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Modelling climate related performances of building wall coatings and understanding the portability of the "Künzel" rule in different climates

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Abstract. How may a coating affect the hygrothermal performance of the building envelope in different climates? Years ago, Helmut Künzel, one of the fathers of Building Physics, proposed, a simple, well-known rule, relating two characteristics of a coating: its water absorption coefficient and its vapour diffusion. The "Künzel rule" (and the associated diagram), based on a model confirmed by field tests in the German climate, set an upper limit to both parameters and their product, became a German standard and a practice among experts, practitioners and manufacturers, in many European countries. This paper proposes the results of an analysis aiming to verify its portability in other climates and is based on an extensive simulation of the hygrothermal performances of a reference wall in six different climatic conditions.

1. Introduction

High energy performance buildings are a must, in the actual construction field, and highly insulated envelopes are fundamental to minimize energy consumption in many climates. The simple, old, masonry wall of the past deeply changed in the last sixty years, pushed by a constantly growing request for performances but also by the simultaneously growing knowledge about degradation processes and failure modes, most of which are directly or indirectly related to the control of water transport, and humidity in general, through them. Humidity, if not properly controlled, can change the behaviour of many materials, like increasing thermal conductivity or induce chemical or physical transformation and decay. For this reason, over the past century, various models have been developed and refined to understand the basic behaviour of construction materials and to simulate water, vapour and heat transport processes in complex components exposed to specific climatic conditions [1,2,3]. These models were integrated in software applications, capable of performing dynamic simulations, taking into account numerous transport processes at the same time [3,4] and, with certain limits, through complex geometries.

Before these applications, and even before computers, experts proposed diagrams and rules, based on physical principles, some clever simplifications of transport processes and conditions and, as much as possible, on verified evidence, to support and to validate design choices, in terms of position, thickness and properties of the envelope layers. The Glaser method [5], at the basis of the international standard (ISO 13788) is the most known and still used for simple evaluation of what has been called hygrothermal performance of a building component. Another basic method was proposed by Helmut Künzel, who proposed an even simpler principle to evaluate the rain protection performance of a paint or a finishing system, based on a criterion that correlates the main parameters characterizing them, i.e. their water absorption coefficient A_w and their equivalent thickness S_d (water vapour diffusion-equivalent air layer thickness) [6]. Following the Künzel rule, the external coating of a building must satisfy the following inequation:

$$A_w \cdot S_d < C_{RP} \tag{1}$$

Different values have been assigned to the C_{RP}, initially equal to 0.1 kg/mh$^{0.5}$ but subsequently assumed equal to 0.2 kg/mh$^{0.5}$ in the current German standard DIN 4108-3:2014. It should be noted that this formula has been validated based on experimental tests carried out on the IBP field test in Holzkirchen and the analysis was never extended to climates other than Central Europe.

The aim of this publication is to verify the applicability of the Künzel principle to a reference Autoclaved Aerated Concrete (AAC) wall exposed to different climatic conditions.

2. Methodology

2.1. Materials' properties

An AAC wall rendered both externally and internally is investigated. More specifically, from indoor to outdoor, it is composed of 1 cm of lime cement plaster, 40 cm of autoclaved aerated concrete and 1.5 cm of surface coating plaster on which an additional layer of paint is applied (table 1). Twenty-one "ideal" paints characterized by different values of A_w and S_d were tested, to analyse their effect on the wall hygrothermal performances (figure 1). In particular, the analysed paints lie on three curves based on different wind driven rain protection coefficients (C_{RP}): the adopted one in the current German standard (0.2 kg/mh$^{0.5}$), the original value proposed by Künzel (0.1 kg/mh$^{0.5}$) and its half (0.05 kg/mh$^{0.5}$).

Table 1. Reference wall configuration and materials' properties.

Type	Density [kg/m^3]	Th. [m]	μ [-]	λ [W/mK]	A_w [kg/m^{2}h$^{0.5}$]
Lime cement plaster (Int)	1024	0.01	6.1	0.225	7.6
AAC	390	0.40	7	0.095	2.6
Surface coating plaster (Ext)	1390	0.015	33	0.75	1.8

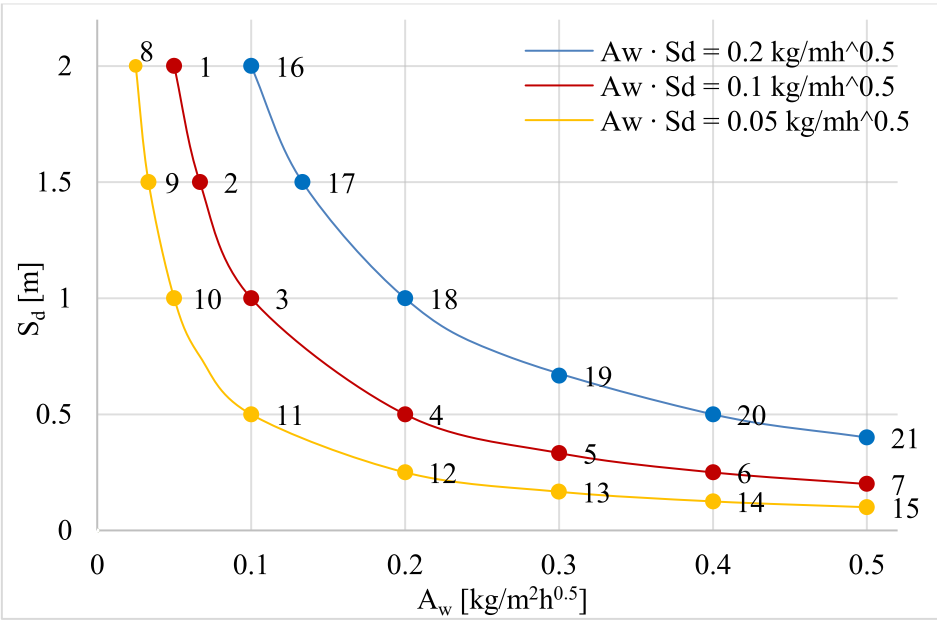

Figure 1. Water absorption coefficients and equivalent air layer thickness of the modelled paints.

2.2. Paint modelling
The wall hygrothermal performances were analysed on Delphin [7], a dynamic simulation tool for coupled heat and moisture transport in porous building materials widely used in the last few years. In the current version of the software, it is not possible to directly assign an external coating to the wall. Therefore, the outermost layer of plaster was assumed to have modified properties, with different values of A_w and μ, to take into account the effect of an applied coating. A sensitivity analysis of the results was conducted, in order to establish the correct paint thickness to be assigned to the model. Three different thicknesses were considered, equal to 2, 3 and 5 mm, reducing the external plaster layer to 13, 12 and 10 mm. The assigned properties are such that all possible solutions are characterized by equal total thickness and constant total resistance in terms of water absorption and vapour diffusion.

2.3. Boundary conditions
The AAC wall is exposed on north orientation under six external climatic conditions: the climates of Milan, Bergen, Mangalore, Stuttgart, Ljubljana and Galway were chosen as they are characterized by different distributions of temperatures and rainfall levels. Among them, Milan is characterized by the lowest amount of total yearly rainfall (644 mm), while Mangalore has the highest one (3345 mm).

As external boundary conditions, the transport mechanisms associated to heat, humidity, radiation (short-wave and long-wave) and wind driven rain were considered (table 2). For the internal ones, the distributions of temperature and relative humidity proposed by the ISO 13788 standard were applied: they vary between 20-25°C and 35-65% according to the external temperature values. Besides, a simulation time of 10 years was considered to avoid the effect of the initial conditions, assumed as 20°C of temperature and 80% of relative humidity: only the results of the 10th year were analysed, examining the moisture content in the outermost 5 cm of the AAC wall.

Table 2. Boundary conditions on Delphin.

External exchange coefficients	Value
Convective heat conduction exchange coefficient	20 W/mK
Vapour diffusion mass transfer coefficient	1.22e-07 s/m
Solar adsorption coefficient	0.4
Long-wave emissivity	0.9
Reduction/splash coefficient	0.7

Internal exchange coefficients	Value
Surface heat transfer coefficient (convective + radiative)	8 W/mK
Surface vapour diffusion coefficient	2.5e-08 s/m

3. Discussion and Results

3.1. The modelled paint thickness
As mentioned in *2.2*, one of the modelling criticalities is the reasonable thickness of paint that should be implemented in Delphin. For this purpose, a comparative analysis has been conducted by changing the properties (A_w and S_d) of the outermost 2, 3 or 5 mm of the external plaster. Figure 2 shows the wall moisture content for paint n.7 (A_w = 0.5 kg/m^{2}h$^{0.5}$; S_d = 0.2 m) under Milan and Mangalore climatic conditions: the results are reported only for the above-mentioned climates, but the same analyses have been performed for Bergen, Stuttgart, Ljubljana and Galway. A general observation is that modelling the paint as a 2, 3 or 5 mm leads to different levels of moisture content. This affirmation is valid for each of the considered climate, although the variability is more evident for Bergen and Mangalore, while for the other climates (for paints with low A_w), it is minimal. The described trend is mainly due to the climate rainfall levels: therefore, the painting thickness will have a greater influence if a higher amount of precipitations is involved.

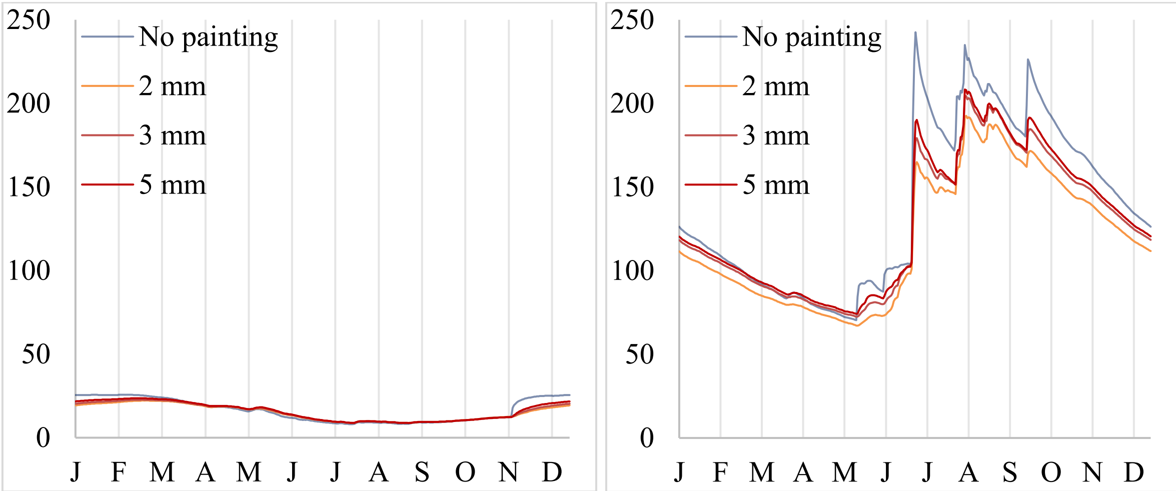

Figure 2. Moisture content [kg/m^3] in the outermost 5 cm of wall for Paint 7 when modelled as 2, 3 or 5 mm thick layer respectively under Milan and Mangalore climates.

3.2. The moisture content distribution for paints characterized by the same product $A_w \cdot S_d$

The wall moisture content has been studied comparing the effect of the external coatings belonging to the same $A_w \cdot S_d$ curve: figure 3 shows the moisture content for paints 1-7 characterized by the product $A_w \cdot S_d$ = 0.1 kg/mh$^{0.5}$ under Milan and Mangalore climates when modelling the paint as a 3 mm thick layer. Although not reported here, the same analyses have been performed for paints 8-21. The results show that there are discrepancies among the response of paints characterized by the same product between A_w and S_d: these discrepancies increase with the increasing rainfall levels. For this reason, these are more evident for Bergen and Mangalore, while the opposite can be observed for Milan. Moreover, there is a more direct influence of the A_w value on the moisture content.

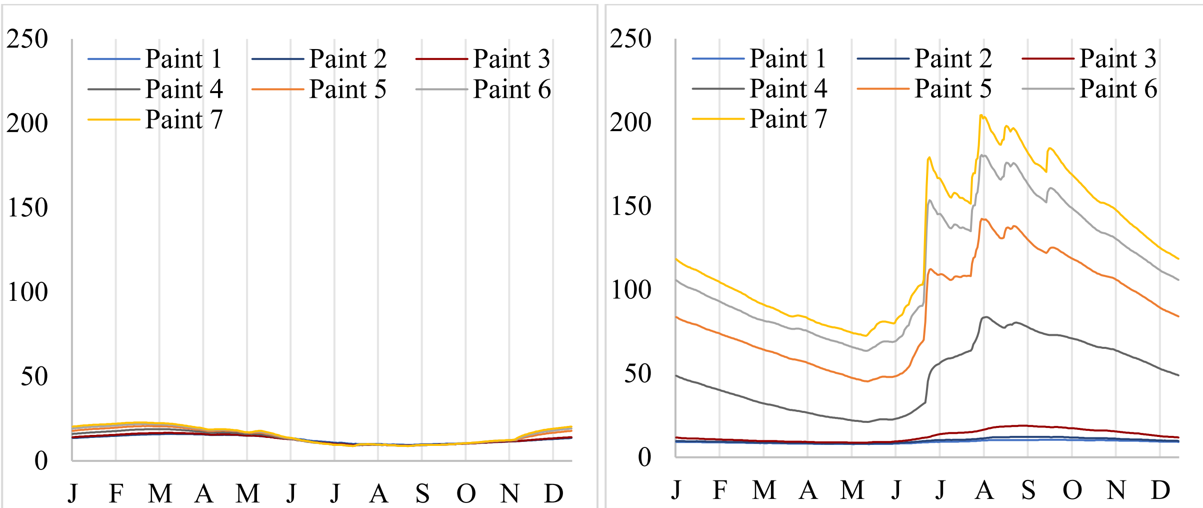

Figure 3. Moisture content [kg/m^3] in the outermost 5 cm of AAC wall for paints 1-7 modelled as 3 mm thick layer respectively under Milan and Mangalore climates.

3.3. The relation between moisture content and $A_w \cdot S_d$

For a comprehensive understanding of the moisture content associated to the analysed paints, it was necessary to study the relation among the various parameters involved. Starting from the annual moisture content average for each paint modelled as a 2, 3 or 5 mm thick layer, a linear interpolation has been performed, evaluating its relation with the water absorption coefficient and the product $A_w \cdot S_d$: Figure 4 shows the results for the case of C_{RP} equal to 0.1 kg/mh$^{0.5}$ and paint modelled as 3 mm.

For a better understanding, a 3D representation of the results could be useful: therefore, an additional axis has been added to the original Künzel diagram expressing the average moisture content. Starting from the points representing the twenty-one paints considered, an interpolated surface has been obtained for each climate (figure 5). In figure 4, the results show clearly that paints characterized by the same $A_w \cdot S_d$ do not lead to the same moisture content levels. It can be seen even better in the 3D representation of the results (figure 5), as in fact, the obtained surfaces have different inclinations which indicate the variation of moisture content. The interpolated surface is horizontal only for Milan, which is explained by the low precipitation levels that characterize its climate. Another interesting data is that the surface for Bergen is more inclined with respect to that for Mangalore although the last has higher total rainfall levels. It is mainly due to the higher temperatures in Mangalore that cause higher evaporation potentials. In general, different moisture content values are reached for paints with the same $A_w \cdot S_d$.

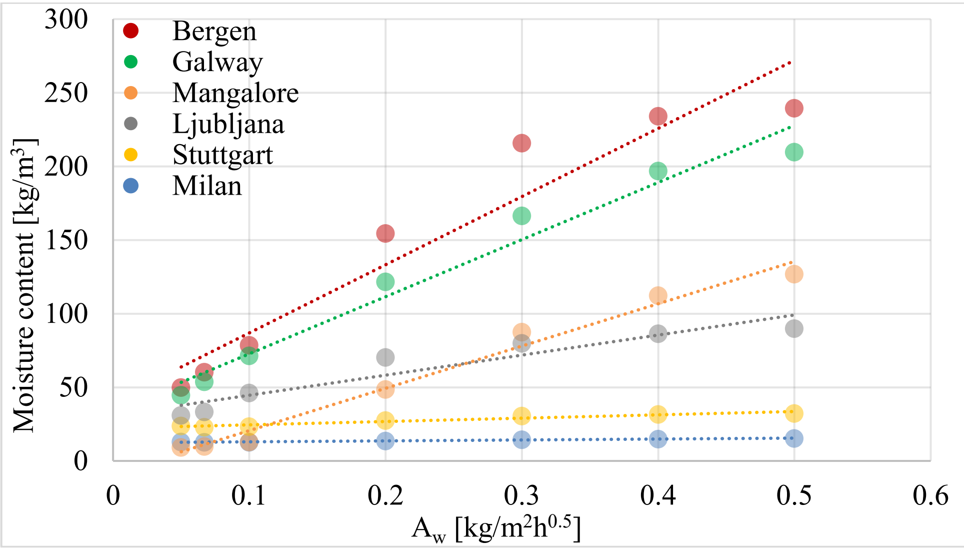

Figure 4. Moisture content trendline as function of A_w for paints characterized by the product $A_w \cdot S_d$ equal to 0.1 kg/mh$^{0.5}$.

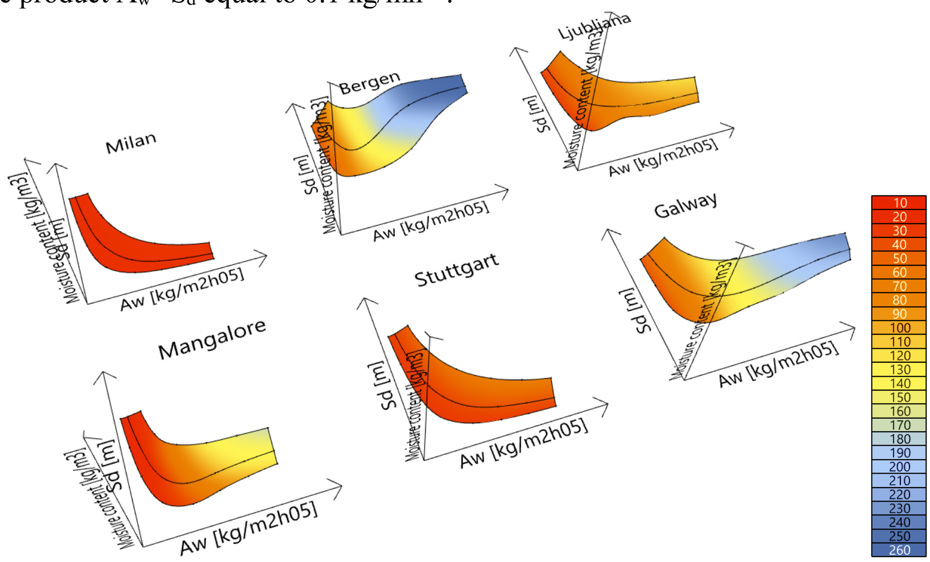

Figure 5. 3D representation of the relation among moisture content, A_w and S_d.

4. Conclusion

The aim of the presented work is investigating a criterion for the external coating selection proposed by Helmut Künzel and adopted in the current German standard. The hygrothermal behaviour of a reference AAC wall was analysed on Delphin, evaluating its moisture content considering twenty-one external coatings under six climatic conditions. The first problem to deal with was about the modelling process since, due to a software limitation, it was not possible to directly assign the coatings to the wall: for this reason, it was necessary to modify the properties of the outermost 2, 3 or 5 mm of external plaster and keeping a constant wall thickness. In this sensitivity analysis, small differences were found for climates characterized by low precipitation levels, which do not significantly affect the wall moisture content measured in its outermost 5 cm. On the contrary, for rainy climates, the modelled paint thickness leads to variable moisture contents. Afterwards, by keeping a fixed modelled paint thickness, equal to 3 mm, the wall moisture contents were then compared applying paints with the same C_{RP}, trying to find a correlation among the involved parameters. The simulation results highlighted the importance of the reference climate: if low precipitations were involved, paints characterized by the same C_{RP} lead to similar moisture contents. On the contrary, for high precipitation levels, paints belonging to the same Künzel curve lead to variable moisture contents. Moreover, for these climates, A_w has a more significant influence than S_d on the wall hygrothermal performances, and thus it should be kept as low as possible to reduce building pathologies risks. This work which aimed to evaluate the Künzel principle effectiveness for climates different from the central European leads to several open questions which could constitute the basis for future studies. In particular, the paint modelling problem could be studied by means of laboratory tests and comparing them with simulation results in order to increase the simulation accuracy. Besides, a deeper study could involve the relation among moisture content, A_w and S_d and the introduction of a correction coefficient that could account for the climates variability.

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