Numerical modeling of heat transfer through the air interlayer considering the surface radiation

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Abstract. Current numerical models of façade's cladding do not account for ventilated air cavity heat resistance. The major problem in assigning its properties is the complexity of the air thermal conductivity coefficient calculation inside a ventilated air cavity. National standards and building codes provide design methods for calculating thermal resistance values for non-ventilated air layers depending on their thickness and location in the structure. The procedure of ventilated air cavity thermal design is not correct when its thermal conductivity coefficient is used as for a non-ventilated interlayer. In order to overcome the lack in the adequate design method, an approach utilizing both the finite element and analytical solutions of the heat exchange equation has been proposed in the present paper. In doing so, the formula derived for calculating the equivalent value of the air thermal conductivity in a ventilated air layer takes into account the heat exchange by radiation as a design value.

1. Introduction

It is known that air in a static state is a material with high thermal insulation properties, since its coefficient of thermal conductivity is lying within the interval of $\lambda = 0.21\text{-}0.25$ W / m ºC. However, in real conditions, under which structures are operated, air in the air layers does not exist in the static state, it is subjected to the dynamic conditions, what significantly influences the heat-protecting qualities of air layers. However, in the building code, standards and Russian technical literature [1-4] the thermal resistance values for closed air layers of small thickness (up to 50-100 mm) are only given and nothing is mentioned about heat protection properties of a ventilated air gap.

The solution of problems dealing with the evaluation of the thermal protection of building envelope elements is rather difficult without carrying out calculations via various computer programs [5-6]. Different authors [7-12] performed numerous researches on mathematical modelling of heat transfer problems in building envelope made of different building materials. Closed air cavities inside bricks were investigated in [13]. However, none of those works [7-13] account for ventilated air cavity and radiation heat exchange inside them. In the process of mathematical modelling within the framework of thermal engineering of wall constructions with an air interlayer via software complexes based on finite element methods it is necessary to take as initial data the coefficients of material thermal conductivity and the coefficient of air thermal conductivity when considering the air gaps. The thermal conductivity coefficient for a non-ventilated interlayer cannot be used for ventilated air gaps because it is not correct, as it does not reflect the actual process of the heat transfer within the interlayer in the presence of the convective and radiant heat exchange. Calculations of the temperature fields carried out using the finite element software package ANSYS [23] show that in this case the temperature

values on the inner surface of the wall are too high. The temperature field of the log wall for the case when the coefficient of thermal conductivity of the ventilated air layer taken as for dead-air space is shown in Figure 1. It can be seen that in this case, the outdoor temperature is 26 ºC, and the temperature on the inner surface of the wall varies from 17.46 ºC to 17.61 º C. The comparison of this temperature distribution with the results of thermal engineering studies in full-scale conditions has shown that overestimated values were obtained in this case.
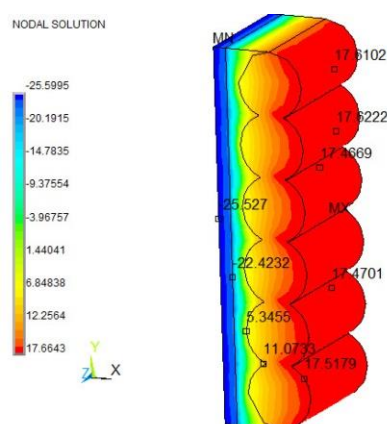

Figure 1. Temperature distribution on the outer and inner surfaces of the wooden log wall with the wooden cladding on the inner surface. The coefficient of thermal conductivity of the ventilated air layer was taken as for dead-air space.

Therefore, during the process of the engineering calculations of the temperature and heat flows, it is necessary to consider the value of the thermal conductivity coefficient, λ_{eq}, W/(m °C), as the thermal protective characteristic of the air layer. The part of heat transfer by radiation that passes through the air layer with the increase in its thickness from 60 mm to 180 mm is approximately 72-79%, while the part of heat transfer by convection accounts for only about 19% [1,14].

At the present time, the cladding systems with a ventilated air gap have become widespread. The analysis of the constructive solutions [15-16] existing for wooden log walls in houses, carried out by the author [17-18], has shown that beginning from the 17th century the wooden log walls in ancient Russia were covered from outside with wooden boards. These boards protected the main bearing structure of the wooden walls (logs) from the impact by sun, rain and snow. The wooden cladding of the walls had gaps between the boards. Under the influence of air wind ventilation, a layer occurred through these gaps. As this takes place, all the moisture from the structure of the log was removed outward, resulting in the increase of its longevity. Such structures with a cladding made of wooden boards with a ventilated air layer, which were wide spread in ancient Russia, were the prototypes of modern design solutions for hinged ventilated facades [17-18], which are now widely distributed all over the world. The investigation of the heat exchange within the air gap of cladding facade systems could be found in [19-22], wherein only the effect of wind or only the radiation coefficients of the surfaces of the air layers used for the thermal protection have been studied. However, the calculations in these studies did not take into account the change in the coefficient of thermal conductivity of air in ventilated air layers.

2. Solution of the problem
In case of the infiltration from outside air through a wooden cladding, the share of heat transfer by heat conduction and convection is almost insignificant. Therefore, it is necessary to consider a magnitude of the coefficient of equivalent thermal conductivity in calculating the temperature fields in

wooden structures with a ventilated air gap that characterizes the radiant heat transfer, which could be determined by the following formula derived by the author on the base of known functions [1]:

$$\lambda_{eq} = \alpha_{r.air.gap}\delta_{air.gap} = \frac{1}{\dfrac{1}{C_{cl}}+\dfrac{1}{C_{\log}}-\dfrac{1}{C_o}} \cdot \frac{\left[\left(\dfrac{\tau_{cl}+273}{100}\right)^4 - \left(\dfrac{\tau_{\log}+273}{100}\right)^4\right]}{\tau_{cl}-\tau_{\log}} \cdot \delta_{air.gap} \qquad (1)$$

where C_{cl} and $C_{\log}$ are the radiation coefficients of the wooden boards facing the air layer, W/ m^{2}K^4, which for wooden cladding and hewn timber could be taken as C_{cl} and $C_{\log}$ = 4.44 W / m^{2}K^4, and τ_{cl} and $\tau_{\log}$ are the temperatures on the surface of the wooden board cladding and logs facing the air layer, ^{0}C.

The term $\left[\left(\dfrac{\tau_{cl}+273}{100}\right)^4 - \left(\dfrac{\tau_{\log}+273}{100}\right)^4\right]/\left[\tau_{cl}-\tau_{\log}\right]$ in (1) is called the temperature coefficient and is presented in Table 1.

Table 1. The value of the temperature coefficient depending on the average temperature of the air-layer surfaces.

Average temperature of the air layer $((\tau_{cl}+\tau_{\log})/2$, ^{0}C	0	–5	–10	–15	–20	–25
Temperature coefficient	0.81	0.77	0.73	0.69	0.65	0.61

For the internal temperature t_{int} = 20 ºC and the temperature of outside air t_{ext} = -26 ºC, the temperature of the board cladding faced into the air gap is τ_{cl} = -20.02ºC and average temperature on the log's surface, faced into the air gap is $\tau_{\log}$ = - 19.42ºC. The average air temperature in the interlayer is $t_{voz.pr}$ = -19.72ºC, and the temperature coefficient will be equal to 0.65. The reduced emission factor according to Eq. (1) will be the following: $1/\left[\dfrac{1}{4,44}+\dfrac{1}{4,44}-\dfrac{1}{5,76}\right]=3,61$ W/m^{2}K^4.

The coefficient of heat exchange by radiation in the air layer will be $\alpha_{r.air.gap}$ = 3.61 · 0.65 = 2.34 W/(m^2 °C).

For an air layer with the thickness of $\delta_{air.gap}$ = 60 mm, the equivalent thermal conductivity coefficient is $\lambda_{eq} = \alpha_{r.air.gap}\delta_{air.gap} = 2,34 \cdot 0,06 = 0,14\ W/m^2 \cdot {}^0 C$, and for an air layer of the thickness of $\delta_{air.gap}$ = 180 mm is equal to λ_{eq} = 2.34 · 0. 18 = 0.42 W/(m^2 ° C).

Note that the magnitudes of the equivalent thermal conductivity coefficient obtained above differ from the data presented in [1], wherein one could find λ_{eq} = 0.18 W/m ^{0}C for $\delta_{air.gap}$ = 60 mm and λ_{eq} = 0.64 W/m ºC for $\delta_{air.gap}$=180 mm. This discrepancy could be explained by the fact that the radiation coefficients of the material surfaces of the air layers, in particular, wood, were not taken into account in [1].

3. Mathematic simulation
In order to calculate the wooden wall temperature fields with the external wooden cladding, the following design parameters have been taken: the coefficient of thermal conductivity for spruce or

pine with the density γ= 560 kg/m^3 across the fibers in the outer walls equal to $\lambda = 0.167$W/(m^2 ^{o}C) and for fir or pine with the density $\gamma = 500$ kg/m^3 across the fibers in the inner walls equal to $\lambda = 0.139$ W/(m^2 ^{o}C). In the existing Building Cole [2], the coefficient of thermal conductivity of spruce or pine for conditions A is equal to $\lambda = 0.14$ W/(m^2 ^{o}C) and for conditions B is equal to $\lambda = 0.18$ W/(m^2 ^{o}C); for oakum with the density $\gamma = 150$ kg/m^3 this coefficient is taken as $\lambda = 0.069$ W/(m^2 ^{o}C); the coefficient of thermal conductivity of vegetable moss is $\lambda = 0.065$ W/ (m^2 ^{o}C). As it can be seen, the coefficients of thermal conductivity for oakum and vegetable moss differ a little from each other.

In order to calculate the temperature fields, the structures with 260 mm-thick log walls without cladding and with board cladding have been chosen. The thickness of the ventilated air interlayer between logged wall and cladding was 60 mm and 180 mm in the first and second variants, respectively.

To obtain a real picture of the temperature distribution along the inner logs surface, a mathematical model has been developed and temperature fields have been constructed using the software complex for two variants of logged walls. The design value of the thermal conductivity coefficient of the ventilated air layer has been taken according to (1) as an equivalent coefficient of thermal conductivity.

Figure 2 (a) shows the temperature fields of a logged wall without cladding. Thus, the temperature on the inner surface is 13.9 ^{o}C, while at the corner it decreases up to 8.8 ^{o}C. At a temperature of 20 ^{o}C and relative humidity above 47%, the condensation will appear in the corner, resulting in the decay of the wood.

The outer board cladding will increase thermal protection properties of timber walls. Mathematical modeling of the heat transfer through the construction of a wooden wall with cladding enables one to obtain the temperature distribution on its internal surface.

When the coefficient of equivalent thermal conductivity for the 60 mm-thick ventilated air layer is $\lambda_{eq} = 0.14$ W/(m^2 ^{o}C) and if it is taken as the design value, then as a result of the mathematical modeling of the temperature fields the inner surface temperature of the log wall is equal to 14.6 ^{o}C (Figure 2 (b)). At the same time, from the calculated results it is evident that the temperature in the corner of the log is lowered to 9.17 ^{o}C.

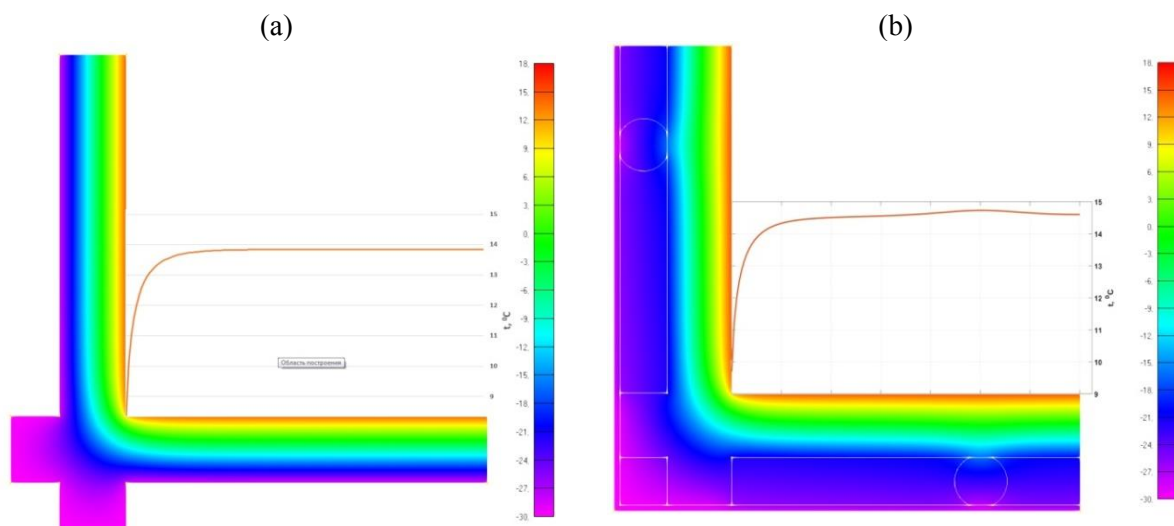(a)   (b)

Figure2. Temperature distribution along the inner surface of a wooden log wall without a wooden cladding (a), and with the wooden cladding of 60 mm thickness (b).

If the thickness of the ventilated air gap is up to 180 mm, then the coefficient of equivalent thermal conductivity is equal to $\lambda_{eq} = 0.42$ W/(m^2 ^{o}C). Calculations of the temperature fields show that the

temperature on the inner surface of the log is 17.5 °C, while in the corner it could lower till 10.1 °C (Figure 3).

The temperature values obtained using an equivalent thermal conductivity are approximate with respect to the real temperature distribution on the inner surface of the walls. Special attention should be made to temperatures in the frame corners. Traditionally, the destruction of wooden log houses occurs in the corners, where the temperature is below the dew point.

It could be seen that the structure of the wall with the planking could make it possible not only to raise the surface temperature by more than 3 °C, but also it could allow one to reduce the heat losses through the wall and to reduce the consumption of firewood going to the heating of the building. In addition, the wooden cover protected logs from destructive effect of the sun, rain and promoted increase in endurance of walls.
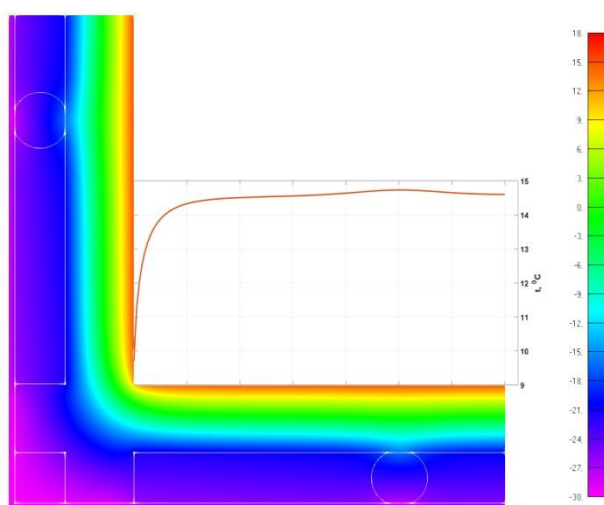

Figure 3. Temperature distribution along the inner surface of wooden log wall with a wooden cladding and ventilated air gap of the 180 mm thickness.

4. Conclusions

The mathematical modeling presented in the given paper reveals the advantage of the application of wooden cladding on logged walls, since it has a positive effect on their temperature regime. In doing so it is important to choose correctly the coefficient of air thermal conductivity for a ventilated air layer. The results obtained have shown that the proposed method of calculating the coefficient of equivalent thermal conductivity for the ventilated air layer allows one to construct the temperature fields for a wall, which are very close to real conditions.

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