Water Vapour Permeance under Isothermal and Non-Isothermal Conditions

by

Manpreet Singh
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Supervisory Committee

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Dr. Min Sun

Chair Member (Department of Civil Engineering)

Abstract

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This report describes the effect of temperature gradient on the water vapour transmission properties of building materials. The generated temperature gradient across a test material is validated with thermal analysis by using SOLIDWORKS (3D CAD software). The water vapour transmission measurement technique used for this study is a modified cup method, which has constant 50% mean relative humidity. The two wall sheathing membranes, asphalt saturated kraft building paper and Polymer based sheathing membrane were tested under isothermal and non-isothermal boundary conditions. The comparison was made between the results of isothermal and non-isothermal boundary conditions. The results obtained from non-isothermal test conditions show increase in water vapour transmission rate (WVT) and water vapour permeance of asphalt saturated kraft building paper. On the other hand, the results of polymer based sheathing membrane show decrease in WVT rate and not much significant change in water vapour permeance.

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1. Introduction

Building envelopes are subjected to various types of environmental hygrothermal (i.e. heat-air-moisture) loads such as temperature, water vapour, rain, solar radiation, air pressure etc. These loads fluctuate and have different ranges depending on the climate regions. The building envelope design should provide stability and durability against these exterior loads to the interior conditions of a building. In case of moisture design for the building envelope, moisture entry and moisture accumulation, as well as drying rate of building assemblies are the important factors. Additionally, moisture storage capacity also greatly contributes to the design and performance of the building envelope. For example, wood frame walls have higher hygric buffer capacity as compared to steel frames [1]. It can store some amount of water easily, whereas in steel frames even small amount of water can lead to corrosion.

Moisture management plays a vital role in building envelope design. The fundamental moisture flow mechanisms through the building components are: 1) water vapour diffusion caused by vapour pressure gradients, 2) water vapour displacement by air movement, 3) capillary suction of liquid water in porous materials and 4) liquid water flow due to air pressure gradients (i.e. wind driven rain). The moisture control strategies for entry, accumulation and removal should be applied simultaneously. The control strategies include the use of drainage plane to protect from rain; air barriers to control the air movement and vapour barriers to prevent or slow down the water vapour diffusion through the different components of a building assembly. The techniques of these control strategies are dependent on the climatic conditions. For example, in cold climates, vapour barrier is installed to protect the building assemblies getting wet from the interior side. Conversely, in hot climates, these barriers are installed on the exterior side of the sheathing. Whereas, in mixed climatic conditions, two general strategies such as “flow- through” approach in which permeable materials are used on the both interior and exterior side and the second way is installing a vapour barrier in the thermal middle of the building assembly[2].

The effective implementation of moisture control strategies requires reliable and realistic moisture properties. Water vapour permeance is an important moisture property and it is determined by research laboratories as per ASTM Standard E-96[3]. The Canadian Building Code CAN CGSB Standard 51.32 define water vapour permeance range of 170 $ng/Pa.s.m^2$ to 1400 $ng/Pa.s.m^2$ for sheathing membranes (see materials in Methodology section) used for wood framed walls. Water vapour permeance is measured under isothermal conditions. However, in real world applications, sheathing membranes are subjected to non-isothermal conditions.

2. Objectives

The objectives of this study were:

- To determine the dependency of water vapour transmission (WVT) rate and its related properties on non-isothermal conditions by creating freezing conditions (below 0°C).
- Investigate the effect of non-isothermal conditions on two widely used wall sheathing membranes i.e. asphalt saturated kraft building paper and polymer based sheathing membrane.
- To compare the results obtained under isothermal and non-isothermal conditions.

3. Research Background

3.1 Definitions

Water vapour permeance is the measure of water vapour diffusion through a material and it is derived from the water vapour transmission rate. The definitions of water vapour transmission and its derived properties are as follows:

a) **Water Vapour Transmission:** Water vapour transmission rate of a building material is a measure of the mass of water vapour passed per unit time through unit area of a body, normal to both surfaces of a material, under specific conditions of temperature and humidity at each surface.

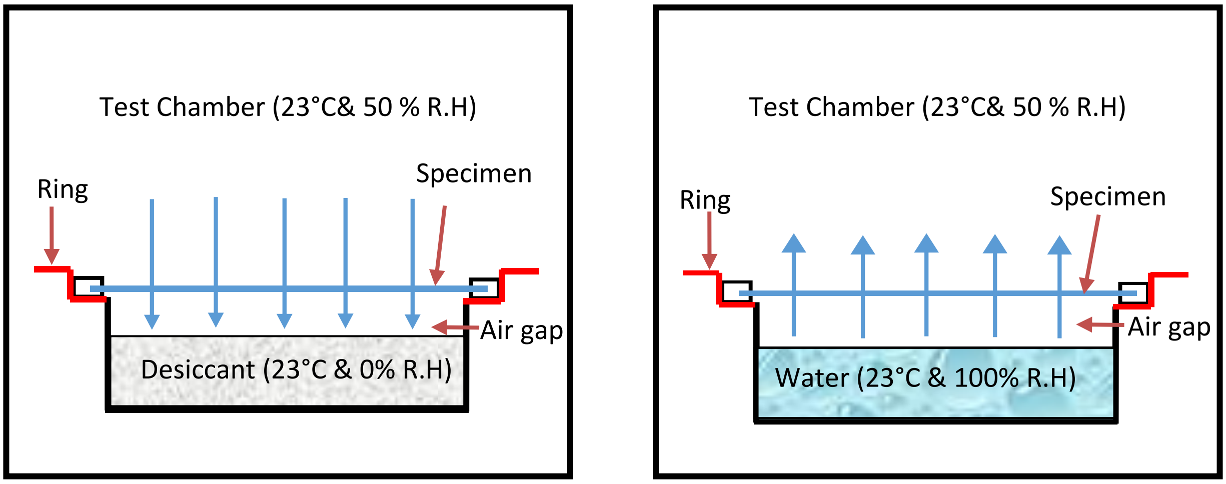
b) **Water Vapour Permeance:** Water vapour permeance is derived from the water vapour transmission rate. It is derived by dividing the water vapour transmission rate to the vapour pressure difference across that material.

c) **Water Vapour Permeability:** Water vapour permeability is the product of the thickness of a material and water vapour permeance.

3.2 Measurement Methods

3.2.1 Conventional Cup Methods

ASTM Standard E-96 [3] is currently used to measure the water vapour permeability of building materials. It explains about the dry-cup method and wet-cup method to test this property. In dry- cup method, the cup is partially filled with desiccant (e.g. $CaCl_2$), which maintains 0% relative humidity (R.H), and has a test specimen attached to it (see Figure 1a). The dry-cup kept in an environmental chamber maintained at a constant standard temperature and relative humidity (R.H). Similarly, wet-cup method also has a test specimen attached on top of the water filled dish and the cup is kept in the controlled environmental chamber (Figure 1b). The water generates 100% relative humidity on one side of the testing material, whereas desiccant creates 0% relative humidity (see Figure 1). Both these methods represent the extreme climatic conditions, i.e. dry-cup methods used for extremely dry conditions and whereas wet cup method used for extremely wet conditions.



(a) Dry Cup **(b) Wet Cup**

Figure 1: Conventional Cup Methods

3.2.2 Modified Cup Method

The modified cup method was used in past experiments [4, 5] to determine the temperature effect at isothermal conditions. It was established that results obtained from this modified cup method were very similar to the conventional cup methods at 50% mean relative humidity [5].

The modified cup test assembly (Figure 2) has desiccant on the top and water on the bottom side of the cup. The testing material is placed between water and desiccant dish as shown in Figure 2. Thus, it can provide results of both wet- and dry-cup at the same time.

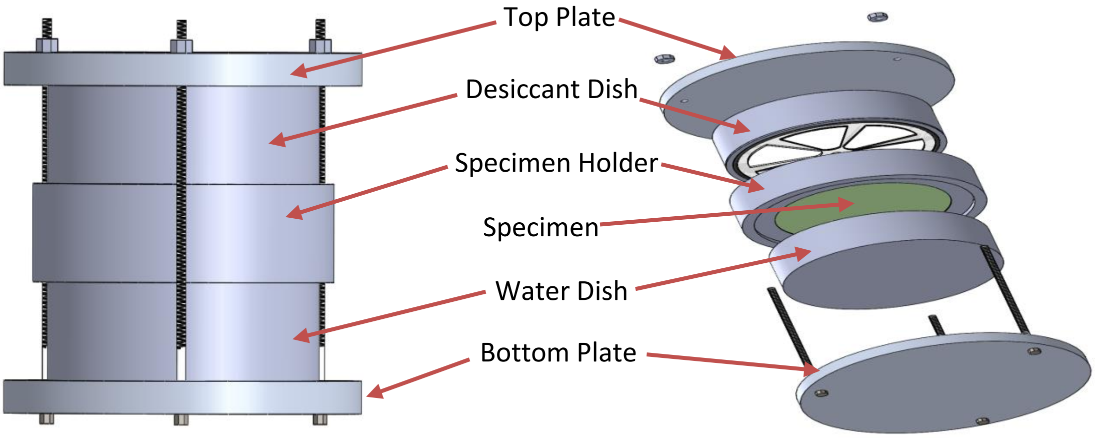


Figure 2: Modified Cup Assembly & Its Exploded View

3.3 Literature Review

The numerous experiments had been performed to measure the water vapour permeability of building materials [4, 5, 6, 7, 8]. It started with determining the dependence of water vapour permeability on vapour pressure or relative humidity [6, 7]. In addition to that, dependence of temperature was also studied at isothermal conditions [4, 5]. On the contrary, there is not much data available of this property under non-isothermal conditions [8].

Water vapour permeance of polyurethane and polyisocyanurate foams was investigated [4] by using three different methods- dry cup at 21.5°C mean temperature and 25% mean relative humidity (isothermal conditions), modified cup at 10°C, 21.5°C, 32°C, 51°C mean temperature values and 50 % average relative humidity (isothermal conditions), and modified cup at 27.5°C mean temperature and 50% average relative humidity (non-isothermal). The Thermal gradient is formed in the latter one by using hot plate (50°C) on water side and cold plate (5°C) on desiccant side of the modified cup. The results shows increase in water vapour permeance at temperatures range from 21.5 to 51^{0} C. However, there is not much difference in WVP values at 10 and 21.5 ^{0} C.

The study [5] was conducted about the newly developed modified cup method by testing water vapour permeability of fibreboard and gypsum board at temperature ranges from 7°C to 43°C and 50 percent mean relative humidity. The results shown that water vapour transmission rate obtained from this modified cup method has same values as those obtained from conventional dry and wet cup method, based on the standard ASTM E 96. Additionally, WVT rate increases with increase in temperature at isothermal conditions. However, water vapour permeability results shows to be independent of temperature conditions.

In one of the previous experiment, Valovirta and Vinha [6] tested water vapour permeability of various commonly used building materials in Nordic climatic conditions by using wet cup method, which includes thermal insulation, interior boards and sheathing membranes. These materials were studied at different relative humidity values (35%, 50%, 70% and 90%) and three different temperatures (23°C, 5°C and -10°C) at isothermal conditions. The wet cup with constant 33% relative humidity inside the dish was used and the relative humidity was varied inside the testing chamber. Most of these building materials show increase in water vapour permeability above 50 percent relative humidity at constant temperature conditions.

Chang [7] discussed about the permeability coefficient and average permeability for the building materials, as well as the temperature and humidity variations along the path of transmission. The permeability curve can be obtained at the 20 percent increment of the relative humidity in isothermal conditions by using trial and error method. The water vapour permeability data for three sheathing membranes had shown that increase in this property with increase in relative humidity and temperature at isothermal conditions. The kraft building paper has less increase in water vapour permeability as compared to asphalt saturated sheathing felt and asphalt saturated building paper.

Samuel V. Glass [8] reported experiment results for plywood material under isothermal and non-isothermal conditions. Results obtained at isothermal conditions for this wood based material are compared with past experimental data, which shows same increasing trend with relative humidity but the results values varied by factor of four or more due to variation in species of wood and manufacturing processes etc. The Non-isothermal experiment was conducted by controlling the temperature and humidity independently in two steel framed cylinders and tested material was attached between these two chambers. The vapour pressure was kept constant across the membrane by making temperature and humidity gradients in the opposite directions as the boundary conditions for the test. The results had shown not much moisture transfer due to temperature gradient under the selected boundary conditions.

Table 1 summarizes the experiments mentioned in the literatures above for WVT rate, water vapour permeance and water vapour permeability.

Table 1: Summary of Previous Experiments

Reference	Materials	Parameters	Test Method	Conclusion
Schwartz, Bomberg, Kumaran [4]	Polyurethane, Polyisocyanurate foam	Dry Cup (mean temperature 21.5 °C& 25% mean R.H), Modified Cup (mean R.H 50% and mean temperature 10, 21.5, 32, and 51°C under isothermal conditions), Modified Cup (mean temperature 27.5 °C and mean R.H 50 % under non-isothermal conditions)	Dry Cup, Modified Cup	Increase in water vapour permeance at temperature range from 21.5 to 51^{o} C
Mukhopadhyaya, Kumaran, Lackey[5]	Fibreboard, Gypsum board	Mean R.H 50% Temperature Range from 7°C to 43°C under isothermal conditions	Modified Cup	Increase in WVT rate with increase in temperature and not much change in water vapour permeability with temperature
Valovirta, Vinha[6]	Insulation materials, Sheathing membranes, interior boards used in Finland	Mean R.H 35%, 50%, 70% and 90% and temperature 23°C, 5°C and -10°C under isothermal conditions	Wet Cup	Increase in water vapour permeability with increase in R.H
Chang[7]	Building Paper and Felt Paper	Test Chamber R.H 20% to 95%, temperature -12.2, -3.9, 1.6, 22.7 and 32.2 °C under isothermal conditions	Dry Cup	Increase in water vapour permeability with increase in R.H and temperature
V. Glass[8]	Plywood	Temperature 23 °C and mean R.H 22%, 51.5%, 59%, 70%, 73.5% under isothermal conditions and constant vapour pressure under non-isothermal conditions.	Modified Cup	Increase in water vapour permeance with increase in R.H under isothermal conditions and not much moisture transfer under non-isothermal conditions.

4. Methodology

The modified cup method [4, 5] developed earlier to study the temperature dependency of water vapour transmission under isothermal conditions, is used in this study for both the isothermal and non-isothermal conditions. The non-isothermal conditions is generated with the help of dry ice.

Dry ice is a solid form of carbon dioxide and it has lower temperature than water ice. Dry ice has a sublimation temperature[1] of -78.5°C and turns directly into gaseous state from solid state at atmospheric pressure. Dry ice could be sourced in variety of shapes and sizes i.e. snow, slabs and blocks, but experimental specifications required dry ice to be used in slabs, which could provide intermediate rate of refrigeration while lowering the sublimation rate with lesser surface area exposed [9].

4.1 Materials: The two widely used wall sheathing membranes for wall assemblies, asphalt saturated kraft building paper and polymer based sheathing membrane were selected for this study. Both these materials were tested at isothermal and non-isothermal conditions. Three samples of each material were tested at isothermal conditions and non-isothermal conditions.

Table 2: Physical properties of materials

Material	Thickness (mm)	Basis Weight[2] (lb/100 ft^2)
Building Paper	0.25	4.13
Polymer Based Membrane	0.15	1.25

4.2 Test Conditions: Following are the test conditions used for isothermal and non-isothermal tests:

a) Isothermal Test: Mean temperature 23°C and 50 % mean relative humidity (R.H).

b) Non-isothermal Test: Mean temperature of air gap on water side 8.5 ±1°C and desiccant side -5± 2°C and 50 % mean relative humidity (R.H).

4.3 Experimental Setup: Figures 3a, 3b and 3c below show the experimental setup for non-isothermal conditions. The water side is open to the room temperature and the desiccant side of the testing membrane is enclosed by the foam box, and it is maintained below 0°C to generate the required temperature gradient across the testing membrane. Surface temperatures is measured at the centre of the water, specimen and desiccant dish of the modified cup, as well as the temperature of the closed chamber.

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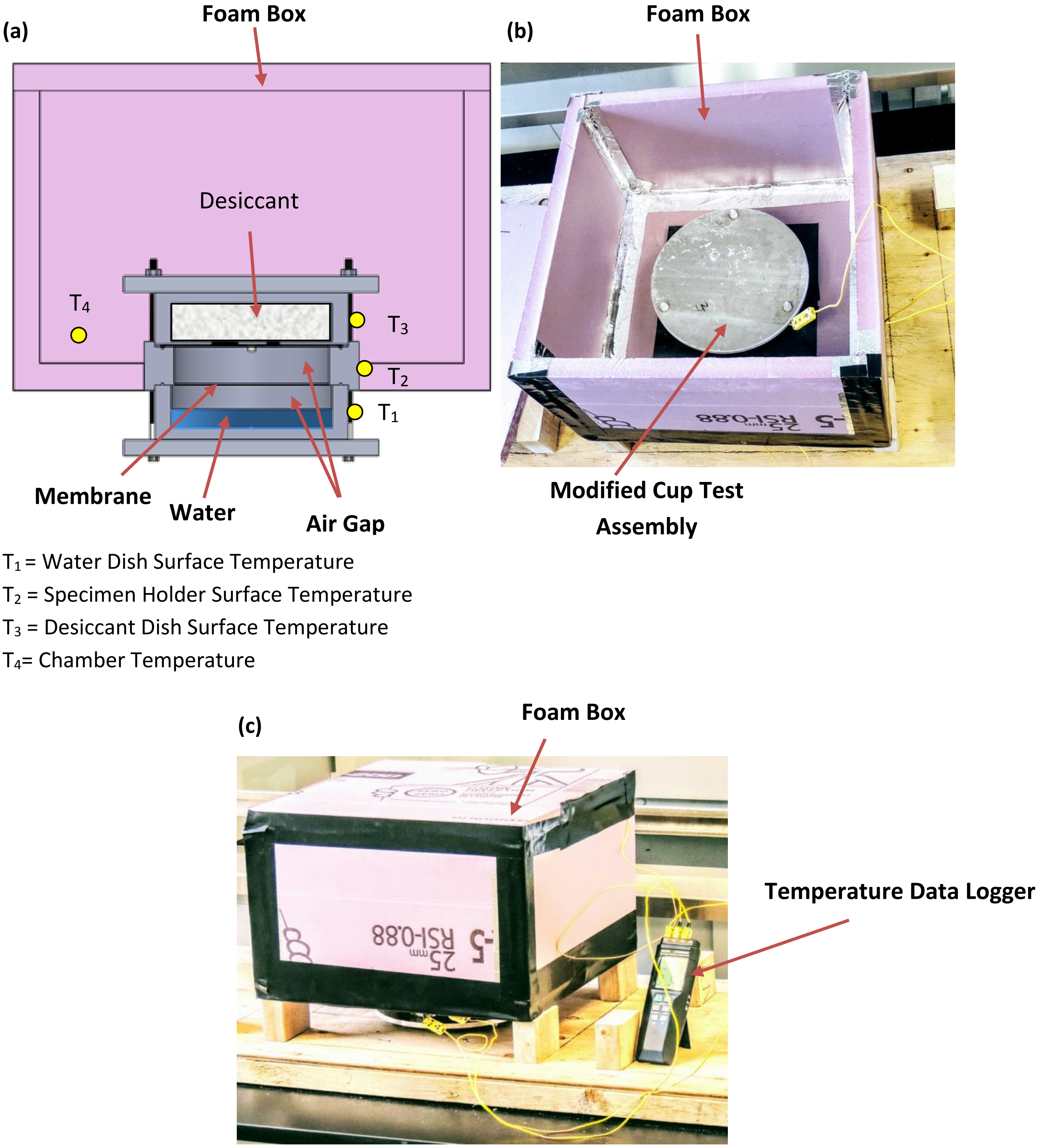
[1] It is a temperature at which phase transition occurs from solid to gas without undergoing through the liquid phase

[2] It is the weight measured in pounds of 500 sheets of paper cut into the basic size for a particular grade of a paper[12]



T_1 = Water Dish Surface Temperature

T_2 = Specimen Holder Surface Temperature

T_3 = Desiccant Dish Surface Temperature

T_4= Chamber Temperature

Figure 3: Experimental set up for non-isothermal conditions (a) Schematic diagram, (b) & (c) Pictures from laboratory

4.4 Experimental Procedure

The experiment was performed following the procedure defined in the ASTM Standard E-96 [3]. The following steps were taken during this experiment.

- Water depth level and desiccant was used for the test as per the ASTM Standard E-96 [3]. The water dish was filled with distilled water to a level of 24±1 mm from the surface of the testing membrane. The anhydrous calcium chloride was used as a desiccant for the test.
- The specimen was attached by using microcrystalline wax (60%) and refined crystalline paraffin wax (40%) as per the sealing methods defined in the ASTM Standard E-96 [3].
- The weighing scale used for the experimental test has sensitivity of .01 grams. Figure 4 shows weighing scale with desiccant dish.
- Ten data points were recorded during both testing conditions, isothermal and non-isothermal. The materials tested were very thin sheathing membranes, which gets saturated in less time. Therefore, periodic readings were taken after every one hour.
- The whole assembly, modified cup, foam box were disassembled for every reading and dry ice taken out from the foam box. The weights of water dish, specimen holder and desiccant dish were recorded for every reading. Total time taken for this whole process, which included disassembly, assembly, taking dry ice out from the foam box and placing it back, was approximately 8 ±1 minutes.

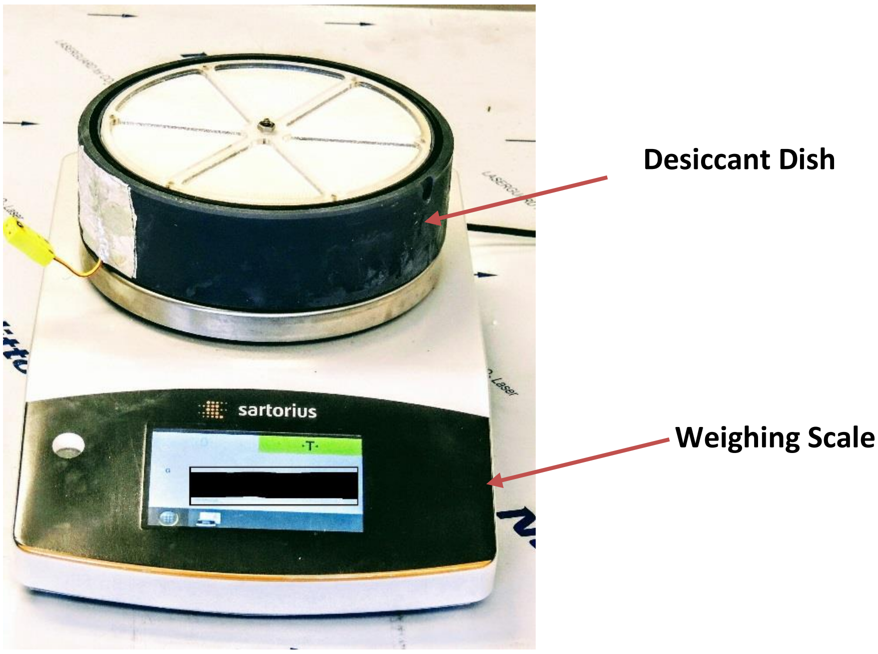


Figure 4: Weight measurement of desiccant dish

- The desiccant dish was kept in the freezing conditions for the experiment and separated from the water cup by using foam box. During the weighing period, it also kept to the room temperature to take the readings after every hour. There was a temperature difference between the temperature of desiccant dish and room temperature where readings were taken place. Thus, there was a high possibility of condensation to occur on the desiccant dish.
  Therefore, the dummy specimen was used, and same process with similar boundary conditions was repeated. The recorded weights of the tested specimens were adjusted by using dummy specimen as defined in ASTM E-96 [3].

Figure 5 shows the setup for dummy specimen, there is desiccant with 0% relative humidity (R.H) on both sides of the tested membranes, thus there is no driving force or vapour pressure gradient across the tested specimens.

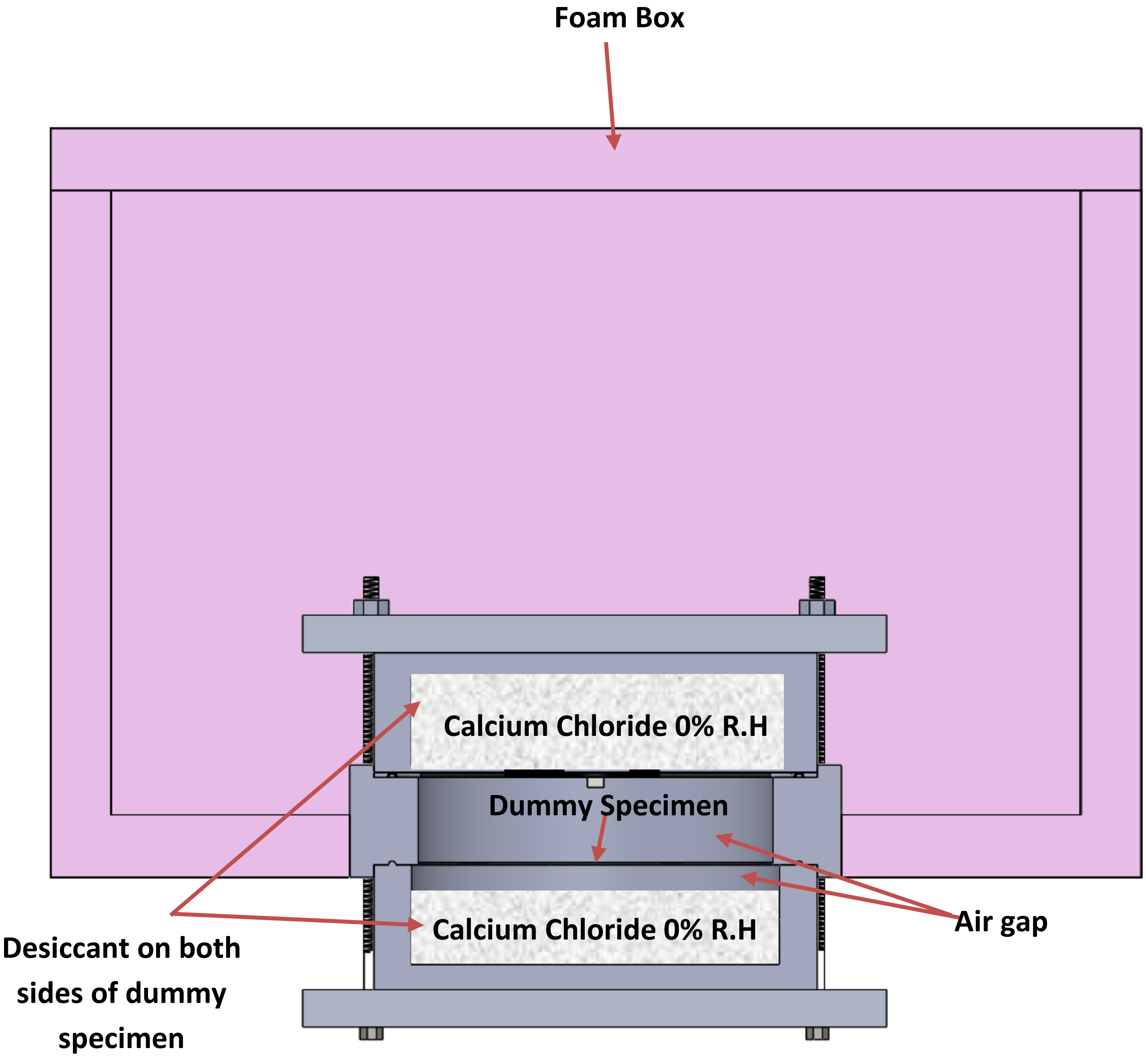
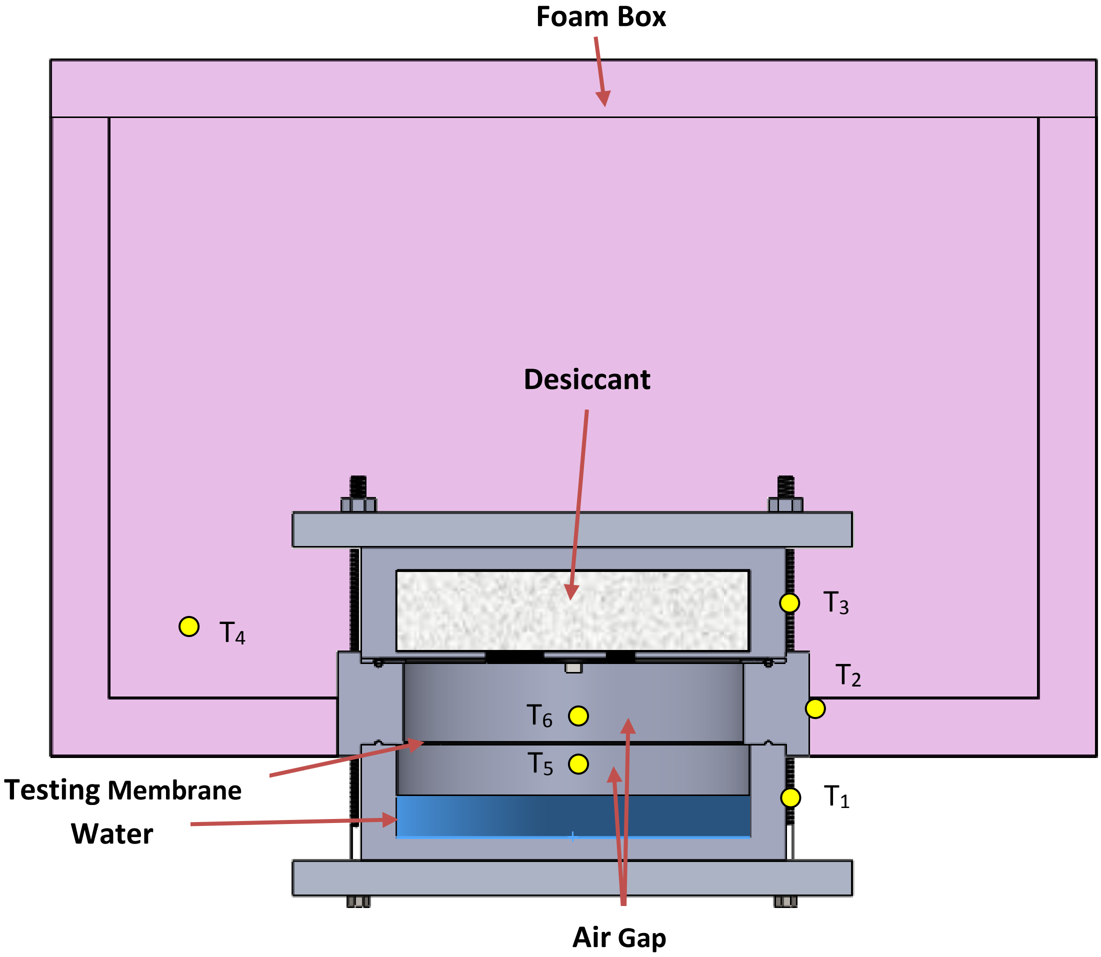


Figure 5: Set up for Dummy Specimen

4.5 Temperature Validation

As explained in the experimental set up for non-isothermal conditions, surface temperatures at different locations of the modified cup assembly as well as the temperature of the chamber was measured. However, temperature inside the modified assembly and across the testing specimen was unknown. In addition to that, installing any instrument inside the modified cup assembly could affect the water vapour transmission and its properties results. Therefore, to solve this problem, thermal simulations were performed with the help of SolidWorks software. The thermal simulation results were validated by comparing it with measured experimental temperature results. The temperature sensors were placed on both sides of the testing specimen inside the modified cup assembly and surface temperatures were also measured as shown in Figure 6. After that, the recorded surface temperature data was used as the boundary conditions for thermal simulation. Then, these thermal simulation results were compared with recorded temperature data inside the modified cup assembly.



T_1 = Water Dish Surface Temperature

T_2 = Specimen Holder Surface Temperature

T_3 = Desiccant Dish Surface Temperature

T_4 = Chamber Temperature

T_5 = Inside location of Temperature Sensor on desiccant side

T_6 = = Inside location of Temperature Sensor on water side

Figure 6: Location of Temperature Sensors

The recorded data from the laboratory experiment was used as the boundary conditions for thermal analysis. SolidWorks offers time dependent thermal simulations and temperature data from the laboratory was also recorded with time. The default properties were selected as defined in the SolidWorks for water and air. However, calcium chloride properties shown in Table3 below were defined manually for the thermal simulations [10].

Table 3: Properties used of calcium chloride for thermal simulations *[10]*

$CaCl_2$ Properties	
Density	2150 kg/m^3
Dynamic viscosity	0.003 Pa.s
Specific heat	670 J/kg.K
Thermal conductivity	0.54 W/m.K

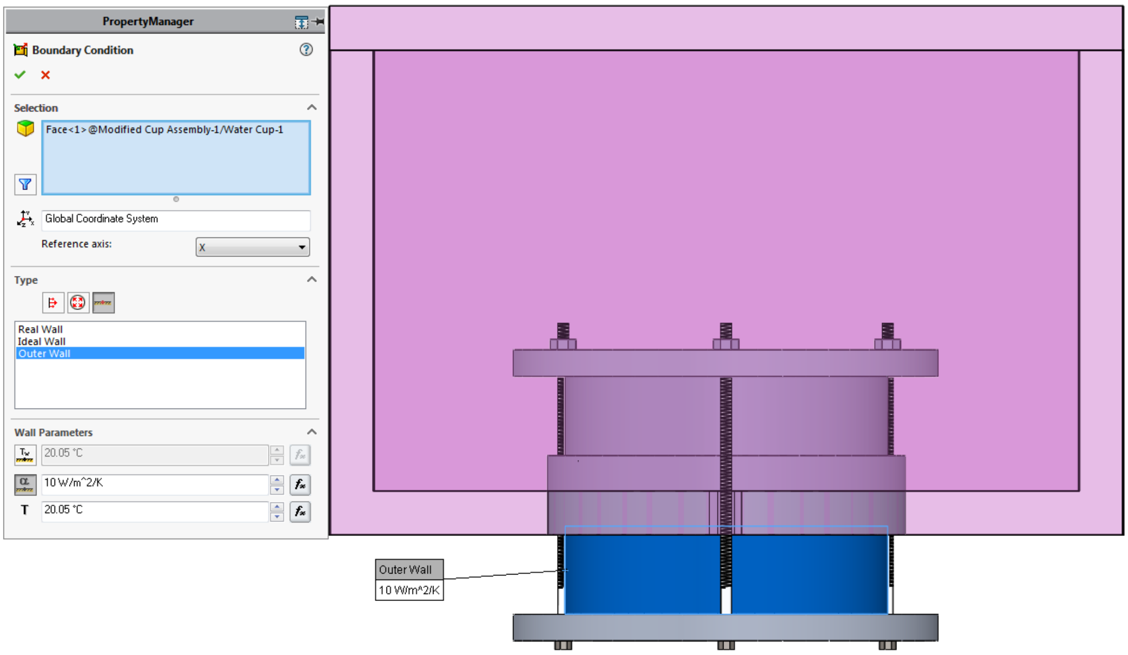
Similarly materials were defined for thermal simulations. Table 4 shows the materials defined for the thermal simulations.

Table 4: Materials defined for thermal simulations

Parts Name	**Material**
Water Dish	Polyvinyl chloride (PVC)
Specimen Holder	Polyvinyl chloride (PVC)
Desiccant Dish	Polyvinyl chloride (PVC)
Top and Bottom Plate	Aluminium
Bolts & Nut	Nylon-66
Foam Box	Extruded Polystyrene

4.5.1 Boundary Conditions: The boundary conditions for thermal simulations were defined as follows:

- The outer wall of the water dish was defined open to room temperature of 20 °C.



Face<1>@Modified Cup Assembly-1/Water Cup-1

Global Coordinate System

Reference axis: X

Real Wall
Ideal Wall
Outer Wall

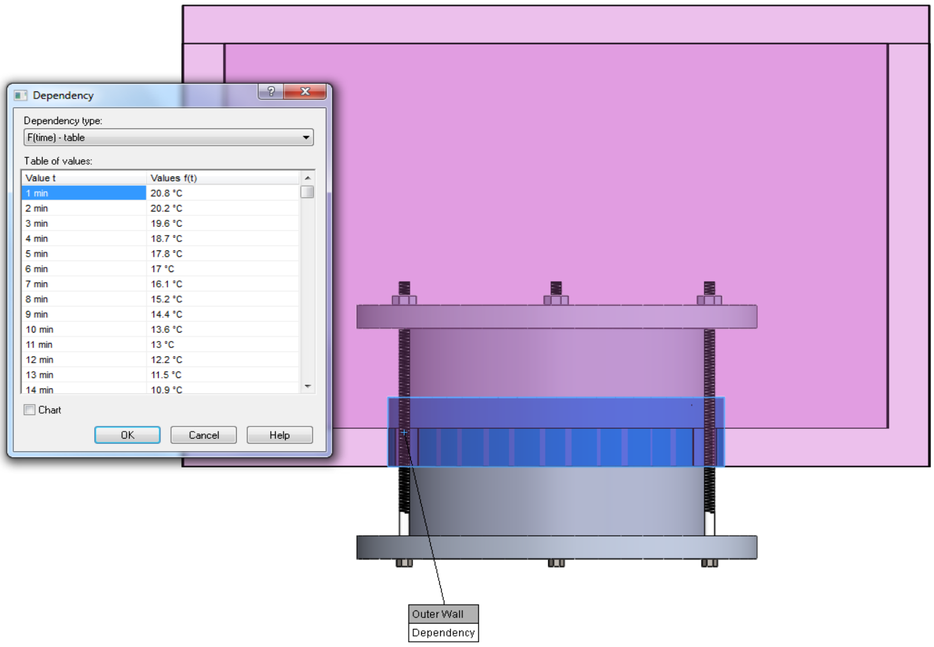
T_w 20.05 °C

α 10 W/m^2/K

T 20.05 °C

Figure 7: Boundary Conditions for Water Cup

- The recorded surface temperatures of specimen holder and desiccant dish with time was defined as shown in Figure 8 and 9.

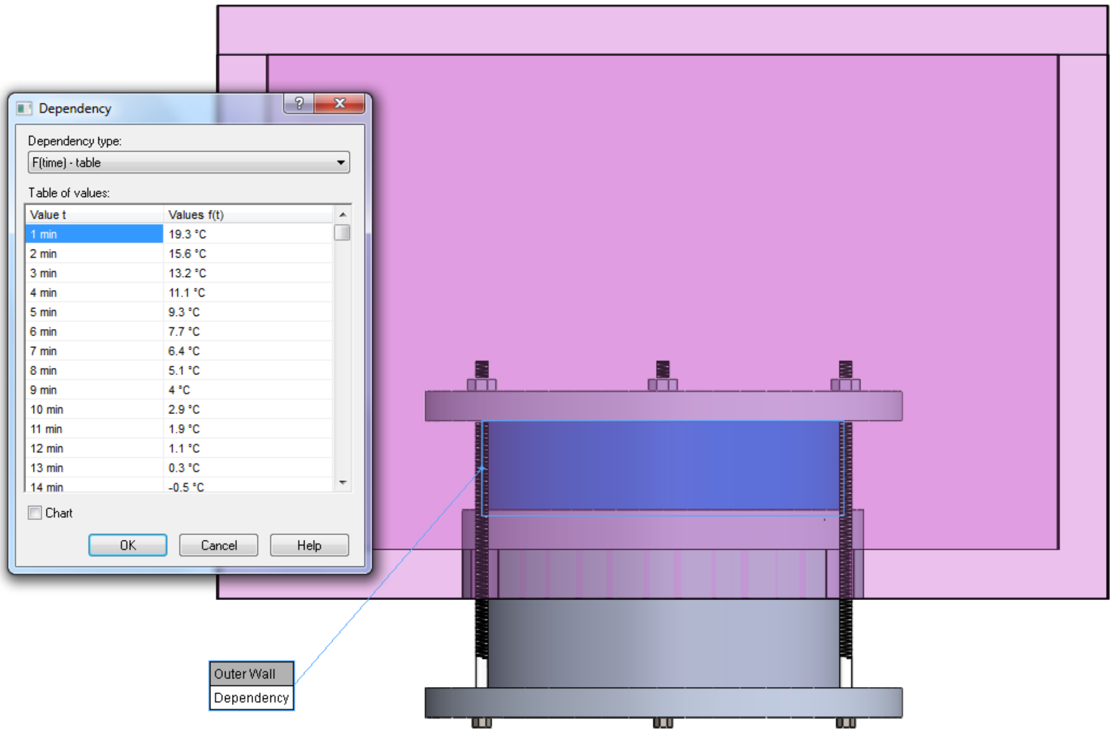


Dependency type: F(time) - table

Table of values:

Value t	Values f(t)
1 min	20.8 °C
2 min	20.2 °C
3 min	19.6 °C
4 min	18.7 °C
5 min	17.8 °C
6 min	17 °C
7 min	16.1 °C
8 min	15.2 °C
9 min	14.4 °C
10 min	13.6 °C
11 min	13 °C
12 min	12.2 °C
13 min	11.5 °C
14 min	10.9 °C

Figure 8: Boundary Conditions for Specimen Holder



Dependency

Dependency type: F(time) - table

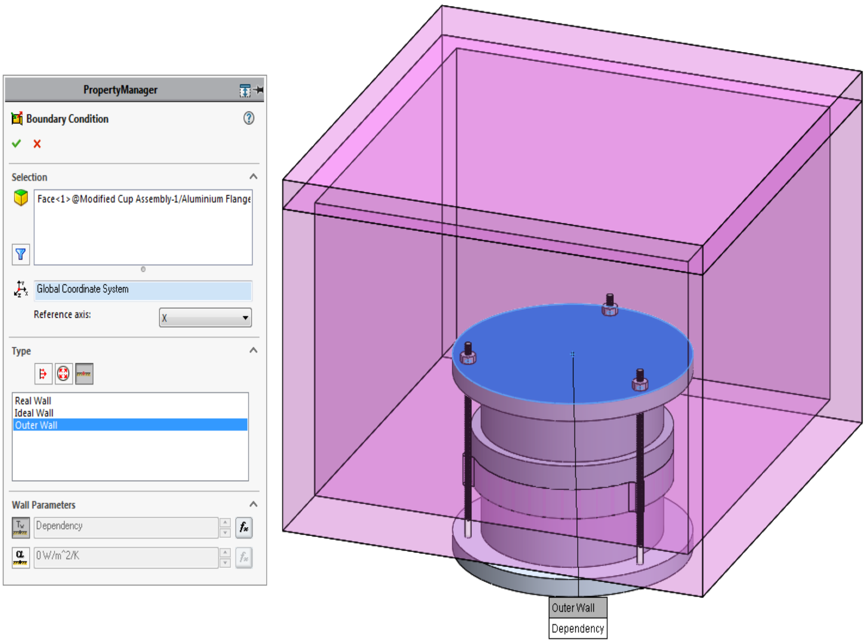
Table of values:

Value t	Values f(t)
1 min	19.3 °C
2 min	15.6 °C
3 min	13.2 °C
4 min	11.1 °C
5 min	9.3 °C
6 min	7.7 °C
7 min	6.4 °C
8 min	5.1 °C
9 min	4 °C
10 min	2.9 °C
11 min	1.9 °C
12 min	1.1 °C
13 min	0.3 °C
14 min	-0.5 °C

☐ Chart

Figure 9: Boundary Conditions for Desiccant Cup

- The measured temperature data of chamber with time was defined as the boundary conditions for top plate of the modified cup assembly as shown in Figure 10.



PropertyManager

Boundary Condition

Selection: Face<1>@Modified Cup Assembly-1/Aluminium Flange

Global Coordinate System

Reference axis: X

Type: Outer Wall

Wall Parameters

Dependency

0 W/m^2/K

Figure 10: Boundary Conditions for Top Plate

5. Analysis of Test Results

The analyses and calculations of the water vapour transmission and water vapour permeance were done by using the analysis procedure and equations explained in ASTM Standard E-96 [3].

5.1 Isothermal Experiment

Water Vapour Transmission: Water vapour transmission rate was obtained by plotting the six steady-state weight changes data points against the elapsed time. It is calculated by using the following equation:

$$\mathrm{WVT} = \frac{(\mathrm{G/t})}{3600 \times \mathrm{A}} \tag{1}$$

Where,

G= weight change of desiccant dish of testing sample, in grams (g)

t = time, in hours (h)

G/t = mean slope of desiccant dish weight change, in grams/hour (g/h)

A = test area of sample material, in m^2

WVT = Water Vapour Transmission Rate, in $g/s.m^2$

Water Vapour Permeance: Water vapour permeance was derived from the water vapour transmission rate by using the following equation:

$$\text{Water Vapour Permeance} = \frac{\mathrm{WVT}}{\mathrm{S}\,(R_1 - R_2)} \tag{2}$$

S = Saturation vapour pressure at test temperature, in Pa

R_1 = Relative humidity at the source expressed as a fraction

R_2 = Relative humidity at the vapour sink expressed as a fraction

5.2 Non-Isothermal Experiment

Water Vapour Transmission: In this case, water vapour transmission rate was also plotted by using the six steady-state data points of desiccant dish weight change. In addition to that, the mean slope of desiccant dish weight change of dummy specimen was subtracted as defined in the ASTM Standard E-96[3].

$$\mathrm{WVT} = \frac{{}^{G_1}\!/_{t} - {}^{G_2}\!/_{t}}{3600\ \times \mathrm{A}} = \frac{(\mathrm{G/t})}{3600\ \times\ \mathrm{A}} \tag{3}$$

Where,

G= original weight change of desiccant dish, in grams (g)

t = time, in hours (h)

G_1/t = mean slope of desiccant dish weight change of testing sample, in grams/hour (g/h)

G_2/t = mean slope of desiccant dish weight change of dummy specimen, in grams/hour (g/h)

A = test area of sample material in m^2

WVT = Water Vapour Transmission Rate, $g/s.m^2$

Water Vapour Permeance: After the water vapour transmission, water vapour permeance was calculated by using the following equation:

$$\text{Water Vapour Permeance} = \frac{\mathrm{WVT}}{p_{v1} - p_{v2}} = \frac{\mathrm{WVT}}{S_1R_1 - S_2R_2} \tag{4}$$

Where,

p_{v1}= Vapour Pressure on water side of the modified cup, in Pa

p_{v2} = Vapour Pressure on desiccant side of the modified cup, in Pa

S_1 = Saturation vapour pressure at average temperature on water side, in Pa

R_1 = Relative humidity at the water side expressed as a fraction

S_2 = Saturation vapour pressure at average temperature on desiccant side, in Pa

R_2= Relative humidity at the source expressed as a fraction

6. Results& Discussion

The modified cup combines both the dry-cup and wet-cup tests. Ideally, both wet-cup and dry-cup measurements should produce same water vapour transmission values. However, in this study, the temperature gradient was generated; thus, condensation occurred on the surface of the tested specimens, as shown in Figure 11below. Therefore, water vapour left from the water side was not equal to the water vapour absorbed by the desiccant side. Hence, dry-cup results were used and presented in this report for comparison between non-isothermal results and isothermal results.

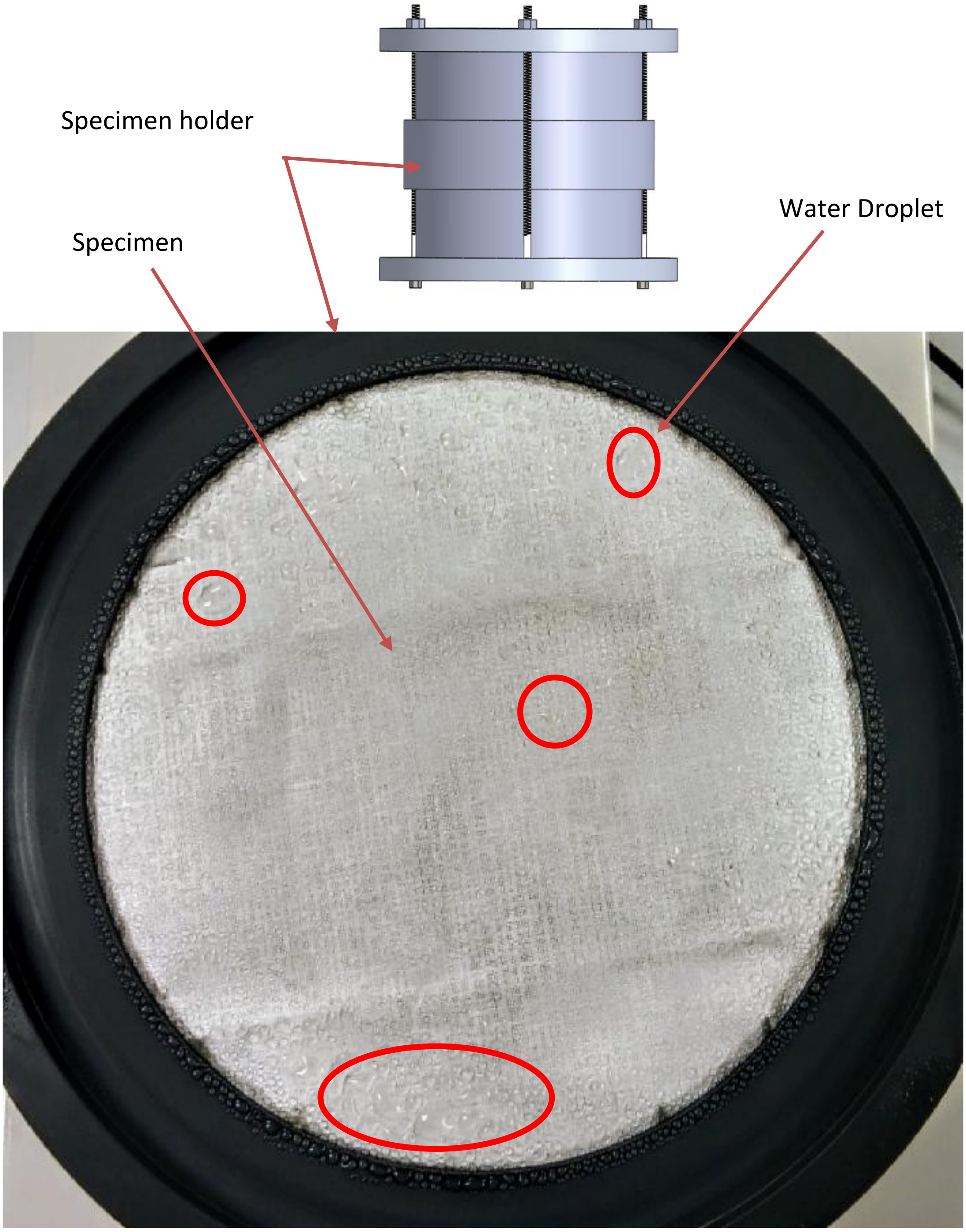


Figure 11: Condensation on polymer based membrane surface

6.1 Temperature Validation Results

The temperature was measured inside the modified cup assembly for validation purpose, on both sides of the tested specimen and then compared with thermal simulation results. Table 5 shows the difference between measured temperatures and thermal simulation temperatures for three hours. The difference between results was found to be approximately ± 2 °C.

Table 5: Comparison between experimental and temperature simulation results

Time (Hours)	Simulation Water Side Temperature (°C)	Measured Water Side Temperature (°C)	Simulation Desiccant Side Temperature (°C)	Measured Desiccant Side (°C)
00	21	21	24	24
01	15.06	14.08	13.09	12.24
02	13.08	12.64	8.75	10
03	11.98	11.32	6.48	8.32

Figures 12, 13, 14 show section view of the modified cup assembly after one, two and three hours respectively.

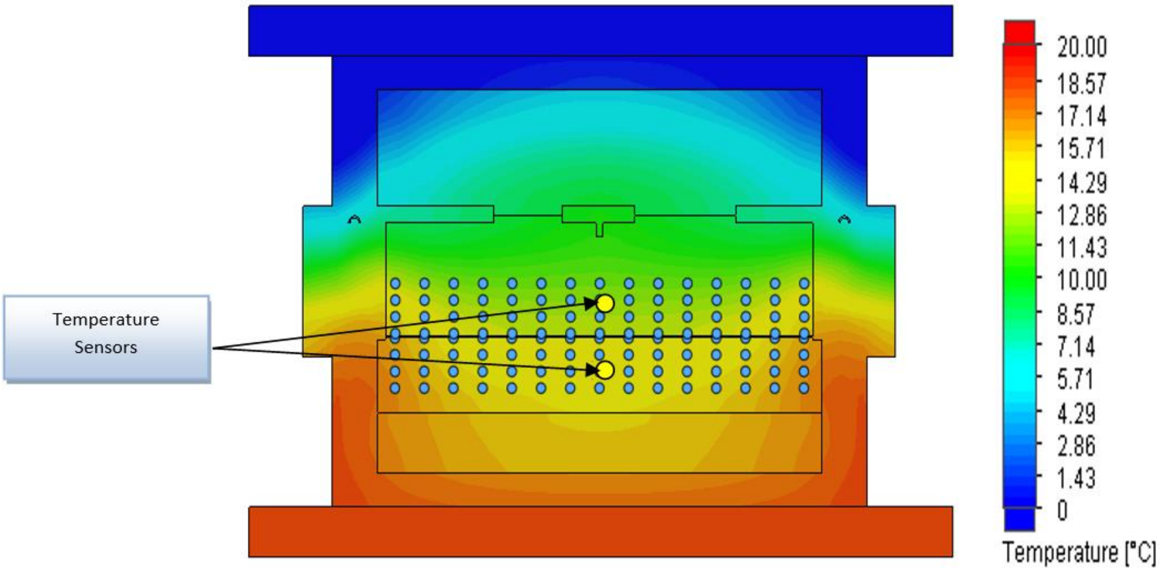


Figure 12: Section View of Modified Cup after one hour

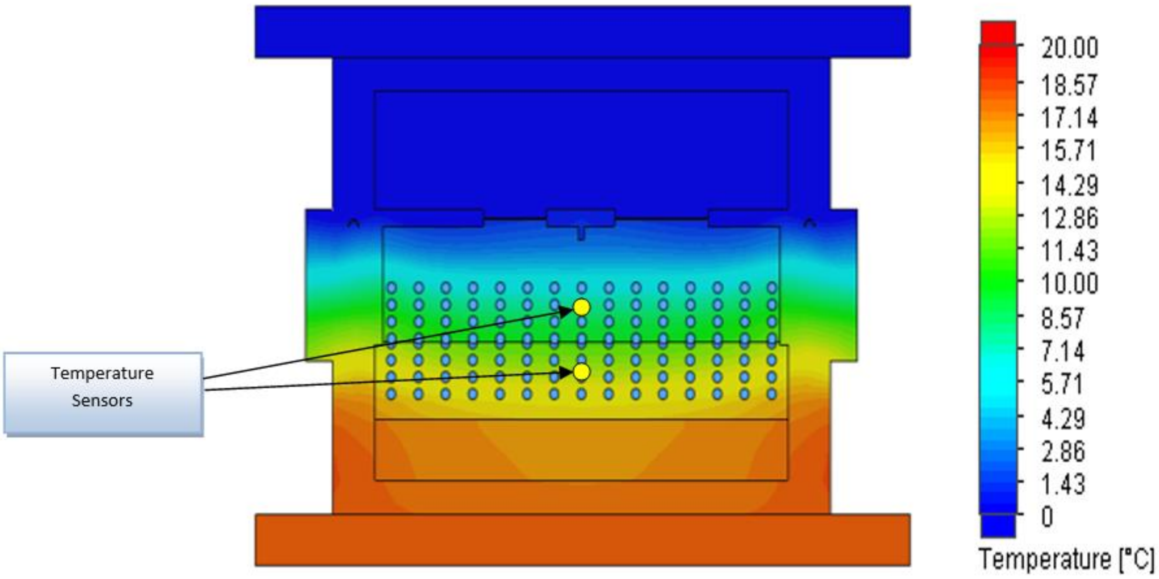


Figure 13: Section View of Modified Cup after two hour

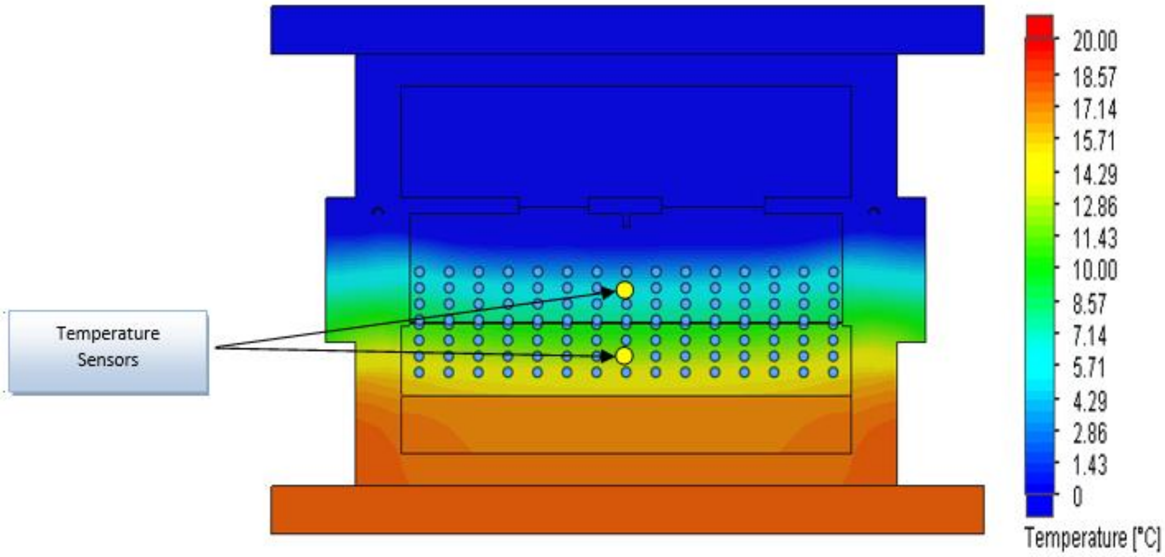


Figure 14: Section View of Modified Cup after three hour

After the validation of the measured temperature data with thermal simulation, the average temperature on water side was used to calculate the non-isothermal results for both the sheathing membranes, building paper and polymer based sheathing membrane. The relative humidity (R.H) on desiccant side is 0% and thus, vapour pressure is also zero on desiccant side. Therefore, to calculate the water vapour permeance, only temperature on water side of the modified cup assembly is required (see equation 4 in Section 4).

Figure 15 shows the points selected in the air gap of the modified cup on both sides of the tested sheathing membranes, these points were used as the average temperature on water side and desiccant side after every hour.

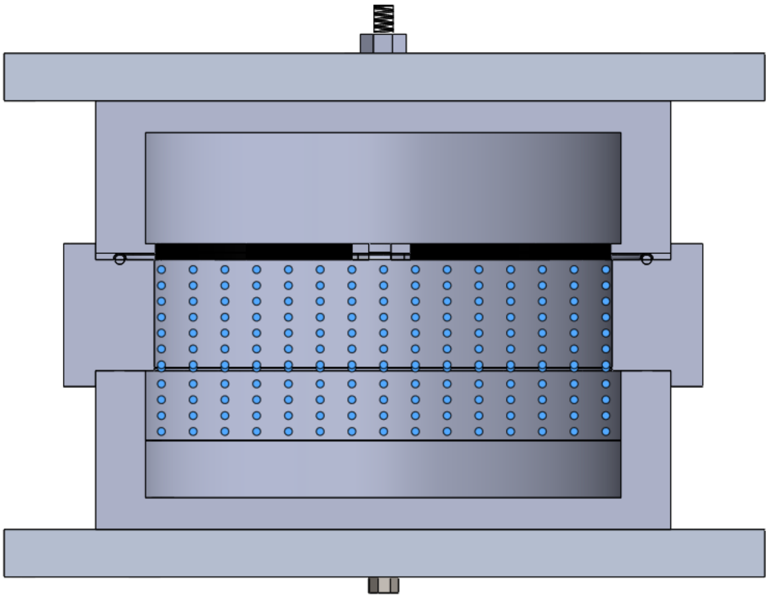


Figure 15: Selection of Points to calculate average temperature across the membrane

It can be seen in Figure 16 that the approximate steady temperature was achieved on the water side and desiccant side of the modified cup. By using these temperature values, the six points of weight change of the desiccant dish were selected to calculate the water vapour transmission rate and water vapour permeance.

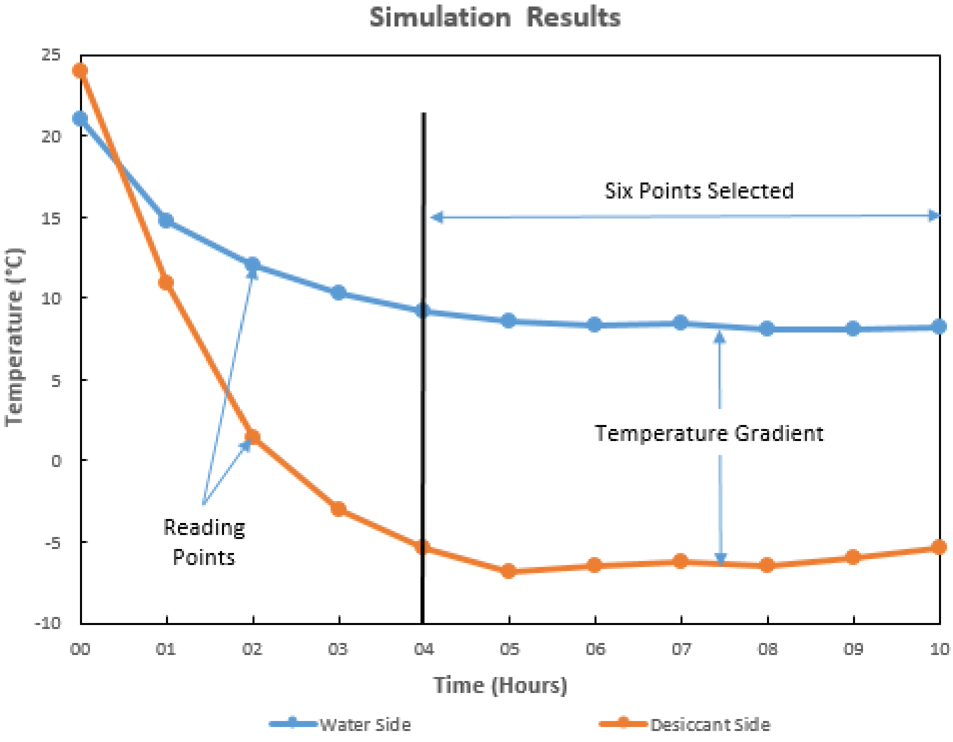


Figure 16: Temperature Gradient in Modified Cup

The vapour pressure on water side of the modified cup was also varied with temperature. However, on the desiccant side, it was zero because the relative humidity was always zero on this side of the modified cup. Figure 17 shows the vapour variation with time on water side and desiccant side of the modified cup. As it can be seen, from the graph that vapour pressure difference was also steady during the selected data points.

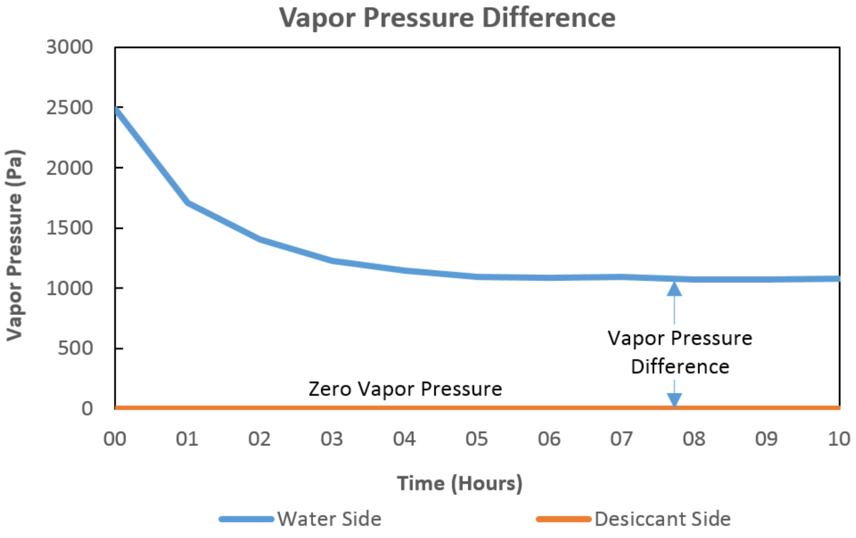


Figure 17: Vapour Pressure Difference across the tested membranes

6.2 Building Paper

The isothermal and non-isothermal results of the medium weight asphalt saturated kraft building paper were discussed below:

6.2.1 Isothermal Results

Figure18 shows the desiccant dish weight change with time, which is equally spaced six points and gives a straight line fit. The average water vapour transmission rate of three specimen was found to be 1.90 x 10^{-3} g/m^2.s, whereas the average water vapour permeance was 675.82 ng/m^2.s.Pa. Table 6 shows the isothermal results of building paper.

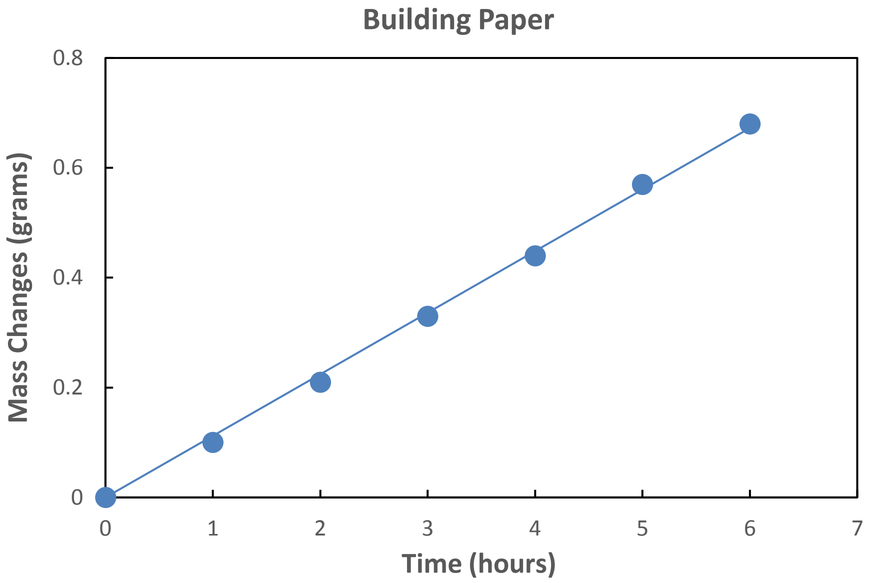


Figure 18: Weight gained by dry cup under isothermal conditions

Table 6: WVT Rate and Water Vapour Permeance of building paper under isothermal conditions

	WVT Rate (g/s.m^2) x 10^{-3}		Water Vapour Permeance (ng/m^2.s.Pa)	
Specimen	**Dry Cup**	**Mean**	**Dry Cup**	**Mean**
I	1.87	1.90	664.20	675.82
II	1.95		693.37	
III	1.88		669.89	

6.2.2. Non-Isothermal Results

The building paper shown higher water vapour transmission rate as well as higher water vapour permeance as compared to isothermal results. Following graph in Figure 19shows six equally spaced data points which means steady state water vapour transmission rate was achieved with non-isothermal boundary conditions.

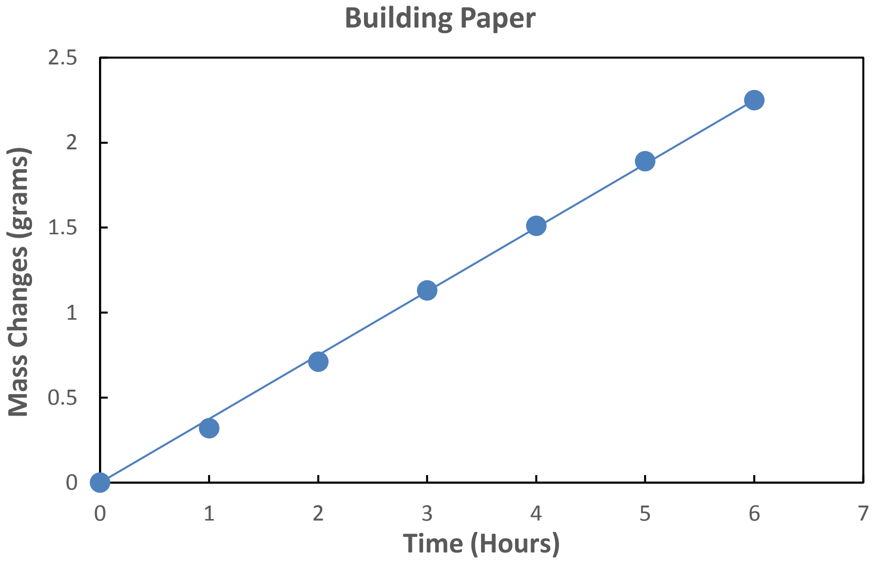


Figure 19: Weight gained by dry cup under non- isothermal conditions

The average water vapour transmission rate obtained under non-isothermal conditions was 3.54 X 10^{-3} g/s.m^2, which is approximately two times higher than the isothermal results. On the other hand, the water vapour permeance also shows significant increase in the value, which is approximately 4.5 times higher. Table 7 shows the non-isothermal results.

Table 7: WVT Rate and Water Vapour Permeance of building paper under non- isothermal conditions

	WVT Rate (g/s.m^2) x 10^{-3}		Water Vapour Permeance (ng/m^2.s.Pa)	
Specimen	**Dry Cup**	**Mean**	**Dry Cup**	**Mean**
I	3.26	3.54	2861.50	3078.01
II	3.61		3077.73	
III	3.76		3294.81	

As explained in the methodology section, dummy specimen was used because there was a possibility of error in mass readings of desiccant dish. The mass readings of desiccant dish were taken place at room temperature, which could lead to condensation on the desiccant dish. Figure 20 shows the weight change slope of desiccant dish for the dummy specimen test.

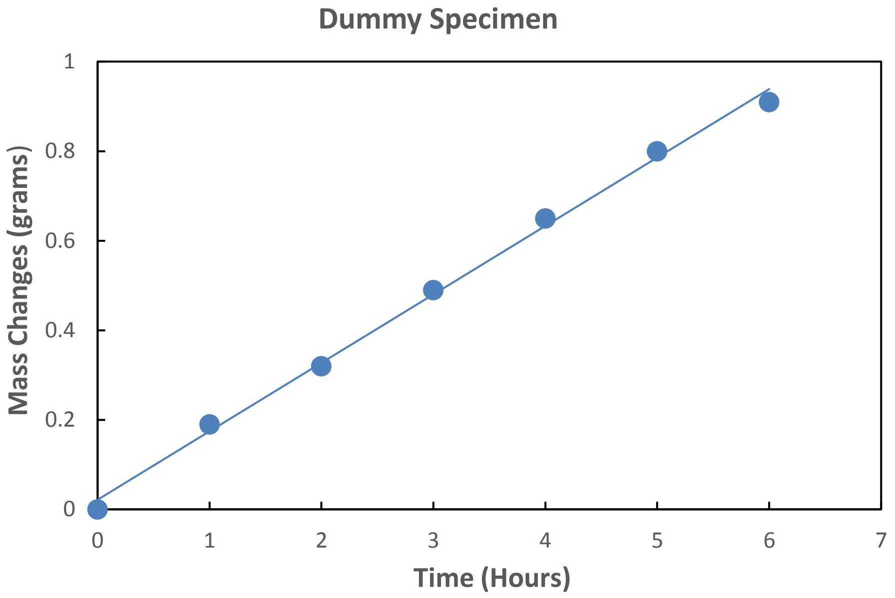


Figure 20: Weight gained by desiccant dish during dummy specimen test

6.3 Polymer based sheathing membrane

Polymer based sheathing membranes are known to have higher water vapour permeance than building paper [11]. The results for this sheathing membrane under isothermal and non-isothermal conditions were discussed below:

6.3.1. Isothermal Results

The isothermal results of polymer based sheathing membrane shown higher water vapour transmission rate and water vapour permeance as compared to building paper isothermal results. Table 8shows these results, the average water vapour transmission rate is 4.13 X 10^{-3} and average water vapour permeance is 1468.64 ng/m^2.s.Pa.

Table 8: WVT Rate and Water Vapour Permeance of Polymer based sheathing membrane under isothermal conditions

	WVT Rate (g/s.m^2) x 10^{-3}		Water Vapour Permeance (ng/m^2.s.Pa)	
Specimen	**Dry Cup**	**Mean**	**Dry Cup**	**Mean**
I	4.12	4.13	1465.72	1468.64
II	3.78		1344.69	
III	4.48		1595.50	

Figure 21 shows the six equally spaced points of weight change of dry cup of the modified cup assembly, it is clear from the graph that steady state was achieved.

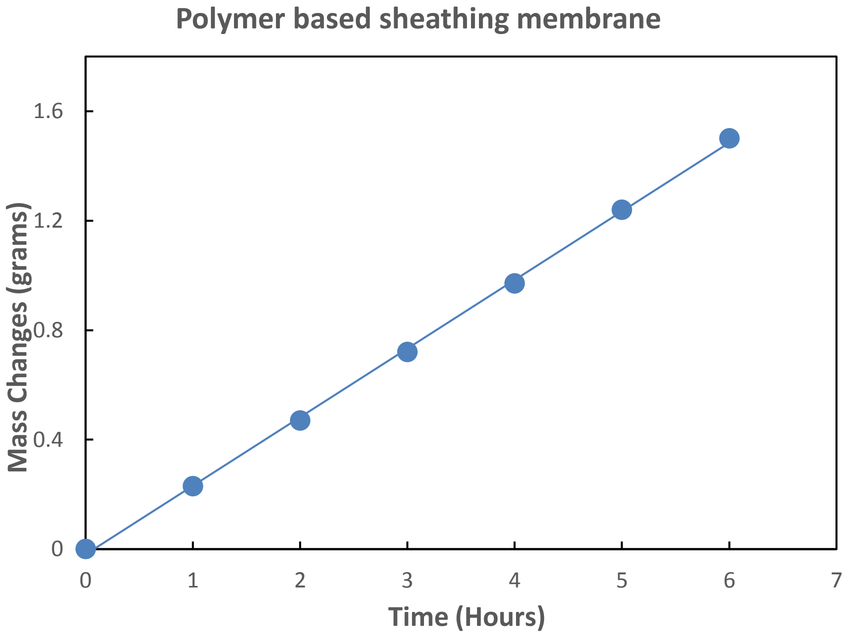


Figure 21: Weight gained by dry cup under isothermal conditions

6.3.2. Non-isothermal Results

The results obtained with temperature gradient for polymer based sheathing membrane is shown in Table 9 below. The average water vapour transmission rate is lower as compared to isothermal conditions, it is half of the average WVT rate under isothermal conditions. Whereas, the average water vapour permeance does not show much difference, if it is compared to isothermal conditions.

Table 9: WVT Rate and Water Vapour Permeance of Polymer based sheathing membrane under non- isothermal conditions

	WVT Rate (g/s.m^2) x 10^{-3}		Water Vapour Permeance (ng/m^2.s.Pa)	
Specimen	**Dry Cup**	**Mean**	**Dry Cup**	**Mean**
I	2.08	2.06	1797.55	1863.92
II	2.26		2068.22	
III	1.83		1725.98	

Figure 22 shows the steady state of weight change of desiccant dish was achieved under non-isothermal conditions

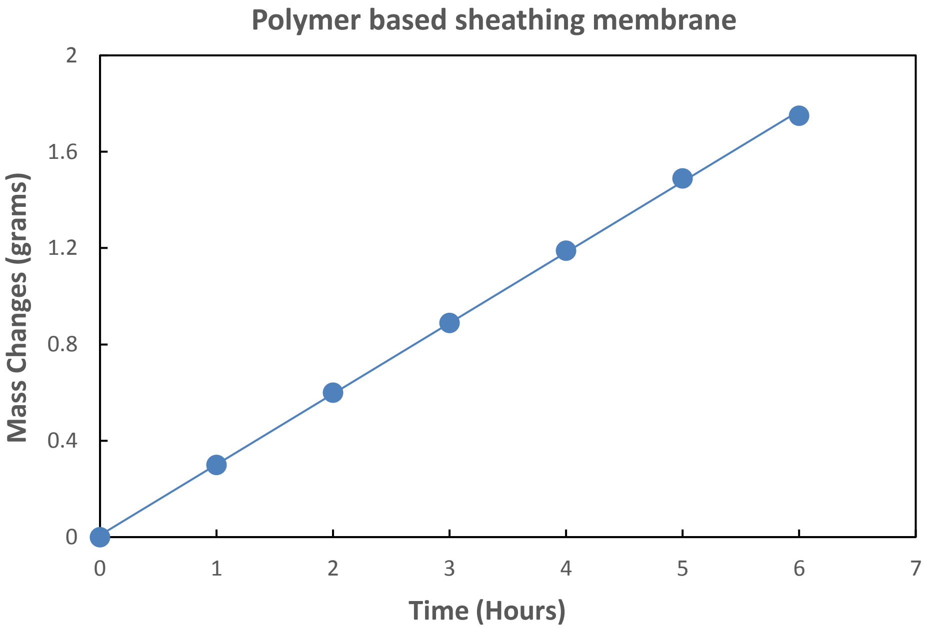


Figure 22: Weight gained by desiccant dish under non- isothermal conditions

Likewise non-isothermal test of building paper, during the non-isothermal test for polymer based sheathing membrane, dummy specimen was also used. Figure 23 shows the graph for the dummy specimen.

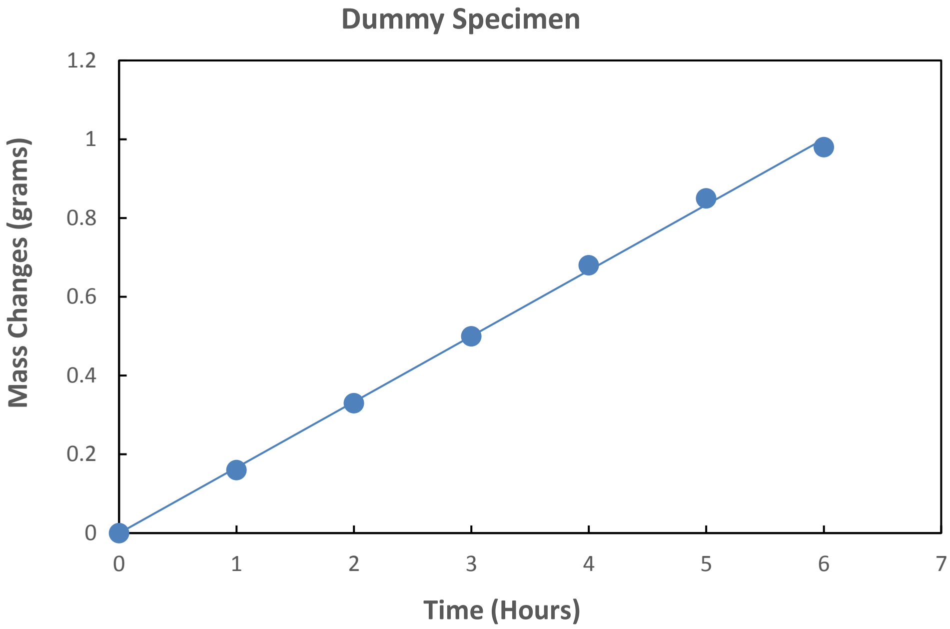


Figure 23: Weight gained by desiccant dish during dummy specimen test

6.4 Comparison between Polymer based sheathing membrane and Building paper

Figure 24 shows the effect of non-isothermal conditions on both the materials. The building paper gets highly influenced under non-isothermal conditions, it shows increase in water vapour permeance value from 675.82 to 3078.01ng/m^2.s.Pa. On the other side, polymer based sheathing membrane shows change in water vapour permeance from 1468.64 to 1863.92ng/m^2.s.Pa. So, these results shows that polymer based sheathing membrane has more stable water vapour permeance under non-isothermal conditions as compared to kraft building paper.

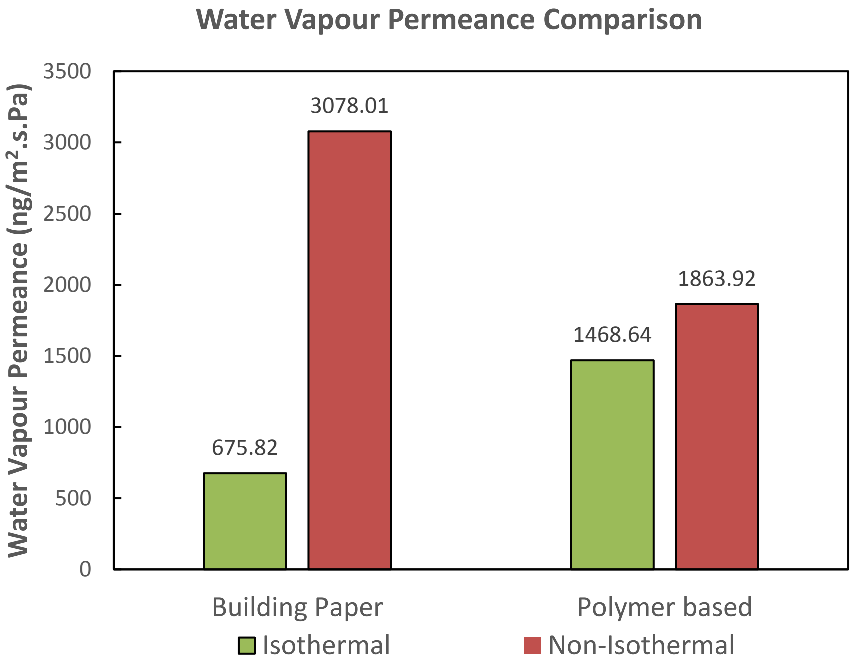


Figure 24: Comparison between polymer based sheathing membrane and building paper

7. Conclusions

This investigation explored the influence of non-isothermal conditions on the water vapour transmission properties of building materials. The temperature gradient for the non-isothermal boundary condition was created with a warmer side temperature 8.5±1°C and colder side -5± 2°C. Two wall sheathing membranes (i.e. kraft based building paper and polymer based sheathing membrane) were tested. Based on the observations from this investigation, following conclusions can be made:

- The water vapour transmission properties of kraft building paper are influenced by non-isothermal boundary condition. Both water vapour transmission rate (WVT) and water permeance increase under the aforementioned non-isothermal condition.
- The WVT of polymer based sheathing membrane shows dependency on temperature gradient, but water vapour permeance does not show much change under the temperature gradient.
- In cold climates, especially those below 0 °C or freezing conditions and under non-isothermal conditions, the water vapour permeance of polymer based sheathing membrane is more stable than the kraft building paper.

8. References

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Appendix A: WVT Rate and Water Vapour Permeance Calculations

Building Paper

Isothermal Boundary Conditions

Specimen I

Sample Area = .0169 m^2, Test Temperature = 23 °C, Saturation Vapour Pressure = 2810.9 Pa

$$\mathrm{WVT(Eq.\,1)} = \frac{.1136}{(.01690) \times 3600}$$

$$= 1.867\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\mathrm{Water\ Vapour\ Permeance(Eq.\,2)} = \frac{1.867\ \times 10^{-3}}{(2810.9) \times (1-0)}$$

$$= 664.20\ \mathrm{ng/m^2.s.pa}$$

Specimen II

Sample Area = .0169 m^2, Test Temperature = 23 °C, Saturation Vapour Pressure = 2810.9 Pa

$$\mathrm{WVT(Eq.\,1)} = \frac{.1186}{(.01690) \times 3600}$$

$$= 1.95\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\mathrm{Water\ Vapour\ Permeance(Eq.\,2)} = \frac{1.95\ \times 10^{-3}}{(2810.9) \times (1-0)}$$

$$= 693.37\ \mathrm{ng/m^2.s.pa}$$

Specimen III

Sample Area = .0169 m^2, Test Temperature = 23 °C, Saturation Vapour Pressure = 2810.9 Pa

$$\mathrm{WVT(Eq.\,1)} = \frac{.1146}{(.01690) \times 3600}$$

$$= 1.88\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\mathrm{Water\ Vapour\ Permeance(Eq.\,2)} = \frac{1.88\ \times 10^{-3}}{(2810.9) \times (1-0)}$$

$$= 669.89\ \mathrm{ng/m^2.s.pa}$$

Non-Isothermal Boundary Conditions

Specimen I

Sample Area = .0169 m^2, Average Temperature on water side = 8.87°C

Vapour Pressure on water side = T_{sat} × R.H = 1138.3 x 1 = 1138.3 Pa

Vapour Pressure on desiccant side = 0 Pa

$$\mathrm{WVT(Eq.3)} = \frac{.3511 - .1529}{(.01690) \times 3600}$$

$$= 3.26 \ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\mathrm{Water\ Vapour\ Permeance(Eq.4)} = \frac{3.26 \ \times 10^{-3}}{1138.3}$$

$$= 2861.50\ \mathrm{ng/m^2.s.pa}$$

Specimen II

Sample Area = .0169 m^2, Average Temperature on water side = 9.31°C

Vapour Pressure on water side = T_{sat} × R.H = 1172.6 x 1 = 1172.6 Pa

Vapour Pressure on desiccant side = 0 Pa

$$\mathrm{WVT(Eq.3)} = \frac{.3725 - .1529}{(.01690) \times 3600}$$

$$= 3.61 \ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\mathrm{Water\ Vapour\ Permeance(Eq.4)} = \frac{3.61 \ \times 10^{-3}}{1172.6}$$

$$= 3077.73\ \mathrm{ng/m^2.s.pa}$$

Specimen III

Sample Area = .0169 m^2, Average Temperature on water side = 8.92°C

Vapour Pressure on water side = T_{sat} × R.H = 1141.7 x 1 = 1141.7 Pa

Vapour Pressure on desiccant side = 0 Pa

$$\mathrm{WVT(Eq.3)} = \frac{.3818 - .1529}{(.01690) \times 3600}$$

$$= 3.76 \ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\mathrm{Water\ Vapour\ Permeance(Eq.4)} = \frac{3.76 \ \times 10^{-3}}{1141.7}$$

$$= 3294.81\ \mathrm{ng/m^2.s.pa}$$

a) Polymer based sheathing membrane

Isothermal Boundary Conditions

Specimen I

Sample Area = .0169 m^2, Test Temperature = 23 °C, Saturation Vapour Pressure = 2810.9 Pa

$$\mathrm{WVT(Eq.\,1)} = \frac{.2507}{(.01690) \times 3600}$$

$$= 4.12\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\text{Water Vapour Permeance(Eq. 2)} = \frac{4.12\ \times 10^{-3}}{(2810.9) \times (1-0)}$$

$$= 1465.72\ \mathrm{ng/m^2.s.pa}$$

Specimen II

Sample Area = .0169 m^2, Test Temperature = 23 °C, Saturation Vapour Pressure = 2810.9 Pa

$$\mathrm{WVT(Eq.\,1)} = \frac{.230}{(.01690) \times 3600}$$

$$= 3.78\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\text{Water Vapour Permeance(Eq. 2)} = \frac{3.78\ \times 10^{-3}}{(2810.9) \times (1-0)}$$

$$= 1344.69\ \mathrm{ng/m^2.s.pa}$$

Specimen III

Sample Area = .0169 m^2, Test Temperature = 23 °C, Saturation Vapour Pressure = 2810.9 Pa

$$\mathrm{WVT(Eq.\,1)} = \frac{.2729}{(.01690) \times 3600}$$

$$= 4.48\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\text{Water Vapour Permeance(Eq. 2)} = \frac{4.48\ \times 10^{-3}}{(2810.9) \times (1-0)}$$

$$= 1595.50\ \mathrm{ng/m^2.s.pa}$$

Non-Isothermal Boundary Conditions

Specimen I

Sample Area = .0169 m^2, Average Temperature on water side = 9.13°C

Vapour Pressure on water side = T_{sat} × R.H = 1159.2 x 1 = 1159.2 Pa

Vapour Pressure on desiccant side = 0 Pa

$$\mathrm{WVT(Eq.\,3)} = \frac{.2936 - .1668}{(.01690) \times 3600}$$

$$= 2.08\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\text{Water Vapour Permeance}(\mathrm{Eq.\,4}) = \frac{2.08\ \times 10^{-3}}{1159.2}$$

$$= 1797.55\ \mathrm{ng/m^2.s.pa}$$

Specimen II

Sample Area = .0169 m^2, Average Temperature on water side = 8.38°C

Vapour Pressure on water side = T_{sat} × R.H = 1095 x 1 = 1095 Pa

Vapour Pressure on desiccant side = 0 Pa

$$\mathrm{WVT(Eq.\,3)} = \frac{.3046 - .1668}{(.01690) \times 3600}$$

$$= 2.26\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\text{Water Vapour Permeance}(\mathrm{Eq.\,4}) = \frac{2.26\ \times 10^{-3}}{1095}$$

$$= 2068.22\ \mathrm{ng/m^2.s.pa}$$

Specimen III

Sample Area = .0169 m^2, Average Temperature on water side = 7.83°C

Vapour Pressure on water side = T_{sat} × R.H = 1060.7 x 1 = 1060.7 Pa

Vapour Pressure on desiccant side = 0 Pa

$$\mathrm{WVT(Eq.\,3)} = \frac{.2782 - .1668}{(.01690) \times 3600}$$

$$= 1.83\ \times 10^{-3}\ \mathrm{g/m^2.s}$$

$$\text{Water Vapour Permeance}(\mathrm{Eq.\,4}) = \frac{1.83\ \times 10^{-3}}{1060.7}$$

$$= 1725.98\ \mathrm{ng/m^2.s.pa}$$

Appendix B: Water Vapour Transmission Graphs of Building Paper

Isothermal Boundary Conditions

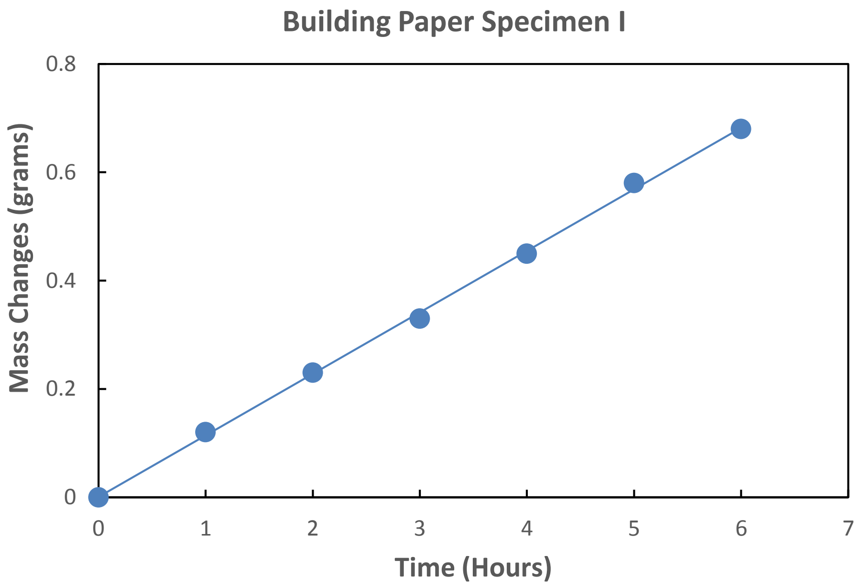

Figure 25: Building Paper Specimen I under isothermal conditions

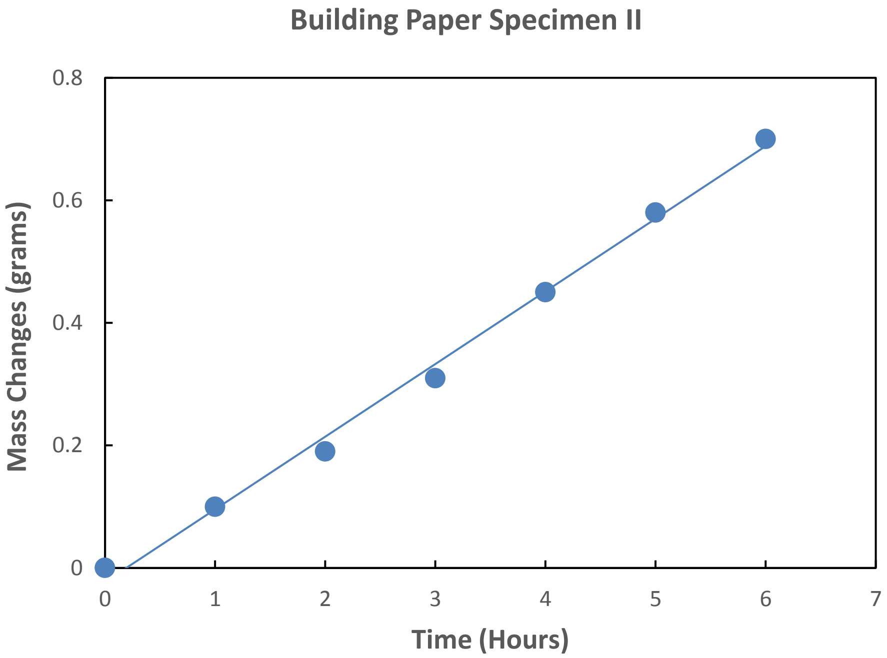

Figure 26: Building Paper Specimen II under isothermal conditions

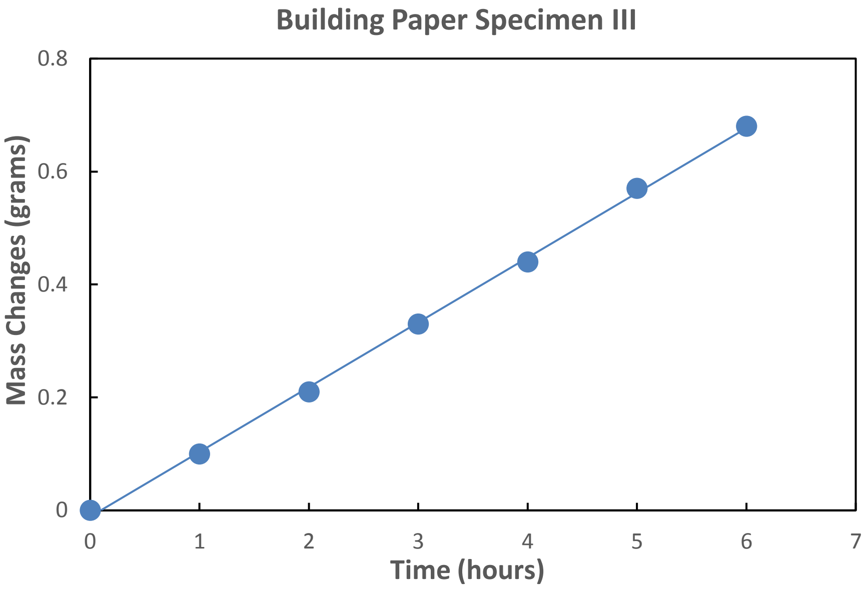

Figure 27: Building Paper Specimen III under isothermal conditions

Non-Isothermal Boundary Conditions

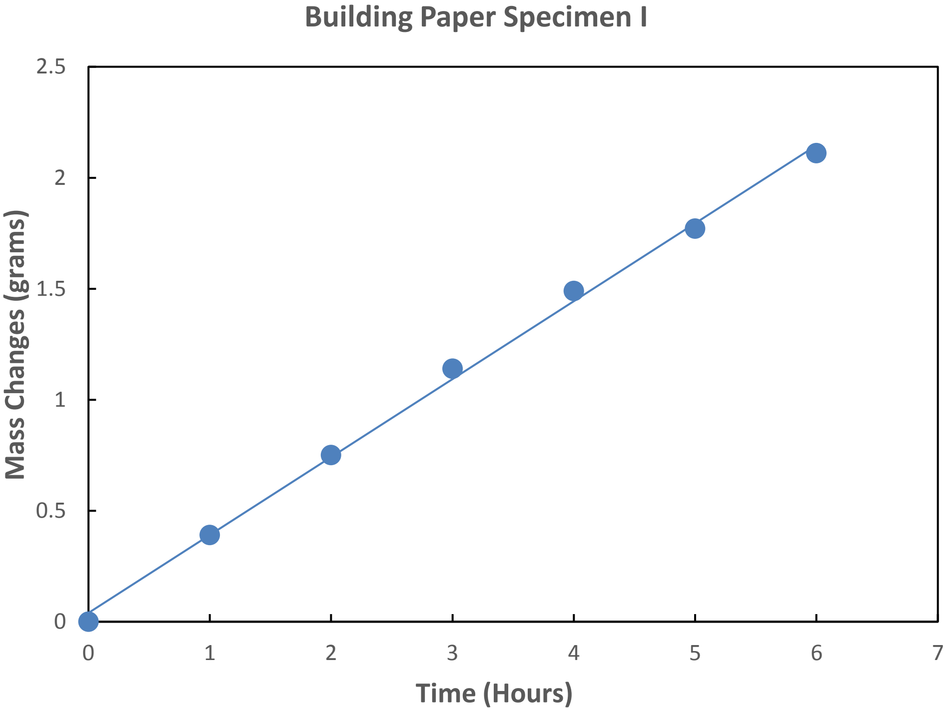

Figure 28: Building Paper Specimen I under non-isothermal conditions

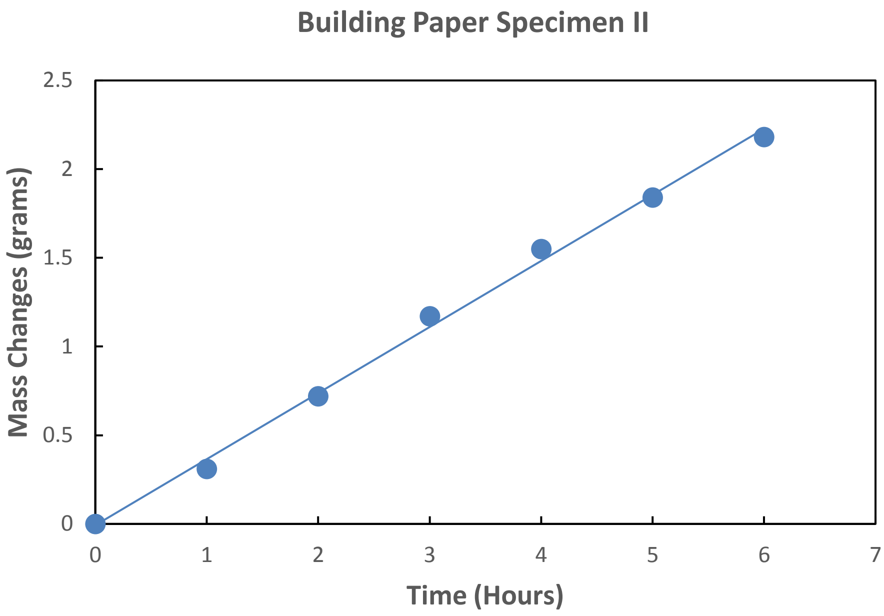

Figure 29: Building Paper Specimen II under non- isothermal conditions

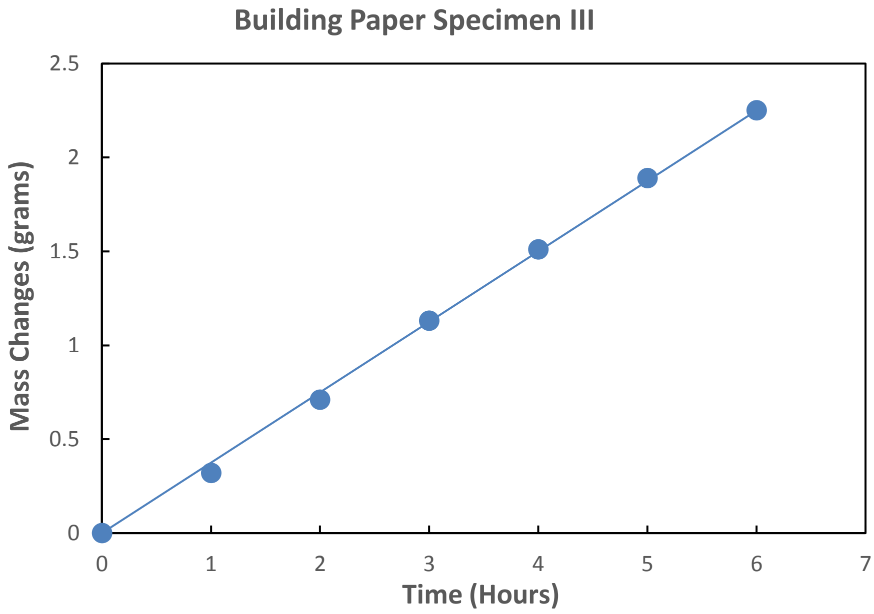

Figure 30: Building Paper Specimen III under non-isothermal conditions

Appendix C: Water Vapour Transmission Graphs of Polymer based sheathing membrane

Isothermal Boundary Conditions

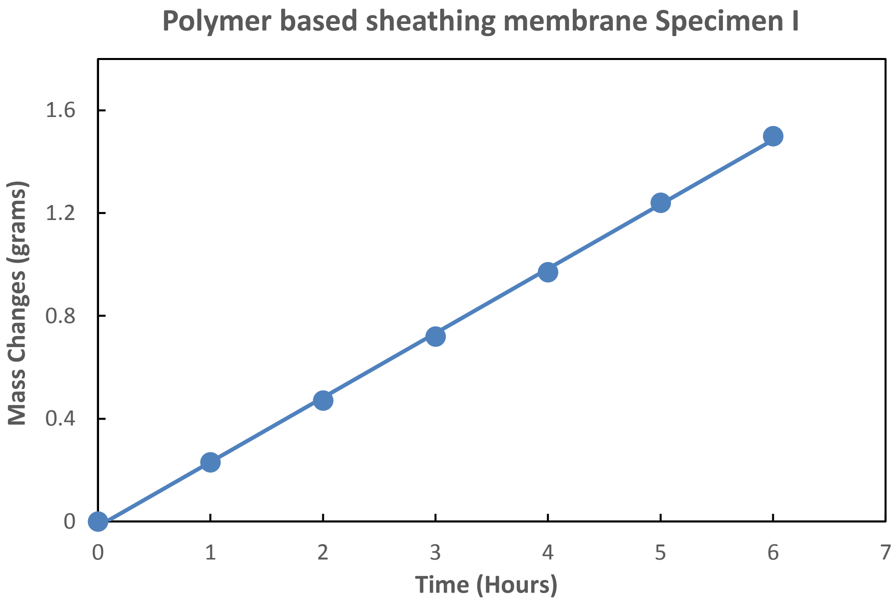

Figure 31: Polymer based sheathing membrane Specimen I under isothermal conditions

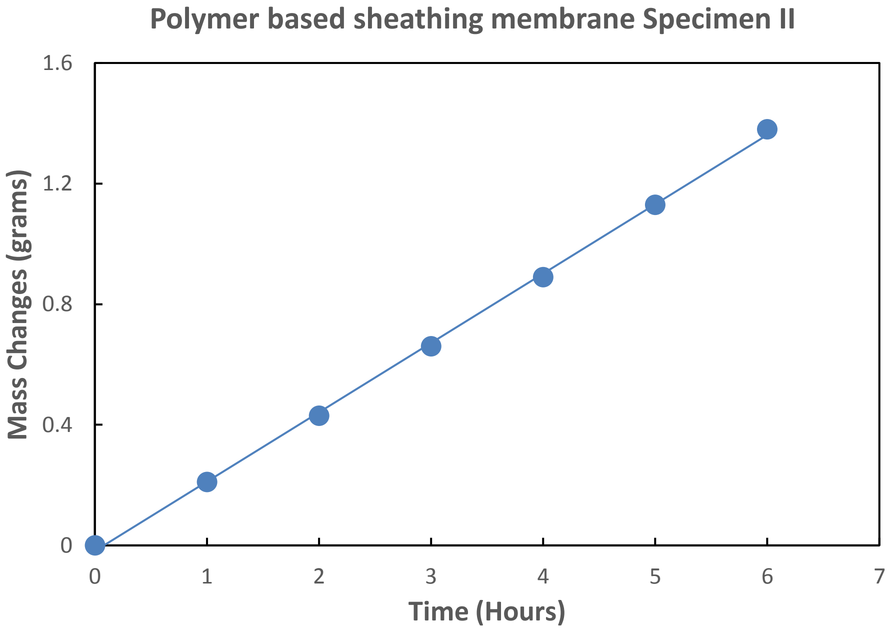

Figure 32: Polymer based sheathing membrane Specimen II under isothermal conditions

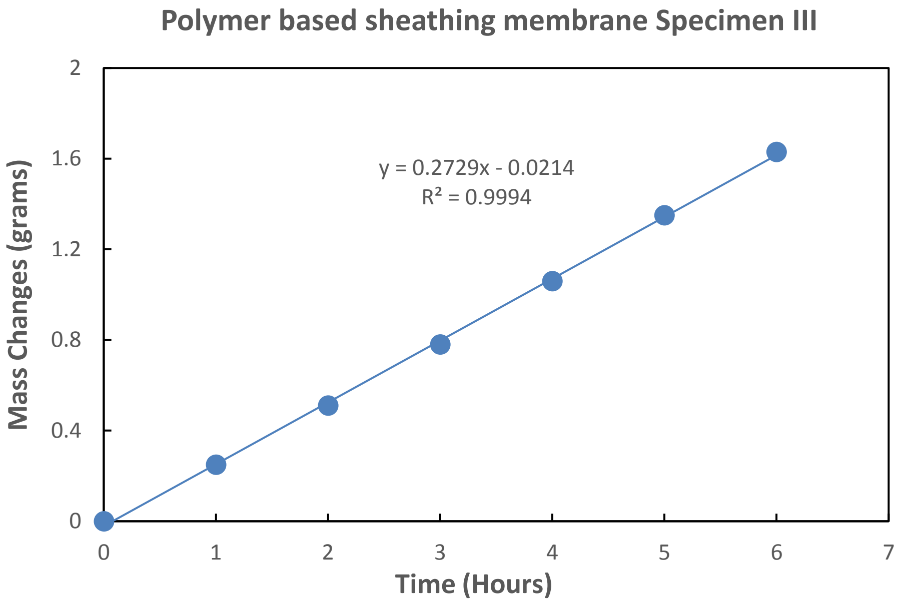

Figure 33: Polymer based sheathing membrane Specimen III under isothermal conditions

Non-Isothermal Boundary Conditions

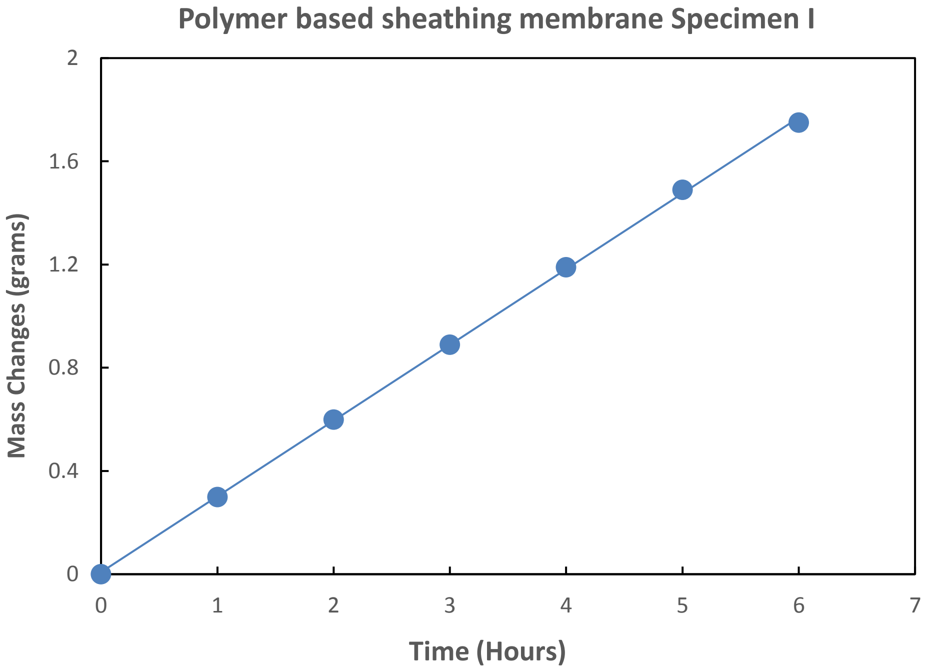

Figure 34: Polymer based sheathing membrane Specimen I under non-isothermal conditions

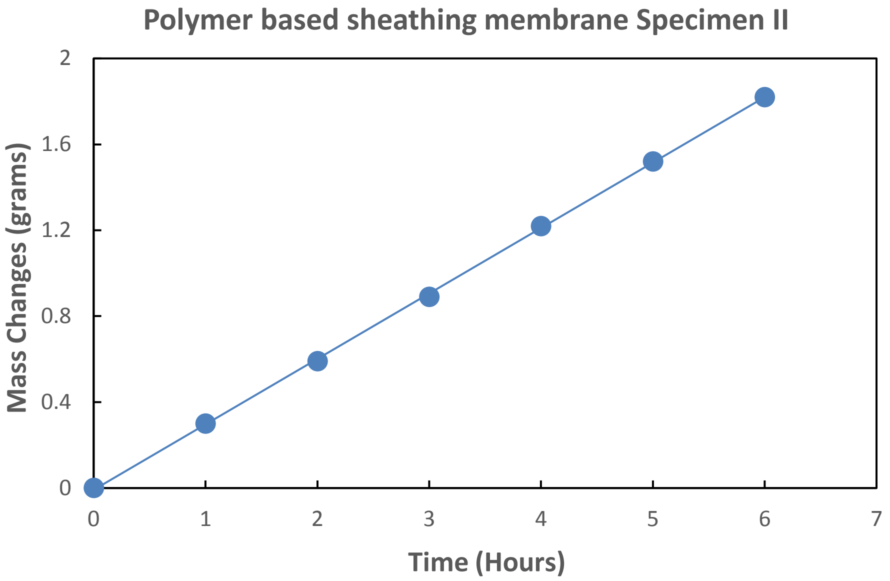

Figure 35: Polymer based sheathing membrane Specimen II under non-isothermal conditions

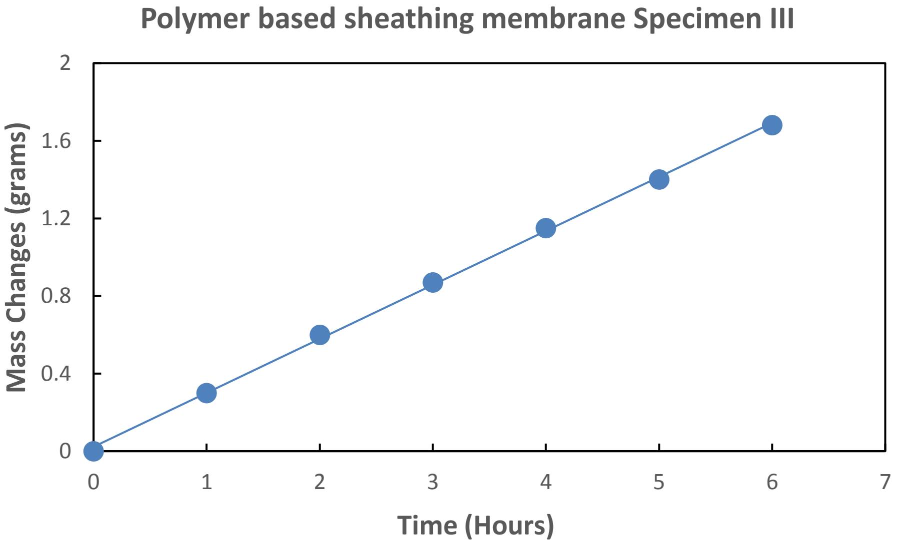

Figure 36: Polymer based sheathing membrane Specimen III under non-isothermal conditions

Appendix D: Temperature Gradient Graphs

a) Building Paper

Specimen I

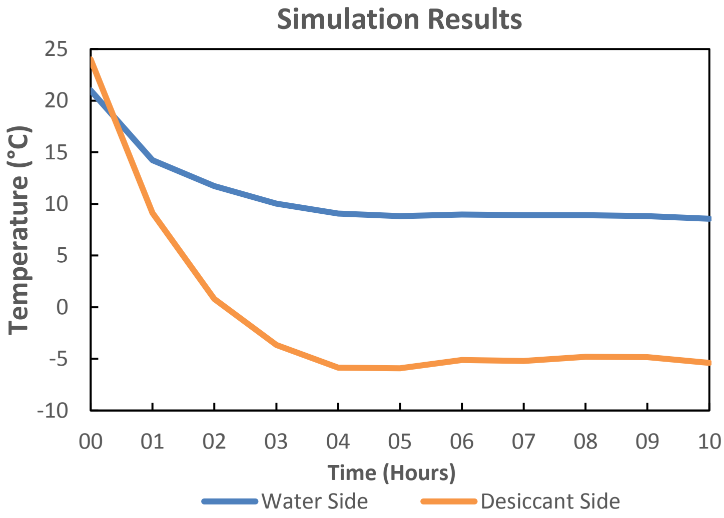

Figure 37: Temperature Gradient for Building Paper Specimen I

Specimen II

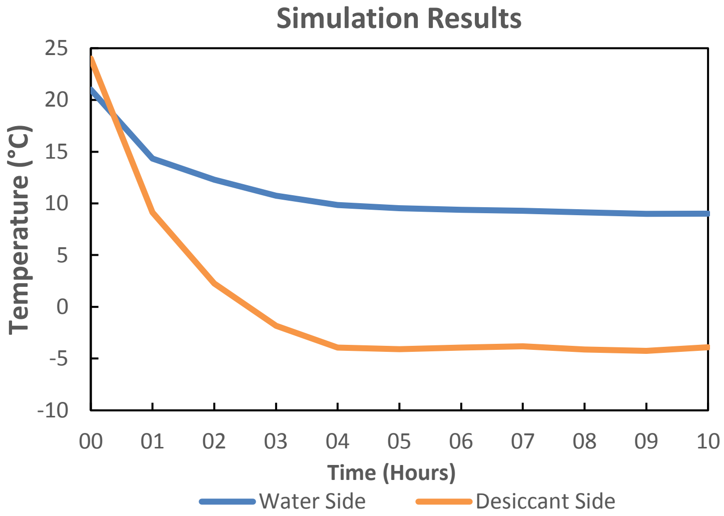

Figure 38: Temperature Gradient for Building Paper Specimen II

Specimen III

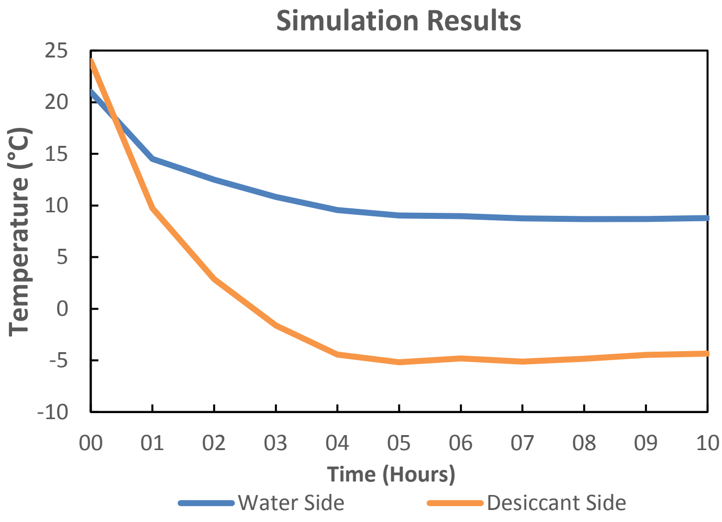

Figure 39: Temperature Gradient for Building Paper Specimen III

b) Polymer based sheathing membrane

Specimen I

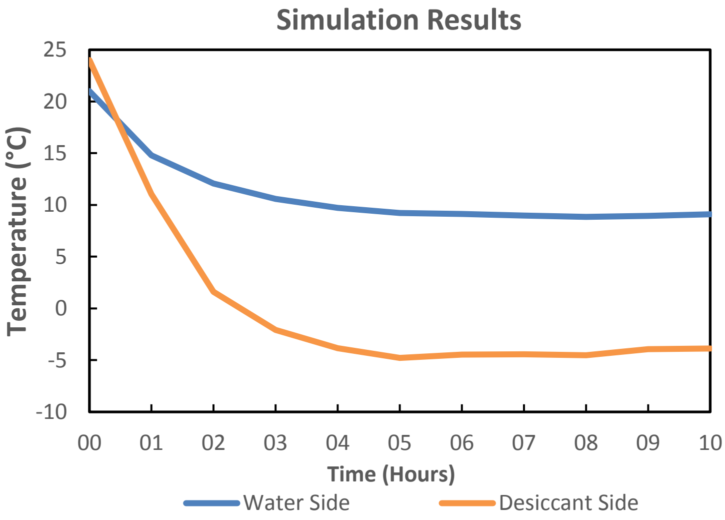

Figure 40: Temperature Gradient for Polymer based sheathing membrane Specimen I

Specimen II

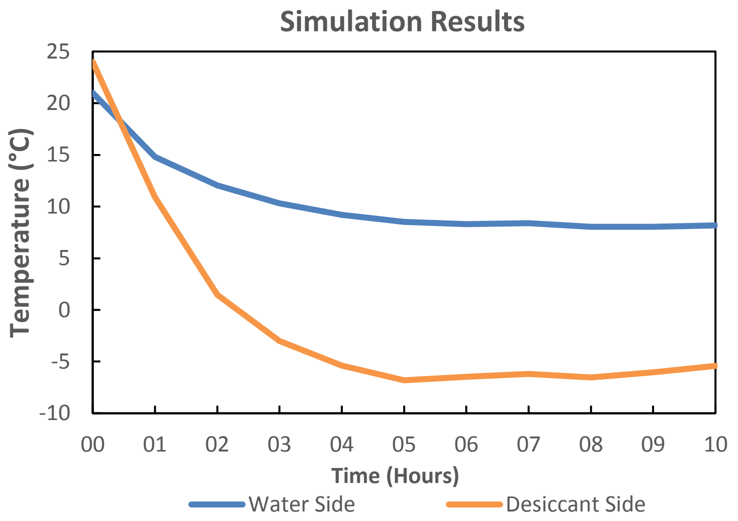

Figure 41: Temperature Gradient for Polymer based sheathing membrane Specimen II

Specimen III

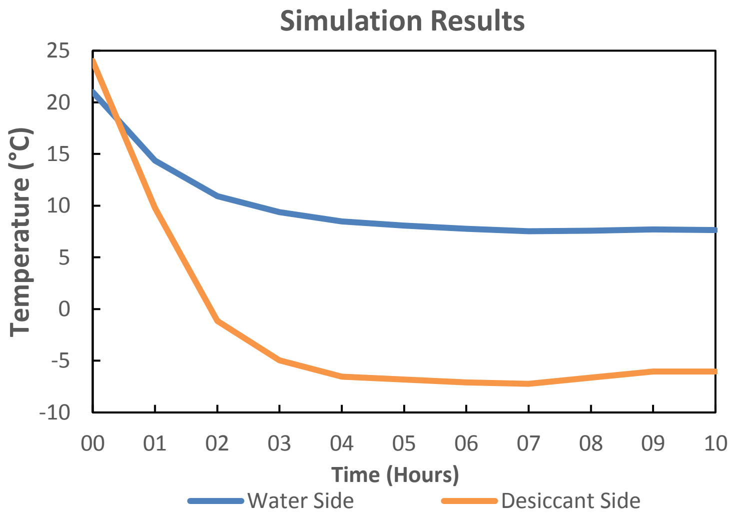

Figure 42: Temperature Gradient for Polymer based sheathing membrane Specimen III