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Effect of external facing vapor permeability on humidification of facade materials

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Keywords: facade system, heat- insulation layer, external facing, vapor permeability resistance, heat and moisture transfer, calculation model

Abstract. In this paper, the influence of the vapor permeability resistance of insulated facades external facing on the moisture content was numerically studied. The calculations were carried out for the climatic conditions of regions with a continental climate with relatively cold winters and warm summers. The WUFI computer program was used to perform heat and humidity calculations. The calculations found that the moisture content of the insulation layer increases with a decrease in the vapor permeability of the external façade facing in the cold season. Thus, the calculations found that with an increase in the resistance to vapor permeability of the external facing Sd > 0.2 m, the average moisture content of mineral wool increases by more than 3 % in the winter period. To reduce the moisture content of insulation, a version of installing an interlayer vapor permeability retarder is proposed. According to calculations, the relationships between the vapor permeability resistances of the external facing and the interlayer retarder were established. The proposed approach using an interlayer retarder can be applied in the development of various designs of building facades with external insulation to protect the insulation layer from humidification during the cold season in regions with a continental climate.

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1. *Introduction*

The facade systems of modern buildings are the multifunctional structures that ensure comfortable conditions for people living. In cold and temperate climatic regions, facade systems, which include layers of heat-insulating materials, are used. Currently, two main facade systems with external insulation are widely applied: Ventilated Facade Systems (VFS) [1] and External Thermal Insulation Composite Systems (ETICS) [2]. Both of these facade systems in the summer season protect the interior from overheating and reduce air conditioning costs [3], and in winter they provide a low level of heat loss [4].

The ETICS is a facade system consisting of prefabricated thermal insulation panels glued or mechanically fixed to the wall and an external plaster layer or external brick facing. The advantages of this facade system are its high thermal uniformity in comparison with other facade systems [2], relatively low cost, and usability when renewing previously constructed buildings [5]. Operation of ETICS revealed two main problems. The first is caused by low impact resistance [2]. The second relates to defacement due to biological growth. Biological growth is driven by high levels of surface moisture, which is the result of the combined action of four parameters: wetting by surface condensation, which occurs mainly at night with clear skies, wetting by wind-driven rainfall, drying processes, and properties of the outer layer [6, 7].

Ventilated facades appeared with the development of Double-Skin Facades (DSFs) systems at the beginning of the 20th century [8]. Initially, the DSF consisted of two layers of glass separated by an inter-glass air gap. According to the practice of using such facades, buildings with DSFs overheated in summer, so later they began to be constructed with natural or forced ventilation, and such facades became known as ventilated facades (VFs) [9–11]. Later, not only transparent VFs, but also opaque ones, which were called “opaque ventilated facades” (OVFs) began to be used in construction [12–15]. Opaque ventilated facades were initially used in northern Europe to protect buildings from rain, wind and temperature fluctuations [14, 16]. Conventional VFSs during operation proved to be more resistant to moisture as compared to ETICS [17], but inferior to them in terms of thermal uniformity [18]. To improve the heat-shielding characteristics of ventilated facades, as well as to increase the speed and quality of installation, a new facade system based on prefabricated panels with ventilated channels has been developed and put into production [19, 20]. Laboratory and full-scale experimental and computational studies of the heat and humidity parameters of panels with ventilated channels were carried out, and they confirmed their high performance characteristics [21, 22].

One of the functions of facade systems is protection of the outer wall materials from excessive moisture. A high moisture content leads to additional heat losses due to a decrease in the efficiency of heat-insulating materials [23–27], and the growth of mold and algae is observed on facade facings [27, 28]. The limited frost resistance of porous materials at high humidity can be the cause of their structural damage [29, 30].

A number of papers draw attention to significant energy losses in buildings associated with increased air permeability of building envelopes. According to the results of analysis of heat losses in buildings located in the northern part of Spain, air infiltration consumes from 10.5 % to 27.4 % of energy in winter [31]. Studies performed in Finland have shown that air leakages in single-family houses are responsible for wasting 15–30 % of heating energy [32]. As a result, in these and some other works, it is concluded that when renovating buildings, the air permeability of building envelopes should be significantly reduced. However, a change in air permeability and vapor permeability of envelopes cannot be considered without taking into account their influence on the moisture content of materials in their composition, otherwise reconstruction of buildings may adversely affect the condition of building envelopes, internal environment and people health [33–35].

Barrier layers are used to limit moisture accumulation in building envelope materials. Usually, in a warm and humid climate, when the flow of vaporous moisture is directed inwards from the facade outer surface, the barrier layer is installed on the outer side of the facade [36]. In regions with a long cold period, the main flow of vaporous moisture during the year is directed from the facade inner surface to the outer one, and it is recommended to place the barrier layer on the inner surface of the facade [22]. However, internal vapor barriers are very sensitive to various mechanical damages [37]. Such barriers are difficult to install when renovating previously constructed residential buildings, since it is usually carried out from the outside without resettlement of residents. They try not to use internal vapor barriers when renovating historical buildings [38]. In the scientific literature, the issue of a possible use of vapor barrier layers inside facade systems is still insufficiently covered, although, in some cases, this position of the barrier layers can provide certain advantages.

The facade of a modern building can be considered as a multilayer structure consisting of porous materials with different vapor permeability. With different outdoor climatic parameters, as well as certain temperature and humidity conditions inside the premises, there is a difference in the partial pressures of water vapor of the outdoor and indoor air, which in turn causes the movement of water vapor through the multilayer porous structure of the facade. When water vapor moves, depending on vapor permeability of the materials of the facade layers and their sorption properties, condensation and moisture accumulation can occur.

Vapor permeability of the external facade facing (the facade layer or several layers located outside the thermal insulation layer of the facade) plays an important role in the moisture transfer process in facade systems. Analyzing the influence of vapor permeability of the external facing on moisture accumulation in the facade materials, one can abstract from specific features and consider ETICS and OVS facades from a unified position, characterizing the external facade facing with certain resistance to vapor permeability. For ventilated facades, this resistance reflects the resistance of ventilated layers or channels and the resistance of their inlets and outlets, and for ETICS facades, this resistance is caused by the resistance to vapor permeability of the outer plaster layers or the outer layer of the brickwork.

This work is aimed at consideration of the influence of vapor permeability resistance of the external facade facing on the moisture content in its materials during the long-term cycle of building operation in a continental climate with cold winters and relatively warm summers. The possibility of using thin retarder layers inside the facade with different vapor permeability of the external facade facing to reduce the moisture content of the heat-insulating layer is also considered.

2. Methods

The influence of vapor permeability of the external facing on the moisture state of the building wall materials was analyzed using the outer wall construction, widespread in practice, shown in Fig. 1. The main structural layer of the outer wall is made of clay bricks with a thickness of 250 mm. From the side of the room, a layer of cement-sand plaster 20 mm thick is applied to the brickwork, and from the outside, the brickwork is insulated with a layer of mineral wool 160 mm thick. On the outer side of the mineral wool there is a facade facing with a given vapor permeability resistance. The external facade facing can be a plaster layer, or a layer of another material, or the outer layer of a ventilated facade or panels with ventilated channels [20].

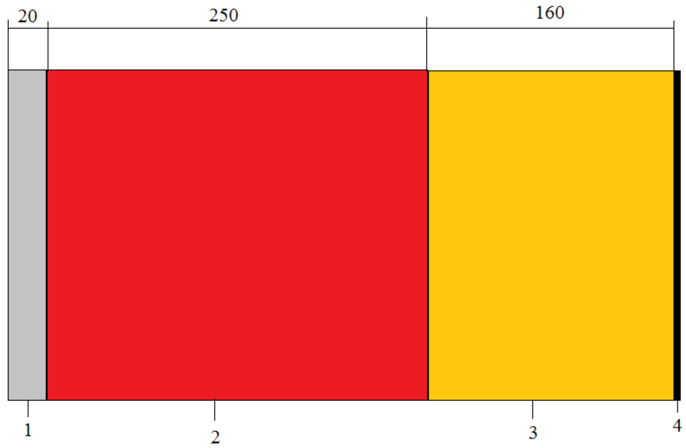

Figure1. The outer wall composition: 1 – cement-sand plaster, 2 – brickwork, 3 – mineral wool insulation, 4 – outer facing.

The WUFI computer program [39], developed and maintained by Franhofer-IBP (Germany), was used to perform heat and humidity calculations. In this program, the process of heat and moisture transfer in hygroscopic multilayer porous materials as applied to building structures is described by a system of two partial differential equations for each of the layers, which is solved by a finite volume procedure. Equation (1) describes a change in the enthalpy of a wet material over time, caused by thermal conductivity and thermal processes associated with evaporation and condensation of moisture. Equation (2) is the balance of moisture in a hygroscopic material, taking into account the movement of liquid and vaporous moisture.

$$\frac{dH}{d\vartheta}\frac{\partial\vartheta}{\partial t}=\nabla(\lambda\nabla\vartheta)+h_V\nabla(\delta_p\nabla(\varphi p_{sat}))+S_h \quad (1)$$

$$\frac{dw_V}{d\varphi}\frac{\partial\varphi}{\partial t}=\nabla(D_\varphi\nabla\varphi)+\delta_p\nabla(\varphi p_{sat}))+S_w \quad (2)$$

where H is enthalpy [J/m^3]; ϑ is temperature [K]; w_V is volumetric moisture [kg/m^3]; φ is relative humidity [-]; λ is coefficient of heat thermal conductivity [W/mK]; h_V is heat of water evaporation [J/kgK]; δ_p is water vapor diffusion coefficient [kg/msPa]; p_{sat} is water vapor saturation pressure [Pa]; D_φ is liquid transport coefficient [kgm/s]; S_h is additional heat source strength (W/m^3); S_w is additional moisture source strength (kg/sm^3)

Table 1 shows the properties of materials, and Fig. 2 and 3 show the moisture storage function and dependences of liquid transport coefficient, thermal conductivity on volumetric moisture content w_V, used in calculations (taken from the WUFI library).

Table 1. Material properties.

Material	Bulk density, kg/m^3	Porosity, m^3/m^3	Specific Heat Capacity (Dry), J/kgK	Thermal conductivity, (Dry), W/mK	Water Vapor Diffusion Resistance Factor
Brickwork	1900	0.24	850	0.6	10
Mineralwool	115	0.95	850	0.043	3.4
CementLime Plaster (Stuco)	1900	0.24	850	0.8	19

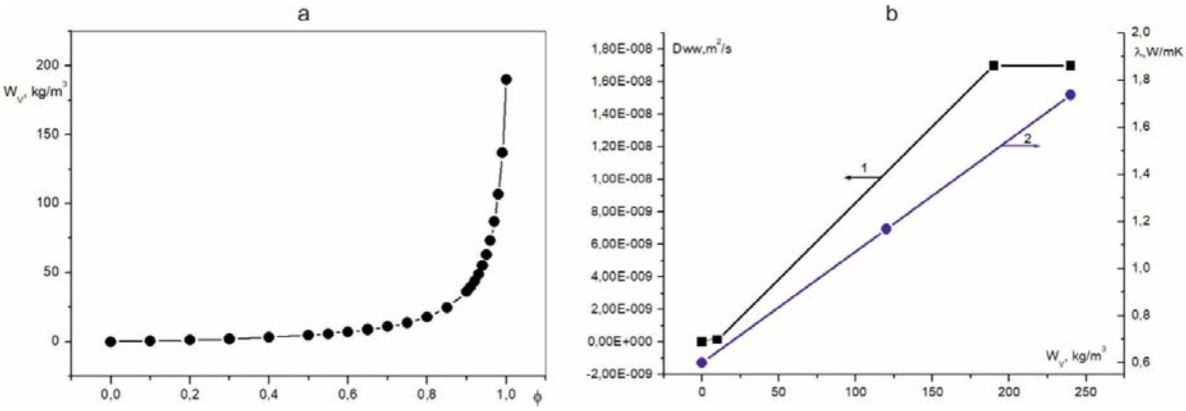

Figure2. Brickwork a) moisture storage function, b) 1 – liquid transport coefficient, 2 – thermal conductivity.

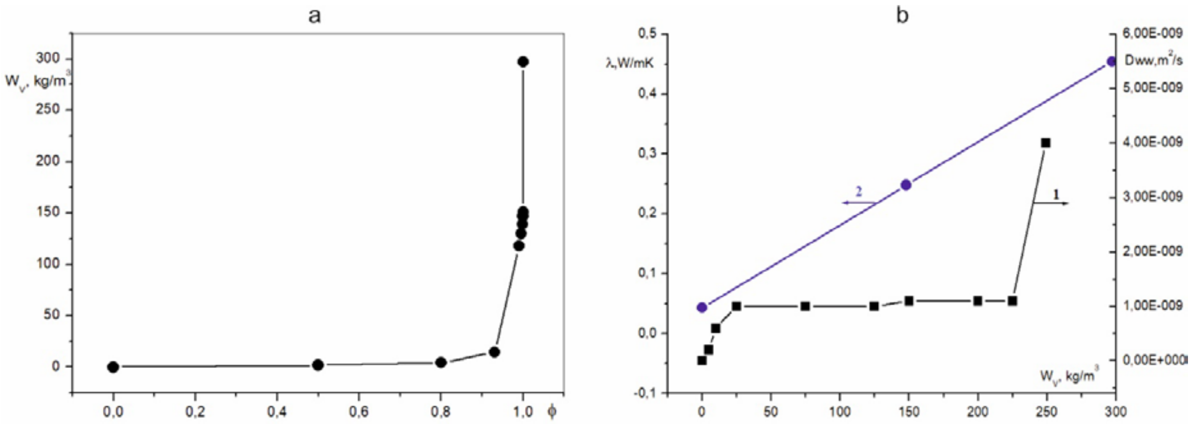

Figure3. Mineral wool a) moisture storage function, b) 1 – liquid transport coefficient, 2 – thermal conductivity.

The calculations were carried out for the climatic conditions of regions with a continental climate with relatively cold winters and warm summers. The city of Edmonton (Canada, 53.37ºN) was taken as a specific point. Calculations used hourly data of a typical year in Edmonton (Fig. 4, taken from the WUFI library). For indoor calculations, the air temperature was assumed to be 21 °C and its humidity was assumed to be 55 %. October 1 was taken as the start of calculations, while the moisture content of the brickwork and the plaster layer corresponded to the moisture content of the sorption isotherm at 80 % relative air humidity, and the moisture content of mineral wool corresponded to that at 55 % relative humidity, which is typical of the moisture content of materials at the end of building erection.

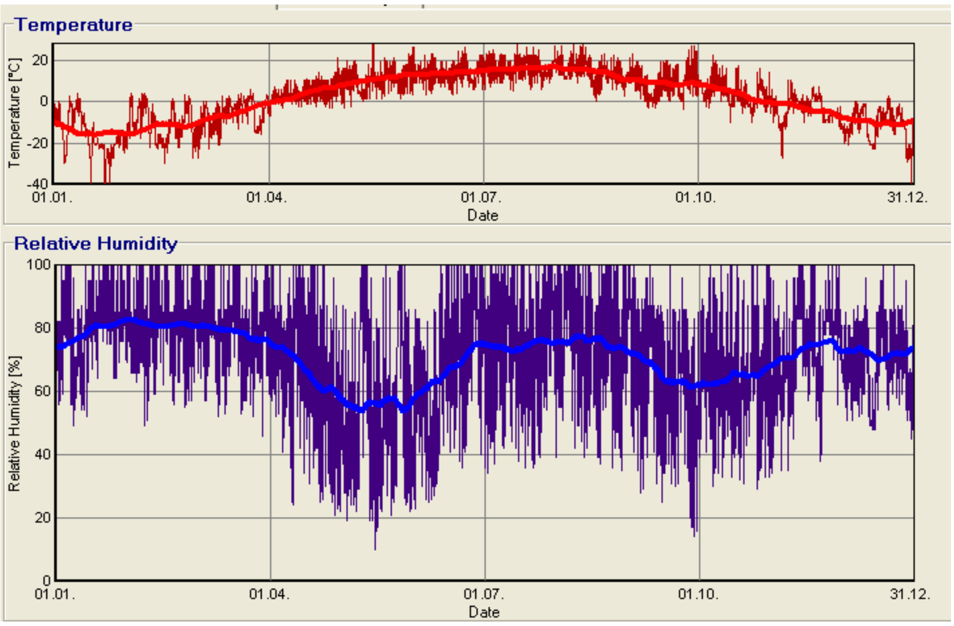

Figure 4. Temperature and relative air humidity in a standard year (Canada, Edmonton).

The computational grid was built with thickening towards the boundaries from the central zone of each material (Fig. 5).

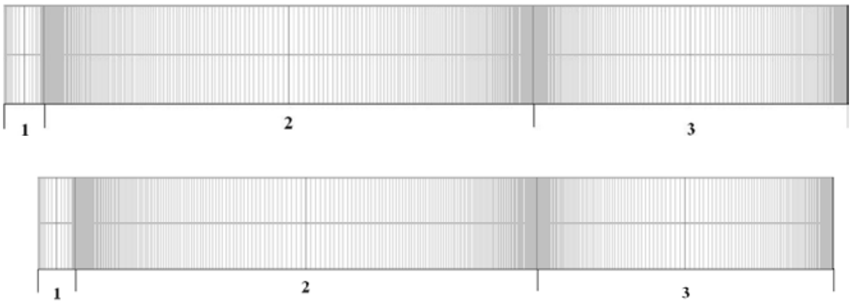

Figure 5. Computational grid 1 – plaster layer, 2 – brickwork, 3 – mineral wool.

To select the grid size, calculations at hourly intervals were carried out during the year to determine the average relative mass humidity w_i of a brickwork and mineral wool layer with the number of cells i = 128, 172, 258, and 386. As a result of determining abs$(w_{386} - w_i)/ w_{386}$ × 100 %, a grid with 258 cells was chosen for calculations, which, as compared to a grid with 386 cells, gave a deviation for brickwork of < 0.2 % (Fig. 6a), and for mineral wool, it was < 2 % (Fig. 6b).

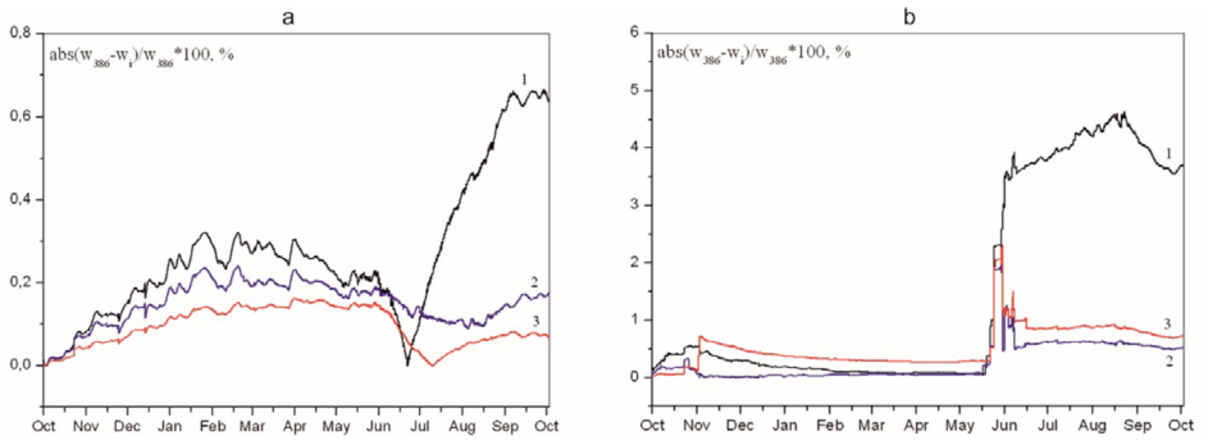

Figure 6. Comparison of average relative humidity for: a) brickwork,
b) mineral wool with a different number of grid cells: 1 – i = 128, 2 – 172, 3 – 258.

3. Results and Discussion

All calculation results presented in this section were performed during a 3-year period. At the initial stage, heat and humidity were calculated for the wall structure shown in Fig. 1, but without the external facing. Figure 7a shows calculation results on a change in the average mass moisture content in the mineral wool layer. According to calculation results, periodic annual fluctuations in humidity were observed with its increase to 3 % in late summer and early autumn: namely during this period of time there was high air humidity outside while the air temperature was still high (Fig. 4).

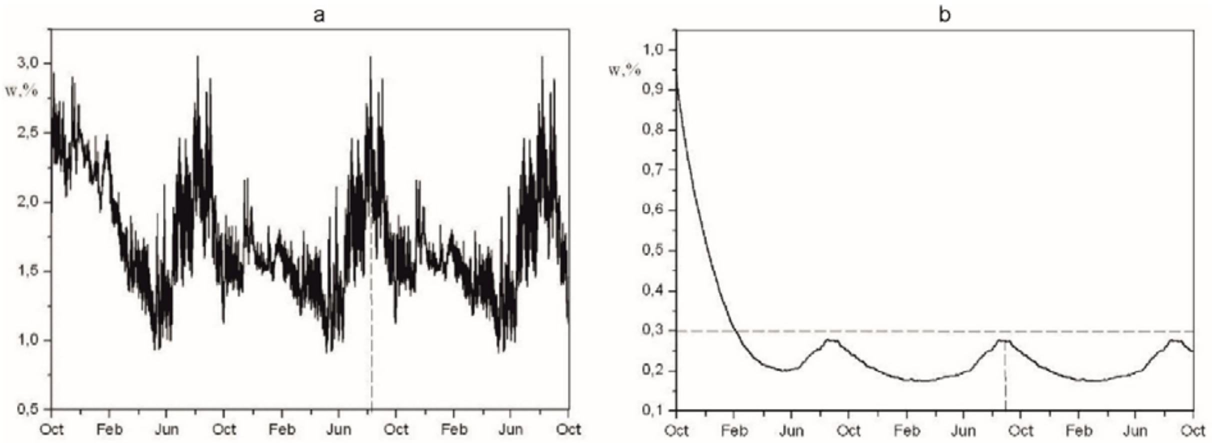

Figure 7. Relative mass humidity without external facing: a) mineral wool, b) brickwork.

The average mass moisture content in brickwork for the first six months after construction completion decreased rapidly, and then there were slight annual fluctuations with a maximum relative humidity of <0.3 % in September (Fig. 7b).

The results of calculating the density of the diffusion moisture flow at the boundary between brickwork and insulation for a wall structure without an outer coating are shown in Fig. 8. According to calculations for a 3-year period, a steady periodic annual change in the direction of the diffusion moisture flux was observed. In the summer period, the diffusion flow of moisture was directed towards the premises, and in the rest of the year, it was directed outside.

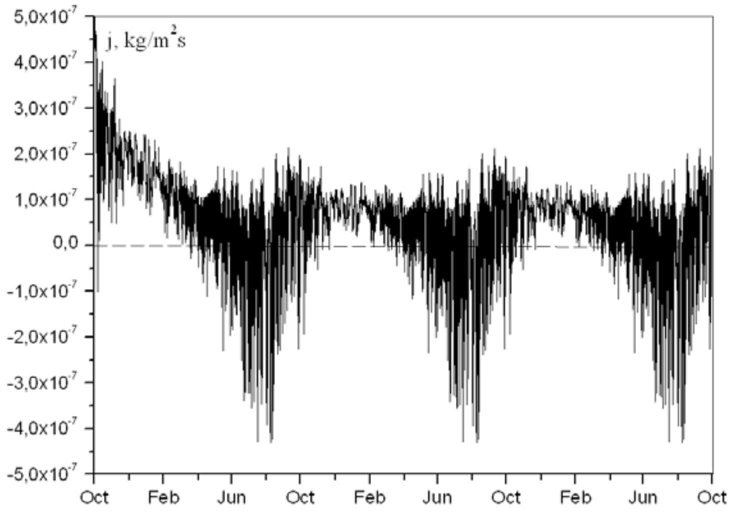

Figure 8. The density of diffusion moisture flow at the brickwork-insulation boundary.

The results of the average monthly density of the diffusion moisture flow for 3 years, which confirm this conclusion, are shown in Fig. 9 for clarity.

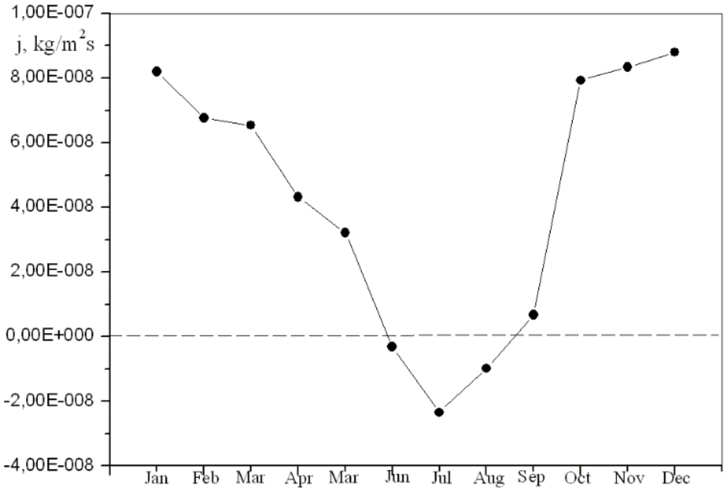

Figure 9. The average monthly density of the diffusion moisture flow at the brickwork-insulation boundary.

The inward direction of the diffusion moisture flow led to an increase in humidity in mineral wool and brickwork (Fig. 7). The magnitude and duration of the diffusion flow of moisture directed outside were large, but this did not lead to noticeable wetting of the mineral wool layer, since there was no external facing that would contribute to accumulation of moisture in the insulation.

Let us consider the results of calculations of the moisture state of the wall structure with an external facing on the outer surface with different vapor permeability resistance. The results of calculating a change in the average relative humidity of a mineral wool layer with vapor permeability of the external facing Sd = 0.2 m (which corresponds to vapor permeability of 10-mm layer of cement-sand plaster) are presented in Fig. 10a, b.

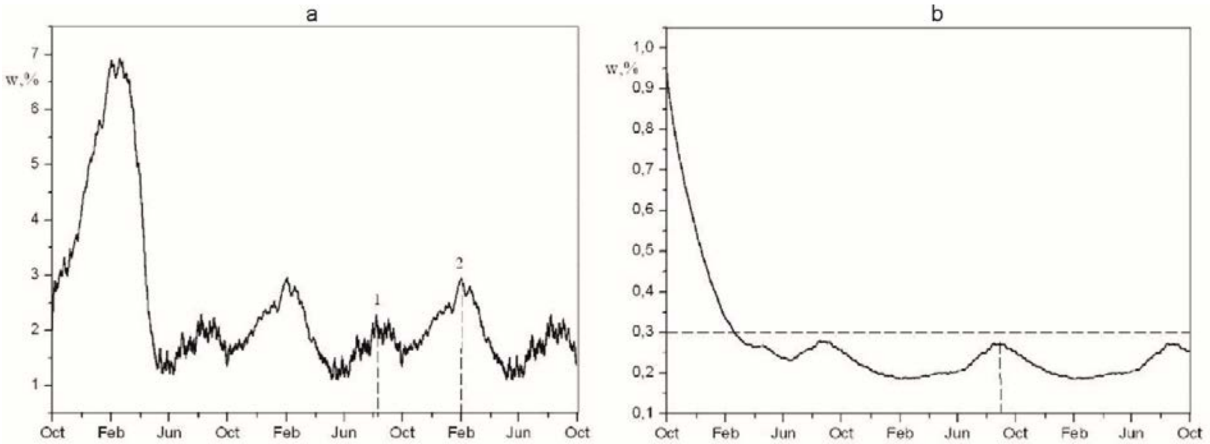

Figure10. Relative mass humidity at external facing resistance to vapor permeability Sd = 0.2 m: a) mineral wool, 1, 2 – annual humidity maxima; b) brickwork.

According to the calculation results, in the first year after construction completion, in February, there was a maximum increase in the average relative humidity of mineral wool up to 7 %, which is associated with the influence of vapor permeability resistance of the coating to the removal of moisture from the brickwork at its increased level in the initial period after construction completion. In subsequent years, the moisture level in mineral wool enters into cyclic annual fluctuations, but in contrast to the previously considered case (Fig. 7a), two humidity maxima are observed during the year. Maximum 1 is similar to the maximum in Fig. 7a in the warm period, but it is smaller in magnitude. Maximum 2 appears during the cold season, and its appearance is associated with the resistance to vapor permeation of the external facing.

The change in the average relative humidity of the brickwork with external facing resistance to vapor permeability Sd = 0.2 m (Fig. 10b) slightly differed from calculation results without coating (Fig. 7b). The conclusion about non-accumulation of moisture over the annual period in a brick facade with external insulation and facing resistance to vapor permeability Sd = 0.2 m is also confirmed by the results of calculations performed earlier for the climatic conditions of Holzkirchen (Germany) [40].

With a further increase in vapor permeability resistance of the external facing up to Sd = 0.5 m, a further increase in the maximum values of relative average humidity of the mineral wool layer in the cold season was observed (up to 10 % in the first year, and up to 5 % in the next two years; Fig. 11).

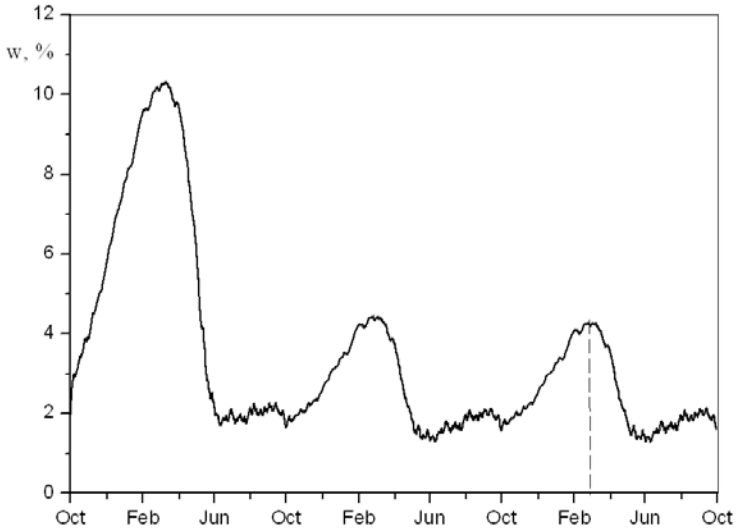

Figure 11. Average relative humidity of mineral wool at external facing resistance to vapor permeability Sd = 0.5 m.

It should be noted that humidity was not evenly distributed over the mineral wool layer, the moisture content of the outer half of the mineral wool layer (Fig. 12a) was significantly higher than that of the inner half of the layer (Fig. 12b), where the moisture content was less than 3 % and changed little over time throughout the year.

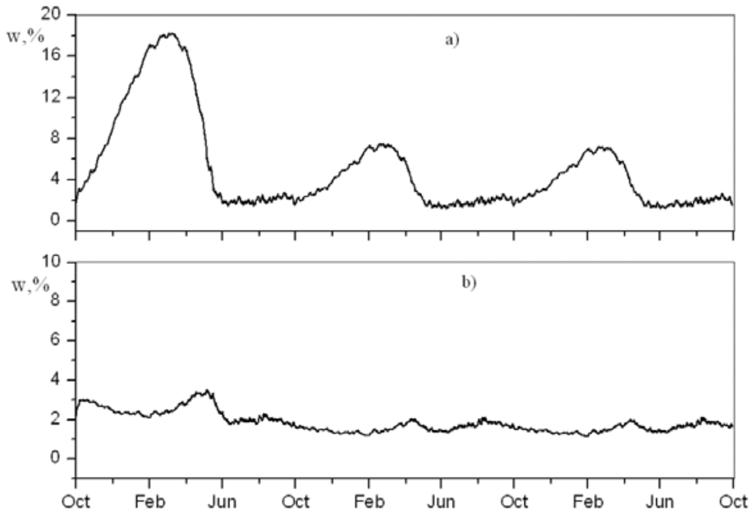

Figure12. Average relative humidity of mineral wool at external facing resistance to vapor permeability Sd = 0.5 m over the layers: a) outer half, b) inner half.

The results of calculating the changes in relative humidity of the brickwork with coating resistance to vapor permeability Sd = 0.5 m are shown in Fig. 13.

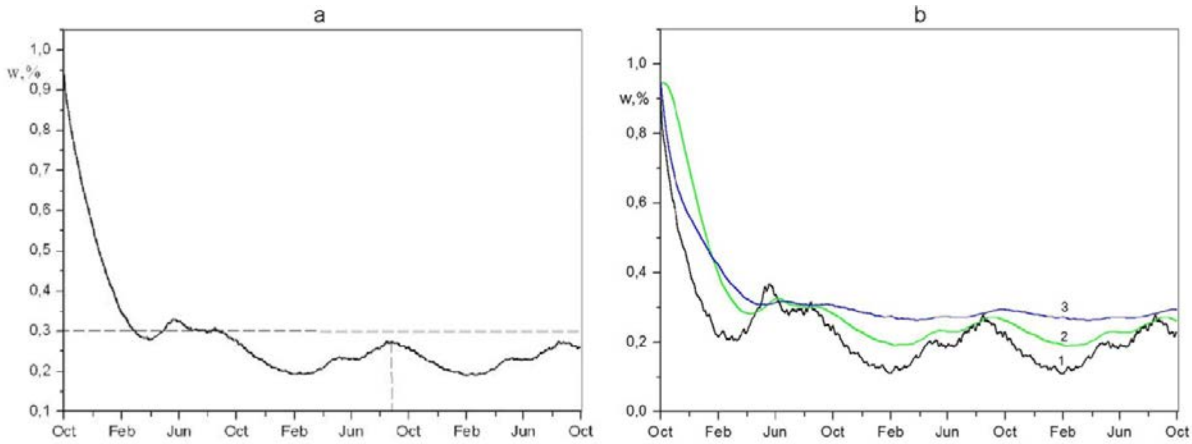

Figure13. Relative humidity of brickwork at external facing resistance to vapor permeability Sd = 0.5 m: a) average, b) 1 – outer layer, 2 – middle layer, 3 – inner layer.

The average humidity over the entire layer of brickwork in the summer of 1 year slightly exceeded 0.3 %; then it decreased and underwent annual fluctuations with an increase in humidity in the summer-autumn period (Fig. 13a). To analyze moisture distribution along the brickwork thickness, we conditionally divide it into 3 equal layers: outer, middle and inner ones. Fig. 13b shows the results of changing the relative humidity of the brickwork by layers. According to the results of calculations, the highest and most stable humidity, starting from year 2, was in the inner layer, and the lowest humidity, changing in the annual cycle, was observed in the outer layer (Fig. 8b).

Calculations were performed with a further increase in the resistance to vapor permeability of the external facing in the range Sd = 1 ÷ 20 m, as well as with an impermeable external facing (Fig. 14). As a result of calculations, it was found that with an increase in external facing resistance to vapor permeability, a consistent increase in the maximum average relative humidity of mineral wool in the cold season was observed, and for vapor-impermeable external facing it reached 16 % (Fig. 14a).

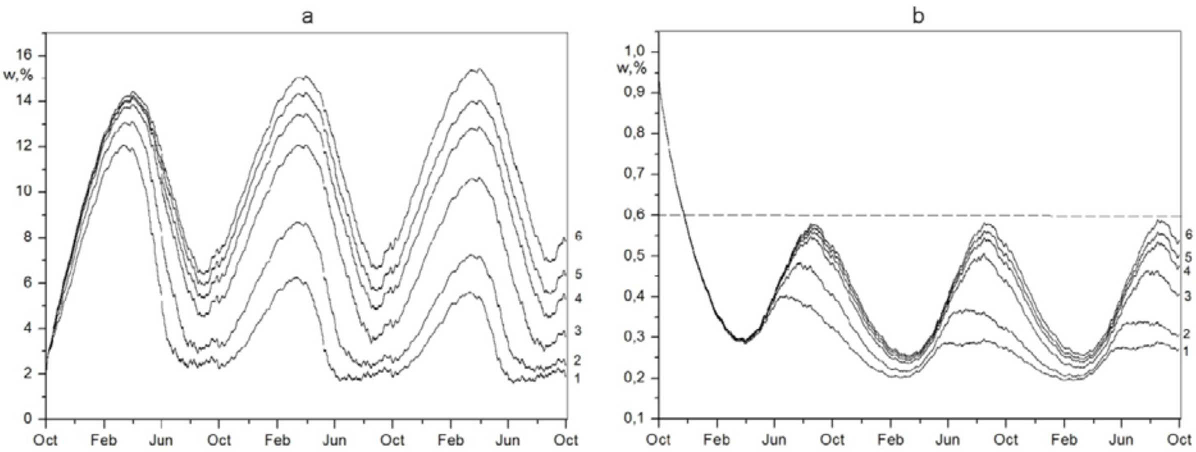

Figure14. Relative mass humidity: a) mineral wool, b) brickwork at different resistances of facing to vapor permeability: 1 – Sd = 1m, 2 – 2m, 3 – 5m, 4 – 10m, 5 – 20m, 6 – impermeable.

The average humidity of the brickwork increased during the summer-autumn period with an increase in external facing resistance to vapor permeability, while the maximum value obtained for the vapor-impermeable facing was about 0.6 % (Fig. 14b).

Thus, the calculations found that with an increase in the resistance to vapor permeability of the external facing Sd > 0.2 m, the average moisture content of mineral wool increases by more than 3 % in the winter period. To reduce the humidity of mineral wool, let us consider the option of installing an interlayer vapor permeability retarder (a thin layer with varying resistance to vapor permeability) between brickwork and mineral wool.

The results of calculations of average relative humidity of mineral wool (Fig. 15a) and brickwork (Fig. 15b) when installing an interlayer retarder with vapor permeability Sd = 1, 5, 10 and 20 m and vapor permeability of the external facing Sd = 1 m are shown in Fig. 15.

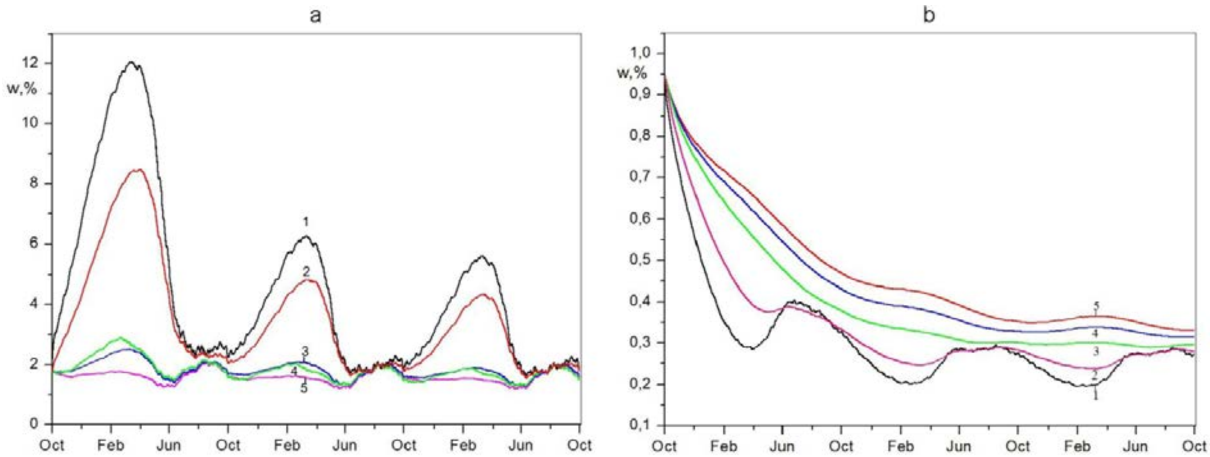

Figure15. A change in relative mass humidity of a) mineral wool and b) brickwork at facing resistance to vapor permeability Sd = 1 m and retarder resistance to vapor permeability: 1 – Sd = 0 m, 2 – 1 m, 3 – 5 m, 4 – 10 m, 5 – 20 m.

According to calculation results, with an increase in the resistance to vapor penetration of the interlayer retarder, a decrease in mineral wool humidity was observed in the winter-spring period, since the retarder provided additional resistance to the water vapor flow from the brickwork. With retarder resistance to vapor permeation Sd > 5, the maximum average humidity decreased below 3 %. It should be noted that when installing an interlayer retarder, a decrease in the moisture content of the mineral wool is accompanied by a slight increase in brickwork humidity (Fig. 15b), but this increase is insignificant and acceptable for brickwork. So, for an interlayer retarder with Sd = 5, the average moisture content of brickwork starting from the 2nd year after construction completion was less than 0.35 %.

The results of calculations of changes in humidity of mineral wool and brickwork with vapor permeability resistance of the external facing Sd = 10 m and when installing an interlayer retarder with vapor permeability resistance Sd = 1 ÷ 20 m are shown in Fig. 16.

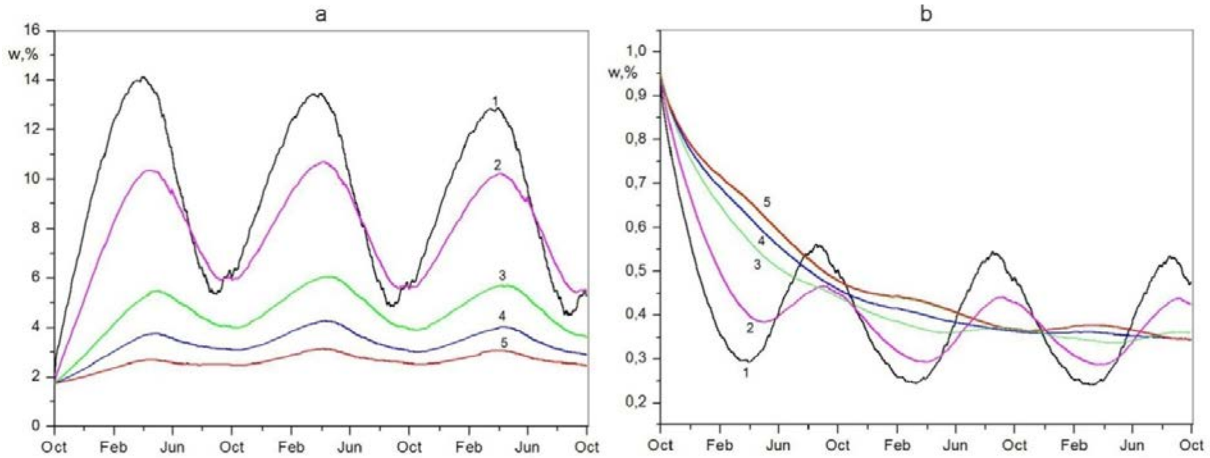

Figure16. A change in relative mass humidity of a) mineral wool and b) brickwork at facing resistance to vapor permeability Sd = 10 m and retarder resistance to vapor permeability: 1 – Sd = 0 m, 2 – 1 m, 3 – 5 m, 4 – 10 m, 5 – 20 m.

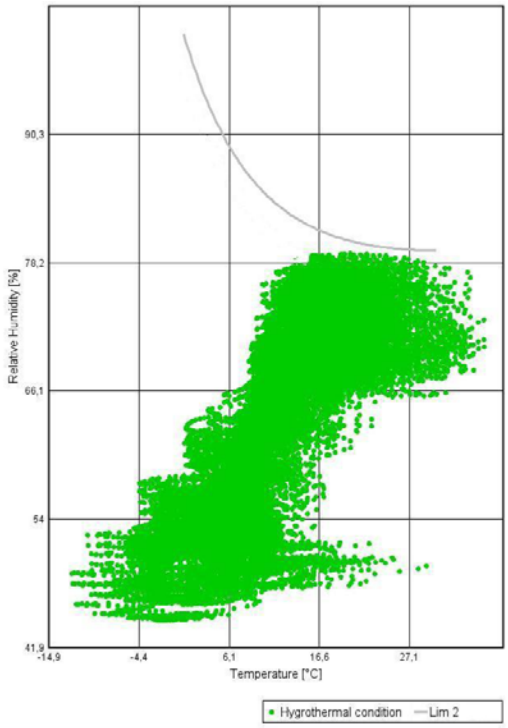

Figure17. Geothermal state of mineral wool with resistance to vapor permeability of the external facing and interlayer retarder Sd = 10 m.

It follows from the results presented in Fig. 17 that relative humidity in mineral wool did not exceed 80 % over a 3-year period and its geothermal state was characterized by points located below the limit line LIM 2, which provided its normal geothermal state.

It should be noted that new facade systems of buildings with high resistance to vapor permeability of the outer layers are beginning to be used in construction practice. As an example, we can cite facades using ballistic panels, in which the vapor permeability resistance can be Sd = 20 m ÷25 m [41]. For such facade systems, the possible moistening of facade materials due to the condensation of vaporous moisture is especially acute [42].

The result obtained on the advisability of using vapor retards on the inner surface of the thermal insulation of brick walls with external insulation is in good agreement with the results of experimental and computational studies concerning the use of vapor barriers and retards in wood frame wall structures [43–45]. In countries such as Canada, Norway and Sweden, it is obligatory to use a vapor barrier layer on the inner surface of the insulation in wooden frame walls.

4. Conclusions

To determine the effect of vapor permeability of the external facing on the moisture state of the outer wall materials during building operation in a continental climate, comprehensive heat and humidity calculations were carried out for a typical outer wall, consisting of an internal structural brick layer, an external mineral wool insulation layer and an external facing with different vapor permeability on the example of Edmonton. The numerical results allow to draw following conclusions:

1. It was found that with the resistance to vapor permeability of the external facing Sd ≤ 0.2 m, the average relative humidity in the mineral wool insulation layer is < 3 %, and in the brickwork, it is < 0.3 %, and special measures to prevent humidification of the outer wall materials are not required.

2. With an increase in the resistance to vapor permeability of the external facing Sd > 0.2 m, a consistent increase in the average moisture content of the mineral wool layer in the winter-spring period, and brickwork in the summer-autumn period, was observed. Thus, with vapor permeability resistance of the external facing Sd = 0.5 m, an increase in average relative humidity in mineral wool during the cold period was about 5 %; at that, the moisture in the layer was unevenly distributed: the outer layer was significantly more moistened as compared to the inner one. In the limiting case of an impermeable external facing, according to the results of calculations, the maximum increase in average relative humidity in the mineral wool layer was 16 %, and in the brickwork, it was 0.6 %.

3. To reduce mineral wool humidity with the resistance of external facing to vapor permeability Sd > 0.2 m, a case of location of a retarder (a thin layer with different vapor permeability) between the brickwork and the mineral wool layer was considered. As a result of calculations, it was found that installation of an interlayer retarder led to a decrease in the moisture content of mineral wool in the winter-spring period, while the greater the resistance to vapor penetration of the external facing, the higher the resistance of the interlayer retarder was required to reduce humidity. Based on the calculation results, the following relationships between the vapor permeability of the external facing and interlayer retarder can be recommended:

- Facing 0.2 m < Sd < 1 m – retarder Sd = 1 m;
- Facing 1 m < Sd < 5 m – retarder Sd = 5 m;
- Facing 5 m < Sd < 10 m – retarder Sd = 10 m.

4. The suggested approach using an interlayer retarder can be applied in the development of various designs of building facades with external insulation to protect the insulation layer from humidification during the cold season in regions with a continental climate.

References

1. Ibanez-Puy, M., Vidaurre-Arbizu, M., Sacristan-Fernandez, J.A., Martin-Gomez, C. Opaque ventilated facades: thermal and energy performance review. Renewable and Sustainable Energy Reviews. 2017. 79. Pp. 180–191. DOI: 10.1016/j.rser.2017.05.059
2. Barreira, E., de Freitas, V.P. External thermal insulation composite systems: critical parameters for surface hygrothermal behaviour. Advances in Materials Science and Engineering. 2014. 16. DOI: 10.1155/2014/650752
3. Shameri, M.A., Alghoul, M.A., Sopian, K., Fauzi, M., Zain, M., Elayeb, O. Perspectives of double skin facade systems in buildings and energy saving. Renewable Sustainable Energy Rev. 2011. 15. Pp. 1468–1475. DOI: 10.1016/j.rser.2010.10.016
4. Cristina Sanjuan, Maria Nuria Sánchez, Maria del Rosario Heras, Eduardo Blanco. Experimental analysis of natural convection in open joint ventilated façades with 2D PIV. Build Environ. 2011. 46. Pp. 2314–2325. DOI: 10.3390/en13010146
5. Becker, R. Patterned staining of rendered facades: hydrothermal analysis as a means for diagnosis. Journal of Thermal Envelope and Building Science. 2003. 26. Pp. 321–341. DOI: 10.1177/1097196303026004001
6. Barberousse, H., Ruot, B., Yepremian, C., and Boulon, G. An assessment of facade coatings against colonisation by aerial algae and cyanobacteria. Building and Environment. 2007. 42. Pp. 2555–2561. DOI: 10.1016/j.buildenv.2006.07.031
7. Barreira, E., Freitas, V. P. Experimental study of the hydrothermal behavior of external thermal insulation composite system (ETICS). Building and Environment. 2013. 63. Pp. 31–39. DOI:10.1016/j.buildenv.2013.02.001.
8. Aparicio-Fernández, C., Vivancos, J.-L., Ferrer-Gisbert, P., Royo-Pastor, R. Energy performance of a ventilated facade by simulation with experimental validation. Applied Thermal Engineering. 2014. 66. Pp. 563–570. DOI: 10.1016/j.applthermaleng.2014.02.041
9. Marinosci, C., Strachan, P.A., Semprini, G., Morini, G.L. Empirical validation and modelling of a naturally ventilated rainscreen façade building. Energy Build. 2011. 43. Pp. 853–863. DOI: 10.1016/j.enbuild.2010.12.005
10. Wang, Ya., Chen, Yo., Li, C. Airflow modeling based on zonal method for natural ventilated double skin façade with Venetian blinds. Energy and Buildings. 2019. 191. Pp. 211–223. DOI: 10.1016/j.enbuild.2019.03.025
11. Lin, Zh., Song, Ye., Chu, Yi. Summer performance of a naturally ventilated double-skin facade with adjustable glazed louvers for building energy retrofitting. Energy and Buildings. 2022. 267. 112163. DOI:10.1016/j.enbuild.2022.112163.
12. Giancola, E., Sanjuan, C., Blanco, E., Heras, M.R. Experimental assessment and modelling of the performance of an open joint ventilated facade during actual operating conditions in Mediterranean climate. Energy and Buildings. 2012. 54. Pp. 363–375. DOI: 10.1016/j.enbuild.2012.07.035
13. Peci Lopez, F., Jensen, R. L., Heiselberg, P., Ruiz de Adana Santiago, M. Experimental analysis and model validation of an opaque ventilated façade. Building and Environment. 2012. 56. Pp. 265–275. DOI: 10.1016/j.buildenv.2012.03.017
14. Davidovic, D, Piñon, J, Burnett, E.F.P., Srebric J. Analytical procedures for estimating airflow rates in ventilated, screened wall systems (VSWS). Build Environ. 2012. 47. Pp. 126–137. DOI: 10.1016/j.buildenv.2011.04.002
15. Maciel, A.C.F., Tereza Carvalho, M.T. Operational energy of opaque ventilated façades in Brazil. Journal of Building Engineering. 2019. 25. 100775. DOI: 10.1016/j.jobe.2019.100775
16. Falk, J, Sandin, K. Ventilated rainscreen cladding: a study of the ventilation drying process. Build Environ. 2013. 60. Pp. 173–184. DOI: 10.1016/j.buildenv.2012.11.015
17. Kvande, T., Bakken, N., Bergheim, E., Thue, J.V. Durability of ETICS with rendering in Norway–experimental and field investigations. Buildings. 2018. 8(7). 93. DOI: 10.3390/buildings8070093
18. Mashenkov, A.N., Cheburkanova, E.V. Determination of the coefficient of thermotechnical homogeneity of hinged facade systems with an air gap. Construction materials. 2007. 6. Pp. 10–12.
19. Nizovtsev, M.I., Bely, V.T., Sterlyagov, A.N. New facade system with ventilated channels for insulation of new and reconstructed buildings. Proceedings of the Scientific and Practical Conference "Energy and Resource Efficiency of Low-Rise Residential Buildings". Institute of Thermal Physics. S.S. Kutateladze SB RAS. 2013. Pp. 64–74.
20. Nizovtsev, M. I., Belyi, V. T., Sterlygov, A. N. The facade system with ventilated channels for thermal insulation of newly constructed and renovated buildings. Energy and Buildings. 2014. 75. Pp. 60–69. DOI: 10.1016/j.enbuild.2014.02.003
21. Nizovtsev, M. I., Letushko,V. N., Borodulin, V. Yu., Sterlyagov, A. N. Experimental studies of the thermo and humidity state of a new building facade insulation system based on panels with ventilated channels. Energy and Buildings. 2020. 206. 109607. DOI: 10.1016/j.enbuild.2019.109607
22. Borodulin, V.N., Nizovtsev, M.I. Modeling of the thermal and humidity state of the building facade insulation system based on panels with ventilated channels. Journal of Building Engineering. 2021. 40. 102391. DOI: 10.1016/j.jobe.2021.102391

23. Safin, I.Sh., Kupriyanov, V.N. Calculation-experimental study of moistening of building envelopes structures with vaporous moisture. Bulletin of the Volga Regional Branch of the Russian Academy of Architecture and Building Sciences. 2011. 14. Pp. 183–187.

24. Asphaug, S.K., Kvande, T., Time, B., Peuhkuri, R.H., Kalamees, T., Johansson, P., Berardi, U., Lohne, J. Moisture control strategies of habitable basements in cold climates. Build. Environ. 2020. 169. 106572. DOI: 10.1016/j.buildenv.2019.106572

25. Charisi, S., Thiis, T.K., Stefansson, P., Burud, I. Prediction model of microclimatic surface conditions on building façades. Building and Environment. 2018. 128. Pp. 46–54. DOI: 10.1016/j.buildenv.2017.11.017

26. Harriman, L.G., Grimes, C., Hart, K.Q., Hodgson, M., Thi, L.C.N., Offermann, F., Rose, W., Harriman, L.G., Zhang, J. Position Document on Limiting Indoor Mold and Dampness in Buildings. ASHRAE: AtlantaGA USA. 2021. 18. https://www.ashrae.org/file%20library/about/position%20documents/ashrae---limiting-indoor-mold-and-dampness-in-buildings.pdf.

27. Sedlbauer, K. Prediction of mould growth by hygrothermal calculation. J. Therm. Envelope Build. Sci. 2002. 25. Pp. 321–336. DOI: 10.1177/0075424202025004093

28. Feist, W.C. Outdoor wood weathering and protection. Adv. Chem. 1989. 225 (11). Pp. 263–298. DOI: 10.1021/ba-1990-0225.ch011

29. Thelandersson, S., Isaksson, T. Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions. Build. Environ. 2013. 65. Pp. 18–25. DOI: 10.1016/j.buildenv.2013.03.016

30. Safin I.Sh., Kupriyaov V.N. Raschetno-eksperimentalnoye issledovaniye uvlazhneniya ograzhdayushchikh konstruktsiy paroobraznoy vlagoy, Vestnik Volzhskogo regionalnogo otdeleniya Akademii Arkhitektury i stroitelnykh nauk 4 (2011) 183–187.(Safin I.Sh., Kupriyov V.N. Calculation and experimental study of moistening of building envelopes with vaporous moisture, Bulletin of the Volga Regional Branch of the Academy of Architecture and Building Sciences 4 (2011) 183–187.)

31. Meiss. A., Feijó-Muñoz, J. The energy impact of infiltration: A study on buildings located in north central Spain. Energy Effic. 2015. 8. Pp. 51–64. DOI: 10.1007/s12053-014-9270-x

32. Jokisalo, J.; Kurnitski, J.; Korpi, M., Kalamees, T., Vinha, J. Building leakage, infiltration and energy performance analyses for Finnish detached houses. Build. Environ. 2009. 44. Pp. 377–387. DOI: 10.1016/j.buildenv.2008.03.014

33. Recart, C., Dossick, C.S. Hygrothermal behavior of post-retrofit housing: A review of the impacts of the energy efficiency upgrade strategies. Energy and Buildings. 2022. 262. 112001. DOI: 10.1016/j.enbuild.2022.112001

34. Collins, M., Dempsey, S. Residential energy efficiency retrofits: potential unintended consequences. J. Environ. Plann. Manage. 2019. 62 (12). Pp. 2010–2025. DOI: 10.1080/09640568.2018.1509788

35. Ortiz, M., Itard, L., Bluyssen, P.M. Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review. Energy and Buildings. 2020. 110102. DOI: 10.1016/j.enbuild.2020.110102

36. Bendouma, M., Colinart, T., Glouannec P., Noël, H. Laboratory study on hygrothermal behavior of three external thermal insulation systems. Energy and Buildings. 2020. 210. 109742. DOI:10.1016/j.enbuild.2019.109742.

37. Tomson, J., Vimmrova, A., Cerny, R. Long-term on-site assessment of hygrothermal performance of interior thermal insulation system without water vapour barrier. Energy Build. 2009. 41 (1). Pp. 51–55. DOI: 10.1016/j.enbuild.2008.07.007

38. Andreotti, M., Calzolari, M., Davoli, P., Pereira, L.D. Hygrothermal performance of an internally insulated masonry wall: Experimentations without a vapour barrier in a historic Italian Palazzo. Energy and Buildings. 2022. 260. 111896. DOI: 10.1016/j.enbuild.2022.111896

39. Kunzel, H.M. Simultaneous Heat and Moisture Transport in Building Components. Fraunhofer IRB Verlag. Suttgart. 1995.

40. Kunzel, H.M. Effect of interior and exterior insulation on the hygrothermal behaviour of exposed walls. Materials and Structures. 1998. 31. Rr. 99–103.

41. Borodinecs, A., Geikins, A., Barone, E., Jacnevs, V., Prozuments, A. Solution of bullet proof wooden frame construction panel with a built-in air duct. Buildings. 2022. 12. 30. DOI: 10.3390/buildings12010030

42. Borodinecs, A., Prozuments, A., Zemitis, J., Zajecs, D., & Bebre, G. Hydrothermal performance of the external wooded frame wall structure reinforced with ballistic panels. 2020. Paper presented at the E3S Web of Conferences. 172. 07005. DOI: 10.1051/e3sconf/202017207005

43. Geving, S., Holme, J. Vapour retarders in wood frame walls and their effect on the drying capability. Frontiers of Architectural Research. 2013. 2. 1. Pp. 42–49. DOI: 10.1016/j.foar.2012.12.003

44. Nik, V. Application of typical and extreme weather data sets in the hygrothermal simulation of building components for future climate – A case study for a wooden frame wall. Energy and Buildings. 2017. 154. Pp. 30–45. DOI: 10.1016/j.enbuild.2017.08.042

45. Straube, J., Smith, R., Finch, G. Spray Polyurethane Foam: The Need for Vapor Retarders in Above-Grade Residential Walls. Research Report – 0912. 2009. Building Energy Group, University of Waterloo. 49 P.

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