time sum of so-called decision-making and the time to prepare for evacuation (the information awareness time and current situation assessment). For both these components, there are no sufficiently justified values, since they are not only specific for individual people groups, but also specific for each person, taking into account the probable restricted mobility of individual residents (young children, the elderly and sick people). Special research is devoted to these issues [15], [17], [18].

Regulations of the Russian Federation prescribe to take into account the fixed values given in the reference tables [3]. In this case, the \( \tau_0 \) value depends on the buildings functional fire hazard class, the people contingent characteristics, the presence and type of FAVES or its absence.

When performing numerical experiments, the initial characteristic physical parameters were selected from the following prerequisites: since the intensity of the exothermic combustion reaction increases with the development of the fire, the corresponding rate of increase in the thermal power of the fire [3], [4], [14], [19] determines the rate of increase in the values of hazardous fire factors.

The fire thermal capacity \( W \) is found by the formula:

\[
W = H_f \psi \tau S, \text{ kW} \tag{2}
\]

where \( H_f \) is the lowest combustible materials combustion heat (the so-called fire load), kJ/kg; \( \psi \) – fire load burnout specific mass rate, kg/(m\(^2\) s); \( S \) is the combustion area at the current time, m\(^2\).

In the case of circular combustion propagation, which is typical for the main group of residential premises (excluding narrow, long passages and corridors), \( S \) is determined by the formulas [3], [4], [14]:

\[
S = \pi v^2 \tau, \tag{3}
\]

where \( v \) is the linear combustion propagation velocity, m/s; \( \tau \) is the time counted from the moment of ignition, s.

Then:

\[
W = K_W \tau^2, \text{ kW} \tag{4}
\]

where \( K_W = H_f \psi \pi v \tau \) is the coefficient that takes into account the rate of change in the fire thermal capacity, kW/s\(^2\).

The \( K_W \) coefficient is a complex hazard indicator for specific fire load types: it characterizes the heat release value and is proportional to the absolute mass burnout rate of these fire load types, for which reference data on specific toxic gaseous combustion products released mass values, oxygen consumed, and smoke emission parameters per burned fire load unit mass are known [4].

### 3. Experimental Section

For the typical fire load of typical residential premises (furniture, floor, wall and ceiling finishing materials, window frames, household appliances, clothing, bedding, etc.), it was found that the \( K_W \) coefficient value in the vast majority of cases is in the range from 0.01 to 0.09 kW/s\(^2\).

The greater the \( K_W \) value, the greater the fire thermal capacity and the greater the danger for the people evacuation from this fire load.

The calculations were made taking into account the quadratic law of changes in the fire thermal capacity (formula (4)) in the above \( K_W \) range of changes.

The most unfavorable fire development scenario is realized in the case of a fire in an apartment on the first floor, as it represents the greatest danger to upper floors residents. At the same time, their evacuation path length increases as the floor height increases, and the last floor residents of the building must overcome the longest escape route to the first floor landing, blocked by the DFF.
The calculations were made for sectional buildings with the most common standard apartments, where three people live, and the total area is about 60 square meters. It was found that for such apartments any premises the fire hazards values as the fire develops very quickly become almost the same in all rooms, regardless of the initial fire location in one of the rooms.

The worst-case scenario for people evacuating from other apartments was considered, when the door from the apartment to the stairwell was open. Thus, the gas-smoke environment freely exited from the burning apartment to the staircase landing without any time delays and spread along the stairwell area. However, it took into account the apartment windows opening as the fire developed in accordance with the laws presented in [20], which reduced the gas-smoke environment components concentration leaving the apartment on the staircase landing.

The calculations results in the form of fire hazards values dependences on the first floor staircase landing on the time elapsed since the ignition in the apartment located on the first floor, in the boundary values range $K_W$, as well as the human critical (limit) values for each DFF (according to [3], [4]) are shown in fig. 1-5.

**Figure 1.** Change of gas temperature medium $T$ on the first floor landing staircase as the time changes from the ignition start in the apartment on floor 1 ($T_{cr}$ is a critical temperature value for a human).

**Figure 2.** Oxygen concentration change $C(O_2)$ on the first floor landing staircase as the time changes from the ignition start in the apartment on floor 1 ($C(O_2)_{cr}$ is a critical oxygen concentration value).

**Figure 3.** Carbon dioxide concentration change $C(CO_2)$ on the first floor landing staircase as the time changes from the ignition start in the apartment on floor 1 ($C(CO_2)_{cr}$ is a critical carbon dioxide concentration value).

**Figure 4.** Carbon monoxide concentration change $C(CO)$ on the first floor landing staircase as the time changes from the ignition start in the apartment on floor 1 ($C(CO)_{cr}$ is a critical carbon monoxide concentration value for a human).
carbon dioxide concentration value for a human).

![Graph](image)

**Figure 5.** Optical smoke density change on the landing staircase of floor 1, floor 5 of a five-story house, floor 9 of a nine-story house as the time change from the ignition start in the apartment on floor 1 ($\mu_{cr}$ – critical optical smoke density for human evacuation:

- - - - - - - 1st floor,
- - - - - - - - - 5th floor of a 5-storey building,
- - - - - - - - - - 9th floor of a 9-storey building.

At the specified fire load, the optical smoke density increases most rapidly in comparison with other DFF (the smoke degree increases). Toxic combustion products concentration increases slower, oxygen concentration reduces slower, temperature increases more slowly.

It was found that the smoke and gas medium rises quickly enough up the stairwell and its concentration increases intensively in the building last floors location. This medium is based on fine particles that reduce visibility, as well as those toxic gases whose density is less than the density of air, in particular, extremely toxic carbon monoxide.

The calculations results show that at a certain time value, the optical smoke density and the carbon monoxide concentration on the last floors of the building due to their accumulation (in the smoke and gas removal means absence) begin to exceed the corresponding values occurring on the first floor. This effect is shown in Fig. 5 as an optical smoke density example.

The estimated people movement duration values along the stairwell to the building exit, taking into account the smoke presence, toxic gases and low oxygen concentrations that make it difficult to breathe (which was indirectly taken into account in the calculations by reducing the movement speed), was 1.6 minutes from the 5th floor and 3.1 minutes from the 9th floor. In practice, the actual movement time values may be significantly higher than those obtained due to the probability of a low-mobility evacuating residents contingent.

According to the Russian Federation standards [3], the evacuation start time from residential buildings apartments in the absence of FAVES should be taken as 9 minutes. When a building is equipped with a fire detection system (fire alarm system - FAS) and FAVES, the standard evacuation start time for residential buildings according to [3] should be assumed to be 6 minutes (if there is a FAVES of the first and second types, which meets the requirements [16]).

The values of the evacuation time intervals in the absence and presence of FAVES are shown in the table.
Table 1. Time intervals for evacuation in the absence and presence of FAVES.

| Absence of FAVES (I-II type) | $\tau_0$, min | $\tau_c$, min (from 5th floor) | $\tau_c$, min (from 9th floor) | $\tau_0 + \tau_c$, min (from 5th floor) | $\tau_0 + \tau_c$, min (from 9th floor) |
|-----------------------------|---------------|--------------------------------|--------------------------------|----------------------------------------|----------------------------------------|
| -                           | 9             | 1.6                            | 3.1                            | 10.6                                   | 12.1                                   |
| +                           | 6             | 1.6                            | 3.1                            | 7.6                                    | 9.1                                    |

4. Discussion

The obtained calculated results show that with the type and number of fire load typical for residential apartments, the greatest danger for people evacuating during a fire is smoke, since the time when optical smoke density reaches the critical value is less than the time when other fire hazards reach their critical values.

Thus, the exit blocking time from the building is determined by the time of reaching the critical smoke optical density on the first floor landing staircase.

Fig. 6 shows the calculated dependence of the building exit blocking time (including the safety factor $K_s = 0.8$) on $K_W$ coefficient, characterizing the thermal fire capacity rate of change and, accordingly, the heat and mass exchange development intensity in combustion processes, as in the apartment fire, and throughout the staircase volume.

The presented data show that the intensity of heat and mass exchange processes significantly affects the safe people evacuation possibility. Thus, safe evacuation (inequality realization according to the formula (1)) is possible even if the building is equipped with FAS and FAVES from the 5th floor at the values of $K_W < 0.033$ kW/s², and from the 9th floor - at $K_W < 0.024$ kW/s². Safe evacuation
without equipping the building with FAS and FAVES is possible at even lower intensity of combustion processes, that is, if there is a relatively rare fire load with extremely small parameters in an apartment with the fire center. Safely people evacuation becomes impossible when the fire load parameters are more likely for residential apartments and, consequently, heat and mass exchange processes have higher intensity.

As noted above, the presented results were obtained at fixed normative evacuation start time value $\tau_0$. However, in reality, the evacuation start time may be either less or often more than the standard time. If the evacuation start time standard value can be selected with some validity degree when equipping the building with the FAS and FAVES [3], [15], [17], if the building does not have the FAS and FAVES, it is very conditional to accept a particular value for the evacuation start time, since the reasons why people learned about the fire can significantly affect the time period from the fire start to receiving information about it. This duration time interval cannot be accurately determined, since information about a fire in a building may (or may not be received) completely random. Moreover, the sealed doorways installation leading to the stairwell in modern apartments significantly increases the time and possibilities for independent detection by apartment residents of smoke and gas contamination presence in the stairwell. Thus, the absence of automatic FAS and FAVES in the building leaves open questions: from whom (what), how and when people who are in the apartment (especially at night) learn about the fire and the need to evacuate.

5. Conclusion

The study results convincingly prove the heat and mass exchange processes intensity influence significance in fires on the safe people evacuation possibility. The obtained time intervals estimates available to residents for safe and timely evacuation show that such evacuation is possible only at relatively low fire load, which is not typical for most modern residential apartments. The installation of small and medium-rise residential buildings with fire alarm systems, preferably with hot detectors for early fire detection [21] and systems for notifying people about fire, reduces the evacuation start time, although it is not always possible, as calculations results show, to ensure safe and timely evacuation. To increase the residents notifying reliability about a fire at night, it is advisable to install fire alarms in the apartments sleeping areas.

Note that autonomous fire detectors installation in apartments [18], [22] mainly solves the apartment residents evacuation problem where the fire occurred. Residents notification of all other apartments depends on a significant subjective factors number, including the physical and mental condition, age, burning apartment residents mobility degree, as well as the probability of their absence in the fire moment.

An effective technical solution that increases the evacuation routes blocking time by fire hazards, and therefore increases the time interval available for evacuation, is the equipment of small and medium-rise residential buildings with automatic active gas removal systems [18], which are triggered by a fire from the FAS signal. Installing an exhaust fan in the upper part of each stairwell will significantly reduce the optical smoke density and the toxic gases concentration, while installing a supply fan in the lower part will provide fresh air and increase the oxygen concentration.

Structural solutions aimed at improving the evacuation safety include the intersectional passages construction (internal or external) in residential buildings in order for residents could leave the building through neighboring stairwells.

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