Use of Imposed Boundary Conditions on Two-Dimensional Wall Assembly Models in Delphin

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Abstract

Predicting the movement of heat, air, and moisture through building wall assemblies is essential in building energy performance. While hygrothermal modelling tends to be validated with in-situ data, the motivation for this research is to develop hygrothermal models in Delphin, that can be validated with data collected from a guarded hot box using predetermined environmental conditions over a short period. This paper details the development of a 2D model in Delphin, with user defined environmental conditions. Consideration is given in simulation results and analysis for different initial boundary and surface transfer conditions, default initial conditions, and impact of different output variable elevations. While many model parameters impacted hygrothermal performance, the initial relative humidity selected was the most impactful in this paper. It was also found that the interior vapour diffusion parameters have a high sensitivity for wall assemblies without an interior vapour barrier.

Introduction

Hygrothermal simulation is used to predict the movement of heat, air, and moisture through the building envelope (Hamdaoui et al. 2021). It is essential when planning building retrofits or designing new buildings to consider the hygrothermal performance of wall designs as the movement of heat, air and moisture will impact energy use, occupant comfort and long term building performance (Havinga and Schellen 2019).

Within the field of hygrothermal simulation, the American Society of Testing and Materials (2016) gives the standard E3054 for hygrothermal modelling of building envelopes, with the possible input parameters and design considerations shown in Figure 1.

In development of a hygrothermal model, many parameters are considered, such as boundary conditions, materials, calculation period, assembly geometry, etc. (Knarud et al. 2023). An open question is how impactful each design decision will be in the results of the simulation.

This paper will investigate the effect of varying model design conditions such as default initial conditions, boundary and surface transfer conditions, and output elevations on the hygrothermal modelling performance of wood frame wall assemblies.

These key decisions in modelling will be investigated using models of two lightweight wall assemblies. The sensitivity of each parameter will be simulated and analysed. Based on the results, these choices will aid in validation and calibration of the model in future work with experimental data.

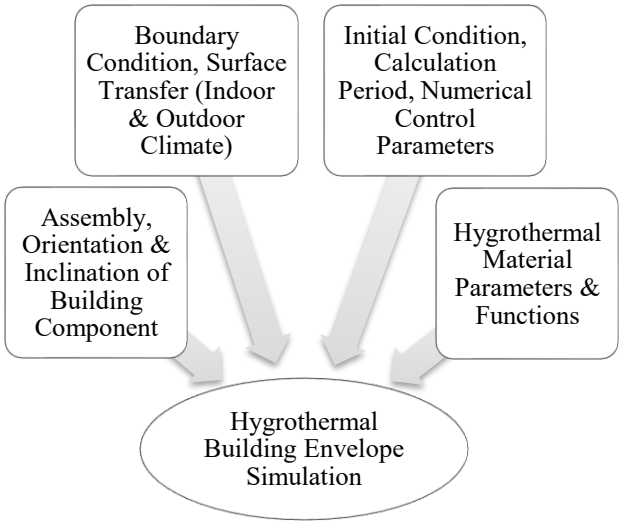

Figure 1:Hygrothermal Simulation Design Input Parameters, adapted from ASTM-E3054

There are a variety of methods to model hygrothermal systems, including purely mathematical, physical models, computational fluid dynamics (CFD) models such as ANSYS or COMSOL Multiphysics, or simulation tools specifically designed for hygrothermal modelling such as WUFI or Delphin (Hamdaoui et al. 2021). Delphin, developed at the Technical University of Dresden (Grunewald et al. 2023), was chosen for this research as it was designed and optimized for parametric simulation of two dimensional building envelopes. Also, Delphin contains a large database of material properties for typical building

constructions (Fechner, 2020), and it was important to simplify modelling by using these default material properties.

While one dimensional modelling of hygrothermal assemblies is common in heat, air, and moisture transport research (Havinga and Schellen 2019), accurately representing two dimensional buildings is less frequent due to increased computational time and modelling complexity (Bishara et al. 2021). Using two-dimensional modelling allows for the thermal bridging effects and more complexity in the wall construction to be captured in hygrothermal models (Bottino-Leone et al. 2018).

Boundary conditions in hygrothermal models impact the heat and mass transfer rates through the building wall envelope (Zhao et al. 2021). The boundary conditions are determined by environmental conditions used in simulation, and the surface transfer conditions set in the model. Environmental conditions for the exterior are generally set with climate data files based on past recorded weather or future shifted weather files (Vandemeulebroucke et al. 2021). The interior environmental conditions are generally determined by industry standards or field measurements from local buildings (Ilomets et al. 2019).

This research was conducted at Carleton University's Centre for Advanced Building Envelope Research (CABER). This facility is equipped with a two-storey guarded hot box capable of controlling temperature, relative humidity, and air pressure for testing vertical wall assemblies at full scale (sample size of 4.8 m by 7.2 m). This research in model sensitivity will be validated in the future, with experimental hygrothermal data collected from a series of experimental tests completed within the guarded hot box at CABER.

Methods

The models used in this research were developed in Delphin based on actual physical wall assemblies built for testing in the guarded hot box at CABER.

Wall assembly configurations

Two wall designs were used in this simulation, both based on typical construction for Canadian housing markets (Wang and Ge 2018). Exterior vinyl cladding and a wood frame insulated wall were used to ensure that the weight of a fully constructed wall would remain within the capacity of the testing apparatus. The wall construction is nearly identical, with the first wall including a vapour barrier between the interior gypsum board and wood frame wall, while this vapour barrier was removed for the second wall. The wall construction for both assemblies from exterior to interior is described in Table 1 with material layers and their corresponding material properties in Delphin.

The walls used in this simulation had identical materials to control for sensitivity to material parameters. Modelling a second wall without a vapour barrier was included in this research to check if varying the boundary condition parameters on both wall designs would impact the hygrothermal performance in similar ways. There is also evidence that there is a difference in hygrothermal performance between 1D and 2D models with and without vapour barriers, which would be interesting to observe in these simulations (Bottino-Leone et al. 2018).

Material Properties

One of the objectives of this project is to determine how closely a model can follow the behaviour of an experimental dataset without needing a high degree of customization. As part of this, standard material libraries were used in the modelling of the wall assembly. The use of default materials had been seen in other hygrothermal performance research (Knarud et al. 2023) across multiple modelling platforms (Ibrahim et al. 2019; Boardman and Glass 2020). While there may be higher uncertainty in moisture storage and transport properties in Delphin and other hygrothermal modelling tools compared to thermal properties (Zhao et al. 2021), it is still valid for this analysis to use the default material libraries given in Delphin.

For the first wall, the 0.15 mm thick polyethylene vapour barrier between was modelled as a foil type (Fechner, 2020), with no liquid flux, no air flow, and a constant vapour diffusion. The initial vapour diffusion air equivalence layer (sd value) was modelled as 10 m.

Table 1: Material Properties Used in Delphin (Grunewald et al. 2023)

Material Layer from Exterior to Interior	Delphin Material Index	Thickness (mm)	Density (ρ) (kg/m^3)	Specific Heat Capacity (c_p) (J/kgK)	Open Porosity (θ_{por}) (m^3/m^3)	Dry Thermal Conductivity (λ_{dry}) (W/mK)	Water Uptake Coefficient (A_w) (kg/m^{2}s^5)	Water Vapour Diffusion Resistance Factor (μ)
PVC Siding	786	4	900	1000	-	0.17	-	-
Air Gap	11	25	1.3	1050	1	0.156	1e-07	0.4
Tyvek House Wrap	448	5	463.033	1000	0.593831	0.23	0.0001	519.269
OSB	172	11.9	630	1880	0.4	0.13	0.0019	280
SPF Frame	844	152	414.605	2416.33	0.723597	0.147833	0.011789	3.80723
Mineral Wool	649	152	195	840	0.92	0.04	0	1
Gypsum Board	81	12.7	850	850	0.65	0.2	0.277	10

Geometry

The experimental walls built for future validation are two stories tall, measuring 7.2 m tall by 4.8 m wide. To decrease processing time of the simulation, it was decided to model a vertical subsection of the wall.

This vertical subsection, from a double framing plate at the bottom to a single framing plate above with a full piece of mineral wool insulation between plates, measures approximately 1284 mm tall. There is potential future work to check if assuming the same hygrothermal performance across the entire elevation of the wall is valid, but was deemed low priority due to the increased number of grid elements and therefore computation time required (Bishara et al. 2021). This wall assembly was cut vertically, instead of horizontally as moisture sensors installed in the physical wall assemblies were installed in the framing plates, instead of the studs.

While these wall assemblies are modelled with 2D geometries, the individual materials are still modelled as homogenous. This is another simplification, as hygrothermal properties of individual materials can change with varying internal composition (Gutland et al. 2022).

These modelled walls also have 2D details for the vinyl siding, to represent the air movement through the exterior cladding. Modelling the vinyl siding accurately was challenging, as there is air flow through the exterior cladding to the air gap in the form of infiltration around the edges of the siding, gaps in construction, and drainage holes. This infiltration through the cladding meant that a solid 1D layer of PVC could not represent the actual wall geometry accurately (Boardman and Glass 2020). To allow for a vapour bridge, notches were set intermittently in the vinyl layer in the model (Xie, 2022), which would represent the drainage holes in the siding and other infiltration points.

The models were discretised with variable grid sizes, with a minimum element size of 1 mm, maximum element size of 5 cm and a stretch factor of 1.3. The total number of grid elements used was just over 49000. While 3D modelling in Delphin is possible (Knarud et al. 2023), it was outside of the scope of this research.

Boundary Conditions

While most hygrothermal simulation use weather data files (Hamdaoui et al. 2021), one of the goals of this project was to control the exterior and interior environment to specifically validate the effects of temperature and relative humidity. To accomplish this, the interior and exterior boundary conditions were set using heat conduction and vapour diffusion conditions in Delphin.

These models excluded any radiation (short wave and long wave), wind, and rain. The wall orientation was kept constant as well, although the orientation would not have influenced hygrothermal performance as the solar and wind parameters are not included in this model. Removing all these boundary conditions simplified modelling and isolated the effects of heat conduction and vapour diffusion through the wall assemblies.

The environmental conditions imposed approximately followed a six-week sequence, with both steady state conditions and transient conditions, given in Table 2.

From the actual experiments in the guarded hot box at CABER, with the two wall assemblies, approximately 1200 hours of environmental condition data was recorded, with some temperature anomalies and extended test periods due to operational issues with the guarded hot box. The hourly averages from the experimental testing completed for each wall assembly was used to create environmental condition files for each wall assembly modelled.

The first wall test (with a vapour barrier) had test data for 1187 hours and the second wall test (vapour open) had data for 1198 hours. To have an even simulation time of 50 days (1200 hours), the remaining weather conditions were filled in as a summer conditioning temperature of 23°C and a relative humidity of 50%RH. Any missing experimental data in these environmental conditions from the recorded testing data were interpolated.

All surface transfer conditions used exchange coefficient models with constant exchange coefficients, based on default values and literature (Wang and Ge 2018). Exterior vapour diffusion has no sd value to represent no coating condition (Boardman and Glass 2020).

Table 2:Interior and Exterior Climate Conditions

Sequence Name	Sequence Time Planned	Interior Temperature(°C)	Interior Relative Humidity (%RH)	Exterior Temperature (°C)	Exterior Relative Humidity (%RH)
Summer Conditioning	1 Week	23°C	50%RH	23°C	50%RH
Summer Steady State	1 Week	23°C	50%RH	32°C	80%RH
Summer Transient	1 Week	23°C	50%RH	Day:23°C Night:17.5°C	Day:60 %RH Night:80%RH
Fall Conditioning	1 Week	20°C	30%RH	20°C	30%RH
Fall Steady State	1 Week	20°C	30%RH	9°C	70%RH
Fall Transient	1 Week	20°C	30%RH	Day:23°C Night:17.5°C	Day:70%RH Night:77.5%RH

The vapour diffusion parameters such as equivalent layer thickness (sd value) and exchange coefficient were developed from work by Vandemeulebroucke et al. (2021).

To summarize, the boundary and surface transfer conditions used in the base model are given below.

- Indoor heat conduction: meter box temperature data, heat conduction exchange coefficient = 8 W/m^{2}K.
- Indoor vapour diffusion: meter box temperature and relative humidity data, heat conduction exchange coefficient = 2.5e-08 W/m^{2}K, sd value = 0.5 m.
- Outoor heat conduction: climate box temperature data, heat conduction exchange coefficient = 12 W/m^{2}K.
- Indoor vapour diffusion: climate box temperature and relative humidity data, heat conduction exchange coefficient = 7.5e-08 W/m^{2}K, sd value = 0 m.

These models were limited in that only internal and external boundary conditions were applied, there was no air cavity ventilation (Vandemeulebroucke et al. 2021). Further development work would need to be undertaken to determine the impact of greater air exchange in this cavity.

Simulation Options

Delphin version 6.1.5 was used for simulation of these models with a 50-day simulation time frame to match the experimental time frame. Default model options were used, with energy balance and moisture equations enabled. Use of Kirchhoff potential for liquid flux calculation was enabled. The solver and performance options were all set at default conditions.

Output Variables

There are a practically infinite number of output variables possible in a Delphin model, constrained only by grid size and imagination. For ease of analysis, variables that mirror the actual physical walls were selected. The physical monitoring points are shown in Figure 2.

The exact elevations of output temperature, relative humidity, saturation, etc, are discussed in the sensitivity analysis later in this paper.

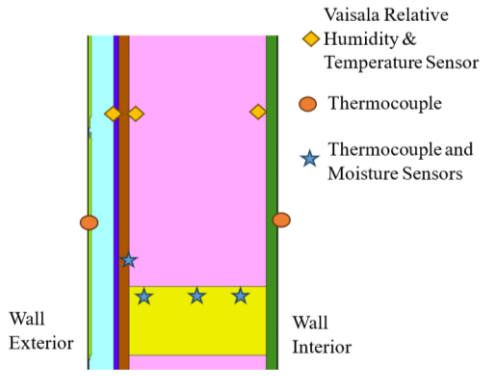

Figure 2: Instrumentation location on model detail of bottom framing plate

Results and Analysis

As the goal of this project is to quickly develop a model that can by validated using experimental hygrothermal performance data from a guarded hotbox, it is essential to analyse the impact of design decisions used in developing each model. For this, parametric tests were completed modifying the base model initial conditions, material properties, and complexity of thermal bridging. The results of these simulations are given in the following sections.

Sensitivity to Default Initial Conditions

One of the questions in conducting a simulation over a short simulation time is whether the default initial conditions in a simulation make an impact on the hygrothermal performance. To investigate, the default initial temperature, and relative humidity were varied one at a time.

First, the default initial temperature was changed, holding relative humidity constant. For both wall assemblies, changing the default initial temperature condition did not have an impact beyond the first 48 hours (two days) of simulation time. This is seen in Figure 3, where the temperature equalizes after less than 48 hours, with a base model temperature of 23.5°C, over a range of possible initial temperatures from 19°C to 27.5°C.

The hygrothermal outputs for both wall one and two with changing initial temperature behaved as expected by analytical models, especially as there were no elements of thermal storage in these wall designs.

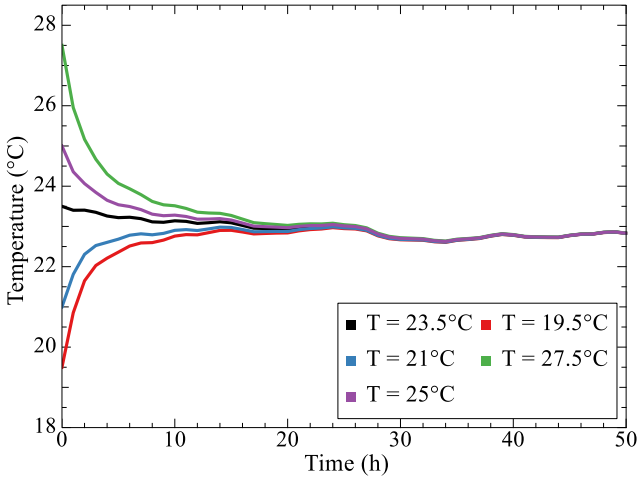

Figure 3: Wall 2 OSB Temperature with varying initial default temperature

In contrast, changing the default initial relative humidity had a large impact on hygrothermal performance of these models. As seen in Figure 4, varying the initial relative humidity caused a shift over the entire simulation time. The response in relative humidity over the different climate sequences remained similar, but the scaling changed. This parameter has also been noted as important in other hygrothermal calibration and validation studies (Ibrahim et al. 2019). The importance of initial relative humidity is well

explained through the moisture storage of materials (Hamdaoui et al. 2021), which with greater initial relative humidity will have greater future relative humidity, even under the same climate conditions.

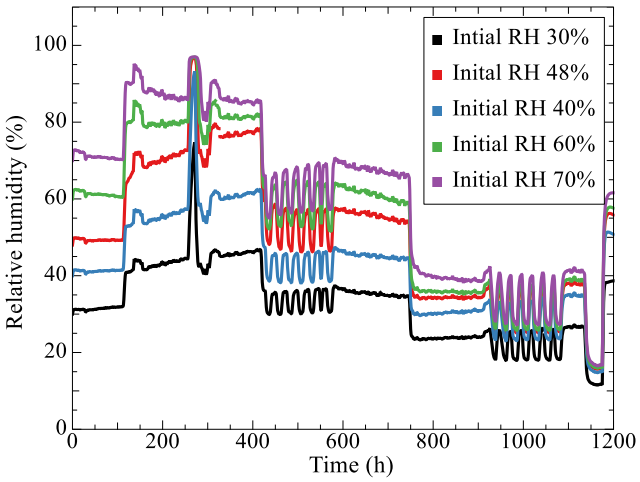

Figure 4:Wall 1 Insulation/Vapour Barrier Interface Relative Humidity Sensitivity to Initial Relative Humidity

Therefore, for future validation of models, it is essential to monitor the starting conditions of wall assemblies used in experiments before conducting tests in climate chambers. For this research, the initial relative humidity values for all materials in the wall assemblies are set from laboratory relative humidity measurements with wall one initial value of 48%RH, and wall two initial value of 35%RH.

An open question about the sensitivity to initial relative humidity conditions is whether it remains over a long time period, considering most hygrothermal simulations are conducted over a span of years rather than days (Vandemeulebroucke et al. 2021). In work by Ibrahim et al. (2019), the sensitivity with varying relative humidity was still present after 120 days of simulation. Further research using a long-term simulation with an annual weather data file and validated models over ten years would be ideal to investigate this initial parameter impact on hygrothermal performance.

Surface Transfer Parameter Sensitivity

In modelling the boundary conditions in Delphin, the surface transfer parameters need to be selected to best represent the experimental conditions. There are many choices for surface transfer parameters with the tested options given in Table 3. When comparing ranges for surface transfer coefficients tested in this paper to recommended ranges given by Zhao et al. (2021), some of the tested parameters in this paper were outside of realistic bounds discussed. However, it was still desired to test these extremely small or large values to see the exaggerated effect on hygrothermal performance.

Table 3: Surface Transfer Parameters

Boundary Condition	**Exchange Coefficient for still air (W/m^2K)**	**sd value of Surface Coating (m)**
Indoor Heat Conduction	4,8*,12,16	-
Indoor Vapour Diffusion	2.5e-08*	0,0.25,0.5*,0.75,1
Outdoor Heat Conduction	4,8,12*,16,100	-
Outdoor Vapour Diffusion	7.5e-08*	0*,0.25,0,0.5,0.75,1

Note that values with an asterisk in Table 3 were used in the base models for both walls.

Interior Heat conduction

For interior heat conduction coefficients, decreasing values have impacts on temperatures, as seen in Figure 5. But considering the range for interior heat coefficient given by Zhao et al. (2021) was 5 - 8.33 W/m^2K, there is a physical limit on how low of a conduction can realistically be used in models. The base model uses an exchange coefficient of 8 W/m^2K, so it may be possible to reduce this parameter during validation. This parameter would still need to be limited to physically reasonable values to accurately represent the test wall.

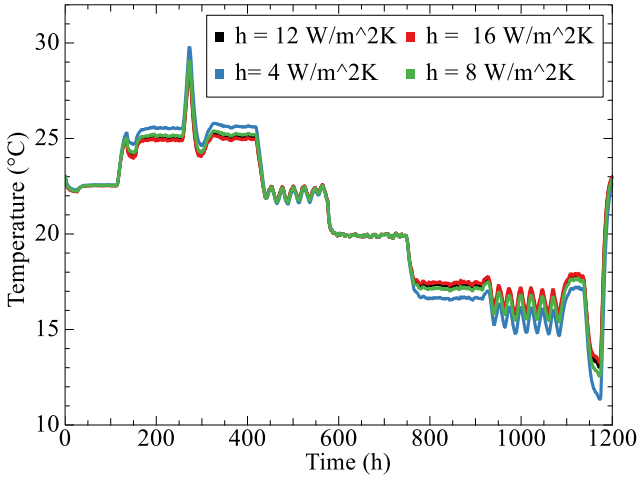

Figure 5: Wall 1 Interior Framing Temperature with Varying Interior Heat Conduction Coefficient

Interior Vapour Diffusion

Changing the interior diffusion equivalent air layer thickness, or sd value, for the first wall with an interior vapour barrier had a minimal observable difference in Figure 6. Instead, the interior vapour barrier between the gypsum board and the insulation and framing has the greater impact on the moisture movement between the interior climate and wall assembly.

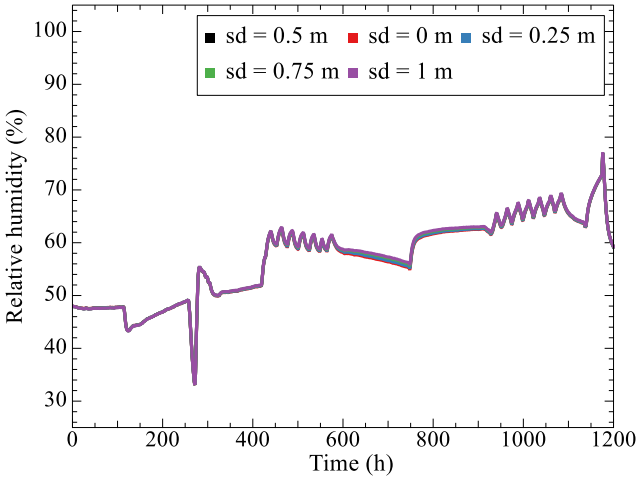

Figure 6: Wall 1 Relative Humidity at OSB/Insulation Interface with varying interior sd value

For the second wall, which does not have a vapour barrier, there is a visible difference seen in Figure 7 between no coating (sd value=0) and increasing sd value. As the interior wall in the physical tests is coated with one layer of paint primer, this is an important parameter to consider as part of future validations. It was assumed that the one layer of primer would be best represented by a sd value=0.5m representing typical interior painting (Boardman and Glass 2020), but this might not be the case, as the single layer of primer may be less than 0.5 m.

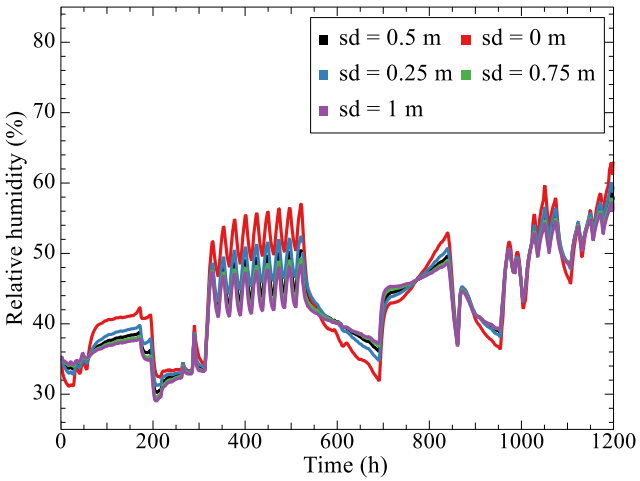

Figure 7: Wall 2 Relative Humidity at OSB/Insulation Interface with varying interior sd value

Outdoor heat conduction

Like the interior case, a small conductivity coefficient results in a shift in temperature, but as the conductivity coefficient increases, the marginal change in performance is less significant. This is seen in Figure 8, where reducing the exchange coefficient has a small impact on performance, but once the coefficient is larger than 12 W/m^{2}K the difference in thermal performance is not perceptible. However, any calibration of the conduction values would need to be within physically feasible values (Zhao et al. 2021).

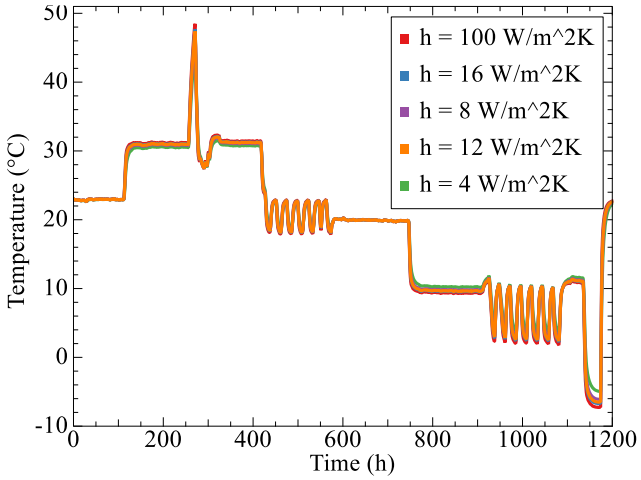

Figure 8: Wall 1 OSB Temperature with varying exterior heat conduction coefficient

Outdoor vapour diffusion

Changing the diffusion equivalent layer thickness (sd value) has a noticeable impact on hygrothermal performance as seen in Figure 9. The default value of 0 causes significantly more moisture to travel into the air gap between the exterior cladding and OSB, as there are some vapour bridges in the 2D geometry of the exterior cladding where infiltration is possible. Any non-zero sd value for the exterior surface inserts an equivalent air layer and affects the relative humidity performance compared to the base model.

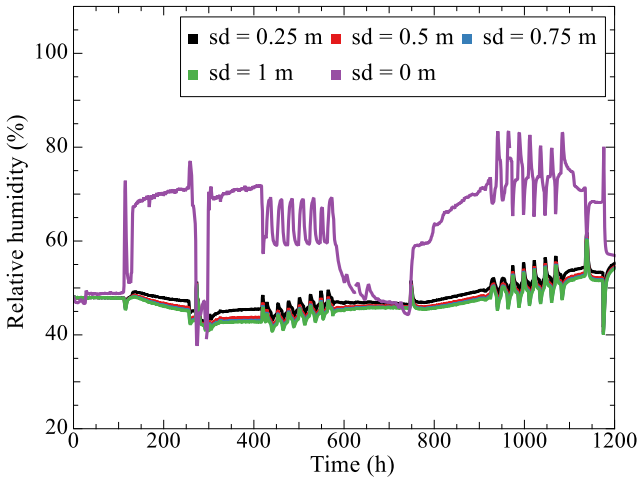

Figure 9: Wall 1 Air Gap Relative Humidity with varying exterior sd value

Even though altering this sd value for the exterior cladding has a significant impact on hygrothermal performance, it would not accurately represent how the wall assembly was built (Boardman and Glass 2020). So, while it is an interesting exercise, changing the sd value is not appropriate for future validations of these wall assemblies as this would misrepresent the actual physical characteristics of the walls.

Sensitivity to Output Elevation

Determining ideal measurement elevations for accurate hygrothermal data is of interest in this research, as there is variation in this dimension (Ibrahim et al. 2019; Knarud et al. 2023). For these models, the measurement elevation does have an impact, generally due to thermal bridging from the wood frame wall construction, and infiltration effects of the leaky exterior cladding. These differences are most evident in temperature and relative humidity profiles seen in Figure 10 and Figure 11 respectively.

While the temperature gradient is largely an effect of the different thermal conductivities of wood framing and insulation, the changes in relative humidity at different elevations seems to be impacted by the air flow direction through the air gap. There is still some effect by the different materials in the wood stud wall. The decision to model a vertical subsection from the center of the two-storey wall, with the double framing plate at the bottom of the model also shows the uneven bridging that would occur with the double versus single framing plate.

Because of these observed differences in hygrothermal performance at different elevations, this is a consideration for validation. If only one elevation for instrumentation is used for physical experiments, the variation in readings could be missed.

These temperature and humidity profiles also demonstrate the importance of selecting output element locations in the model that match the physical elevations. Using hygrothermal data from an area close to the framing in the model, but mid-height in the experimental data will likely result in larger error than matching elevations between models and experiments.

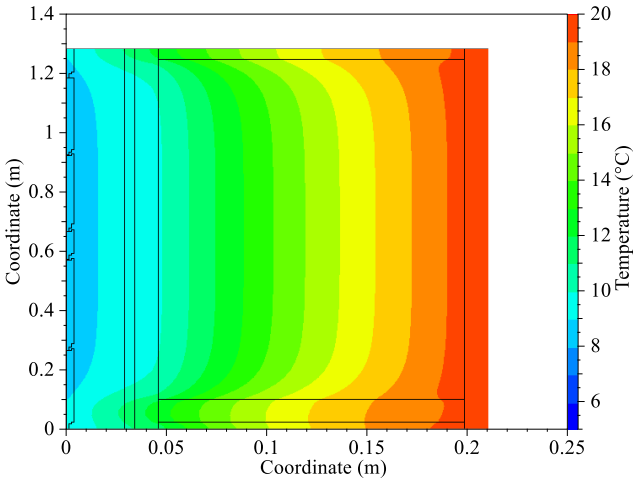

Figure 10: Wall 1 Temperature Profile

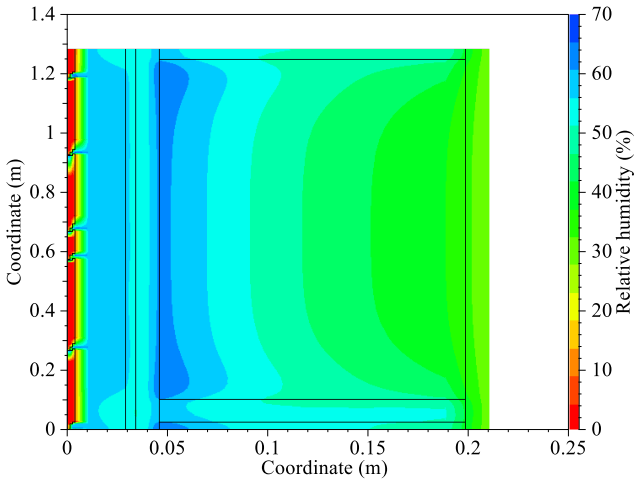

Figure 11: Wall 1 Relative Humidity Profile

Limitations

While a useful analysis was presented in this paper, it was limited by some of the design decisions in modelling. First, the models were developed using material data files only from the Delphin library. While this use of default material data files did not impact the results in this paper, it will likely impact future validation. This model is also limited by its geometry, only modelling a sub-section of the wall, not model the whole system, as well as only modelling a 2D vertical cross section of a 3D wall.

In the analysis of boundary and climate conditions, these models were limited to only temperature and relative humidity in the heat conduction and vapour barrier boundary conditions. Air pressure, wind, and radiation were not investigated and therefore these simulations did not consider solar drying effects or wind driven rain. Also, there was no consideration of air cavity ventilation between the exterior cladding the OSB.

Conclusion

In this research, models of two-dimensional, lightweight wall assemblies were developed for future validation with an experimental data set. The use of climate conditions from experimental data for boundary conditions was implemented for two wall assemblies. Different elements of the model design were discussed, and the sensitivity of these modelling choices were demonstrated.

Of these parameters the greatest impacts to hygrothermal performance were the initial relative humidity and the vapour diffusion equivalent thickness. Of note, changing the interior vapour diffusion parameters only effected the second wall assembly, which did not have an interior vapour barrier. Also noted was the sensitivity of changing the outdoor vapour diffusion parameters, with the practical restriction on future validation that changing this parameter would no longer accurately represent the physical characteristics of the system.

Changing strictly thermal parameters, such as initial temperature, or conductivity had a very minimal impact on the hygrothermal performance of either wall. The only noticeable effects of changing conductivity coefficients occurred at values that were outside the bounds of realistic physical performance.

This paper also showed the impact of modelling the wall assembly in two dimensions, and the variance of hygrothermal data at different elevations through the wall assembly. Instrumentation elevation in physical models, and output locations in models do have an impact on the potential for error when conducting validations between experimental and simulation data.

Overall, this paper gives several possible parameters for modification when for calibration when validating hygrothermal models with experimental data.

Future Work

This paper outlines the initial development of hygrothermal models in Delphin and the importance of various modelling parameters. With these models, future work includes performing the actual validation and calibration of the model using experimental data. Further sensitivity studies of material properties should also be conducted.

After validation and calibration, the goal of future work is to use these models to simulate long term hygrothermal performance of these walls with various climate files, including those with climate shifting to measure the impact of climate change on hygrothermal performance.

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