Modeling Fire Spread along the Non-combustible Building Façades of Different Geometry

Khasanov I.R., Karpov A.V.*

[1] *All-Russian Research Institute for Fire Protection (VNIIPO), Balashikha, Moscow region, Russia*
**Corresponding author's email: avkhome@inbox.ru*

ABSTRACT

Mathematical modeling of fire development is widely used for solving different problems of fire safety. This modeling, as a rule, considers only the development of fire inside the building. However, the fire spread along the external façade structures can also create hazard even when the external walls and façade structures are made from non-combustible materials. In particular the spread of fire along the façades can lead to smoke filling of open passages (balconies) of staircases, appearance of smoke in the points of air intakes of smoke ventilation systems, covering of helicopter area at the roof with smoke, and fire spread on the upper floors through open and glazing filled openings. This work presents the results of CFD modeling of fire spread along the non-combustible façades of different geometrical configurations with glazing structures.

KEYWORDS: Façade, fire spread, fire modeling, CFD.

INTRODUCTION

Exterior façade systems are widely used for buildings in Russia and the experience of their use indicates particular risks of fire spread along the outer façades. So the consideration of peculiarities of such fire development is needed.

The main ways of fire spread from one floor to another are as follows [1, 2].

- By combustible materials (construction) of the façade (fire lining ignition can occur as a result of flame ejecting from the window, as well as from the flames on an adjacent building and other sources);
- Directly from the flames ejecting from the openings (transition of fire from floor to floor through the window; flame spread to neighboring buildings is also possible);
- Through the holes and cracks in joints of floors and external walls due to insufficient fire resistance of structure fastening; through holes in floors due to insufficient fire resistance of structures;
- By burning drops produced by melting of constructions and other materials (metals, alloys, composite materials), with the possible fire spread downwards;
- Through the technological holes in the ceilings and walls (cable penetrations, air ducts, etc.);
- Through the corridors and staircases.

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Compilation of data on the spread of fires along the façade shows that the following features are observed [3, 4]: fire develops in the room of fire origin in 10-15 min; the average flame height above the window opening is 2.5-3 m; maximum flame height above the window opening is 4-6 m; maximum heat release rate in the flame above the window opening is 1-2 MW; fire spread from one floor to another through the windows occurs after 15-20 min.

Flame ejecting from the window opening is produced by an intense fire in the enclosure. Convective and radiative heat fluxes generated by the flame are high enough to ignite the combustible facing of external walls. Therefore, the fire impact on the building structures and the outside façade is mainly determined by the flammability properties of the materials used. Use of combustible materials in façades significantly increases the fire hazard and can cause a rapid spread of fire and toxic combustion products.

The fire spread along the combustible facing is influenced by [5]: the external conditions (thermal effect from the flame ejecting though the window; heat released in the burning lining; heat losses to the inner part of the lining); characteristics of the facing material (ignition temperature; flame propagation speed, etc.); mechanical behavior of the façade lining at elevated temperatures.

A typical example of the fire spread over the combustible façade is the fire in a 24-storey building which occurred in the Grenfell Tower block of flats in North Kensington, West London [6]. The fire started in the early hours of Wednesday 14 June 2017, when a fridge-freezer caught fire on the 4th floor. The fire then spread on the building façade and reached the upper floors in 15 minutes. Such a rapid spread of fire over the building was facilitated by the ventilated façade with combustible insulation of PIR (polyisocyanurate) foam plates.

The use of a non-combustible façade is less dangerous. However, in this case the spread of fire from floor to floor is also possible through the window openings, and this can also lead to dramatic results. For example, a fire broke out in a 106-m high building in Madrid in February 2005 and spread over the entire building [7]. Fire began on the 21st floor, most likely from a short circuit. The presence of large apertures without fire-resistant glass in the façade protection facilitated the fire spread towards the upper floors.

The vertical fire spread over the building is influenced not only by the materials used in building constructions but also by the construction geometry and by the parameters of the fire. In previous studies (for example in [8], [9]) the fire spread along the flat vertical façade was considered. In this work, the fire spread along the non-combustible façade with different configurations and slopes of the external constructions is simulated.

PROBLEM FORMULATION

In this work, the fire in the office building with glazing break-up in the enclosure of fire origin followed by the fire spread along the façade is investigated numerically. The following fire scenarios were considered.

- **Scenario-1**. Fire spread along the flat vertical façade (Fig. 1 a);
- **Scenario-2**. Fire spread along the façade zone with 5° slope and the presence of a step 1.3 m deep (Fig. 1 b);
- **Scenario-3**. Fire spread along the façade with 10.8° slope (Fig. 1 c);
- **Scenario-4**. Fire spread along the façade with curved 1.5 m radius glazing, flat vertical glazing and flat 3° sloped glazing adjacent to the façade (Fig. 1 d).

As a worst-case scenario, it was assumed in the simulations that the glazing breakage in the enclosure of fire origin occurs in the first seconds of fire development. The properties of fire load for office rooms were taken according to [10] with the presence of the automatic fire extinguishing system taken into account. The dynamics of the heat release rate corresponds to the dependence $Q = 6t^2$ W.

(a) (b) (c) (d)

Fig. 1. The geometry of façades for the considered fire scenarios.
(a) scenario-1; (b) scenario-2; (c) scenario-3; (d) scenario-4.

The fire tests performed in VNIIPO with translucent exterior walls on aluminum frame with similar characteristics (design and frame material, type and dimensions of the filling of the frame fastening, etc.) showed that the loss of integrity (E) by such structures occurs when the temperature in the firing chamber grows up to 750-770 °C. In view of these results, the temperature of 750 °C (1023 K) in the immediate vicinity of translucent construction was considered as the criterion for glazing breakage.

MATHEMATICAL MODEL

The mathematical model implemented in the code SOFIE [11] includes the following governing equations:

- the continuity and momentum equations.

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial \rho u_j}{\partial x_j} = 0, \tag{1}$$

$$\frac{\partial \rho u_i}{\partial \tau}+\frac{\partial \rho u_j u_i}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left((\mu+\mu_t)\frac{\partial u_i}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left(\mu_t\frac{\partial u_j}{\partial x_i}\right)+\rho g_i\,, \tag{2}$$

- the equations of k-ε turbulence model [12] with buoyancy correction [13]

$$\frac{\partial \rho k}{\partial \tau}+\frac{\partial \rho u_j k}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right)+G_K+G_B-\rho\varepsilon\,, \tag{3}$$

$$\frac{\partial \rho \varepsilon}{\partial \tau}+\frac{\partial \rho u_j \varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right)+c_1\left(G_K+G_B\right)\frac{\varepsilon}{k}-c_2\rho\frac{\varepsilon^2}{k}\,, \tag{4}$$

where $\mu_t=c_\mu\rho\dfrac{k^2}{\varepsilon}$, $G_K=\mu_t\left(\dfrac{\partial u_i}{\partial x_j}+\dfrac{\partial u_j}{\partial x_i}\right)\dfrac{\partial u_i}{\partial x_j}$, $G_B=-\beta g\dfrac{\mu_t}{\sigma_t}\dfrac{\partial T}{\partial x_j}$,

- the enthalpy equation

$$\frac{\partial \rho h}{\partial \tau}+\frac{\partial \rho u_j h}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\left(\frac{\mu}{\sigma_h}+\frac{\mu_t}{\sigma_t}\right)\frac{\partial h}{\partial x_j}\right)+S_{h,rad}\,, \tag{5}$$

- the species equations

$$\frac{\partial \rho Y_i}{\partial \tau}+\frac{\partial \rho u_j Y_i}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\left(\frac{\mu}{Sc}+\frac{\mu_t}{Sc_t}\right)\frac{\partial Y_i}{\partial x_j}\right)+S_i\,. \tag{6}$$

The model constants were assignied according to Ref. [14].

The eddy break-up model was used in combustion modelling [15]:

$$S_f=-\rho\frac{\varepsilon}{k}\min\left(CY_f,C\frac{Y_{ox}}{s},B\frac{Y_{pr}}{s+1}\right), \tag{7}$$

where $C = 4$, $B = 2$.

Radiative heat transfer was simulated by the discrete transfer radiation method (DTRM) [16]. Radiative properties of combustion products were determined by the weighed sum of grey gases model [17] with the Truelove' approximation coefficients [18].

SIMULATION RESULTS

Predicted mean temperatures for the considered fire scenarios are presented in Figs. 2-9. The pictures show that the critical temperature value of 1023 K (for this type of glazing) near the façade is not achieved at elevations above 0.6 m from the top edge of the opening in the enclosure of fire origin. At the same time, the simulation results show that the façade geometry has a significant impact on the temperature distribution near the exterior of the building. In particular, the maximum temperature near the upper edge of the opening varies from 500 to 750 K depending on the considered scenario.

Figures 2, 4, 6, and 8 show that the flame (defined as the region with the mean temperature above 823 K) does not appear outside the opening. Therefore, the predicted heat fluxes to the outer building surface are relatively small. By this reason and because of non-combustible façades these scenarios were not of interest.

In Fig. 3, the temperature distribution near the façade surface in scenario-1 (flat vertical façade) is presented. It shows that the predicted mean temperature is almost uniform in the region of 1.2 m above the upper edge of the opening, followed by the decrease of the temperature upwards. In Figs. 7 and 9 for scenarios with sloped façades (scenarios 3 and 4) we can see that the temperature is predicted to decrease immediately above the opening upper edge. Comparison of these figures shows that the greater slope of the façade results in a faster temperature decrease. In scenario-2, the temperature distribution (Fig. 9) differs from that in other scenarios with the sloped façade. In this scenario we can see the region of the uniform temperature similar to scenario-1, but this region is of 0.6 m height only. A possible reason for this is the deeper step.

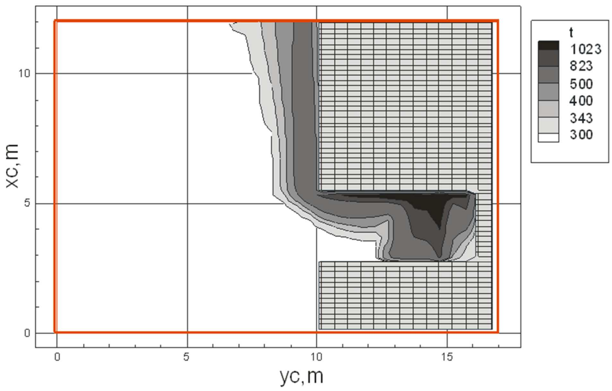


Fig. 2. Predicted mean temperature distribution (K) in the vertical cross-section at time instant 1200 s. Scenario-1.

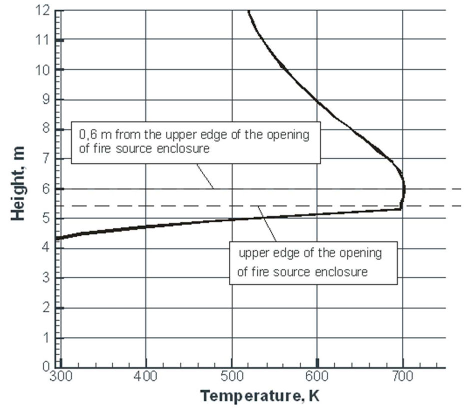


Fig. 3. Predicted mean temperature profile near the façade surface at time instant 1200 s. Scenario-1.

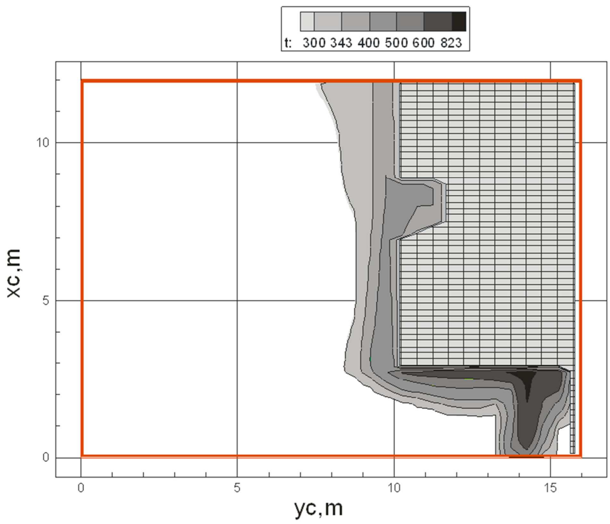


Fig. 4. Predicted mean temperature distribution (K) in the vertical cross-section at time instant 1200 s. Scenario-2.

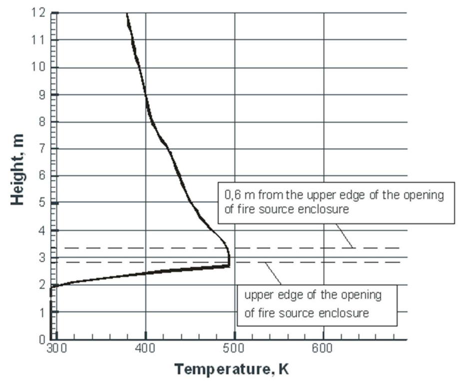
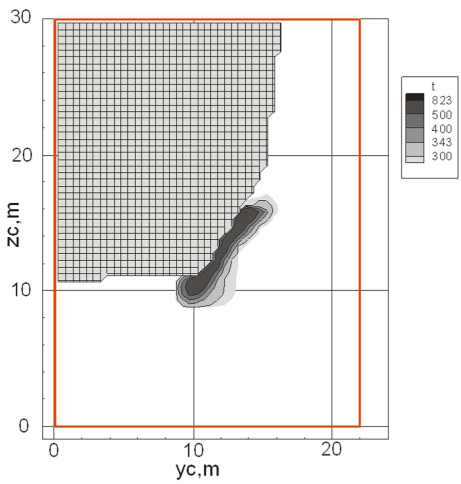
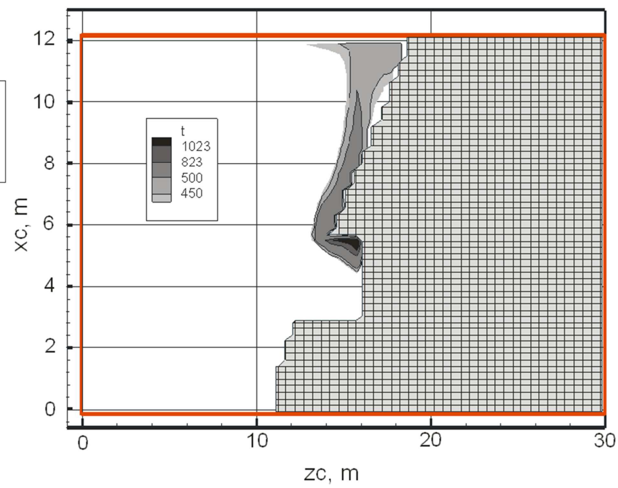


Fig. 5. Predicted mean temperature profile near the façade surface at time instant 1200 s. Scenario-2.





(a) (b)

Fig. 6. Predicted mean temperature distribution (K) at time instant 1200 s: (a) horizontal cross-section 0.6 m above the upper egde of the opening; (b) vertical cross-section. Scenario-3.

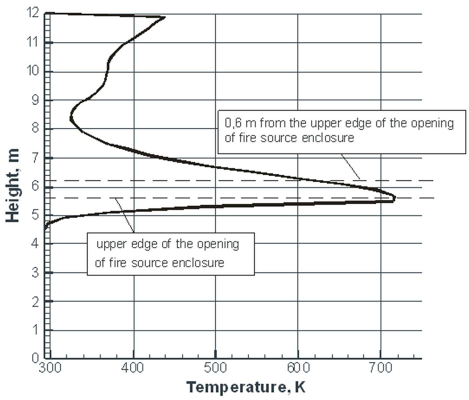
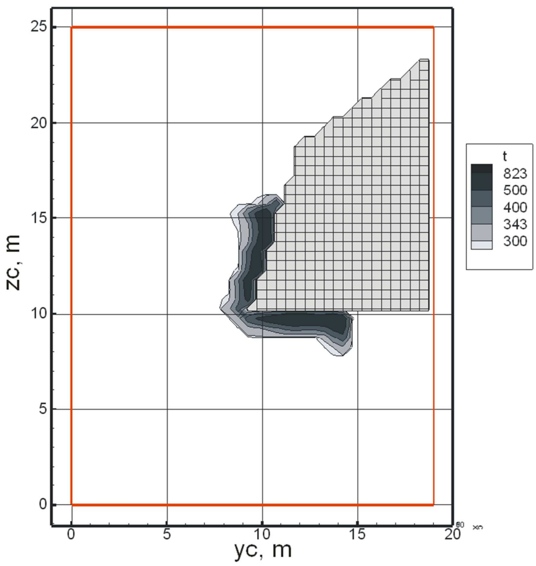
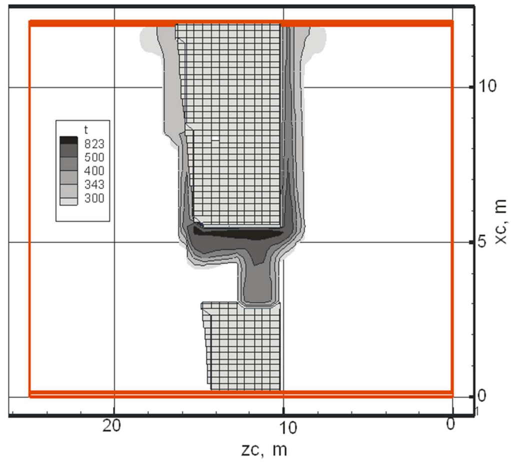


Fig. 7. Predicted mean temperature profile near the façade surface at time instant 1200 s. Scenario-3.

CONCLUSIONS

For the considered fire scenarios, the temperature fields near the exterior façade above the opening in the enclosure of fire origin have been predicted. The mean temperature distributions were used to assess the possibility of fire spread to the higher floors. The simulation results have shown that the geometry of the façades has a significant impact on temperature distributions.





(a) (b)

Fig. 8. Predicted mean temperature distribution (K) at time instant 1200 s: (a) horizontal cross-section 0.6 m above the upper egde of the opening; (b) vertical cross-section. Scenario-4.

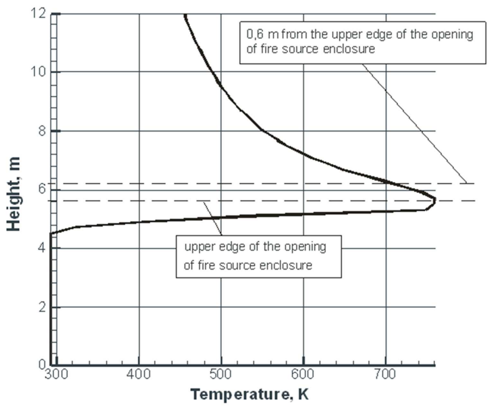


Fig. 9. Predicted mean temperature profile near the façade surface at time instant 1200 s. Scenario-4.

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