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# Temperature in linear elements of enclosing structures

# Температура в линейных элементах ограждающих конструкций

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**Ключевые слова:** оконный блок; откос; теплотехническая неоднородность; температурное поле; вогнутый угол; энергоэффективность; здания и сооружения

**Abstract.** Window slopes are one of the most important linear elements of external wall structures with two-dimensional and even three-dimensional temperature field. Thereby, they cause additional risk of non-compliance of sanitary and hygienic requirements. In the proposed work one of the typical designs of window slopes is considered as the object of study, namely the fastening of the window unit with steel fixings to one of the two major layers of the wall – insulation or constructive. Peculiarities of designing two-dimensional stationary temperature field in the structure of the site abutting window units to the aperture of residential and public buildings are considered. Results of calculation of temperature in hazardous adjunction points for the design winter conditions with the help of software that implements the finite element method are presented. The analysis of the obtained data is given and the comparison of the behavior of minimum temperatures in the zone of adjacency of the fill of the lighting aperture with the results of analytical calculation based on the conform transformation for the concave corner is proposed if you move the window block in the cross section of the outer wall. It was discovered that the closer the fill to the outer plane of the facade a minimum of the temperature decreases according to the law which coincides enough closely with the analytical solution. Recommendations on the optimal placement of fill within the structural layer of the wall for the best sanitary-hygienic requirements for outdoor enclosures are confirmed. The presentation is illustrated with examples of temperature fields for the node of adjunction in a residential building on one of the modern projects.

**Аннотация.** Оконные откосы являются одним из важнейших линейных элементов конструкций наружных стен с двумерным и даже трехмерным температурным полем. Поэтому они вызывают дополнительную опасность невыполнения санитарно-гигиенических требований. В предлагаемой работе исследуется одна из типовых конструкций оконных откосов с креплением оконного блока с помощью стальных закладных деталей к одному из двух основных слоев стены – теплоизоляционному или конструктивному. Рассмотрены особенности расчета стационарного двумерного температурного поля в конструкциях узла примыкания оконных блоков к светопроемам гражданских зданий. Приведены результаты вычисления температуры в опасных точках примыкания для расчетных зимних условий с помощью программы для ЭВМ, реализующей метод конечных элементов. Дан анализ полученных данных и проведено сопоставление характера поведения минимальной температуры в зоне примыкания заполнения светопроема при перемещении оконного блока по сечению наружной стены с результатами аналитического расчета на основе конформного преобразования для вогнутого угла. Обнаружено, что по мере приближения заполнения к наружной плоскости фасада минимальная температура понижается по закону, достаточно близко совпадающему с аналитическим решением. Подтверждены рекомендации по оптимальному размещению заполнения в пределах конструктивного слоя стены для наилучшего обеспечения санитарно-гигиенических требований к наружным ограждениям. Изложение проиллюстрировано примерами температурных полей для узла примыкания в жилом здании по одному из современных проектов.

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# Introduction

Window slopes are one of the most important linear elements of external wall structures with two-dimensional and even three-dimensional temperature field. Thereby, they make a significant contribution to the overall thermal non-uniformity of walls and cause additional risk of non-compliance of sanitary and hygienic requirements. These requirements relate mainly to the absence of water vapor condensation in the dangerous points of inner surface of enclosures, in order to prevent the development of harmful microorganisms and the destruction of structures themselves; in some cases, mainly for translucent elements – to ensuring of positive temperatures in order to prevent condensate freezing. In the proposed work one of the typical designs of window slopes currently used in residential and public buildings is considered as the object of study, namely the fastening of the window unit with steel fixings to one of the two major layers of the wall – insulation or constructive. As embedded parts are used parts from rolled steel, fixed by anchors to the constructive layer of reinforced concrete, and place of the interface of the window block to the slopes is treated with a sealant and filled with foam. For clarity, the scheme of this solution is shown in figure 1. The more detailed design of this construction is presented in figure 1a. Because of the commonality of the design the obtained results can be applicable for a very wide range of buildings for various purposes.

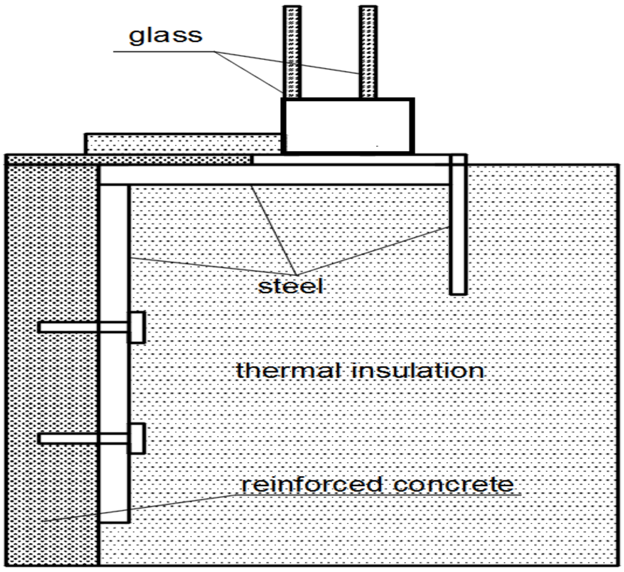


**Figure 1. The scheme of the design of the contiguity of the window unit to the building opening (simplified diagram for calculation)**

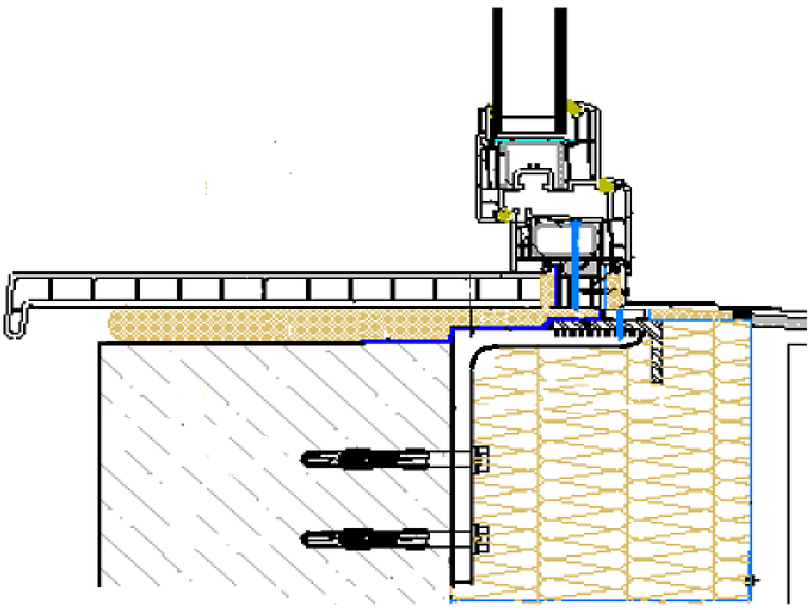

**Figure 1a. The detailed scheme for the construction shown in Figure 1**

Compliance with sanitary and hygienic requirements to thermal protection of the exterior wall envelopes is currently regarded as a mandatory component of the overall system of measures to reduce energy consumption in residential and public buildings, along with ensuring of comfort and safety of their users [1–3]. Herewith, it is necessary to note that reducing energy costs for heating of buildings seems by itself primarily an economic category, so, first of all, it is necessary to consider low-cost and fast-payback measures [4–8]. However, it is in the buildings with the level of external-walls thermal protection, limited by economic viability, that the risk of non-compliance with the conditions of absence of condensation or freezing in separate points is possible in the first place. To verify this fact, the calculations of temperature fields are carried out [9–10]. And, in view of complexity of the considered areas configuration, it is extremely problematic to use analytical methods here, as was done, for example, in [11–12]. So, the majority of native and foreign authors, who explore similar questions, use the numerical modeling of all others. As a rule, this applies approximation of differential equation of thermal conductivity by the method of finite differences or finite elements. And, on this way, a significant number of computer programs have been developed at the present time, which, among other things, also carry out the visualization of calculated temperature fields, as well as the calculation of their certain integral characteristics [13–19]. However, using such programs is not always an easy task for an average specialist, and for the same reason the need remains for relatively simple engineering techniques in order to estimate temperatures in hazardous areas of exterior enclosures. Thus, the relevance of obtaining analytical dependences to check for condensation or freezing continues to the present time.

Therefore, the goal of our research is the development of relatively simple engineering techniques in order to estimate temperatures in one of the most hazardous areas of exterior enclosures, namely, in the area between the window unit to a building aperture, which could be used for a preliminary assessment, especially under the conditions of the limited terms of designing. To achieve this goal it is necessary to obtain the solution of a problem of calculation of temperature fields in the specified area and creating the mathematical descriptions which is available for use in engineering practice.

## *Methods.*

If you pay attention to the geometry of the area of the window block abutting to the opening shown in the scheme at the figure 1, you may notice that a part of the window slope and the adjacent wall part, facing into the room, are sufficiently similar in form to the element, which is called “concave angle”. As it is known, such distribution of temperature is described by the differential equation of stationary heat conduction (Laplace equation):

$$\frac{\partial^2 t}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}=0 \qquad (1)$$

where $t$ – temperature, $^{O}$C, in the cross section of the structure at the point with coordinates $x$ and $y$, m.

The solution of (1) for such area can be quite easily obtained by conformal transformations method. Herewith, the angle π/2 remains, which can be obtained from the upper half-plane, i.e., the straight angle equal to π, by the transformation $z' = z^2$, where 2 = π/(π/2). In this case, the projecting angle vertex, i.e. the joint of the wall and the slope from the room side, is accepted as the origin of coordinates.

Now, if we assume, as is usually done, that the temperature is the imaginary part of the obtained solution, we find:

$$\theta=\mathrm{Im}\left(Cz^2\right)=\mathrm{Im}\left(C[x+iy]^2\right)=2Cxy, \qquad (2)$$

where $C$ is a certain constant. In other words, the isotherms are a set of hyperbolas with asymptotes coinciding with the coordinate axes. For generality, the solution is written down with respect to the dimensionless temperature $\theta = (t - t_{ext})/(t_{in} - t_{ex})$, where $t_{in}$ and $t_{ex}$ are correspondingly the calculated temperatures of inner and outer air, °C. Strictly speaking, the expression (2) holds for the boundary conditions of the 1st kind, when the temperature on the surface is set, but, without much error, this can be taken into account by introducing an additional conditional layer with thickness $\delta_o = \lambda_{in}/\alpha_{in}$, m, where $\alpha_{in}$ is the coefficient of total heat exchange on the surface facing into the room, W/(m$^2$•K); $\lambda_{in}$ is the thermal conductivity of material of this surface, W/(m•K).

Figures 2 and 2a shows the temperature field in the area of abutting of the light-opening filling to the window slope, which is obtained by numerical calculation according to one of the standard computer programs (FEMLAB – multipurposal and multifunctional product of Comsol), using an approximation of the Laplace equation by the finite element method which was accepted also in the international engineering guidelines [20], [21]. These figures present the distribution of the temperature like one of the most used sources of such solutions [22]. In the simplest case of identical elements the corresponding differential ratio, allowing to calculate the temperature $t_{i,j}$ in a regular grid, as it is known, can be written as follows:

$$t_{\mathrm{i,j}} = \left(t_{\mathrm{i-1,j}} + t_{\mathrm{i+1,j}} + t_{\mathrm{i,j-1}} + t_{\mathrm{i,j+1}}\right)/4\ ; \tag{3}$$

i.e. the temperature at the node is obtained as the arithmetic average between its value in the neighboring nodes. In this case on the surfaces of glazing and of the wall the boundary conditions of the 3rd type are used. They can be written as follows:

$$-\lambda_{in}\left(\frac{\partial t}{\partial n}\right)_{in} = \alpha_{in}\left(t_{in} - \tau_{in}\right). \tag{4}$$

Here, $n$ is the distance along the internal normal to the surface angle, m; $\tau_{in}$ is the temperature of the surface in the considered point, °C; the rest of the notation is given above. The value of $\alpha_{in}$ is equal to 8.7 W/(m$^2$•K) for the wall surface and to 8 W/(m$^2$•K) for the glazing.

It is easy to see that the distribution of temperatures from the room side indeed sufficiently closely resembles the one obtained by the equation (2).

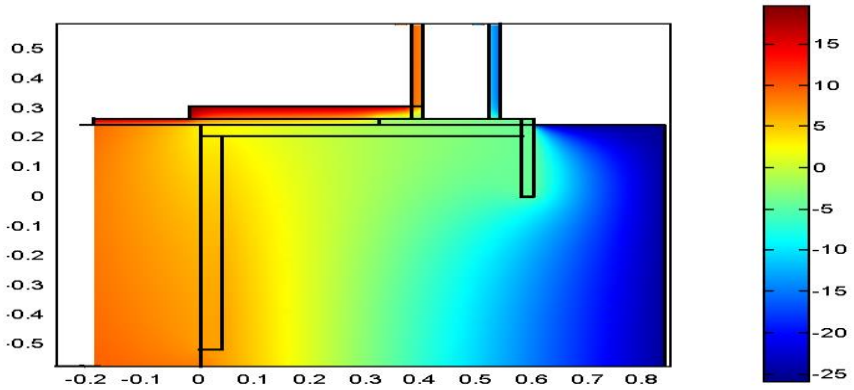


**Figure 2. Temperature field of the side section of the window slope**

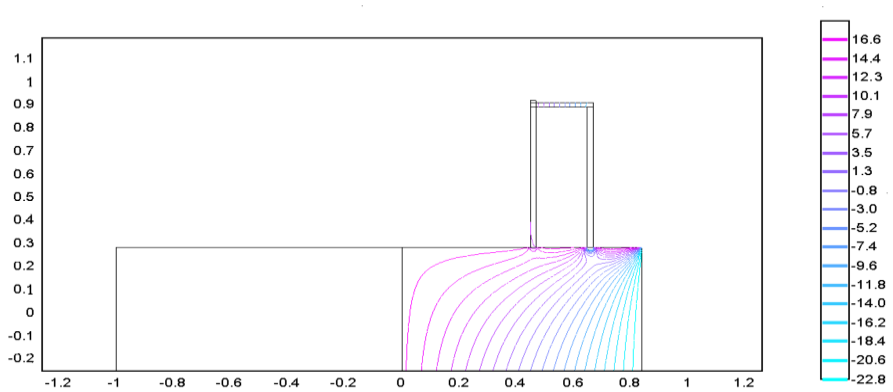


**Figure 2a. Isotherms of the side section of the window slope (simplified view)**

Here, the constructional layer of reinforced concrete with thermal conductivity $\lambda_{cl}$ = 2.04 W/(m•K) and thickness $\delta_{cl}$ = 0.2 m is located on the left, from the room side; and the thermal insulation one, with $\lambda_{ti}$ = 0.035 W/(m•K) and $\delta_{ti}$ = 0.16 m, on the right. Herewith, 0.2 m of width or thickness of the structure corresponds to one unit of the coordinate grid. Let's note that the constructional layer presence has almost no effect on the distribution of isotherms. As a matter of fact, its thermal resistance away from the thermal non-uniformities equals to $\delta_{cl}/\lambda_{cl}$ = 0.2/2.04 = 0.1 m$^2$•K/W, which is only two percent of the total conditional heat transmission resistance of the wall, which can be estimated by the value

$R_{o.cond}$ = 4.85 m$^2$•K/W. Therefore, this layer can be added to the conventional layer associated with heat exchange on the inner surface. Then $\delta_o = \lambda_{ti} = (1/\alpha_{in} + \delta_{cl}/\lambda_{cl})$.

## Results and Discussion

In paper [23] and some other sources, it is indicated that the zone of thermal non-uniformity influence extends to a distance from it, roughly equal to two calibers, with the caliber value which can be taken as the thermal insulation layer thickness. Then we can assume that, with $x = \delta_o$ and $y = 2\delta_{ti}$, or, conversely, with $y = \delta_o$ and $x = 2\delta_{ti}$, the dimensionless temperature $\theta_{slope}$ in the expression (1) coincides with the temperature on the inner wall surface away from the slope $\theta_{in}$, which, obviously, is equal to $1 - R_{in}/R_{o.cond}$. Here, $R_{in} = 1/\alpha_{in}$ is heat exchange resistance on the inner surface, m$^2$•K/W (Figure 3).

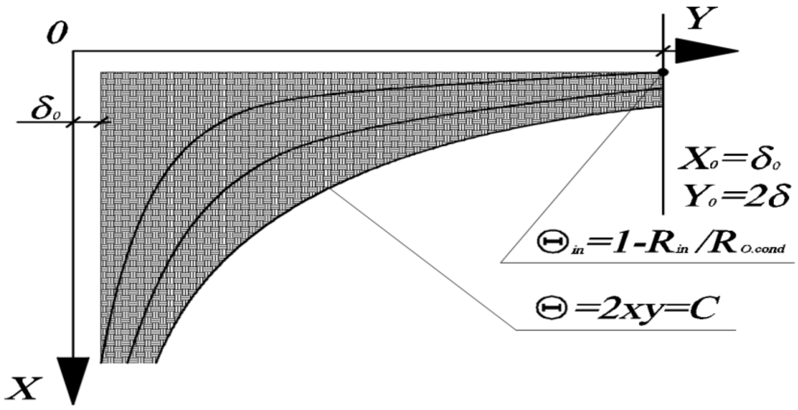


**Figure 3. Theoretical distribution of the temperature field at the outer surface of the angle**

Consequently, on one side there is $2xy = 4\delta_o\delta_{ti}$, from which $y = 2\delta_o\delta_{ti}/x$, and, simultaneously, for arbitrary $y$ in case of single-layer structure, the current thermal resistance from the inner surface, taking into account the additional layer, is equal $R_y = y/\lambda_{ti}$. Then we get:

$$\theta = 1 - \frac{y/\lambda_{ti}}{\delta_{ti}/\lambda_{ti}} = 1 - \frac{y}{\delta_{ti}} = 1 - \frac{2\delta_o\delta_{ti}/x}{\delta_{ti}} = 1 - \frac{2\delta_o}{x} \quad (5)$$

Thus, it appears that as the window block abutting moves away from the origin of coordinates, for which the vertex of the angle of the thermal insulation layer is taken, i.e., with the approach of the filling to the outer plane of the facade, the relative temperature value should increase gradually.

Figure 4 shows a comparison of $\tau_{slope}$ values obtained by direct calculation using a computer program (solid line), and by calculation according to the expression (5) – dotted line.

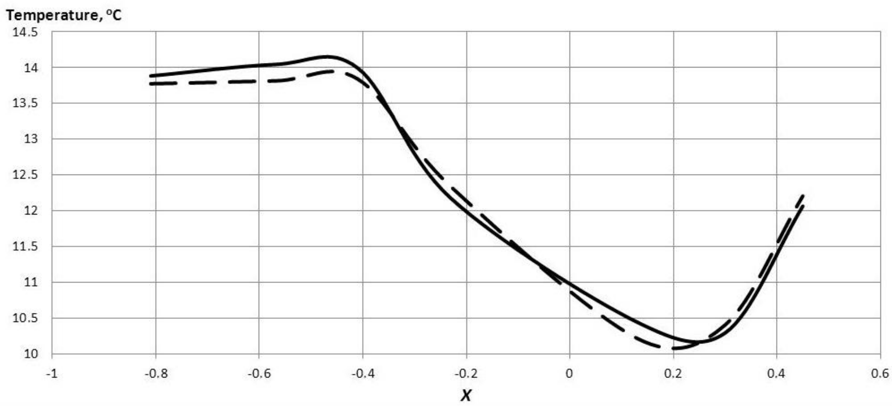


**Figure 4. Values of the minimum temperature $\tau_{slope}$ by changing the window block position**

In the transition to the dimensional values, it was thought that $t_{in}$ = +20°C, $t_{ex}$ = -25°, as is the case with Figure 2 plotting. It can be noted that both curves have quite good qualitative and quantitative matching, which was further improved by a certain modification (5). Basically it resolved itself to the fact that, while calculating $\delta_o$, the conditional equivalent thermal conductivity of the wall was used, reduced to a single-layer embodiment: $\lambda_{cond} = \frac{\delta_{ti} + \delta_{cl}}{\delta_{ti}/\lambda_{ti} + \delta_{cl}/\lambda_{cl}}$ and, moreover, the value *x* was substituted with some shift: 0.13 m within the constructional layer, and 0.05 m – in the thermal insulation one. It is easy to see that the theoretical expression (5) subject to the adopted amendments is confirmed very well. Moreover, the minimum temperature in figure 4 coincides well with the theoretical temperature at the edge of the corner [11], if the value of $R_{in}$ to be set taking into account the thermal resistance of the structural layer $1/\alpha_{in} + \delta_{cl}/\lambda_{cl}$:

$$\theta_{cor} = 1 - \frac{R_{in}}{R_{o.cond}} + \frac{1}{2}\left(\frac{R_{in}}{R_{o.cond}}\right)^2 - \sqrt{\frac{R_{in}}{2R_{o.cond}}} + \left(\frac{1}{\sqrt{2}} - \frac{1}{2}\right)\left(\frac{R_{in}}{R_{o.cond}}\right)^{3/2}, \quad (6)$$

where for higher adopted $R_{o.cond}$ we get $\theta_{cor}$ = 0.19, and therefore $\tau_{cor}$ = 20 – 0.19·(20 + 25) = 11.45 °C. We should also pay attention to the fact that the resistance to heat transfer on the inner surface of the glazing, of course, is different from the resistance on the inner surface of the wall $R_{in}$, but in this case it is not critical, since in the theoretical formula (5), which compares the data of numerical calculation, this resistance does not appear anywhere.

The result is also consistent with the concept of the distribution of the temperature field in the area of contiguity of translucent structures to building openings, considered in [13–15], although their authors don't present the specific analytical dependences similar to (5), and with recommendations for the implementation of energy saving measures presented in [3], [6], [8], [19]. Thus, the proposed solution is qualitatively confirmed by other sources and is therefore sufficiently reliable.

## *Conclusions*

1. It is shown that the presentation (5) basically corresponds to the actual distribution of the temperature field in the zone of the window slope abutting to the light-opening filling, and therefore, the results obtained by numerical calculation, are also valid.
2. It is discovered that the minimum value τslope is obtained by placing the window unit within the insulating layer near its boundary with the constructional one.
3. It is noted that the preferred installation of the window block is from the room side within the constructional layer, as the one which mostly meets sanitary and hygienic safety requirements. Otherwise there might be condensation of water vapor in the zone of contiguity since the calculated value τslope may be below the dew point of the interior air.
4. It is noted that the expression (5) is the main form of the theoretical description of the temperature distribution in the area of the window reveal and can be considered as the most significant result of the study.
5. It is proposed to apply the relations of the type (5) in some cases and for analytical assessment of minimum temperature, which will allow using not only program-based, but also engineering methods of verification of compliance with sanitary and hygiene norms.
6. It is found that the greatest accuracy of the engineering method is achieved by calculating the thickness of the additional conditional layer δo using conditional equivalent thermal conductivity of the wall λcond. In this case, the maximum error does not exceed 0.5 °C.

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