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Risk of Mould Growth in Future Climate in Different European Locations for Two Bio-based Insulation Systems for Interior Retrofitting

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Abstract. This research project investigated the hygrothermal performance of two bio-based insulation systems for interior retrofitting solid masonry walls; loose-fill cellulose insulation and hemp fibre insulation mats. The study was carried out through HAM simulations calibrated with 1 year and 2 months of measurements and material data from a field experiment in Denmark's Nordic, maritime climate. The experimental setup comprised a 40-foot (12.2 m) insulated reefer container with controlled indoor climate, reconfigured with several holes (1x2 m each) accommodating the solid masonry walls. Some of the masonry walls had exterior hydrophobisation. The calibrated simulation models were used to investigate the long-term robustness of the bio-based insulation systems to the future climate conditions caused by different emission scenarios between year 2020 and 2050, for several locations around Europe. The focus of the study was on the conditions in the interface between the masonry and the internal insulation, and the mould risk was evaluated using the VTT mould growth model. The findings showed high relative humidity levels in the masonry/insulation interface with a high risk of mould growth, already exposed to the current climate data. The results indicate that the future climate conditions would exacerbate the hygrothermal conditions in the insulated masonry walls. Exterior hydrophobisation positively affected the hygrothermal balance in the insulated masonry walls, lowering the risk of mould growth under future climate conditions. However, the results indicate that in some cases, the insulation systems would still experience critical relative humidity levels despite the combination with hydrophobisation.

INTRODUCTION

Retrofitting historic building facades has been a hot topic in recent years due to the considerable energy conservation potential. Many of these buildings are protected as their aesthetic, historical and/or cultural values are considered worthy of preservation. This places several restrictions on exterior alterations, which often leaves internal insulation as the remaining option for energy saving measures at the facade. Internal insulation is generally considered problematic as the reduced heat flow to the existing wall results in a lower temperature gradient, and the original wall becomes colder [1], [2]. This increases the risk of interstitial condensation and moisture-induced damage. Furthermore, with the increased focus on sustainability and resource efficiency, the use of alternative building materials such as bio-based insulation materials are becoming both relevant and necessary. This includes bio-based insulation for internal retrofitting historic masonry walls. However, bio-based materials are typically susceptible to biodegradation at high relative humidity (RH). Previous studies on the hygrothermal performance of internal insulation still do not agree on when it can be performed safely [3-7]. Another obstacle is the predictions of a future with more severe weather events and, for some regions, increased annual precipitation [8], which could exacerbate the risk of moisture-induced damage. It is, therefore, necessary to investigate the long-term hygrothermal performance of bio-based insulation, to determine under what types of climates it will be feasible to use for internal retrofitting, and if the combination with additional measures such as exterior hydrophobisation could improve the performance.

METHODS AND MATERIALS

Test Stand Description

An experimental set-up was constructed in Kongen Lyngby north of Copenhagen, comprising a 40-foot insulated reefer container with eight 1 x 2 m cut-outs made in the façade. The cut-outs would accommodate eight identical solid masonry walls with the dimensions (HxWxD) 1987 mm by 948 mm by 358 mm (including 10 mm interior rendering), constructed with masonry bricks and mortar resembeling those used in Danish historic multi-story building from the period 1850-1930. Additional information are available in [3-4]. The test walls were internally insulated with two bio-based insulation materials. The indoor climate was kept at 20 °C and 60 % Relative Humidity (RH) throughout the year. No cooling or dehumidification were installed. RH and temperature were logged every 10 minutes using digital HYT221 sensors installed and embedded in several different locations in each test wall and for the indoor and outdoor climates. Solar, wind and rain were obtained from a climate station located 160 m from of the test site. The test walls were facing south-west, which is the most critical direction in Denmark for wind driven rain.

Simulation Study

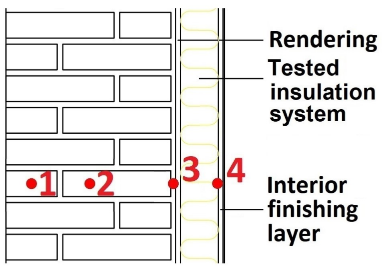
Numerical simulations were conducted to study the long-term hygrothermal performance of two bio-based diffusion-open insulation systems for interior retrofitting solid masonry walls: 1) hemp fibre mats, and 2) loose-fill cellulose fibres. The simulations were performed using the Delphin 6 software [9]. Measurements for 1 year and 2 months (07-12-2020 to 09-02-2022) from the test set-up were used to calibrate the models. The simulation results for different climate scenarios from 2020-2050 were post-processed with a mathematical mould-growth model.

Model Configurations

In this paper, 1-dimensional HAMT models were created for four of the eight test walls, applying the correct wall geometries and material data: two walls fitted with 170 mm hemp insulation (with/without hydrophobisation), and two walls with 170 mm cellulose insulation (with/without hydrophobisation). Both insulation systems had an interior cladding of 13 mm fibre gypsum board. The properties of the used materials may be found in Table 1. Note that moisture retention and liquid conductivity curves are available in the supplementary files [14].

TABLE 1. Density, thermal conductivity, vapour diffusion resistance factor and water absorption coefficient for materials used in the Delphin simulations. [a)] Tested in the present project, [b)] From Delphin materials databased, [c)] Provided by manufacturer, [d)] Obtained from [10]. Unmarked were tested prior to this project. On the right: vertical section of a test wall.

	ρ [kg/m^3]	Θ [m^3/m^3]	λ [W/(m·K)]	C_p [J/kg·K]	μ [-]	A_w [kg/(m^2·s^{½})]
Yellow masonry brick	1643	0.385	0.6	942	16.9	0.278
7.7% lime mortar	1243	0.531	0.44	998	22.4	0.39
Hemp fibre insulation	35[c]	0.981	0.039[c]	1700	2[a]	0.032[d]
Cellulose insulation	46[c]	0.926	0.039[c]	2544	1[a]	0.56[b]
Fibre gypsum board	1133[b]	0.626	0.341[b]	1228	14.2[b]	0.057[b]



Model Calibration

The simulation models were calibrated against measured RH and temperature data for sensors 1-4 (red dots on wall section in Table 1), using the experimental setup's measured initial and interior/exterior boundary conditions.

Exterior hydrophobisation was simulated by reducing the water uptake coefficient, A_w, by a factor 1000 for the outermost 10 mm of the masonry wall. After carrying out the model calibrations, the boundary coefficients were set as follows: Ground reflection (albedo) 0.25 [-], Short wave absorption 0.75 [-], Long wave emission 0.9 [-], Rain exposure coefficient 0.7-1.0 [-], Internal/external heat exchange coefficient 5.0/13.5 [W/(m^2·K)], Internal/ external vapour exchange coefficient $3.0 \cdot 10^{-8}/2.0 \cdot 10^{-7}$ [s/m].

Model Variations

After calibration, the hygrothermal conditions in the 4 wall models were simulated using 3 sets of climate data: 1) Typical meteorological year (TMY) based on data from the period 2004 until 2018, 2) Special Report on Emissions Scenarios (SRES) [8] A1B for the period 2020 until 2050, and 3) RCP 4.5 emission scenario [8] for the period 2020 until 2050. Simulations for the 4 wall models were carried out for 7 locations around Europe: Bologna (BO)(67.5°), Bratislava (BTS)(315°), Copenhagen (CPH)(247.5°), Dublin (DUB)(247.5°), Kiruna (KRN)(180°), Moscow (MSK)(225°), and Munich (MU)(247.5°). The wall models were simulated both facing the prevailing direction for wind driven rain as well as facing North. Note that in figures and tables, the numbers given after the location and emission scenarios describe the wall orientation, with North = 0, East = 90, South = 180, and West = 270.

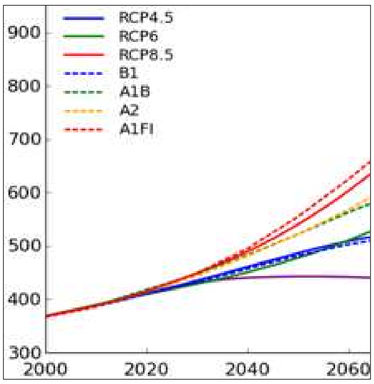
Boundary Conditions

Table 2 provides an overview of the outdoor boundary conditions in the 3 climate data sets for each of the 7 cities around Europe. It was observed that there were no clear tendencies in terms of changes in the wind velocity. A rise or drop in the average wind velocity did not correlate with a rise or drop in the maximum wind velocity. Therefore, the maximum wind velocity has been left out in Table 2. In terms of the CO_2 concentration of the used emission scenarios, the graph shows that in year 2050, emission scenario A1B is predicted to be around 525 ppmv and emission scenario RCP 4.5 to be around 490 ppmv [8]. All models were simulated with an outdoor temperature-dependent indoor temperature and humidity according to EN/ISO 13788:2013 Annex A.1 'Continental' and tropical climates level A [11], and the initial RH in the wall model set to 80%.

TABLE 2. Outdoor boundary conditions (shown as average or total annual value) and CO_2 concentration of IPCC emission scenarios [8].

Parameter	Climate	BO	BTS	CPH	DUB	KRN	MSK	MU
Average Temperature [°C]	TMY04-18	14.5	11.2	9.4	9.9	0.0	6.5	9.4
	A1B	16.1	12.0	9.3	10.3	0.4	5.2	10.2
	RCP4.5	16.3	11.1	9.1	9.5	-1.2	4.0	9.7
Average Relative Humidity [%]	TMY04-18	70.8	69.4	79.5	82.8	78.1	78.0	78.2
	A1B	57.9	70.5	84.9	83.3	87.9	85.4	77.1
	RCP4.5	59.4	68.9	85.1	87.1	89.5	87.8	73.3
Average Water Vapour Content [%]	TMY04-18	8.8	7.0	7.2	7.7	3.8	5.8	7.1
	A1B	7.9	7.5	7.7	8.0	4.4	5.9	7.3
	RCP4.5	8.2	6.9	7.5	7.9	3.9	5.6	6.8
Total Direct Normal Radiation [kW/m²]	TMY04-18	1509	1344	824	554	597	953	969
	A1B	1103	879	712	657	589	674	769
	RCP4.5	1110	885	781	633	633	743	843
Average Wind Velocity [m/s]	TMY04-18	2.6	2.5	5.0	5.4	3.1	1.1	3.5
	A1B	2.5	3.9	4.3	4.6	2.7	2.9	3.5
	RCP4.5	3.4	3.6	4.1	4.9	2.6	3.6	2.9
Total Rainfall [l/m²h]	TMY04-18	678	901	469	791	411	704	544
	A1B	642	645	866	1104	824	803	1028
	RCP4.5	820	952	997	1040	706	705	945

CO_2 concentration (ppmv) of IPCC emission scenarios.
A1B: dashed green
RCP4.5: solid blue



Assessing the Risk of Mould Growth

The VTT mould-growth model by Hukka and Viitanen [12] was applied to produce a theoretical prediction of the risk of mould growth. Model output is the mould index (M), ranging from 0 to 6, where 0 corresponds to no growth and 6 to heavy growth (100% coverage). Values 3-6 are mould growth within the visual range. Two variations were made for the sensitivity of the interface materials, based on if the additives hampering fire and mould growth are washed out over time or not, or if the additives are ineffective in hampering the growth of present mould species [13]: 1) "medium resistant" when additives are effective and not washed out, and 2) "very sensitive" for when additives are ineffective or washed out. In both cases the decline factor was set to "wood recession", corresponding to untreated wood, for mould growth on cellulose-based insulation materials. For the evaluation of the VTT mould growth results, M > 2 is considered as unacceptable, with respect to the mould growth in the masonry/insulation interface.

RESULTS AND DISCUSSION

Due to space limitation, the model calibration result will not be presented in this paper. However, they are available in the the supplementary files [14]. It was found that the model calbrations generally were good, following the same tendencies as the measurements but with less extrame variations in temperature and RH levels. The applied model calibration settings are in line with previous results in [15].

Hygrothermal Conditions and the Risk of Mould Growth

A further look into the three climate data sets for the investigated cities showed that the annual average moisture content in the air is predicted to increase during the period 2020 to 2050, and so is the total annual rainfall for most of the simulated scenarios (please see supplementary files [14]). However, this was not clearly visible when examining the RH results for the masonry/insulation interface. No worsening of the RH in the interface over the 30-year period was observed, the RH levels seemed rather stable with only minor variations from year to year. In addition, no clear tendencies were observed by looking only at the RH levels. Therefore, the focus was primarily on the predicted risk of mould growth over time using the VTT mould-growth model. The hygrothermal results are available in the supplementary files [14]. The risk of mould growth over time showed several different trends for the two emission scenarios, and Fig. 1-4 are selected representatives for these trends.

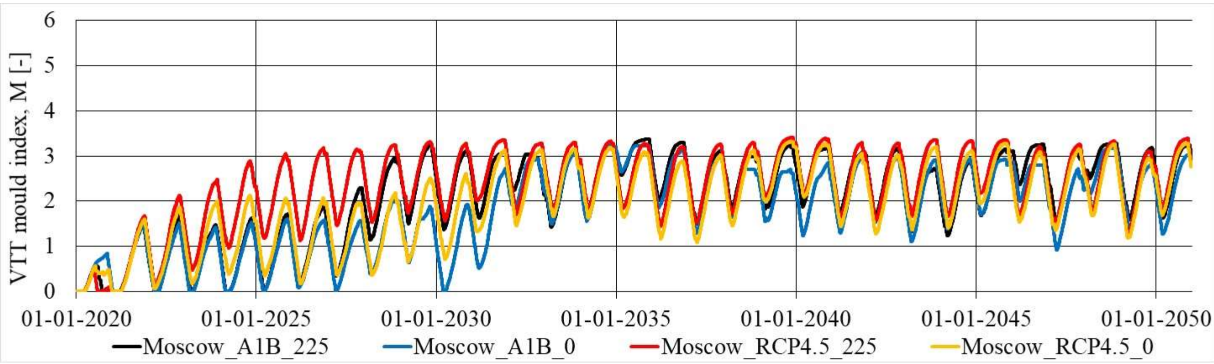


FIGURE 1. Predicted VTT mould growth risk (medium resistant) for the prevailing direction for wind driven rain in Moscow, with the A1B and RCP4.5 emission scenarios. Shown for unhydrophobised masonry wall with cellulose insulation.

Figures 1-2 show a trend, where the risk of mould growth stabilises after the first 5-10 year and the seasonal levels are rather similar year after year, with some minor variations in certain years. As seen from the figures, the risk was rather similar between the two emission scenarios as well as between the two investigated wall orientations. This trend was observed in locations with cold temperature or large amounts of wind driven rain. The trend for the risk of mould growth in Kiruna was similar to what is presented for Moscow in Fig. 1, but with considerably lower risk levels due to the overall colder temperatures.

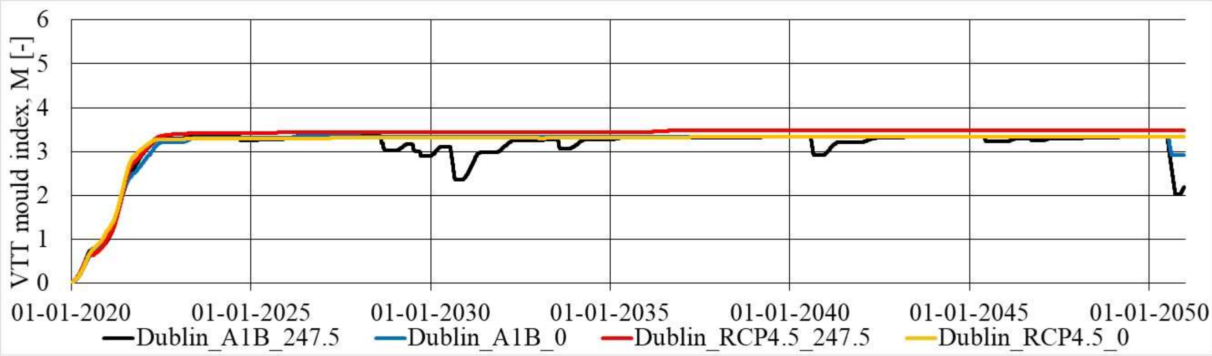


FIGURE 2. Predicted VTT mould growth risk (medium resistant) for the prevailing direction for wind driven rain and for the North direction in Dublin, with the A1B and RCP4.5 emission scenarios. Shown for hydrophobised masonry wall with cellulose insulation. Due to the settings of sensitivity (medium resistant), the mould index cannot exceed 3.5. Due to high wind driven rain and RH in Dublin, limited seasonal variations could be observed in terms of the VTT mould growth risk.

Figures 3 show a trend, where the risk of mould growth in the emission scenario RCP 4.5 do not stabilise, resulting in larger differences between the two emission scenarios in certain years. Meanwhile, Fig. 4 show a scenario where the risk of mould growth does not stabilise or increase over time; instead, large variations occur between the individual years. In addition, there are considerable differences between the two emission scenarios and the two investigated wall orientations. Alone calculated amounts of wind-driven rain on the wall surfaces and the annual average water vapour contents in the air in the RCP 4.5 emission scenario did not show a clear relation to the increased risk of mould growth during certain periods in Bologna and Bratislava, as shown in Fig. 3-4.

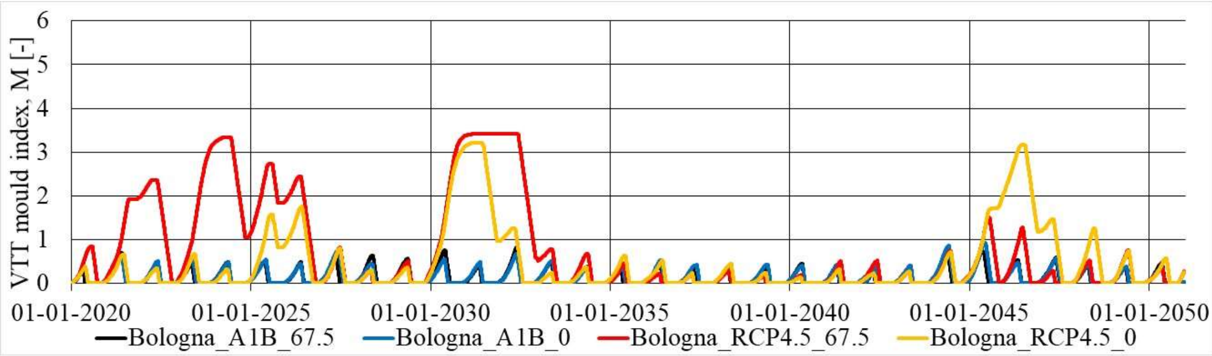


FIGURE 3. Predicted VTT mould growth risk for the prevailing direction for wind driven rain and for North direction in Bologna, with the A1B and RCP4.5 emission scenarios. Shown for hydrophobised masonry wall with cellulose insulation.

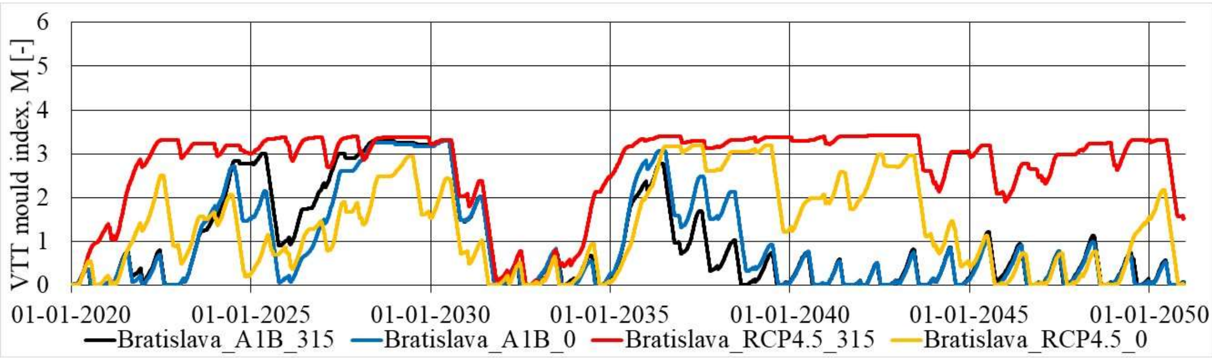


FIGURE 4. Predicted VTT mould growth risk for the prevailing direction for wind driven rain and for North direction in Bratislava, with the A1B and RCP4.5 emission scenarios. Shown for hydrophobised masonry wall with cellulose insulation.

Aside from the different trends observed for the risk of mould growth over time, the average and maximum levels of mould growth from the VTT model were considered. Table 3 shows the average RH and the predicted risk of mould growth (based on VTT medium resistant) in all the 168 simulated cases. VTT mould growth predictions based on the very sensitive material sensitivity assumption are available in [14], and will be addresses later in the discussion.

The results show that the mould growth predictions for the masonry/insulation interface in internally insulated solid masonry walls, were generally relatively similar for the two investigated emission scenarios over time. As shown in Fig. 1-3 and Table 3, the two emission scenarios often showed similar tendencies and risk levels during most of the simulated period, and the average and maximum risks levels were likewise rather similar in most of the 168 simulated cases.

Assessment of the RH levels in the 168 simulated cases showed that in around 45% of the cases, the North direction was worse than the prevailing direction for wind driven rain. Meanwhile, focus on the predicted risk of mould growth showed North direction to be worse in 38% of the cases. This indicates that it is recommended to consider both directions when assessing the hygrothermal performance of the insulated walls. This was found to be valid for the wall models with and without exterior hydrophobisation.

Assessment of the mould growth predictions indicated that the amount of wind-driven rain is the most important factor for the hygrothermal performance in the internally insulated solid masonry walls. From the climate data, it was found that Dublin has the highest annual rainfall and the highest average annual wind velocity, resulting in the highest amount of wind-driven rain and the overall highest risk of mould growth between the 7 cities, followed by Copenhagen, which had the second highest amount of wind driven rain. The comparison between Copenhagen and Dublin shows that over the three climate data sets, Dublin has 5-68% higher total rainfall and 8-19% higher average wind velocity. A comparison between Copenhagen, Bratislava, and Munich showed that these three locations have a relatively similar amount of annual rainfall over the year and average annual RH. However, the average wind velocity is lower in Bratislava and Munich compared with Copenhagen, resulting in lower RH levels in the masonry/insulation interface hence a lower risk of mould growth. In addition, the results indicated that for some locations, the risk of mould growth was less of an issue. In Kiruna and Moscow, the temperatures are generally too cold during the 4-5 coldest months of the winter for mould growth to occur in the interface of the internally insulated solid masonry wall constructions. Meanwhile, in Bologna the climate was generally too dry for mould growth to occur, with the average annual RH ranging between 52 and 64% in the A1B scenario and between 55 and 65% in the RCP 4.5 scenarios.

Previous studies, including [3-7], have shown that exterior hydrophobisation or similar measures are important measures to reduce the RH levels and the risk of mould growth in internally insulated solid masonry walls. The present study supports the previous findings, showing improved hygrothermal performance because of the exterior hydrophobisation. However, in cities such as Dublin, Copenhagen and Munich, which are predicted to have high amounts of wind-driven rain and high levels of water vapour content in the air in the future, the risk of mould growth was still at unacceptably high levels despite the exterior hydrophobisation. In addition, a comparison between the four wall models showed that the effect of the exterior hydrophobisation was more important than the choice of insulation material in terms of the hygrothermal performance.

The predictions for the risk of mould growth were performed assuming two different scenarios for the material sensitivity in the masonry/insulation interface: 1) “medium resistance”, for insulation with flame and mould hampering additives (presented in Table 3), and 2) “very sensitive”, for insulation where additives have been washed out or are inefficient against the present mould species, as documented in [13]. In the case of insulation without mould hampering additives, the predicted risk of mould growth was at an unacceptable level in all 168 simulated cases, including the cold climate in Kiruna and the rather dry climate in Bologna (please see supplementary files in [14]). This indicated that mould hampering additives are necessary when internal retrofitting solid masonry walls with bio-based insulation systems, as the masonry/insulation interface is generally a high-risk position in terms of mould growth.

TABLE 3. Relative humidity and VTT mould growth risk in the mason/insulation interface (point 3).

City	Emission scenario	Orientation	RH [%] Average				VTT mould index, M [-] Medium resistant Average				VTT mould index, M [-] Medium resistant Max			
			Hemp	Hemp+H	Cellulose +H	Cellulose	Hemp	Hemp+H	Cellulose +H	Cellulose	Hemp	Hemp+H	Cellulose +H	Cellulose
BO	TMY04-18	67.5	79.2	77.7	78.4	80.2	0.08	0.07	0.09	0.12	0.34	0.32	0.40	0.44
BO	A1B	67.5	80.3	77.9	78.7	81.4	0.13	0.09	0.13	0.20	0.82	0.59	0.83	1.15
BO	RCP4.5	67.5	96.6	82.5	83.9	98.3	2.31	0.50	0.71	2.91	3.43	3.40	3.42	3.44
BO	TMY04-18	0	81.4	80.7	81.2	82.0	0.11	0.10	0.13	0.14	0.42	0.38	0.49	0.54
BO	A1B	0	81.9	80.1	80.7	82.7	0.14	0.10	0.14	0.20	1.00	0.69	0.92	1.34
BO	RCP4.5	0	86.3	82.0	83.2	87.5	0.81	0.25	0.45	1.08	3.34	2.68	3.22	3.39
BTS	TMY04-18	315	88.7	86.3	86.7	89.3	0.16	0.12	0.14	0.22	0.63	0.53	0.63	0.77
BTS	A1B	315	93.9	90.5	91.0	99.3	2.08	0.80	0.95	3.27	3.40	3.22	3.30	3.47
BTS	RCP4.5	315	99.1	95.5	96.1	99.3	3.26	2.62	2.72	3.26	3.47	3.42	3.42	3.47
BTS	TMY04-18	0	89.8	88.1	88.3	90.2	0.20	0.14	0.18	0.23	0.69	0.58	0.67	0.84
BTS	A1B	0	93.3	90.7	91.0	93.8	1.79	0.81	0.93	1.99	3.40	3.21	3.29	3.40
BTS	RCP4.5	0	94.8	92.2	92.5	95.4	2.44	1.20	1.31	2.50	3.40	3.17	3.19	3.42
CPH	TMY04-18	247.5	98.6	94.6	96.1	98.7	3.04	2.84	2.91	3.10	3.42	3.33	3.34	3.44
CPH	A1B	247.5	99.5	97.1	97.9	99.5	3.30	3.12	3.14	3.30	3.49	3.42	3.42	3.49
CPH	RCP4.5	247.5	95.9	97.3	97.5	96.1	0.67	2.03	2.11	0.73	2.42	3.49	3.49	2.59
CPH	TMY04-18	0	91.9	91.7	91.6	91.9	0.29	0.27	0.26	0.27	0.75	0.72	0.73	0.76
CPH	A1B	0	95.8	94.9	95.1	96.2	3.13	3.07	3.02	3.10	3.38	3.34	3.32	3.37
CPH	RCP4.5	0	96.5	95.5	95.8	96.9	3.06	2.98	2.94	3.05	3.38	3.35	3.34	3.38
DUB	TMY04-18	247.5	99.0	97.0	98.0	99.1	3.18	2.99	3.03	3.20	3.45	3.37	3.37	3.44
DUB	A1B	247.5	97.7	94.8	95.6	98.8	3.29	3.04	3.11	3.31	3.41	3.35	3.35	3.42
DUB	RCP4.5	247.5	99.4	99.0	99.1	99.5	3.22	3.31	3.31	1.61	3.49	3.48	3.47	3.49
DUB	TMY04-18	0	99.1	99.1	98.9	98.9	0.45	0.45	0.43	0.43	1.19	1.19	1.13	1.14
DUB	A1B	0	96.7	96.2	96.4	97.9	3.25	3.21	3.19	3.26	3.40	3.36	3.35	3.40
DUB	RCP4.5	0	96.6	96.9	97.1	98.0	3.23	3.22	3.20	3.24	3.37	3.36	3.34	3.37
KRN	TMY04-18	180	98.6	98.1	98.1	98.6	0.47	0.41	0.43	0.49	1.23	1.05	1.14	1.29
KRN	A1B	180	99.4	99.3	99.2	99.4	0.70	0.68	0.65	0.67	2.00	1.92	1.92	1.99
KRN	RCP4.5	180	99.6	99.5	99.4	99.5	0.56	0.55	0.53	0.54	1.64	1.62	1.60	1.62
KRN	TMY04-18	0	89.4	89.3	89.1	89.3	0.11	0.11	0.12	0.12	0.46	0.45	0.49	0.49
KRN	A1B	0	99.6	99.5	99.4	99.5	0.55	0.55	0.52	0.53	1.72	1.70	1.65	1.66
KRN	RCP4.5	0	99.6	99.6	99.5	99.5	0.44	0.44	0.41	0.41	1.34	1.34	1.28	1.28
MSK	TMY04-18	225	85.4	85.2	85.1	85.4	0.04	0.04	0.05	0.05	0.29	0.28	0.33	0.35
MSK	A1B	225	98.0	96.6	97.2	98.5	1.91	0.90	1.23	2.10	3.33	2.71	3.11	3.37
MSK	RCP4.5	225	99.2	98.6	98.8	99.2	2.35	1.92	2.14	2.34	3.41	3.34	3.36	3.41
MSK	TMY04-18	0	92.5	92.4	92.0	92.1	0.11	0.11	0.12	0.12	0.46	0.46	0.53	0.53
MSK	A1B	0	98.0	97.3	97.6	98.3	1.73	1.29	1.44	1.80	3.26	2.89	2.94	3.26
MSK	RCP4.5	0	99.0	98.7	98.8	99.0	2.02	1.68	1.70	1.95	3.33	3.19	3.24	3.32
MU	TMY04-18	247.5	88.8	85.4	85.8	89.7	0.13	0.08	0.10	0.17	0.55	0.40	0.48	0.68
MU	A1B	247.5	99.6	98.7	99.1	99.5	2.72	3.28	3.29	2.69	3.48	3.48	3.48	3.48
MU	RCP4.5	247.5	98.5	93.9	94.8	98.9	3.17	2.02	2.29	3.18	3.46	3.38	3.39	3.46
MU	TMY04-18	0	91.7	91.0	91.2	92.0	2.00	0.31	0.32	2.16	2.73	0.72	0.76	2.84
MU	A1B	0	95.7	93.7	94.0	96.2	3.04	2.48	2.42	3.04	3.39	3.28	3.28	3.38
MU	RCP4.5	0	93.7	92.5	92.5	93.9	1.95	1.03	0.92	1.90	3.21	2.85	2.82	3.24

TMY04-18: Typical meteorological year (TMY) data for the period 2004 to 2018; BO: Bologna; BTS: Bratislava; CPH: Copenhagen; DUB: Dublin; KRN: Kiruna; MSK: Moscow; MU: Munich. Red: unacceptable mould growth level; Yellow: level should be evaluated; Green: acceptable level; Blue: simulation was terminated due to excessive calculation time caused by near 100% RH in the existing masonry wall. VTT results related to terminated simulations are based on available hygrothermal results generated prior to termination. +H: indicate that the wall had exterior hydrophobisation.

CONCLUSION

This paper presented a simulation study of solid masonry walls internally retrofitted with two diffusion-open bio-based insulation systems; cellulose insulation and hemp fibre. The models were calibrated using 1 year and 2 months of field measurements. The models were used to investigate the long-term hygrothermal performance of the insulated masonry walls for different climate scenarios (2020-2050) in seven locations all over Europe. The results were post-processed with a mathematical mould-growth model. The following conclusions were drawn:

- The mould growth predictions showed that the two investigated emission scenarios generally result in relatively similar risk levels over time.
- In around 38-45% of the cases the North direction was worse than the prevailing direction for wind-driven rain, showing the need to consider both directions when assessing the hygrothermal performance of the insulated walls.
- The results indicate that the amount of wind-driven rain on the exterior facades is the most important factor for the hygrothermal performance of the internally insulated solid masonry walls.
- Walls with exterior hydrophobisation performed better in terms of relative humidity and risk of mould growth in the masonry/insulation interface compared to the walls without. However, in cities with large amounts of wind-driven rain and high water vapour content, a high risk of mould growth still occurs despite the exterior hydrophobisation.
- In terms of long-term hygrothemal performance, the effect of the exterior hydrophobisation was found to be more important than the choice of insulation material.
- In the case that the mould hampering additivities in the insulation materials would be washed out over timer or be ineffective against some mould species, the risk of mould growth in the masonry/insulation interface was found to be unacceptable in all 168 simulated cases.

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