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The effect of ambient moisture conditions on heat flux time shift and decrement factor of multi-layered walls

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ABSTRACT
Thermal properties of the opaque building envelope components are crucial for limiting the energy needs of a building. In particular, dynamic thermal properties of envelope components can significantly contribute to the minimization of heat transfer through the envelope and to the appropriate utilization of the internal and solar gains. This is particularly important in the cooling operation, especially in hot climates. Previous experimental and numerical studies on the determination of dynamic thermal parameters of opaque building components neglected the influence of moisture conditions prevailing within the ambient climate. This paper utilizes a calibrated and validated dynamic heat and mass transfer model to analyse the impact of ambient moisture conditions on the determination of dynamic thermal parameters. Time shift and decrement factor are determined for different wall structures (internally insulated or externally insulated) with regard to different outdoor climatic conditions (dry and humid climate). The impact of moisture conditions on the results is analysed and assessed. The results of this study clearly show that the effect of ambient moisture conditions on time shift and decrement factor can be significant and that an application of purely thermal models will lead to inaccurate predictions of the dynamic thermal behaviour of building components.

KEYWORDS
Building envelope, moisture dependent response, heat flux time shift, decrement factor

1) INTRODUCTION

The thermal quality of opaque building envelope is a key factor in buildings whole energy performance. In order to reduce the energy consumption in the building sector and to preserve comfortable indoor conditions, heat losses and gains have to be controlled in both, new and rehabilitated buildings, which are particularly incline to overheating problems. Especially for climates with important annual cooling season, Dynamic Thermal Properties (DTP) are determined to assess the thermal performance of a building envelope and its ability to damp and delay externally impinging heat waves with respect to the building's interior. In this context, the DTP are also important indicators to prescribe efficient solutions for building envelopes.
Some researchers have already shown that, besides thermal conditions, further boundary conditions have an effect on the DTP of building components. For example Kontoleon and Bikas (2007) showed that solar absorptivity is affecting time shift and decrement factor. Moreover, a study conducted by Bishara (2017) showed that internally applied convective heat transfer conditions have a non-negligible impact on the DTP of a wooden wall structure. With regard to material moisture content, Kontoleon and Giarma (2016) showed that a certain impact of a single layer wall's moisture content on its thermal inertia parameters exists. However, the effect of hygrothermal boundary conditions on the DTP of an opaque envelope component has not been extensively investigated yet. In particular, it is not known to which extend relative humidity (RH) conditions are affecting the DTP of multi-layered envelope components.

This paper aims at a preliminary analysis of the influence of hygrothermal boundary conditions on the dynamic thermal behaviour of both, insulated and non-insulated, multi-layer walls, considering different materials and layer order.

2) METHODS

2.1) Wall structures and climatic boundary conditions

The wall structures studied in this work (see Figure 1) are similar to those analyzed with respect to thermal insulation performance by Ozel (Ozel, 2011) and Al-Sanea et.al (Sanea et.al, 2011). Case (a) is a concrete wall, 25 cm thick with external (2 cm) and internal (1.5 cm) plaster layer. In case (b), an external EPS insulation layer of 10 cm thickness is applied to the same concrete wall. Case (c) considers the same EPS insulation layer as well as an OSB layer of 1 cm thickness, installed at the internal side of the concrete wall. In a further step, two further insulation materials, namely wood fiber (WF) and mineral wool (MW) are applied, instead of the previously considered EPS layer (externally and internally, respectively).

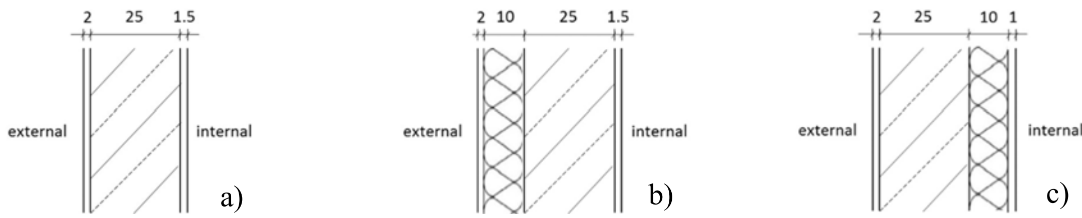


Figure 1. Investigated wall structures a) concrete wall with plaster, b) concrete wall with external EPS insulation layer, c) concrete wall with internal EPS insulation layer.

The external boundary conditions considered in this study are intended to depict summer conditions within a warm-humid (e.g. Nice, France) and a warm-dry (e.g. Madrid, Spain) European climate. The influence of radiation was neglected at this point. Internally, constant hygrothermal boundary conditions are applied (25°C, 45%RH). Both climates, climate 1 (warm-humid), and climate 2 (warm-dry), are shown in Figure 2a.

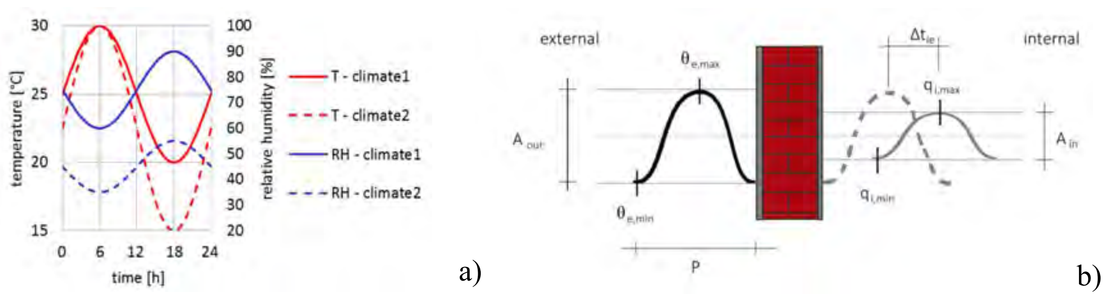


Figure 2. a) External climatic boundary conditions, b) Principal of dynamic heat wave propagation through an opaque building envelope component.

2.2) Calculation of decrement factor and time shift

The dynamic thermal behaviour of an opaque building envelope is induced by an external temperature solicitation with a period P of 24 h. This heat wave can be approximated with a harmonic function (in black in Figure 2b), which ranges from a temperature minimum ($\theta_{e,min}$) to a maximum ($\theta_{e,max}$) that define the solicitation amplitude (A_{out}). Due to storage effects that dependent upon the thermal mass of the building component, the internal response to an external temperature signal is damped and delayed. The resulting heat flux profile exhibits maximums

($q_{i,max}$) and minimums ($q_{i,min}$) with a decreasing amplitude moving to the internal surface heat flux amplitude (A_{in}). Moreover, the temporal occurrence of minimum and maximum is shifted with respect to the external original signal. This temporal shift between external and internal peak values occurrence time is the time shift (Δt_{ie}).

For the analysis of DTPs, the values of internal heat flux and external temperature are needed. They are used to determine decrement factor and time shift according to EN ISO 13786 (European Committee for Standardization, 2007), for each analysed day.

The decrement factor f is calculated by correlating periodic thermal transmittance and steady state thermal conductance:

$$f = \frac{|\hat{q}_i|}{|\hat{\theta}_e| \cdot C_S} = \frac{Y_{ie}}{C_S} \quad \text{with} \quad C_S = \frac{\phi}{(T_1 - T_2) \cdot A} \tag{1, 2}$$

The time shift Δt_{ie} is calculated as the difference of phase displacements of the first harmonics, which are φ for the external surface temperature and ψ for the internal heat flux respectively:

$$\varphi_e = \overline{\theta}_e + \theta_{e,1} \cdot \cos(\omega \cdot t + \varphi) \quad \text{and} \quad \psi_i = \overline{\phi}_i + \phi_{i,1} \cdot \cos(\omega \cdot t + \psi) \tag{3, 4}$$

$$\Delta t_{ie} = \frac{(\psi - \varphi)}{(2\pi)} \cdot 24 \tag{5}$$

2.3) Numerical simulation model

For each wall structure presented in 2.1., a two-dimensional numerical thermal simulation as well as a simulation considering heat, air, and mass (HAM) transport processes are conducted. The numerical models (thermal and HAM) are implemented within the software tool Delphin which provides a validated tool set for the representation of hygrothermal transport processes (Nicolai, 2011). This software has been applied in previous studies for analyzing decrement factor and time shift of different wall structures and under various hygrothermal boundary conditions, whereas a very good correlation with laboratory measurement results could be achieved (Bishara, 2017). For climate 1, initial conditions are set to 25°C and 80% RH. In case of climate 2, initial conditions are 22.5°C and 80% RH. Since the initial moisture content may also affect the calculation results, the same value was chosen for both climates in order to ensure comparable calculation conditions. The material data are taken from the extensive Delphin material database. Output values of temperature and heat flux are generated each minute of calculation, for a simulation period of 10 days. In total, a set of 28 simulation cases is analysed.

3) RESULTS AND DISCUSSION

Decrement factors are calculated, considering the steady thermal conductances, which are provided in Table 1. Time shifts and decrement factors are calculated for each day of the analysis and the results are evaluated for the 10^{th} day, when steady periodic conditions have been reached for each of the analysed cases.

Table 1. Steady state thermal conductances.

	concrete	EPS ext.	EPS int.	WF ext.	WF int.	MW ext.	MW int.
Cs [W/m²K]	5.46	0.339	0.333	0.391	0.384	0.374	0.367

The decrement factor results for climate 1 are shown in Figure 4a. Each of the three wall structures show deviations between thermal and hygrothermal simulation results. In case of the concrete wall, the thermal simulation leads to a decrement factor overestimation of 2.5%. In case of the EPS insulated walls, the thermal values are underestimated (external 7.1%, internal

1.8%). With regard to time shift, differences between thermal and hygrothermal results are visible, as well. They are lowest for the concrete wall without insulation (thermal overestimation of 0.5%), and highest for the case of external insulation (thermal underestimation of 1.6%).

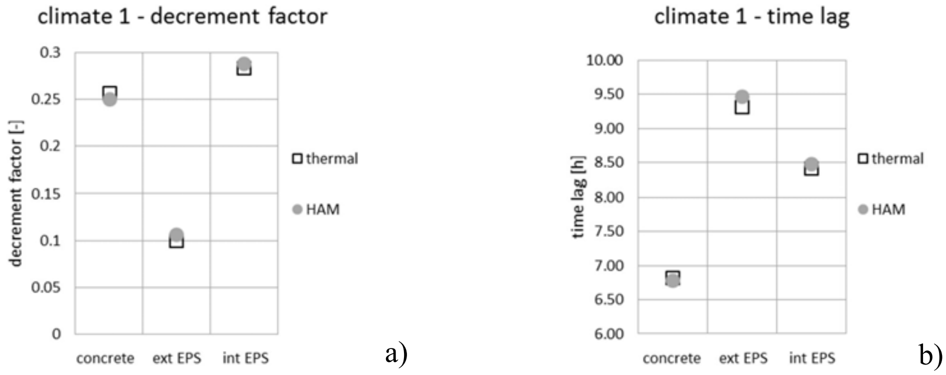


Figure 4. Results for climate1: a) decrement factor, b) time shift

The moisture gradient, which induces through over the wall components due to the different ambient humidity conditions, affects the energy transport. Therefore, the concrete wall's internal surface heat flux is reduced, whereas the insulated wall variants show increased heat flux values. It is well known that porous materials show a relation between material moisture content and thermal conductivity, which is rising with increasing moisture content. Initial material moisture contents for both simulations, thermal and hygrothermal, is set to 80% RH. The Delphin software automatically scales the initial thermal conductivity of all materials to the given humidity reference value. Consequently, the initial thermal conductivities applied to the thermal numerical model remain at a high level, whereas they decrease during the HAM simulations due to the lower ambient humidity values. As a result, time shift values of the hygrothermal simulation are higher than those of the thermal analysis.

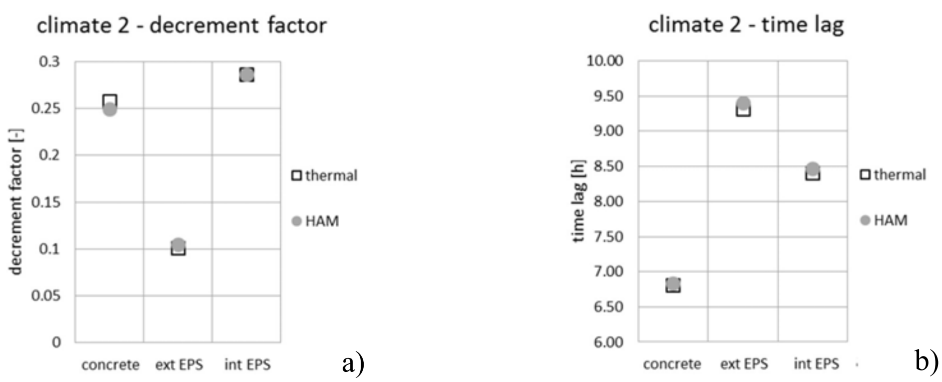
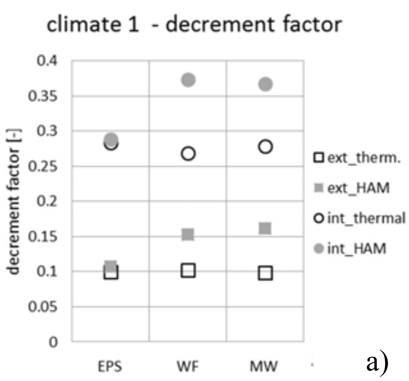


Figure 5. Results climate2: a) decrement factor, b) time shift

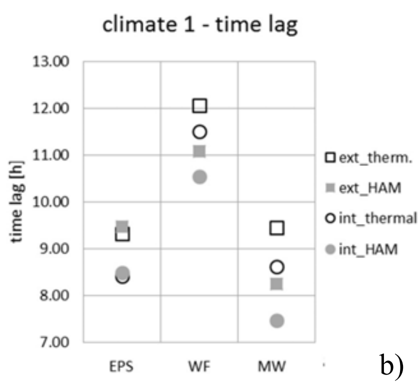
With regard to climate2 external conditions, the difference between thermally and hygrothermally determined decrement factor is about 3.3% for the concrete wall. Moreover, the thermal and hygrothermal time shift values are in accordance with each other.

For both insulation variants, the deviations are minimized compared to the climate 1 results. The decrement factor deviation for an external insulation variant is about 3%, and for an internal insulation variant 0.2%. The deviation is small too, in case of time shift (<1%).
With climate 2, the partial pressure difference between indoors and outdoors is less than with climate 1 ambient conditions. Therefore, the differences between thermal and hygrothermal calculation of decrement factor and time shift are also smaller.

Figure 6 shows the thermally and hygrothermally determined decrement factors and time shifts for the different insulation materials and in dependence of different insulation layer positions.
It can be seen from Figure 6a, that for all considered insulation materials under climate 1 conditions, external insulation is promoting lower decrement factors, and thus a better heat insulation capability, than internal insulation. At the same time, installing EPS insulation leads to the smallest difference between thermal and HAM simulation results. Differences in case of wood fiber are 48.8% for external and 39.3% for internal installation. Deviation is highest for externally installed mineral wool, reaching 63.9%, and lowest for internal installation (32.0%).
Also with regard to time shift, external insulation promotes better results than internal insulation (see Figure 6b). Again, deviations between thermal and hygrothermal values are lowest for EPS. They are higher in case of wood fiber (external 8.1%, internal 8.3%) and highest in case of mineral wool (external 12.7%, internal 13.3%).
Differences between thermal and hygrothermal values are relatively low for a wall being insulated with EPS. The major differences between thermal and hygrothermal results in case of a wall being insulated with wood fiber or mineral wool are due to a higher material porosity of these insulating materials, compared to EPS. Thus, moisture diffusion is higher and leads to higher moisture contents and thus to increased thermal conductivity and thermal diffusivity values. Consequently, energy transport is enhanced, which raises decrement factor and minimizes time shift.



a)



b)

Figure 6. Climate 1 – Results for different insulation materials and layer position.

External insulation achieves preferable results under climate 2 conditions too, as can be seen from Figures 7a and 7b. Differences between thermal and hygrothermal simulation are lowest for the wall structure with EPS insulation. In case of wood fiber insulation, the difference between thermally and hygrothermally determined decrement factor is 35.7% in case of external insulation, and 36.9% in case of internal insulation. For the external application of mineral wool, the decrement factor difference is even higher, being 67.9%, whereas internally applied mineral wool leads to a difference of 17.2%.
The time shift analysis under climate 2 external conditions also reveal differences between thermal and hygrothermal values. They are low for the concrete wall and higher in case of wood

fiber insulation (external 7.6%, internal 8.0%). In case of the mineral wool insulation, deviations are highest (external 11.4%, internal 9.5%).

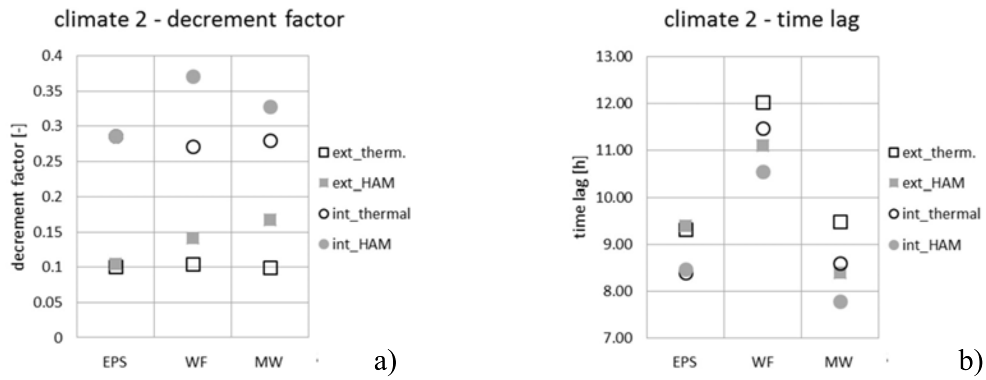


Figure 7. Climate 2 – Results for different insulation materials and arrangement.

4) CONCLUSIONS

In the present work, the influence of ambient moisture conditions on the determination of decrement factor (DF) and time shift (TS) was analyzed. In this context, various multi-layered wall structures were investigated by means of thermal and hygrothermal numerical simulations. The results clearly showed that ambient relative humidity affects dynamic thermal characteristics of the analyzed wall structures. Especially when porous materials are considered, a purely thermal determination of DF and TS leads to erroneous results. The errors in these cases were up to 68% in terms of DF, and up to 13% in case of TS. As a result, this can have a negative effect on the predicted cooling demand of a building. Future research will focus on an analysis of real ambient moisture conditions and their impact on dynamic thermal characteristics of various wall structures. In this context, also the initial material moisture content will be varied in order to determine its impact on the hygrothermal solutions. Moreover, different insulation thicknesses and the impact of external radiation will be regarded.

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