Adaptive Water-Resistive Barrier for Building Envelopes

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ABSTRACT

Excessive moisture transport into building enclosures can lead to elevated moisture levels in wall cavities and associated damage. Such conditions can also produce increased energy consumption. Currently, architects and builders are limited to using static membranes as water-resistive barriers that exhibit a single vapor permeance irrespective of environmental conditions. Membranes with a high permeance may allow moisture ingression under hot and humid ambient conditions, while membranes with a low permeance may not allow wall cavities to dry out when moisture accumulates within them.

An electrostatically actuated, dual permeance membrane previously demonstrated for protective apparel is under development for use as a water-resistive barrier for building envelopes. When outdoor temperature and relative humidity are high as detected by sensors, the membrane exhibits low permeance (~0.5 perms) to inhibit water vapor ingression into the building enclosure; but when humidity in the wall cavity is high, the membrane exhibits high permeance (~50 perms) to facilitate water vapor egression to the outside. The membrane changes state by electrostatic actuation using a very low current electrical power supply.

In order to quantify the benefits of a dual permeance water-resistive barrier, WUFI® hygrothermal modeling simulations were completed comparing the adaptive membrane to conventional fixed permeance membranes relative to inhibiting mold growth for various US climates and several wall constructions. The WUFI® code was modified to accommodate switching the permeance of the adaptive membrane between low and high permeance states for several humidity setpoint control strategies. The effect of liquid water leakage into the wall cavity was also considered.

This report summarizes the initial steps in development of dual permeance, electrostatically actuated water-resistive barriers focusing on the results of hygrothermal model simulations of these adaptive structures and testing of subscale adaptive structures to demonstrate the capability of the technology to achieve the preferred permeance levels suggested by the modeling.

INTRODUCTION

Water-resistive barriers (WRB) are installed between the sheathing and cladding of building structures to prevent excessive moisture ingression into the wall cavity which can result in mold growth and structural damage. However, the WRB should have sufficient permeance to allow the wall cavity to dry if it becomes wet from high ambient humidity conditions, e.g. solar driven moisture ingression from reservoir cladding, or direct water leakage into the wall cavity, e.g. at window and door penetrations. Current WRBs provide a single, static permeance level covering a broad range leaving the designer with the challenge to select the best material for the climate and construction details of a given project.

Ideally, the WRB would have, at least, dual permeance: a low permeance when there is a large humidity driving force into the wall cavity and a high permeance when a high humidity condition is detected in the wall cavity. A dual permeance, electrostatically actuated membrane (EAM) based on US Patent 7,597,855 is currently being developed for

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the WRB application. An EAM structure is depicted schematically in Figure 1 in side views in the unactuated state (a) and the actuated state (b). The structure comprises two multi-layer membrane films each typically 0.001" to 0.002" thick. Each film is produced from a substrate, e.g. polyester or polyvinylfluoride film, which has an electrically conducting layer applied to it. The conducting layer is further coated with an electrically insulating material. The multi-layer films each contain an array of holes which are identical in each film except that they are offset from each other such that there is no line-of-sight through the two films when viewed normal to the plane of either film.

As shown schematically in Figure 1, the two conducting layers are electrically connected to each other through a high voltage supply (typically 500 to 1000 VDC) allowing the two conducting layers to act as the plates of a capacitor when the switch depicted in the figure is closed. In the unactuated state (Figure 1a) the two films are separated by a gap, typically 0.005" to 0.01", which is formed by a third film, not shown, which includes a large aperture positioned so that the regions containing the arrays of holes in the two membrane films can come in contact with each other in the actuated state (Figure 1b). Closure of the switch imposes a high voltage across the two conducting layers and draws the membranes together by electrostatic attraction. Upon opening the switch, the two membrane films part and return to their original unactuated geometry by release of the elastic energy stored in the deformed membranes.

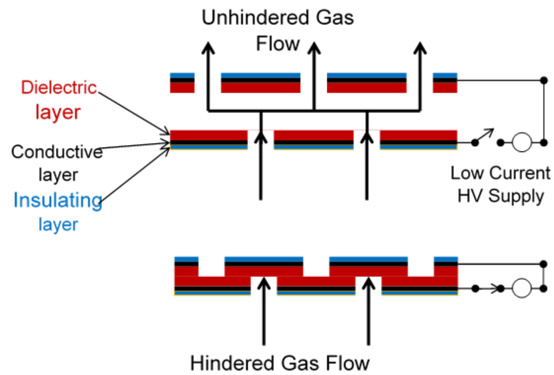


Figure 1. Side-view schematic of Electrostatically Actuated Membrane (EAM). (a) upper figure, in unactuated state; (b) lower figure, in acutated state

As depicted in Figure 1a, the EAM assembly in the unactuated state has very high permeability normal to the membrane films consequent to the unhindered flow path created by the hole arrays and the spacing between the membranes. However, as depicted in Figure 1b, the EAM assembly in the actuated state has very low permeability since the hole arrays are now blocked consequent to the out-of-registration geometry. Permeabilities 50 to 100X higher in the unactuated state vs the actuated state are readily achieved with EAM structures. Unactuated state permeability can be adjusted by altering the size and number of holes in the membrane arrays and by changing the spacing between the membranes.

The objective of the study reported here is to determine, by simulation, if a dual permeance WRB membrane is beneficial from a durability and energy perspective. More specifically, the goals are to (1) determine if such a membrane can reduce moisture levels and mold growth risk in building assemblies, (2) determine the energy impact of such a membrane, and (3) identify the most beneficial application cases and their required permeance range and switching control strategy. Additionally, testing of small-scale assemblies of EAM membranes in both the unactuated and actuated states is completed to demonstrate that the desired permeance levels can be achieved with this technology.

METHODOLOGY

Simulation Boundary Conditions and Assumptions

The simulations were carried out with the WUFI® Pro software version 6.2. The boundary conditions acting on the modelled walls are the measured weather data for the outdoor climate, and the indoor climate derived from the exterior conditions using methods described in standards like ASHRAE Standard 160 [1]. The simulations were performed for the cities and climate zones (CZ) Houston (CZ 2), Atlanta (CZ 3), Baltimore (CZ 4), Seattle (CZ 4 marine), and Chicago (CZ 5). Weather data for those locations is provided in the WUFI® database. The "ASHRAE Year 3" climate file was selected as it identifies the 3rd worst year in terms of hygrothermal impact on building components out of a 30 year dataset according to ASHRAE RP-1325 [Salonvaara 2011]. The indoor climate was derived from the outdoor climate with the ASHRAE 160 intermediate method [ASHRAE 2016]. It was assumed that the indoor climate is controlled with a heating, ventilation and air conditioning (HVAC) system. The specified temperature range was set to values between 21.1 °C and 23.9 °C. The maximum relative humidity was set to 55%.

The modelled wall assemblies consisted of the following material layers:

- Brick old (4")
- Air Layer (1") ventilated with 50 air changes per hour (ACH) of outdoor air
- Conventional, static permeance WRB (0.5 perm in CZ 2 and 50 perm in CZs 3, 4, and 5)
- Oriented Strand Board or Exterior Gypsum (0.5")
- Glass Fiber Batt Insulation (3.5" in CZ 2 and 5.5" in CZs 3, 4, and 5)
- Kraft Paper as interior vapor retarder in climate zones 3, 4, and 5
- Gypsum Board (USA) with 8 perm interior paint (0.5")

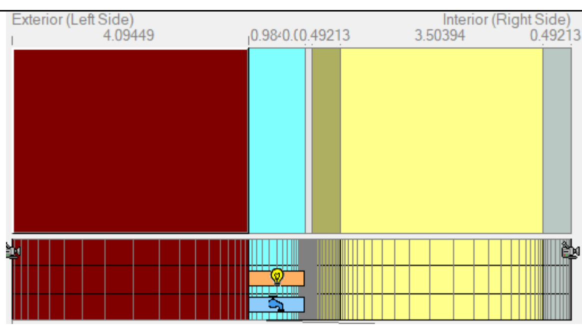
<table>
<tr><th>Houston</th><th>Atlanta, Baltimore, Seattle*, Chicago*</th></tr>
<tr><td>• 2x4 with brick cladding
• With 0.5 perm WRB
• No interior vapor retarder</td><td>• 2x6 with brick cladding
• With 50 perm WRB
• *With kraft paper as interior vapor retarder</td></tr>
<tr><td>

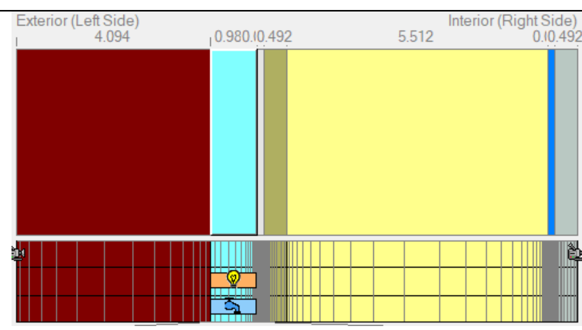
Figure 2. 2x4 wall with OSB sheathing</td><td>

Figure 3. 2x6 wall with OSB sheathing</td></tr>
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The baseline simulations were conducted with Exterior Gypsum sheathing. Some variants for the Chicago and Houston climates were modelled with Oriented Strand Board sheathing. The insulation thickness was adjusted to fulfil IECC 2015 [International Code Council 2015] code requirements which resulted in a 2x4 wall with an R-value of 13 for Houston and a 2x6 wall with an R-value of 20 everywhere else. The modelled assemblies and climate specific settings are shown in Figures 2 and 3.

All material properties were chosen from the WUFI® material database. The material properties of the dual permeance membrane were adjusted from a regular WRB membrane. The important material property of this layer is the water vapor permeability. As thin layers in WUFI need to be modelled with a thickness of at least 1 mm for reasons of numerical stability, the WRB material properties were converted to a layer of 1 mm thickness.

The high and low permeance values of the dual permeance, switchable membrane were set to 50 perms and 0.5 perms (i.e., permeability of 1.96 perm·in and 0.02 perm·in with an assumed material layer thickness of 1 mm) as a base case based on the highest permeance achieved in contemporary commercial WRBs and the capability of EAM technology to produce a 100 fold reduction in permeance upon actuation. For the control of the switch it was planned to utilize the WUFI® feature to add a water vapor diffusion resistance dependent on the relative humidity. The control had to be implemented based on the RH inside the membrane. In case the RH drops from above 80% to below 80% over the thickness of the material layer, part of the layer (i.e. the switchable membrane) will be modelled as impermeable and part of the layer as permeable, resulting in an only partially/delayed working switch and control.

Therefore, a new approach to model the switchable membrane was developed. As the vapor pressure difference between the sheathing and the air layer should really determine switching, a double layer approach with integrated logic was chosen. With two artificial 1 mm thick layers with different material properties the desired behavior of the switching membrane could be modelled. For this the permeability of the open and closed state of each of the 1 mm layers had to be re-computed to represent 50 perms (or the chosen maximum perm value) if both are open and 0.5 perm if both are closed. The logic was created in a way that:

- Whenever the humidity in the air gap is high and low in the sheathing, the membrane should be closed (less permeable).
- Whenever the humidity in the air gap is low and high in the sheathing, the membrane should be open (permeable).

This resulted in the material characteristics and control logic with a membrane layer with high permeance in humidity ranges below the switching point and low permeance in humidity ranges above the switching point facing the air gap and a second membrane with low permeance in humidity ranges below the switching point and high permeance in humidity ranges above the switching point facing the sheathing. As a result, the two above described cases result in a fully open or fully closed membrane as desired. However, there are also intermediate closed states (with half the closed permeability) whenever humidity of the air layer and the sheathing are either both low or both high.

Additional boundary conditions for the simulation are documented in [Antretter et al. 2019]. The parametric set-up for the simulations was designed to compare various cases with WRBs with fixed and switchable permeabilities. The cases assessed how climate zone, type of sheathing (OSB or Gypsum), rain leakage, switching point and the upper switching perm rating impact the effectiveness of the switchable membrane. In total 21 cases were evaluated and the simulation results are presented below.

Results - General Assessment

To achieve the goals outlined above, several output parameters of the hygrothermal simulation were considered. Figure 4 shows a screenshot of an example of an assembly with the parameters that were used to analyze the simulation results. Mold growth was assessed at the interface between the sheathing and the insulation in the cavity as well as at the interface between cavity insulation and interior gypsum or vapor retarder. To assess the mold growth, the hourly temperature and relative humidity conditions at that interface are exported to the WUFI VTT postprocessor which uses the VTT Technical Research Center of Finland mold model [Viitanen et al. 2010] according to ASHRAE Standard 160 [ASHRAE 2016]. The settings that were used to assess mold growth were conservative; that is, a sensitive material class and a decline factor of 0.1 were selected.

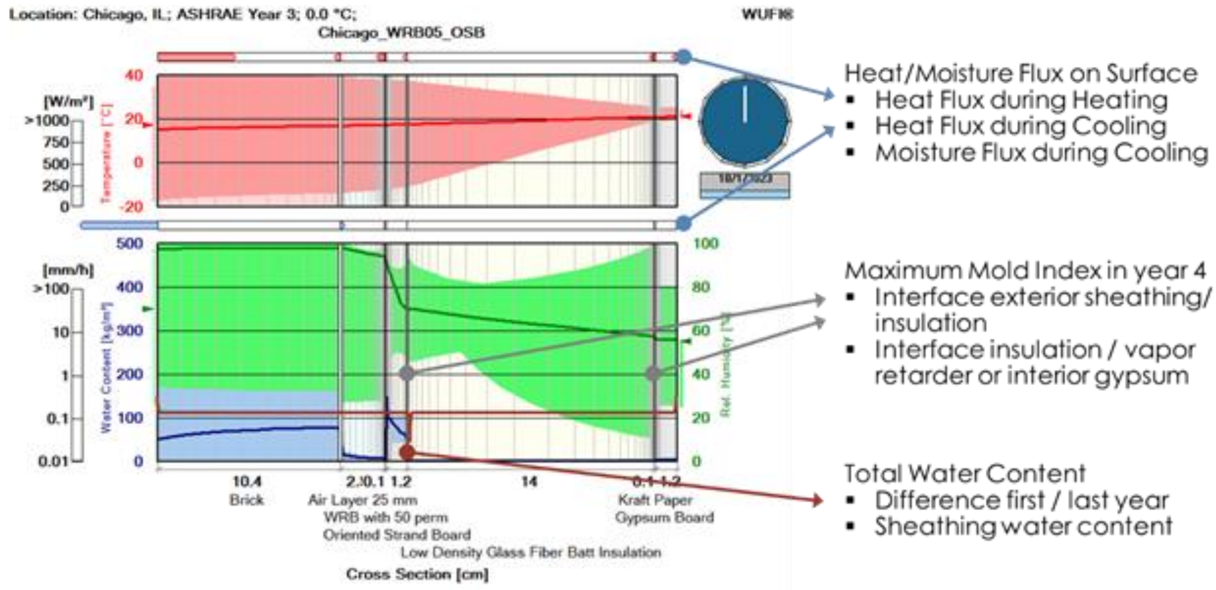

Figure 4. Screenshot of an example of a wall assembly modelled with WUFI with indicators of the simulated parameters that were assessed

The maximum mold index (MI) in the fourth full year of the simulations was compared for the 21 cases, i.e. January to December 2022 with a simulation start date of October 2018. A mold index of 0 means no mold growth, maximum mold index is 6 and with a mold index above 3 visible mold growth can be assumed. Another indicator for moisture related problems is the moisture content (MC) of the sheathing. To compare the cases, the mean moisture content of the sheathing as well as the hours above a certain moisture limit (18 Mass-% for OSB and 1 Mass-% for gypsum sheathing) in the fourth year of the simulation were calculated.

The energy impact was determined by looking at the heat flux through the interior surface of the wall. The heat flux must be separated for heating and cooling season. Heating and cooling season are determined by indoor conditions at the set-points. Negative heat flux density (energy loss from indoors to the wall component) add to heating loads during the heating season (indoor temperatures at lower set-point), positive heat flux density and moisture flux density (sensible or latent heat gain from the wall component to the indoor space) add to the cooling loads during cooling season (indoor temperatures at upper set-point). This analysis results in cumulative gains/losses per year.

RESULTS – DETAILED ASSESSMENT AND DISCUSSION

Effect of Sheathing Type

Table 1 summarizes and compares the assessment values for CZ2 (Houston) and CZ5 (Chicago) for simulations with OSB and gypsum sheathing for wall constructions including single permeance and dual permeance WRBs.

In CZ2 (Houston), the mold index (MI) at both the sheathing/insulation interface and the interior gypsum/insulation interface are both zero for the OSB sheathing for the conventional, single state WRB as well as for the dual permeance WRB. The outdoor vapor pressure is so high most of the time that the impermeable WRB (0.5 perm) used for the baseline, single permeance WRB case in this climate zone is effective and the dual permeance

WRB provides no advantage. The use of gypsum instead of OSB as the sheathing increases the mold index at the sheathing/insulation interface as seen in Table 1 consequent to the higher permeance of gypsum. There is a slight reduction in the mold index assessment values for the dual vs. single permeance WRB for this climate zone at this interface when gypsum is used as the sheathing.

Climate zone 5 (Chicago) shows a much greater effect of WRB type and demonstrates the potential efficacy of the dual permeance WRB for this climate. The MI at the sheathing/insulation interface is greater for the single permeance WRB vs. the dual permeance WRB for both sheathing types but the effect is larger for gypsum sheathing. The MI at the interior gypsum/insulation interface is also higher for the single permeance WRB when gypsum is the sheathing. The differences found in this climate zone for the two sheathings are a consequence of the lower permeance of OSB which, for example, can raise the RH at the sheathing/insulation interface due to vapor diffusion from indoors during the winter and also retard drying from the wall cavity. OSB will, in contrast, slow moisture ingression after rain events. In any case, for this climate zone, the dual, switchable permeance WRB provides a reduced moisture load and a significant reduction in mold index, especially when gypsum sheathing is used. Figure 5 illustrates this in detail in a plot of mold index vs. time for both the interior gypsum/insulation interface and the sheathing/insulation interface for CZ5 with gypsum sheathing.

Table 1. Simulation assessment values comparing for single and dual permeance WRBs in Climate Zones 2 (Houston) and 5 (Chicago) for both OSB and gypsum sheathing

Climate Zone	**CZ2 Houston**				**CZ5 Chicago**			
Sheathing	OSB		Gypsum		OSB		Gypsum	
WRB Perm Type	Single	Dual	Single	Dual	Single	Dual	Single	Dual
Max MI sheathing/insulation	0.0	0.0	0.16	0.05	0.93	0.0	2.21	0.23
Max MI interior gypsum/insulation	0.0	0.0	0.0	0.0	0.52	0.53	2.69	0.02
Heating Load [kWh/m²]	-9.45	-9.45	-9.67	-9.66	-20.70	-20.68	-21.03	-21.00
Cooling Load [kWh/m²]	7.97	7.97	8.14	8.12	2.26	2.24	2.37	2.29
Moisture Load [g/m²]	593.8	702.9	676.7	965.9	311.1	290.5	346.1	198.3
Sheath mean MC [kg/m²]	11.9	10.9	3.31	3.20	78.8	68.3	7.0	5.7
Hours above crit MC [hr]	0	0	458	208	0	0	4285	2015

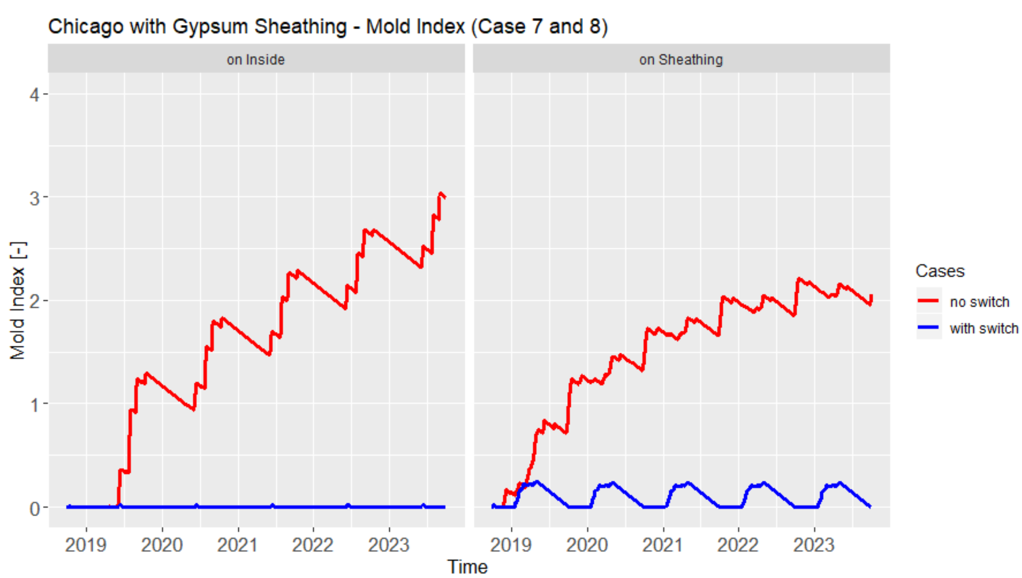

Figure 5. Mold index at the interface between interior gypsum and cavity insulation (inside) and interface between exterior gypsum sheathing and cavity insulation (on Sheathing) for the case with static (no switch = red) and with dual, switchable (with switch WRB

Effect of Climate Zone

Table 2 summarizes and compares the simulation assessment values for all five climates zones for wall constructions using gypsum sheathing. The simulations for CZ2 and CZ5 discussed above indicated that the lower permeance gypsum sheathing provides the best construction for seeing the advantages, if any, of the dual permeance WRB technology. These results show that the mold index at the sheathing/insulation interface is reduced for the dual permeance WRB for all climate zones with the most significant improvement apparent in CZ5 (Chicago) where the reduction in MI is nearly 10X. The reduction in MI by using the dual permeance WRB is in the range of 25 to 35% for CZ3 (Atlanta) CZ4 (Baltimore) but the nominal MI for these climate zones is only about half that of Chicago. As we saw earlier, although there is a significant percentage improvement in MI with the dual permeance WRB for CZ2, there is no substantial mold growth risk in this climate zone for these simulations where a lower permeance (0.5 perm) static WRB was the baseline condition imposed and the outdoor RH is chronically high. The unique conditions characterizing the oceanic climate of CZ4 (Seattle) give rise to the highest mold risk of all the climates simulated and the dual permeance WRB does not provide a significant change in this risk. Clearly, the improvement in MI level with the dual permeance WRB is highly climate dependent and would likely be enhanced by a more optimal switching control method including the use of vapor pressure difference across the membrane rather than a single RH level as used in these simulations because of limitations in altering the underlying code for this initial modeling study.

Table 2. Simulation assessment values comparing single and dual permeance WRBs in all climate zones with gypsum sheathing

Climate Zone	CZ2 Houston		CZ3 Atlanta		CZ4 Baltimore		CZ4Mar.Seattle		CZ5 Chicago	
WRB Perm Type	Single	Dual	Single	Dual	Single	Dual	Single	Dual	Single	Dual
Max MI sheathing/insulation	0.16	0.05	1.33	.98	1.10	0.72	3.08	3.01	2.21	0.23
Max MI interior gypsum/insulation	0.0	0.0	0.05	0.0	0.12	0.0	0.18	0.05	2.69	0.02
Heating Load [kWh/m²]	-9.67	-9.66	-12.60	-12.54	-18.06	-18.01	-17.39	-17.43	-21.03	-21.00
Cooling Load [kWh/m²]	8.14	8.12	3.71	3.78	1.86	1.85	0.14	0.17	2.37	2.29
Moisture Load [g/m²]	676.7	965.9	2192.5	530.1	1496.1	359.6	61.3	62.0	346.1	198.3
Sheath mean MC [kg/m²]	3.31	3.20	5.20	4.59	5.20	5.26	8.13	7.11	7.0	5.7
Hours above crit MC [hr]	458	208	2058	1362	2039	1417	4539	3503	4285	2015

Effect of RH Switch Level for Dual, Switchable WRB

The four simulation cases summarized in Table 3 and Figure 6 consider the effect of changing the RH value at the sheathing at which switching of the dual permeance WRB occurs. Switching points of 80%, 65% and 50% were studied. All simulations are for CZ5 (Chicago) with gypsum sheathing.

If a lower RH switching point is used, drying starts later after the sheathing has gained more moisture during winter months. This results in longer periods with higher RH and moisture content (MC) in the sheathing and a higher mold growth risk. These results suggest that there is an optimum switching point for every climate zone if switching is controlled by RH of the sheathing rather than the more appropriate strategy of using vapor pressure difference between the sheathing and ventilated air space to control switching.

Table 3. Simulation assessment values comparing single and dual permeance WRBs in CZ5 (Chicago) and gypsum sheathing with three different RH switching points for the dual permeance system

WRB Perm Type	Single	Dual Switch @ 80% RH	Dual Switch @ 65% RH	Dual Switch @ 50% RH
Max MI sheathing/insulation	2.21	0.23	1.42	1.79
Max MI interior gypsum/insulation	2.69	0.02	0.02	0.01
Heating Load [kWh/m²]	-21.03	-21.00	-21.01	-21.01
Cooling Load [kWh/m²]	2.37	2.29	2.30	2.30
Moisture Load [g/m²]	346.1	198.3	191.9	190.0
Sheath mean MC [kg/m²]	7.0	5.7	6.0	6.4
Hours above crit MC [hr]	4285	2015	3127	3485

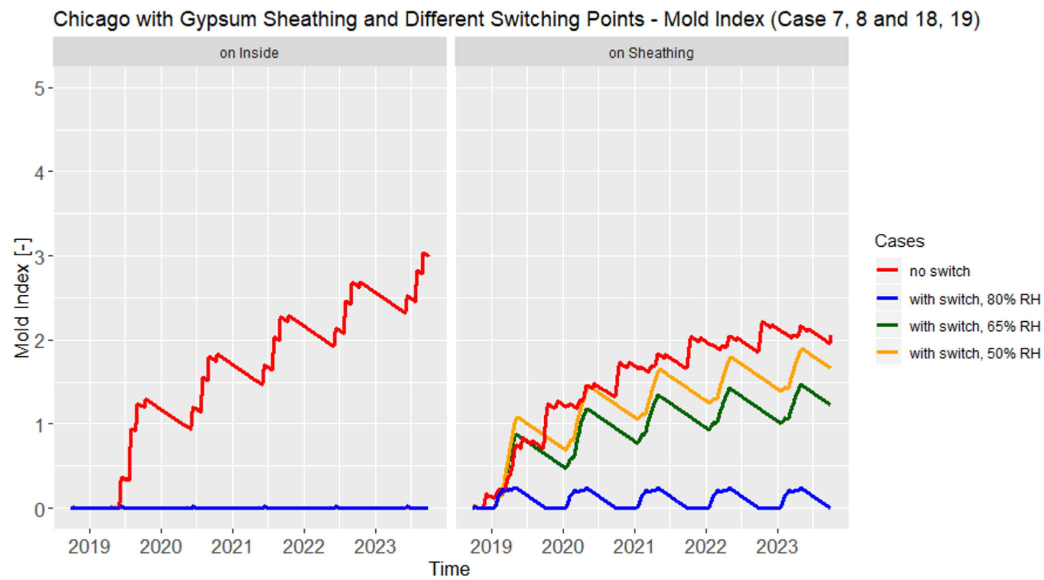

Figure 6. Mold index at the interface between interior gypsum and cavity insulation (inside) and interface between exterior gypsum sheathing and cavity insulation (on Sheathing) for the case with static (no switch = red) and with switchable membrane with switching at relative humidity of 50% (orange), 65% (green) and 80% (blue) in Chicago

Effect of Upper (Unactuated) Permeance Level for Dual, Switchable WRB

Table 4 and Figure 7 summarize four simulations comparing a single permeance WRB and dual permeance WRBs with three upper permeance levels – 50, 20 and 5 perms. Again, the simulations are for CZ5 (Chicago) with gypsum sheathing.

As seen in the Table 4 and Figure 7 the 50 and 20 perm upper level dual WRBs behave similarly. The dual permeance WRB with 20 perm upper level accumulates more moisture in the winter as it is less permeable with temperature dependent vapor drive. It dries out such that the mold index for the simulated case does not accumulate. The dual permeance WRB with 5 perm upper level is too impermeable to allow the cavity to dry out the combined moisture load due to diffusion from indoor sources during the winter and solar driven moisture from outdoors during the summer. This results in moderate mold growth at the sheathing/insulation and interior gypsum/insulation interfaces.

Table 4. Simulation assessment values comparing single and dual permeance WRBs in CZ5 (Chicago) and gypsum sheathing with three different RH upper permeance levels for the dual permeance system

WRB Perm Type	Single	Dual Upper 50 perm	Dual Upper 20 perm	Dual Upper 5 perm
Max MI sheathing/insulation	2.21	0.23	0.38	1.09
Max MI interior gypsum/insulation	2.69	0.02	0.02	1.01
Heating Load [kWh/m²]	-21.03	-21.00	-21.02	-21.00
Cooling Load [kWh/m²]	2.37	2.29	2.29	2.34
Moisture Load [g/m²]	346.1	198.3	198.0	306.2
Sheath mean MC [kg/m²]	7.0	5.7	5.9	6.5
Hours above crit MC [hr]	4285	2015	2360	3198

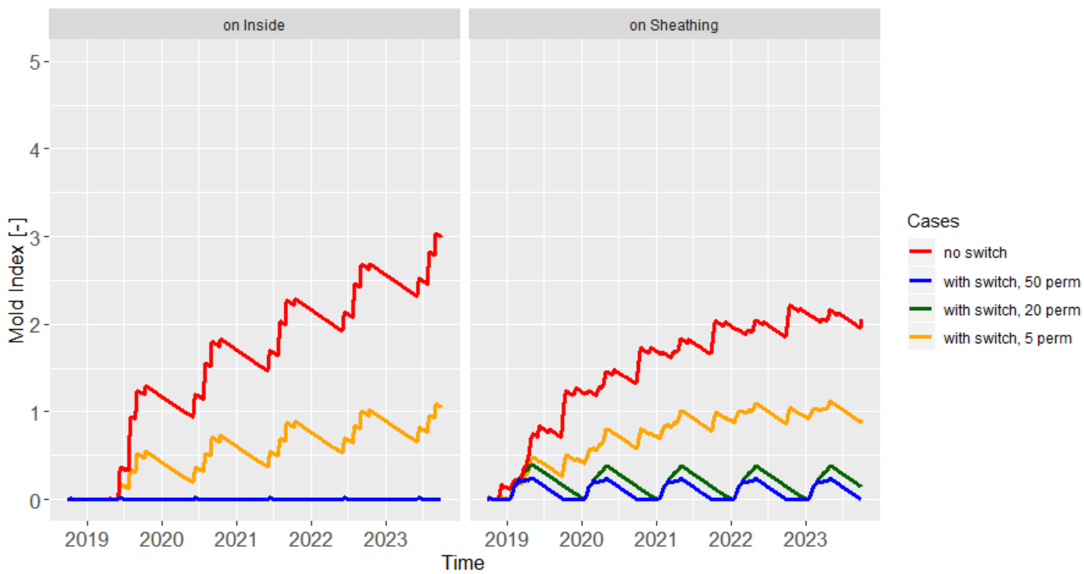

Figure 7. Mold index at the interface between interior gypsum and cavity insulation (inside) and interface between exterior gypsum sheathing and cavity insulation (on Sheathing) for the case with static (no switch = red) and with switchable membrane with maximum permeance of 5 perm (orange), 20 perm (green) and 50 perm (blue) in Chicago

Impact on Energy Usage

Table 1 through Table 4 include the heating loads and cooling loads computed for each simulation. Comparing these loads for the single permeance vs. the dual permeance WRB shows that there is little difference in energy use between the two systems. The differences in sensible losses/gains in heating/cooling period are very small even in cases with a high moisture level. Significant differences in latent gains during cooling period were observed, but those were orders of magnitudes lower than moisture loads from ventilation and interior loads.

SUBSCALE TESTING OF ELECTROSTATICALLY ACTUATED MEMBRANE STRUCTURES

Before designing and fabricating full scale prototypes of a dual permeance EAM WRB (e.g. 4' X 8' sheets suitable for wall testing), subscale testing was performed to confirm that the preferred permeance levels suggested by the hygrothermal modeling work could be achieved. A typical subscale EAM membrane design for the WRB application is shown in Figure 8 (a). In this case the array of holes in the membrane comprise rectangular holes in dense rectangular arrays aimed at maximizing porosity. Membranes were fabricated from 0.001" metalized polyester and metalized Tedlar® polyvinylfluoride film. A second subscale membrane with the same array geometry but offset from the array shown in Figure 8 (a) was also fabricated. A spacer fabricated from 0.005" polyester film comprising four 1" X 6" rectangular apertures which align with the four arrays of holes shown in Figure 8 (a) is placed between the two membranes to complete the EAM structure described earlier. Two circular locator holes in each of the three components are used to insure proper alignment. Figure 8 (b) is an exploded assembly drawing of the membrane-spacer-membrane structure. The membrane array holes, spacer apertures and all locator holes were produced by laser cutting (Preco, Inc, Somerset, WI).

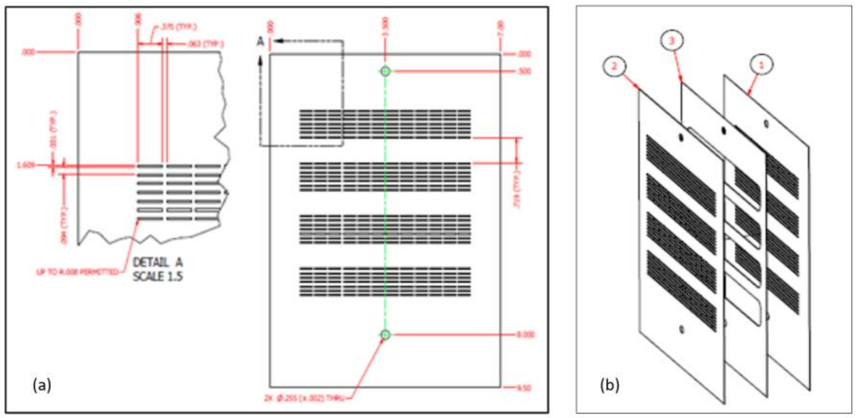

Figure 8. (a) Subscale EAM membrane design and (b) exploded assembly of the subscale EAM structure

A custom test system was designed and fabricated to measure the permeance of these subscale EAM structures in both the higher permeance, unactuated state and the lower permeance, actuated state following a procedure consistent with ASTM E96 but designed to accommodate the testing of the EAM system in both the unactuated and the actuated states for which a high voltage is applied.

Figure 9 is a typical output from the test; Figure 9(a) shows the weight change from the water reservoir on the high RH side of the membrane vs. time and Figure 9(b) shows the permeance vs. time computed from the weight loss and measured RH and temperature. The specific test shown comprised Tedlar® PVF membranes in the unactuated and actuated state, with actuation at 500 VDC. By varying the porosity of the EAM membranes, unactuated permeances in the range of 20 to 50 perms were demonstrated using this test. Table 5 summarizes open, unactuated permeance results for an EAM design with a relatively high porosity (Figure 8 (a)) as well as a design with a lower porosity and compares these to three commercial single, static WRB materials which were tested in the same subscale tester. Values for the commercial controls are consistent with those reported by the manufacturers.

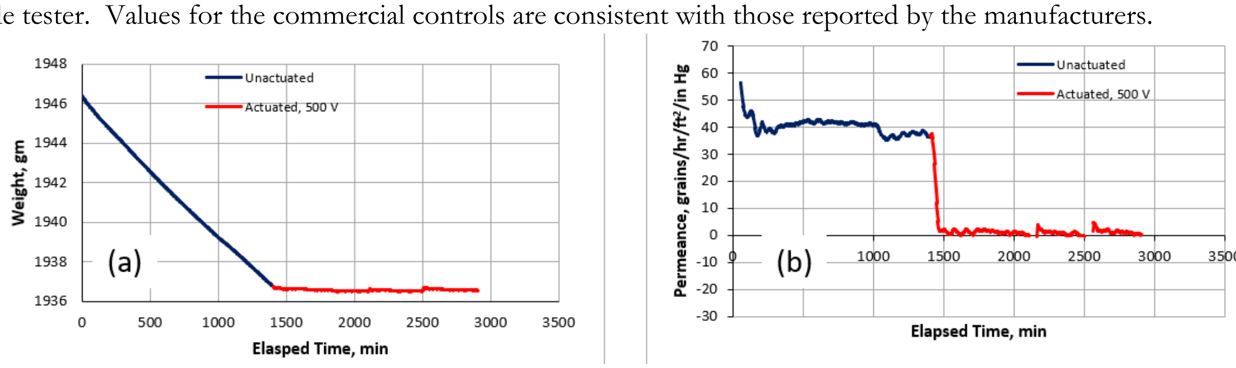

Figure 9. Typical Subscale Test Output. (a) weight vs. time, (b) permeance vs. time

Table 5. Open, unactuated state permeance of two electrostatically actuated membrane (EAM) designs for potential use as WRBs compared with three commercia single permeance WRB materials all measured in test system developed in this study

Item	Permeance, grains/hr/ft²/in Hg
EAM High Perm Design, Open State	53
EAM Low Perm Design, Open State	26
Tyvek® Homewrap	42
Tyvek® Commercial	23
Dow Weathermate Plus®	10

So, open, unactuated state permeance levels consistent with the range demonstrated as effective in the modeling study are achievable with these EAM designs. Closed (lower) state permeance levels as measured by our subscale test were generally <1 perm which was essentially the lower limit of the test capability. Again, these results are consistent with the lower permeability level (0.5 prems) baselined in the modeling work.

SUMMARY AND CONCLUSIONS

This study introduced the development of a unique dual permeance water-resistant barrier (WRB) based on electrostatically actuated membrane (EAM) technology and, using hygrothermal modeling, evaluated its effect on moisture conditions, mold growth potential and energy demand in comparison with conventional, single permeance WRB materials.

Modelling the functionality of the dual permeance, switchable membrane is not possible in a direct way with the selected simulation model WUFI® (and no other commercially available hygrothermal component simulation model). Therefore, some workarounds were developed that allowed modeling the dual permeance membrane with a conservative approach. Switching the membrane properties means introducing a step change in the simulation model that can result in numerical stability issues. This was successfully resolved by using an adaptive time-step control. The control of the switch is implemented by changing material properties at a certain relative humidity and a two-layer approach to model the membrane. As a consequence, a fully open state of the membrane is not always modeled whenever it would be beneficial for drying which leads to conservative simulation results. A switch that is controlled by vapor pressure difference would improve the performance and be a less conservative approach for the simulation but cannot be implemented in the current version of WUFI Pro.

The simulation study shows that the switchable membrane can reduce the water content in the sheathing and reduce the mold growth risk in the cavity in all climate zones. The effect of the switchable membrane on energy use is small. The differences in sensible losses/gains in heating/cooling period are very small even in cases with a high moisture level. Significant differences in latent gains during cooling period were observed, but those were orders of magnitudes lower than moisture loads from ventilation and interior loads.

The ideal switching point for dual permeance WRB is climate dependent. The switching should be initiated by measured vapor pressure difference across the membrane for practical applications. The maximum (i.e. 50 perm) and minimum (i.e. 0.5 perm) permeance values appear to be the only necessary switching permeances, intermediate states are not required to achieve full performance of the membrane. The acceptable range for the maximum permeance is expected to be climate dependent. One example case was computed and still shows good performance in climate zone 5 with a maximum permeance of 20 perms.

Further benefits during the presence of additional moisture sources (leakage) in the cavity were not observed. With a moisture source based on driving rain, high moisture levels inside and outside of the WRB occur at the same time. With a control that is based on vapor pressure difference and moisture sources independent from driving rain a more beneficial behavior is expected. The same applies to constructions that show high moisture levels due to insufficient design that leads to moisture problems as in those cases the full potential of the switchable membrane is utilized.

Finally, subscale testing of EAM designs in both the unactuated and actuated states showed that the preferred permeance levels suggested by the modeling studies can be achieved with this technology.

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