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ENGINEERING ESTIMATION OF AIR REGIME OF BUILDING FACADE SYSTEMS WITH FIRE CUT OFFS

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Abstract

The facade is one of the most important elements of the building in terms of its fire safety, as a fire leads to serious building damage and human casualties. The article considers the influence of fire cut-offs on the parameters of the airflow in the ventilated gap of the hinged facade system. An engineering estimation of solid and perforated horizontal fire cut-offs used in Azerbaijan is presented. As air exchange in the ventilated gap occurs in the thermo-gravitational mode, the features of the airflow movement in the gap are analyzed using the aerodynamic estimation method with the assumption that the gap is a single vertical air duct. Engineering estimation of the impact of cut-offs on the facade air regime is performed by the dependence on the coefficient of airflow velocity. It has been established that when using even a cut-off with a significant percentage of perforation it prevents necessary air exchange in the gap. A motivated justification is given for the need to use modernized cut-offs, which, during normal operation of the facade, do not interfere with the required air exchange in the gap, but in case of fire, cut-offs block the air movement in the gap and the ingress of burning drops of molten thermal insulation into the lower zones. The results of the engineering assessment can be used to further improve the regulatory framework for the design, installation, and reliable operation of facade systems with a ventilated air gap.

Keywords: hinged facade system, ventilated air gap, fire cut-off, coefficient of airflow velocity, engineering estimation, fire safety

I. Introduction

Every year, many natural disasters occur in various parts of the world, including earthquakes, causing significant social, economic, and energy damage to people. One of the potential and greatest dangers of earthquake consequences is the fire threat. In addition to earthquakes, the cause of fires in buildings and structures can be a violation of construction safety, the use of combustible building materials, and faulty structures [1].

Currently, hinged facade systems (HFS) with a ventilated air gap (VAG) are becoming increasingly popular in the construction of new and reconstruction of old buildings, which significantly increases the energy efficiency of the building [2]. In the modern construction industry, this facade system is also in demand due to its versatility and multi-functionality. In addition, these facades give the building an expressive exterior, they have improved thermal-shielding properties and normalize the heat and humidity regime of the building, which is achieved due to their design features [3]. Along with all the advantages, the main and most significant drawback of HFSs with VAG is their fire hazard [4], which was proved by resonant fires in Baku: 12-story residential building, near the Azadlig metro station, 2015 (Fig.1), and 9-story residential building on the Zykh highway in the Khatai district, 2017. Both buildings had HFS with VAG. The gap acted as an open chimney and allowed the fire quickly spread both vertically and horizontally across the building`s facade. It proves that the problem of preventing fire spread in the air gaps of the facade systems is relevant and it is of decisive importance for ensuring the safety of life and people activities.

Fig. 1: *Facade system with a ventilated air gap of a residential building after a fire, Baku, next to Azadlig metro station, 2015*

This study is devoted to the study of structural and technological solutions for fire prevention in buildings with VAG in HFS. The article discusses the influence of various types of horizontal fire cut-offs (FC) used in the facades on the parameters of the airflow in the gap. The negative impact of both solid and perforated cut-offs on the speed of air movement in the gap is evaluated and proved, as a result of which the heat and humidity characteristics of the facade deteriorate during normal operation and the expediency of using cut-offs as a fire protection measure is called into question [5]. Alternative design solutions are considered and proposed, in which the cut-off in the normal operation mode of the facade does not interfere with the movement of air in the gap, and in emergency situations blocks the movement of air in the gap, which helps to stop the fire.

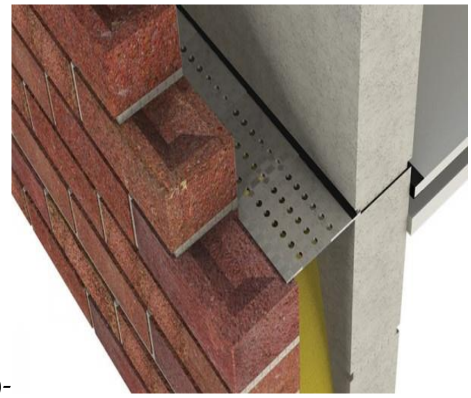
II. Methods

Many researchers studied HFSs with VAG in terms of their fire safety [6]. Gagarin V.G. in their research works studied the thermos-physical properties and problems of HFSs from the point of view of the flow of aerodynamic processes in a ventilated gap in the event of a fire [7], studied the speed of air movement in the gap. The method for calculating wind loads on the facade of a building in emergency situations was given in [8,9]. Sparrow E.M. studied the phenomena of heat transfer, natural convection, and mass transfer in a gap, and conducted experiments to study the gap as a vertical air duct [10]. Gagarin et.al. substantiated the need to use fire cut-offs to comply with fire safety requirements, as well as to prevent the spread of combustion products in the event of fire [7]. Jensen G. in his work considered various European and American standards for testing HFSs for exposure to fire [11]. He also compared perforated and solid cut-offs based on the European test standard E2912-13. Pakhomov A.A. considered how the perforation degree of cut-off affects the thermo-gravitational flow during a fire and analyzed various variations of the facade design itself [12]. The full-scale tests of facades with realistic imitation of fire attacks and evaluated the fire resistance of cut-offs are shown in the article of [13].

Despite a significant number of studies on this topic, there is still no research containing an objective assessment of the effect of fire cut-offs on the air movement in the HFSs with VAG and the corresponding engineering assessment [14]. There is also great potential for the development of structural and engineering proposals to improve the design of fire cut-offs in order to minimize their negative impact on the airflow parameters during normal operation and reliable operation in the case of a fire.

III. Design features of the HFSs

The fire safety of HFSs is largely determined both by the properties of materials of construction structures, their combustibility, and the fire resistance and by the corresponding engineering and design solutions in accordance with the requirements of construction codes [15]. Engineering and design solutions include the installation of fire-prevention vertical and horizontal cut-offs, fire arresters, installation of fire-prevention windows and door protective boxes, etc. Design of HFSs (Figure 2a). includes a layer of thermal insulation with a hydro-windproof membrane and facing material, which are attached to the main masonry of the enclosing wall using special substructure elements: brackets and guides (Fig.2a). There is an air gap between the cladding panel and the thermal insulation [16]. In order to ensure the fire safety of the facade, horizontal fire cut-offs are attached in the gap (Fig.2b, 7).

a)-

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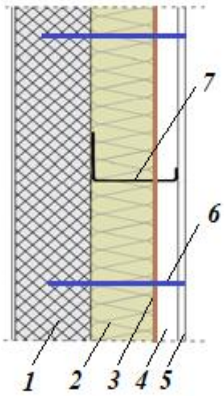

Fig. 2: *a - General view of the HFS with a fire cut-off:*
b - scheme of the vertical cross-section of the HFS structure with a cut-off:
1 - main masonry, 2- heat-insulating layer, 3- hydro-windproof membrane, 4- air gap, 5- cladding panel, 6- fastening bracket, 7- fire cut-off

The cut-off is a metal plate made of thin sheet steel with a thickness of at least 0.6 mm and a length of at least 6 m. The cut-off is set with a given specific step along the building height and it divides the wall into zones. According to the current fire safety requirements for buildings, the distance between the cut-offs should not exceed 6 meters. The cut-offs are mounted directly to the wall around the entire perimeter of the building. In the event of a fire, cut-offs on the façade prevent the spread of flames inside the gap and the ingress of burning drops of molten thermal insulation into the lower zones. Cut-offs may be perforated or without perforation- solid. The perforation of the cut-offs should provide the necessary air circulation inside the gap and meet the requirements for the heat and humidity state of the HFS. When designing and applying a fire cut-off, it is necessary to take into account the fact that the cut-off cannot completely block the movement of air in the gap, therefore, it is necessary to leave a gap between the facing material and the cut-off, or the cut-off must be perforated. But even taking into account perforation, the cutoff significantly affects the parameters of air exchange in the gap, and therefore its presence must be taken into account when calculating the fire protection of the HFSs.

IV. Estimation of effect of cut-off on airflow velocity in a ventilated gap

The object of field research is the HSF of the educational building of the Azerbaijan University of Architecture and Construction (Figure 3) located in the most weathered part of Baku, i.e. the building is operated in conditions of significant and prolonged wind effects. The average annual wind speed is 11-16 m/s in the building`s location. The building facade has 55 m high, is lined with smooth composite panels measuring 1800x700mm, there is also a steel frame substructure for fixing the facing panels and a ventilated gap with a wide of approximately 120mm. The facing panels has entry and exit slots with almost equal sizes at the base and top of the facade for ventilation of the air gap, the seal between the plates is tight and hermetic. Only the northern facade of the building has perforated cut-offs in the gap at the level of the ceilings on even-numbered floors [17].

Fig. 3: *Northern facade of the educational building of the Azerbaijan University of Architecture and Construction*

As the air in the gap of the facade has a non-uniform temperature and density, here the process of thermo-gravitational convection takes place. In this case, it is suitable to use aerodynamic calculation methods for an engineering assessment of the air flow parameters in the gap. Engineering assessment of the effect of cut-offs on the HFS`s air regime is performed according to the main dependence [18] where the average speed of thermo-gravitational air movement in the vertical air gap is determined by the formula:

$$\vartheta = \varphi \cdot \sqrt{2 \cdot g \cdot L \cdot (1 - \frac{T_c}{T_h})} \tag{1}$$

g - acceleration of gravity;
L - height of the ventilated gap;
T_c - temperature of the inner surface of the facing panels;
T_h - temperature of the outer surface of the windproof membrane or heat-insulating layer;
$\varphi -$ coefficient of airflow velocity in the gap:

$$\varphi = \frac{1}{\sqrt{\xi + \lambda \cdot \frac{L}{h} + 1}} \tag{2}$$

λ- friction coefficient in the gap;
h - initial width of the gap;
ξ - coefficient of local pressure losses resulting from the use of cut-offs;

$$\xi \approx (\frac{h}{\delta})^4 \tag{3}$$

δ - width of the flow constriction (Fig.4).

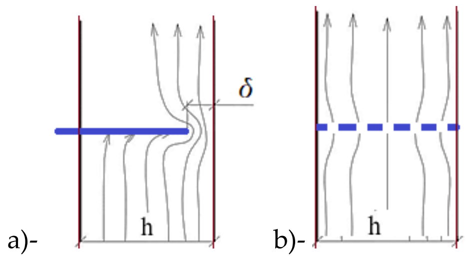

Fig. 4: *Diagram of the airflow movement in the gap with: a) - solid cut-off, b) - perforated cut-off*

Three different cases of HFS with VAG are considered:

1. there is no cut-off in the gap;
2. the cutoff is solid;
3. the cutoff is perforated.

Case 1 - there is no cut-off in the gap. According to formula (2), coefficient of the airflow velocity is:

$$\varphi_1 = \frac{1}{\sqrt{\xi+\lambda\frac{L}{h}+1}} = \frac{1}{\sqrt{1+0.035\frac{55}{0.12}+1}} = 0.24 \quad (4)$$

h – width of the gap, h = 0.12 м;
L – height of the gap, L = 55 м;
λ – friction coefficient in the gap, λ = 0.035.
When there is no the cut-off in the gap coefficient of local pressure losses is:

$$\xi \approx \left(\frac{h}{\delta}\right)^4 = \left(\frac{120}{120}\right)^4 = 1 \quad (5)$$

Case 2 - the cutoff is solid and does not reach the edge of the vertical cladding panel by 24 mm (Figure 4a). Then the coefficient of local pressure losses is (Fig.4a):

$$\xi \approx \left(\frac{h}{\delta}\right)^4 = \left(\frac{120}{24}\right)^4 = 625 \quad (6)$$

δ- width of the flow constriction, δ = 24 mm.
For this case, according to formula (2), the coefficient of airflow velocity in the gap is:

$$\varphi_2 = \frac{1}{\sqrt{625+0.035\frac{55}{0.12}+1}} = 0.04 \quad (7)$$

$$\frac{\varphi_1}{\varphi_2} = 7 \quad (8)$$

When there is a solid cut-off, the coefficient of airflow velocity is decreased by seven times.
Case 3 - there is perforated cut-off in the gap (Fig.4b), δ - flow constriction width, δ = 30 mm.
Coefficient of local pressure losses is:

$$\xi \approx \left(\frac{120}{30}\right)^4 = 256 \quad (9)$$

$$\varphi_3 = \frac{1}{\sqrt{256+0.035\frac{55}{0.12}+1}} = 0.06 \quad (10)$$

$$\frac{\varphi_1}{\varphi_3} = 4 \quad (11)$$

In this case, the coefficient of airflow velocity is decreased by four times

V. Results

The above engineering calculation shows that setting any cut-off sharply reduces the airflow velocity in the gap:

- without any cut-off, the coefficient of airflow velocity is 0.24;
- with a solid cut-off, coefficient of airflow velocity is decreased by 7 times;
- with a perforated cut-off, coefficient of airflow velocity is decreased by 4 times.

All values are shown in Table 1.

As a result of the engineering calculation, it was found that when using even a perforated cut-off with a significant percentage of perforation, the role of the air gap is reduced to zero, because the facade stops working as ventilated. When using a continuous cut-off, even with a relatively small width of the flow constriction δ = 30-50 mm, the air flow velocity drops to almost zero, air movement in the gap occurs. On the one hand, this means that the cut-off really works as a means of preventing the spread of flame along the facade during a fire, but, on the other hand, it interferes with the normal air convection inside the facade during operation. it can be concluded that the necessary solution to the problem is the use of such a cut-off design that would work only during an emergency- a fire, and the rest of the time would not interfere with the required air exchange of the gap.

VI. Discussion

Protecting the HFS from the fire spread in the gap is a complex problem since today in Azerbaijan there are no strictly standardized structural and engineering measures to prevent and minimize the impact of fires, and there are no test standards for selecting appropriate fire protection measures for building facade systems. Protection is achieved through the installation of fire cut-offs that limit the fire spread through the ventilated air gap by reducing the free cross-section or completely blocking the gap. In the world practice of ensuring the fire safety of buildings with HFS, only stationary cut-offs are used. However, as the practice of their use shows, cut-offs interfere with the operation of the facade under normal operating conditions. Ways to improve the cut-off`s design involve the free flow of air under operating conditions and the prevention of air movement due to cut-off during an emergency- a fire. The designs of these types of cut-offs are shown in Fig.5.

According to the cut-off design in Figure 5a, during a fire the polyamide plastic thread 6 burns out, and the spring 4 pushes the cut-off 90°, bringing it to a horizontal position and stopping the movement of the airflow, i.e. the access of the fire to other zones is blocked, which leads to its non-distribution and subsequent termination.

Figure 5b,c show a schematic representation of the modernized cut-off made of intumescent material that expands at high temperatures and closes the cross-section of the ventilated gap, providing fire resistance up to 120 minutes [19]: 1- before expanding, 2- after expanding, 3- steel mesh with an intumescent fire barrier.

As can be seen from the scheme, the new cut-off design works only during an emergency- in case of fire. In the normal operation time, the cut-off is in a vertical position and creates only negligible losses in the airflow velocity at local resistances and does not interfere with the movement of air in the gap. This improved design differs from the analogs by the vertical location of the cut-off [20, 21].

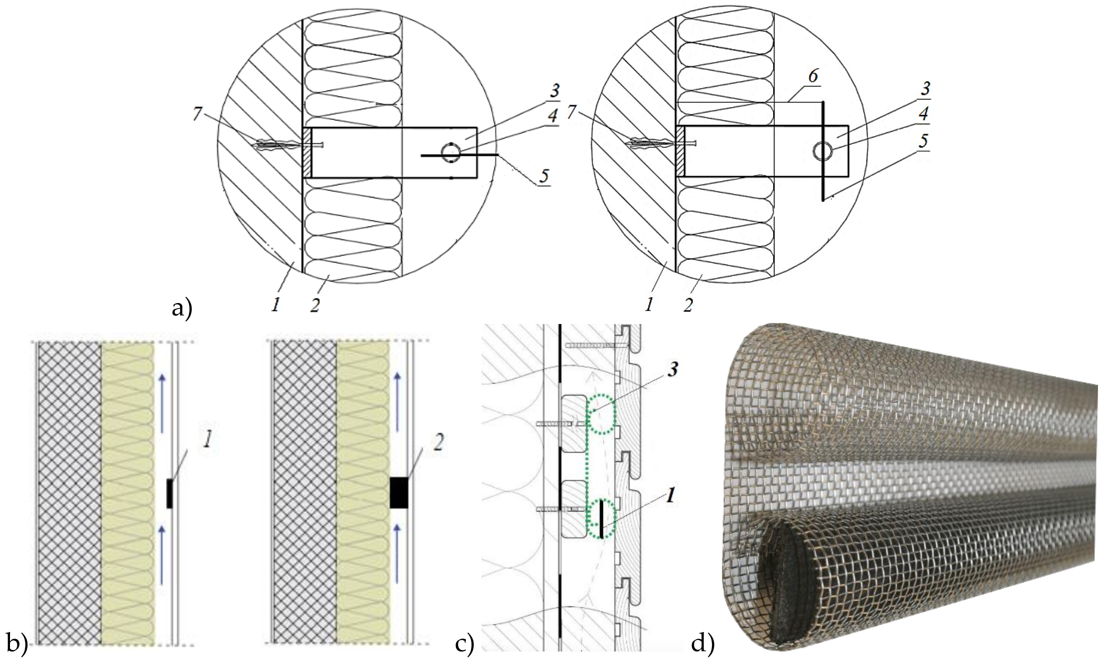

Fig. 5: *Schemes of HFS with an improved fire cut-offs:*
a- with polyamide thread:
1-wall; 2- insulation; 3 - fastening, 4 - torsion spring, 5 - fire cut-off,
6- polyamide plastic thread, 7- dowel-anchor
b,c - with intumescent material:
1- intumescent strip before expanding, 2- intumescent strip after expanding, 3-steel mesh
d- photo of steel mesh with intumescent strip

The coefficient of the airflow velocity in the gap for improved designs of cut-offs is shown in Table 1.

Table 1: *Dependence of the coefficient of airflow velocity φ on the design solution of the ventilated facade*

Constructive decisions of the HFS	coefficient of airflow velocity φ
Without cut-off	0.24
Without perforation a continuous cut-off	0.04
With a perforated cut-off	0.06
With modernized cut-off in normal operation regime	0.24
With modernized cut-off in case of fire	0

VII. Conclusions

The facade is one of the most important elements of a building in terms of its fire safety, especially when, in the event of a fire, its inadequate fire protection leads to the spread of fire, serious damage to the building, and loss of life. Examples of fires in residential buildings with hinged facade systems in Baku demonstrated how vulnerable modern facades could be to fires, which directly affected people's safety.

The article considers the influence of the horizontal fire cut-off on the parameters of the airflow in the HFS with a ventilated air gap. An engineering assessment of the applied types of cut-offs is given. Since the movement of air in the gap occurs in the thermo-gravitational mode, to analyze the features of the movement of the airflow, the coefficient of airflow velocity is used, which has different values for different types of cut-offs. Quantification of the airflow movement in the gap shows the negative impact of fire cut-offs on the required air exchange in the gap and a decrease in the coefficient of airflow velocity by four times (equation 11) and seven times (equation 8), depending on the cut-off configuration. The requirement for natural ventilation of the facade and the requirement for its fire protection contradict each other. Improved designs of cut-offs are considered, which act as intended only during the onset of a fire, and during normal operation do not interfere with the necessary air exchange of the structure. The introduction of an improved design cut-off is a solution to the problem of ensuring air exchange of the gap and shutting off the air supply to the place of ignition in case of fire, as evidenced by the coefficients of airflow velocity, which are given in Table. 1. Assessments of the coefficient of airflow velocity in the gap of the HFS and analysis of the studied works allow us to substantiate the need for a new design solution in relation to fire safety in the structures of the HFS with VAG.

The practice has shown that the only reliable way to prove the effectiveness of cut-offs in preventing the fire spread in such complicated systems is to conduct extensive tests of facades [22]. Unfortunately, it is not recognized by current local legislation. The results of the engineering assessment can be used to further improve the regulatory framework for the design, installation, and long-term operation of HFS with VAG, for computational-experimental control during an energy audit of a building.

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