Comparative Analysis of Hygrothermal Behaviour of the Exterior Walls in Transient Regime

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Abstract. Energy conservation and an intelligent use of resources are among primary objectives in the contemporary society. The decrease of energy consumption in buildings has many benefits both on operating costs and environment preservation too. During the buildings life-cycle, the energy consumption for operation, in winter through heating and in summer through ventilation, is more important than the energy used in the construction phase, requiring passive measures from the design stage. The paper presents the results of a study of the behaviour, in a variable regime, of the external wall with different structures, to the mass transfer and temperature variations. The influence of the placement of interior or exterior thermal insulation layers on the hygrothermal behaviour of the envelope element was determined by means of WUFI® Pro software, which takes into account the built-in moisture, driving rain, solar radiation, long-wave radiation, capillary transport, and summer condensation.

1. Introduction

Massive walls exposed to the natural climate, without special rain protection, show a dynamic moisture balance influenced by the alternating events of rain and solar radiation. The moisture reduces the thermal insulation capacity of the wall. In this case, thermal rehabilitation solutions are necessary to improve the building performances. But, if existing walls are usually breathable and they can withstand rain and snow as they will dry out during the year, when they are additional insulated, the whole dynamic of the wall is changed, because the vapours cannot pass through the wall and the heat cannot dry out, having negative consequences on the wall structure.

When a building envelope wall has to be thermally insulated, it is advisable to apply the thermal insulation layer to the external face of the façade (besides avoiding the most of the thermal bridges, it increases internal thermal inertia, maintains building structure at constant temperature and diminishes the interstitial condensation risk in building elements). However, sometimes may be too costly or undesirable because the original façade should remain unaltered for aesthetic reasons. In such cases, the only possible alternative is the insulation of the indoor face of the wall.

In this situation are the patrimony buildings which are often made of load bearing masonry walls. In this situation, besides increasing the thermal bridge effect, the decrease in temperature of the masonry element, caused by this type of thermal insulation will reduce the drying process of precipitation moisture. Elevated moisture contents, due to the impact of driving rain on exposed walls, can also lead to frost damage or accelerated degradations.

In addition to accounting for the thermal response of buildings and building components, it is also important to know the level of the moisture and the effects of humidity on building elements. Long-term exposure to high moisture level can cause degradation in the building's closing elements, and the development of mould on surfaces where condensation occurs may lead to significant health problems. Heat and mass transport in buildings elements are coupled. It is well known that high moisture levels result in higher heat losses, and the temperature conditions in building elements influence the mass
transfer phenomenon. The analysis of the coupling of heat and mass transfer is known as “hygrothermics”.
During time, different models for the coupled heat, air, moisture and salt transport have been developed, beginning with old manual analysis tools as "dew point method" and "Glaser diagram" to more accurate modern HAM models (heat, air and moisture) which combine the flow equations with the mass and energy balances [1-3].

1.1. The simplified graphical and numerical method: Glaser
The traditional method for assessing the moisture balance of a building component has been the Glaser method (described in the DIN 4108 standard) which analyses the vapour diffusion transport in the building component, and is based on the following diffusion equation:

\[ w = - \frac{(\delta'/\mu') \Delta p}{d} \]

where:
- \( w \) = vapour flow per unit of area, [kg/m²⋅s];
- \( \delta' \) = diffusion coefficient of water vapour in air, [s];
- \( \mu' \) = diffusion resistance factor of the material, [-];
- \( p \) = vapour pressure [Pa];
- \( d \) = flow path or thickness of the material, [m].

However, this method does not take into account the mass transfer through capillarity and the absorption capacity of the material, both of them reducing the risk of degradation due to condensation. Furthermore, because the Glaser method takes into account only the steady-state mass transfer phenomenon under simplified boundary conditions, it cannot have in view short-term events or to consider the rain and solar radiation. It was intended to offer a general assessment of the hygrothermal behaviour of a building element, not to give a simulation of the real heat and moisture transfer into a building element exposed to location specific climatic conditions at a certain location.

1.2. Simultaneous heat and moisture transfer in building elements
Advanced hygrothermal computer models available today are based on the latest knowledge and deeper understanding of the combined heat, air and moisture transfer in building materials and components. The main advantage of modelling is that it can predict the long-term hygrothermal behaviour of the building envelope elements under different climatic and interior conditions and the effect of various energy retrofit methods on the building lastingness [2].

The equations proposed by Künzel [3] for the simultaneous heat and moisture transfer are:

\[ \frac{dH}{dT} \frac{dT}{dt} = \nabla \left( \lambda \nabla T \right) + h_v \nabla \left( \delta_p \nabla (\varphi p_{sat}) \right) \]  

(2)

\[ \frac{dw}{d\varphi} \frac{d\varphi}{dt} = \nabla \left( D_\varphi \nabla \varphi + \delta_p \nabla (\varphi p_{sat}) \right) \]  

(3)

where:
- \( H \) = enthalpy, [J/m³];
- \( T \) = temperature, [K];
- \( h_v \) = latent heat of phase change, [J/kg];
- \( \delta_e \) = water vapour permeability of the building material, [kg/m⋅s⋅Pa];
- \( p_{sat} \) = water vapour saturation pressure, [Pa];
- \( \lambda \) = thermal conductivity of the moist building material, [W/m-K];
- \( \varphi \) = relative humidity, [-];
$D_\varphi =$ liquid conduction coefficient of the building material, [kg/m⋅s];

$w =$ water content [kg/m$^3$];

$t =$ time, [s].

During the last decades, many hygrothermal simulation methods have been developed [4, 5] to analyse the physical phenomena that influence heat and moisture transfer within building materials. There are also many experimental studies signalled in literature which aim to compare the results from numerical models with experimental measurements and the general trend shows that discrepancies are observed most particularly for highly hygroscopic or bio-based materials than for traditional construction materials such as concrete or brick [6].

WUFI is a computer program for the calculation of the simultaneous heat and moisture transfer in multi-layer building components, developed by the Department of Hygrothermics at Fraunhofer IBP. WUFI® is an acronym for Wärme Und Feuchte Instationär - which means heat and moisture transiency. It has repeatedly been validated by comparison with experimental results and provide realistic simulation of hygrothermal conditions in building elements and buildings under actual climate conditions.

2. Case study

One of the constructive solutions for the thermal insulation of the external wall of the buildings, which is preferred due to its simplicity, is the ETICS (External Thermal Insulation Composite System), and consists in the attachment of a thermal insulating material layer directly on the outer face of the structural wall. Often the structural wall is made of brickwork masonry, and sometimes due to particular restrictive conditions (as heritage building façade preservation), the thermal insulating layer is fixed on inside part of the envelope wall.

By means of experimentally-validated heat and moisture transfer calculation software, the effect of different thermal insulation constructive solutions on the hygrothermal behaviour of brick wall will be studied in this research. The study approach is the behaviour, in time and in a variable hygrothermal regime, of the external wall to the mass transfer and temperature variations.

The 25 cm thick solid brick masonry external wall is insulated in three constructive versions, which have been modelled in the experiment. In the first case (a.) it is considered a 10 cm thick EPS insulation layer fixed on the outer face of the wall, in the second case (b.) it is considered a 10 cm thick EPS insulation layer fixed on the inside part of the wall, and in the third case (c.) it is considered a 10 cm thick mineral wool insulation layer fixed on the outer face of the wall.

The main physical and geometrical characteristics ($\rho$ - material density, $c$ - specific heat capacity, $\lambda$ - thermal conductivity, thickness) of the constitutive materials used in each wall element are given in the tabular and graphical manner presented in Figure 1. The thermal resistance of all layers for each of the three studied cases is comprised between 2.87 m$^2$K/W - see Figure 1.b - and 3.05 m$^2$K/W - see Figure 1.a - values that recommend them as effective solutions for energy conservation.

As outdoor climate data, the hourly values of air temperature, humidity and solar radiation on a south-east oriented façade and the driving rain recorded during an average year in Graz (Austria) (the nearest location to Romania included in database of the software) were used.

Indoor air temperature for dwelling buildings, according to EN15026 standard is $T_i=+20^{\circ}C$ during winter (heating season) and $T_i=+25^{\circ}C$ (cooling season). The indoor relative humidity varies between 30% (winter) and 60% (summer).

For new reinforced concrete frame building constructions, the constructive materials were exposed to the open air during storage and construction time, thus having attained equilibrium moisture. In this case, the initial moisture (water content) can be set to the equilibrium water content of the material at 80% RH (relative humidity). In Romania, this is the annual mean outdoor RH, if sheltering of the material from the rain and direct sunshine action is assumed.
Figure 1. The structure and main hygrothermal characteristics of the studied walls

| Nr. | Material/Layer (from outside to inside) | $\rho$ [kg/m³] | $c$ [J/kgK] | $\lambda$ [W/mK] | Thickness [m] | Color |
|-----|----------------------------------------|----------------|-------------|------------------|---------------|-------|
| 1   | Mineral Finishing Coat                  | 1482           | 850         | 0.954            | 0.002         |       |
| 2   | Mineral Plaster (stucco, A-value: 0.1 kg/m2h0.5) | 1900           | 850         | 0.8              | 0.005         |       |
| 3   | EPS (heat cond. 0.04 W/mK - density: 15 kg/m³) | 15             | 1500        | 0.04             | 0.1           |       |
| 4   | Solid Brick Wienerberger                | 1786           | 889         | 0.519            | 0.25          |       |
| 5   | Lime Cement Mortar, fine               | 1880           | 850         | 0.6              | 0.03          |       |
| 6   | Interior Plaster (Gypsum Plaster)       | 850            | 850         | 0.2              | 0.002         |       |

**a. external wall with polystyrene insulation on outer face**

| Nr. | Material/Layer (from outside to inside) | $\rho$ [kg/m³] | $c$ [J/kgK] | $\lambda$ [W/mK] | Thickness [m] | Color |
|-----|----------------------------------------|----------------|-------------|------------------|---------------|-------|
| 1   | Mineral Finishing Coat                  | 1482           | 850         | 0.954            | 0.002         |       |
| 2   | Mineral Plaster (stucco, A-value: 0.1 kg/m2h0.5) | 1900           | 850         | 0.8              | 0.005         |       |
| 3   | Mineral Insulation Board                | 115            | 850         | 0.043            | 0.1           |       |
| 4   | Solid Brick Wienerberger                | 1786           | 889         | 0.519            | 0.25          |       |
| 5   | Lime Cement Mortar, fine               | 1880           | 850         | 0.6              | 0.03          |       |
| 6   | Interior Plaster (Gypsum Plaster)       | 850            | 850         | 0.2              | 0.002         |       |

**b. external wall with mineral wool insulation on outer face**

| Nr. | Material/Layer (from outside to inside) | $\rho$ [kg/m³] | $c$ [J/kgK] | $\lambda$ [W/mK] | Thickness [m] | Color |
|-----|----------------------------------------|----------------|-------------|------------------|---------------|-------|
| 1   | Mineral Finishing Coat                  | 1482           | 850         | 0.954            | 0.002         |       |
| 2   | Cement Lime Plaster (stucco, A-value: 2.0 kg/m2h0.5) | 1900           | 850         | 0.8              | 0.02          |       |
| 3   | Wienerberger Solid Brick               | 1744           | 889         | 0.5438           | 0.25          |       |
| 4   | EPS (heat cond. 0.04 W/mK - density: 15 kg/m³) | 15             | 1500        | 0.04             | 0.1           |       |
| 5   | Lime Cement Plaster (stucco, A-value: 2.0 kg/m2h0.5) | 1900           | 850         | 0.8              | 0.02          |       |
| 6   | Interior Plaster (Gypsum Plaster)       | 850            | 850         | 0.2              | 0.002         |       |

**c. external wall with polystyrene insulation on inner face**
3. Results and discussion
Some or the result of the computer simulation are described in this section. Form the entire period of simulation of three years, the results from the middle of last summer and winter (in the third year of analyse) are presented in Figures 2 and 3.

A time history simulation performed by the model is presented as a film file (Figure 3), which allows the display, as an animation, the thermal and hygric processes in the walls, hour by hour, during the middle of last winter season. The temperature profile from outdoors (left) to indoors (right) is presented in the upper graph. The red line shows the level of the temperature at twelve o’clock on 1 January in the third year of simulation. The pink area shows all the temperatures values reached in the various layers. The graph below with the green and blue lines and areas represents the moisture analysis. Relative humidity is in green colour and water content is represented in blue (the lines refer also for twelve o’clock on 1 January in the third year of simulation).

It can be observed that, in case c. with thermal insulation on the inner face, the masonry wall is submitted to a greater range of negative temperatures, with an undesirable impact on the mechanical characteristics and durability of this structural element.
The fluxes of heat and moisture across the layer interfaces and the component surfaces are presented by the red and blue arrows above each graph. On the left side of the screen are shown the current amounts of solar radiation and rain.

The film is useful for gaining insights into the hygrothermal processes in the component. In this way, the reaction of different building elements to the changing of climatic conditions could be seen. The moisture migration in different seasons and the construction parts which might be critical with respect to relative humidity are also shown.

The placement of thermal insulation materials with low vapour permeability on the external face of the wall can significantly reduce the drying capacity of a wall system (especially during winter season). This constructive solution could be appropriate if it is sufficient and available the drying of the wall to the interior space of the building without affecting the indoor climate / comfort. Exterior position of

Figure 3. Temperature and water content variation along the structure of exterior wall, in the middle of the winter, in the 3rd year of analysis: a. – exterior wall with polystyrene insulation on the outer face, b. – exterior wall with mineral wool insulation on the outer face, c. – exterior wall with polystyrene insulation on the inside part of the wall.
the thermal insulating materials with high vapour permeability facilitates drying to the outdoor space as well as wall systems with no exterior insulation.

![Figure 4](image.png)

**Figure 4.** Variation of water content: red line - external wall with polystyrene insulation on the outside face, green line - external wall with polystyrene insulation on the inside face, blue line - external wall with mineral wool insulation on the outside face.

The interior insulation leads to higher average water content in the masonry (see Figure 4). In order to improve the moisture situation induced by the interior insulation, a water-repellent impregnation may be applied to the façade.

Due to higher vapour diffusion resistance, the EPS insulated wall dries somewhat more slowly than the wall insulated with mineral wool, but the effect is not significant because the main moisture flux is directed to the outside of the wall.

A mineral wool insulation system leads to a faster drying of the masonry underneath than do insulation systems with polystyrene. There may be, however, one danger: a frost damage risk if a thermal insulation system with mineral wool is applied to a rather wet wall during a period when frost is imminent. Due to the almost unhindered vapour diffusion through the mineral wool, moisture can accumulate behind the surface plastering, especially if this rendering layer material has an elevated vapour diffusion resistance. This risk can be avoided by using polystyrene or by installing a cladding instead of a rendering.

In cases where an exterior insulation cannot be installed, a water-repellent impregnation or paint coat should be applied to the façade prior to the interior insulation; otherwise, there will be an increase in the risk of frost damage due to influence of the insulation on the drying capacity of the masonry, along with a slight decrease in thermal resistance of the masonry. It is recommended to improve the rain protection of the façade some time before installing the interior insulation. If the vapour diffusion resistance of the exterior wall surface is negligible, any insulation material can be used inside, as long as convection of the room’s air beneath the insulation layer can be safely avoided.

### 4. Conclusion

Modern calculation methods are a valuable tool to assess the hygrothermal behaviour of wall constructions. As a general rule, it is recommended the exterior insulation method of the external
walls, mainly because is the most effective method to avoid the thermal bridges from the building structure, which can result in low surfaces temperatures values, increasing the risk of mould. Simulation tools to estimate moisture movement in building elements (new or retrofitted by adding internal or external thermal insulation) are very useful for estimating moisture accumulation and interstitial condensation risk, contributing to the choice of the best design option. Together with experimental testing results, simulation studies conclusions should be included in norms and codes of practice in construction, for the guidance of building practitioners.

5. References
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