

Estimation of indoor temperatures on condition that building envelope is damaged

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Viktor Petrenko[1], Kostiantyn Dikarev[2], Al'ona Skokova[3], Oleksandra Kuzmenko[4]

[1]Prydniprovska State Academy of Civil Engineering and Architecture
Dnipropetrovsk, Ukraine, 24-A Chernishevskogo str., tel. +38 (0562) 47-59-77
E-mail: petrenko@mail.pgasa.dp.ua
ORCID ID: 0000-0002-4331-6844

[2]Prydniprovska State Academy of Civil Engineering and Architecture
Dnipropetrovsk, Ukraine, 24-A Chernishevskogo str., tel. +38 (0562) 46-98-76
E-mail: kdikarev@ukr.net,
ORCID ID: 0000-0001-9107-3667

[3]Prydniprovska State Academy of Civil Engineering and Architecture
Dnipropetrovsk, Ukraine, 24-A Chernishevskogo str., tel. +38 (0562) 46-98-76
E-mail: a_skokova@mail.ru,
ORCID ID: 0000-0002-0443-0222

[4]Prydniprovska State Academy of Civil Engineering and Architecture
Dnipropetrovsk, Ukraine, 24-A Chernishevskogo str., tel. +38 (0562) 46-98-76
E-mail: aleksandra_kuzmenko@i.ua,
ORCID ID: 0000-0001-5976-5436

Abstract. *The purpose of this paper is to represent inside temperature calculation algorithm provided that building envelope is damaged. Brick wall with erosion area was chosen as the building envelope. We examine one-dimensional thermal transfer in steady-state conditions. The temperatures at both sides of the wall are constant. The derived equation allows calculating the estimated inner temperature of the air on condition that outside wall is damaged by erosion.*

Keywords: inner surface temperature, microclimate, thermal transfer, steady state condition

1. Introduction

The problem relates to the determination of microclimate parameteres in case of wall properties modification and provided that the building envelope is affected by erosion. This topic focuses on items of architectural heritage, widely represented in

Dnipropetrovsk, which require more thorough reconstruction without modifying facade external layers.

Previous researches consider thermal transfer (steady state or non-steady state condition) through a plane wall which has one surface at a high temperature and another one at a lower temperature [1, 2, 3, 5, 6, 7, 8, 11, 12]. However there are no investigations devoted to the estimation of indoor air temperature on the assumption of wall erosion impact.

Thereby purpose mentioned above leads to the following tasks:

– to specify the initial data of the problem concerned;

– to derive a mathematical expression for inner air temperature determination provided that the external wall is damaged by a certain area of erosion.;

– to calculate and analyze the results of estimation for particular case.

2. Case study and general assumptions

Taking into consideration [9, 10], it seems reasonable to postulate that:

– we examine plane wall containing several construction layers with different thicknesses $\delta_{1,2...n}$, mm, this solid is infinite in y and z direction ($\frac{\partial t}{\partial y} = \frac{\partial t}{\partial z} = 0$ - the temperature is depending on one variable only in case of one-dimensional heat conduction);

– material properties are constant ($\lambda_{1,2...n} = const$, $\rho_{1,2...n} = const$, $c_{1,2...n} = const$);

– the outside surface of the wall is exposed to ambient air with temperature t_{ext}, ^{o}C for the cold season while inside surface has heating air next to it with defined interior temperature t_{int}, ^{o}C according to the building standard [7]

– there are no time dependence of the temperatures for one-dimensional steady state heat transfer ($\frac{\partial t}{\partial \tau} = 0$);

– coefficient of heat-transfer from warm indoor air to the wall denoted by α_{int}, $\frac{W}{m^2 \cdot K}$, from wall to cool outside ambience - α_{ext}, $\frac{W}{m^2 \cdot K}$, (those values have no time dependence as well);

– the heat transfer between plane wall and the outdoor air space can be expressed as equation $q = \alpha \cdot \Delta t$.

According to [4], heat flux density $\frac{W}{m^2}$ through multi-layer plane wall can be defined as:

$$q = \frac{t_{\text{int}} - t_{ext}}{\frac{1}{\alpha_{\text{int}}} + \sum \frac{\delta}{\lambda} + \frac{1}{\alpha_{ext}}} \qquad (1)$$

$\frac{1}{\alpha_{int}}$ - thermal resistance on the inner surface of the wall, $\frac{m^2 \cdot K}{W}$;

$\frac{1}{\alpha_{ext}}$ - thermal resistance on the exterior surface of the wall, $\frac{m^2 \cdot K}{W}$;

$\sum \frac{\delta}{\lambda}$ - total thermal transfer for multi-layer wall, $\frac{m^2 \cdot K}{W}$.

We can derive expression (2) from (1) :

$$k = \frac{1}{\frac{1}{\alpha_{\text{int}}} + \sum \frac{\delta}{\lambda} + \frac{1}{\alpha_{ext}}} \qquad (2)$$

k - coefficient of heat transmission, which characterizes the intensity of thermal transfer through the wall from one air ambiance to another. It can be calculated as the quantity of heat transmitted through unit area and per unit time provided that the temperature difference between interior and exterior airspaces is 1 degree, $\frac{W}{m^2 \cdot K}$.

The reciprocal value of this parameter k, $\frac{W}{m^2 \cdot K}$, gives us a total thermal resistance R, $\frac{m^2 \cdot K}{W}$.

$$R = \frac{1}{k} = \frac{1}{\alpha_1} + \sum \frac{\delta}{\lambda} + \frac{1}{\alpha_2} \qquad (3)$$

If we take in consideration mentioned above the expression (1) can be written as:

$$q = k \cdot (t_{\text{int}} - t_{ext}),\ \frac{W}{m^2}. \qquad (4)$$

Heat flux through the wall with the surface F, m^2, can be given as:

$$Q = q \cdot F = k \cdot F \cdot (t_{int} - t_{ext}) \qquad (5)$$

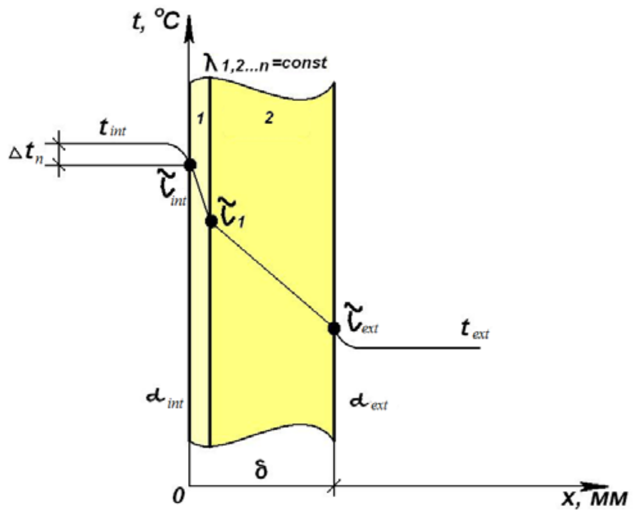


Fig. 1 Heat transfer through the plane multi-layer wall

3. Derivation of a formula

According to mentioned above we can postulate that the plane multi-layer wall contains damaged area caused by erosion. The thickness of this area is ranging from 0 to $\sum \delta_{wall}$ (Fig. 2).

a) b)

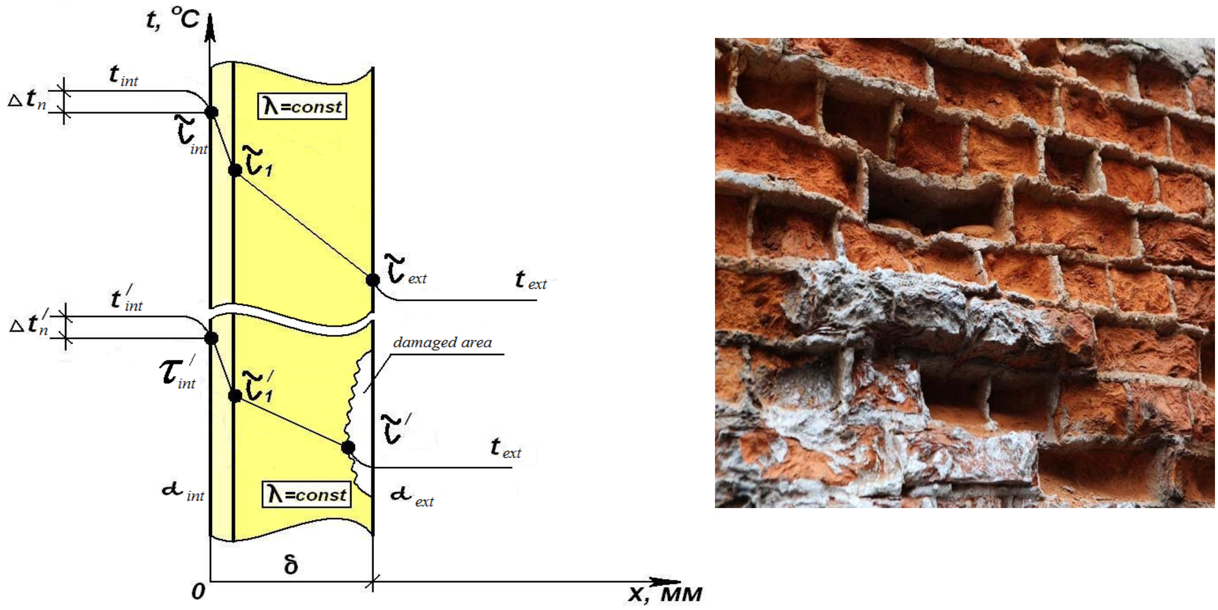


Fig. 2 a) Heat transfer through the plane multi-layer wall containing damaged area; b) The possible severe erosion

It is plausible to assume that the presence of damaged area on the external side of the wall results in the temperature change of the both inner and exterior surfaces (τ'_{int}, ^{o}C, τ'_{ext}, ^{o}C), the same phenomenon happens to the temperature between layers τ'_1, ^{o}C.

If we take into consideration expression (5) the heat transfer through multi-layer damaged wall F, m^2, can therefore be given as :

$$Q' = k_1 \cdot (F - F_{dam}) \cdot (t'_{\text{int}} - t_{ext}) + k_2 \cdot F_{dam} \cdot (t'_{\text{int}} - t_{ext}),\ W \qquad (6)$$

k_1 - coefficient of heat transmission for undamaged wall, $\dfrac{W}{m^2 \cdot K}$;

k_2 - coefficient of heat transmission for damaged wall, $\dfrac{W}{m^2 \cdot K}$;

F_{dam} - area of the affected surface on the wall, m^2,

After the transformation we can obtain the following formula :

$$Q' = (k_1 \cdot F + F_{dam} \cdot (k_2 - k_1)) \cdot (t'_{\text{int}} - t_{ext}),\ W \,.(7)$$

Experience leads us to believe that the heater produces the equal quantity of thermal energy whether the wall contain damaged area or not. The condition $Q = Q'$ implies that:

$$k_1 \cdot F \cdot (t_{\text{int}} - t_{ext}) = (k_1 \cdot F + F_{dam} \cdot (k_2 - k_1)) \cdot (t'_{\text{int}} - t_{ext}),\ W\,. \quad (8)$$

The estimated temperature of the interior air can be derivated from (8) :

$$t_{\text{int}}^{/} = \frac{k_1 \cdot F \cdot (t_{\text{int}} - t_{ext})}{(k_1 \cdot F + F_{dam} \cdot (k_2 - k_1))} + t_{ext}, \ {}^oC \qquad (9)$$

We can introduce the parameter which characterizes the part of damaged area in whole wall and which can be expressed as:

$$x_{dam} = \frac{F_{dam}}{F}, \quad (10)$$

The value of x_{dam} is ranging from 0 to 1.

Using the expression (10) we find

$$F_{dam} = x_{dam} \cdot F, \ m^2. \quad (11)$$

We insert (11) in expression (9) and after transformation we obtain

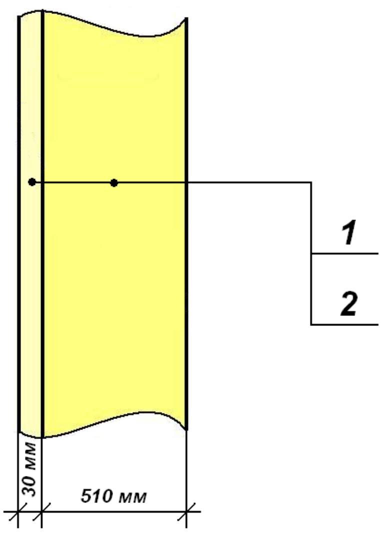
$$t_{\text{int}}^{/} = \frac{k_1 \cdot (t_{\text{int}} - t_{ext})}{k_1 + x_{dam} \cdot (k_2 - k_1)} + t_{ext}, \ {}^oC \qquad (12)$$

Or

$$t'_{int} = \frac{k_1 \cdot (t_{int} - t_{ext})}{x_{dam} \cdot k_2 + k_1 \cdot (1 - x_{dam})} + t_{ext}, {}^\circ\text{C} \qquad (13)$$

4. Analysis

The widespead in Dnipropetrovsk composition of multi-layer wall was chosen as an exemple for calculation. Figure 3 shows the cross-section of the wall.



1 – plaster, $\lambda = 0{,}81 \ \frac{W}{m \cdot K}$;

2 – masonry of silicate brick on a cement-sand mortar, $\lambda = 0{,}87 \ \frac{W}{m \cdot K}$

Fig. 3 Cross-section of the wall

Using (2) and (3) we can calculate coefficient of heat transmission for the wall and thermal resistance on condition that the thickness of damaged area can take the next values $\delta_{dam}^1 = 0 \ mm$; $\delta_{dam}^2 = 10 \ mm$; $\delta_{dam}^3 = 20 \ mm$; $\delta_{dam}^4 = 30 \ mm$. The results of calculation are shown in Table 1 and in Fig. 4.

Table 1

Caracteristics of materials

Thermal properties of the external wall	Thickness of the wall containing damaged area, *mm*			
	540 *mm*	530 *mm*	520 *mm*	510 *mm*
Thermal resistance of the wall, $\frac{m^2 \cdot K}{W}$	0,78	0,77	0,76	0,75
Coefficient of heat transmission, $\frac{W}{m^2 \cdot K}$	1,28	1,30	1,32	1,34

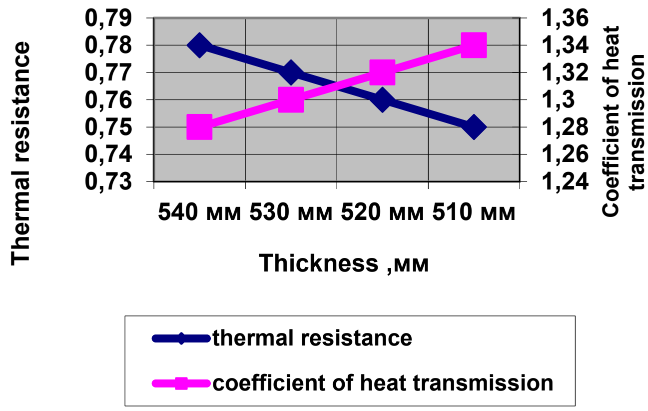


Fig. 4 Thermal properties of the external wall

Coefficient of heat transfer and thermal resistance of the wall varies linearly for $1{,}3\ \%$ per each $10\ mm$ of damaged area thickness.

Taking into consideration (11) or (12) we can calculate estimated temperature of interior airspace $t'_{\text{int}},\ {}^{o}C$, provided that external wall contains damaged by erosion area. We take into account the part of damaged area x_{dam}. The results are shown in Table 2 and in Fig. 5.

Table 2

Estimated temperatures on each layers surfaces of the damaged wall

Temperature values on the layers surfaces of the wall	Thickness of the wall enclosing erosion area, *mm*			
	540 *mm*	530 *mm*	520 *mm*	510 *mm*
Temperature on the inner surface of the wall, $\tau'_{\text{int}},\ {}^{o}C$	13,68	13,58	13,49	13,39
Temperatures between the layers of the wall, $\tau'_1,\ {}^{o}C$	11,64	11,51	11,39	11,25
Temperature on the exterior surface of the wall, $\tau'_{ext},\ {}^{o}C$	-20,61	-21,21	-21,84	-22,48

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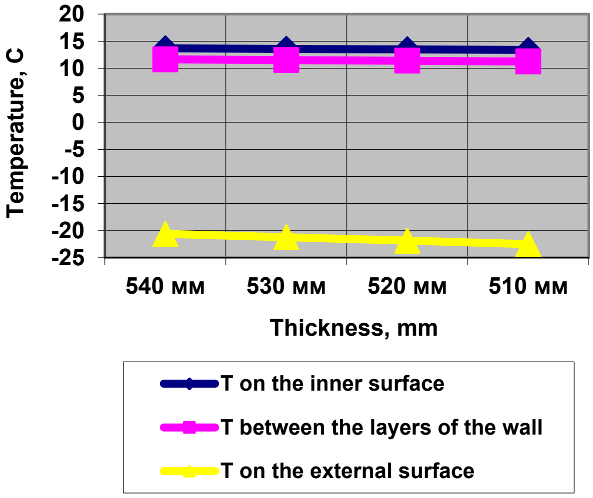

Fig. 5 Distributions of estimated temperature values on the layers surfaces of the wall

Table 3

Estimation of interior airspace temperature on condition that external wall encloses damaged by erosion area

$x_{dam} = \dfrac{F_{dam}}{F}$	Thickness of the damaged wall, mm			
	540 mm	530 mm	520 mm	510 mm
0	20,00	20,00	20,00	20,00
0,1	20,00	19,94	19,87	19,80
0,2	20,00	19,87	19,74	19,61
0,3	20,00	19,81	19,61	19,41
0,4	20,00	19,74	19,49	19,22
0,5	20,00	19,68	19,36	19,03
0,6	20,00	19,62	19,23	19,23
0,7	20,00	19,56	19,11	18,65
0,8	20,00	19,49	18,98	18,47
0,9	20,00	19,43	18,86	18,29
1	20,00	19,37	18,74	18,10

Obtained data reveals the variation of interior airspace temperature values which can change up to:

– $3\,\%$ provided the thickness reduces by $10\ mm$ and the part of damaged area varies as well;

– $6{,}3\,\%$ provided the thickness reduces by $20\ mm$ and the part of damaged area varies as well;

– $9{,}5\,\%$ provided the thickness reduces by $30\ mm$ and the part of damaged area varies as well;

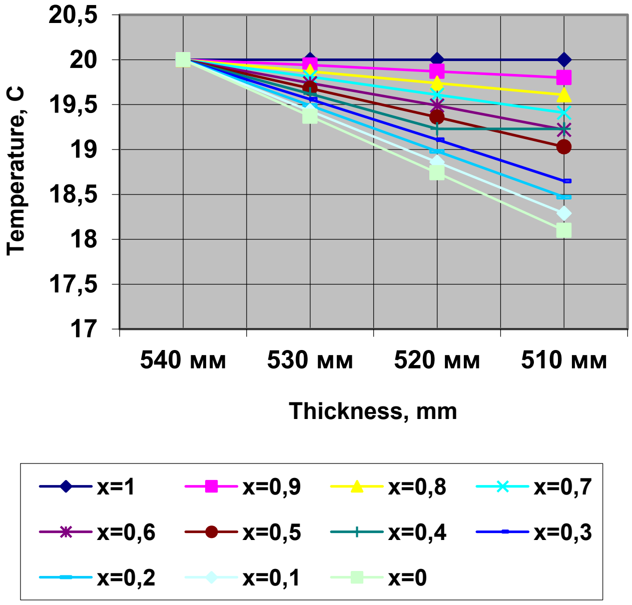

Fig. 6 Evaluation of indoor airspace temperature depending on the damaged area change

Analysis of the results leads to the next statement: damaged area has an important impact on the temperature values for the each layer of the wall.

When dealing with boundary conditions of Dnipropetrovsk we take into account the temperature of the exterior air $t_{ext} = -23\ ^{o}C$ and we observe the next variations:

– Temperature on the inner surface of the wall, $\tau^{/}_{\text{int}}$, ^{o}C changes by $1\ \%$ per each $10\ mm$ of damaged area thickness;

– Temperature between the layers of the wall $\tau^{/}_{1}$, ^{o}C changes by $1{,}2 \div 1{,}5\ \%$ per each $10\ mm$ of damaged area thickness;

– Temperature on the exterior surface of the wall, $\tau^{/}_{ext}$, ^{o}C changes by $2{,}9\ \%$ per each $10\ mm$ of damaged area thickness.

Conclusions

This paper is devoted to analytical investigation (for climite conditions of Dnipropetrovsk) of indoor airspace temperature variation provided that the external wall is affected by erosion. The obtained data reveals that the reduction of wall thickness from 0 to 30 mm due to erosion provokes the variation of thermal resistance. This phenomenon leads to decrease of temperature values at the border of each wall layer, therefore we observe the drop of indoor airspace temperature. Presented method allows to estimate indoor airspace temperature if we take into consideration all features of under study building envelope. Presented algorithm offers the possibilities to carry out numerical modeling in order to improve the method of calculation.

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