The Effects of Moisture and Addition of Rigid Insulation to Exterior Walls on Building Envelope Performance

By

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Abstract

In the northern prairie climate of Manitoba, the thermal resistance provided by the building envelope is an on-going concern. To improve thermal performance, some existing buildings need to be renovated. One common approach to achieve a higher thermal resistance for building enclosures is the addition of rigid insulation, such as extruded polystyrene foam (XPS), on the exterior side of a building without any changes to the inside of the structure. One challenge of this strategy is the possibility of having a damaged or absent vapour barrier, and the effect this may have on the building envelope performance. The field-based study presented in this thesis was conducted on two identical wood frame test buildings with different insulation materials inside the wall cavities. One had fiberglass batt and other with dense pack cellulose. The test program was completed at the Alternative Village at the University of Manitoba. Combinations of external rigid insulation and vapour barrier systems were compared to a typical wall assembly over a heating season. Three different indoor RH levels were used to compare hygrothermal behaviour and the potential for condensation and mold growth within the wall cavity.

It was found that the addition of XPS in fiberglass and cellulose wall assemblies rose the outer wall cavity temperature. Also, the outer RH within the wall cavity increased in the cellulose building, while the addition of XPS did not affect outer RH in the fiberglass

wall assembly considerably. It was found, however, that for the fiberglass building with a non-consistent vapour barrier, the average outer RH increased dramatically to 80% and 90% in mid and high levels of indoor RH, respectively. Similarly, in cellulose wall assemblies with non-consistent vapour barrier, the average outer RH in high-level indoor RH rose considerably to 49% and 63% considering without and with XPS, respectively. Therefore, the potential for condensation and mold growth on outside sheathing increased in both buildings.

In terms of heat flux density, both the addition of rigid insulation and having consistent vapour barrier improved the thermal resistance of fiberglass wall assemblies. That is, the heat flux density through the wall assembly with non-consistent vapour barrier was 2.6 to 2.8 times greater than the value through the wall assembly with XPS and continuous vapour barrier. Furthermore, even though vapour barrier system did not affect the heat flux noticeably in cellulose enclosure, the heat flux density decreased considerably due to the addition of rigid insulation.

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List of Abbreviations and Symbols

Bldg.: Building

Cha.: Chamber

EPS: Expanded Polystyrene Foam

HFS: Heat Flux Sensor

MC: Moisture Content

OSB: Oriented Strand Board

Poly.: Polyethylene

RH: Relative humidity

SIP: Structural Insulated Panel

Temp.: Temperature

XPS: Extruded Polystyrene Foam

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Chapter 1

Introduction

1.1 Context and objectives

In regions with a cold climate such as Manitoba, both an airtight construction method and a high thermal resistance values in a building envelope are important to reduce energy consumption. The city of Winnipeg in south central Manitoba, Canada experiences a wide annual range of climatic conditions. The design temperature is considered from a low -35°C (heating season) to a high +30°C in the summer (NBCC, 2010). However, extreme ranges have been reported from -45°C to +41°C without considering the wind (Canadian Climate Normals 1971-2000, Environment Canada, 2014). It is evident, then, that for a city with such a harsh climate in-situ tests on different wall assemblies are valuable. As discussed by Straube et al, field studies are complementary to laboratory experiments (Straube, Onysko, & Schumacher, 2002).

Moisture can potentially flow through wall assemblies from different sources, including ground water, rain, or indoor water vapour. The research presented in this thesis focuses on water vapour migration through a wall assembly. This study was conducted on two test buildings at the Alternative Village at the University of Manitoba in Winnipeg, Canada. Both structures were wood frame stud walls, one with fiberglass batt and the other with dense pack blown-in cellulose insulations. The data reported in this study was collected over three periods between January 31 and March 16, 2014 (heating season).

Based on an assumption of four-person family within a home who take five-minute showers every other day, make three meals and wash dishes every day, and occupy their home 16 hours daily, the average moisture production (excluding the moisture created by floor mopping, pets, plants, etc.) would be about 2000 litres of water vapour, annually (Lstiburek & Carmody, 1991). Since a large amount of water vapour is produced annually in a residential building, there is a high likelihood of water vapour migrating through enclosures. The possibility of migration increases during the heating season when the inside of a building has minimal ventilation and is kept warm. Sedlbauer stated that mold fungi damages in Germany cost 200 million Euros per year according to the report from the Federal Government of Germany in 1996. Insufficient ventilation in airtight building envelopes causes increasing moisture-related problems (e.g. mold formation). However, before the energy crisis in the 1970s, ventilation was manually operated by opening windows. Today, the practices of opening windows and unintentional ventilation (e.g. leakages) have been decreased due to energy saving initiatives. Therefore, air humidity is trapped in the building, and hence the relative humidity increase would be an issue, which raises the risk of moisture-related problems, not only in the building, but also in the wall cavities (Sedlbauer, 2001).

Moisture transfer through the building envelope occurs either due to exfiltration or diffusion. Wall assemblies with point defects on their warm-side present moisture accumulation opposite to that point on the cold surface (Forest, 1989). Having non-consistent vapour barriers in building enclosures are considered a defect and create a passage way for vapour through the wall assembly by diffusion. The water vapour then condenses against the cold surface and affects the thermal value of the building envelope as well.

One common approach to achieve higher insulation value, especially for the residential buildings with low enclosure thermal value, is the addition of a rigid insulation layer (e.g. extruded polystyrene foam) on the exterior side of the envelope. One easy approach to increase the thermal value of enclosures in old houses with no proper insulation within the wall cavity is renovating from the outside rather than the inside. The existing insulation within the wall cavity (e.g. wood chips) can be exchanged with blown-in cellulose or fiberglass batt in addition to exterior rigid insulation. These houses may not have an intact vapour barrier after renovation. Furtheremore, vapour barriers are cut around conduits or electrical outlets in order to repair them. These spots are not sealed properly afterwards, which create non-consistent vapour barriers. It should be noted that the consequences of the extra rigid insulation layer addition, such as changing the moisture profile, risk of condensation, and the potential for mold growth (as the most critical moisture concern) through the exterior wall assembly, are rarely taken into account. In fact, the combination of no vapour barrier or non-consistent vapour barrier with rigid insulation is higher in old buildings, which are likely to be renovated. Adding an insulation layer to a building envelope might modify the temperature and moisture profiles within wall cavity; therefore, if there is a potential for water vapour to flow through, it may increase the potential of condensation within wall cavity. The question is whether adding exterior rigid insulation increases the likelihood of moisture-related problems in wall assemblies.

As summarized in the literature review section, there are a number of studies regarding hygrothermal behaviour of different insulations and vapour barrier effects on building enclosures. The present study was carried out due to the lack of field-based research in cold and harsh climates such as Winnipeg, comparison between various building envelopes at the same time considering different indoor RH levels, and residential wall cross sections (instead of laboratory tests on only the insulation) in real ambient outdoor fluctuation

A common material used as insulation in wood-frame residential buildings in Canada is fiberglass batt. Blown-in cellulose is frequently used to fill the wall cavity for renovations in old properties. For both insulation types vapour barrier on the warm side of enclosures is a common solution to manage moisture transfer. A study was conducted at the Alternative Village at the University of Manitoba, where five identical test buildings with different wall cross sections were compared to each other. The tests showed that fiberglass batt insulation and dense packed blown-in cellulose had almost the same energy consumption over the 209-day test period in the heating season (Dick, Safavian, & Rayner, 2014). Finally, a simulation software, WUFI (Wärme und Feuchte instationär), was applied to model multi-layered wall components considering moisture and heat migration under given indoor and outdoor conditions.

The objectives of this experiment-based thesis were:

- To study the effects of compromising vapour barrier on thermal performance and moisture related problems of building envelope considering various wall assemblies;
- To study the relationship between external rigid insulation layer and hygrothermal behavior of building enclosure with a combination of consistent and non-consistent vapour barrier; and
- To evaluate of new systems and assemblies tested in the Manitoba climate

1.2 Thesis organization

Chapter 2 begins with an overview covering background information about building envelope and thermal performance followed by a review on moisture management. Detailed explanation of test buildings, test setups and protocol, the data acquisition system, materials and the methods employed to conduct the experiment for both the fiberglass and cellulose buildings is described in Chapter 3. The results of the field-based experiments and the analysis with discussion on both fiberglass and cellulose wall assemblies are covered in Chapter 4. Finally, Chapter 5 provides a summary of the major findings of the experiment with recommendations for future investigations arising from this project.

Chapter 2

Literature Review

A building envelope forms a physical separation by connecting individual components to enclose outdoor environment from the interior of a building. The building enclosure especially in cold countries such as Canada is the key factor to improve the energy efficiency and high performance of buildings and plays a primary role in maintaining and protecting the indoor environment from cold outdoor climate. Building envelopes must be strong enough to meet building codes and be able to resist heat, mass, water, air, light (solar radiation), and noise transfer from inside of the building to the outside or vice versa. Different components in a building envelope are considered to control the above parameters, such as a vapour barrier to control vapour flow, an air barrier to prevent air transfer, thermal insulation (e.g. fiberglass batt or blown-in cellulose) to control heat flow, or a rain screen to protect the envelope form rain to come through. It is important to account for how the components are not independent of each other and may affect other components. For instance, the air barrier within an enclosure will be increased by using vapour barriers as well. Moisture management is complicated due to the interaction between heat and air. Uncontrolled heat, air, and moisture flow within a building enclosure cause moisture accumulation and increase the risk of occurrence of one or more of the following problems afterwards (Kumaran, et al., 2003; Rousseau, 2003):

- Reduction in the structural integrity of the component;
- Rotting and corrosion of materials due to uncontrolled moisture accumulation and condensation within wall cavities;
- Mold formation in wall assemblies;
- Chemical, mechanical, or biological deterioration of building materials;
- Reduction in durability and performance of systems and materials within wall cavities;
- Increasing energy costs;
- Poor conditions inside the building due to uncontrolled interior environment; and
- Unacceptable appearance of the building envelope.

Field measurements are useful to model the whole picture of a building envelope in real environmental conditions (Straube, Onysko, & Schumacher, 2002). Field studies, by their very nature, take into account more variables than laboratory experiments since wind, temperature, RH and solar radiation all affect a building in reality.

There are different forms of insulation materials including rigid, loose-fill, batt or blanket, foamed in place and reflective form (Abdou & Budaiwi, 2005). Interaction between different kinds of insulation in building enclosure (i.e., rigid insulation on the exterior side and loose-fill or batt insulation in wall cavity) and the method of vapour control (i.e., using 6 mil. polyethylene as vapour barrier inside of building) may affect hygrothermal behaviour of a building envelope. Some materials have the ability to absorb water called hydrophilic, while others called hydrophobic do not. For instance, gypsum wallboard (interior sheathing of the wall assembly tested in this research) is a hydrophilic, and theoretically able to absorb water until its pores entirely are filled. Hygroscopic materials gain moisture (adsorption) when the relative humidity rises and release moisture (desorption) when the relative humidity drops. The amount of water absorbed or released by a material at a constant temperature and equilibrium condition is recorded experimentally and called a sorption isotherm (ASHRAE Handbook Fundamentals, 2009).

2.1 Thermal performance

The amount of heat flowing through the building envelope must be minimized to make the indoor conditions comfortable and minimize the energy consumption of the building. Light wood-frame construction is the most common type of residential building in Canada considering material with high thermal resistance (high R-value) used within exterior wall cavities. Two of the common insulation materials used in Canada for wood frame buildings are fiberglass batt and blown-in cellulose.

There was little or no insulation in early wood-frame buildings in the 1920s; therefore, air leakage was a major problem in this kind of construction. Research on the effect of air leakage on these enclosures at the University of Minnesota led to building papers being used as acceptable weather-resistive barrier. However, this type of barriers was known as rain barrier and resisted wind washing and a lack of insulation materials was still felt. After further research conducted by the University of Saskatchewan in the 1920s to show the importance of adding thermal insulation in the envelope, insulation use within wall cavities and attic increased in the 1930s (Bomberg & Onysko, 2002). An emphasis on well-insulated houses with airtightness and better thermal insulation materials began during the energy crisis in the mid-1970s (especially in Canada), and most focus was still on the importance of vapour diffusion (Rousseau, 2003).

If water vapour contacts a non-porous surface that has a temperature lower than the dew point, condensation may appear on the surface. Also, if the moisture content rises within wall assemblies, it may have a negative impact on building enclosure thermal behaviour (ASHRAE Handbook Fundamentals, 2009). The thermal insulation value of building components decreases with increased moisture content (Künzel, 1998). However, this effect differs depending on the chosen insulation material. For instance, the impact of moisture on the thermal value of loose-fill cellulose insulation (27 kg/m^3 density) was not considerable within hygroscopic range (moisture content in equilibrium with relative humidity under 98%) according to laboratory tests conducted to show cellulose insulation behaviour in roof spaces (Sandberg, 1992). The same study also showed that 10% and 16% moisture content (mass based) were in equilibrium with 61% and 84% RH. The effect of moisture on thermal conductivity of loose-fill cellulose fibre (thermal resistance per unit thickness of 3.7 $h.ft^2.°F/BTU$) with a density of 40 kg/m^3 was tested under both fixed and cyclic moisture gradient conditions, and the results showed that 10% increase in moisture content of the insulation caused nearly 15% decrease in thermal resistance of the cellulose applied in the attic. In addition, it was seen that after the drying the thermal conductivity decreased again (Tye & Spinney, 1979). Another study (Nicolajsen, 2005) presented that the thermal value of a cellulose loose-fill insulation material applied in wall assembly did not change considerably when moisture content changed under hygroscopic range (fewer than 20% wet basis).

Simonson et al. studied fiberglass insulation in a slab using a one-dimensional transient model. The study showed that, when assuming an RH of 97%, inside temperature of +22°C, and cold boundary temperature of -5°C, the heat flux was 4.9 times greater than the heat flux in dry condition. However, moisture accumulation was only 1.9% by mass causing an increase of the average thermal conductivity of just 3.5%. Therefore, even with small water accumulation, mass transfer had a significant impact on the heat flux (Simonson, Tao, & Besant, 1994). Another set of experiments (Abdou & Budaiwi, 2013) was conducted on the effect of moisture on the thermal behaviour of fiberglass batt, which showed that thermal conductivity of fiberglass batt (27 kg/m³ density) was 4.0% higher at 15% moisture content than a dry sample (at 14°C operating temperature). Also, thermal conductivity increased by 5.7% when operating temperature rose to 24°C. Operating temperature affects the thermal behaviour of the wall assembly, i.e. a higher operating temperature causes higher thermal conductivity (Abdou & Budaiwi, 2005). For instance, the above study showed that in fiberglass batt insulation with 13.1kg/m³ density, thermal conductivity (W/m˚C) was equal to 0.0003368*T*+0.041433 (*T*: operating temperature in ˚C). This means that in the range of -5 to 20˚C, for every 5˚C or 10˚C operating temperature increase, the thermal conductivity rose just 4% or 8%, respectively.

2.2 Vapour barrier and moisture management

Even though some people may separate vapour retarder from air retarder completely, if air retarder behaves as a vapour retarder, it should not be placed where it leads to condensation (ASHRAE Handbook Fundamentals, 2009). Water vapour migration through wall assemblies cools and may condense to form water molecules that could accumulate and cause mold formation and construction damage. As the use of insulation in building enclosures increased, without considering vapour barrier or its location, the potential for condensation within the wall cavity increased. The vapour barrier controls water vapour flow from the warm and humid side to the cold and dry side of the building envelope (indoor to outdoor during heating season in a cold climate). Water vapour diffuses from higher partial pressure to lower partial pressure, and condensation occurs on the surface that has a lower temperature than the dew point. The interior side of an exterior wall is the warmer side, with normally higher vapour pressure than outside in a cold climate. Therefore, vapour barrier is applied on the interior side of the envelope to retard diffusion and condensation within the wall assembly (Bomberg & Onysko, 2002). In fact, control of moisture migration by diffusion is considerable in airtight buildings (ASHRAE Handbook Fundamentals, 2009). In the late 1950s and 1960s, researchers stated that most of the water vapour migrating through the building envelopes is due to air leakage. Also, the amount of moisture transferred through a wall assembly increases and causes problems in buildings in which vapour barriers are not installed consistently (Kumaran & Haysom, 2000). In the mid-1980s, the function of air and vapour controls were separated from each other, and the Airtight Drywall Approach and the External Airtight Sheathing Element were recognized as two strategies to control air leakage in building envelope (Bomberg & Onysko, 2002).

Most building materials are just vapour retarders and do not stop moisture transfer entirely. In fact, the rate of water vapour diffusion drops after applying vapour retarder in building envelopes (ASHRAE Handbook Fundamentals, 2009). Vapour retarders help keep insulation dry to prevent moisture-related problems. If there is potential for condensation, then rot, corrosion, or expansion of freezing water are issues that affect structural stability. Even though vapour retarders are typically a thin plastic sheet or coating, some construction materials may act as a vapour retarder (ASHRAE Handbook Fundamentals, 2009). Polyethylene is commonly used in building enclosures as a vapour retarder to slow moisture migration within wall assemblies. Polyethylene also has a very low air permeance, so it behaves as both an air barrier and a vapour barrier. However, installation or maintenance deficiencies, such as cracks and holes, create the potential to allow water vapour or moisture to go through the wall cavities and cause moisture-related problems (Schwartz, 1991). Some typical leakage locations are from plumbing penetrations, electrical outlets, telephone and television wirings (ASHRAE Handbook Fundamentals, 2009). Compromising vapour barrier results in higher moisture profile within the wall cavity in cold climate. The moisture content of exterior layers increases by elevating the moisture load from indoor air. Therefore, exterior sheathing would able to allow materials within the wall cavity to dry up before spring, when the temperatures are higher and suitable for mold growth (Simonson C. J., 2005). It was seen that initial moisture content dries faster in a south walls than north walls due to solar radiation. In addition, for the same reason the moisture content of the exterior south walls are a few percent (by mass) less than north walls (Simonson C. J., 2005). The key point to control moisture (in the vapour form) in wall assemblies is keeping it out and away from the wall cavity and allowing it to dry up if it gets in (Trechset & Bomberg, 2009).

The ability of woods to safely absorb water is considerably less than masonry materials, so moisture management is an important issue in wood-frame buildings. No individual system or material can manage moisture-related problems within a wall cavity by itself (Rousseau, 2003). Control of moisture entry, accumulation, and removal are three strategies in order to control moisture in wall assemblies, and the best way to do so is considering those strategies in combination (Lstiburek, 2002).

Setting a desirable range of relative humidity for a comfortable environment in a residence depends on the location of the home, construction materials, the time of the year, and the occupants' sensitivity. Raising relative humidity to more than 70% could cause mold corrosion, decay, and other moisture-related problems (Lstiburek, 2002). The occurrence of mold growth is a function of temperature, relative humidity, and substrate over a specific period of time (Sedlbauer, 2001). Condensation due to moisture migration within wood-frame wall cavities can cause mold growth. Mold formation would occur if the minimum temperature of 0˚C (requires 100% RH) or the minimum relative humidity of 80% (requires at least 15˚C) for mold to form is sustained for at least six weeks (Hukka & Viitanen, 1999). A test on exterior walls with no vapour barrier was carried out in a cold climate considering two different insulations in wall cavities (mineral wool and cellulose). The results showed that in order not to satisfy the conditions pointed above for mold growth the interior vapour diffusion resistance must be greater than the exterior value in wall assemblies by a factor of at least 3:1 (Simonson C. J., 2005). Another study showed that the following conditions are necessary and sufficient for mold and other biological growth on surfaces (Trechset & Bomberg, 2009):

- Mold spores;
- Available nutrition;
- Temperature between 4.4°C and 37.7°C; and
- Adjacent RH more than 70%.

Most sheathing materials such as Oriented Strand Board (OSB) provide the first two conditions listed above, so preventing the other two conditions is important. Moreover, wood decay is another moisture-related problem in building envelopes. Wood rot is caused by a group of fungi that feed on cellulose. Wood decay occurs when oxygen, existence of water, wood decay fungus, and appropriate temperature in wood are evident. The temperatures between 24 and 33°C are optimal for wood decay, while growth below

10°C still occurs at a smaller scale. Also, guidelines limit the moisture content of wood to less than 20% to prevent wood decay (Trechset & Bomberg, 2009).

Chapter 3

Materials and Methods

The experimental programmed documented in this thesis was conducted at the Alternative Village at the University of Manitoba, where hygrothermal behaviour of two identical test buildings (fiberglass and cellulose) with different wall cross sections were compared to each other. Data reported in this study was collected in three periods between January 31 and March 16, 2014 (heating season).

3.1 Test buildings

During the summer of 2011 seven test buildings were constructed on the Alternative Village site in order to investigate building envelope performance. All of the structures were oriented similarly with respect to the cardinal compass directions and located such that their shadow

Figure 3-1: Fiberglass batt insulation test building

did not influence adjacent structures. This study was conducted on two of these buildings insulated with fiberglass batt (see Figure 3-1) and dense pack blown-in cellulose (Figure 3-2).

Figure 3-2: Dense pack cellulose insulation test building

The test structures were constructed with common roof and floor systems (see Figure 3-3). Each is 4.87m by 4.87m with a footprint of 23.72m². The construction of the foundation and roof were identical regardless of the wall system in both buildings. Each structure has only one 812mm x 2032mm door opening at the centre of the north wall (no

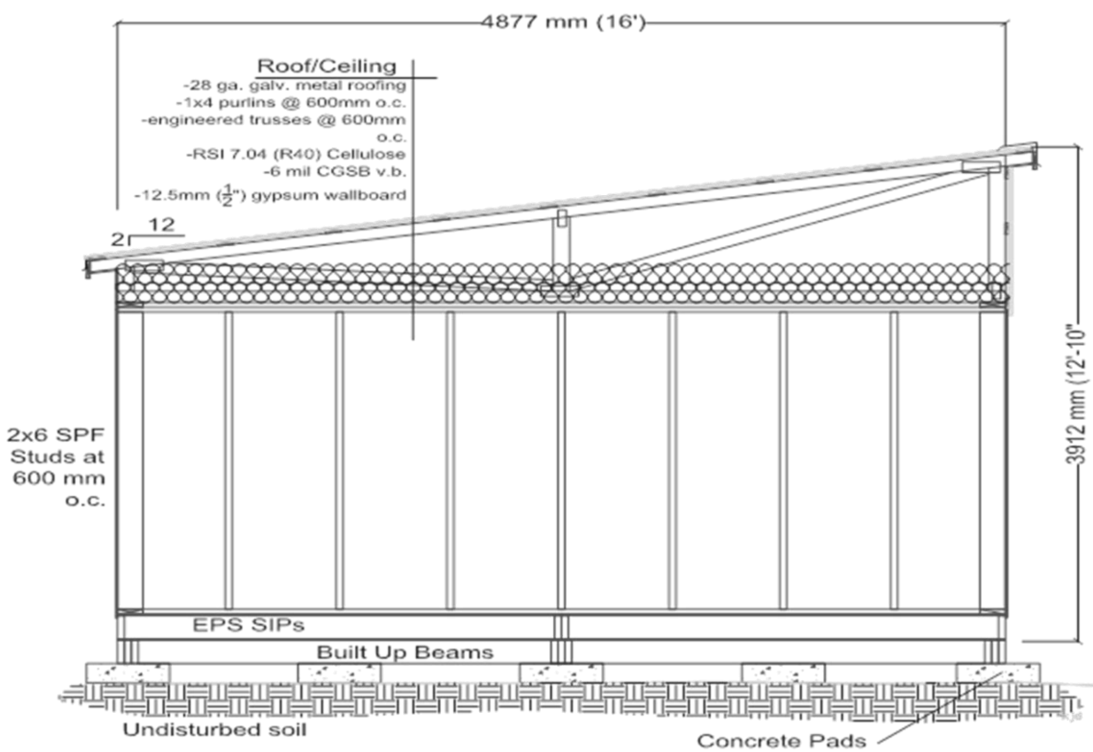

Figure 3-3: Typical cross section of wood frame buildings (source: Dr. K. Dick)

windows were installed). The following components were common to both test buildings.

Roof:

- 28 gauge galvanized metal roofing
- Nominal 1x4 Spruce-Pine-Fir (SPF) (19x89mm) purlins at 610mm on centre
- Engineered trusses at 610 mm on centre
- RSI 7.04 $m^2 \cdot K/W$ blown-in cellulose insulation
- 6 mil (0.152 mm) polyethylene vapour barrier
- 12.5 mm gypsum wall board (GWB)

Floor:

Structural Insulated Panels (SIPs) made with:

- 11mm oriented strand board (OSB)
- Nominal 2x8 SPF No.1/2 joists at 610 mm on centre
- 184 mm of Expanded polystyrene foam (EPS)
- 11mm OSB

Foundation:

- Multi-ply dimensional lumber beams – 3-ply 2x10 SPF No.1/2
- 610mm x 610mm x 150 mm concrete pads.
- 12.5 mm pressure treated plywood skirting.

Each building had two power circuits, a 120V circuit for lighting and another circuit at 220V for a centrally located 2kW resistance baseboard heater, installed on the floor, to maintain indoor of the test building temperature at a constant internal temperature.

3.1.1 Original wall sections

Both buildings consisted of wood frame systems and wall cross sections were selected based on common and typical sizes used in the local construction industry. The most common construction technique for residential buildings in Winnipeg is using a wood frame.

3.1.1.1 Fiberglass wall

A side view of a wall is shown in Figure 3-4. Fibreglass insulated structures are the vernacular for residential construction in Winnipeg. The walls were framed with nominal 2×6 (38×140 mm) dimensional lumber studs at 610mm on centre. The exterior was sheathed with 11mm OSB. Owens-Corning™ fibreglass batt insulation with a nominal thermal resistance of R22 (RSI 3.87) was installed in the cavity between the studs. Then a 6mil (0.152mm) polyethylene vapour barrier was attached and sealed inside to the studs, and a 12.5mm paper-covered gypsum wallboard was installed on top of that to finish the indoor surface (Figure 3-4).

3.1.1.2 Cellulose wall

The cellulose building was constructed with the same wall cross-section and exterior cladding as the fiberglass batt building described in section 3.1.1.1. Two differences exist between these two building cross sections. Firstly, a fabric mesh was attached to the inner stud face (behind vapour barrier) to contain the dense packed cellulose (Figure 3-4). Secondly, the blown-in dense packed cellulose insulation was installed by a certified contractor in accordance with the supplier's procedures. This provided a nominal thermal resistance of R20.37 (RSI 3.585).

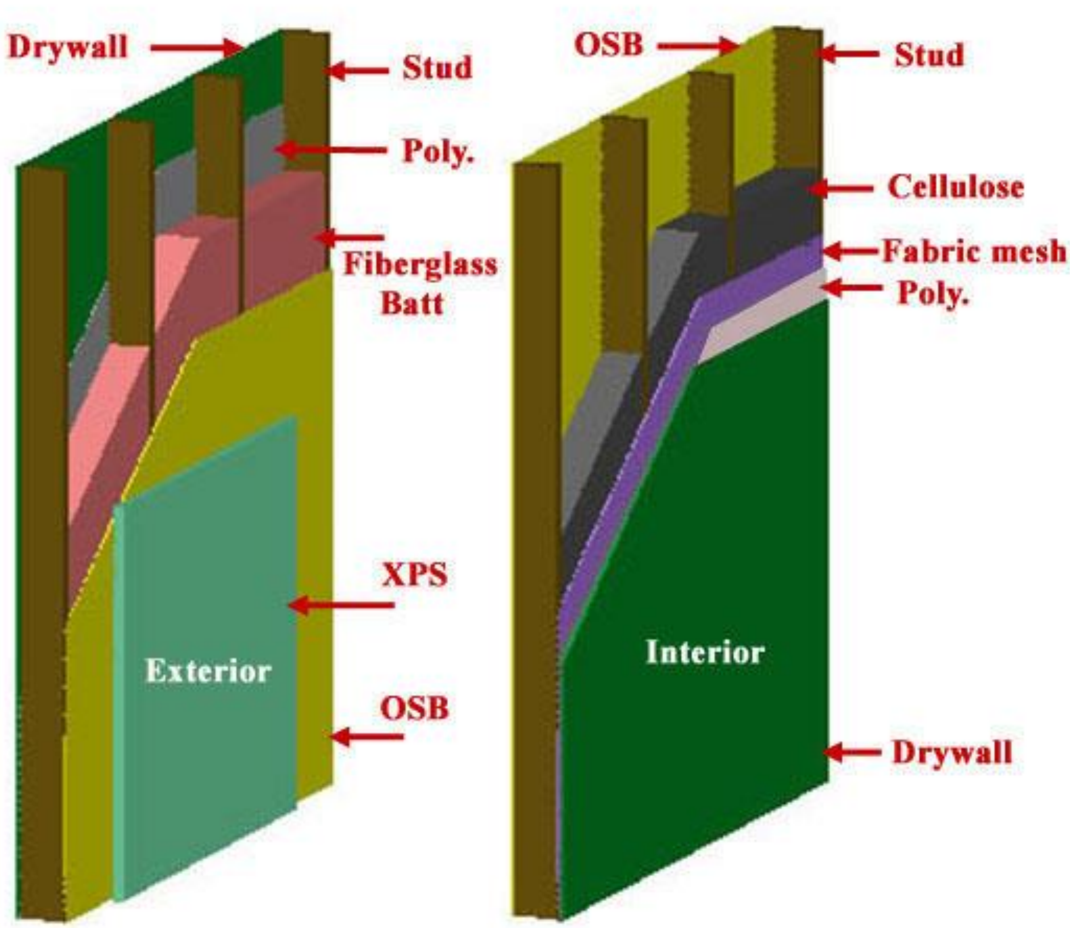

Figure 3-4: Fiberglass with rigid insulation and cellulose walls details

3.2 Test setups

3.2.1 Wall assemblies

Each of the test buildings had two changes to the original wall construction, adding external rigid insulation (XPS) and creating a non-consistent vapour barrier to a portion of the wall. Therefore, combinations of the above two changes to building envelopes provided four different scenarios applied in each test building as follows:

- Chamber 1: Baseline wall assembly
- Chamber 2: Adding rigid insulation on original wall assembly
- Chamber 3: Non-consistent vapour barrier in original wall section
- Chamber 4: The addition of rigid insulation associated with non-consistent vapour barrier in original wall assembly

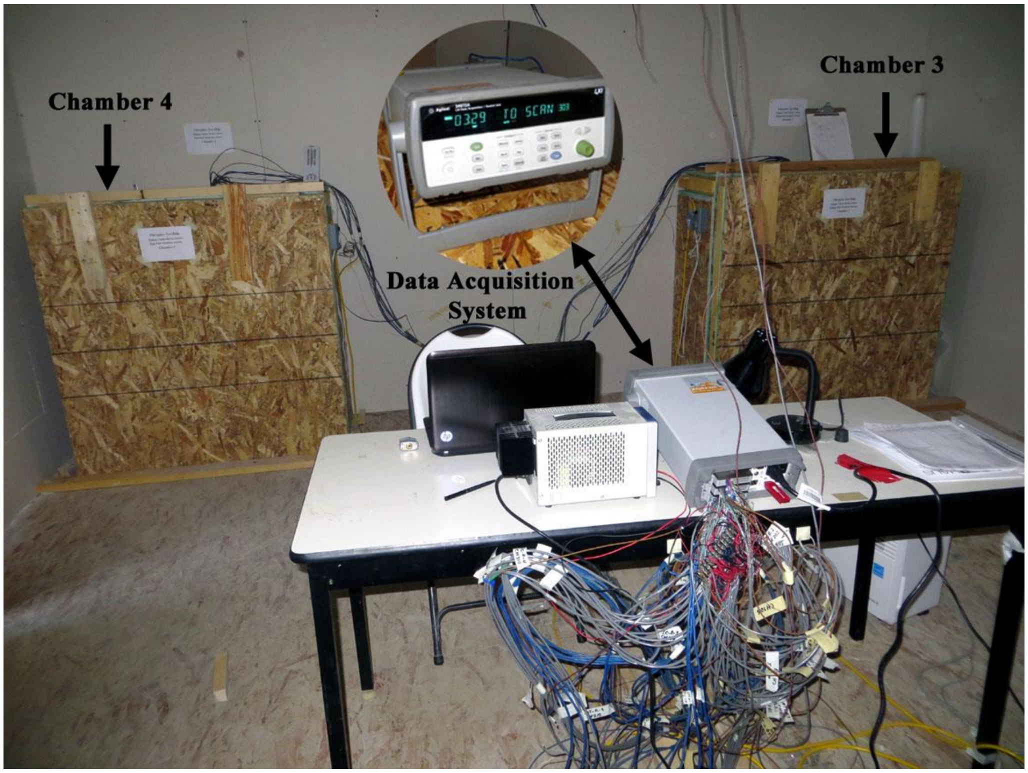

Figure 3-5: Chambers 3 and 4 in fiberglass test building

Each of the test buildings had two chambers attached to the inner face of the east wall (Figure 3-5) and two chambers to the west wall. Figure 3-6 provides a conceptual sketch of how chamber arrangements were accomplished. The east and west walls were chosen in order to eliminate the solar effects on the south wall.

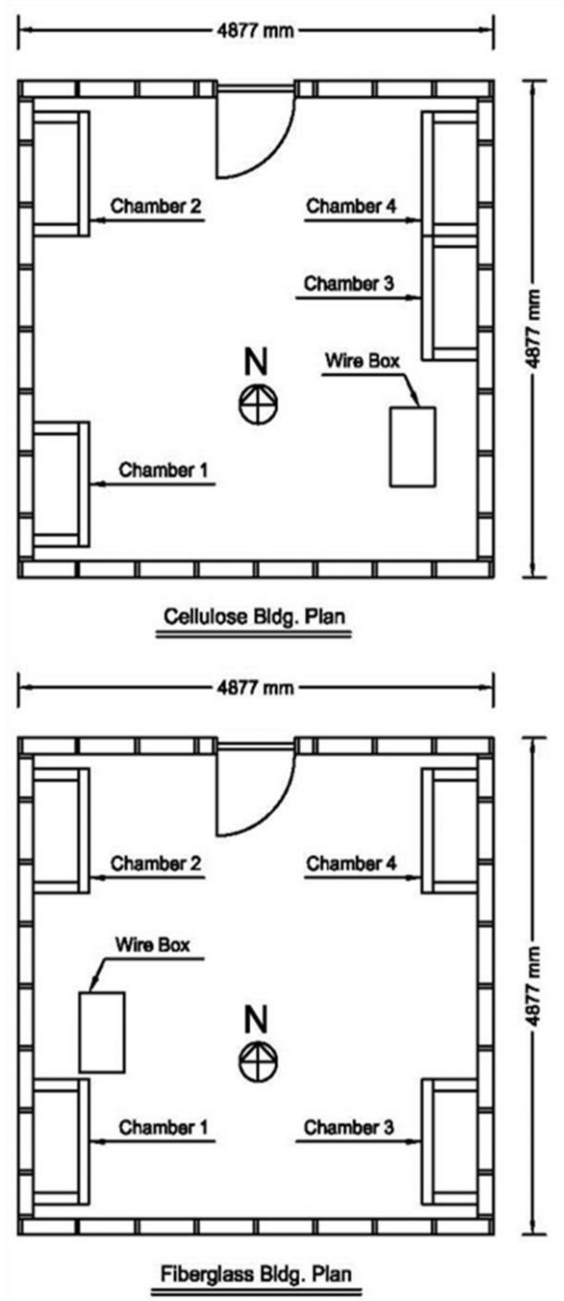

Figure 3-6: Arrangements of chambers in fiberglass and cellulose buildings

As seen in Figure 3-7, each chamber was symmetrically built over two adjacent studs in the wall cavity. The monitored portion (572×572mm) was centered between the two studs and 267mm from the top and bottom of the chamber. The vapour barriers of monitored portions (572×572mm) were cut to make non-consistent vapour barriers in chambers 3 and 4. Also, rigid insulation (XPS) was added on the external walls of chambers 2 and 4 (Figures 3-1 and 3-2). Each XPS was 1220×1220×38mm and installed level with the top of the floor and symmetric to the monitored portion (Figure 3-4).

3.2.2 Chamber specifications

All chambers were identical regardless of wall assemblies which differed between chambers. The back side of each chamber was the wall assembly, the bottom side was the original building floor (Figure 3-7) and the other four sides were structural insulated panels (SIP), which were constructed as follows:

- 11mm OSB
- 90mm Polyurethane Foam
- 11mm OSB

The outside dimension of each chamber was 1220mm long by 1220mm high by 569mm deep (Figure 3-7).

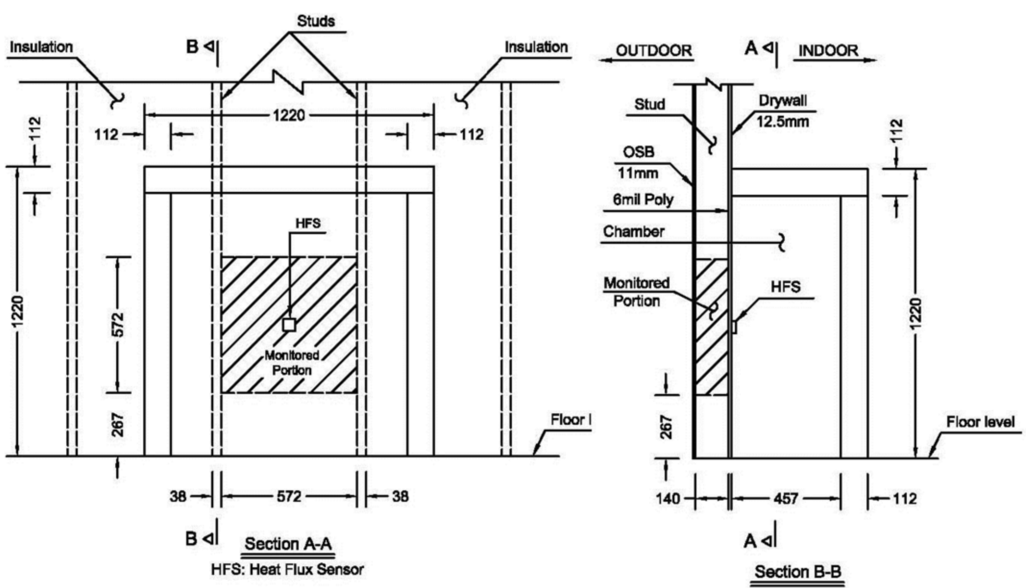

Figure 3-7: Typical chamber location and monitored portion

3.3 Humidity control

A saturated salt solution can be used to create a particular relative humidity in an ideal condition. Therefore, putting the same kind of salt solution in each chamber and considering the same indoor temperature controlled the relative humidity. Three different saturated salt solutions were chosen in order to achieve three different levels of relative humidity inside the chambers.

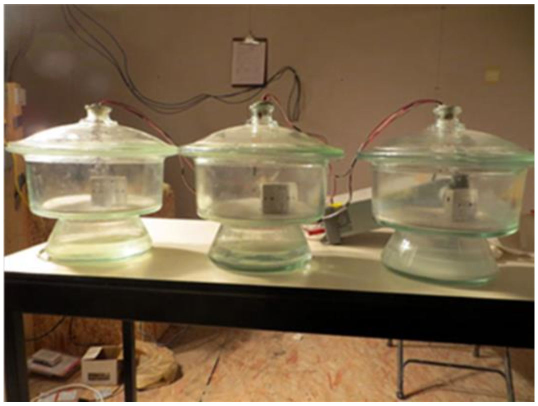

Figure 3-8: Calibration of RH sensors in three different salt solutions

In order to obtain saturated conditions a certain amount of salt was dissolved in distilled water. The standard solubility of each salt is summarized as follows per 100g of water (Lide, 2010):

- Potassium acetate ($KC_2H_3O_2$): 269.25g
- Potassium carbonate (K_2CO_3): 111.25g
- Sodium chloride (NaCl): 36.025g

Each saturated salt solution was monitored with three randomly chosen relative humidity sensors in each desiccator (Figure 3-8). The average RH in each desiccator from December 22 to 24, 2013 (over steady state period) was as follows:

- Low level RH: Saturated potassium acetate solution generated 23.7% equilibrium RH at a temperature of 21°C
- Mid-level RH: Saturated potassium carbonate solution created 43.1% equilibrium RH at a temperature of 24°C

- High level RH: Saturated sodium chloride solution generated 77.3% equilibrium RH at a temperature of 21°C

Almost the same amount of potassium acetate and potassium carbonate salt solution was used in each chamber over the experiment in both test buildings. However, about 1200g of sodium chloride solution was used in each chamber over the last stage of the test period (high level of RH).

The first stage of the test with low-level RH was started with about 750g of saturated solution of potassium acetate in each chamber of both test buildings. That was sufficient for the duration of the test to create equilibrium condition at the desirable indoor RH.

As stated earlier, a fair amount of potassium carbonate was used to create a 750g saturated salt solution for each chamber in second stage of the test (mid-level RH). The average temperature differential between indoor and outdoor was about 37°C from Feb. 13 to Mar. 2, 2014. Therefore, the partial pressure indoors was much higher than outdoors considering the indoor and outdoor RH and temperature, so the potential for moisture migration from inside to outside was significant. As seen in Figure 3-9, crystals formed in the salt solution as water evaporated and migrated through the wall changing the salt content. Additional water was added to the solution on Feb 14th (day after testing period began) at 10:30am to obtain 800g of solution. However, after five more days it was seen that crystals formed in chambers 3 and 4 in both buildings again, and the indoor

RH could not go higher. Thus, more water was added to the solution to obtain 860g of solution for each chamber to reach a higher RH at 10am on Feb. 19th. Finally, additional amounts of salt were added in each chamber in order to achieve desirable indoor RH. 1310g potassium carbonate salt solution was placed at 3pm on Feb. 25th in each chamber in both buildings.

Figure 3-9: Crystal formation of Potassium carbonate solution in chamber 3 of fiberglass bldg.

The last stage with high-level RH was started with 1310g of saturated solution of sodium chloride in each chamber in both buildings. However, the amount of solution was increased to about 1560g by adding more water at 4pm on Mar. 4th after the indoor RH started to decrease due to the amount of water, which had evaporated changing the concentration of salt in the solution.

3.4 Instrumentation and Data Acquisition System

The following equipment was used to monitor temperature and relative humidity of indoor conditions and in the wall assemblies of each chamber. Ambient external conditions were monitored with a thermocouple and RH sensor mounted on the exterior side of north wall under a protective plastic cap. A heat flux sensor (HFS) was attached to the centre of the monitored portion of drywall to measure the heat flux density in each chamber (Figure 3-7). An ONSET HOBO logger was placed in each chamber as a backup system to monitor temperature and RH. The specifications of each piece of equipment are as follows:

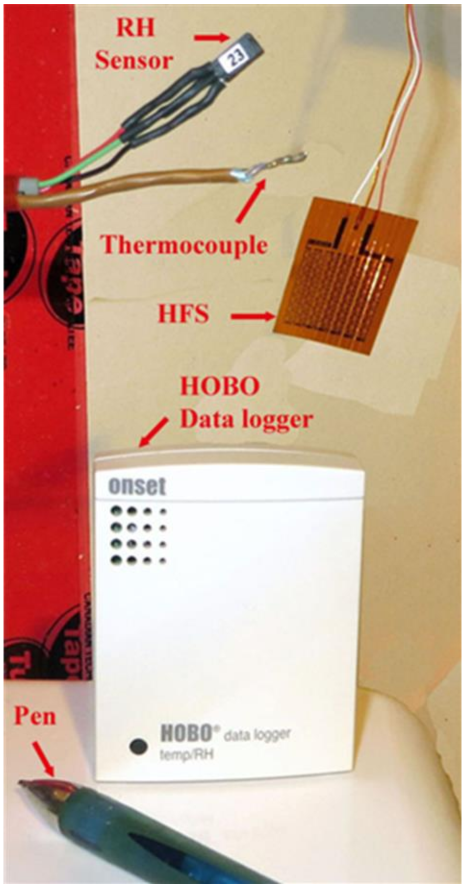

Figure 3-10: Thermocouple, RH sensor, HFS and HOBO data logger

- Agilent 34972A LXI data acquisition system (Figure 3-5)
- 34901A 20 Channel multiplexer
- Honeywell HIH- 4021 relative humidity sensor (Figure 3-10)
- T-type thermocouple (Figure 3-10)
- HFS-4 thin film HFS manufactured by OMEGA (Figures 3-7 and 3-10)
- ONSET HOBO U12 Temp/RH data logger (Figure 3-10)

- 25W and 40W incandescent clear light bulbs (Figure 3-11)
- AC axial fan (800×800mm): Rated Speed 2400/2800 rpm - Maximum Air Flow 0.679/0.837 CMM (Figure 3-11)
- Thermostat-A19 series (manufactured by Johnson Controls)

Figure 3-11: Chamber 4 in fiberglass test building after setting all sensors up

The data acquisition system shown in Figure 3-5 was configured to log the data from sensors at 15-minute intervals. The data acquisition system (one in each building) had three channel multiplexers with 20 channels each. A total of 56 channels were connected to each data acquisition system (Figure 3-5). A resistance baseboard heater (2kW), connected to a thermostat, was installed on the floor of each test building to maintain a constant internal temperature of approximately 20.5°C. There were a HOBO temperature/RH data logger and a T-type thermocouple in each test building (outside of chambers).

3.4.1 Instrumentation and equipment in each chamber

A plastic container including saturated salt solution was put in the centre of each chamber floor (Figure 3-11). Heat was provided with a radiant source, i.e. two 25W and 40W incandescent light bulbs connected in parallel and mounted at a height of 300mm on the side walls of the chamber. The bulbs were connected to a thermostat to maintain the chamber temperature at a desirable value. A fan was mounted at the same height as the bulb in order to circulate indoor heat and humidity (Figure 3-11).

A HOBO temperature/RH data logger was attached to the drywall (monitored portion area) as a backup system for indoor temperature and RH. A thermocouple and RH sensor was hung in the chamber close to the centre of the monitored portion to measure indoor temperature and RH of chambers.

3.4.2 Wall assembly Instrumentation

3.4.2.1 Fiberglass wall enclosure

Making a hole in fiberglass batt insulation might change the thermal behaviour of insulation and make a path for heat and mass to go through, so it would affect the results. Fiberglass batt insulation can be separated in layer in depth easily. Therefore, the drywall of the monitored portion and its vapour barrier were cut to allow the sensors to be placed behind the vapour barrier and in two different layers within the insulation.

The fiberglass batt insulation was cut at an angle at the top of the monitored portion, and sensors were put in place within separated layers. Three pairs of sensors (thermocouple and RH sensor) were put at the centre of the monitored portion in three different positions in depth of wall cavity to measure one direction RH and temperature gradient. One pair of the above sensors (outer sensors) was placed roughly 12mm from the inner face of the OSB and the second bundle (middle sensors) at the mid-depth of fiberglass. The inner bundle of sensors (third pair) was placed exactly at the centre point of the monitored portion on the inside face of the fiberglass batt insulation (Figure 3-12). Another two pairs of sensors were put in place 261mm above and below the middle sensors (see Figure 3-14) as backup and for comparison with the middle sensors.

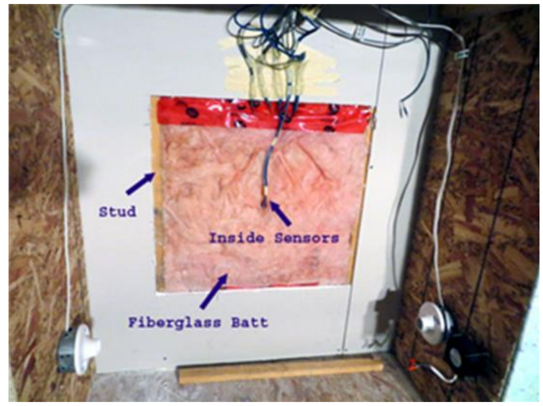

Figure 3-12: Monitored portion and sensors in chamber 4 of fiberglass building

Vapour barriers in chambers 1 and 2 and the drywall in all four chambers were reinstalled, and all the way around the monitored portion on drywall was taped afterward. Then, a bead of caulking was used to cover the sensor wire holes on the drywall. Finally, as Figure 3-11 shows, a HFS was attached to the drywall at the centre point of monitored portions in order to measure the heat flux density in each chamber.

3.4.2.2 Cellulose wall enclosure

The drywall of the monitored portion and its vapour barrier were cut in chambers 3 and 4 to create non-consistent vapour barriers. The drywall was then put back and taped all the way around. A small hole was made just in the drywall for each bundle of sensors (thermocouple and RH sensor), i.e. five holes were made through the drywall in each chamber. Each pair of sensors was fed in different depths by slightly wiggling them through the holes and wall cavity. A bead of caulking was used to cover the holes afterwards. The drywall was then tapped gently, vibrating the cellulose insulation to fill possible voids around the sensors.

Three pairs of sensors were put at mid-height of the monitored portion and in three different locations in depth of each wall cavity to measure one direction RH and temperature gradient. One pair of sensors (outer sensors) was placed about 12mm from the inner face of the OSB and second pair (middle sensors) at the mid-depth of cellulose insulation (exactly at the centre point of monitored portion); third pair (inner sensors) was placed 11mm from the drywall in order to make sure that the sensors were placed inside the vapour barrier layer. The outer and inner pairs of sensors were placed

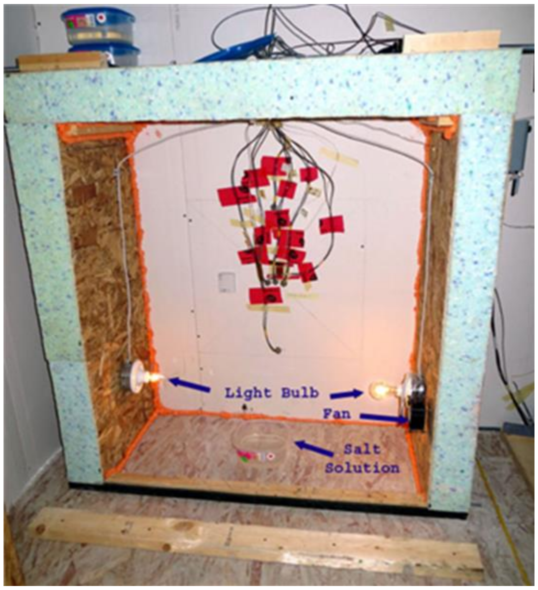

Figure 3-13: Chamber 1 in cellulose test building after setting all sensors up

25mm in horizontal distance from the middle sensors (see Figures 3-13 and 3-14). Two other pairs of sensors were put in place 261mm in height from the middle sensors (see Figure 3-14). Then, as Figure 3-13 shows, a HFS was attached on the drywall close to the centre point of the monitored portions in order to measure the heat flux density in each chamber.

3.5 Test Protocol

This research evaluated a range of conditions in each of the test buildings. As mentioned before, each test building had four chambers, which presented four different wall assemblies. Therefore, this allowed all four building envelopes in each test building to be evaluated at the same time under the same ambient conditions.

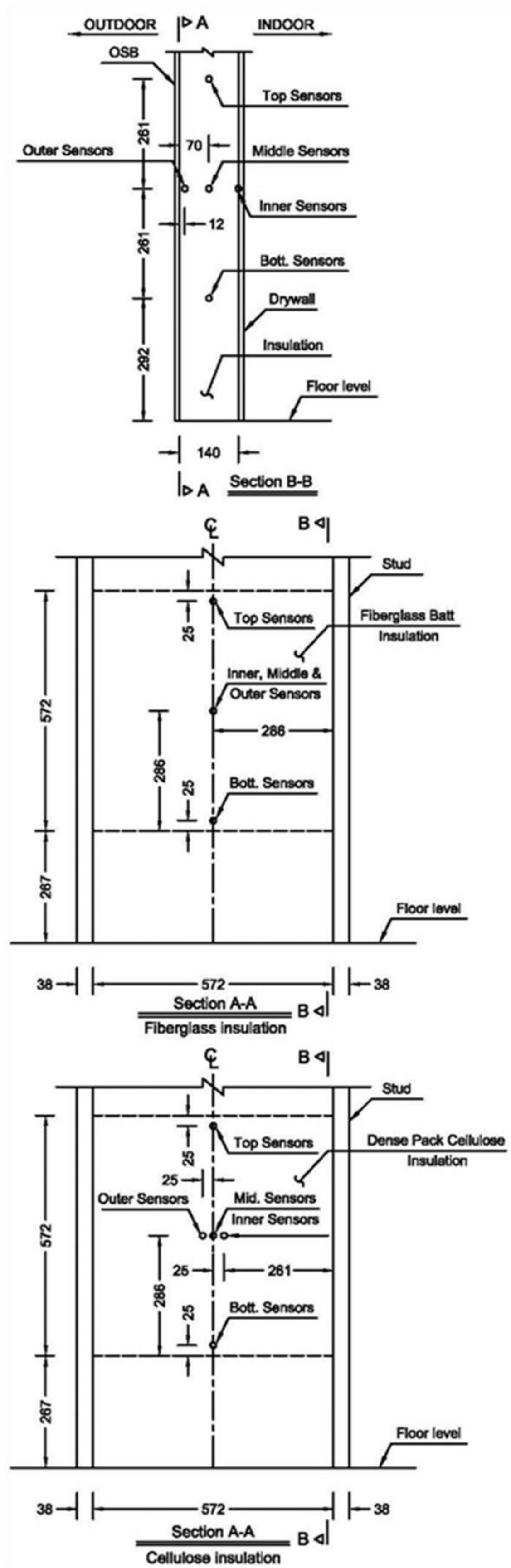

Figure 3-14: Locations of thermocouple and RH sensors

As it was listed in section 3.3, three levels (low, mid and high) of indoor RH were considered in order to measure the impact of elevating the RH profile on moisture regimes and thermal performance through a wall cavity. Therefore, three levels of RH in each of the four chambers provided 12 different scenarios in each test building.

In order to have a clear comparison, four different wall assemblies were compared at each level of RH in section 4. Then, the results of three levels of indoor RH were compared in each building. Finally, overall comparisons were made between the two test buildings.

3.6 Cellulose density test

The contractor that installed the blown-in cellulose in the test building did not provide any documentation about the installed density. Therefore, in-situ tests were done in all four chambers in the cellulose building to determine the dry density of the cellulose. As mentioned in section 3.2.1, the monitored portion within the wall cavity was about 572x572x140mm at 267mm above the floor. However, the exact dimensions of each cavity were measured to obtain the accurate volume for the density test of each chamber.

Figure 3-15: Cellulose density test setup

Before starting the test, temperature and RH within the wall cavity were recorded. The drywall was then taken off the wall assembly. Figure 3-15 shows two metal sheets were used as trays at the top and bottom of the section to limit the test portion to the right height by grooves cut in a wooden box. The top tray was put against the face of the cellulose and the vapour barrier and then the fabric mesh was cut. Then the top tray was gently fed through a groove in the guide and pushed through the cellulose in the wall cavity. The bottom tray was fed similarly afterward. The cellulose was dug out of the desired portion and weighed. The dimensions of the test portion between the studs and two trays were measured individually for each chamber to obtain the exact volume. All samples were dried in an oven at 104°C for at least 24 hours until no weight change was recorded. The dry-basis bulk density was determined using the dry weight and cavity volume.

Chapter 4

Results and Discussion

The results have been divided into three indoor relative humidity categories for each chamber. The categories are identified as low, mid and high with the average indoor RH of roughly 25%, 45% and 65%, respectively. Data was analyzed for the following timelines: Jan. 31st – Feb. 11th, Feb. 13th – Mar. 2nd and Mar. 4th – Mar. 16th, 2014. Temperature, relative humidity and heat flux data were averaged on a six-hour basis representing 12am, 6am, 12pm and 6pm results.

Comparisons between chambers were further subdivided into three cases for both buildings as follows:

- Case 1 - Effect of vapour barrier: Comparing chambers with vapour barriers, which are chambers 1 and 2 (without and with rigid insulation, respectively) with chambers with non-consistent vapour barriers, which are chambers 3 and 4 (without and with rigid insulation, respectively).
- Case 2 - Impact of external rigid insulation: Comparison between chambers without rigid insulation, which are chambers 1 and 3 (with and without consistent

vapour barriers, respectively) and chambers with rigid insulation, which are chambers 2 and 4 (with and without consistent vapour barriers, respectively).

- Case 3 – Effect of vapour barrier associated with external rigid insulation: Comparison between the benchmark chamber 1 and chamber 4 with both rigid insulation and non-consistent vapour barrier.

The specification and chamber arrangements were explained in section 3.2.1. The location of each sensor (e.g. outer and inner) was illustrated in Figure 3.14 in section 3.4.2.

4.1 Fiberglass batt insulation wall

4.1.1 Low level of indoor relative humidity

The first test stage was from January 31 to February 11, 2014. As illustrated in Figure 4.1-1, it was seen that after two days of starting the low RH test, steady-state conditions inside the chambers were established by February 2nd and lasted until February 11th. All of the values (average, minimum and maximum) and comparisons presented were considered over the steady-state conditions from February 2-11, which will be called the "test period" in the following sections.

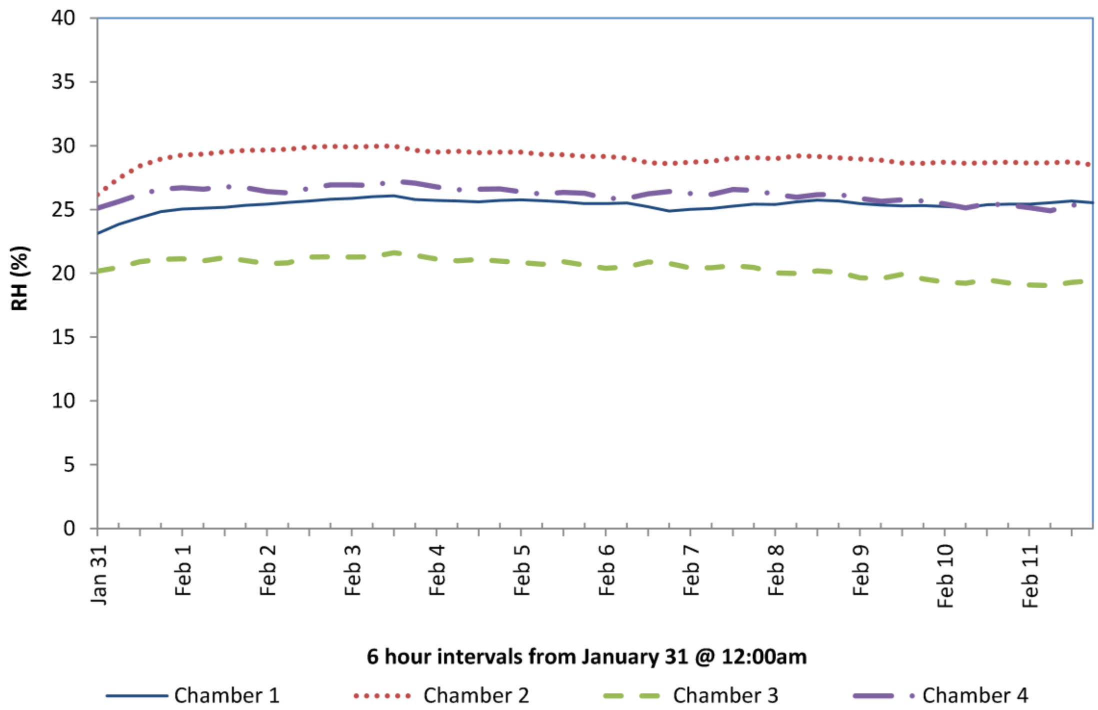

Figure 4.1-1: Indoor RH in fiberglass bldg. (Jan. 31-Feb. 11, 2014)

In addition to the overall trends, a snapshot was selected on Feb. 3rd between 12am and 3am with high outdoor RH (average 84%) associated with low external ambient temperature (-16˚C). The data was retrieved and averaged based on 15-minute intervals between 12am and 3am to eliminate the effect of solar radiation on wall assemblies. Moreover, Figure 4.1-5 shows that the outer RH (within the wall cavity) between 12am and 3am on Feb. 3rd was consistent in each of the four chambers.

4.1.1.1 Moisture migration

The same salt solution was used in all four chambers to keep the relative humidity at a specific level. Based on the data in Table 4.1-1, the average indoor RH in the chambers 3 and 4 (with non-consistent vapour barriers) dropped only 6% and 3% compared to chambers 1 and 2 (with consistent vapour barriers), respectively. It is proposed this happened due to moisture escaping through the wall cavity. It was seen that the indoor RH was maintained approximately at 27±2% for the chambers with consistent vapour barriers and at 23±4% for the chambers with non-consistent vapour barriers, while the outdoor RH fluctuated between 67% and 83% over the test period. Figures 4.1-2, 4.1-3 and 4.1-4 show the RH levels increased from inside to outside, and it was evident that the maximum RH was in chamber 4 in all locations within the wall cavity.

4.1.1.1.1 Case 1 – Effect of vapour barrier

According to Figure 4.1-4 and data in Table 4.1-1, the average outer RH of wall cavity in the benchmark chamber 1 with the intact wall assembly was 54%, while that value was only 1% higher in chamber 3 in the same position by having a non-consistent vapour barrier over the test period. On the other hand, the effect of compromising vapour barriers in the chamber with rigid insulation (chamber 4) exhibits a considerable increase of 30% in the average and maximum outer RH of wall cavity (68% and 74% average and maximum RH) compared to chamber 2 with 38% average outer RH.

Figures 4.1-5 and 4.1-6 illustrate the average outer RH (without rigid insulation) in chamber 3 (55%) was even 4% less than chamber 1 (59%) on Feb. 3rd (between 12am and 3am). However, the same snapshot showed that in the chambers with rigid insulation the average outer RH of wall cavity considering non-consistent vapour barrier (70%) was

28% higher than that with consistent vapour barrier (42%). It was evident that the snapshot had a similar trend as the average over the test period (Feb. 2nd-11th).

4.1.1.1.2 Case 2 – Impact of external rigid insulation

Referring to Figure 4.1-4 and the data in Table 47.1-1, considering consistent vapour barrier, the average outer wall cavity RH was 38% in the chamber with rigid insulation and was 16% lower than without rigid insulation (54% RH). On the other hand, the impact of rigid insulation in the chamber with non-consistent vapour barrier (chamber 4) exhibited a 13% increase in the average of outer RH to 68% compared to chamber 3 with 55% average outer RH.

Also, Figures 4.1-5 and 4.1-6 illustrate the average outer RH of the wall cavity (with consistent vapour barrier) in chamber 2 (42% RH) was 17% lower than chamber 1 by adding rigid insulation on Feb. 3rd (between 12am and 3am). In the chambers with non-consistent vapour barrier, however, the average outer RH was 70% in chamber 4 and 15% higher than chamber 3 (without rigid insulation).

4.1.1.1.3 Case 3 – Effect of non-consistent vapour barrier and with external rigid insulation

Figure 4.1-4 and data in Table 4.1-1 show a 14% increase in outer wall cavity RH from 54% in baseline chamber 1 to 68% in chamber 4 considering both having non-consistent vapour barrier and the addition of rigid insulation. Similarly, the average outer RH in chamber 4 was 70% and 11% higher than chamber 1 on Feb. 3rd between 12am and 3am.

Overall, when the above comparisons are considered, some unexpected results in the outer wall cavity RH in chamber 1 were seen. Apart from the higher outer RH in the wall cavity of chamber 1 over the test period and snapshots, the RH results for the rest were consistent. The following comparisons were made in order to clarify the problem and further discussion will be presented in section 4-1-3 to propose a possible reason for the similar unexpected results. Figures 4.1-2 and 4.1-3 show that the inner and the middle RH of chamber 1 were at the lowest level over the test period. However, the outer RH of chamber 1 was higher than chamber 2 and almost the same level as chamber 3 (Figure 4.1-4). Also, Figure 4.1-6 shows how outer RH in chamber 1 crossed the RH profile of chamber 2 in the graph and went higher than that from the middle to outer, which was not expected.

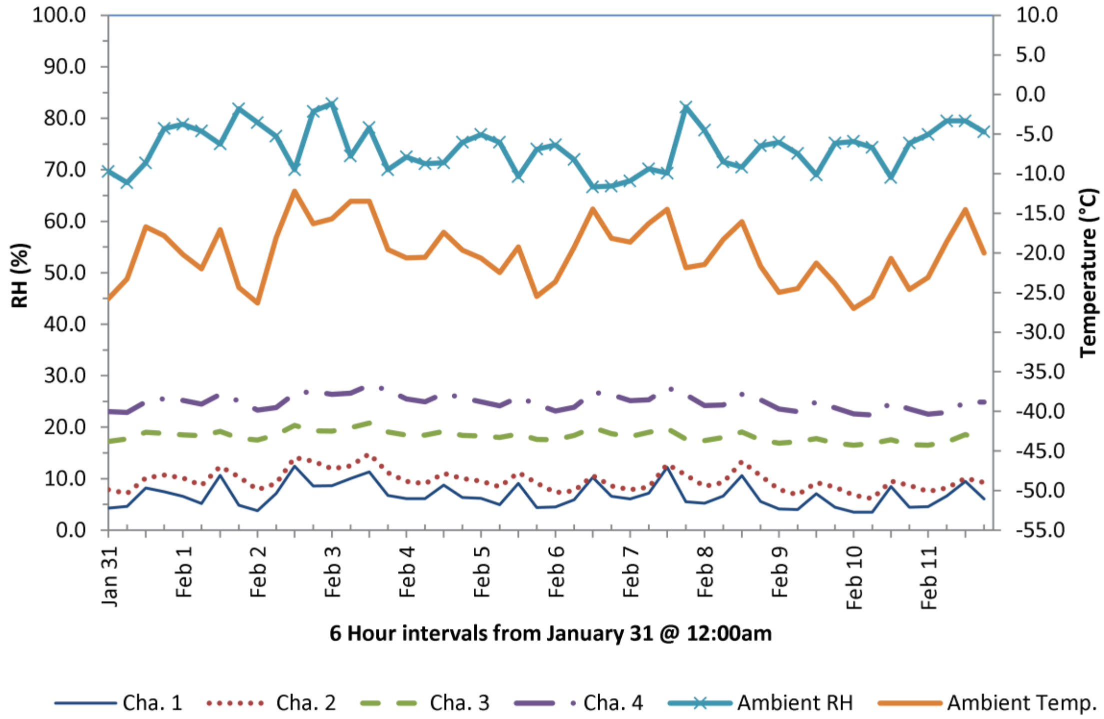

Figure 4.1-2: Ambient outdoor and inner RH in fiberglass bldg. (Jan. 31-Feb. 11)

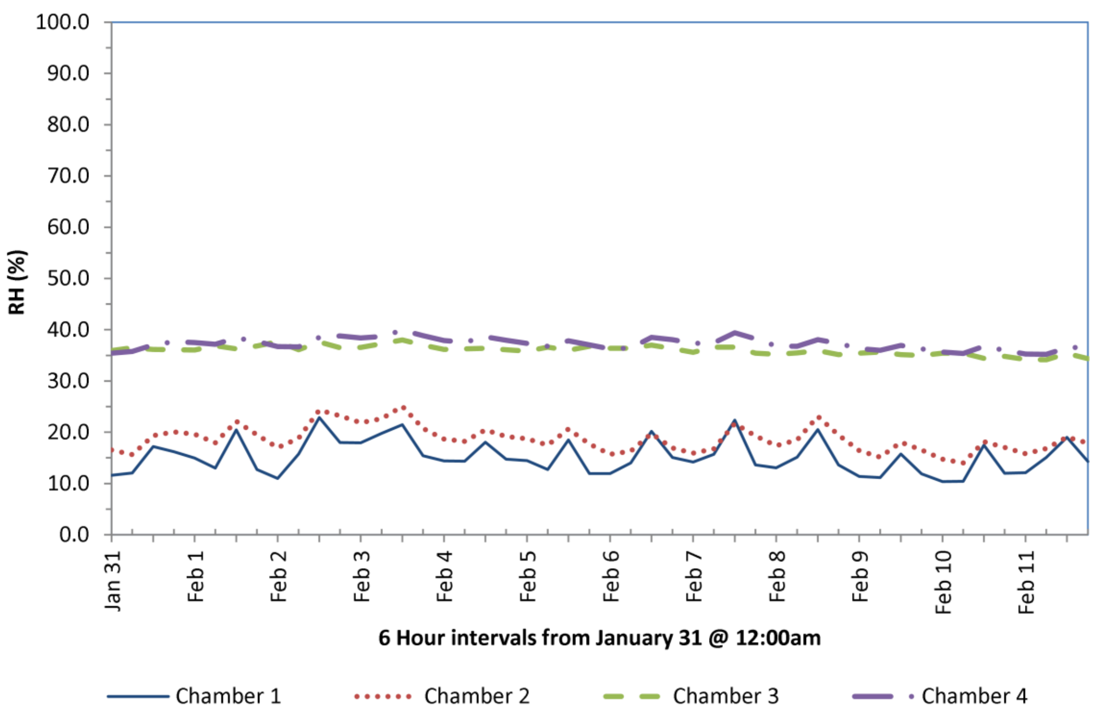

Figure 4.1-3: Middle RH in fiberglass bldg. (Jan. 31-Feb. 11)

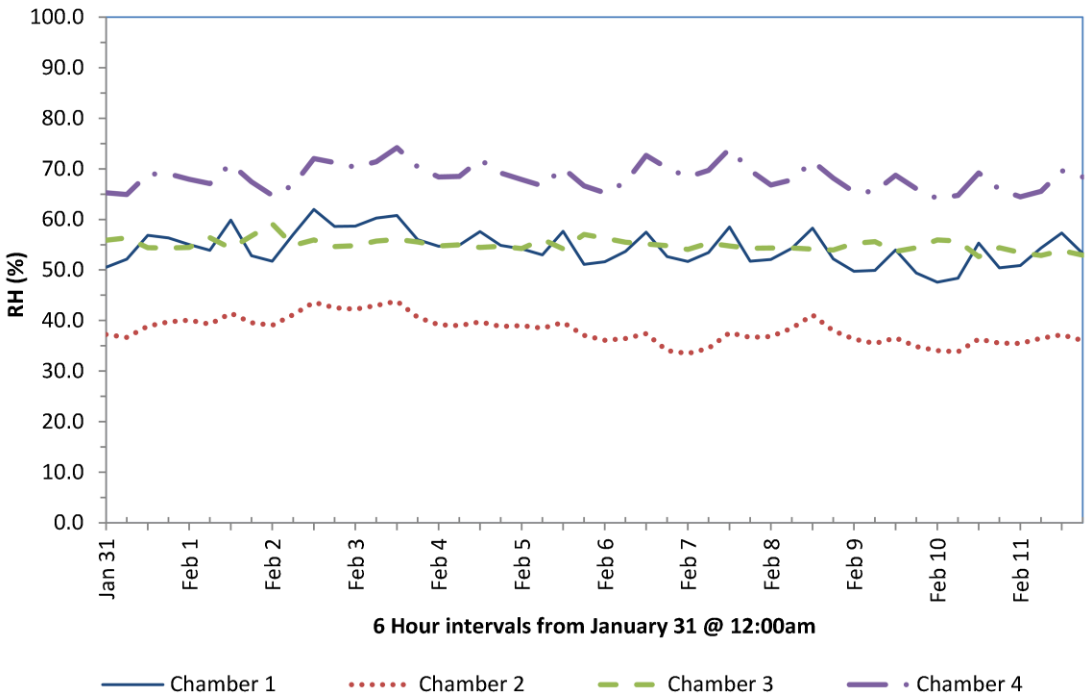

Figure 4.1-4: Outer RH in fiberglass bldg. (Jan. 31-Feb. 11)

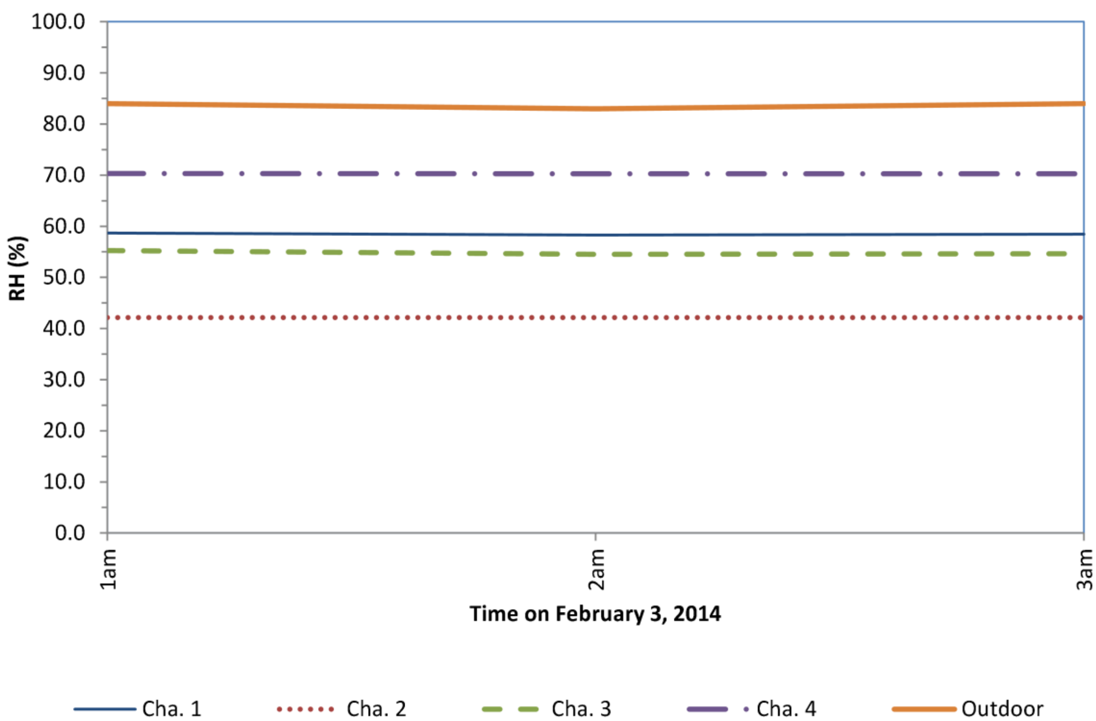

Figure 4.1-5: Outer and ambient outdoor RH in fiberglass bldg. on Feb. 3rd (between 12am and 3am)

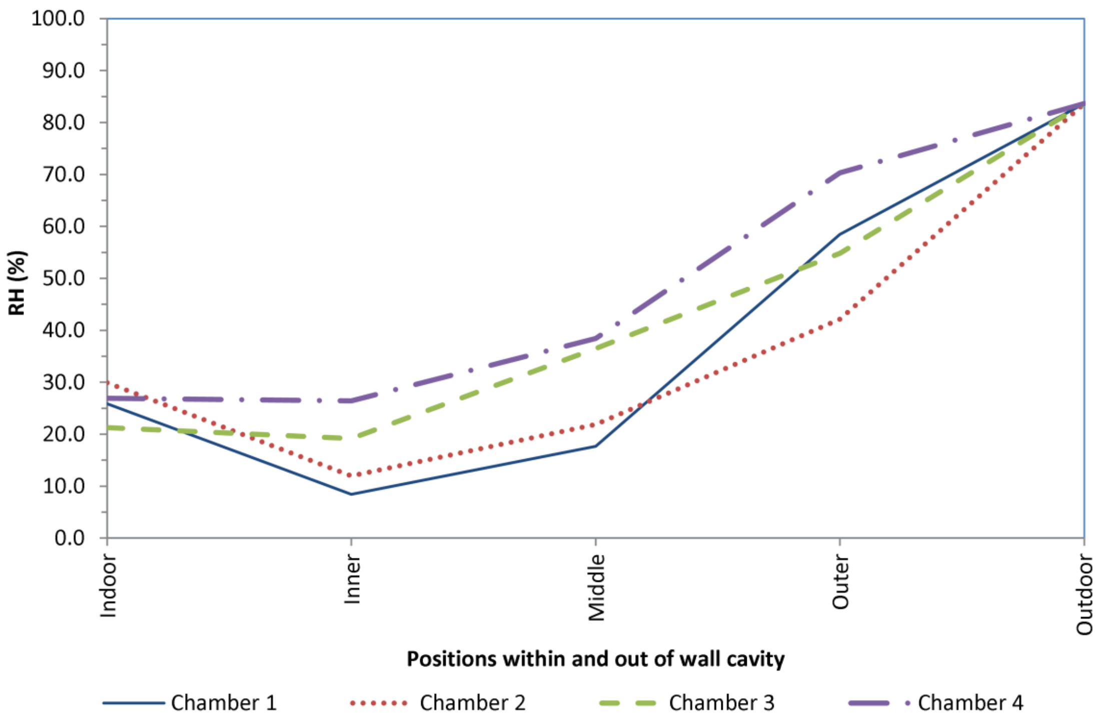

Figure 4.1-6: Average RH profile within wall cavity in fiberglass bldg. on Feb. 3rd (between 12am and 3am)

Table 4.1-1: Average indoor, outer and outdoor RH in fiberglass bldg. (Feb. 2-11)

	Relative Humidity (%)								
	Indoor RH				Outer RH				Outdoor RH
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	25	28	19	25	48	33	53	64	67
Maximum	26	30	22	27	62	44	59	74	83
Average	26	29	20	26	54	38	55	68	74

4.1.1.2 Temperature gradient

The indoor temperature of all chambers was maintained at 20±0.5˚C (Figure 4.1-7). The ambient outdoor temperature fluctuated between -27˚C and -12˚C over the test period, with an average of -20˚C. The outer temperature of the wall cavity followed a similar pattern as ambient outdoor in all four chambers (Figure 4.1-8). As mentioned in section 4, three cases have been compared in the following subsections.

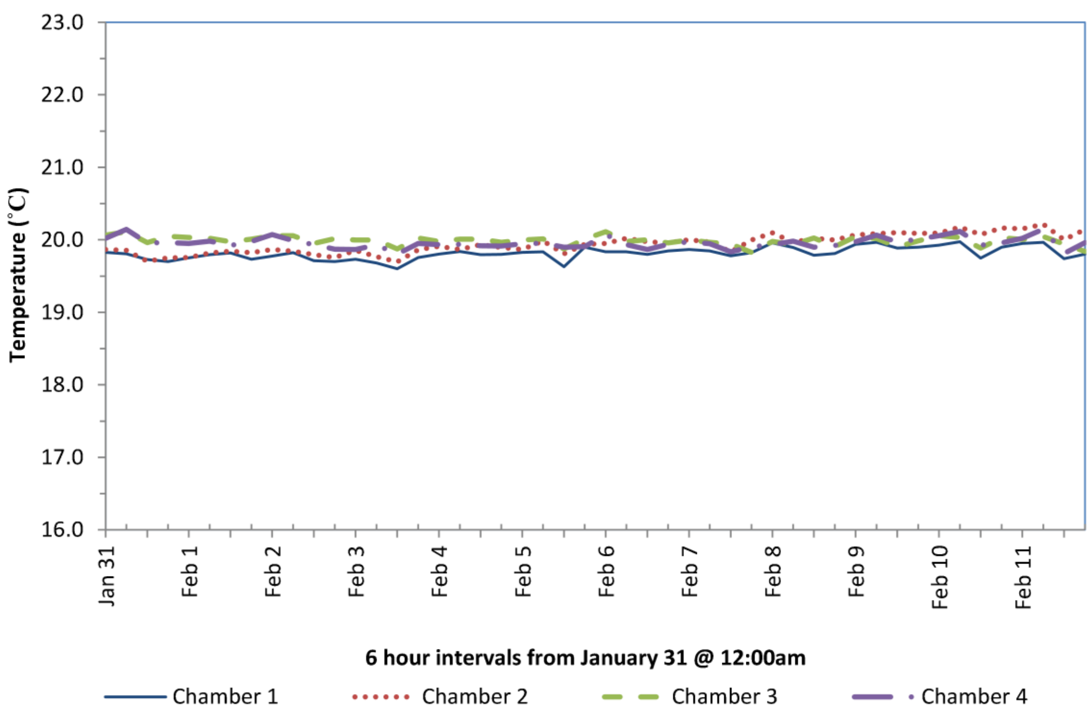

Figure 4.1-7: Indoor temperature in fiberglass bldg. (Jan. 31-Feb. 11, 2014)

4.1.1.2.1 Case 1 – Effect of vapour barrier

Data in Table 4.1-2 shows that the average outer wall cavity temperature in non-consistent vapour barrier chambers 3 and 4 was -8˚C and 0˚C and just 4˚C higher than chambers 1 and 2, respectively. Therefore, as seen in Figure 4.1-8 and above results, the vapour barrier had no significant effect on outer temperatures of the wall section regardless of adding rigid insulation or not. A similar result was seen over the snapshot as well. For instance, Figure 4.1-9 represents 5˚C and 3˚C increase of the average outer temperature in chambers 3 and 4, respectively on Feb. 3rd (between 12am and 3am) by making non-consistent vapour barrier.

4.1.1.2.2 Case 2 – Impact of external rigid insulation

According to Figure 4.1-8 and data in Table 4.1-2, the average outer temperature of wall cavity was -4˚C and 0˚C in chambers 2 and 4 respectively, and 8˚C higher than chambers 1 and 3 due to adding external rigid insulation. In addition, the impact of putting rigid insulation was considerable on the minimum outer temperature over the test period, which resulted in 10˚C higher minimum outer temperature (at -9°C and -3°C in chambers 2 and 4, respectively). Likewise, according to Figure 4.1-9, the average and minimum outer temperature in wall cavity were considerably higher in the chambers with rigid insulation than others on Feb. 3rd (between 12am and 3am).

4.1.1.2.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation)

This scenario is a comparison between the benchmark chamber 1 and chamber 4 with rigid insulation and non-consistent vapour barrier. Figure 4.1-8 and Table 4.1-2 show that the average and minimum outer temperature went up to 0˚C and -3˚C, respectively in chamber 4, which were 12˚C and 16˚C higher than benchmark chamber 1. Moreover, according to Figure 4.1-9, similar results to test period could be seen on Feb. 3rd between 12am and 3am.

Overall, comparing the above three cases it was evident that the average outer temperature increased considerably just by adding rigid insulation on exterior side of the wall assembly.

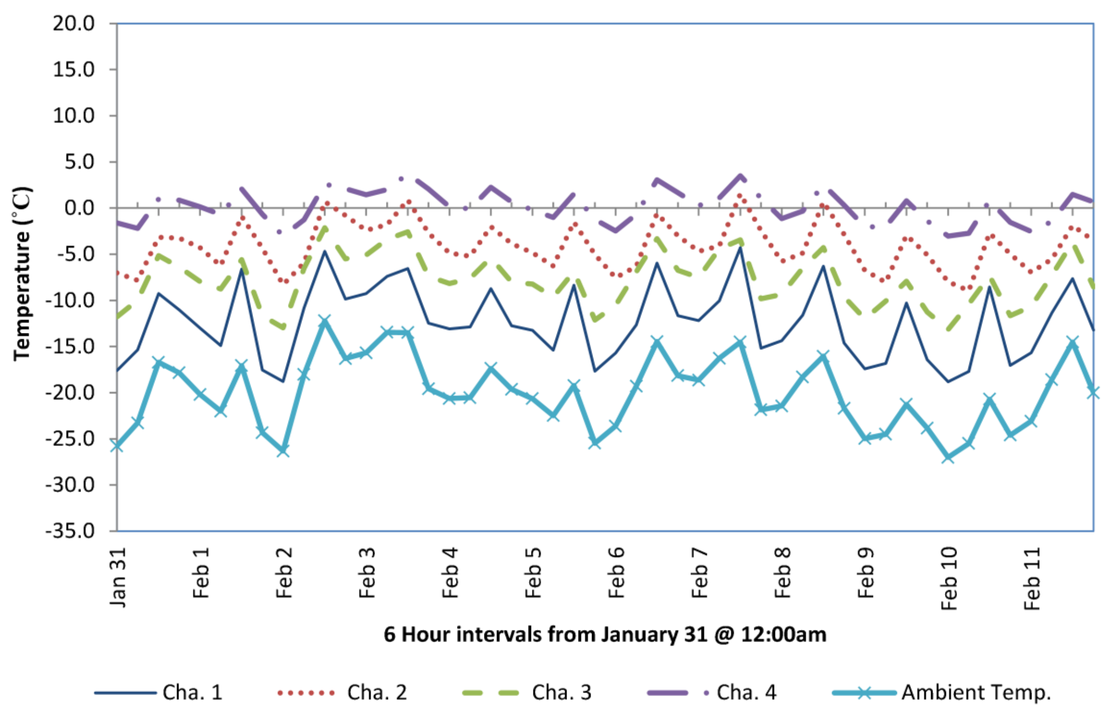

Figure 4.1-8: Outer temperature in fiberglass bldg. (Jan 31-Feb. 11)

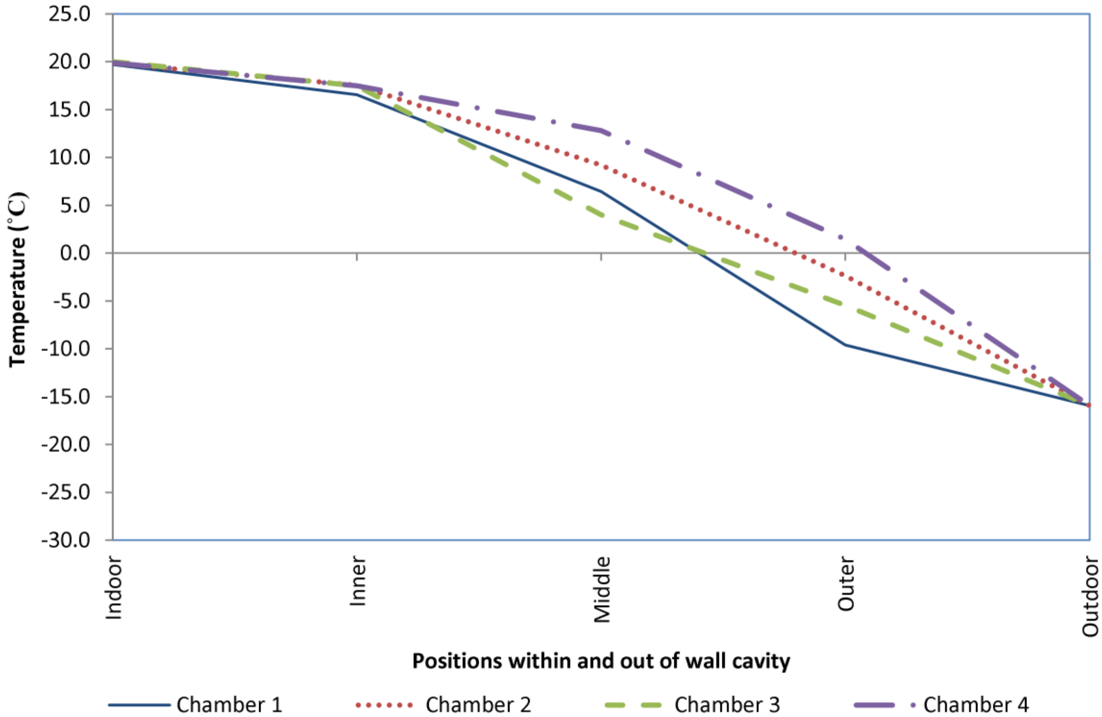

Figure 4.1-9: Average temperature profile within wall cavity in fiberglass bldg. Feb. 3rd (between 12am and 3am)

Table 4.1-2: Average indoor, outer and outdoor temp. in fiberglass bldg. (Feb. 2-11)

	Temperature (°C)								
	Indoor Temp.				Outer Temp.				Outdoor Temp.
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	19.6	19.7	19.8	19.8	-19	-9	-13	-3	-27
Maximum	20.0	20.2	20.1	20.1	-4	2	-2	4	-12
Average	19.8	20.0	20.0	20.0	-12	-4	-8	0	-20

4.1.1.3 Heat transfer

Figure 4.1-10 illustrates that the heat flux density in all four wall assemblies followed an inverse pattern with respect to the ambient outdoor temperature. For instance, when the ambient outdoor temperature went up, the heat flux density declined and vice versa. A direct relationship was observed between the outdoor and indoor temperature gradient and the heat flux density changes. The three cases (as mentioned previously) will be compared in the following subsections.

4.1.1.3.1 Case 1 – Effect of vapour barrier

Figure 4.1-11 shows that in the chambers without rigid insulation the heat flux density considering the non-consistent vapour barrier (chamber 3) was 12.7 W/m^2 and 5.2 W/m^2 higher than chamber 1 (with vapour barrier), while in the chambers with rigid insulation (chamber 4) that value was 6.1 W/m^2 and just 1.5 W/m^2 higher than chamber 2 (with vapour barrier). In addition, according to Figure 4.1-12, the average heat flux density on Feb. 3rd (between 12am and 3am) in chamber 3 was 12.1 W/m^2 and 5.7 W/m^2 higher than chamber 1, while the values in chamber 4 was 5.3 W/m^2 and just 1.1 W/m^2 higher than chamber 2.

Therefore, it was seen from the above results that non-consistent vapour barrier increased the heat flux density by 69% in the chambers without rigid insulation over the test period, while in the chambers with rigid insulation this impact was just 33% increase.

4.1.1.3.2 Case 2 – Impact of external rigid insulation

According to Figure 4.1-11, the average heat flux density through the wall assembly in chamber 2 (4.6 W/m²) was 2.9 W/m² lower than chamber 1 considering the same vapour barrier system but with the addition of the external rigid insulation. However, that value in the chamber with non-consistent vapour barrier (chamber 4) was 6.1 W/m² just by adding rigid insulation and considerably 6.6 W/m² lower than chamber 3.

Figure 4.1-12 shows the average heat flux density in chamber 2 (4.2 W/m²) was 2.2 W/m² lower than chamber 1 on Feb. 3rd between 12am and 3am. The value in chamber 4 (5.3 W/m²) was 6.8 W/m² less than chamber 3.

Overall, both the snapshot and the test period results reflect that the effect of putting rigid insulation was considerable in decreasing the heat flux density in both cases (including consistent and non-consistent vapour barriers). However, this impact was greater in non-consistent vapour barrier chambers (52% decrease) than the consistent vapour barrier (39% decrease) over the test period.

4.1.1.3.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

According to Figure 4.1-11, the average heat flux density through wall assembly went down from 7.5 W/m² in chamber 1 to just 6.1 W/m² by having both non-consistent vapour barrier condition associated with external rigid insulation layer (chamber 4). Also, on Feb. 3rd (snapshot), the average heat flux density was 5.3 W/m² in chamber 4 and just 1.1 W/m² lower than chamber 1 (Figure 4.1-12).

It was seen that even though the addition of rigid insulation had a considerable effect on reducing the heat flux, having a non-consistent vapour barrier increased the heat flux density. Therefore, the combination of both (chamber 4) resulted in just 19% decrease in heat flux density compared to baseline chamber 1 over the test period. Overall, in terms of heat flux, not only the addition of rigid insulation but also having consistent vapour barrier had considerable effect on reducing heat flux density, in other words, the above results show that heat flux density in chamber 2 was 64% less than the value in chamber 3.

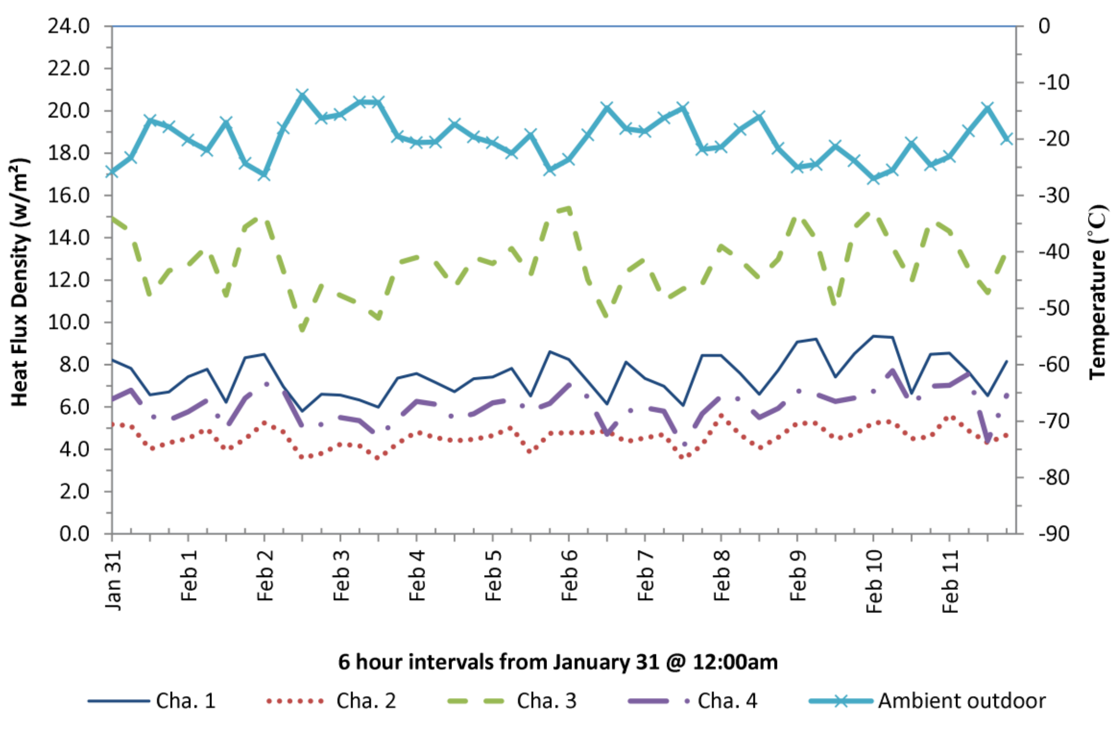

Figure 4.1-10: Heat flux density and ambient outdoor temperature in fiberglass bldg. (Jan. 31-Feb. 11)

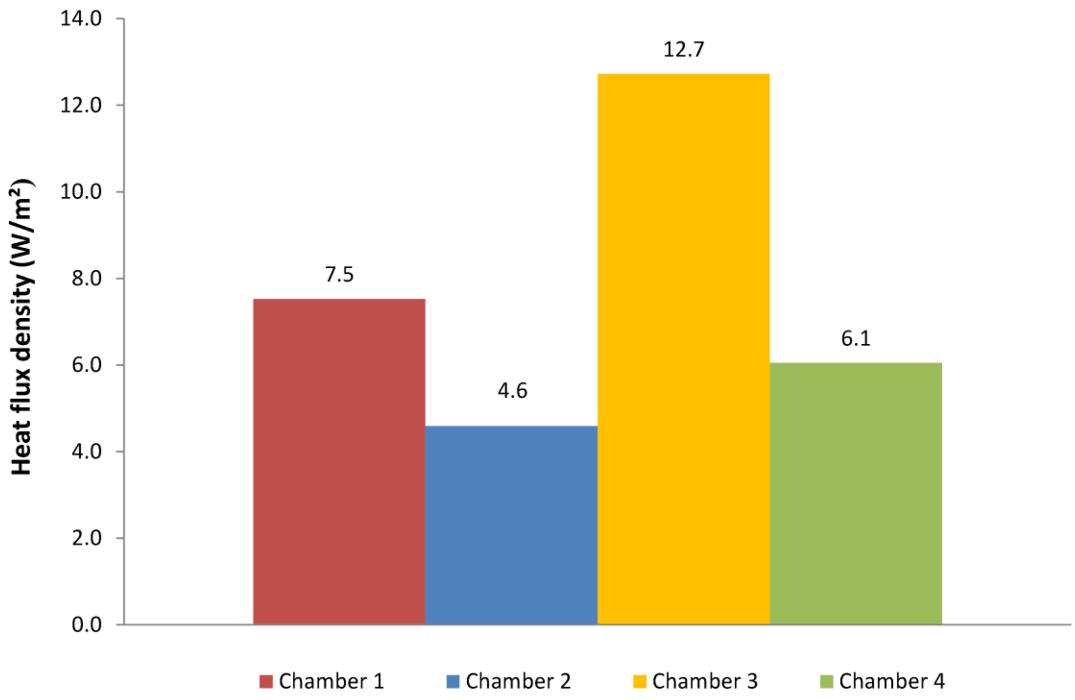

Figure 4.1-11: Average heat flux density in fiberglass bldg. (Feb. 2-11, 2014)

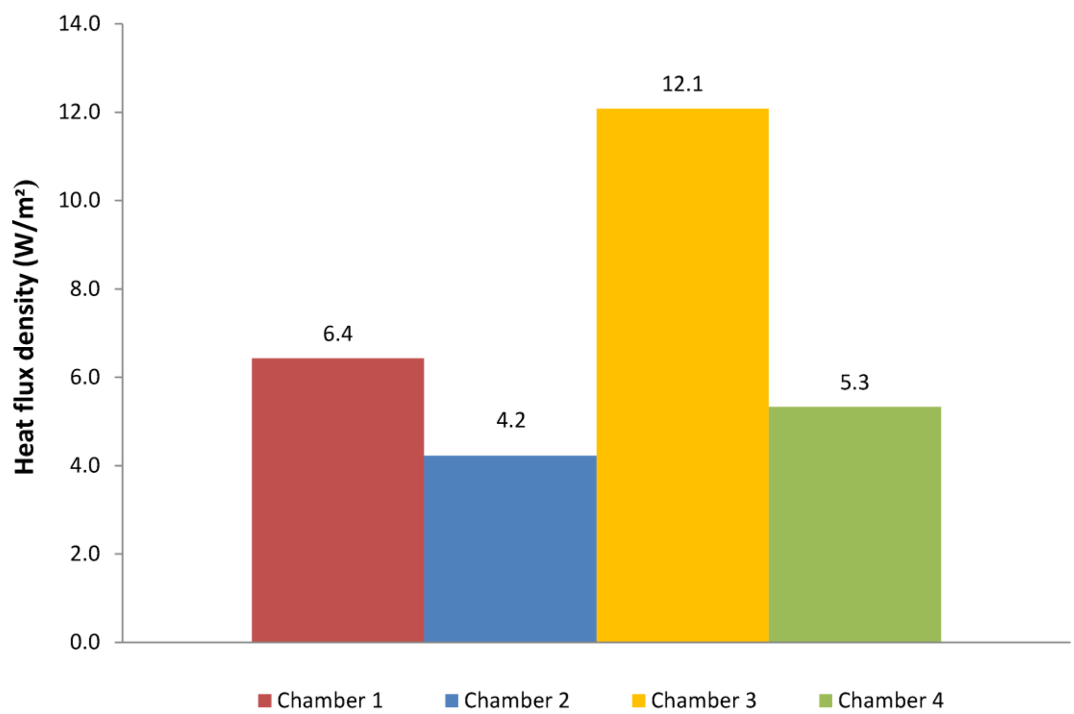

Figure 4.1-12: Average heat flux density in fiberglass bldg. on Feb. 3rd (between 12am and 3am)

4.1.2 Mid-level of indoor relative humidity

The second stage of testing was between Feb. 13 and Mar. 2, 2014. As indicated in section 3-3, water was added to salt solution twice (in the mornings of Feb. 14th and Feb. 19th) to compensate the amount of water evaporated. Finally, the amount of salt solution was increased to reach the desirable indoor RH on the morning of Feb. 25th as it could be seen in Figure 4.1-13. After increasing the amount of salt solution, the steady state condition at desirable indoor RH was achieved between Feb. 26th and Feb. 27th, which will be called “test period” in following sections.

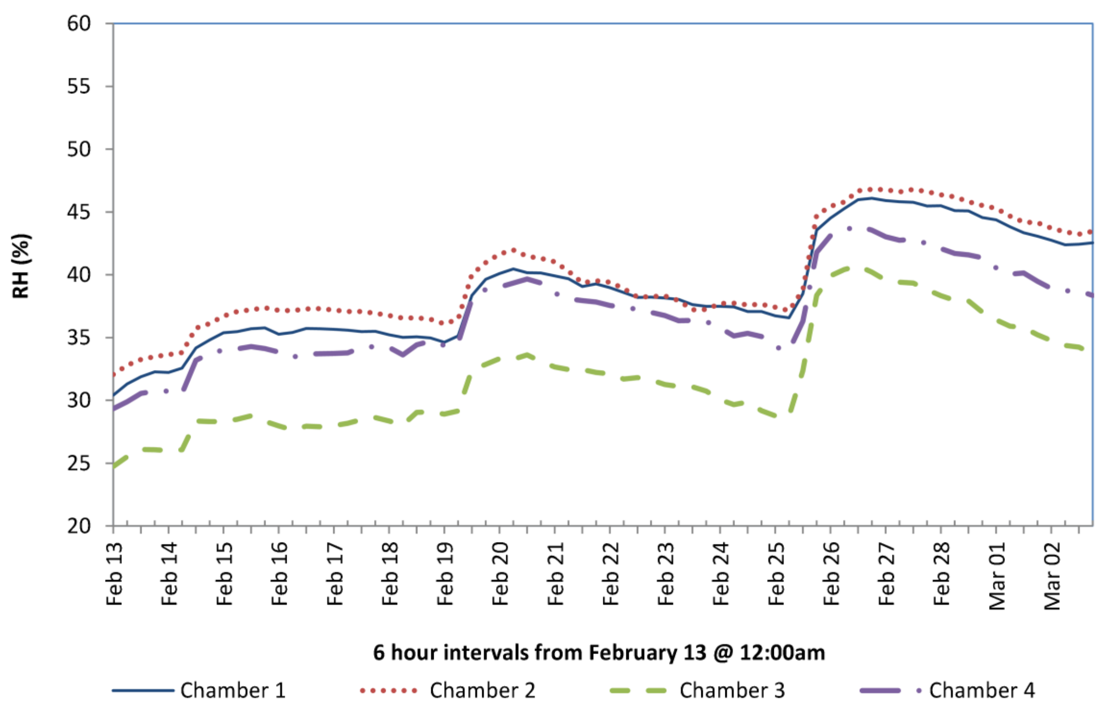

Figure 4.1-13: Indoor RH in fiberglass bldg. (Feb. 13-Mar. 2, 2014)

In addition to the overall trends, a snapshot was selected with the average ambient outdoor temperature and RH of -29°C and 71% on Feb. 27th between 12am and 3am. The data was retrieved and averaged based on 15-minute intervals. Moreover, Figure 4.1-17 shows that the outer RH (within the wall cavity) was consistent in each of the four chambers on Feb. 27th between 12am and 3am.

4.1.2.1 Moisture migration

The same salt solution was used in all four chambers to maintain the relative humidity at a specific level. Based on the data in Table 4.1-3, the average indoor RH in the chambers 3 and 4 (with non-consistent vapour barriers) dropped 6% and 3% compared to chambers 1 and 2 (with consistent vapour barriers), respectively. It was seen that indoor RH was approximately 46±1% for the chambers with consistent vapour barriers and 41.5±2.5% for the chambers with non-consistent vapour barriers, while the outdoor RH fluctuated between 60% and 78% over the test period.

Figures 4.1-14, 4.1-15 and 4.1-16 show that chambers 1 and 2 had lower RH levels than the others without consistent vapour barriers in all three measured locations within the wall cavities. Also, it was clearly seen that overall, the RH levels increased from inside to outside of the wall cavity.

4.1.2.1.1 Case 1 – Effect of vapour barrier

According to Figure 4.1-16 and Table 4.1-3, the average outer RH of wall cavity in the benchmark chamber 1 with the intact wall assembly was 54% (59% maximum outer RH). The average RH was, however, 28% higher at 82% (91% maximum RH) in chamber 3 in the same position by having a non-consistent vapour barrier over the test period. The effect of compromised vapour barrier in the chamber with external rigid insulation was considerable; the average outer RH increased significantly to 76% (80% maximum RH) in chamber 4 and 40% higher than chamber 2 with an average outer RH of 36% (40% maximum RH).

Figures 4.1-17 and 4.1-18 illustrate the average outer RH in chamber 3 (91%) was 41% greater than chamber 1 (50%) on Feb. 27th (between 12am and 3am). Similarly, in the chambers with rigid insulation the average outer RH of wall cavity considering non-consistent vapour barrier (73%) was 37% higher than that with consistent vapour barrier (36%).

Overall, it was seen that the snapshot had a similar pattern as the average over the test period (Feb. 27-28). In fact, making non-consistent vapour barrier in both chambers (with and without rigid insulation) increased the average outer wall cavity RH to more than 75% over the test period.

4.1.2.1.2 Case 2 – Impact of external rigid insulation

According to Figure 4.1-16 and data in Table 4.1-3, in the chambers with continuous vapour barriers, the average outer wall cavity RH with rigid insulation was 36% and 18% lower than without rigid insulation (54% RH). On the other hand, the addition of rigid insulation in the chambers with non-consisting vapour barriers (chamber 4) did not impact significantly on the outer RH of wall cavity, i.e. the value was 76% in chamber 4 and just 6% lower than chamber 3.

Also, Figures 4.1-17 and 4.1-18 illustrate the average outer RH of the wall cavity (with consistent vapour barrier) in chamber 2 (36%) was 14% lower than chamber 1 (50%) on Feb. 27th (between 12am and 3am) by adding rigid insulation. The addition of rigid insulation in the chamber with non-consistent vapour barrier showed 18% decrease in the average outer RH from 91% in chamber 3 to 73% in chamber 4.

4.1.2.1.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

This scenario is a comparison between the benchmark chamber 1 and chamber 4 with rigid insulation and non-consistent vapour barrier. Figure 4.1-16 and Table 4.1-3 show that the average outer RH in chamber 4 went up to 76% by the addition of rigid insulation and having non-consistent vapour barrier, which was 22% higher than baseline chamber 1. Similarly, Figures 4.1-17 and 4.1-18 show the comparable results as the above comparison over the test period on Feb. 27th (between 12am and 3am), i.e. the average outer RH was 23% higher in chamber 4 (73%) than chamber 1.

Overall, when the above comparisons were considered, some unexpected results at the outer wall cavity RH in chamber 1 were seen. Apart from the higher RH value of the outer wall cavity in chamber 1 over the test period and snapshot, the rest RH results were consistent. The following comparisons were made in order to clarify the problem and further discussion will be led in section 4-1-3 to propose a possible reason for the similar unexpected results. Figures 4.1-14 and 4.1-15 illustrate that the inner and the middle RH of chamber 1 were at the lowest level over the test period. However, the outer RH of chamber 1 was higher than chamber 2 (Figure 4.1-16). Also, Figure 4.1-18 shows how outer RH in chamber 1 crossed the data line of chamber 2 in the graph and went higher than that from the middle to outside, which was not expected.

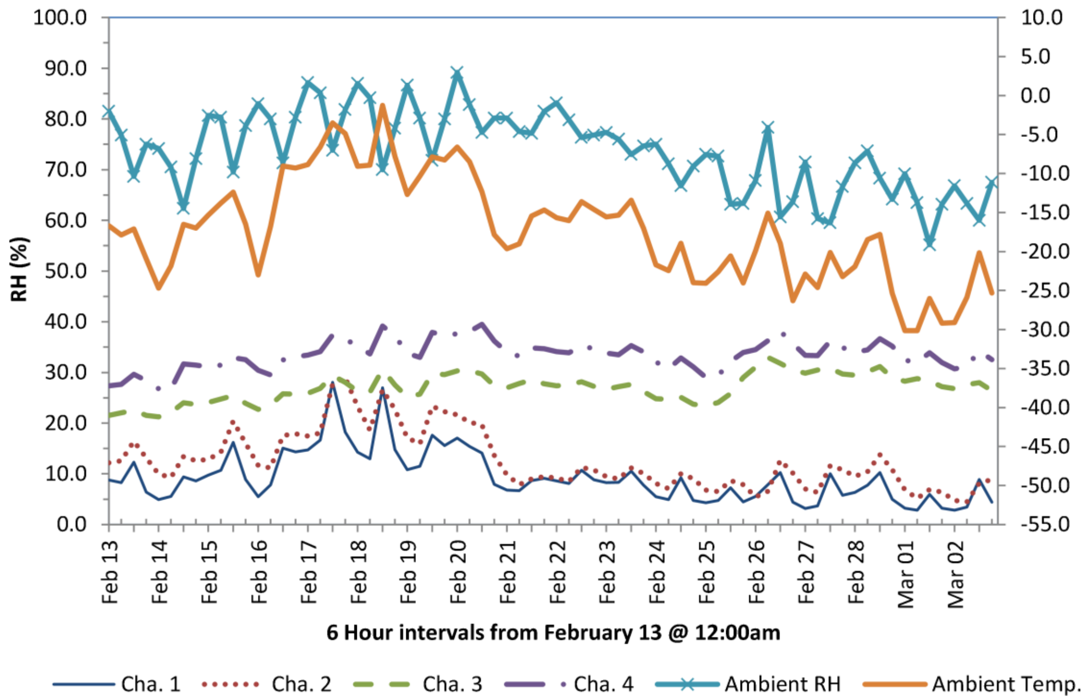

Figure 4.1-14: Ambient outdoor and inner RH in fiberglass bldg. (Feb. 13-Mar. 2)

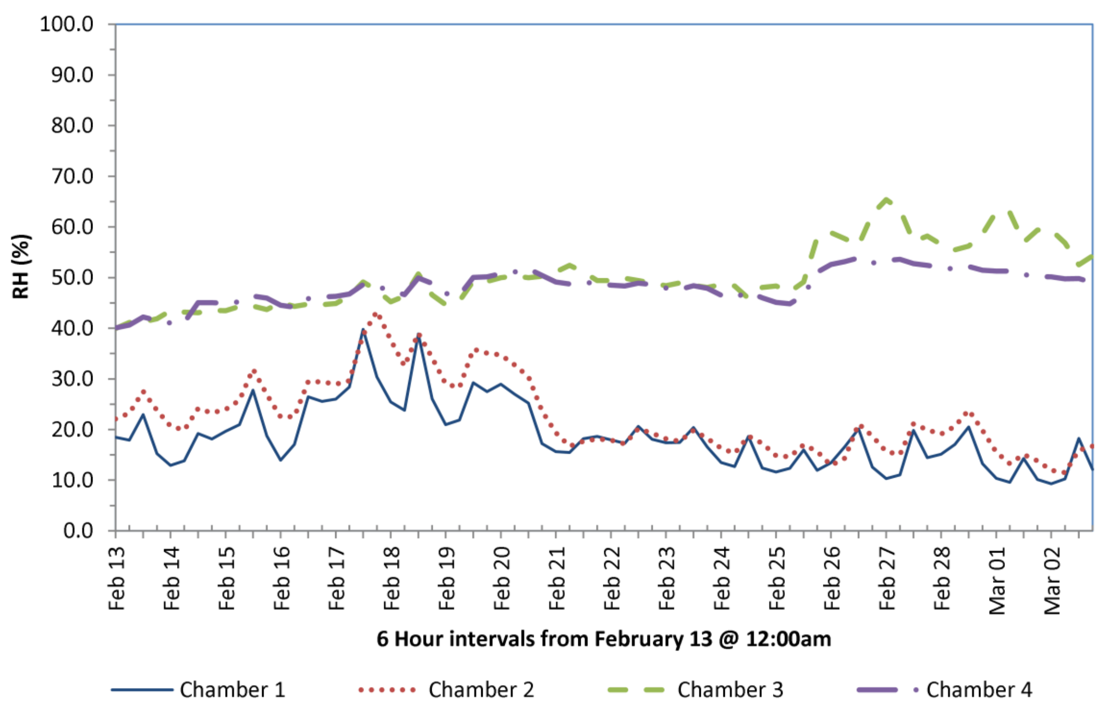

Figure 4.1-15: Middle RH in fiberglass bldg. (Feb. 13-Mar. 2)

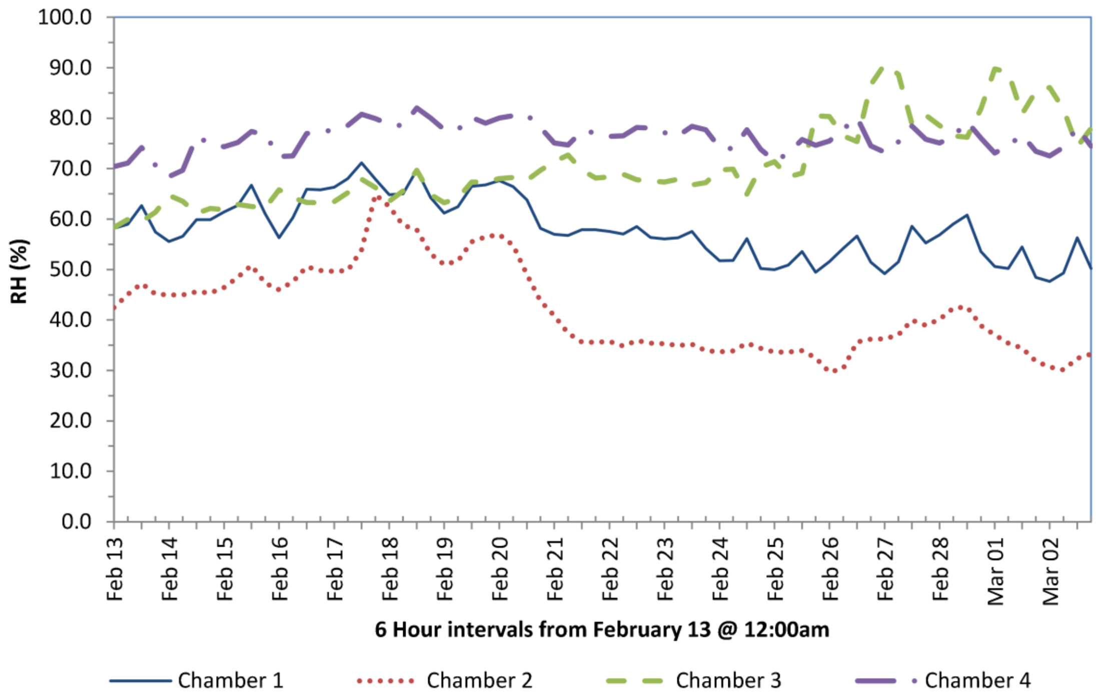

Figure 4.1-16: Outer RH in fiberglass bldg. (Feb. 13-Mar. 2)

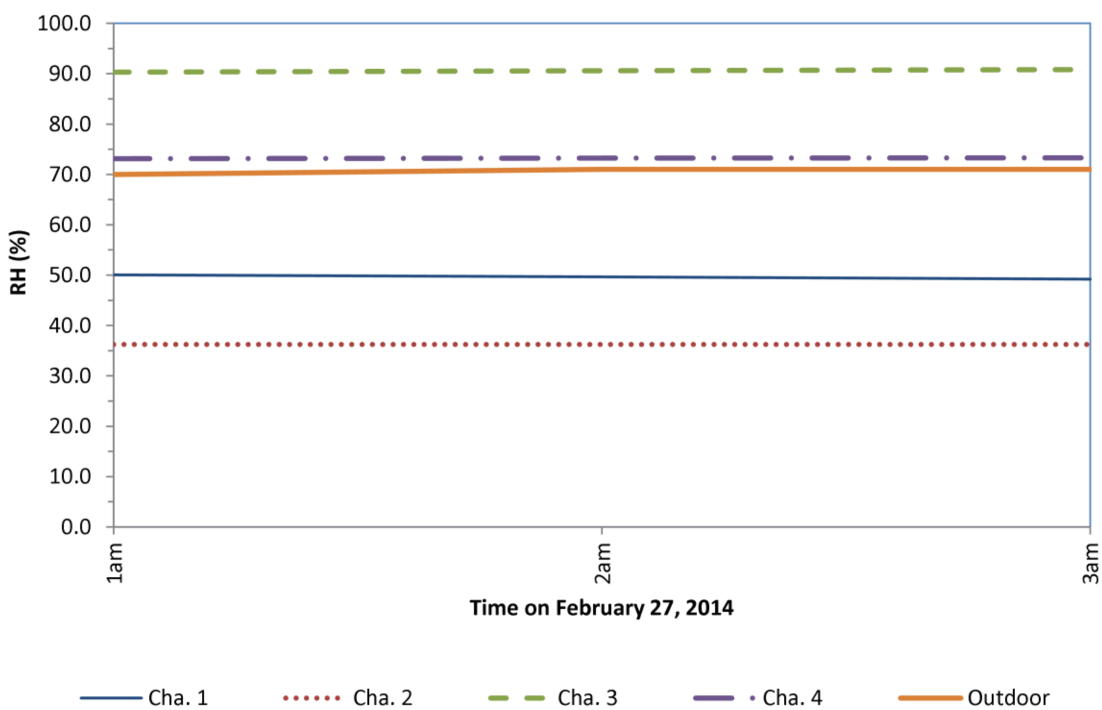

Figure 4.1-17: Outer and ambient outdoor RH on Feb. 27th (between 12am and 3am)

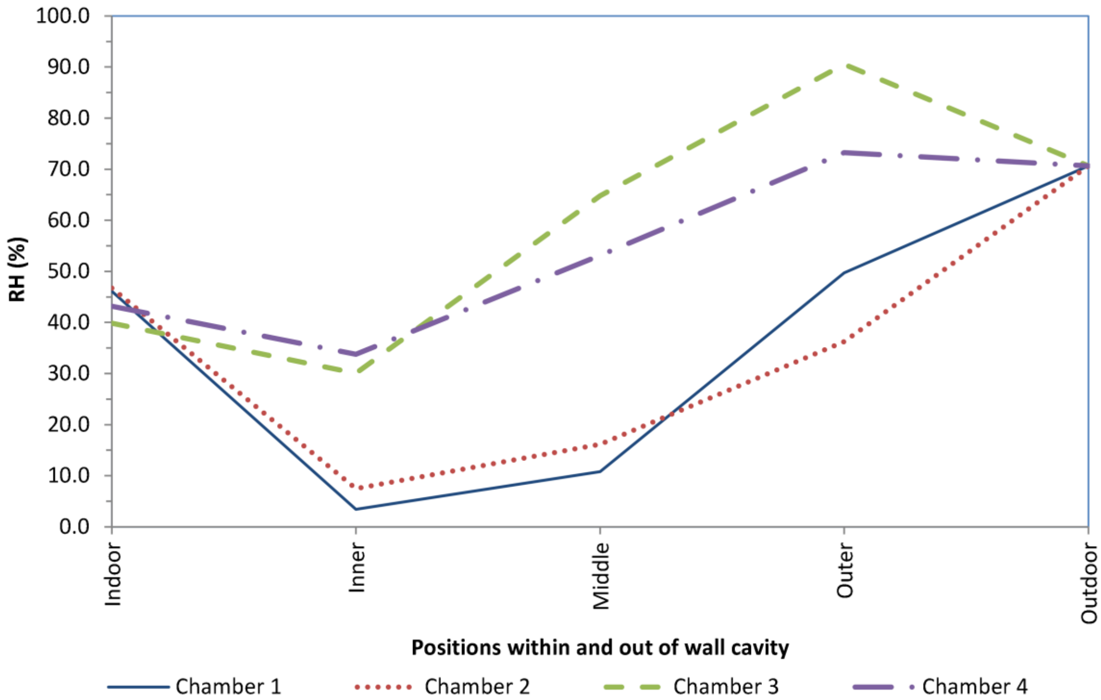

Figure 4.1-18: Average RH profile in fiberglass bldg. on Feb. 27th (between 12am and 3am)

Table 4.1-3: Average indoor, outer and outdoor RH in fiberglass bldg. (Feb. 26-27)

	Relative Humidity (%)								
	Indoor RH				Outer RH				Outdoor RH
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	45	45	39	42	49	30	75	73	60
Maximum	46	47	41	44	59	40	91	80	78
Average	46	46	40	43	54	36	82	76	66

4.1.2.2 Temperature gradient

The indoor temperature of all chambers was maintained at 20±0.5˚C (Figure 4.1-19). The ambient outdoor temperature fluctuated between -26˚C and -15˚C over the test period, with an average of -21˚C. The outer temperature of the wall cavity followed a similar pattern as the ambient outdoor in all four chambers (Figure 4.1-20).

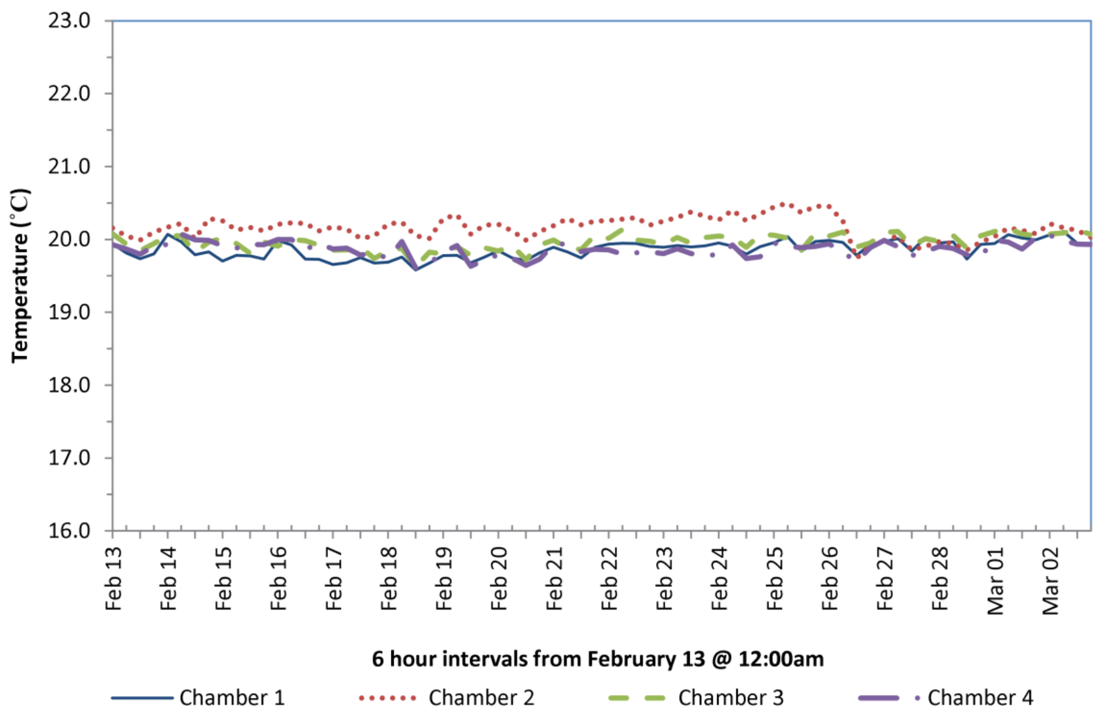

Figure 4.1-19: Indoor temperature in fiberglass bldg. (Feb. 13-Mar. 2, 2014)

4.1.2.2.1 Case 1 – Effect of vapour barrier

Data in Table 4.1-4 shows that the average outer wall cavity temperature for a non-consistent vapour barrier in chambers 3 and 4 was -9˚C and 0˚C, which was 5˚C higher than chambers 1 and 2, respectively. Therefore, as it was seen in Figure 4.1-20 and the above results, the vapour barrier had no significant effect on the outer temperatures of the wall section regardless of adding rigid insulation or not. A similar result was seen over the snapshot as well. For instance, Figure 4.1-21 represents 5˚C increase of the average outer temperature on Feb. 27^{th} (between 12am and 3am) by having non-consistent vapour barrier.

4.1.2.2.2 Case 2 – Impact of external rigid insulation

According to Figure 4.1-20 and data in Table 4.1-4, the average outer temperature of wall cavity was -5˚C and 0˚C in chambers 2 and 4, respectively, and 9˚C higher than chambers 1 and 3 due to adding external rigid insulation. Moreover, the impact of the addition of rigid insulation was considerable on the minimum outer temperature over the test period, which resulted in 12˚C higher temperature at -10°C and -3°C in chambers 2 and 4, respectively. Likewise, Figure 4.1-21 illustrates that the average and minimum outer temperature in wall cavity were considerably higher (approximately 12°C higher) in the chambers with rigid insulation than others on Feb. 27^{th} (between 12am and 3am).

4.1.2.2.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

According to Figure 4.1-20 and data in Table 4.1-4, the average outer temperature rose considerably to 0˚C (14˚C higher than benchmark chamber 1) by having non-consistent vapour barrier condition associated with external rigid insulation (chamber 4). It was also seen that the minimum outer temperature increased significantly by 19˚C to -3˚C in chamber 4. In addition, similar results to test period could be seen on Feb. 27th between 12am and 3am (Figure 4.1-21).

Overall, comparing the above three cases it is evident that the average outer temperature increased considerably with the addition of rigid insulation on the exterior side of the wall assembly. Compromising the vapour barrier did not have the same impact as rigid insulation in terms of temperature. However, considering both non-consistent vapour barrier and rigid insulation caused significant increase in the average outer temperature compared to baseline chamber 1 over the test period.

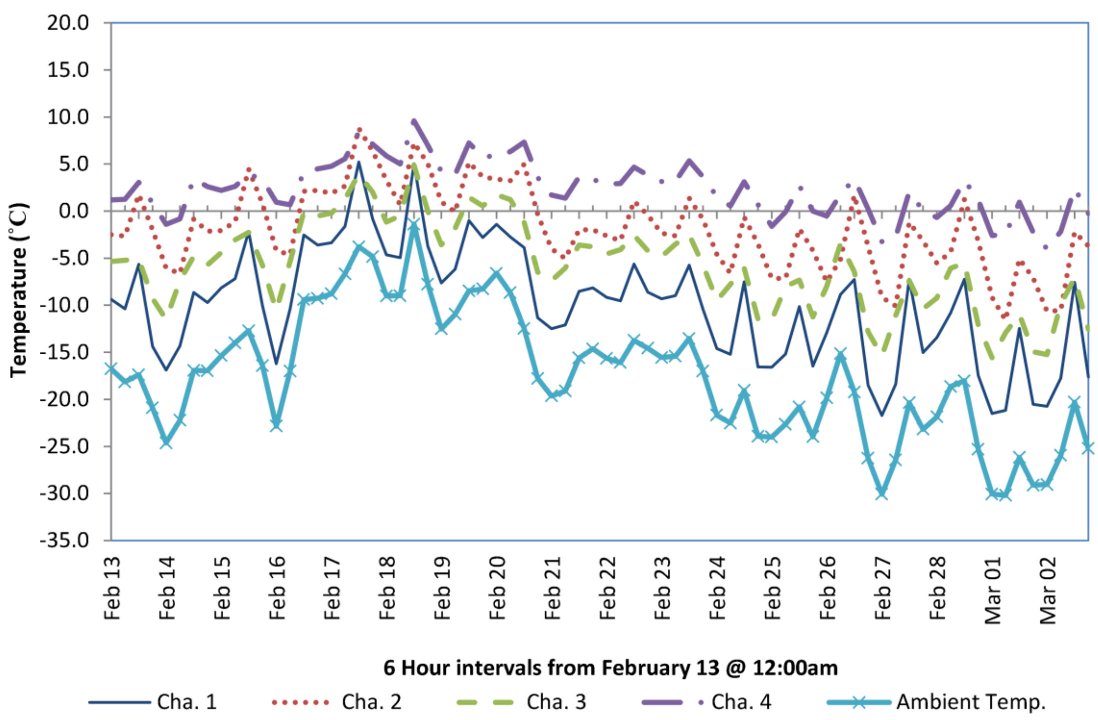

Figure 4.1-20: Outer temperature in fiberglass bldg. (Feb. 13-Mar. 2)

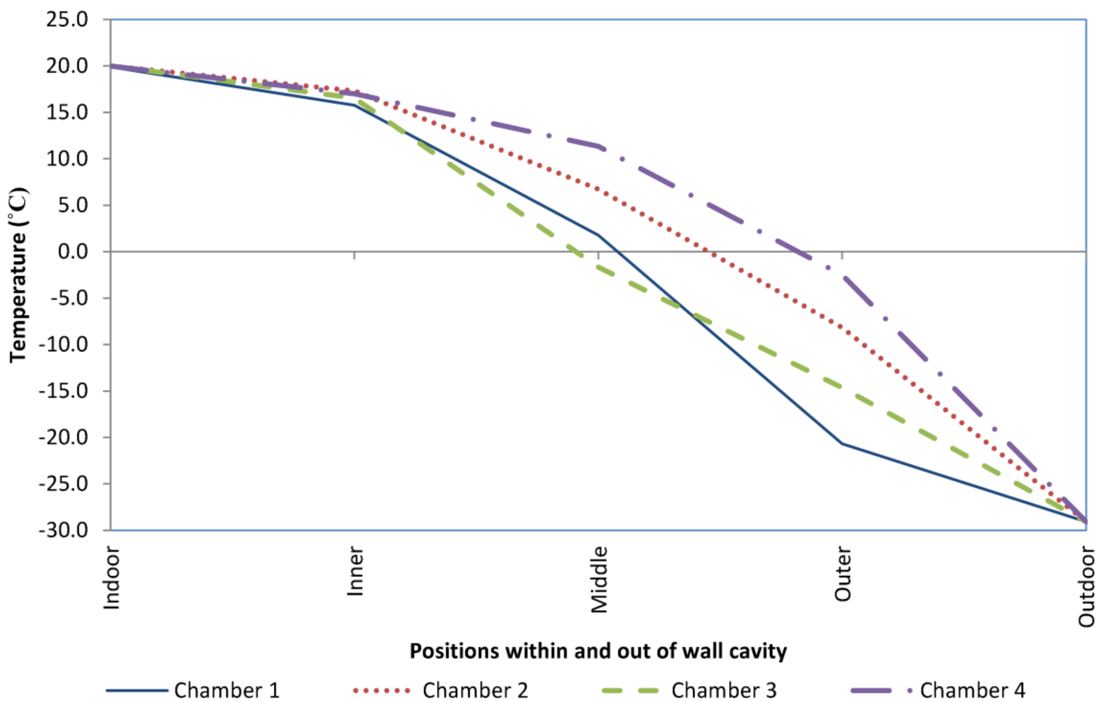

Figure 4.1-21: Average temperature profile in fiberglass bldg. on Feb. 27th (between 12am and 3am)

Table 4.1-4: Average indoor, outer and outdoor temp. in fiberglass bldg.(Feb. 26-27)

	Temperature (°C)								
	Indoor Temp.				Outer Temp.				Outdoor Temp.
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	19.8	19.7	19.9	19.7	-22	-10	-15	-3	-26
Maximum	20.0	20.5	20.1	20.0	-7	2	-3	3	-15
Average	19.9	20.0	20.0	19.9	-14	-5	-9	0	-21

4.1.2.3 Heat transfer

Figure 4.1-22 illustrates that the heat flux density in all four different wall assemblies followed an inverse pattern with respect to the ambient outdoor temperature.

4.1.2.3.1 Case 1 – Effect of vapour barrier

Figure 4.1-23 shows that in the chambers without rigid insulation the heat flux density considering the non-consistent vapour barrier (chamber 3) was 12.3 W/m² and 4.3 W/m² higher than chamber 1 (with vapour barrier), while in the chambers with rigid insulation that value was 6.3 W/m² in chamber 4 and 1.6 W/m² higher than chamber 2 (with vapour barrier). Similarly, according to Figure 4.1-24, the average heat flux density on Feb. 27th (between 12am and 3am) in chamber 3 (13.8 W/m²) and chamber 4 (7.6 W/m²) was 4.7 W/m² and 2.2 W/m² higher than chambers 1 and 2, respectively.

Therefore, it was seen from the above results that non-consistent vapour barrier increased the amount of heat flux density by 54% in the chambers without rigid insulation over the test period, while with the addition of external rigid insulation, this impact was a 34% increase of heat flux density.

4.1.2.3.2 Case 2 – Impact of external rigid insulation

According to Figure 4.1-23, the average heat flux density through the wall assembly in chamber 2 (4.7 W/m²) was 3.3 W/m² lower than chamber 1 with the addition of the external rigid insulation to the consistent vapour barrier chamber. However, that value in the chamber with non-consistent vapour barrier (chamber 4) was 6.3 W/m² and considerably lower than chamber 3 (6 W/m² lower) just by adding rigid insulation. Likewise, Figure 4.1-24 illustrates that the average heat flux density in chamber 2 (5.4 W/m²) was 3.7 W/m² lower than chamber 1 on Feb. 27th between 12am and 3am. This value in chamber 4 (7.6 W/m²) was 6.2 W/m² less than chamber 3.

Overall, both the snapshot and test period results illustrate that the effect of adding rigid insulation was considerable on decreasing the amount of heat flux density in both cases (including consistent and non-consistent vapour barriers). However, this impact was greater in non-consistent vapour barrier chambers (49% decrease) than the consistent vapour barrier (41% decrease) over the test period.

4.1.2.3.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

According to Figure 4.1-23, having both non-consistent vapour barrier conditions associated with external rigid insulation (chamber 4) changed the average heat flux density through wall assembly from 8 W/m² (chamber 1) to 6.3 W/m². Also, on Feb. 27th (snapshot), the average heat flux density was 7.6 W/m² in chamber 4 and 1.5 W/m² lower than chamber 1 (Figure 4.1-24).

It was evident that although the addition of rigid insulation had a considerable effect on reducing the heat flux, having a non-consistent vapour barrier increased the heat flux density. Therefore, the combination of both (chamber 4) resulted just 21% decrease in heat flux density compared to baseline chamber 1 over the test period. Overall, in terms of heat flux, not only the addition of rigid insulation but also having consistent vapour barrier had considerable impact on reducing heat flux density, in other words, the above results show that heat flux density in chamber 2 was 62% less than the value in chamber 3.

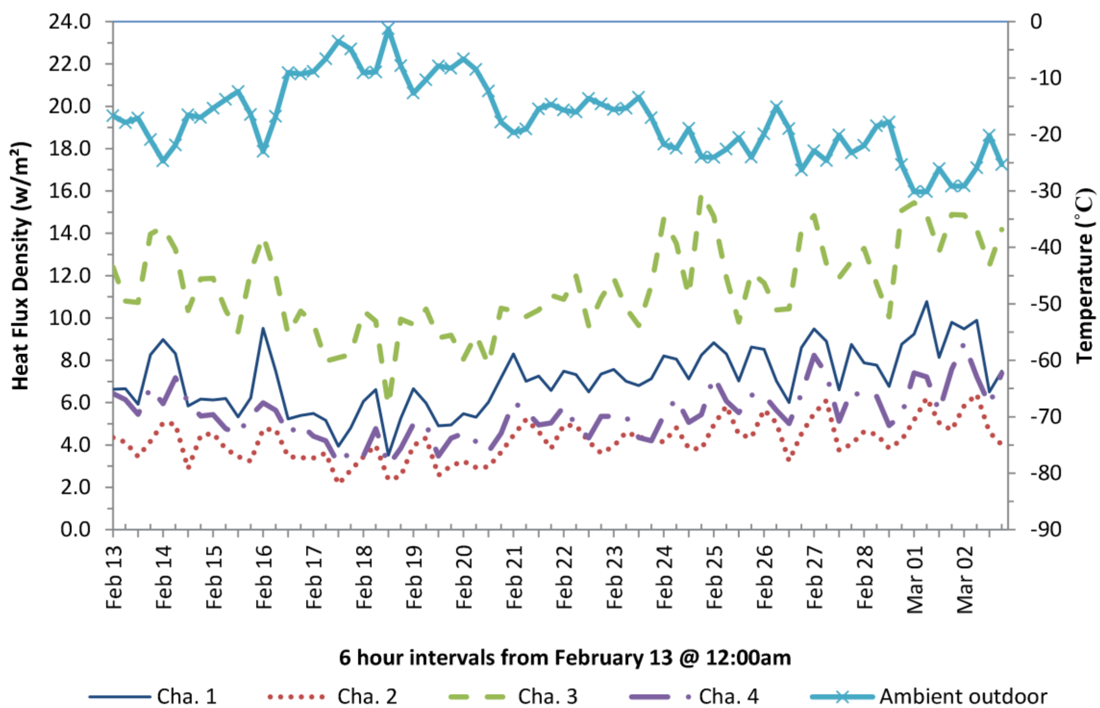

Figure 4.1-22: Heat flux density and ambient outdoor temperature in fiberglass bldg. (Feb. 13-Mar. 2)

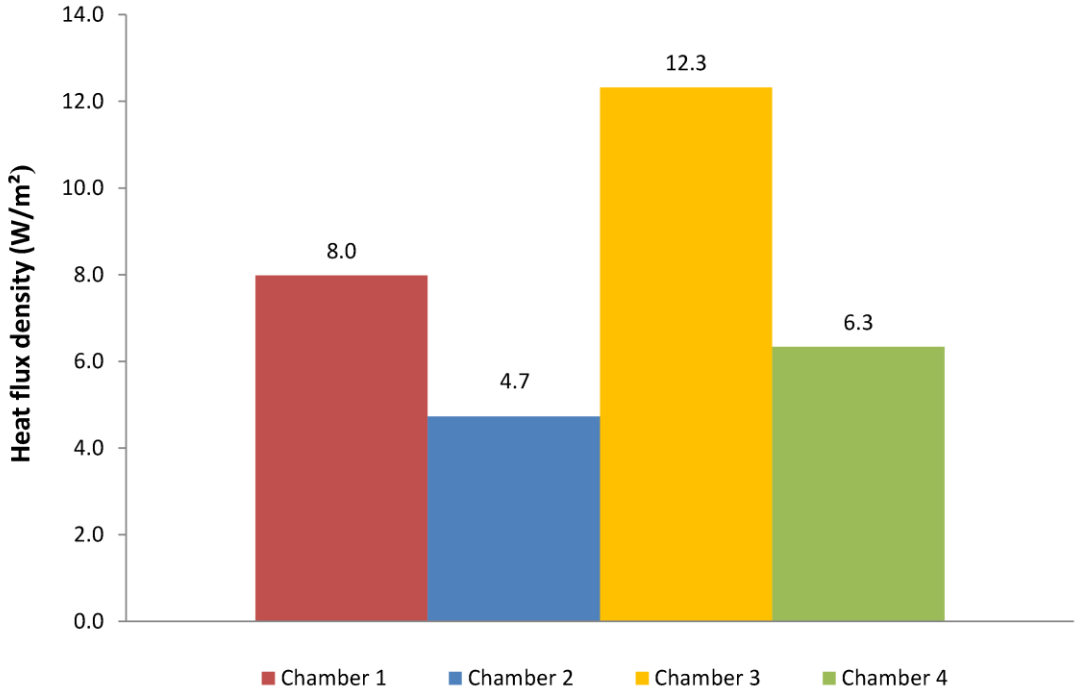

Figure 4.1-23: Average heat flux density in fiberglass bldg. (Feb. 26-27, 2014)

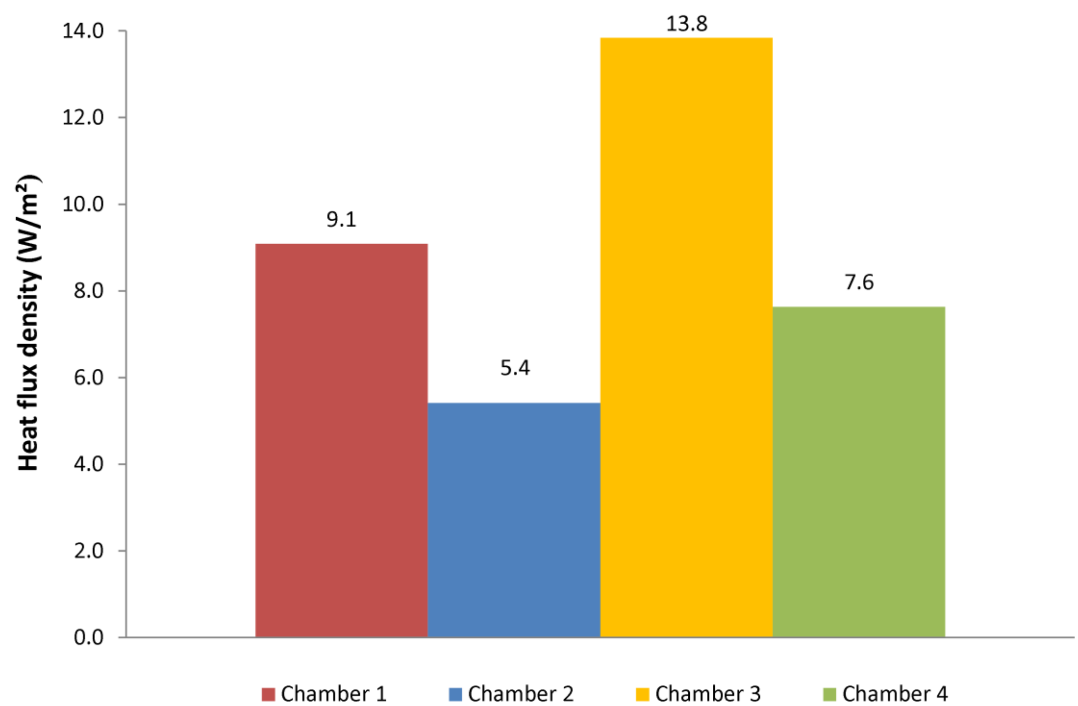

Figure 4.1-24: Average heat flux density in fiberglass bldg. on Feb. 27th (between 12am and 3am)

4.1.3 High level of indoor relative humidity

The third test stage was over March 4-16, 2014. As illustrated in Figure 4.1-25, it was seen that after three days of starting the high RH test, steady-state conditions inside the chambers were established by March 7th and lasted until the end of the test period on March 16th. All of the values (average, minimum and maximum) and comparisons presented were considered over the steady-state conditions from March 7–16, 2014, which will be called "test period" in following sections.

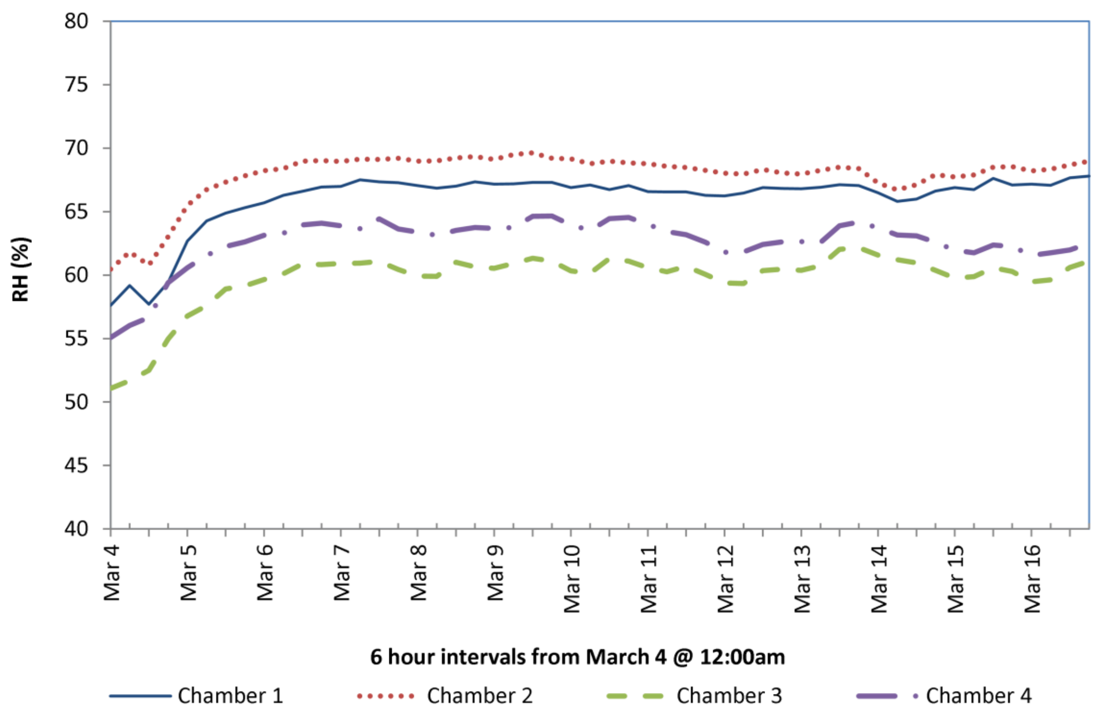

Figure 4.1-25: Indoor RH in fiberglass bldg. (March 4-16, 2014)

In addition to the overall trends, two specific days were selected to provide snapshots of the performance; one was on March 14th between 12am and 3am with high outdoor RH (average 81%) associated with high external ambient temperature (-2˚C), which caused high partial vapour pressure over the test period. The second snapshot, on the other hand, was on March 16th between 12am and 3am with high outdoor RH (average 79%) but associated with low ambient temperature (-25˚C), which created low partial vapour pressure. The data were retrieved and averaged based on 15-minute intervals between 12am and 3am to eliminate the effect of solar radiation on wall assemblies. Moreover, the outer RH (within the wall cavity) between 12am and 3am on both snapshots (March 14th and 16th) were almost consistent in each of the four chambers.

4.1.3.1 Moisture migration

The same salt solution was used in all four chambers to keep the relative humidity at a specific level. Based on the data in Table 4.1-5, the average indoor RH in the chambers 3 and 4 (with non-consistent vapour barriers) dropped just 6% compared to chambers 1 and 2 (with consistent vapour barriers), respectively. It is proposed this happened due to moisture escaping through the wall cavity. It was seen that indoor RH was approximately 68±2% for the chambers with consistent vapour barriers and 62±3% for the chambers with non-consistent vapour barriers, while the outdoor RH fluctuated between 59% and 94% over the test period.

Figures 4.1-26, 4.1-27 and 4.1-28 show that chambers 1 and 2 (with consistent vapour barriers) had considerably lower RH levels than the others without consistent vapour barriers within the wall cavities (inner, middle and outer locations). It was clearly seen that overall, the RH levels increased from inside to outside of the wall cavity (Figures 4.1-26, 4.1-27 and 4.1-28).

4.1.3.1.1 Case 1 – Effect of vapour barrier

According to Figure 4.1-28 and Table 4.1-5, the average outer RH of wall cavity in the benchmark chamber 1 with the intact wall assembly was 67% (74% maximum outer RH). The average RH was, however, 23% higher at 90% (98% maximum RH) in chamber 3 in the same position by simply having a non-consistent vapour barrier over the test period. The effect of compromising vapour barriers in the chamber consisting rigid insulation (chamber 4) exhibits similar behaviour with a 35% increase to 88% average outer RH of wall cavity (92% maximum outer RH) compared to chamber 2 with 53% average outer RH (62% maximum outer RH).

Figures 4.1-29 and 4.1-30 illustrate the average outer RH (without rigid insulation) in chamber 3 (88%) was 20% greater than chamber 1 (68%) on March 14th (between 12am and 3am) with the high outdoor partial vapour pressure. Similarly, the same snapshot showed that in the chamber with rigid insulation the average outer RH of wall cavity considering non-consistent vapour barrier (90%) was 40% higher than that with consistent vapour barrier (50%).

Overall, it was seen that the snapshot with high outdoor partial vapour pressure (March 14th) had a similar pattern as the average over the test period (March 7th-14th). In fact, making non-consistent vapour barrier in both chambers (with and without rigid insulation) increased the amount of the average outer wall cavity RH to just about 90% over the test period.

4.1.3.1.2 Case 2 – Impact of external rigid insulation

According to Figure 4.1-28 and Table 4.1-5, in the chambers with continuous vapour barriers, the average outer wall cavity RH with rigid insulation was 53% and 14% lower than without rigid insulation (67% RH). On the other hand, putting rigid insulation in the chambers with non-consisting vapour barriers (chamber 4) did not impact considerably on the outer RH of wall cavity.

Also, Figures 4.1-29 and 4.1-30 illustrate the average outer RH of the wall cavity (with consistent vapour barrier) in chamber 2 (50%) was 18% lower than chamber 1 (68%) by adding rigid insulation on March 14th (between 12am and 3am) with a high outdoor partial vapour pressure. The addition of rigid insulation in the chamber with non-consistent vapour barrier did not show any significant effect on the outer RH.

4.1.3.1.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

According to Figure 4.1-28 and data in Table 4.1-5, it can be seen that the average outer RH in chamber 4 went up to 88% by the addition of rigid insulation and having non-consistent vapour barrier, which was 21% higher than baseline chamber 1 with 67% RH.

Similarly, Figures 4.1-29 and 4.1-30 show the comparable results on March 14th (between 12am and 3am) as the above comparison over the test.

Overall, when the comparisons above were considered, some unexpected results of the outer wall cavity RH in chamber 1 were seen. Apart from the higher RH value of the outer wall cavity in chamber 1 over the test period and snapshots, the RH results for the rest were consistent.

The following comparisons were made in order to clarify the problem:

- According to Figure 4.1-25, chambers without consistent vapour barriers had the lowest amount of indoor RH, which makes sense, since indoor humidity could escape easier through wall assembly in this case. Moreover, chambers with rigid insulation had slightly higher indoor RH values compared to chambers without rigid insulation due to having extra external layer which retarded the water vapour to go out from wall assembly. Therefore, indoor RH of chamber 1 was in a logical order compared to other chambers.
- Figures 4.1-26 and 4.1-27 show that the inner and the middle RH of chamber 1 were slightly lower (average RH over the test period was 5% lower) than the values in the same locations in chamber 2. However, Figure 4.1-28 illustrates that the outer RH of chamber 1 was higher than chamber 2 (average outer RH over the test period was 14% higher). Chambers 3 and 4, in addition, showed a similar RH pattern in the middle and outside of the wall cavity. In addition, RH increased about 18% from middle to outer position in each chambers (chambers 2 to 4), but this number jumped by 39% in chamber 1 from middle to outer position. Finally,

Figure 4.1-31 shows how outer RH in chamber 1 crossed the data line of chamber 2 in the graph and went higher than that from the middle to outside, which was not expected.

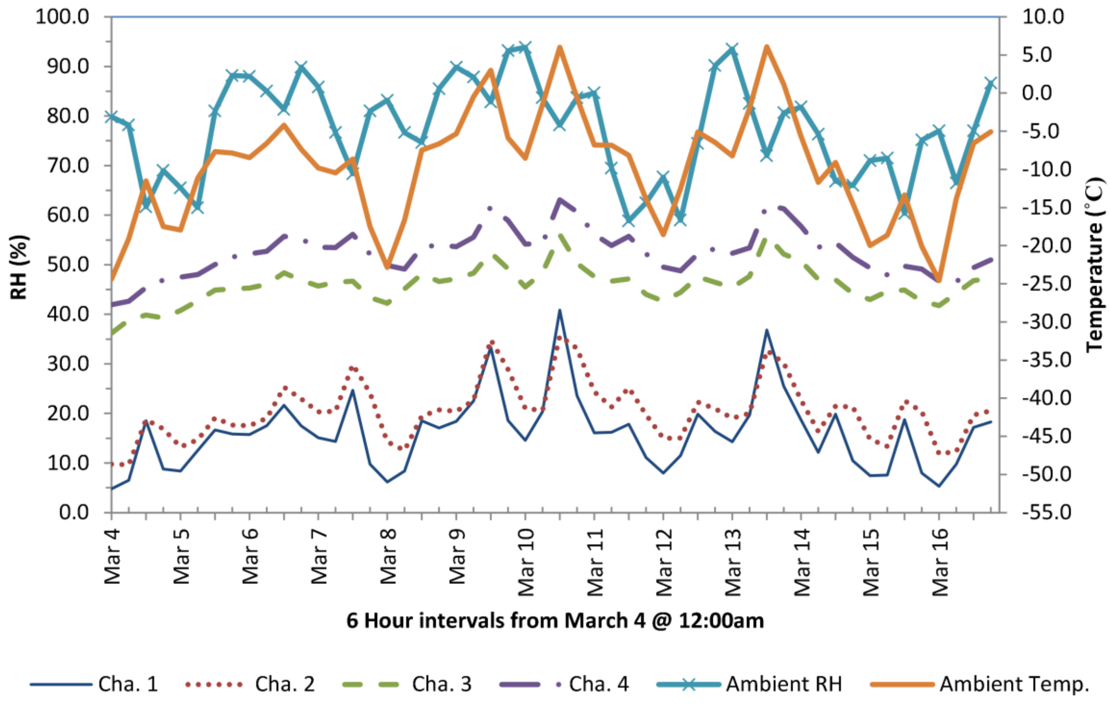

Figure 4.1-26: Ambient outdoor and inner RH in fiberglass bldg. (Mar. 4-16)

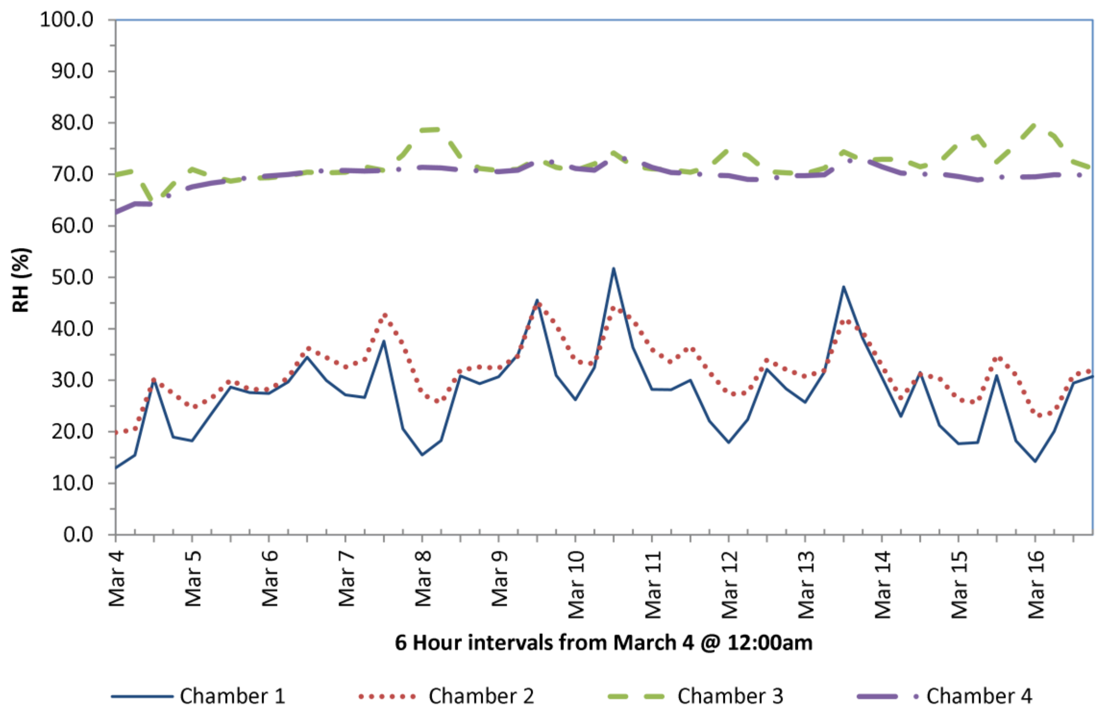

Figure 4.1-27: Middle RH in fiberglass bldg. (Mar. 4-16, 2014)

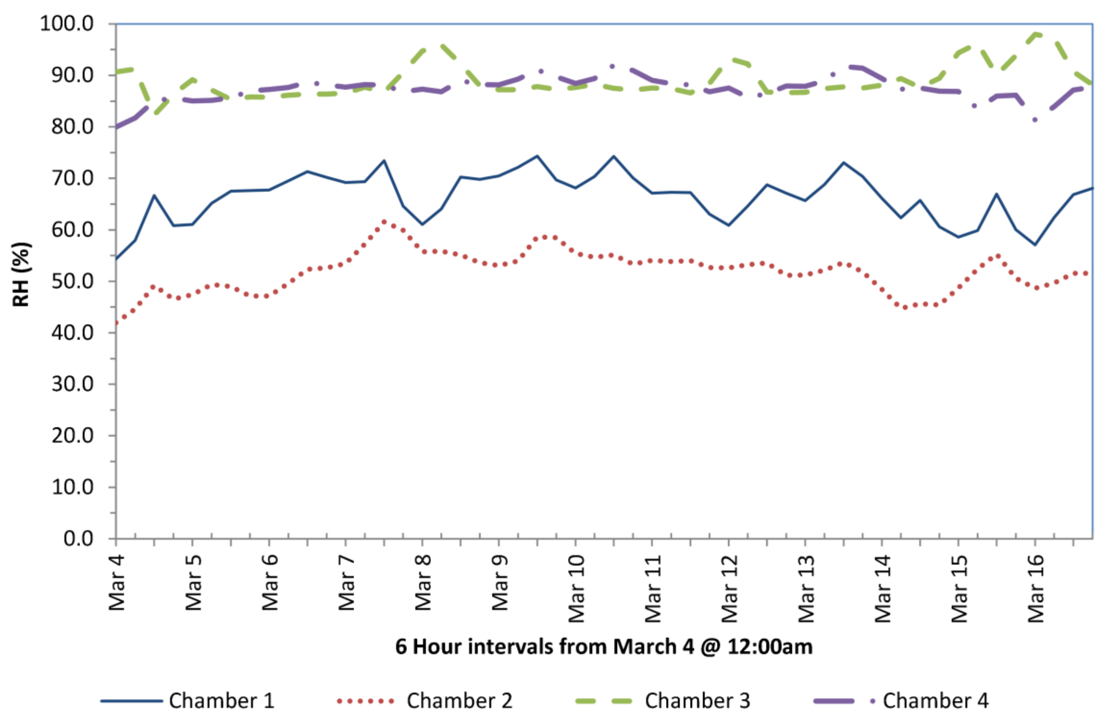

Figure 4.1-28: Outer RH in fiberglass bldg. (Mar. 4-16, 2014)

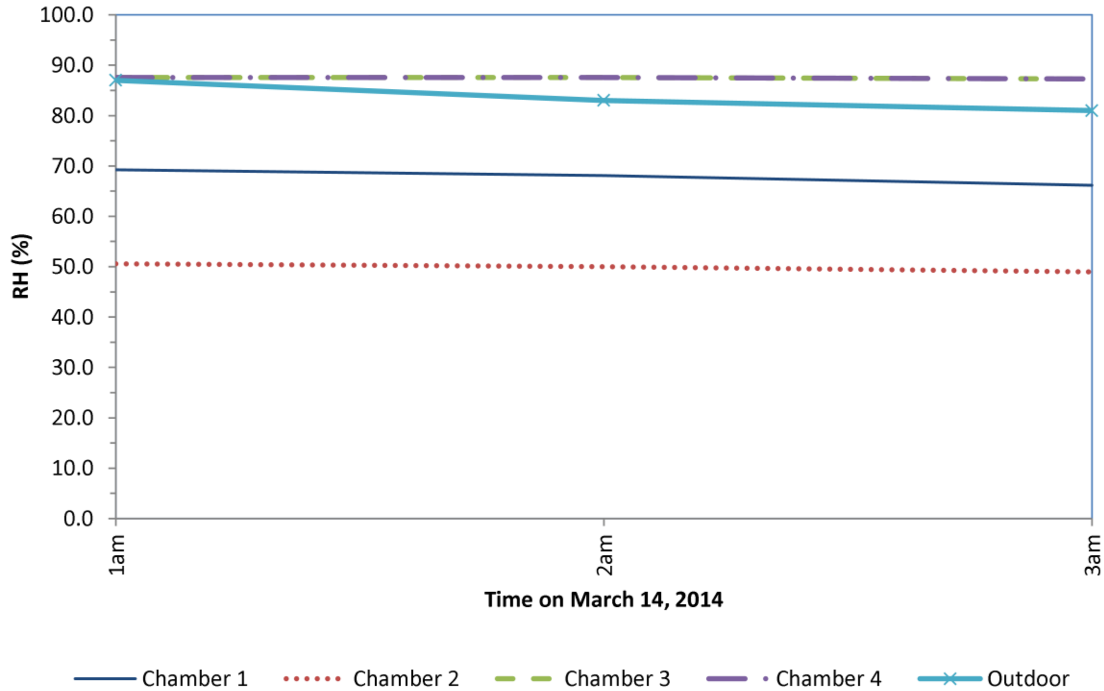

Figure 4.1-29: Outer and ambient outdoor RH in fiberglass bldg. on Mar. 14th (between 12am and 3am)

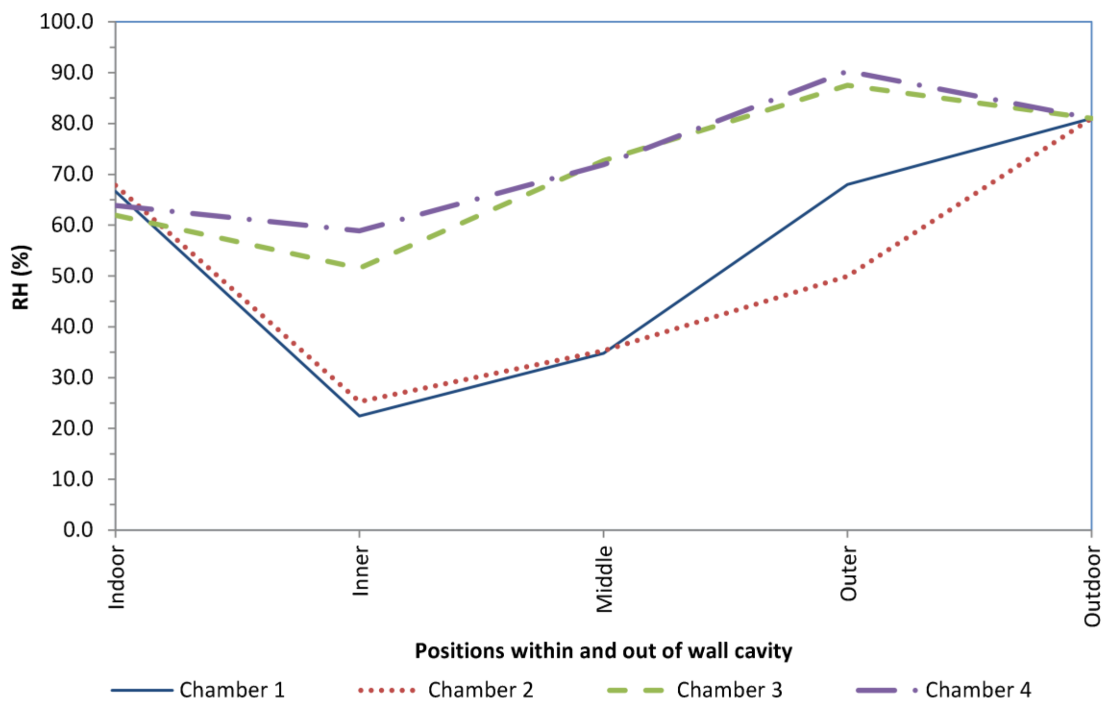

Figure 4.1-30: Average RH profile in fiberglass bldg. on Mar. 14th (between 12am and 3am)

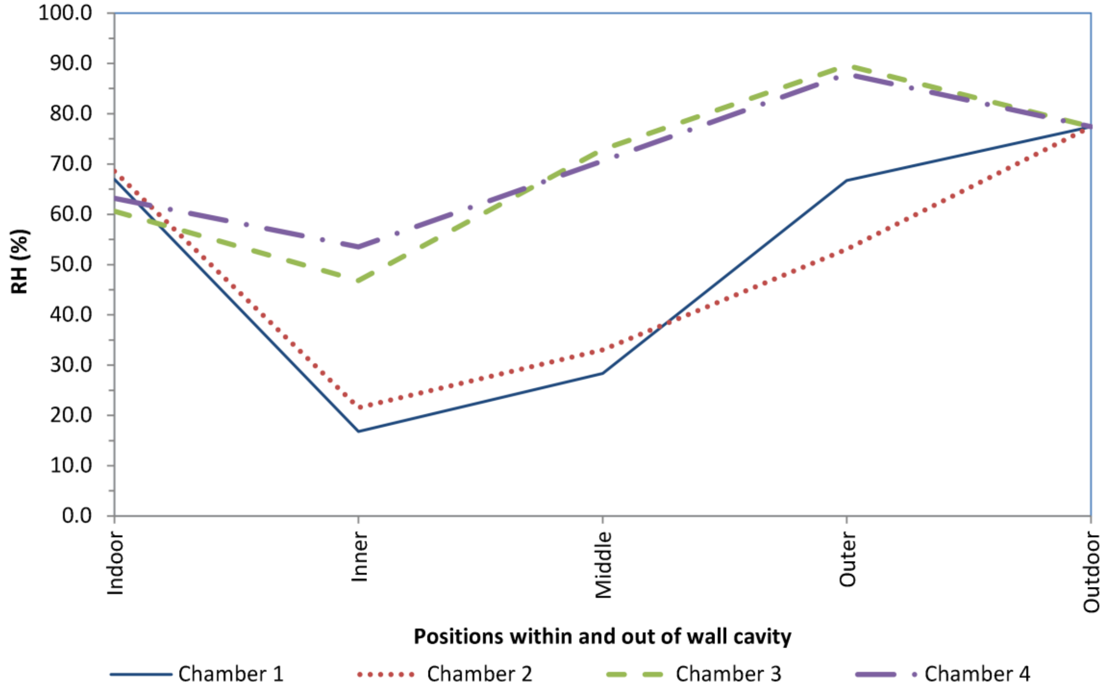

Figure 4.1-31: Average RH profile in fiberglass bldg. (Mar. 7-16, 2014)

Table 4.1-5: Average indoor, outer and outdoor RH in fiberglass bldg. (Mar. 7-16)

	Relative Humidity (%)								
	Indoor RH				Outer RH				Outdoor RH
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	66	67	59	62	57	45	87	81	59
Maximum	68	70	62	65	74	62	98	92	94
Average	67	69	61	63	67	53	90	88	77

4.1.3.2 Temperature gradient

The indoor temperature of all chambers was maintained at 20±0.5˚C (Figure 4.1-32). The ambient outdoor temperature fluctuated between -25˚C and +6˚C over the test period, with an average of -9˚C. The outer temperature of the wall cavity followed a similar pattern as ambient outdoor in all four chambers (Figure 4.1-33). As mentioned in section 4, three cases will be compared in the following subsections.

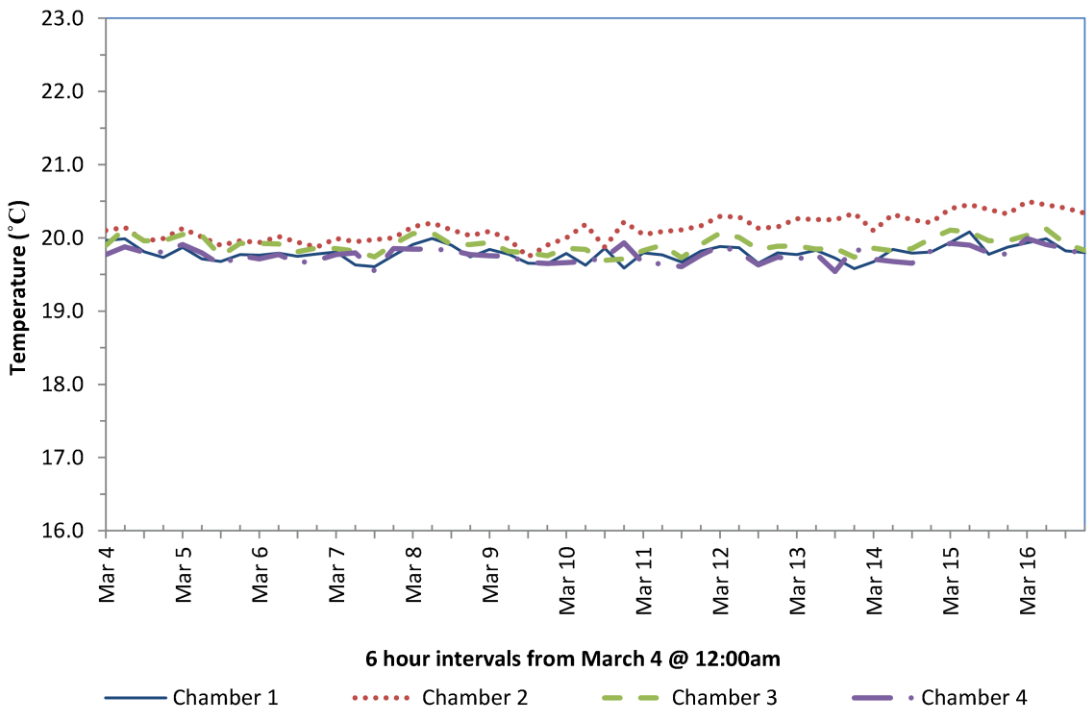

Figure 4.1-32: Indoor temperature in fiberglass bldg. (Mar. 4-16)

4.1.3.2.1 Case 1 – Effect of vapour barrier

Table 4.1-6 shows that the average outer wall cavity temperature for a non-consistent vapour barrier in chambers 3 and 4 was 0˚C and 7˚C (just 3˚C higher than chambers 1 and 2, respectively). Therefore, as it was seen in Figure 4.1-33 and the above results, the vapour barrier had no significant effect on the outer temperatures of the wall section regardless of adding rigid insulation or not. A similar result was seen over the two snapshots as well. For instance, Figure 4.1-34 represents 5˚C increase of the average outer temperature on March 16th (between 12am and 3am) by making non-consistent vapour barrier.

4.1.3.2.2 Case 2 – Impact of external rigid insulation

According to Figure 4.1-33 and the data in Table 4.1-6, the average outer temperature of wall cavity was 4˚C and 7˚C in chambers 2 and 4, respectively, and 7˚C higher than chambers 1 and 3 due to adding external rigid insulation. Moreover, the impact of putting rigid insulation was considerable on the minimum outer temperature over the test period, which resulted in 12˚C higher outer minimum temperature at -5°C and 0°C in chambers 2 and 4, respectively. Likewise, according to Figure 4.1-34, the average and minimum outer temperature in wall cavity were considerably higher in the chambers with rigid insulation than others on March 16th (between 12am and 3am).

4.1.3.2.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation)

This scenario is a comparison between the benchmark chamber 1 and chamber 4 with rigid insulation and non-consistent vapour barrier. According to Figure 4.1-33 and Table 4.1-6, having non-consistent vapour barrier condition associated with external rigid insulation (chamber 4) resulted average outer temperature to go up to 7˚C (10˚C higher than benchmark chamber 1). It was also seen that the minimum outer temperature jumped by 17˚C to 0˚C in chamber 4. In addition, according to Figure 4.1-34, similar results to the test period could be seen on March 16th between 12am and 3am.

Overall, comparing the above three cases it was evident that the average outer temperature increased considerably just by adding rigid insulation on exterior side of the wall assembly. Compromising the vapour barrier did not have the same impact as rigid insulation had on temperature in wall assemblies.

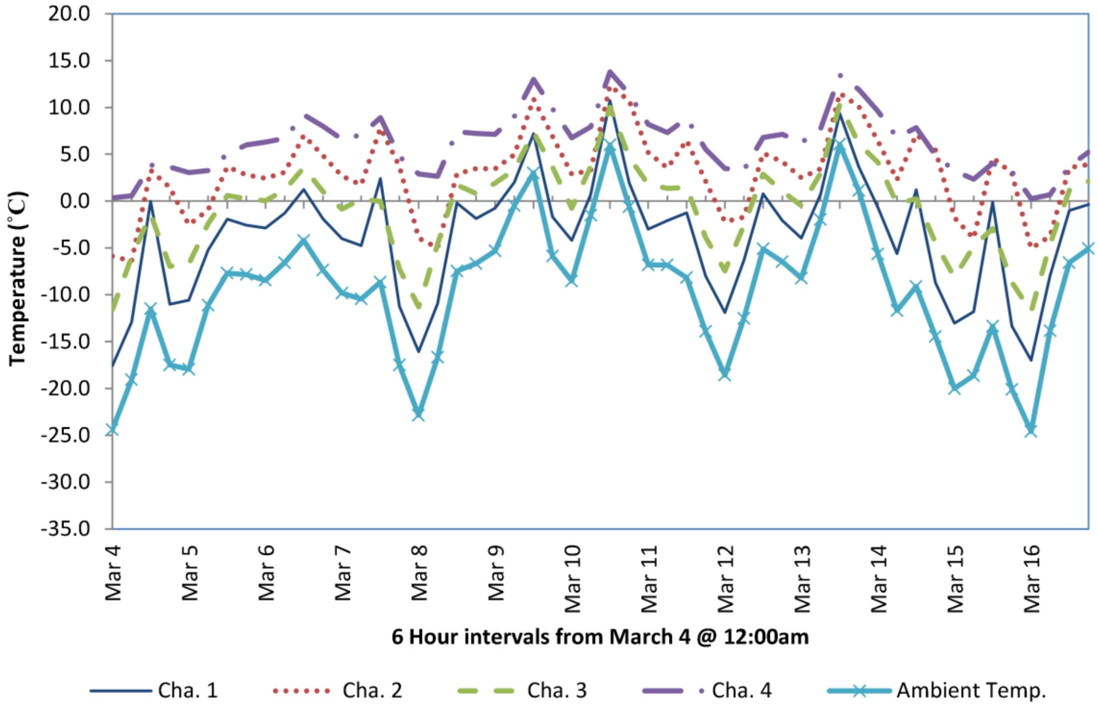

Figure 4.1-33: Outer temperature in fiberglass bldg. (Mar. 4-16)

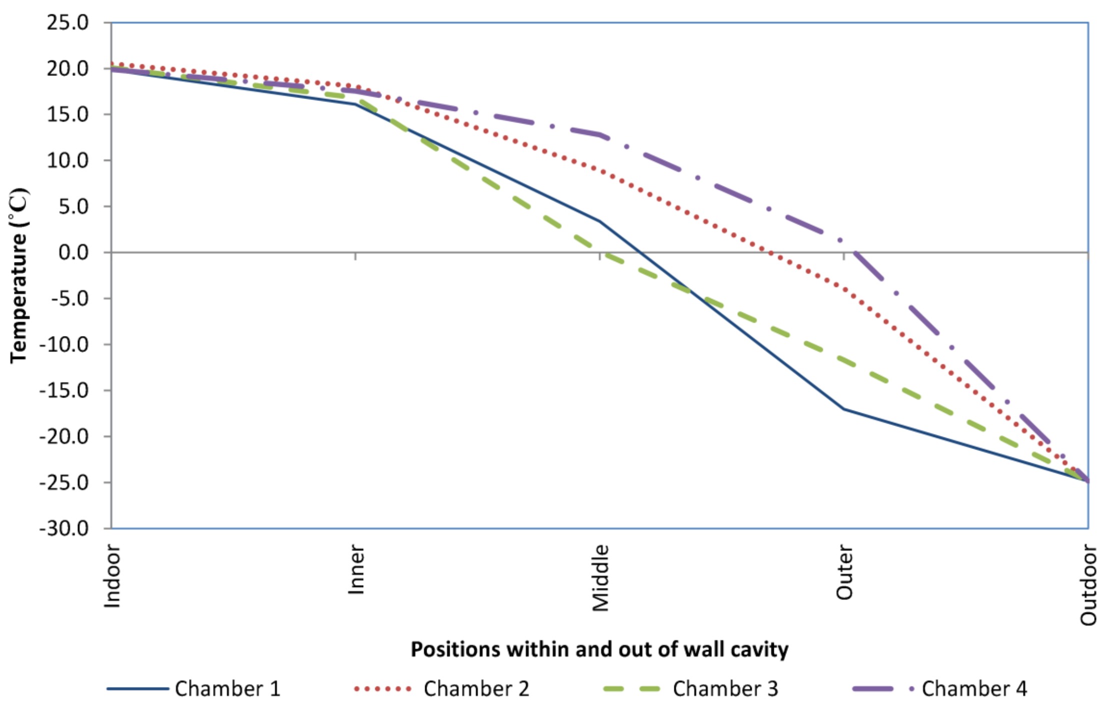

Figure 4.1-34: Average temperature profile in fiberglass bldg. on Mar. 16th (between 12am and 3am)

Table 4.1-6: Average indoor, outer and outdoor temp. in fiberglass bldg. (Mar. 7-16)

	Temperature (°C)								
	Indoor Temp.				Outer Temp.				Outdoor Temp.
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	19.6	19.7	19.7	19.5	-17	-5	-12	0	-25
Maximum	20.1	20.5	20.1	20.0	11	12	10	14	6
Average	19.8	20.2	19.9	19.8	-3	4	0	7	-9

4.1.3.3 Heat transfer

Figure 4.1-35 illustrates that the heat flux density in all four different wall assemblies followed an inverse pattern when compared to the ambient outdoor temperature. As mentioned previously, two snapshots were evaluated, but in terms of heat flux, the snapshot (March 16th) with low ambient outdoor (with the average ambient outdoor as low as -25˚C) resulted in higher heat flux density and a greater heat flux density differential between chambers than the other snapshot.

4.1.3.3.1 Case 1 – Effect of vapour barrier

Figure 4.1-36 shows that in the chambers without rigid insulation the heat flux density considering the non-consistent vapour barrier (chamber 3) was 8.2 W/m² and 2.9 W/m² higher than chamber 1 (with vapour barrier), while in the chambers with rigid insulation that value was 3.8 W/m² in chamber 4 and just 0.6 W/m² higher than chamber 2. In addition, according to Figure 4.1-37, the average heat flux density on March 16th (between 12am and 3am) in chamber 3 was 12.4 W/m² (4.9 W/m² higher than chamber 1), while the values in chambers 2 and 4 were close to each other and just about 5.3 W/m².

Therefore, it was seen from the above results that non-consistent vapour barrier increased the amount of heat flux density by 55% in the chambers without rigid insulation over the test period, while in the chambers with rigid insulation this impact was not considerable (just 19% increase).

4.1.3.3.2 Case 2 – Impact of external rigid insulation

According to Figure 4.1-36, the average heat flux density through wall assembly in chamber 2 (3.2 W/m²) was 2.1 W/m² lower than chamber 1 considering the same vapour barrier system and the addition of the external rigid insulation. However, that value in chamber with non-consistent vapour barrier (chamber 4) was 3.8 W/m² and considerably lower than chamber 3 (4.4 W/m² lower) just by adding rigid insulation.

Moreover, it was seen that the impact of rigid insulation was more outstanding on March 16th than March 14th. According to Figure 4.1-37, the average heat flux density in chamber 2 (5.4 W/m²) was 2.1 W/m² lower than chamber 1 on March 16th between 12am and 3am. This value in chamber 4 (5.1 W/m²) was 7.3 W/m² less than chamber 3.

Overall, both the snapshot and the test period results illustrate that the effect of putting rigid insulation was considerable in decreasing the amount of heat flux density in both cases (including consistent and non-consistent vapour barriers). However, this impact was greater in non-consistent vapour barrier chambers (54% decrease) than the consistent vapour barrier (40% decrease) over the test period.

4.1.3.3.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

This scenario is a comparison between the benchmark chamber 1 and chamber 4. According to Figure 4.1-36, having both non-consistent vapour barrier conditions associated with external rigid insulation layer (chamber 4) changed the average heat flux density through wall assembly from 5.3 W/m² (chamber 1) to 3.8 W/m². Also, on March 16th (snapshot), the average heat flux density was 5.1 W/m² in chamber 4 and 2.4 W/m² lower than chamber 1 (Figure 4.1-37).

It was seen that even though having a non-consistent vapour barrier increased the heat flux density, the addition of rigid insulation simultaneously compensated that negative effect and even caused 28% less heat flux density in chamber 4 than chamber 1 over the test period. Moreover, in terms of heat flux, not only the addition of rigid insulation but also having consistent vapour barrier had considerable effect on reducing heat flux density; in other words, the above results show that the heat flux density in chamber 2 was 61% less than the value in chamber 3.

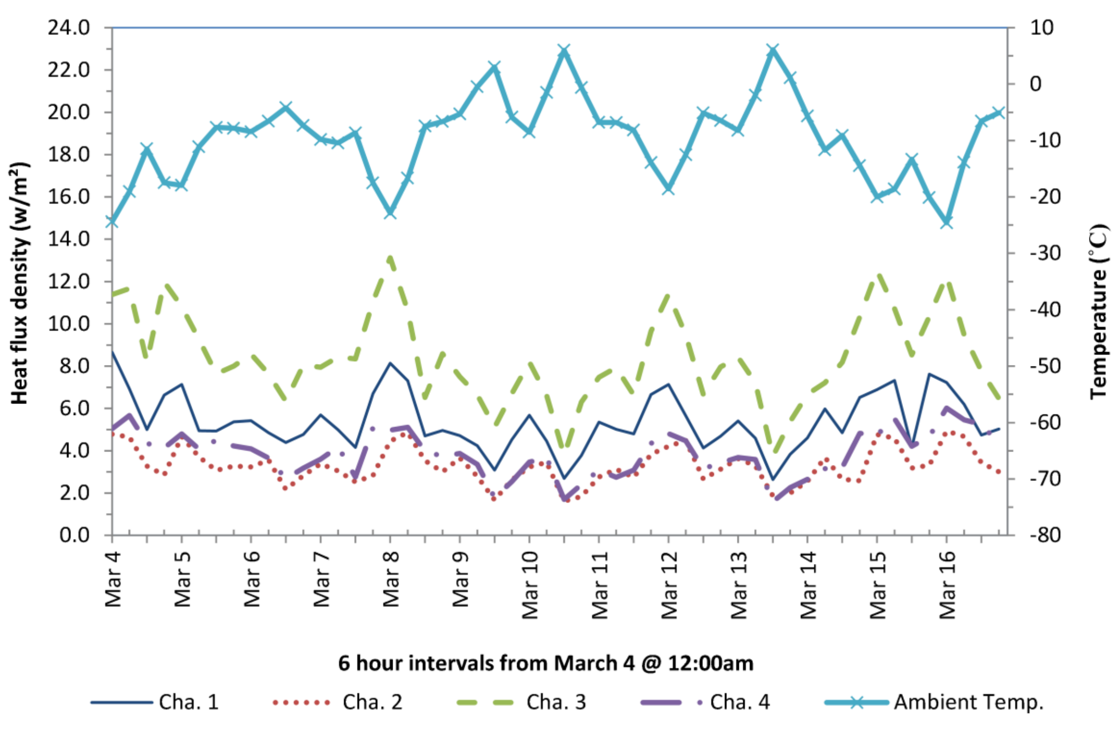

Figure 4.1-35: Heat flux density and ambient outdoor temperature in fiberglass bldg. (Mar. 4-16, 2014)

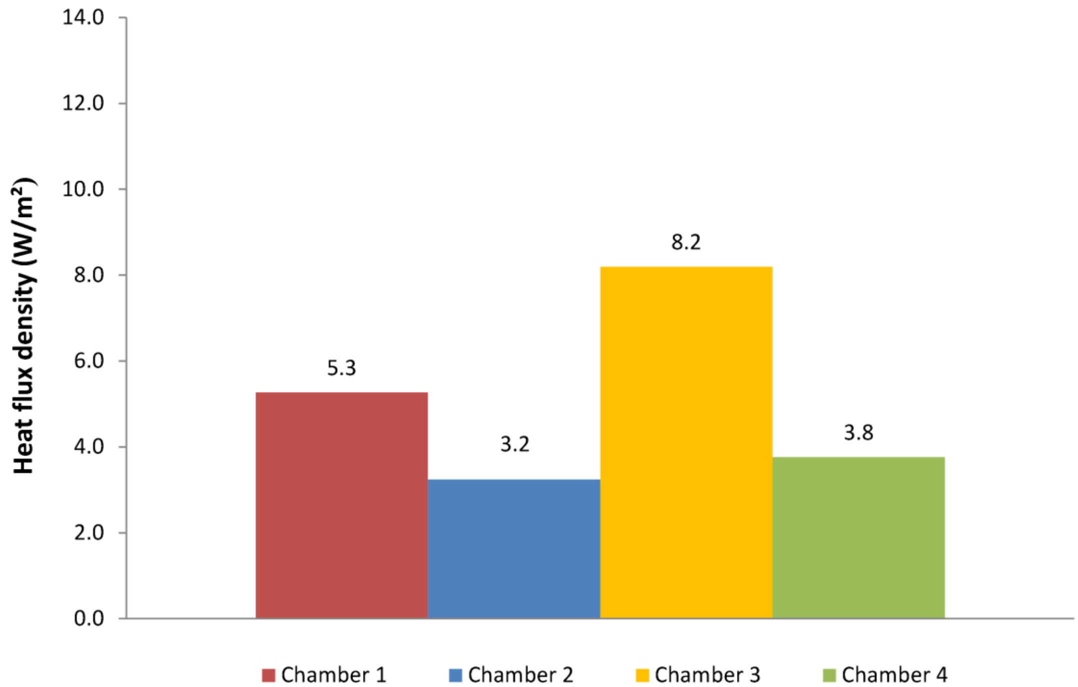

Figure 4.1-36: Average heat flux density in fiberglass bldg. (Mar. 7-16, 2014)

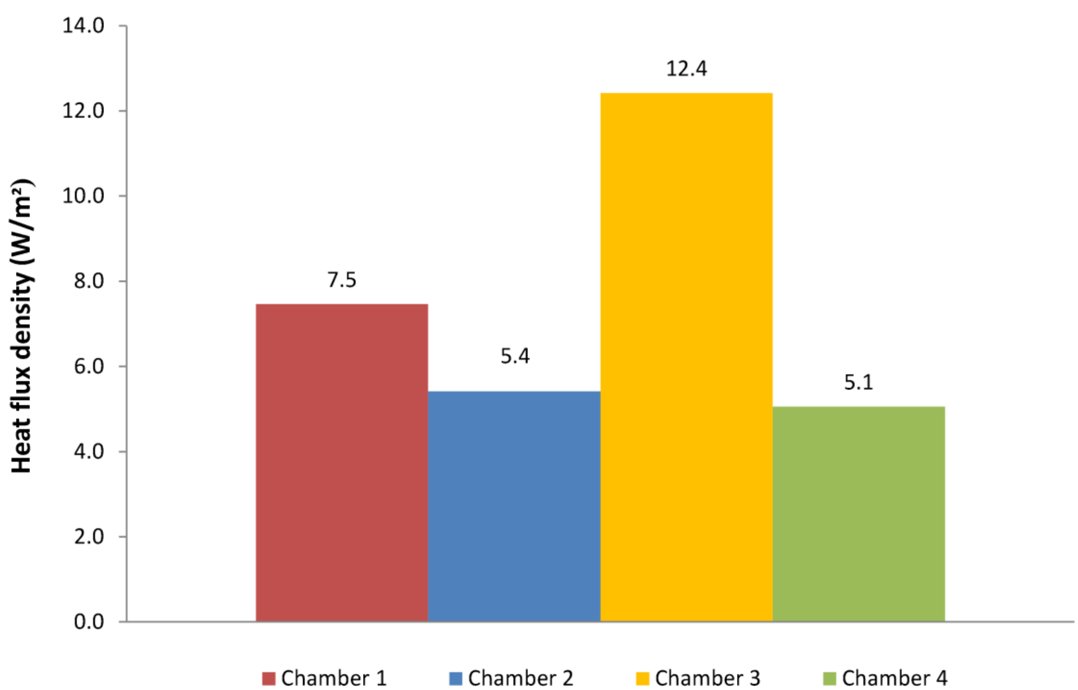

Figure 4.1-37: Average heat flux density in fiberglass bldg. on Mar. 16th (between 12am and 3am)

4.2 Dense pack cellulose wall

4.2.1 Low level of indoor relative humidity

As it was stated in section 4.1.1, the first test was conducted between January 31 and February 11, 2014. The steady-state conditions in the chambers were established by February 2nd and lasted till the end of the test period just like the fiberglass building. All comparisons conducted are over this period of time, which will be called “test period” in following sections.

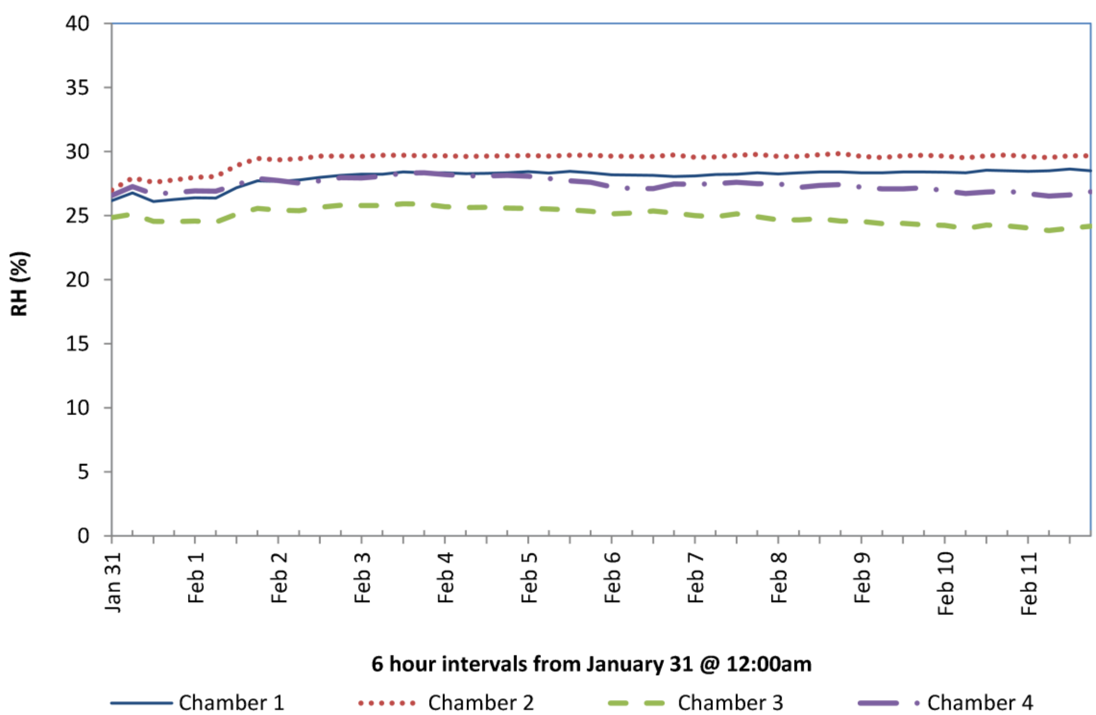

Figure 4.2-1: Indoor RH in cellulose bldg. (Jan. 31-Feb. 11, 2014)

The same snapshot as fiberglass building was chosen, and the data was logged and averaged based on 15-minute intervals between 12am and 3am. Figure 4.2-5 shows that the outer RH in wall cavity was consistent in each of the four chambers on the snapshot.

4.2.1.1 Moisture migration

Data in Table 4.2-1 illustrates that the average indoor RH in the chambers with non-consistent vapour barriers (chambers 3 and 4) dropped only 3%. Figure 4.2-1 shows that indoor RH was 29±1% in the chambers with consistent vapour barrier and 26±2% in the chambers with non-consistent vapour barriers, while the outdoor RH varied between 67% and 83% over the test period.

Figures 4.2-2, 4.2-3 and 4.2-4 illustrate that RH within wall cavities were the lowest and highest in chambers 1 and 4, respectively. Also, it was seen that RH increased from inside to outside of the wall cavity.

4.2.1.1.1 Case 1 – Effect of vapour barrier

According to Figure 4.2-4 and the data in Table 4.2-1, the average outer RH of wall cavity in chamber 3 (with non-consistent vapour barrier) was 25% and 6% higher than the baseline chamber 1 in the same position. However, in the chambers with rigid insulation, the average outer RH was 37% in chamber 4 and just 1% higher than chamber 2 with consistent vapour barrier.

Figures 4.2-5 and 4.2-6 illustrate that the average outer RH (without rigid insulation) in chamber 3 (27%) was 7% greater than chamber 1 on Feb. 3rd (between 12am and 3am). However, in the chambers with rigid insulation, the average outer RH considering non-consistent vapour barrier (39%) was just 2% higher than with consistent vapour barrier over the same snapshot.

4.2.1.1.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-4 and the data in Table 4.2-1, the average outer RH of wall cavity with rigid insulation was 36% and a considerably 17% higher than without rigid insulation in the chambers with continuous vapour barrier. The effect of putting rigid insulation in the chambers with non-consisting vapour barrier (chamber 4) exhibits, similarly, 12% higher average outer RH in the wall cavity (37% RH) than chamber 3.

Also, Figures 4.2-5 and 4.2-6 show the average outer RH (with consistent vapour barrier) in chamber 2 (37%) was 17% higher than chamber 1 on Feb. 3rd (between 12am and 3am). In addition, the effect of adding rigid insulation in the chamber with non-consistent vapour barrier (chamber 4 with 39% average RH) was 12% higher average outer RH than chamber 3.

4.2.1.1.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

The worst case scenario was comparing the benchmark chamber 1 with the chamber considering non-consistent vapour barrier but with rigid insulation (chamber 4). Figure 4.2-4 and Table 4.2-1 illustrate that the average outer RH within wall cavity jumped by 18%, to 37% in chamber 4 over the test period. Similarly, Figures 4.2-5 and 4.2-6 show the average outer RH in chamber 4 (39%) was 19% higher than chambers 1 on Feb. 3rd (between 12am and 3am).

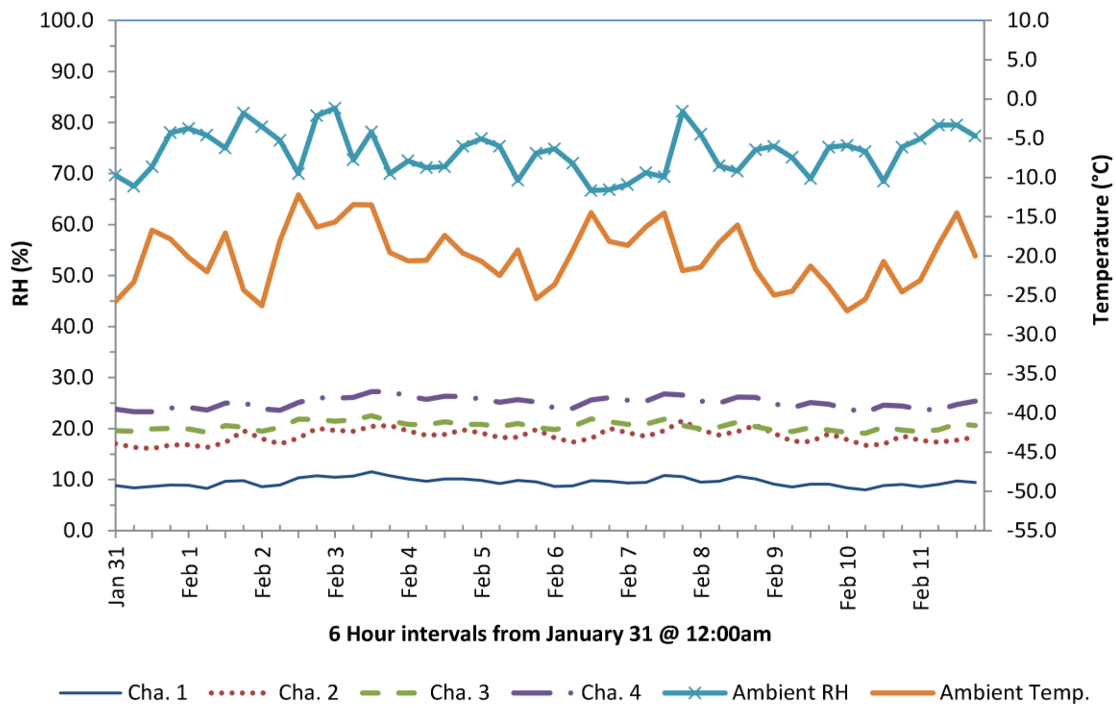

Figure 4.2-2: Ambient outdoor and inner RH in cellulose bldg. (Jan. 31-Feb. 11)

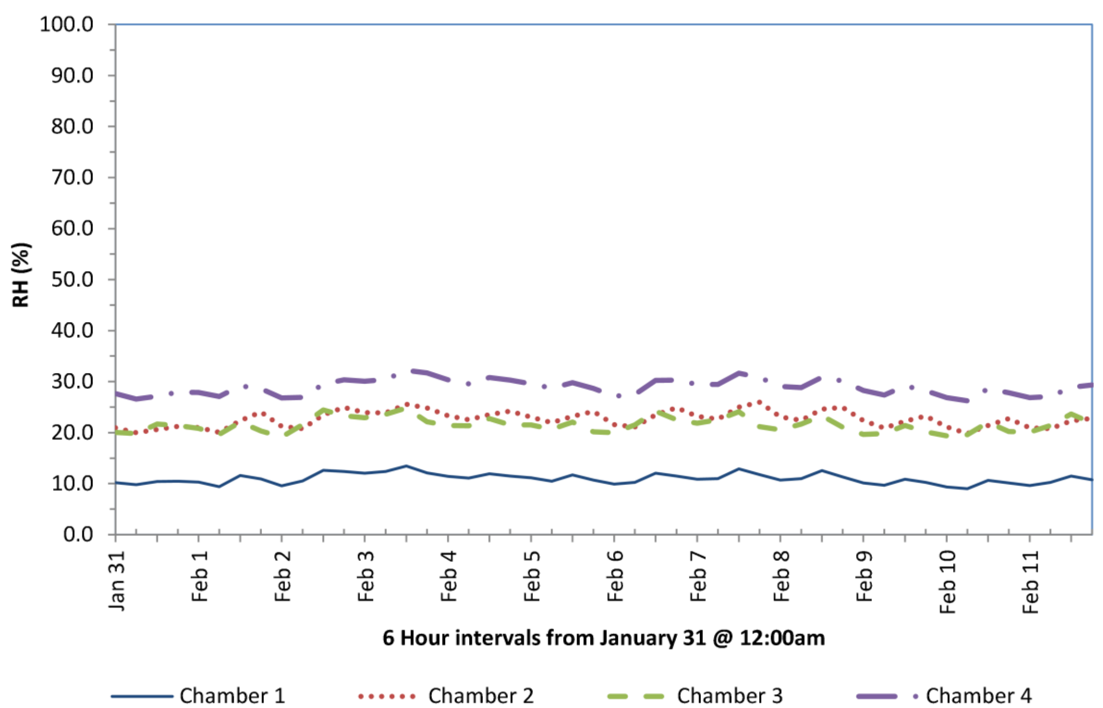

Figure 4.2-3: Middle Rh in cellulose bldg. (Jan. 31-Feb. 11)

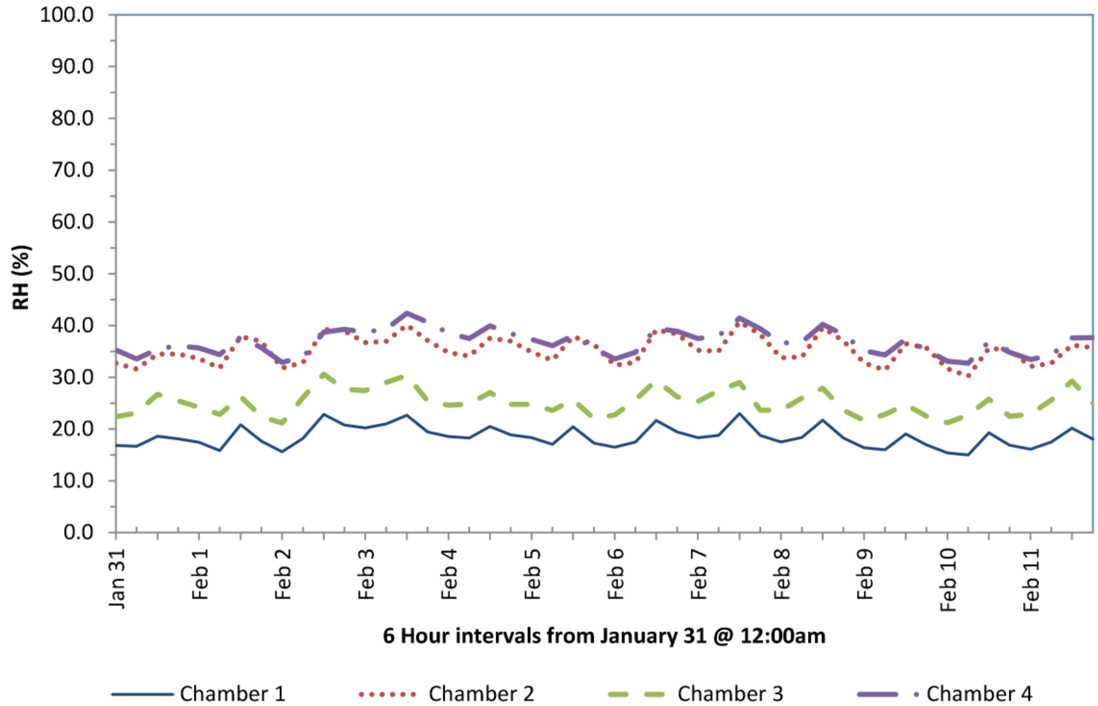

Figure 4.2-4: Outer RH in cellulose bldg. (Jan. 31-Feb. 11)

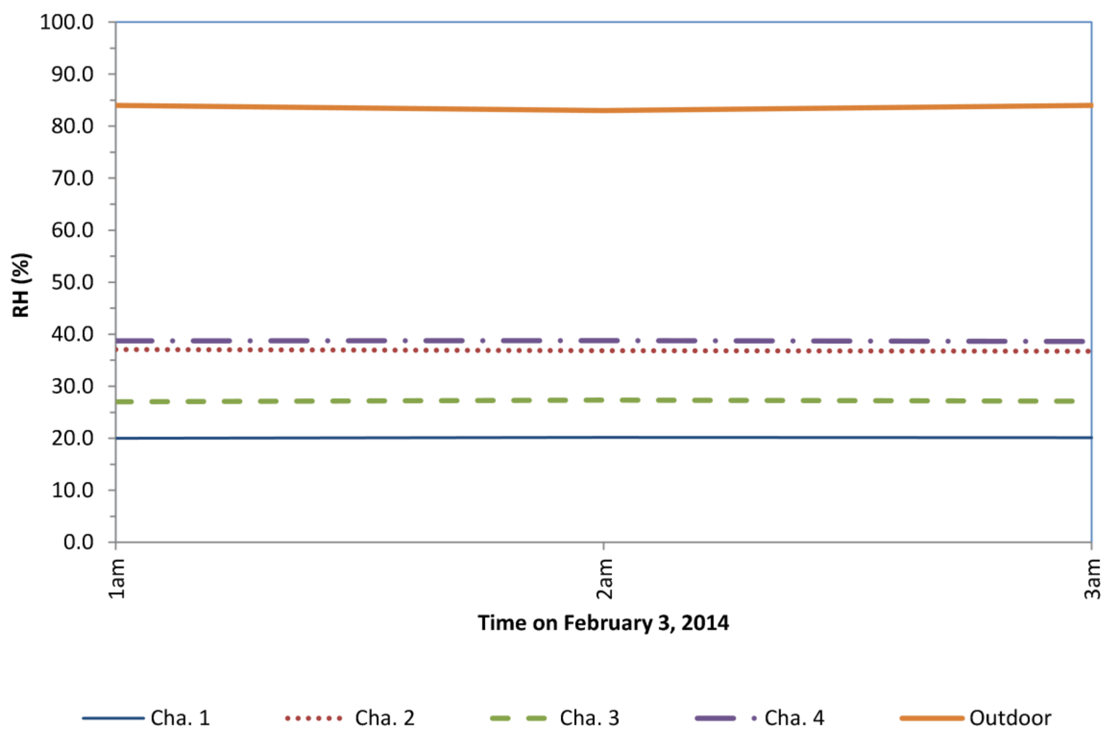

Figure 4.2-5: Outer and ambient outdoor RH in cellulose bldg. on Feb. 3rd (between 12am and 3am)

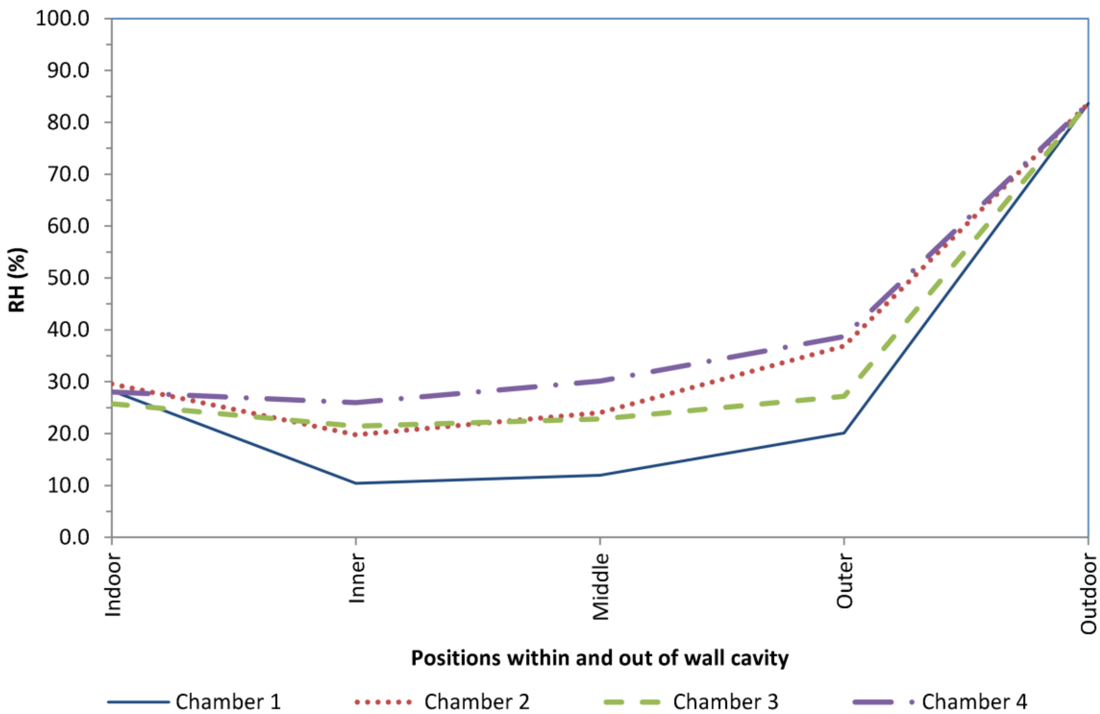

Figure 4.2-6: Average RH profile within wall cavity in cellulose bldg. on Feb. 3rd (between 12am and 3am)

Table 4.2-1: Average indoor, outer and outdoor RH in cellulose bldg. (Feb. 2-11)

	Relative Humidity (%)								
	Indoor RH				Outer RH				Outdoor RH
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	28	29	24	27	15	30	21	33	67
Maximum	29	30	26	28	23	41	31	42	83
Average	28	30	25	27	19	36	25	37	74

4.2.1.2 Temperature gradient

The indoor temperature was consistent at 19.6±0.8˚C in all chambers (Figure 4.2-7). The ambient outdoor temperature varied between -27˚C and -12˚C over the test period. The outer temperature of the wall cavity followed the analogous pattern to ambient outdoor in all four chambers (Figure 4.2-8). As mentioned in section 4, three cases will be compared in the following subsections.

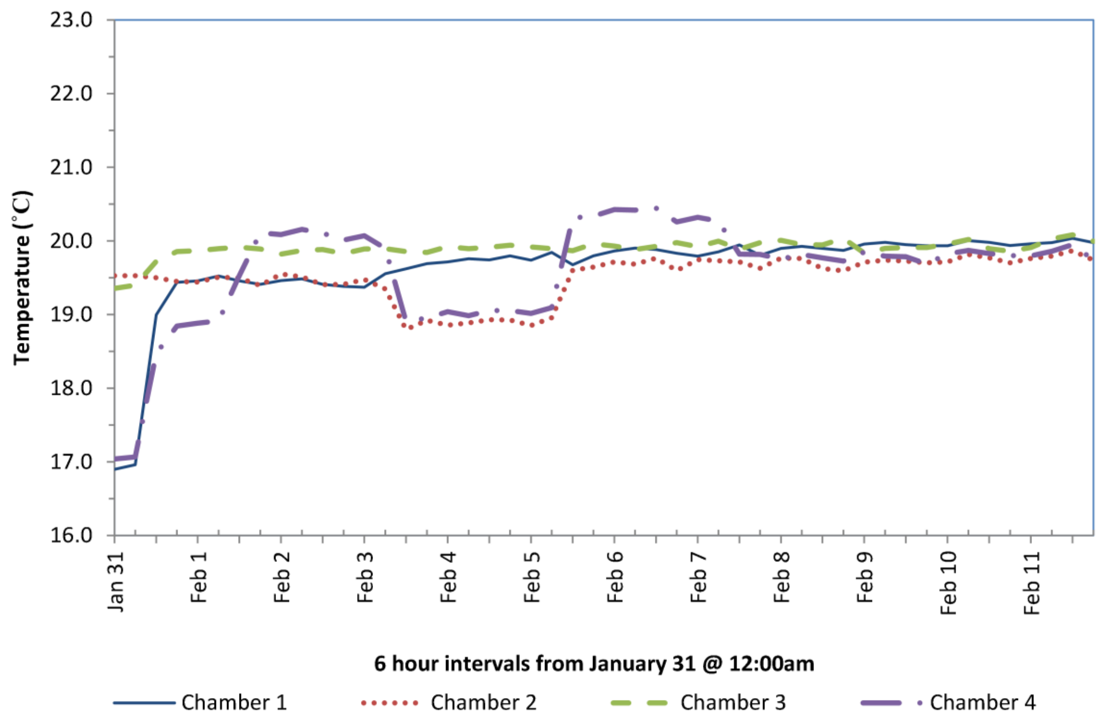

Figure 4.2-7: Indoor temperature in cellulose bldg. (Jan. 31-Feb. 11)

4.2.1.2.1 Case 1 – Effect of vapour barrier

Table 4.2-2 shows that the average outer temperature for non-consistent vapour barrier were 6˚C and 11˚C in chambers 3 and 4 just about 2˚C higher than chambers 1 and 2, respectively. Therefore, as it was seen in Figure 4.2-8 and the above results, the vapour barrier had no significant influence on the outer wall cavity temperature regardless of the addition of rigid insulation. Non-consistent vapour barrier had the similar effect as above over the snapshot as well.

4.2.1.2.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-8 and Table 4.2-2, the average outer temperature in wall cavity was approximately 5˚C higher (9˚C and 11˚C in chambers 2 and 4, respectively) over the test period by the addition of the rigid insulation. Similarly, the average outer temperature was higher in the chambers with rigid insulation than others on Feb. 3rd (between 12am and 3am).

4.2.1.2.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

Figure 4.2-8 and Table 4.2-2 show that this case had the most effect on temperature compared to other cases. The average outer temperature increased by 8°C to 11˚C in chamber 4 compared to baseline chamber 1. Also, similar results to the test period were seen on Feb. 3rd between 12am and 3am.

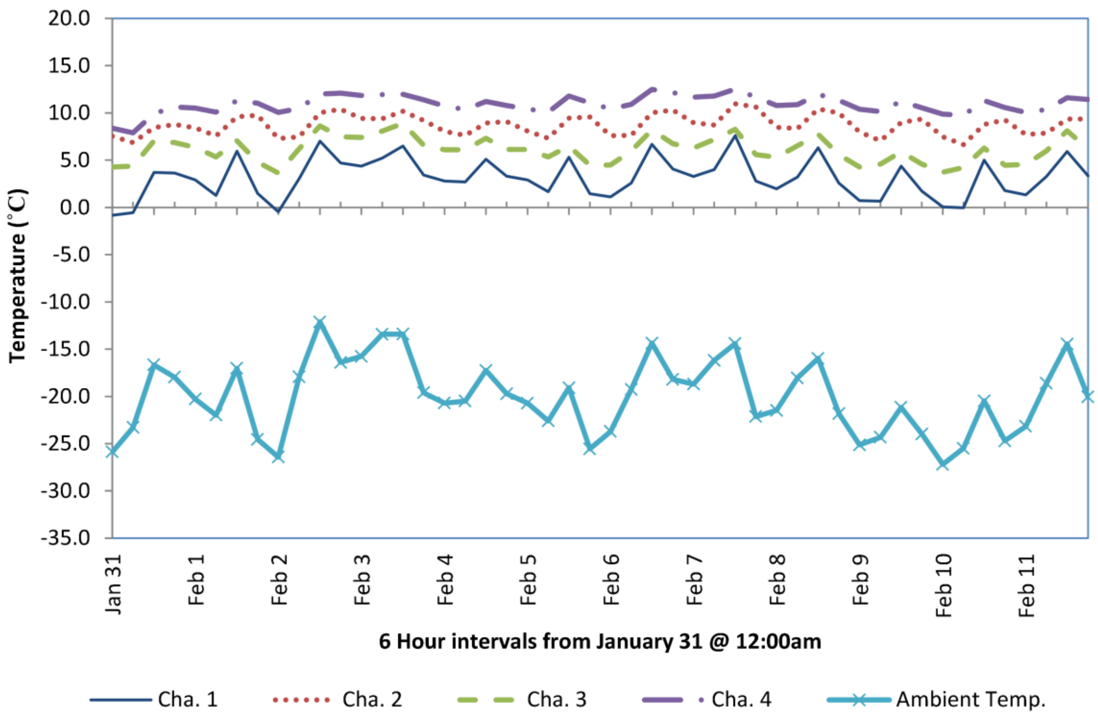

Figure 4.2-8: Outer temperature in cellulose bldg. (Jan. 31-Feb. 11)

Table 4.2-2: Average indoor, outer and outdoor temp. in cellulose bldg. (Feb. 2-11)

	Temperature (°C)								
	Indoor Temp.				Outer Temp.				Outdoor Temp.
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	19.4	18.8	19.8	18.9	0	7	4	10	-27
Maximum	20.0	19.9	20.1	20.4	8	11	9	13	-12
Average	19.8	19.5	19.9	19.8	3	9	6	11	-20

4.2.1.3 Heat transfer

Figure 4.2-9 illustrates that the heat flux density in all four different wall assemblies followed an inverse pattern to the ambient outdoor temperature. In fact, a direct relationship was observed between the outdoor and indoor temperature gradient and the heat flux density changes. The following cases will be discussed to compare the chambers in different wall assemblies.

4.2.1.3.1 Case 1 – Effect of vapour barrier

Figure 4.2-10 summarizes the result of the average heat flux density over the test period and shows that this value considering non-consistent vapour barrier (chamber 3) was 8 W/m^2 and 2.8 W/m^2 less than chamber 1 with vapour barrier. However, the heat flux density was 5.1 W/m^2 in chamber 4, just 0.4 W/m^2 higher than chamber 2. According to Figure 4.2-11, the average heat flux density on Feb. 3rd between 12am and 3am in chamber 3 was 7.4 W/m^2 (2.3 W/m^2 less than chamber 1), while in chamber 4 was 4.7 W/m^2 and almost the same as chamber 2.

It was seen that making non-consistent vapour barrier had no considerable effect in the chambers with rigid insulation. However, in the chambers without rigid insulation, the heat flux density in chamber 1 with consistent vapour barrier was unusually higher than chamber 3. This issue will be discussed further in section 4-2-3.

4.2.1.3.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-10, the average heat flux density through wall assembly in chamber 2 was 4.7 W/m^2 and 6.1 W/m^2 lower than chamber 1 with the same vapour barrier system but considering the addition of an external rigid insulation layer. Similarly, that value in the chamber with non-consistent vapour barrier (chamber 4) was 5.1 W/m^2 and 2.9 W/m^2 lower than chamber 3 just by adding rigid insulation.

Moreover, according to Figure 4.2-11, the average heat flux density in chamber 2 (4.6 W/m^2) was 5.1 W/m^2 lower than chamber 1 on Feb. 3rd between 12am and 3am. Also, this value in chamber 4 (4.7 W/m^2) was 2.7 W/m^2 less than chamber 3.

Overall, both the snapshot and the test period resulted in a considerable decrease of the heat flux density by adding rigid insulation to both consistent and non-consistent vapour barrier categories. However, this effect was considerably greater in the consistent vapour barrier chamber (56% decrease) than non-consistent vapour barrier (36% decrease) over the test period, which will be discussed further in section 4.2.3.

4.2.1.3.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

This scenario would be a comparison between the baseline chamber 1 and chamber 4. Figure 4.2-10 shows that the average heat flux density through wall assembly decreased from 10.8 W/m² to 5.1 W/m² in chamber 4. Also, on Feb. 3rd, the average heat flux density was 9.7 W/m² in chamber 1 and 5 W/m² higher than chamber 4 (Figure 4.2-11) by having both non-consistent vapour barrier condition associated with adding external rigid insulation.

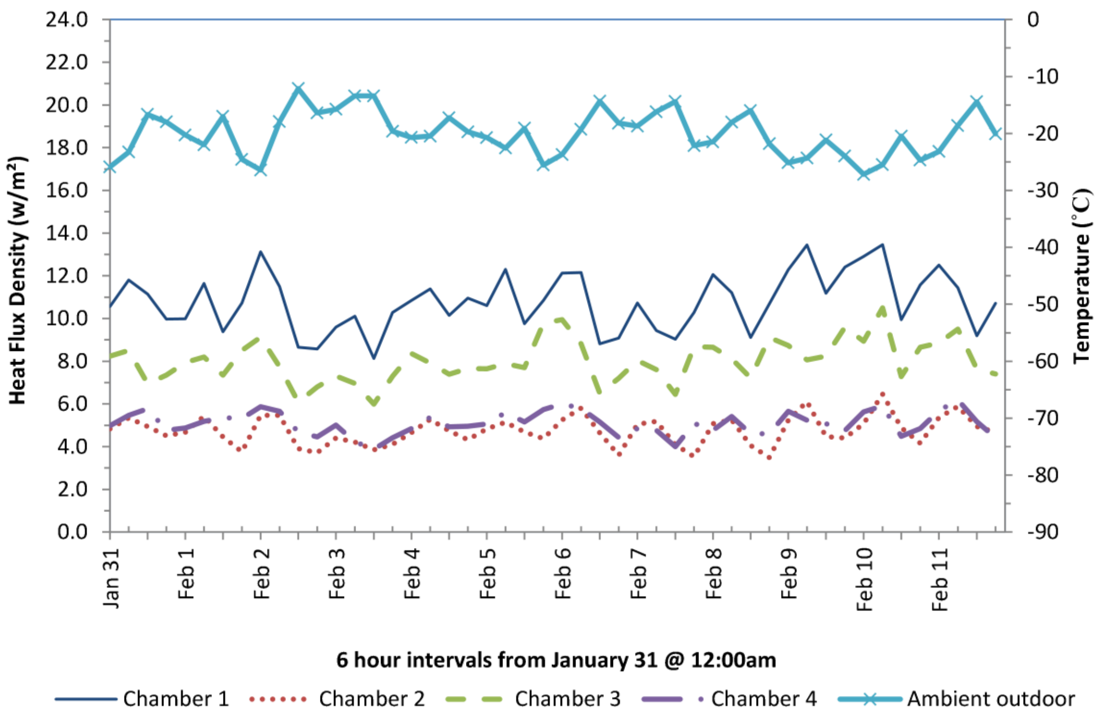

Figure 4.2-9: Heat flux density and ambient outdoor temperature in cellulose bldg. (Jan. 31-Feb. 11)

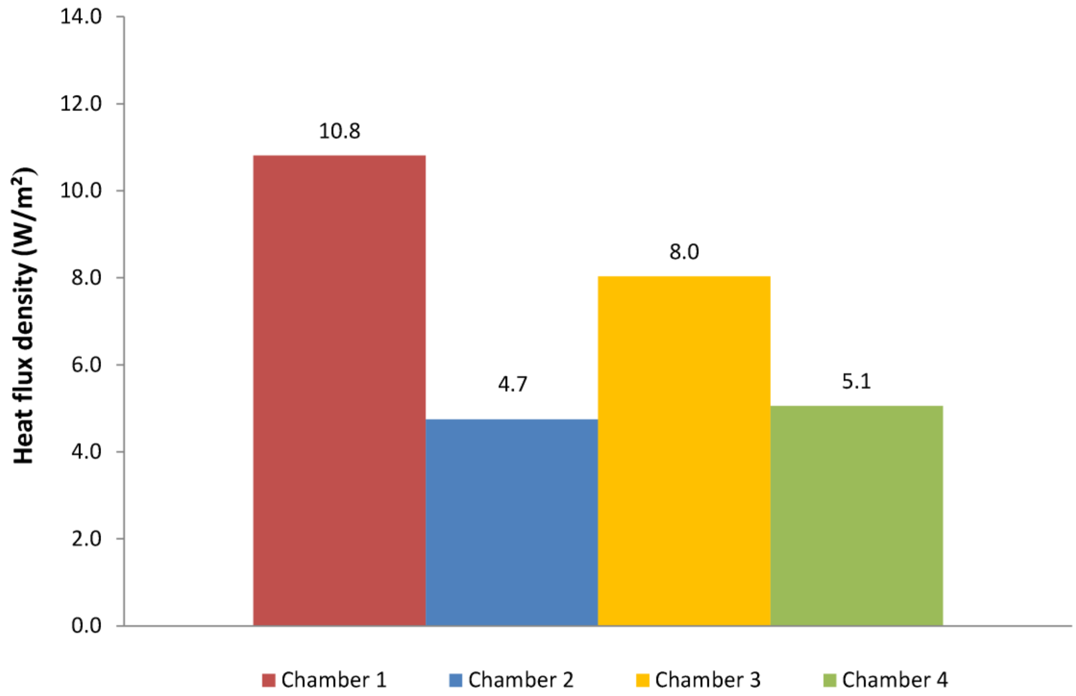

Figure 4.2-10: Average heat flux density in cellulose bldg. (Feb. 2-Feb. 11, 2014)

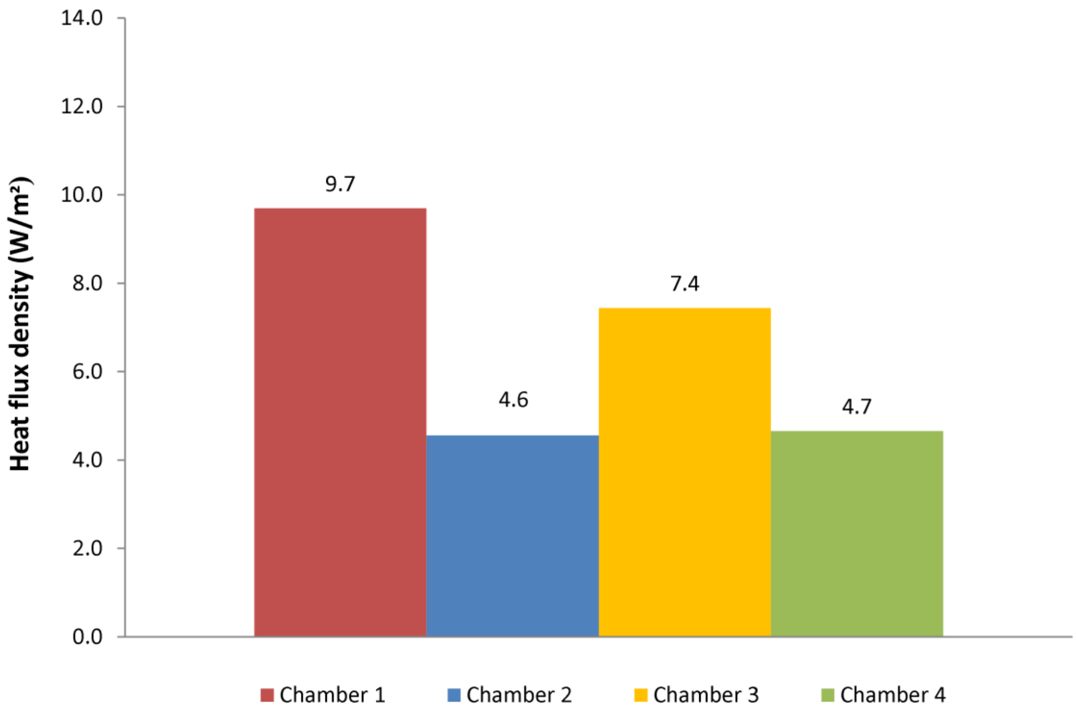

Figure 4.2-11: Average heat flux density in cellulose bldg. on Feb. 3rd (between 12am and 3am)

4.2.2 Mid-level of indoor relative humidity

As it was stated in section 4.1.2, the second test period was between Feb. 13th and Mar. 2, 2014. As pointed out in section 3-3, water was added to salt solution twice (on the morning of Feb. 14th and Feb. 19th) to compensate the amount of water evaporated. Finally, the amount of salt solution was increased to be able to reach the desirable indoor RH on the morning of Feb. 25th as it could be seen in Figure 4.2-12. After increasing the amount of salt solution, the steady state condition at desirable indoor RH was reached between Feb. 26th and Feb. 27th just like fiberglass building. All comparisons conducted are over this period of time (called "test period").

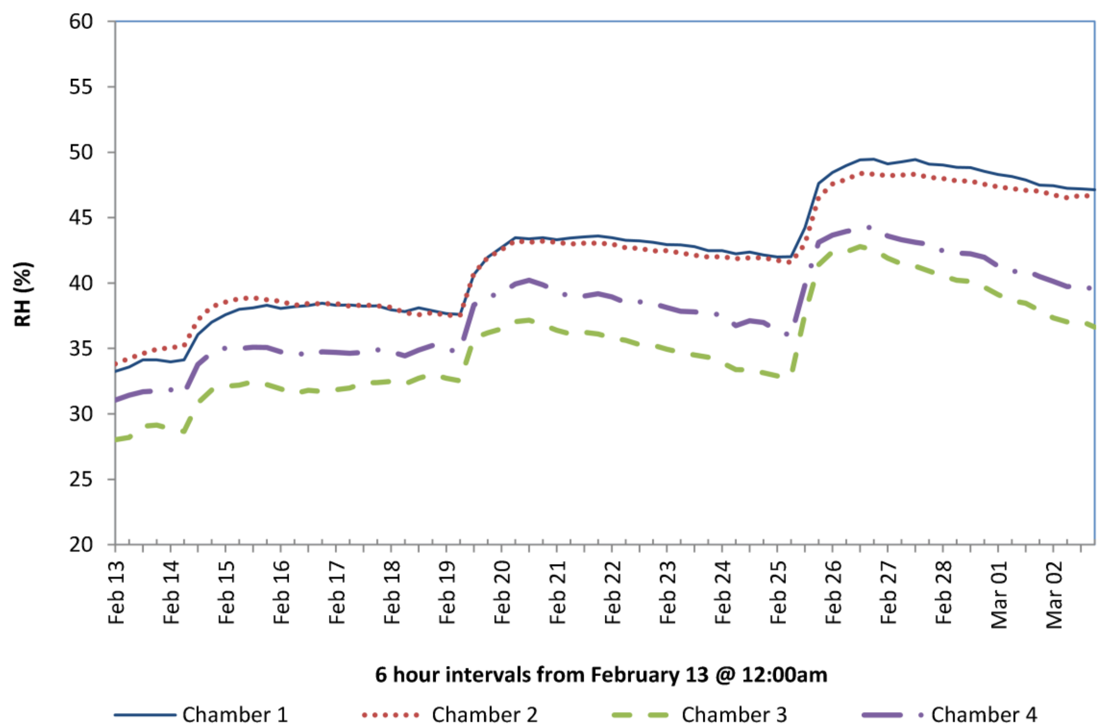

Figure 4.2-12: Indoor RH in cellulose bldg. (Feb. 13-Mar. 2, 2014)

A snapshot was chosen similar to the one in the fiberglass building. The data was logged and averaged based on 15-minute intervals between 12am and 3am. Moreover, Figure 4.2-16 shows that the outer RH in wall cavity was consistent in each of the four chambers on snapshot.

4.2.2.1 Moisture migration

Data in Table 4.2-3 illustrates that the indoor RH in the chambers with non-consistent vapour barriers (chambers 4 and 3) dropped between 4% and 7%. Figure 4.2-12 shows that the average indoor RH was just about 48% in the chambers with consistent vapour barrier and 42.5±1.5% in the chambers with non-consistent vapour barriers, while the outdoor RH fluctuated between 60% and 78% over the test period.

Figures 4.2-13, 4.2-14 and 4.2-15 illustrate that chamber 1 was at the lowest and chamber 4 at the highest level of RH in all three positions within the wall cavity. Also, it was seen that the amount of RH increased from inside to outside of the wall cavity from Feb. 13th to Mar. 2nd.

4.2.2.1.1 Case 1 – Effect of vapour barrier

According to Figure 4.2-15 and the data in Table 4.2-3, the average outer RH of wall cavity in the baseline chamber 1 was 19%, and this value increased by 11% in chamber 3 (30% RH) in the same location but considering non-consistent vapour barrier. Also, the average outer RH in the chamber with rigid insulation was 43% considering non-consistent vapour barrier (chamber 4) and just 7% higher than chamber 2 with vapour barrier.

Figures 4.2-16 and 4.2-17 illustrate that the average outer RH (without rigid insulation) in chamber 3 (25%) was 9% greater than chamber 1 on Feb. 27th (between 12am and 3am). Similarly, in the chambers with rigid insulation, the average outer RH considering non-consistent vapour barrier (42%) was 9% higher than with consistent vapour barrier over the same period of time. It was seen that the snapshot followed the similar pattern as the test period between Feb. 26th and 27th.

4.2.2.1.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-15 and data in Table 4.2-3, in the chambers with continuous vapour barrier the average outer RH of wall cavity with rigid insulation was 36% and 17% higher than without rigid insulation (19% RH). The effect of putting rigid insulation in the chambers with non-consisting vapour barrier (chamber 4) exhibits, similarly, 13% higher average outer RH in the wall cavity (43% RH) than chamber 3 with 30% average outer RH.

Also, Figures 4.2-16 and 4.2-17 illustrate the average outer RH in chamber 2 (33%) and chamber 4 (42%) was 17% higher than chambers 1 and 3, respectively on Feb.27th (between 12am and 3am). Therefore, it was seen that the snapshot showed a similar pattern to the average over the test period.

4.2.2.1.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

The worst case scenario was comparing the benchmark chamber 1 with the chamber considering non-consistent vapour barrier but with rigid insulation (chamber 4). Figure 4.2-15 and Table 4.2-3 illustrate that the average outer RH within wall cavity jumped by 24%, at 43% in chamber 4 over the test period. In addition, Figures 4.2-16 and 4.2-17 show the average outer RH in chamber 4 (42% RH) was 26% higher than chambers 1 on Feb. 27th (between 12am and 3am).

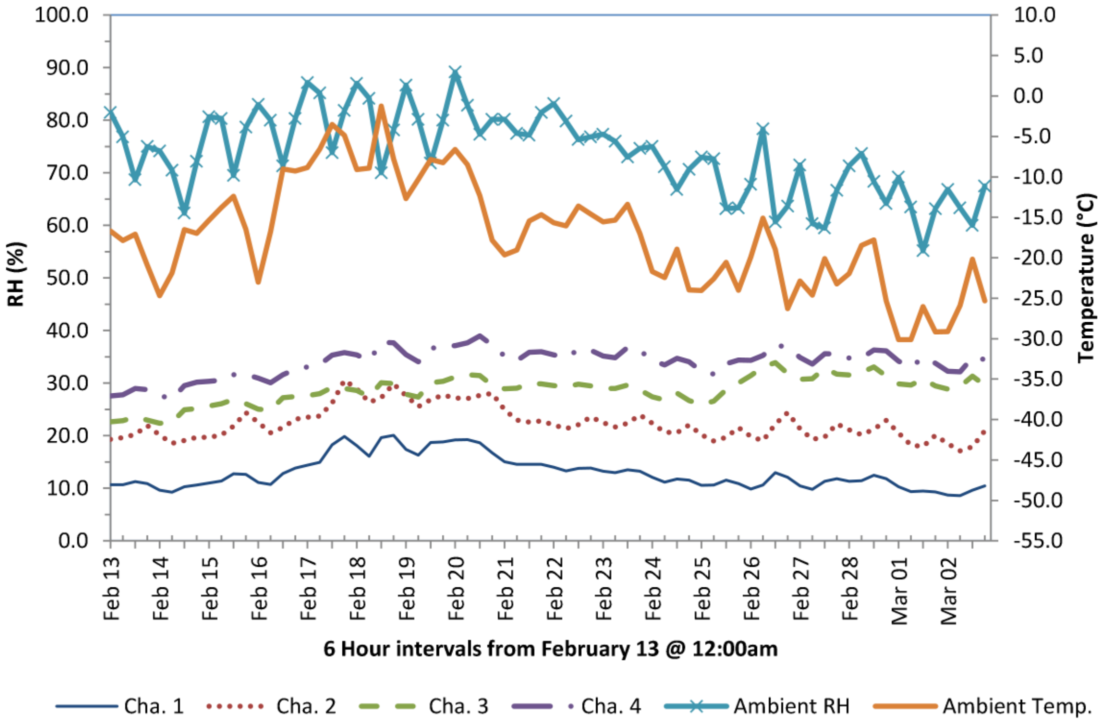

Figure 4.2-13: Ambient outdoor and inner RH in cellulose bldg. (Feb. 13-Mar. 2)

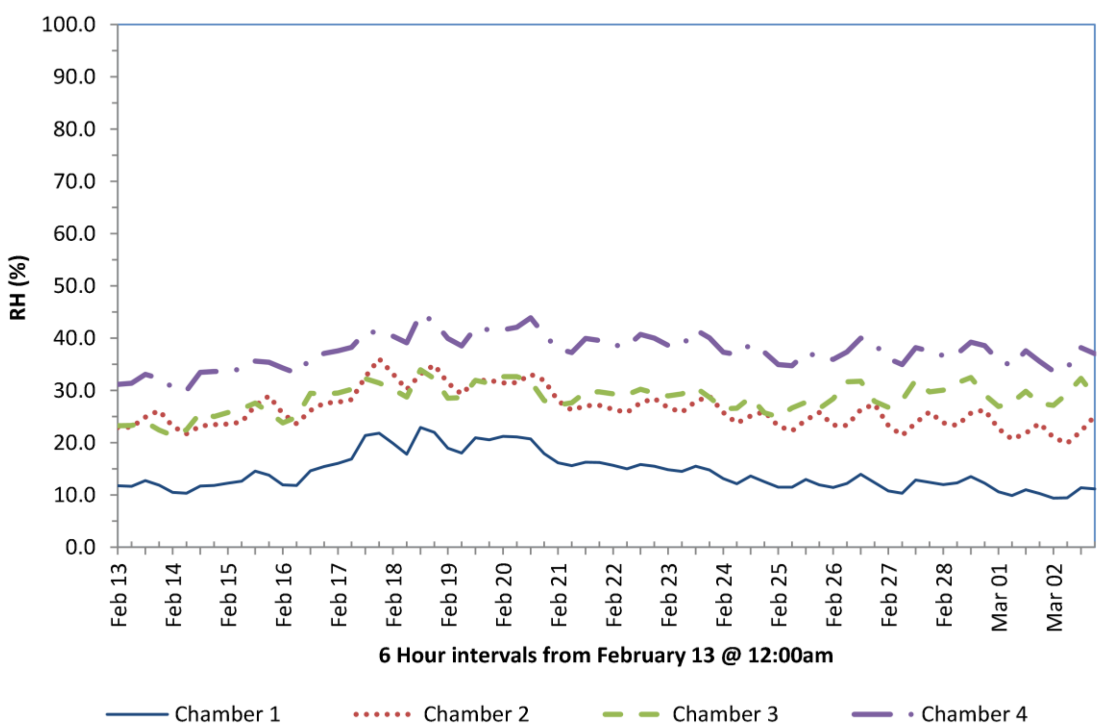

Figure 4.2-14: Middle RH in cellulose bldg. (Feb. 13-Mar. 2)

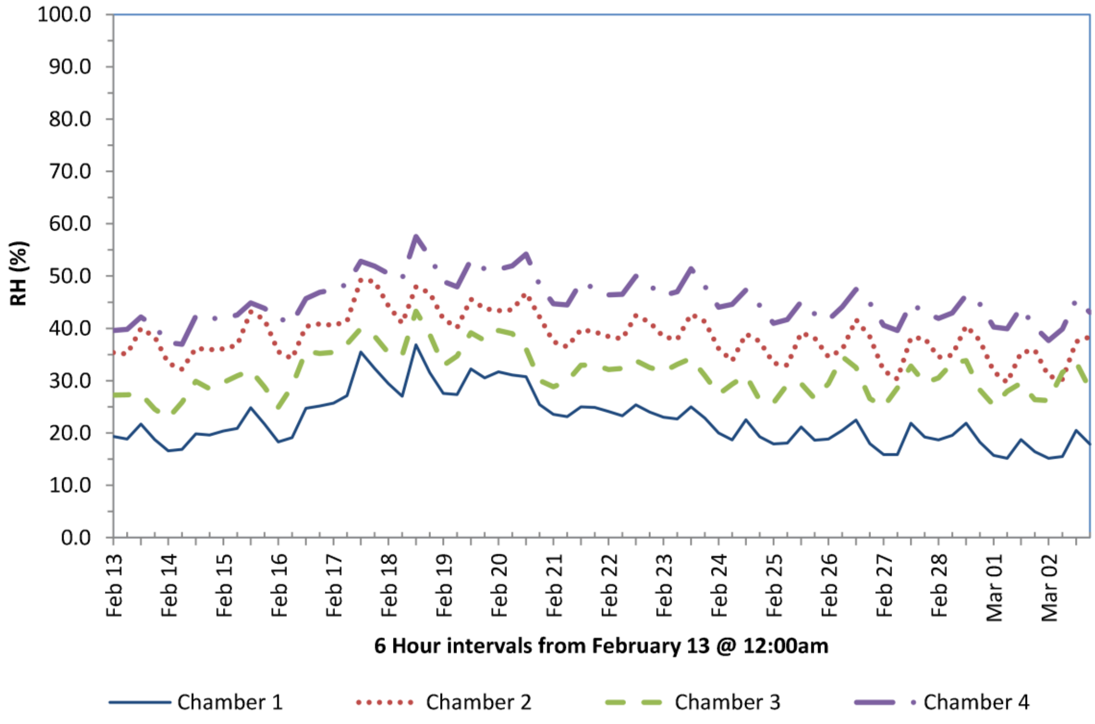

Figure 4.2-15: Outer RH in cellulose bldg. (Feb. 13-Mar. 2)

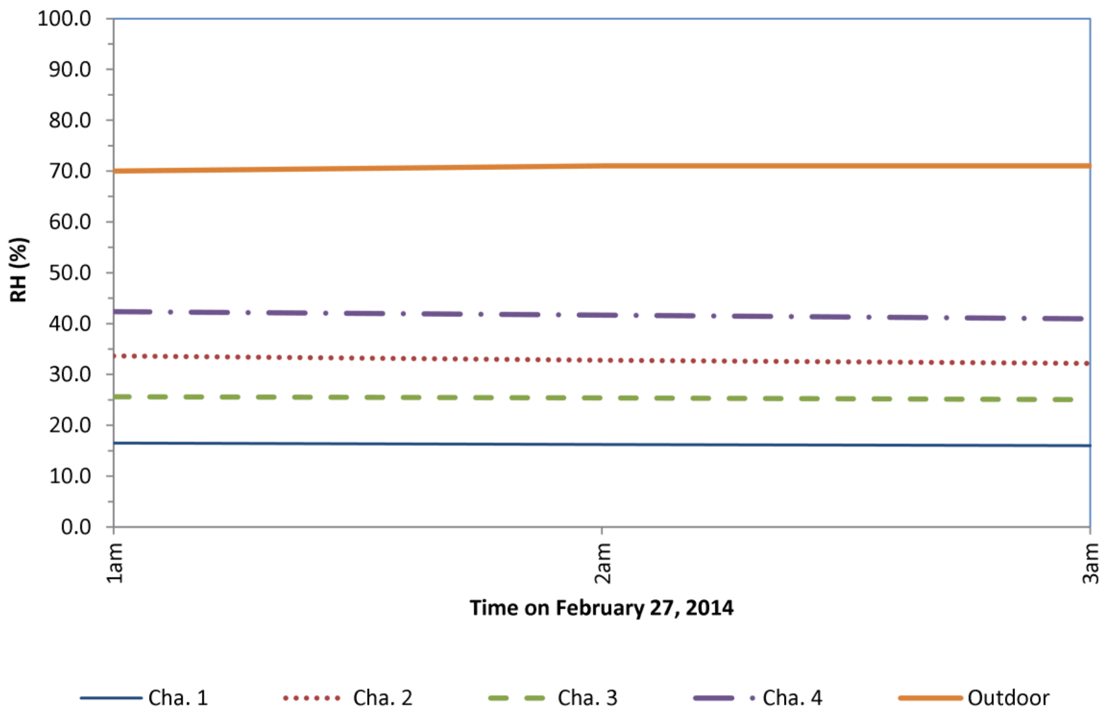

Figure 4.2-16: Outer and ambient outdoor RH in cellulose bldg. on Feb. 27th (between 12am and 3am)

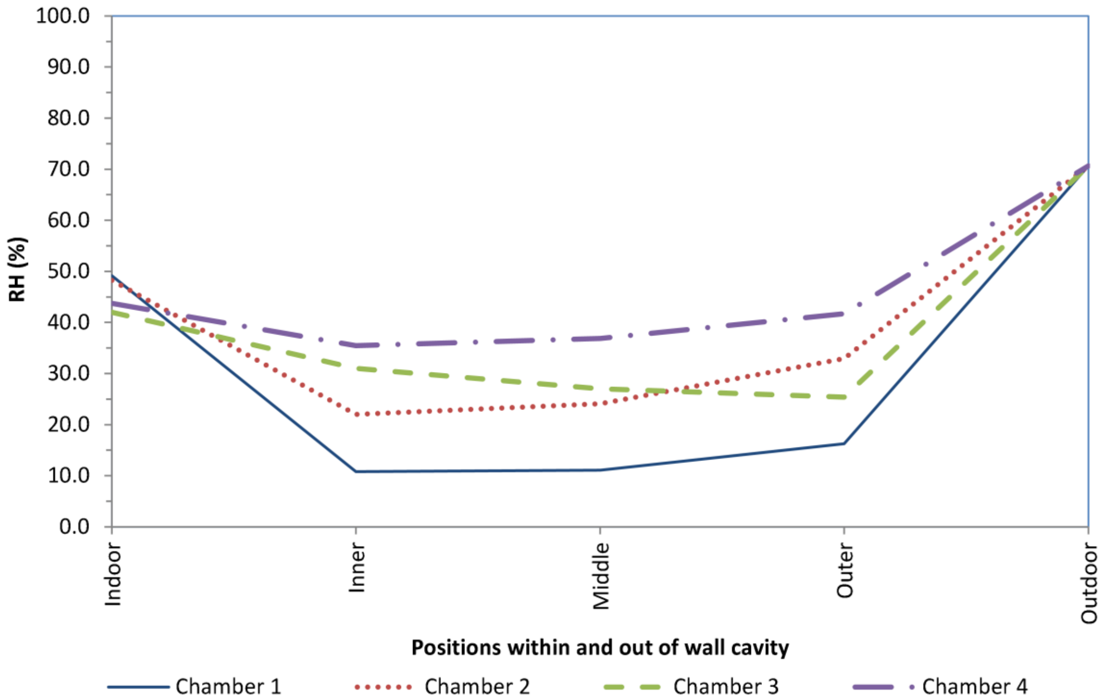

Figure 4.2-17: Average RH profile within wall cavity in cellulose bldg. on Feb. 27th (between 12am and 3am)

Table 4.2-3: Average indoor, outer and outdoor RH in cellulose bldg. (Feb. 26-27)

	Relative Humidity (%)								
	Indoor RH				Outer RH				Outdoor RH
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	48	48	41	43	16	30	25	40	60
Maximum	49	48	43	44	22	42	35	47	78
Average	49	48	42	44	19	36	30	43	66

4.2.2.2 Temperature gradient

The indoor temperature was consistent at 20±0.5˚C in all chambers (Figure 4.2-18). The ambient outdoor temperature fluctuated between -26˚C and -15˚C over the test period. The outer temperature of the wall cavity followed the analogous pattern to ambient outdoor in all four chambers (Figure 4.2-19).

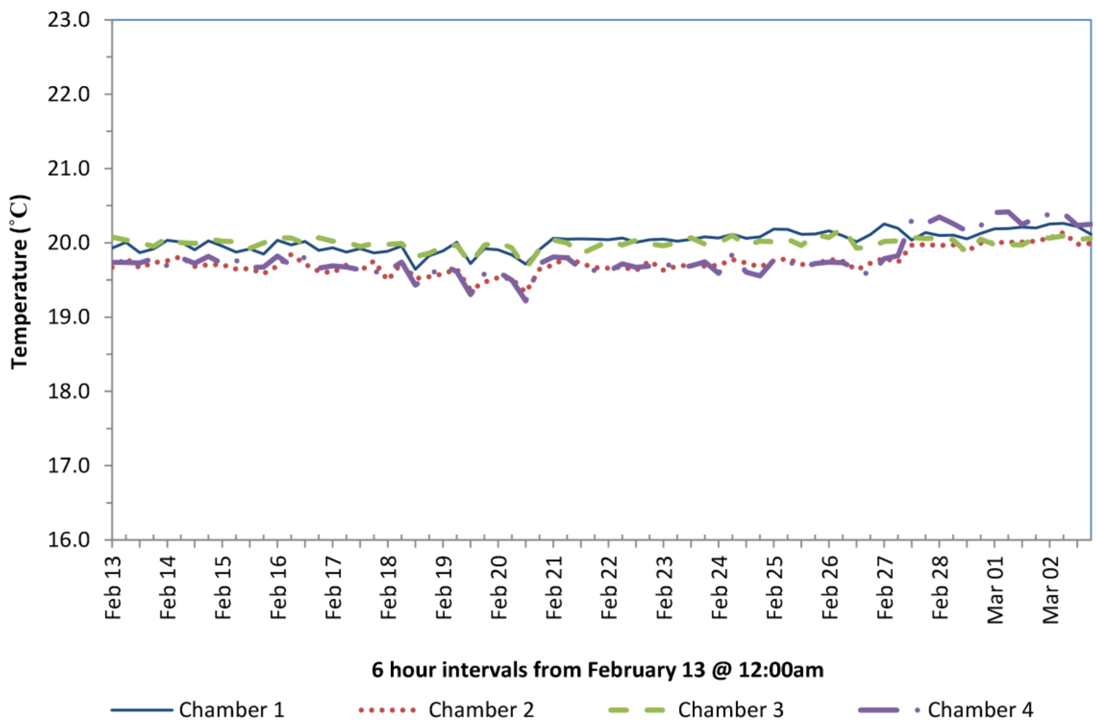

Figure 4.2-18: Indoor temperature in cellulose bldg. (Feb. 13-Mar. 2, 2014)

4.2.2.2.1 Case 1 – Effect of vapour barrier

Data in Table 4.2-4 shows that the average outer temperature considering non-consistent vapour barrier in chamber 3 and 4 was 5˚C and 11˚C, just 2˚C higher than chambers 1 and 2, respectively. Therefore, as it was seen in Figure 4.2-19 and the above results, the vapour barrier had no significant influence on the outer wall cavity temperature regardless of the addition of rigid insulation. Non-consistent vapour barrier had the similar effect as above over the snapshot as well.

4.2.2.2.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-19 and data in Table 4.2-4, the average outer temperature within the wall cavity was 6˚C higher (9˚C and 11˚C in chambers 2 and 4, respectively) over the test period by the addition of the rigid insulation. Moreover, the impact of putting rigid insulation was considerable on the minimum outer temperature, which resulted 7˚C higher outer temperature. Likewise, the average and minimum outer temperature were 8-9°C higher in the chambers with rigid insulation than others on Feb. 27th (between 12am and 3am).

4.2.2.2.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

Figure 4.2-19 and data in Table 4.2-4, illustrate that this case, considering non-consistent vapour barrier condition associated with external rigid insulation (chamber 4), had the most impact on temperature compared to other cases. The average outer temperature went up to 11˚C, which was 8˚C higher than the benchmark chamber 1. Also, it was seen that the minimum outer temperature jumped by 11˚C in chamber 4. Moreover, similar results to the test period were seen on Feb. 27th between 12am and 3am.

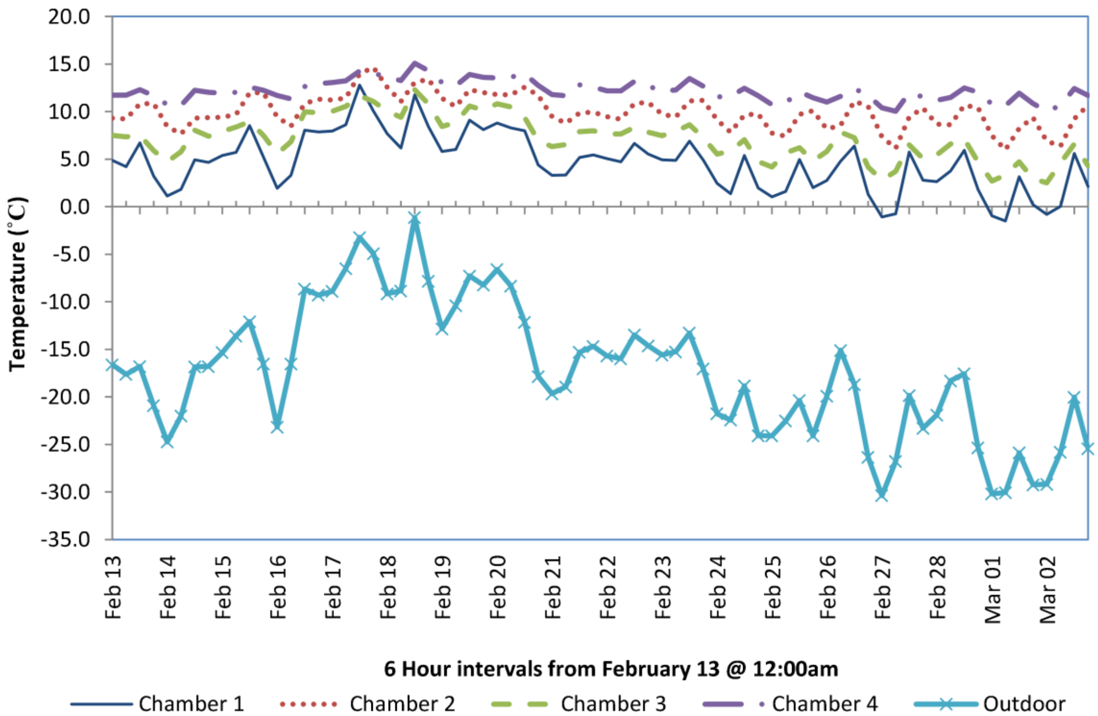

Figure 4.2-19: Outer temperature in cellulose bldg. (Feb. 13-Mar. 2)

Table 4.2-4: Average indoor, outer and outdoor temp. in cellulose bldg. (Feb. 26-27)

	Temperature (°C)								
	Indoor Temp.				Outer Temp.				Outdoor Temp.
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	20.0	19.6	19.9	19.6	-1	6	3	10	-26
Maximum	20.3	20.0	20.2	20.3	6	11	8	12	-15
Average	20.1	19.8	20.0	19.9	3	9	5	11	-21

4.2.2.3 Heat transfer

Figure 4.2-20 illustrates that the heat flux density in all four different wall assemblies followed an inverse pattern to the ambient outdoor temperature. The following three cases will be compared.

4.2.2.3.1 Case 1 – Effect of vapour barrier

Figure 4.2-21 summarizes the result of the average heat flux density over the test period and shows that this value considering non-consistent vapour barrier (chamber 3) was 9.2 W/m^2 and 1.8 W/m^2 less than chamber 1 with vapour barrier. However, considering rigid insulation, the heat flux density was 5.1 W/m^2 in chamber 4 (non-consistent vapour barrier) and just 0.2 W/m^2 higher than chamber 2. According to Figure 4.2-22, the average heat flux density on Feb. 27th between 12am and 3am in chamber 3 was 11.8 W/m^2 (2.8 W/m^2 less than chamber 1), while in chamber 4 was 5.4 W/m^2 and 0.4 W/m^2 greater than chamber 2.

It was seen that having non-consistent vapour barrier had no considerable effect on heat flux density in the chambers with rigid insulation. However, it was not expected to see higher heat flux density in chamber 1 with consistent vapour barrier than chamber 3. This issue will be discussed further in section 4.2.3.

4.2.2.3.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-21, the average heat flux density through wall assembly in chamber 2 was 4.9 W/m² and considerably 6.1 W/m² lower than chamber 1 with the same vapour barrier system but with the addition of an external rigid insulation. Similarly, that value in the chamber with non-consistent vapour barrier (chamber 4) was 5.1 W/m² and 4.1 W/m² lower than chamber 3 by adding rigid insulation. Moreover, it was seen that the average heat flux density in chamber 2 (5 W/m²) dropped by 9.6 W/m² compared to chamber 1 on Feb. 27th between 12am and 3am (Figure 4.2-22). Also, this value in chamber 4 (5.4 W/m²) was 6.4 W/m² less than chamber 3.

Overall, both the snapshot and the test period resulted in a considerable decrease of the heat flux density by adding rigid insulation to both consistent and non-consistent vapour barrier categories. However, this effect was greater in the consistent vapour barrier chamber (55% decrease) than non-consistent vapour barrier (45% decrease) over the test period, which will be discussed further in section 4.2.3.

4.2.2.3.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

According to Figure 4.2-21, having both non-consistent vapour barrier condition associated with adding external rigid insulation decreased the average heat flux density through wall assembly from 11 W/m² in benchmark chamber 1 to 5.1 W/m² in chamber

4. Also, on Feb. 27th, the average heat flux density was 14.6 W/m² in chamber 1 and 9.2 W/m² higher than chamber 4 (Figure 4.2-22).

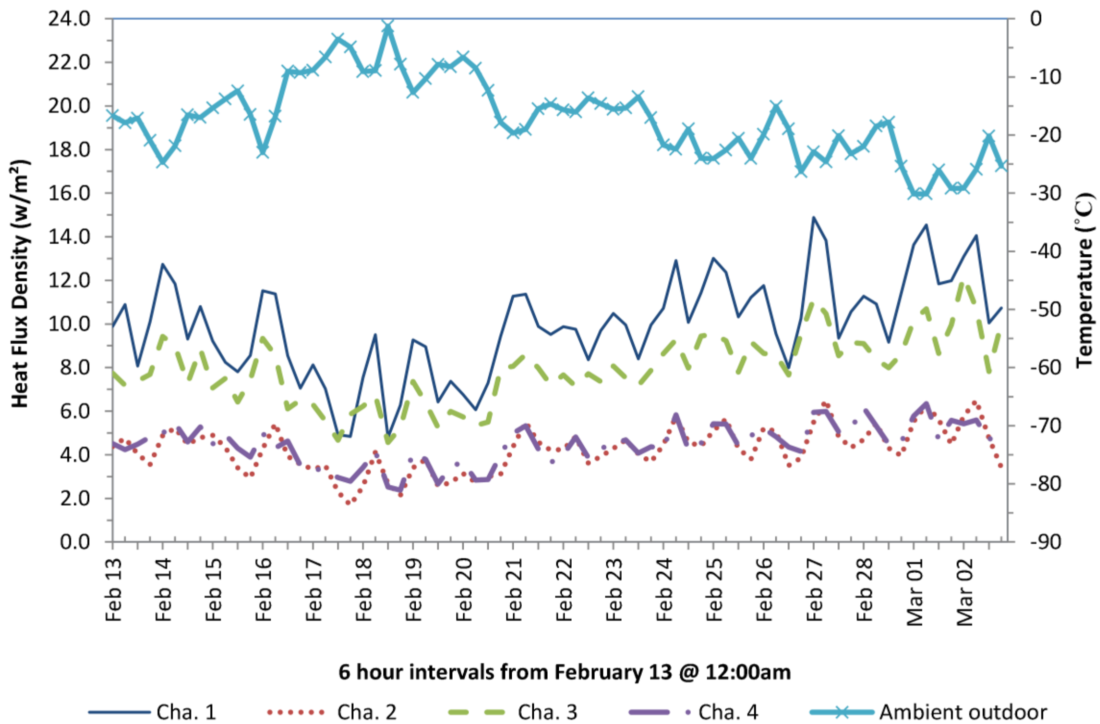

Figure 4.2-20: Heat flux density and ambient outdoor temperature in cellulose bldg. (Feb. 13-Mar. 2)

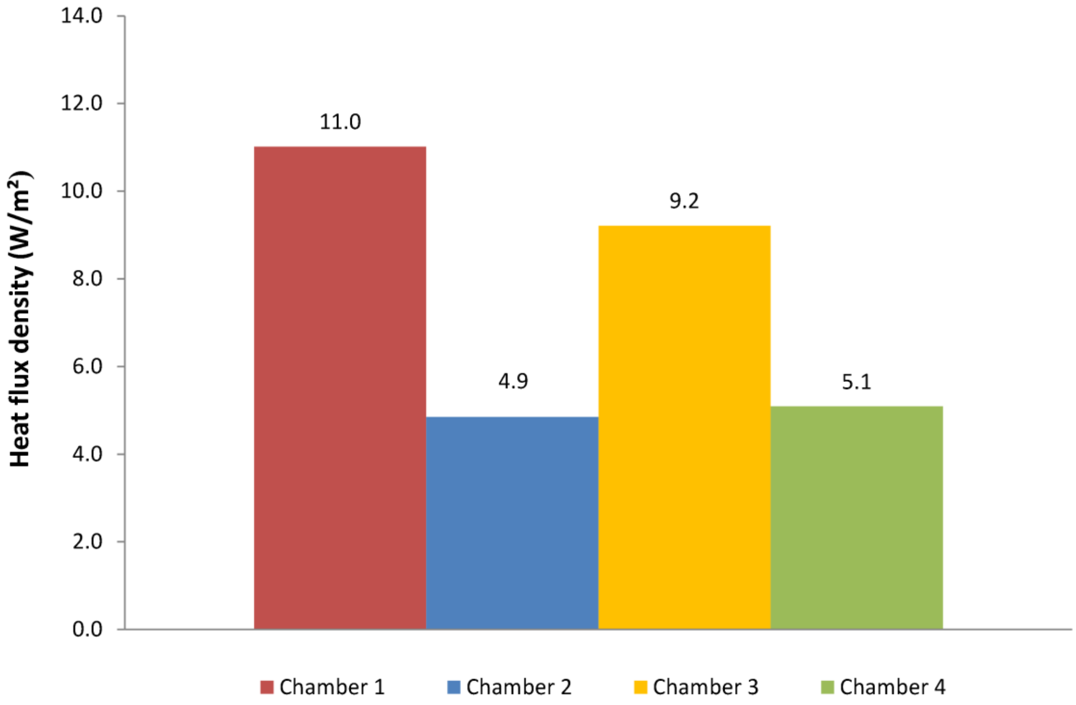

Figure 4.2-21: Average heat flux density in cellulose bldg. (Feb. 26-27, 2014)

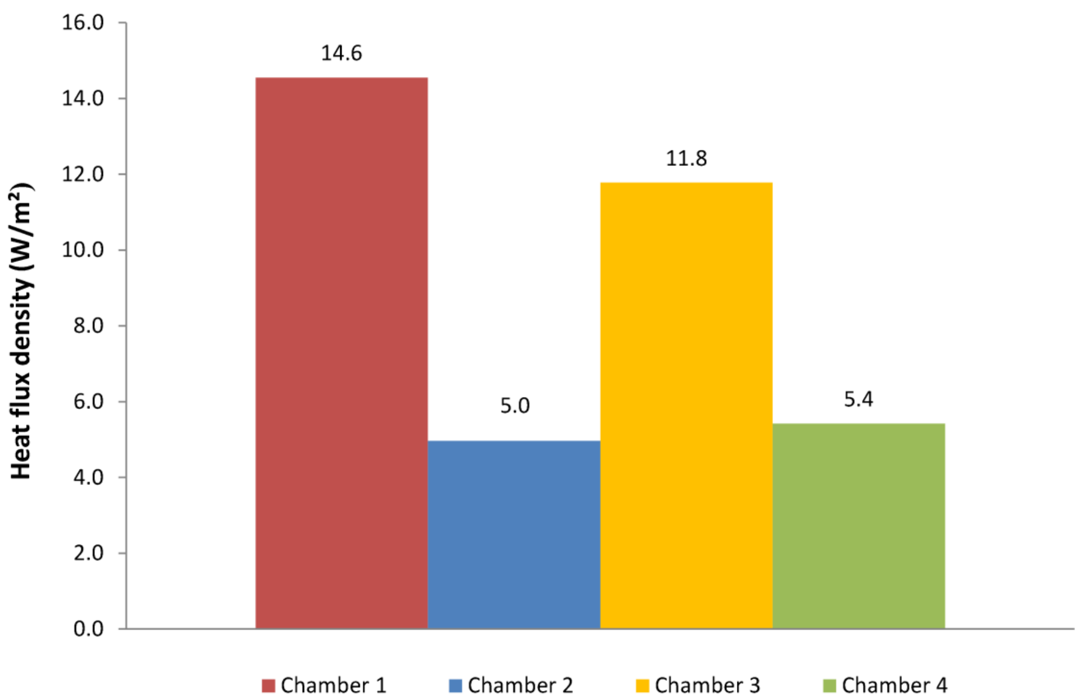

Figure 4.2-22: Average heat flux density in cellulose bldg. on Feb. 27th (between 12am and 3am)

4.2.3 High level of indoor relative humidity

As it was stated in section 4.1.3, the third period of the test was between March 4th and 16, 2014. The steady-state conditions in the chambers were established by March 7th until the end of the test period just like the fiberglass building. All comparisons conducted are over this period of time (called "test period").

Two snapshots were chosen similar to the ones in fiberglass building. The data was logged and averaged based on 15-minute intervals between 12am and 3am. Figures 4.2-27 and 4.2-29 show that the outer RH in wall cavity was consistent in each of the four chambers on both snapshots.

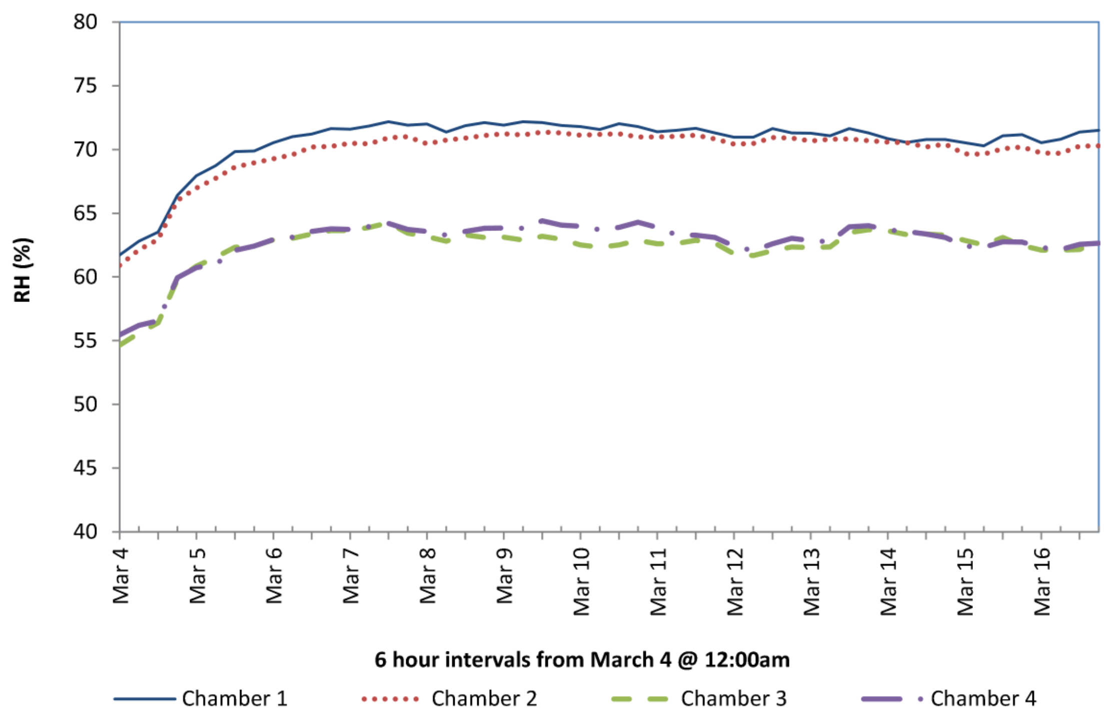

Figure 4.2-23: Indoor RH in cellulose bldg. (March 4-16, 2014)

4.2.3.1 Moisture migration

The data in Table 4.2-5 illustrates that the indoor RH in the chambers with non-consistent vapour barriers (chambers 3 and 4) dropped 8%. Figure 4.2-23 shows that the average indoor RH was 71±1% in the chambers with consistent vapour barrier and 63±1% in the chambers with non-consistent vapour barriers, while the outdoor RH fluctuated between 59% and 94% over the test period.

Figures 4.2-24, 4.2-25 and 4.2-26 illustrate that RH in wall cavities were the lowest in chambers 1 and 2 (with consistent vapour barrier) compared to the others without consistent vapour barriers over the test period. Also, it was clearly seen that chamber 1 was at the lowest and chamber 4 at the highest level of RH in all three positions within the wall cavity. Figures 4.2-24, 4.2-25 and 4.2-26 show that overall the amount of RH increased from inside to outside of the wall cavity.

4.2.3.1.1 Case 1 – Effect of vapour barrier

According to Figure 4.2-26 and the data in Table 4.2-5, the average outer RH of wall cavity considering no rigid insulation in chamber 3 (49% RH) was 16% higher than baseline chamber 1. Likewise, in the chambers with rigid insulation, the average outer RH in chamber 4 (63%) was 18% higher than chamber 2 (continuous vapour barrier).

Figures 4.2-27 and 4.2-28 illustrate that the average outer RH in chamber 3 (59%) was 20% greater than chamber 1 on March 14^{th} (between 12am and 3am) with high outdoor partial vapour pressure. Similarly, in the chambers with rigid insulation, the average outer RH considering non-consistent vapour barrier (71%) was 22% higher than with consistent vapour barrier over the snapshot.

In addition, Figures 4.2-29 and 4.2-30 illustrate that the average outer RH in chamber 3 (34%) was 10% higher than chamber 1 on March 16th (between 12am and 3am) with low outdoor partial vapour pressure and no rigid insulation. Likewise, in the chambers with rigid insulation, the outer RH considering non-consistent vapour barrier (54%) was 15% higher than with consistent vapour barrier. Therefore, it was seen that the snapshot with high outdoor partial vapour pressure (March 14th) showed a similar pattern to the average over the test period between March 7th and 16th.

4.2.3.1.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-26 and Table 4.2-5, in the chambers with continuous vapour barrier the average outer RH of the wall cavity with rigid insulation was 45% and 12% higher than without rigid insulation. The effect of putting rigid insulation in the chambers with non-consisting vapour barrier (chamber 4) exhibits, similarly, 14% higher average outer RH in the wall cavity (63% RH) than chamber 3 with 49% average outer RH.

Also, Figures 4.2-27 and 4.2-28 illustrate the average outer RH (with consistent vapour barrier) in chamber 2 (49%) was 10% higher than chamber 1 on March 14th (between 12am and 3am). In addition, the effect of adding rigid insulation in the chamber with non-consistent vapour barrier (chamber 4 with 71% average RH) was 12% higher average outer RH than chamber 3.

Likewise, Figures 4.2-29 and 4.2-30 illustrate the average outer RH (with non-consistent vapour barrier) in chamber 2 (39%) was 15% higher than chamber 1 on March 16th (between 12am and 3am). Also, the effect of rigid insulation in the chamber with non-consistent vapour barrier (chamber 4 with 54% RH) shows 20% higher outer RH than chamber 3. It was seen that the snapshot with high outdoor partial vapour pressure (March 14th) showed a similar pattern to the average over the test period.

4.2.3.1.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

The worst case scenario was comparing the benchmark chamber 1 with the chamber considering non-consistent vapour barrier but with rigid insulation (chamber 4). Figure 4.2-26 and Table 4.2-5 illustrate that the average outer RH of wall assembly jumped dramatically by 30%, from 33% in chamber 1 to 63% in chamber 4 over the test period.

In addition, Figures 4.2-27 and 4.2-28 show the average outer RH in chamber 4 (71%) was significantly 32% higher than chambers 1 on March 14th (between 12am and 3am). Also, Figures 4.2-29 and 4.2-30 illustrate the average outer RH in chamber 4 (54%) was considerably 30% greater than chamber 1 on March 16th (between 12am and 3am).

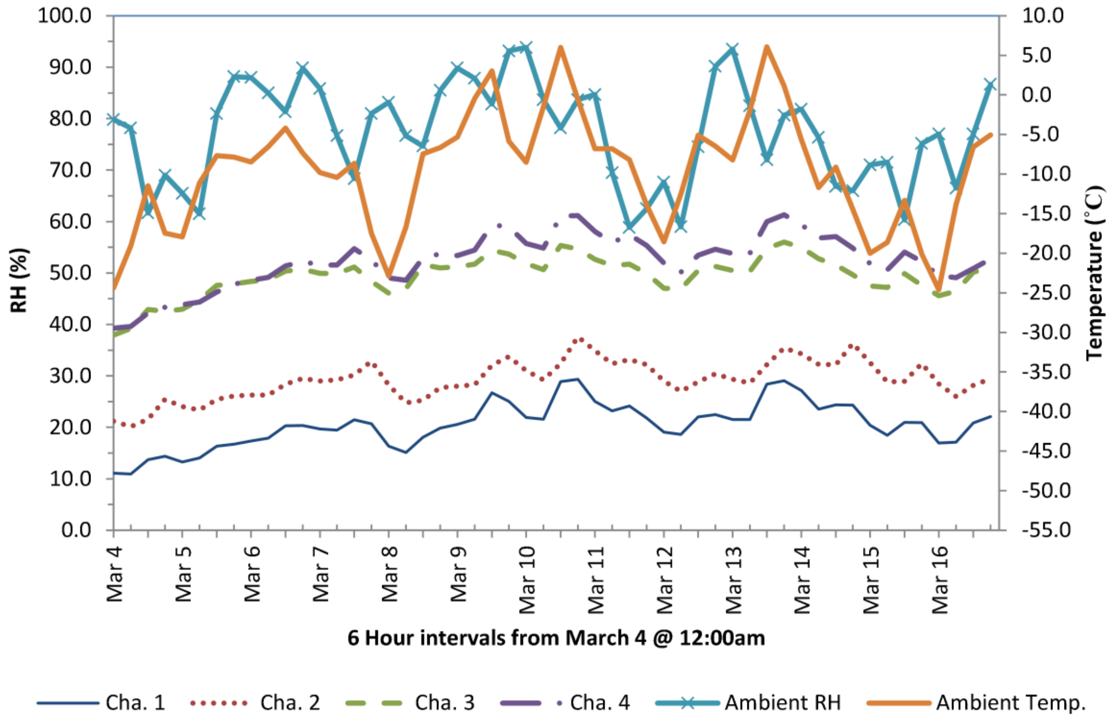

Figure 4.2-24: Ambient outdoor and inner RH in cellulose bldg. (March 4-16)

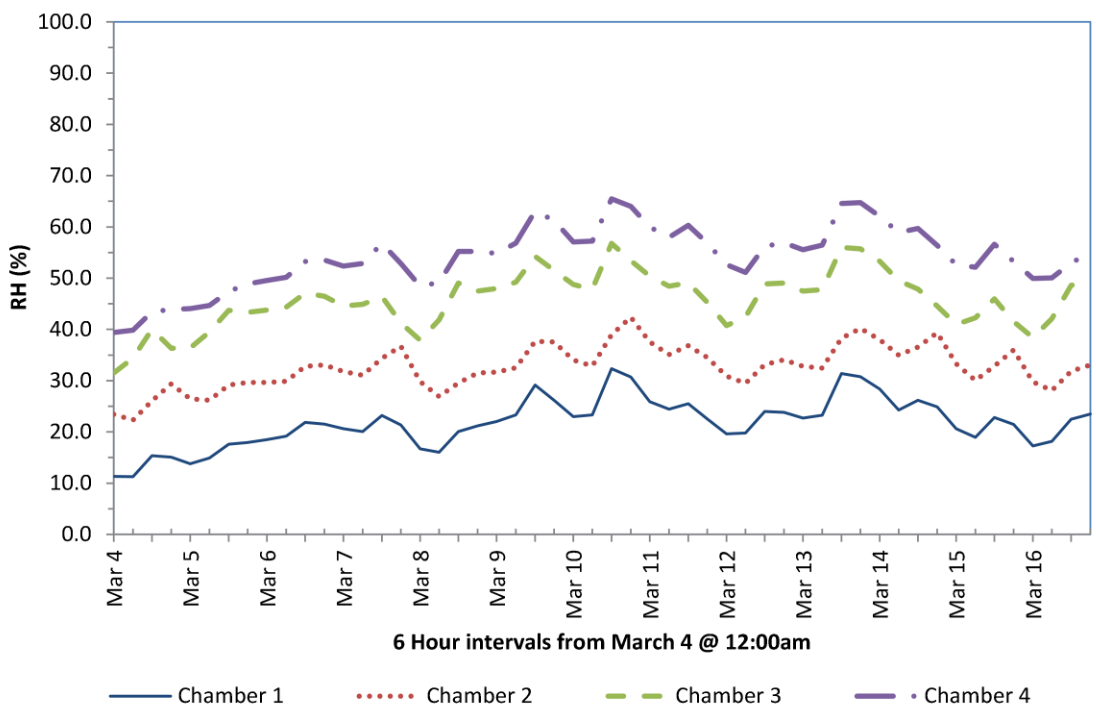

Figure 4.2-25: Middle RH in cellulose bldg. (March 4-16, 2014)

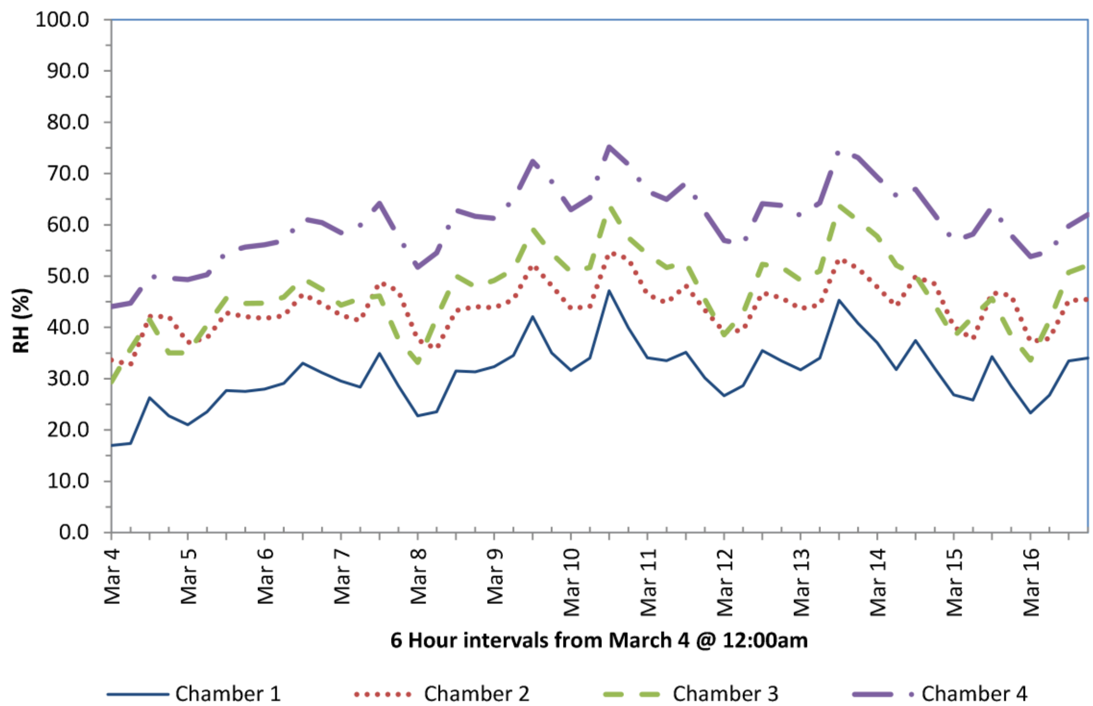

Figure 4.2-26: Outer RH in cellulose bldg. (March 4-16, 2014)

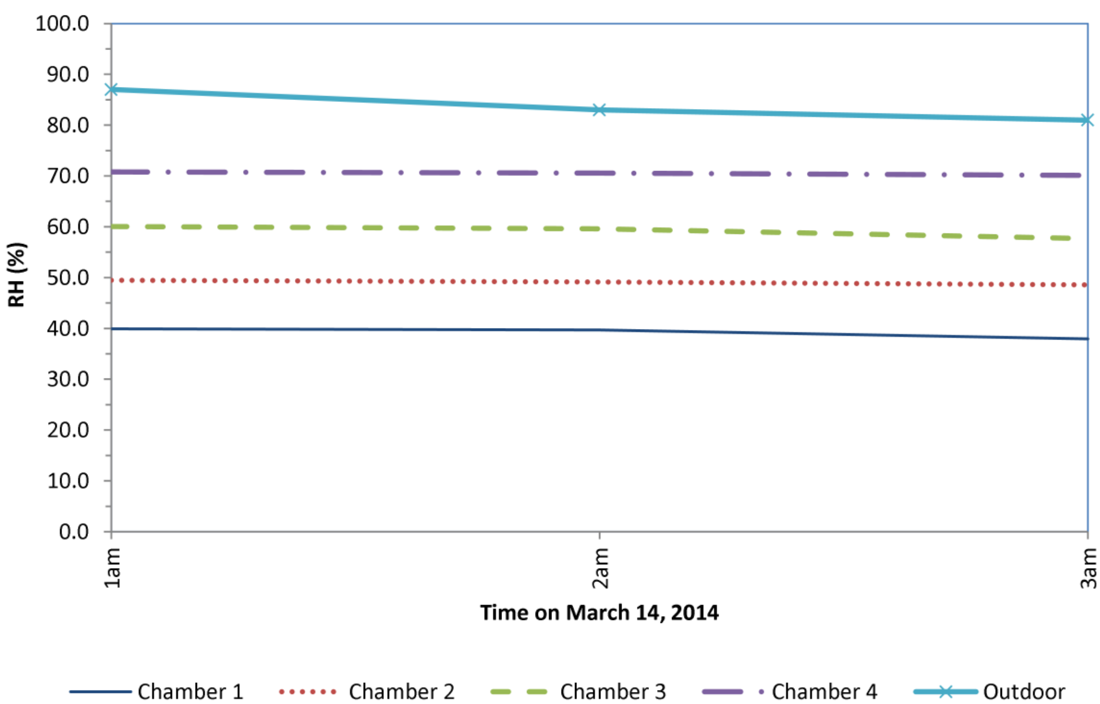

Figure 4.2-27: Outer and ambient outdoor RH in cellulose bldg. on March 14th (between 12am and 3am)

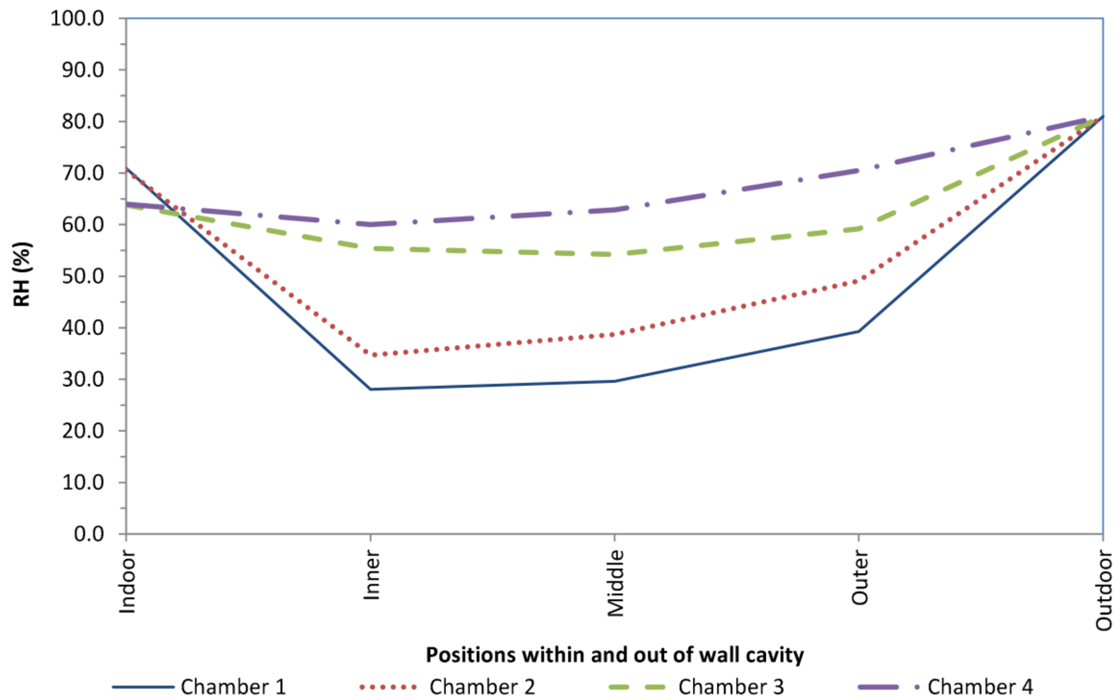

Figure 4.2-28: Average RH profile within wall cavity in cellulose bldg. on March 14th (between 12am and 3am)

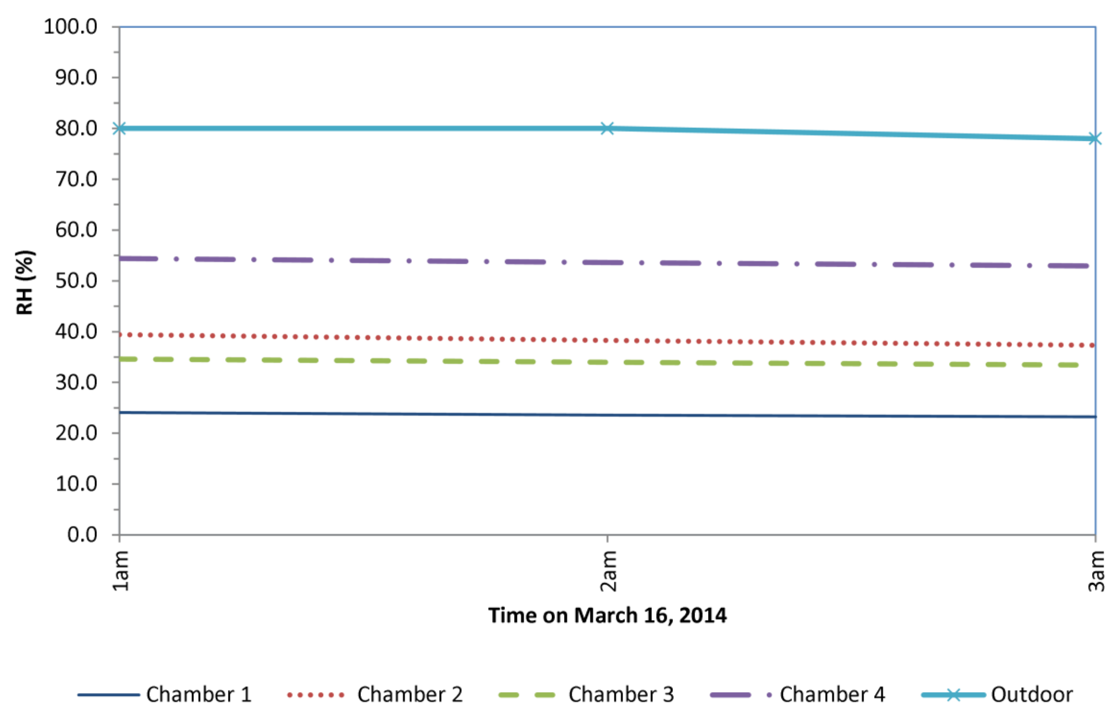

Figure 4.2-29: Outer and ambient outdoor RH in cellulose bldg. on March 16th (between 12am and 3am)

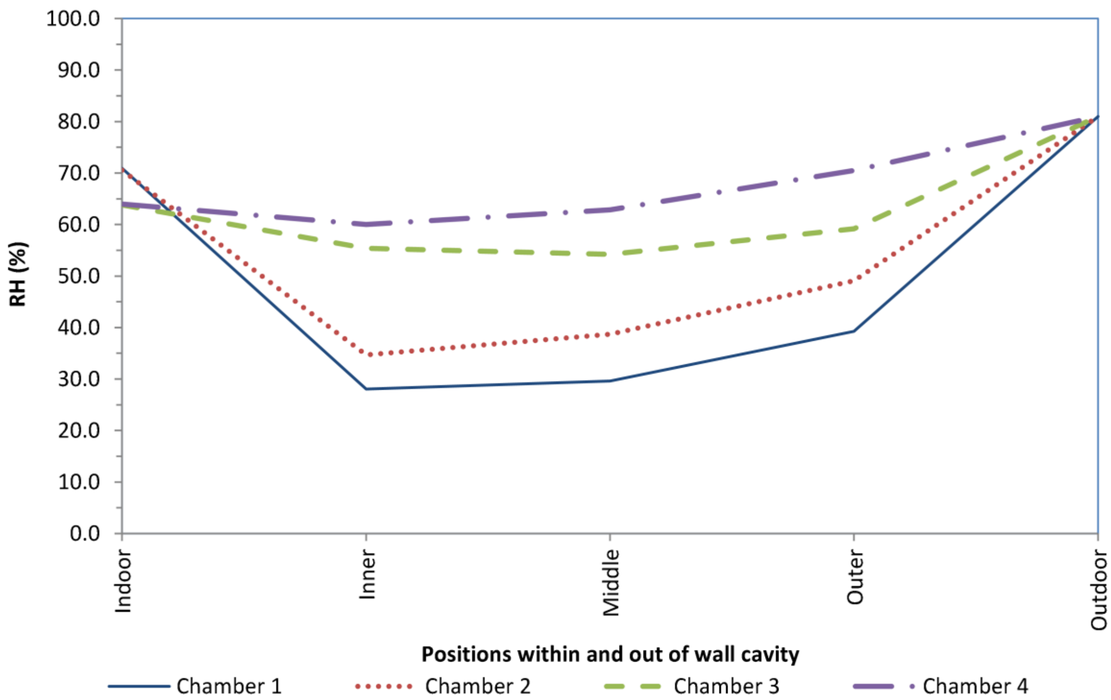

Figure 4.2-30: Average RH profile within wall cavity in cellulose bldg. on March 16th (between 12am and 3am)

Table 4.2-5: Average indoor, outer and outdoor RH in cellulose bldg. (Mar. 7-16)

	Relative Humidity (%)								
	Indoor RH				Outer RH				Outdoor RH
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	70	70	62	62	23	36	33	52	59
Maximum	72	71	64	64	47	55	64	75	94
Average	71	71	63	63	33	45	49	63	77

4.2.3.2 Temperature gradient

The indoor temperature was consistent at 20±0.5˚C in all chambers (Figure 4.2-31). The ambient outdoor temperature fluctuated between -25˚C and +6˚C over the test period. The outer temperature of the wall cavity followed the analogous pattern to ambient outdoor in all four chambers (Figure 4.2-32). As mentioned in section 4, three cases will be compared in the following subsections.

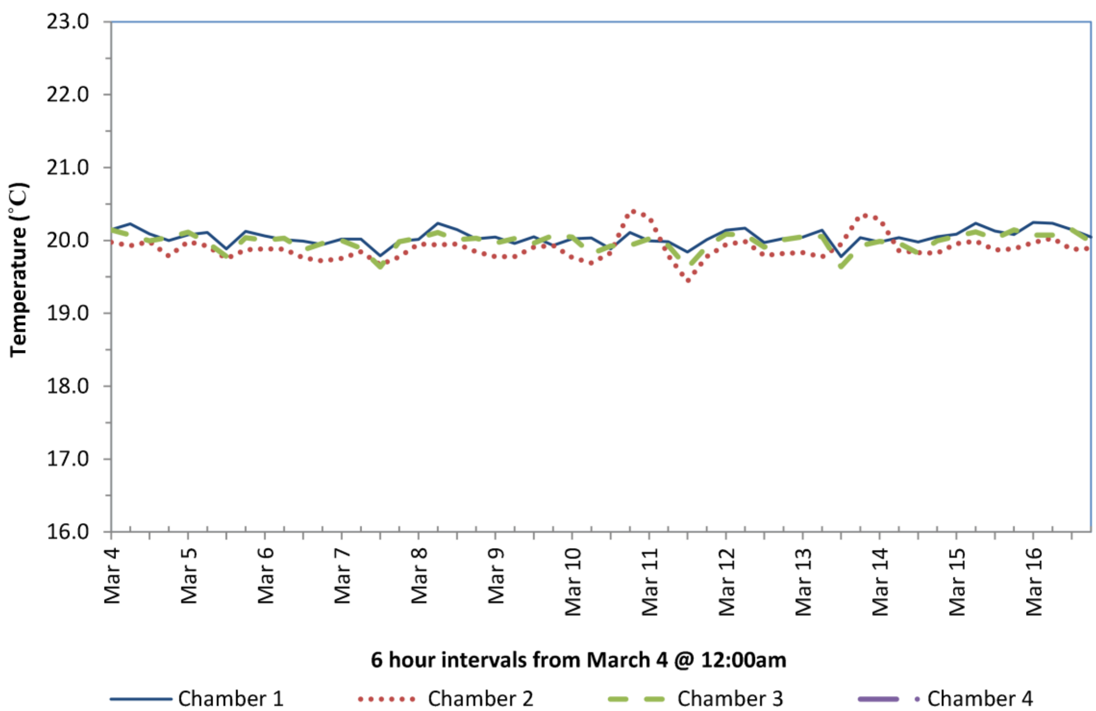

Figure 4.2-31: Indoor temperature in cellulose bldg. (March 4-16, 2014)

4.2.3.2.1 Case 1 – Effect of vapour barrier

Table 4.2-6 shows that the average outer temperature for non-consistent vapour barrier chambers 3 and 4 was 10˚C and 15˚C (just about 2˚C higher than chambers 1 and 2, respectively). Therefore, as it was seen in Figure 4.2-32 and above results, the vapour barrier had no significant influence on the outer wall cavity temperature regardless of the addition of rigid insulation. A non-consistent vapour barrier had the similar effect as above over the two snapshots as well.

4.2.3.2.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-32 and the data in Table 4.2-6, the average outer temperature in wall cavity was approximately 5˚C higher (12˚C and 15˚C in chambers 2 and 4, respectively) over the test period with the addition of the rigid insulation. Moreover, the impact of putting rigid insulation was considerable on the minimum outer temperature, which resulted 8˚C higher outer temperature. Likewise, according to Figure 4.2-33, the average and minimum outer temperature were about 8˚C higher in the chambers with rigid insulation than others on March 16th (between 12am and 3am).

4.2.3.2.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

According to Figure 4.2-32 and Table 4.2-6, this case had the most effect on temperature compared to other cases. The average outer temperature went up to 15˚C, which was 7˚C higher than the benchmark chamber 1, in the case of having non-consistent vapour barrier condition associated with external rigid insulation (chamber 4). Also, it was seen that the minimum outer temperature jumped by 11˚C in chamber 4. In addition, according to

Figure 4.2-33, similar results to the test period could be seen on March 16th between 12am and 3am.

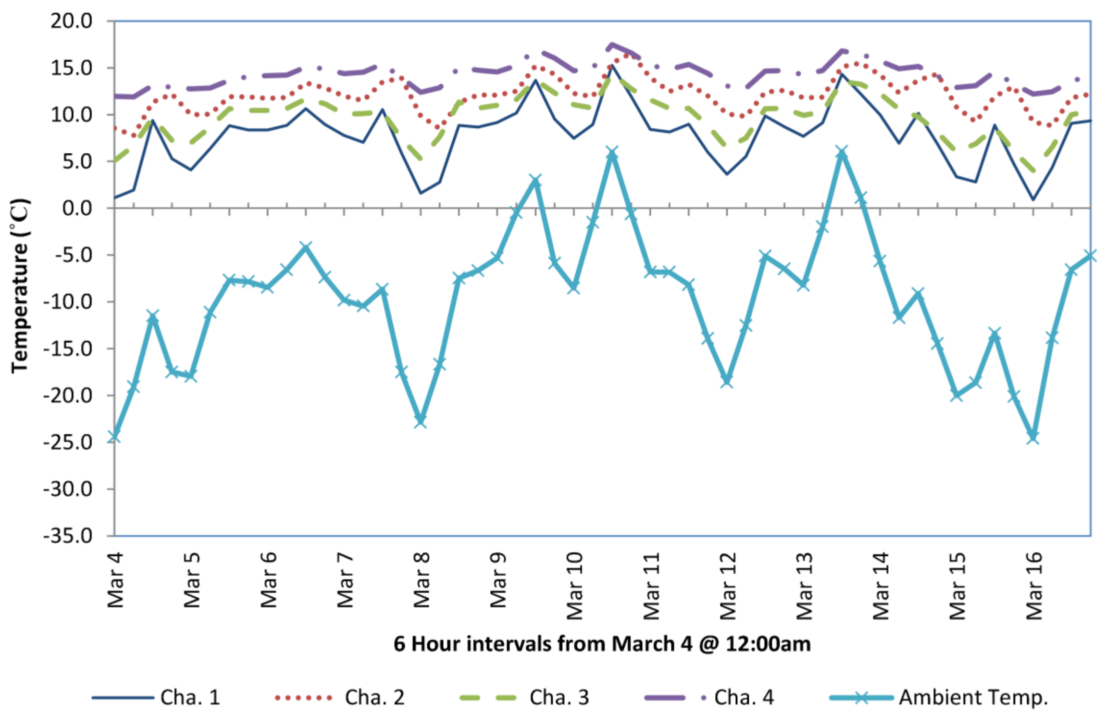

Figure 4-2-32: Outer temperature in cellulose bldg. (March 4-16, 2014)

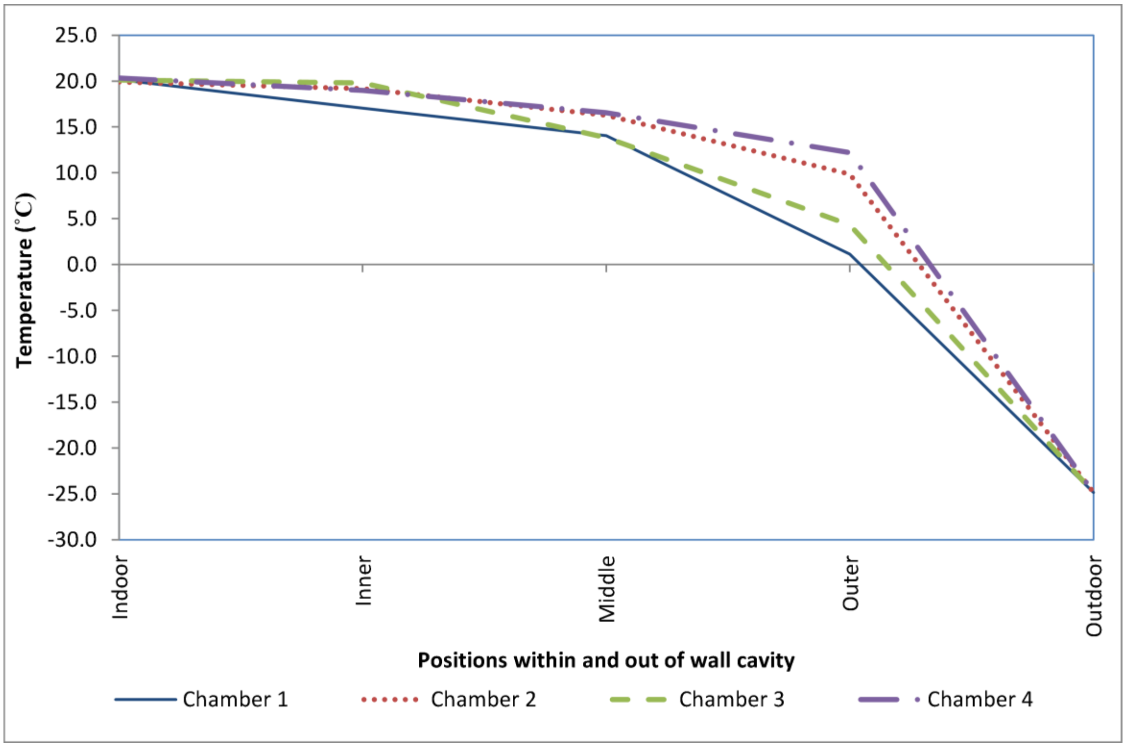

Figure 4.2-33: Average temperature profile within wall cavity in cellulose bldg. on March 16th (between 12am and 3am)

Table 4.2-6: Average indoor, outer and outdoor temp. in cellulose bldg. (Mar. 7-16)

	Temperature (°C)								
	Indoor RH				Outer RH				Outdoor RH
	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 1	Chamber 2	Chamber 3	Chamber 4	
Minimum	19.8	19.4	19.6	19.7	1	9	4	12	-25
Maximum	20.2	20.4	20.1	20.3	15	17	14	17	6
Average	20.0	19.9	20.0	20.1	8	12	10	15	-9

4.2.3.3 Heat transfer

Figure 4.2-34 illustrates that the heat flux density in all four different wall assemblies followed an inverse pattern when compared to the ambient outdoor temperature. The snapshot (March 16th) with low outdoor temperature resulted in higher heat flux density than another snapshot. The lower average outdoor temperature on March 16th compared to the average outdoor temperature over the test period was the reason for higher heat flux over snapshot in following heat flux density results.

4.2.3.3.1 Case 1 – Effect of vapour barrier

Figure 4.2-35 summarizes the result of the average heat flux density over the test period and shows that this value considering non-consistent vapour barrier (chamber 3) was 5.8 W/m² and 1.5 W/m² less than chamber 1 with vapour barrier. However, the heat flux density was 3.2 W/m² in chamber 4, just 0.4 W/m² higher than chamber 2 (with vapour barrier). According to Figure 4.2-36, the average heat flux density on March 16th between 12am and 3am in chamber 3 was 9.1 W/m² (2.4 W/m² less than chamber 1), while in chamber 4 was 4.5 W/m² and 1 W/m² greater than chamber 2.

It was seen that making non-consistent vapour barrier had no considerable effect in the chambers with rigid insulation. However, it was not expected to see higher heat flux density in chamber 1 with consistent vapour barrier than chamber 3. This issue will be discussed in subsection 4.4.2.

4.2.3.3.2 Case 2 – Impact of external rigid insulation

According to Figure 4.2-35, the average heat flux density through wall assembly in chamber 2 was 2.8 W/m² and 4.5 W/m² lower than chamber 1 considering the same vapour barrier system but with the addition of an external rigid insulation. Similarly, that value in the chamber with non-consistent vapour barrier (chamber 4) was 3.2 W/m² by adding rigid insulation and 2.6 W/m² lower than chamber 3.

Furthermore, it was seen that the impact of rigid insulation was more outstanding on March 16th than March 14th. According to Figure 4.2-36, the average heat flux density in chamber 2 (3.5 W/m²) was 8 W/m² lower than chamber 1 on March 16th between 12am and 3am. Also, this value in chamber 4 (4.5 W/m²) was 4.6 W/m² less than chamber 3.

Overall, both the snapshot and the test period resulted in a considerable decrease of the heat flux density by adding rigid insulation to both consistent and non-consistent vapour barrier chambers. However, this effect was greater in the consistent vapour barrier chamber (62% decrease) than non-consistent vapour barrier (45% decrease) over the test period. This will be discussed further in section 4.4.2.

4.2.3.3.3 Case 3 – Effect of simultaneous non-consistent vapour barrier and external rigid insulation

According to Figure 4.2-35, having both non-consistent vapour barrier condition associated with adding external rigid insulation affected the average heat flux density through wall assembly from 7.3 W/m² in baseline chamber 1 to 3.2 W/m² in chamber 4. Also, on March 16th (as snapshot), the average heat flux density was 11.5 W/m² in chamber 1 and 7 W/m² higher than chamber 4 (Figure 4.2-36).

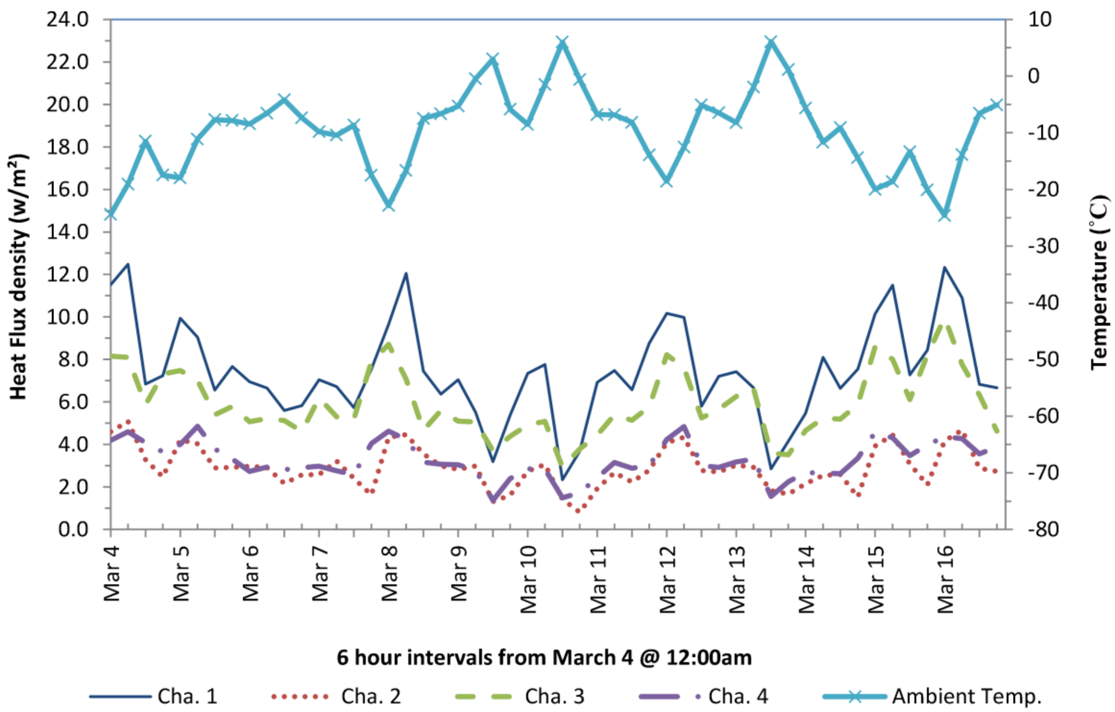

Figure 4.2-34: Heat flux density and ambient outdoor temperature in cellulose bldg. (March 4-16, 2014)

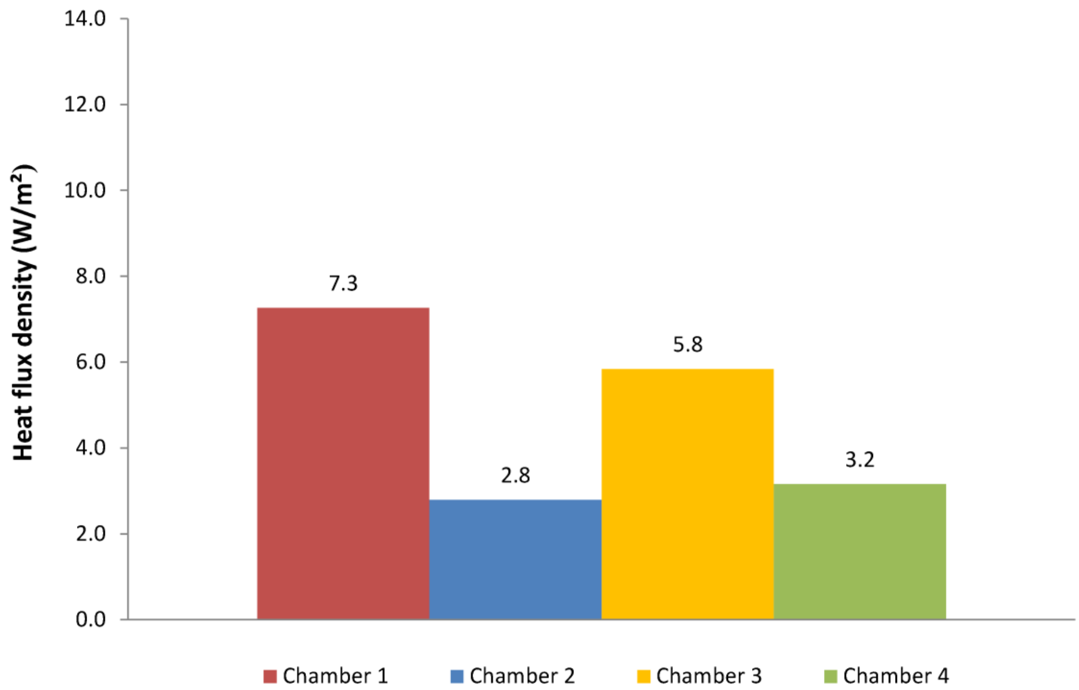

Figure 4.2-35: Average heat flux density in cellulose bldg. (March 7-16, 2014)

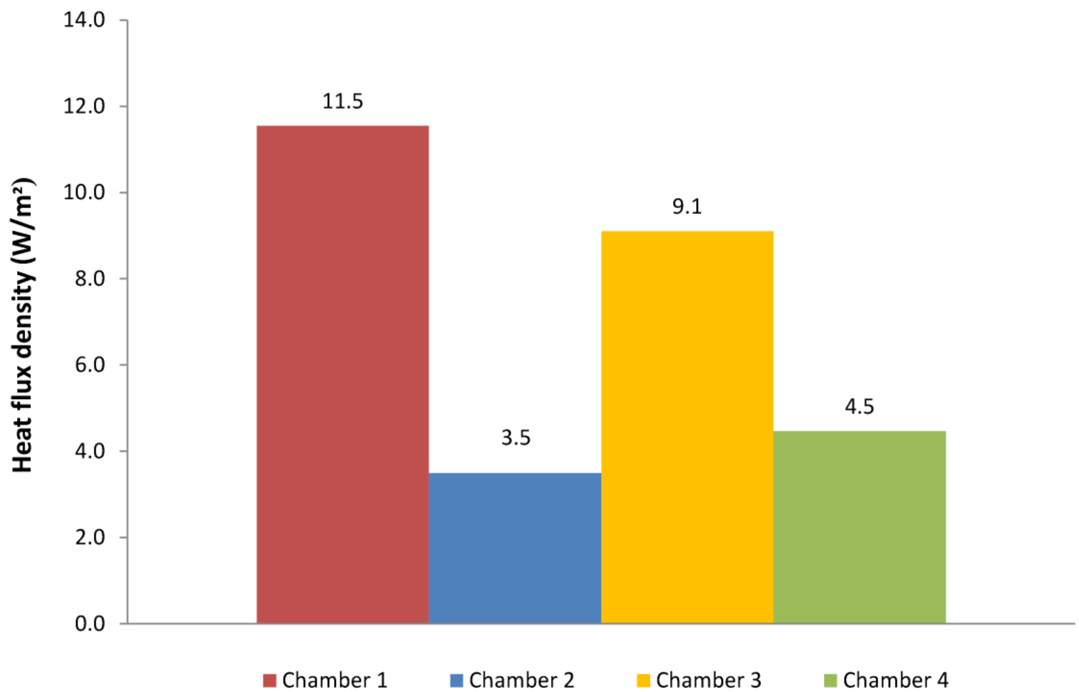

Figure 4.2-36: Average heat flux density in cellulose bldg. on March 16th (between 12am and 3am)

4.2.4 Cellulose density results

The blown-in cellulose from the monitored portion of each chamber was used for density tests. The results showed that the cellulose density in chambers 1, 2 and 4 were 54.19, 54.22 and 54.20 kg/m³ respectively, and the density in chamber 3 was just slightly higher at 54.80 kg/m³. Therefore, it was determined that the cellulose density in all four chambers was consistent and almost the same. ASHRAE standard presents cellulose density between 30-50 kg/m³ (ASHRAE Handbook Fundamentals, 2009). The density of cellulose was more than the expected in all four chambers, which might be due to location near the bottom of the wall or using denser cellulose for the whole wall. Further tests in different heights of walls (out of the test portion) would determine whether or not the density is uniform throughout the wall, which was not within the scope of the present study.

During removal of the cellulose out of all four test portions, voids around wires were observed. Feeding the sensors to the desired locations within the wall cavity (middle and outside) may have pushed the cellulose. As a result, some voids were created around wires afterwards, which might locally disturb the temperature gradient within wall cavities. The above impact of instrumentation could be the reason why the temperature profile within the wall cavity in cellulose was higher than WUFI modeling results, and the temperature gradient from inside to outside was less than simulation results as stated in section 4.4.2.

Density tests were conducted at the end of January 2015, almost one year after the primary test periods with different levels of indoor RH. Therefore, the following evidences in terms of OSB and cellulose moisture related condition are not the results over the test periods but do provide an indication of conditions over the test period.

After the end of the third test period (March 16, 2014), chambers were run without any source of indoor humidity control, and all chambers were open to indoor cellulose building environment. The last two months of data collection (prior to the density test) showed that indoor temperature maintained at about 20.5°C and the average indoor RH was roughly 34% since there were no source of moisture and humidity inside the building after high level RH test period. During density tests, it was seen that cellulose in both chambers with continuous vapour barrier (chambers 1 and 2) was not wet, and there was no evidence of frost on interior face of OSB sheathing. On the other hand, the outer cellulose was wet in chambers with non-consistent vapour barriers. The cellulose close to OSB was completely wet and frozen in chamber 3. Also, frost was apparent on the inner surface of OSB in both chambers 3 and 4 (Figure 4.2-37). These results also confirmed the test results showing high outer RH in both chambers 3 and 4. Also, calculations in Appendix "A" showed possibility of condensation over test periods, in chambers 3 and 4, and this issue was confirmed due to evidence of wet cellulose and frost

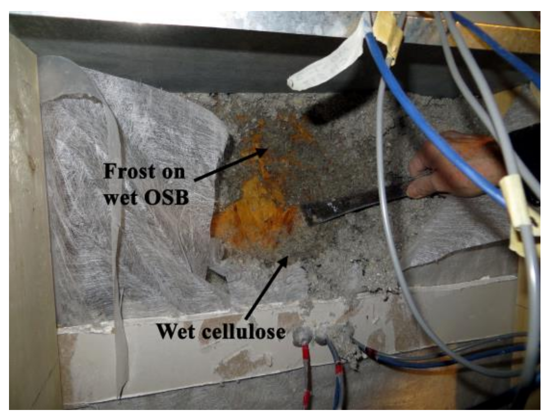

Figure 4.2-37: Wet and dry cellulose in chamber 3 and frost on OSB sheathing

on OSB during the density tests when the ambient outdoor temperature and RH were approximately -5°C and 75% respectively.

Furthermore, it was seen that the cellulose close to inside sheathing (front side) in chamber 1 seemed denser than the back side. Since two different sensors (middle and outside) were fed through cellulose at mid-height to different locations but 25mm away from each other horizontally (Figure 3-14 in section 3.4), pushing the dense cellulose in the locations close to each other might locally change the density of cellulose. The HFS was located at the centre area of the monitored portion and close to the affected area. Therefore, this locally affected location could impact on HFS. The above effect of instrumentation could be seen as an increase on heat flux density in chamber 1 as discussed in section 4.4.2.

4.3 Simulation Results

Heat and moisture migration were simulated using WUFI (Wärme und Feuchte instationär) software. This software allows users to evaluate hygrothermal behaviour of a defined multilayer building envelope for a given data of ambient inside and outside. The version of WUFI used in the present study could calculate heat and moisture transport in one-dimensional multilayer building envelope. The ambient indoor and outdoor temperature and RH were defined as input data. Also, the materials selected for each layer were chosen from the database list and had the specification close to the materials used in the experiments (Table A-1 in Appendix "A"). Moreover, as mentioned earlier, only a portion of the vapour barrier was cut in two of the chambers (chambers 3 and 4) and one-dimensional WUFI version could not simulate completely this kind of wall cross section. Therefore, the present study only shows the results of two chambers (in each building) with consistent vapour barriers (chambers 1 and 2) simulated with WUFI.

The input data from three test humidity levels were simplified to evaluate the impact of just the ambient indoor and outdoor temperature and RH on different wall assemblies over the test period. The climatic data were defined over three test humidity levels including low, mid and high level of indoor RH. It was seen that more consistent material properties and climate data before and over the test period will result in more accurate results. Therefore, the results of the last stage (stage 3 with high level of indoor RH) are presented and averaged over the steady state for comparison in following sections.

Monitored locations in the software were presented in the same locations as experimental sensor locations.

4.3.1 Fiberglass batt enclosure

Figures B-1 and B-2 (Appendix “B”) show the outer temperature within the wall cavity in chambers 1 and 2, respectively from March 4th to March 16th. It could be seen that the average outer temperature was almost the same as the experimental results presented in section 4.1.3.2 over the steady state period (March 7-16, 2014), i.e. the average outer temperature was just 2°C lower than experimental results in both chambers 1 and 2.

According to results presented in section 4.1.3.1 and figures B-3 and B-4, it could be seen that the WUFI results for the averages inner and middle RH were just about 8% less than experimental results in both chambers. Also, almost the same variance was seen in terms of outer RH within wall cavity in chamber 2. On the other hand, the average outer RH in chamber 1 was 20% less than experimental result. As discussed in section 4.1.3.1, the above considerable difference between the simulation and test results could be another reason for the possibility of dislocated outer RH sensor closer to OSB sheathing (in chamber 1). Figures B-3 and B-4 also illustrates that the outer RH ranged almost the same regardless of the addition of extruded polystyrene foam or not over the test period. However, inner and middle RH profiles in chamber 2 were higher than chamber 1.

Figure B-5 illustrates almost the same trend of heat flux density in benchmark chamber 1 as it was presented from field test results. However, the heat flux density in chamber 2 was a little higher in model than experimental result (Figure B-6). The direction of heat flux was from inside to outside. As an assumption the numbers presented are negative in WUFI, while they were taken as positive for the experimental results.

4.3.2 Dense pack cellulose enclosure

Figures B-7 and B-8 (Appendix "B") illustrate temperature fluctuation within wall cavity in both chambers. It could be seen that the average inner temperature was the same as the test results discussed in section 4.2.3.2, but the average middle and outer temperature were approximately 10°C lower than the experimental results over the steady state period. However, the effect of the addition of rigid insulation on temperature was similar to the test, i.e. the average outer temperature was 7°C higher in chamber 2 than chamber 1. Also, it was evident that most of the time the outer temperature was above 0°C and sometimes even over 5°C by the addition of rigid insulation (chamber 2).

According to results presented in section 4.2.3.1 and figures B-9 and B-10, it could be seen that the WUFI results for the average outer RH was almost the same as the test results. The addition of rigid insulation did not affect considerably on the average outer RH compared to chamber 1, while the test results showed increase of the average outer RH.

Figure B-11 and B-12 illustrate heat flux density results in chambers 1 and 2, respectively. It was evident that heat flux densities in both chambers in fiberglass and chamber 2 in cellulose building were higher than field test results. However, the heat flux density in chamber 1 was lower than test result. This could be another evident for unusual heat flux density result in chamber 1, which was discussed in section 4.4.2.

4.3.3 Comparisons between simulation and test results

As stated in sections 4.3.1 and 4.3.2, even though general agreement between the results from WUFI and field test was observed, a number of discrepancies were noted as follows:

- The outer RH in chamber 1 was lower in WUFI compared to test results in fiberglass building, which verifies the possibility of dislocated outer RH sensor as discussed in section 4.1.3.1.
- Heat flux density in chamber 1 was lower than experimental value in cellulose building, which could verify the high heat flux density value in chamber 1 may have been affected by instrumentation as explained in section 4.4.2. Also, lower simulation temperature within wall cavity in both chambers in cellulose building confirmed unusual higher experimental values from field test as stated in section 4.4.2.
- Other differing results between simulation and experiment would be eliminated or decreased by presenting more accurate initial data. Since both buildings were constructed in summer 2011, the materials used in building envelope have

reached equilibrium conditions after construction and before the addition of rigid insulation, so the field test results were based on the real situation. Therefore, if the real initial material properties were available, this would be an asset for WUFI to better represent the test building conditions over a longer timeframe (Karagiozis, Künzel, & Holm, 2001). However, difference in results did not affect the comparisons between chamber performance as mentioned in sections 4.4.1 and 4.4.2, and general agreements were reached.

4.4 Summary of test buildings performance

In this section the performance of fiberglass batt and dense pack cellulose building envelopes from sections 4.1, 4.2 and 4.3 will be summarized and compared.

4.4.1 Fiberglass batt insulation

Non-consistent vapour barrier:

Having a non-consistent vapour barrier increased the average outer RH significantly to about 80% and 90% in mid and high level RH respectively, regardless of the addition of rigid insulation or not. In the low-level RH category, however, the outer wall cavity RH was different in the chambers with and without rigid insulation. That is, having non-consistent vapour barrier increased the average outer RH considerably to about 70% in the chamber with rigid insulation, while that value went up to just 55% in the chamber without rigid insulation.

The effect of having non-consistent vapour barrier on the average outer temperature was insignificant and just between 3°C and 5°C increase over all three test humidity levels. In addition, in chambers with non-consistent vapour barrier, heat flux density was between 54% and 69% greater than consistent vapour barrier chamber considering no rigid insulation, while that value was between 19% and 34% higher considering rigid insulation. Therefore, it was evident that in terms of heat flux, the impact of having non-consistent vapour barrier was higher in the chambers without rigid insulation than the other type. Moreover, it could be clearly seen that in the categories low and mid-level

RH, which the average ambient outdoor temperature was almost the same and about 20°C below zero, each chamber had almost the same heat flux density over low and mid-level RH period regardless of about 20% indoor RH difference between low and mid-level categories.

RH in the wall cavity increased due to a non-consistent vapour barrier condition, so as stated in section 2.1, heat flux density would increase (Simonson, Tao, & Besant, 1994). Since relative decrease in thermal value of whole wall assembly (due to increasing RH) was higher in the chamber just insulated with fiberglass batt (chamber 3) than chamber with rigid insulation as additional insulation (chamber 4), the percentage decrease in heat flux density was greater in chamber 3 than chamber 4 by making non-consistent vapour barrier.

Having a non-consistent vapour barrier increases the RH value within a wall cavity and the possibility of condensation on OSB sheathing over the test periods. Figures A-1 to A-4 (Appendix "A") illustrate vapour pressure profiles through wall assemblies on March 16, 2014 (between 12am and 3am). Condensation would occur wherever partial vapour pressure in the graph was equal or higher than saturation vapour pressure, so it would be developed in chambers with non-consistent vapour barrier (chambers 3 and 4).

Application of external rigid insulation:

In the chambers with non-consistent vapour barrier, the average outer RH did not change considerably in the mid and high level of indoor RH with the addition of rigid insulation.

In low-level RH, however, the average outer RH increased by 13% to 68% by adding rigid insulation. The outer RH data in chamber 1 was higher than the expected value due to a dislocated outer sensor (closer to outside sheathing compared to other chambers), which was discussed in sections 4.1.3.1 and 4.3.1. Therefore, if the values from WUFI (section 4.3.1 and Appendix “B”) were replaced with the experimental outer RH in chamber 1, it was seen that in the chambers with consistent vapour barrier, the average outer RH was not affected noticeable by adding rigid insulation (chamber 2) in all three levels of indoor RH, i.e. the maximum average outer RH in chamber 2 was 53% when third test period was run.

The average and minimum outer temperature increased significantly between 7-9°C and 10-12°C respectively by adding rigid insulation regardless of having consistent vapour barrier or not in all three levels of RH categories. Therefore, the average outer temperature in non-consistent vapour barrier chamber went up to 0°C in low and mid-level categories and even 7°C in high-level category. Finally, the impact of the addition of rigid insulation resulted in approximately a 40% heat flux density decrease in the consistent vapour barrier chamber, while that value reduced significantly by 49%-54% in non-consistent vapour barrier chamber over all three test humidity levels. Therefore, it was evident that in terms of heat flux, the impact of rigid insulation was higher in non-consistent vapour barrier chambers than another type.

Effect of both vapour barrier and rigid insulation simultaneously:

As mentioned in the above discussion, the impact of external rigid insulation was not considerable on outer RH, so adding rigid insulation associated with non-consistent vapour barrier compared to baseline chamber would not be a worst case scenario. On the other hand, a comparison between the benchmark chamber and chamber 4 showed that the average and minimum outer temperature jumped by approximately 13°C and 18°C at 0°C and -3°C, respectively in both low and mid-level RH categories. Similarly, the average and minimum values increased significantly by 10°C and 17°C at +7°C and 0°C, respectively in high level indoor RH. Therefore, the potential for mold growth increased due to high outer RH and temperature increase close to outside sheathing. In addition, the average heat flux density in chamber 4 decreased by about 20% in both low and mid-level RH categories and by 28% in high level RH when compared to baseline chamber.

Overall, in terms of heat flux, not only the addition of rigid insulation but also having consistent vapour barrier appeared to have considerable effect on reducing heat flux density. That is, the heat flux density in chamber 3 with non-consistent vapour barrier was 2.6 to 2.8 times greater than the value in chamber 2 with both rigid insulation and continuous vapour barrier over all three test humidity levels. Also, above summary comparisons between baseline chamber 1 and other chambers showed that the percentage of negative effect of having non-consistent vapour barrier was higher than the percentage of positive impact of the addition of rigid insulation on heat flux density over all three test humidity levels.

4.4.2 Dense pack cellulose insulation

As discussed in sections 4.2.4, during density tests it was seen that the cellulose was denser than expected, so the method of instrumentation in wall cavity may have created some voids around wires. This would be a reason that the temperature results within the wall cavity were higher than the results from WUFI simulation (as presented in section 4.3.2).

It was apparent that the heat flux density was unusual in chamber 1. It was discussed in cellulose density results section that the density of cellulose was higher than standard, so the methods of instrumentation could affect locally the heat flux sensor area in chamber 1. Since both fiberglass batt and dense pack cellulose insulations had almost the same thermal resistance (Table A-1 in Appendix “A”), the simulation data resulted almost the same heat flux density for chamber 1 in both buildings. Therefore, in following discussions, the average heat flux density of chamber 1 was assumed close to fiberglass experimental value just for comparison with other chambers.

Cellulose insulation is a porous material and has the ability to absorb and release water vapour. According to the ASHRAE standard, the sorption isotherm results shows that for dry-blown cellulose insulation the equilibrium MC at 50.5% and 88.1% RH are 6.1% and 24% respectively, while the values for fiberglass batt insulation are just 0.21% and 0.75% (ASHRAE Handbook Fundamentals, 2009). The absorbent nature of cellulose resulted in lower RH values within the wall cavity in the cellulose building when compared to the fiberglass building.

Non-consistent vapour barrier:

The impact of having non-consistent vapour barrier was insignificant on average outer RH over low level RH period, i.e. the average outer RH did not go higher than 37%. Also, it was seen that even though there was about 20% indoor RH difference between low and mid-level categories, the average outer RH in non-consistent vapour barrier chambers rose just about 6% from low to mid-level, i.e. the maximum average outer RH over first and second test periods was 43%. On the other hand, the impact of compromising vapour barrier was significant on outer RH over the high level RH test period. It was evident that the average outer RH in non-consistent vapour barrier chambers jumped by about 20% from the mid- to high-level categories. In other words, the maximum average outer RH was 63%, considering rigid insulation.

As stated in fiberglass building performance (section 4.4.1), having non-consistent vapour barrier will increase the RH value within wall cavities and the possibility of condensation on OSB sheathing over the test periods. Figures A-5 to A-8 (Appendix "A") show vapour pressure profiles through wall assemblies on March 16, 2014 (between 12am and 3am). As pointed out in Appendix "A", condensation would occur in chambers with non-consistent vapour barrier (chambers 3 and 4) regardless of having rigid insulation or not. This issue also was verified during density test as discussed in section

4.2.4. In fact, frost on OSB sheathing and wet cellulose (close to outside sheathing) were observed within wall cavities in chambers with non-consistent vapour barrier.

The impact of having non-consistent vapour barrier on the average outer temperature was insignificant and just 2-3°C increase over all three test humidity levels. Similarly, it was evident that having non-consistent vapour barrier in chamber with rigid insulation did not affect considerably on heat flux density over all three test humidity levels. However, heat flux density in baseline chamber was higher than the chamber with non-consistent vapour barrier. Other studies (Nicolajsen, 2005) showed that increase in moisture content of cellulose insulation did not affect thermal conductivity of cellulose insulation considerably. Therefore, just slightly higher heat flux density in chamber 3 than chamber 1 was expected since non-consistent vapour barrier allow more vapour to go through wall assembly and increased cellulose moisture content.

The period of September 26-28, 2014 was also chosen, and the related data of chambers 1 and 3 were analyzed in order to evaluate this issue further over a warmer period of time. There were no salt solution and heaters in the chambers at that period of time. The ambient outdoor temperature fluctuated higher and lower than the indoor temperature profile over the test period. Figures 4.4-1 and 4.4-2 illustrate that heat flux density and outer wall cavity temperature in both chambers were almost equal between 23 and 30 hours from September 26th (at 12am) when the ambient outdoor temperature was between 16˚C and 20˚C. However, when the outdoor temperature went up to 29˚C after 15 hours from the beginning of this period of the test, the absolute amount of heat flux density in chamber 1 was greater than chamber 3 considering the direction of the heat transfer from outside to inside. Similarly, the heat flux density in chamber 1 went higher than chamber 3 over the last hours of the three-day test period when ambient outdoor temperature dropped to less than 15˚C considering heat transfer direction from inside to outside. It is evident from the above results that heat flux density followed the similar pattern to temperature gradient and ambient temperature. As mentioned previously, it was expected to see just slightly higher heat flux density in chamber 3 (due to higher relative humidity within wall cavity) than benchmark chamber 1. The instrumentation method in the dense cellulose insulation (as discussed in section 4.2.4) could cause this discrepancy which would locally affect cellulose density in chamber 1. Simulation results also showed lower heat flux density in chamber 1 than experimental result as stated in section 4.4.2. The average heat flux results from WUFI were replaced to experimental value for comparison purpose. Therefore, it was evident that non-consistent vapour barrier did not considerably impact the heat flux in the chamber without rigid insulation as well as with rigid insulation.

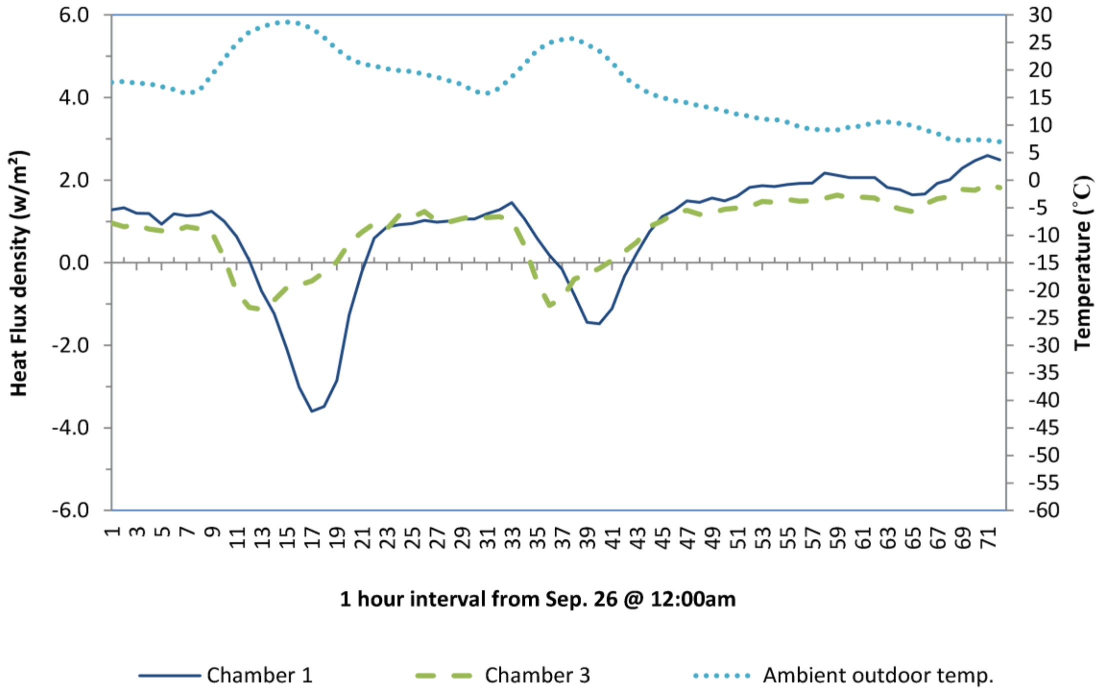

Figure 4.4-1: Heat flux density and ambient outdoor temperature in cellulose bldg. (Sep. 26-28, 2014)

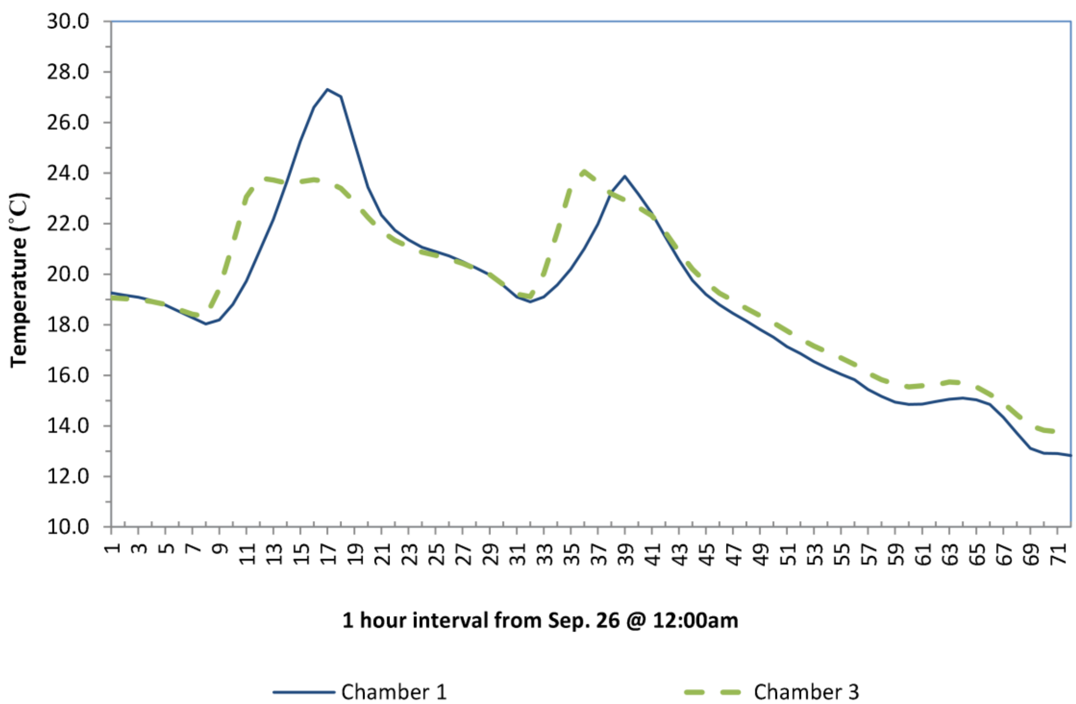

Figure 4.4-2: Outer temperature in cellulose bldg. (Sep. 26-28, 2014)

Application of external rigid insulation:

The effect of the addition of rigid insulation was considerable on the average outer RH (12-17% increase) regardless of vapour barrier conditions, and almost the same values over low and mid-level RH category were seen. Even though the numbers increased from mid to high level, the impact of rigid insulation was almost the same as other two categories, i.e. the average outer RH rose by 12-14% regardless of vapour barrier condition.

In terms of the average outer temperature, test results showed approximately a 4-6°C increase due to adding rigid insulation over all three test humidity levels. The above outer temperature variance between chambers were close to the numbers in fiberglass building and the WUFI results (section 4.3.2) which indicated that general agreement was reached. However, the temperature values in each location within wall cavities were higher than fiberglass numbers. Also, temperature gradients from inside to outside were less than values from simulation results (section 4.3.2). As discussed in section 4.3.2, the method of instrumentation in dense cellulose could cause above discrepancy. Finally, adding rigid insulation decreased the heat flux density by 47-58% in consistent vapour barrier chamber and by 36-45% in non-consistent vapour barrier chamber over all three test humidity levels. As mentioned previously, above numbers were calculated based on using WUFI value for heat flux density in chamber 1.

Effect of both vapour barrier and rigid insulation simultaneously

The addition of rigid insulation associated with having non-consistent vapour barrier (chamber 4) was the worst case scenario in terms of the average outer RH and temperature over all three test humidity levels. The average outer RH increased significantly by 18-24% in chamber 4 in low- and mid-level categories as compared to the baseline chamber. That value jumped by 30% at 63% in chamber 4 over the high-level RH period.

Similarly, the average outer temperature went up considerably by 7-8°C in chamber 4 compared to benchmark chamber over all three test humidity levels. Therefore, the potential for mold growth increased due to high outer RH and the temperature increase close to OSB sheathing. In addition, the average heat flux density in chamber 4 decreased by 43-52% as compared to the baseline chamber 1 (considering simulation values) over all three test humidity levels.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

Reducing energy consumption in a cold climate region such as Manitoba is an important factor in the design of an effective building envelope. Older buildings in the housing stock can benefit substantially by improving their thermal performance. One common approach to achieve higher thermal values in building envelopes is by installing external rigid insulation. One complicating factor with this approach is that many older buildings have either imperfect vapour barriers or no interior vapour barrier, which has to be taken into account during any changes in wall assemblies. Fiberglass batt and dense pack cellulose were chosen as two common materials for insulation in wood frame residential buildings in Canada. These insulations were used within two of the identical buildings at the Alternative Village at the University of Manitoba. The field tests were conducted over three different indoor RH levels (low, medium, and high) defined as approximately 25%, 45% and 65% RH, respectively, from January 31 to March 16, 2014. The principal objective of the experimental program was to evaluate the hygrothermal behaviour of existing building envelopes considering the combinations of vapour barrier system and the addition of external rigid insulation over different indoor RH loads and the possibility of condensation and potential of mold growth within wall cavity.

Fiberglass batt wall assemblies:

Having a non-consistent vapour barrier increased the average outer RH to about 80% and 90% over mid and high level indoor RH, respectively, regardless of the addition of rigid insulation. On the other hand, it was seen that the addition of rigid insulation (XPS) did not have a noticeable impact on the average outer RH. When a combination of non-consistent vapour barrier with external rigid insulation was considered, the average outer temperature increased by 10-14°C over three test humidity levels, i.e. the average outer temperature was between 0°C and 7°C (in chamber 4) over all three test humidity levels. The results also showed that due to an increasing RH within the wall cavity in non-consistent vapour barrier wall assemblies, condensation would occur. As an overall result, the potential for mold growth increased by having higher RH and temperature close to the outside sheathing (OSB) in mid and high indoor RH (about 40% and 60% respectively).

In terms of heat flux, in the chamber without rigid insulation, a 54%-69% increase was evident due to having non-consistent vapour barrier. Similarly, the average heat flux density in chamber with rigid insulation rose by 19-34% by having a non-consistent vapour barrier. In other words, the impact of a vapour barrier was greater on the average heat flux density in chambers without rigid insulation than those with such insulation layer. Moreover, the addition of rigid insulation decreased the average heat flux density by about 40% in consistent vapour barrier chamber and by 49-54% in non-consistent vapour barrier chamber over all three test humidity levels. However, comparison between original wall assembly and two wall assemblies one with non-consistent vapour barrier and the other one with rigid insulation showed that the effect of having non-consistent vapour barrier on increasing of absolute heat flux density was more than absolute heat flux density decrease due to the addition of rigid insulation. Therefore, not only the addition of rigid insulation but also having consistent vapour barrier had considerable effect on reducing heat flux density. That is, the wall assembly with non-consistent vapour barrier had 2.6 to 2.8 times as much heat flux density as the wall assembly with XPS and continuous vapour barrier. This issue has to be taken into account that having a consistent vapour barrier not only reduced moisture-related problem within the wall cavity but also it decreased heat flux density significantly. Therefore, improving thermal resistance during building renovation without considering the vapour barrier system and its effects on overall thermal performance of building envelope is not recommended professionally and is not a cost effective approach in long term.

Dense pack cellulose wall assemblies:

The impact of having non-consistent vapour barrier was considerable on outer RH over high level indoor RH category. In fact, the average outer RH rose significantly to 49% and 63% considering without and with rigid insulation, respectively; it was evident 12-

14% increase of average outer RH due to addition of rigid insulation regardless of vapour barrier system. Also, the outer temperature was not affected noticeably in different interior vapour barrier conditions, while temperature went up 4-6°C with external rigid insulation over all three test humidity levels. Therefore, the worst case scenario was observed by addition of rigid insulation in non-consistent vapour barrier wall assemblies, which caused higher average outer temperature and RH over all three test humidity levels. The results also showed that like the fiberglass building, condensation would occur due to increasing RH within wall cavity in non-consistent vapour barrier wall assemblies. As an overall result, the possibility for mold growth increased by having higher RH and temperature close to outside sheathing (OSB) in high indoor RH. However, the average outer RH and temperature need to be increased to be a real potential for mold growth over heating season.

In addition, the effect of having non-consistent vapour barrier was insignificant on heat flux density over all three test humidity levels. However, the addition of rigid insulation decreased the average heat flux density by 47-58% in consistent vapour barrier chamber and by 36-45% in non-consistent vapour barrier chamber over all three test humidity levels.

5.2 Practical implications of this research

While it is important for a research document to provide specific outcomes emerging from experimental work, in this case it is considered of equal importance to provide insight as to how this information could be used in practice. The reality of improving energy performance of the existing housing stock is upon us. The implementation of model energy codes and ever-increasing costs, in addition to simply wanting to create better buildings makes the results of this research very applicable. While some of the following items may not be new, and have been known anecdotally, the author believes they are lessons learned from this research that can be incorporated into building upgrades and retrofits.

The application of external insulation will improve the thermal resistance of the building, to do so without careful attention to the integrity of a vapour resisting layer on the inside will place the building envelope in jeopardy over the long term. The external insulation layer can cause a build-up of moisture in the exterior sheathing over time. With the right conditions mold can form. Unless the integrity of the vapour barrier can be verified it is not recommended to put external insulation on especially when inside relative humidity may be greater than 50%.

While it was not specifically studied in this research, it is anticipated that as exterior sheathing absorbs moisture, the addition of external insulation will not allow this trapped moisture to dry out completely during summer months.

5.3 Recommendations for future work

The results of this experimental program provided valuable insight into the behaviour of wall assemblies using external rigid insulation strategies. To gain a more in depth understanding the following recommendations for future research are proposed.

a) Since the present study on different wall assemblies except benchmark (original) wall assembly were not conducted over a long period of time prior to the test period. It would be beneficial to monitor the performance of each wall assembly over longer period of time and get moisture content values under different conditions when materials reach the equilibrium conditions.

b) The mold formation should be investigated in non-consistent vapour barrier conditions over at least one year test period, and further test would be conducted in combination of non-consistent vapour barrier with exterior rigid insulation wall assemblies. These further studies would evaluate the effect of external insulation on the dry process of materials within wall cavity after heating season when the potential for mold growth rises and materials need to be dried up faster.

c) Three dimensional version of WUFI with more material and climate data before and over the test will provide more accurate results.

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Appendices

Appendix A- Vapour pressure calculation

The saturation and partial vapour pressures are calculated to find out the possibility of condensation within wall cavity. As an example the average results (between 12am and 3am) on March 16, 2014 are used for comparison. The material properties database was summarized in Table A-1. The following calculations in fiberglass building chamber 2 are a typical method to calculate partial and saturation vapour pressures.

Ambient indoor temperature= Tin= 20.1°C

Ambient outdoor temperature= Tout= -24.8°C

Ambient indoor RH= RHin= 60%

Ambient outdoor RH= RHout= 79%

Inner temperature= T1= 16.8℃ Middle temperature= T2= 0.1℃

Outer temperature= T'3= -11.7℃ (which is 12mm from the inner face of the OSB)

OSB and fiberglass interface temperature (T3) is calculated by extrapolation between the above middle and outer values (T2 and T'3) as follows:

T3= 0.1-140/2×(0.1+11.7)/(140/2-12)= -14.1℃

Other layers temperature and vapour pressures are calculated from theoretical thermal resistance value and vapour resistance of materials and the above experimental data. For instance, the temperature of the interface between XPS and OSB (T4), partial vapour pressure (Pp4) and saturation vapour pressures (Ps4) are calculated as follows:

Total thermal resistance of wall assembly (Rt) = 5.5 $m^2.°K/W$

XPS thermal resistance (Rx) = 1.32 $m^2.°K/W$

Therefore, T4 = Tout + Rx / Rt × (Tin-Tout) = -24.8+1.32/5.5×(20.1+24.8)= -14.0°C

Indoor saturation vapour pressure (Bolton, 1980): Psin= 0.6112 × EXP (17.67 × Tin / (Tin + 243.5))= 0.6112 × EXP (17.67 × 20.1 / (20.1 + 243.5))= 2.35 KPa

Outdoor saturation vapour pressure (Psout)= 0.08 KPa

Indoor partial vapour pressure (Ppin)= RHin × Psin = 0.6×2.35= 1.41 KPa

Outdoor partial vapour pressure (Ppout)= RHout × Psout= 0.79×0.08= 0.06 KPa

Ps4= 0.6112 × EXP (17.67 × (-14.0) / (-14.0 + 243.5))= 0.21 KPa

Exterior paint vapour resistance (Z4)= 0.002646 $Pa.s.m^2/ng$

Cumulative vapour resistance between inside and exterior paint (Zt4)= 0.308 $Pa.s.m^2/ng$

Total cumulative vapour resistance (Zt)= 0.339 $Pa.s.m^2/ng$

Pp4= Ppin - ((Zt4 / Zt) × (Ppin - Ppout))= 1.41-(0.308/0.339×(1.41-0.06))= 0.18 KPa

Similarly calculations are done and the following graphs are resulted (Figures A-1 to A-8).

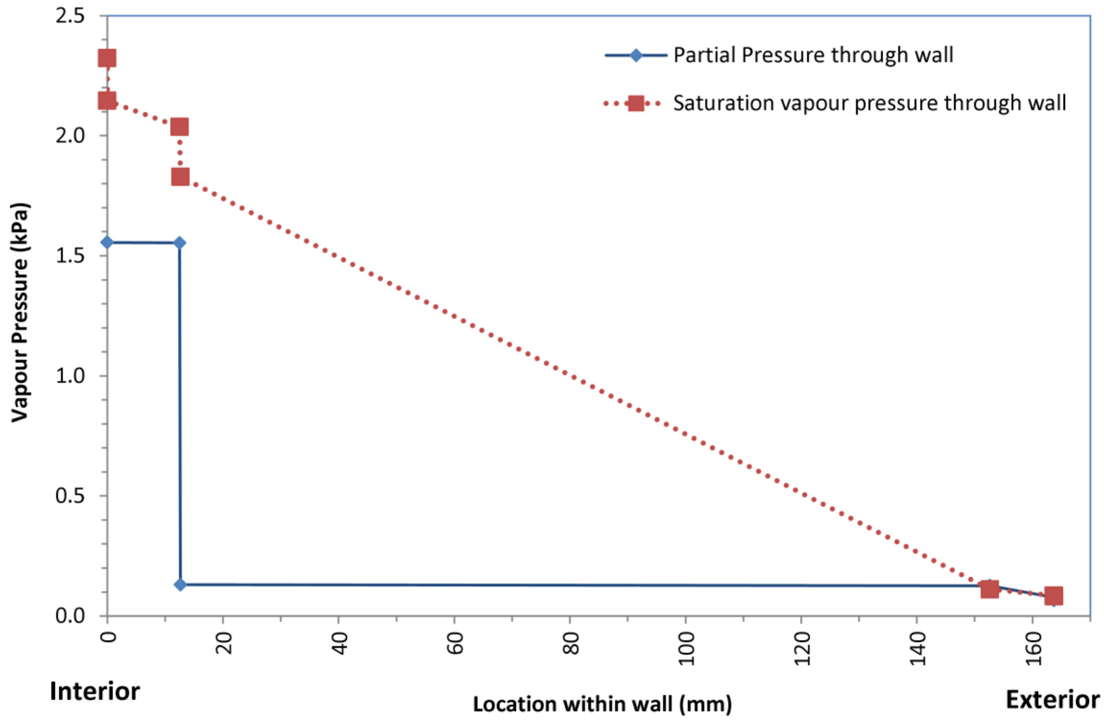

Figure A-1: Average saturation and partial vapour pressures in fiberglass bldg. cha. 1 on March 16th (between 12am and 3am)

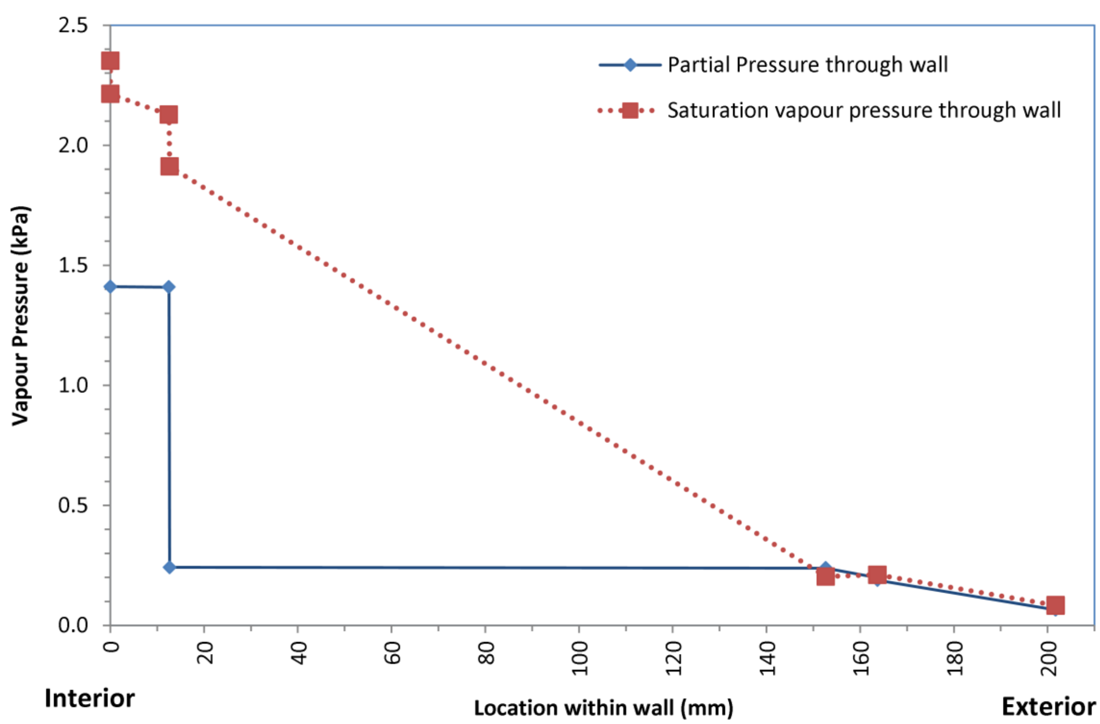

Figure A-2: Average saturation and partial vapour pressures in fiberglass bldg. cha. 2 on March 16th (between 12am and 3am)

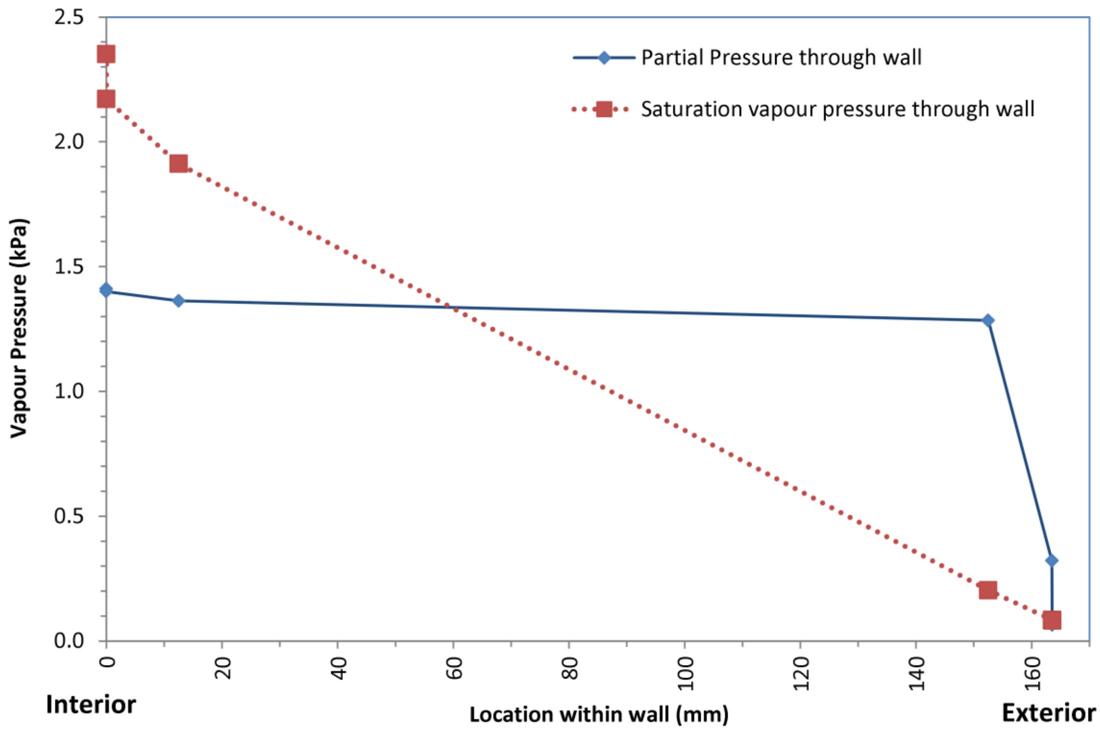

Figure A-3: Average saturation and partial vapour pressures in fiberglass bldg. cha. 3 on March 16th (between 12am and 3am)

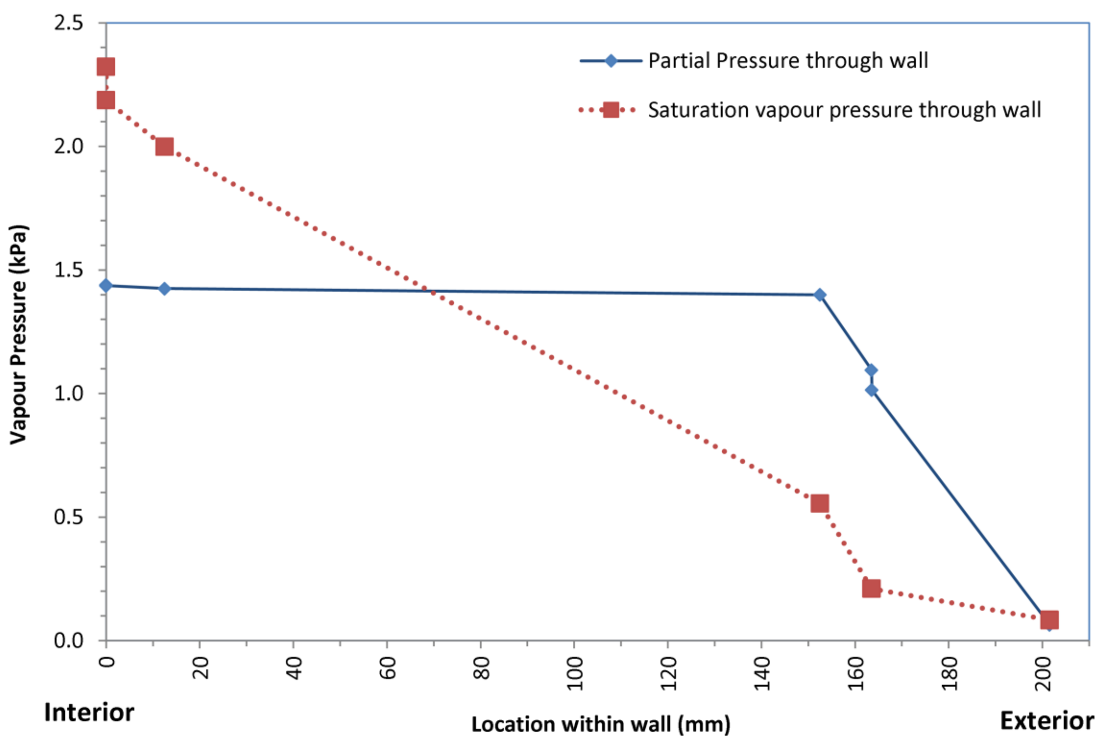

Figure A-4: Average saturation and partial vapour pressures in fiberglass bldg. cha. 4 on March 16th (between 12am and 3am)

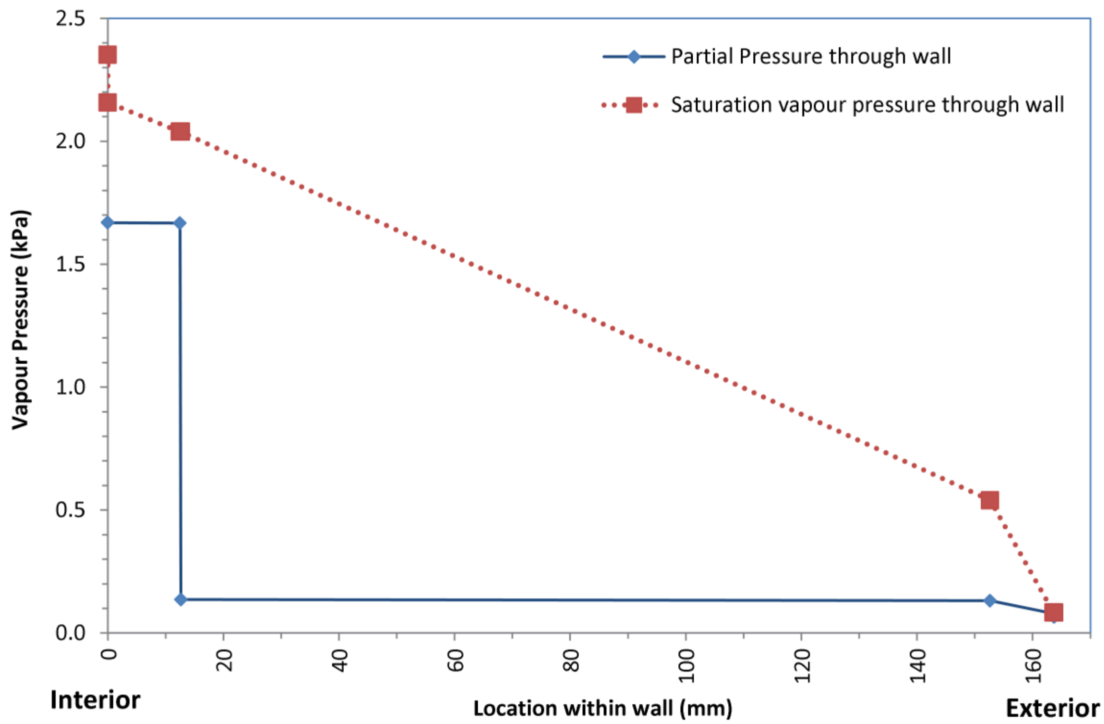

Figure A-5: Average saturation and partial vapour pressures in cellulose bldg. cha. 1 on March 16th (between 12am and 3am)

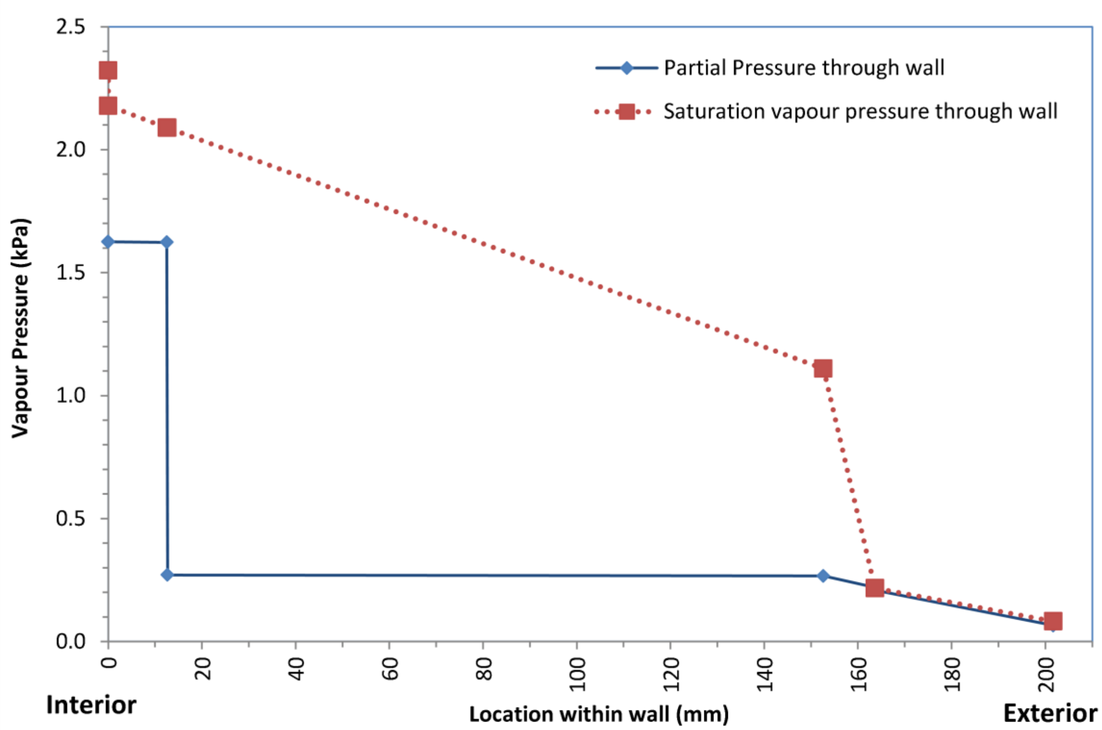

Figure A-6: Average saturation and partial vapour pressures in cellulose bldg. cha. 2 on March 16th (between 12am and 3am)

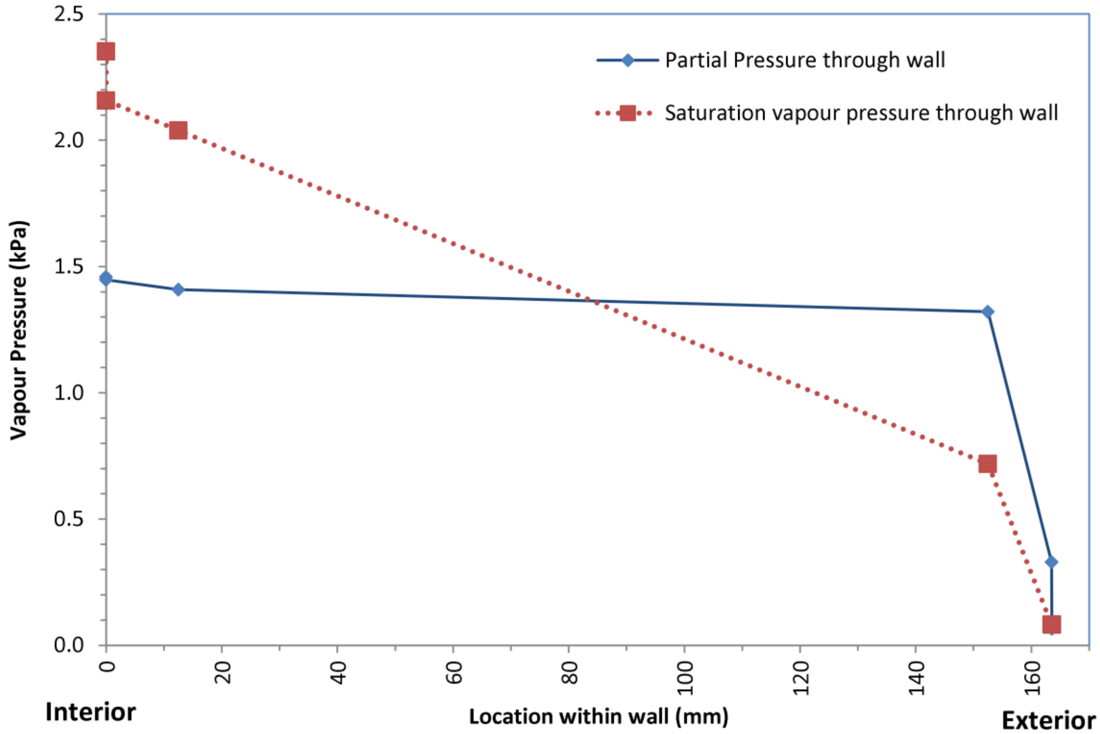

Figure A-7: Average saturation and partial vapour pressures in cellulose bldg. cha. 3 on March 16th (between 12am and 3am)

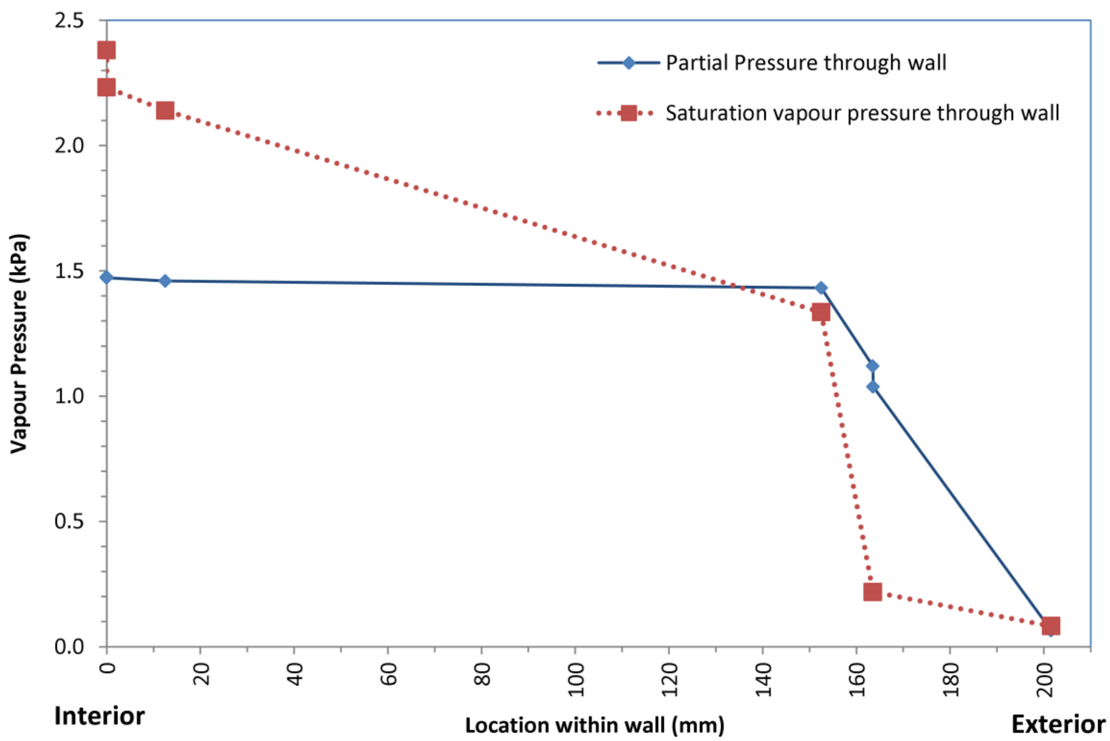

Figure A-8: Average saturation and partial vapour pressures in cellulose bldg. cha. 4 on March 16th (between 12am and 3am)

Table A-1: Thermal resistance, water vapour permeance and permeability of building materials

Materials	***Thickness (mm)***	**** Thermal Resistance RSI (m^2.°K/W)***	**** Water Vapour Permeability (ng/s.m.Pa)***	****Water Vapour Permeance Perms (ng/s.m^2.Pa)***
Fibreglass Batt	140	3.872	172	1228.571
Blown-in Cellulose	140	3.585	156	1114.286
Extruded Polysterene Foam (XPS)	38	1.32	1.22	32.105
Oriented Strand Board (OSB)	11	0.11	1.23	111.818
Gypsum wall board	12.5	0.08	31.9	2552.000
Polyethylene (6mil)	0.15	-	-	3.4
Exterior Paint	0.06	-	-	378
Interior Air Film	-	0.12	-	-
Exterior Air Film	-	0.03	-	-

* ASHRAE Handbook Fundamental 2009 (Chapter 26)

Appendix B- WUFI simulation results

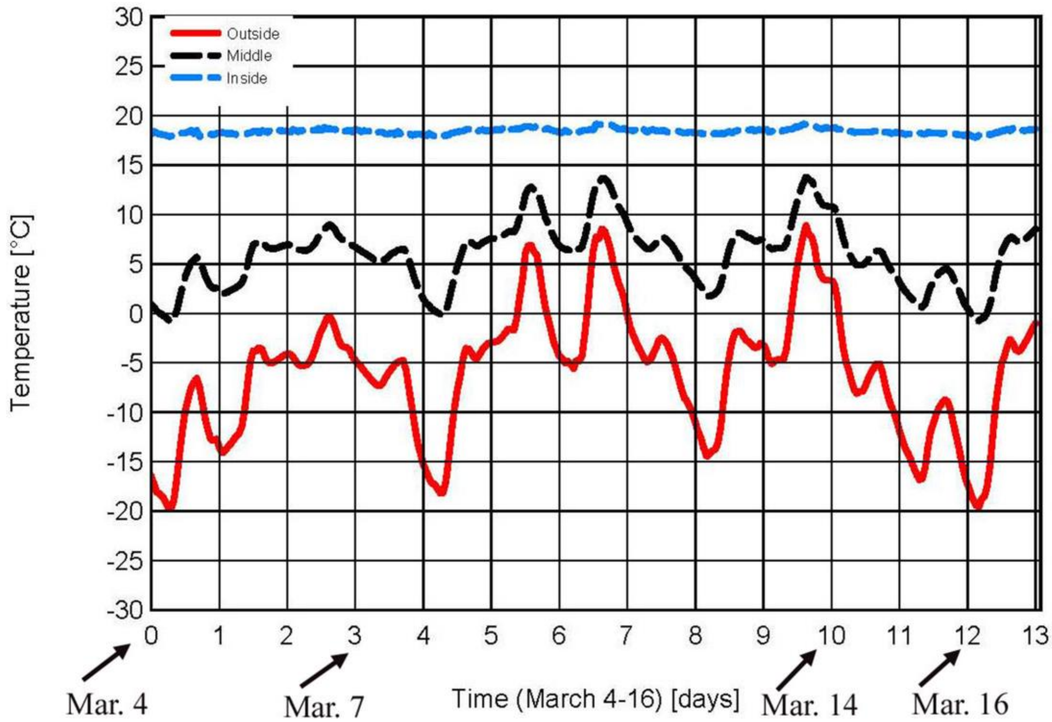

Figure B-1: Daily temp. within wall cavity of cha. 1 in fiberglass bldg. (March 4-16)

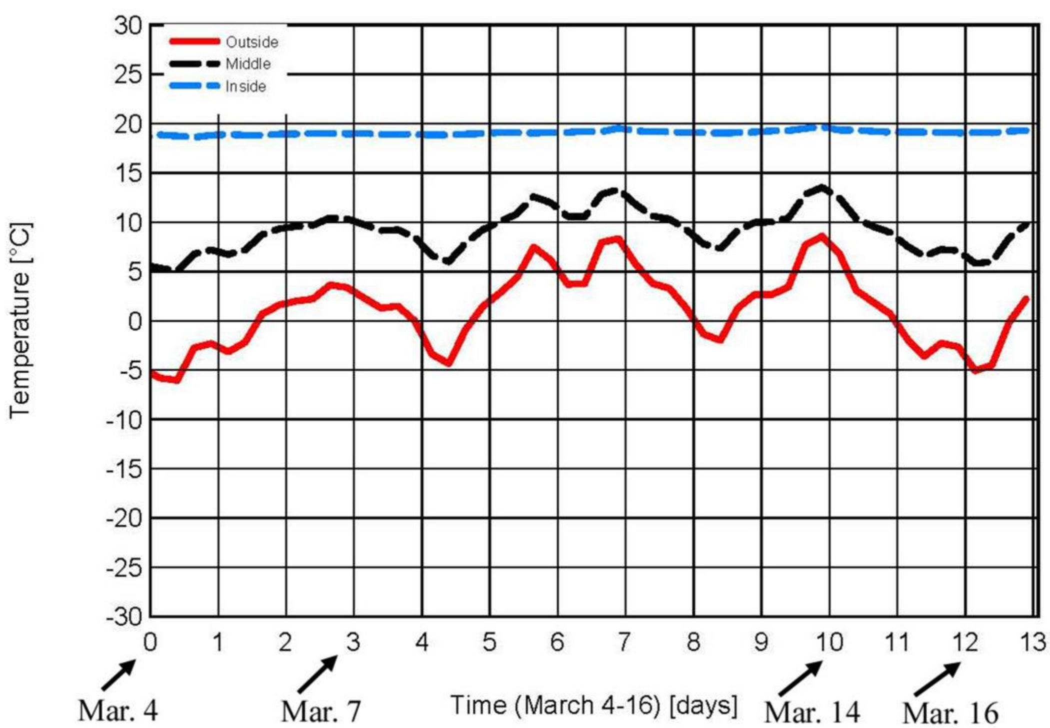

Figure B-2: Daily temp. within wall cavity of cha. 2 in fiberglass bldg. (March 4-16)

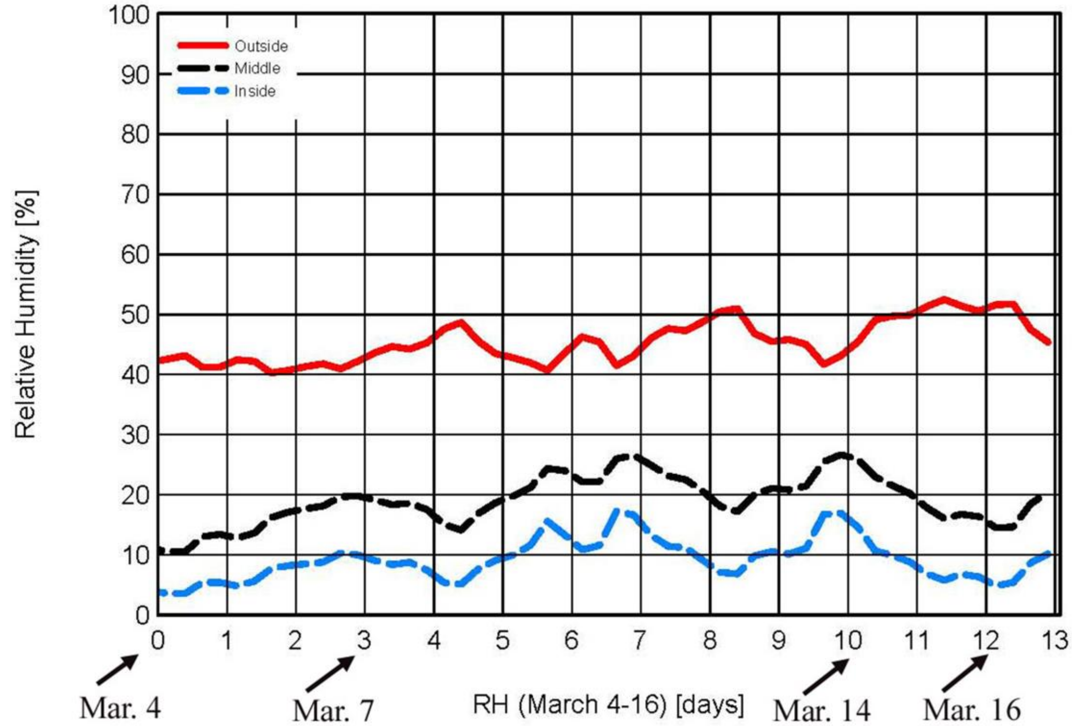

Figure B-3: Daily RH within wall cavity of cha. 1 in fiberglass bldg. (March 4-16)

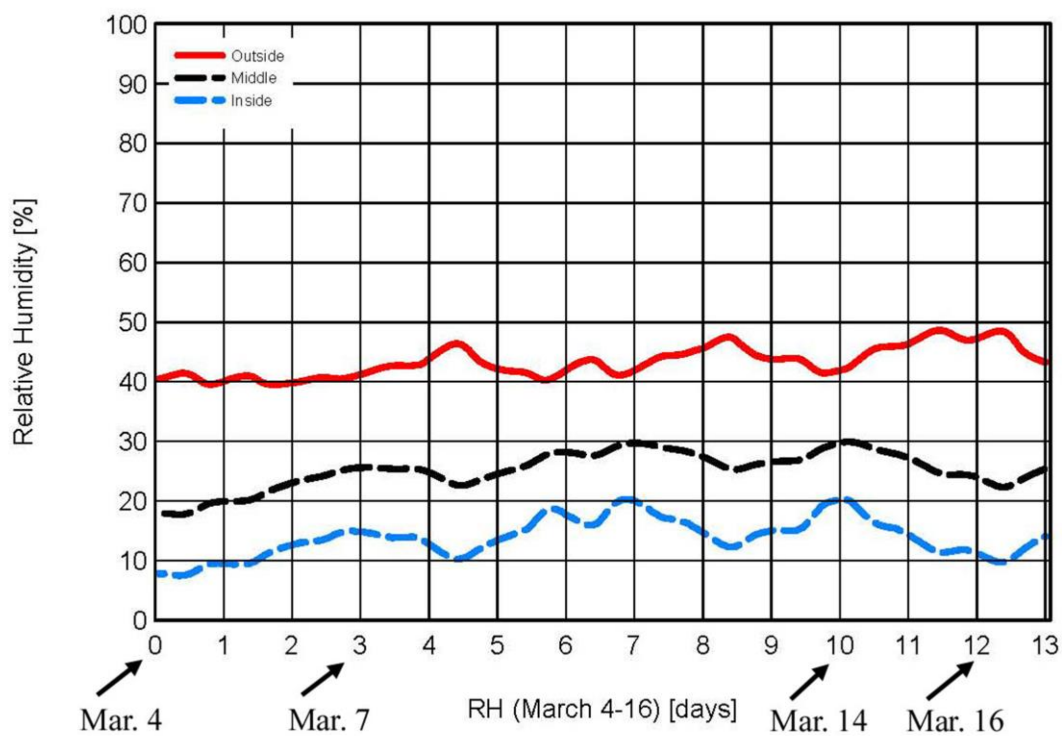

Figure B-4: Daily RH within wall cavity of cha. 2 in fiberglass bldg. (March 4-16)

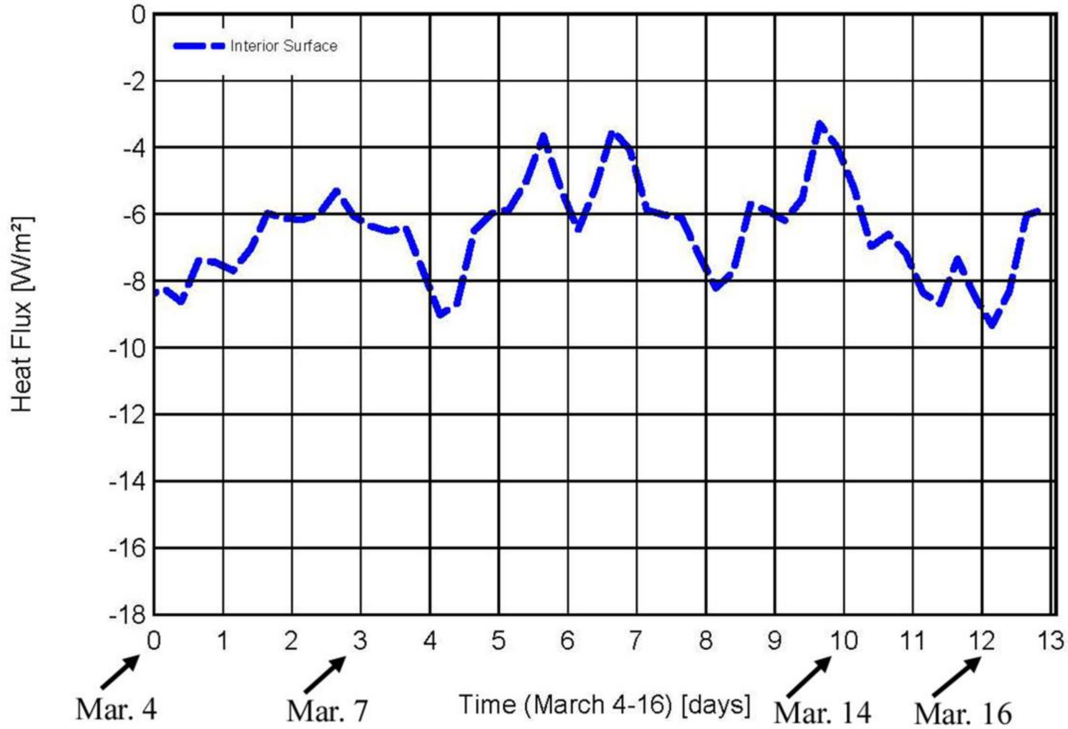

Figure B-5: Daily Heat Flux Density of cha. 1 in fiberglass bldg. (March 4-16)

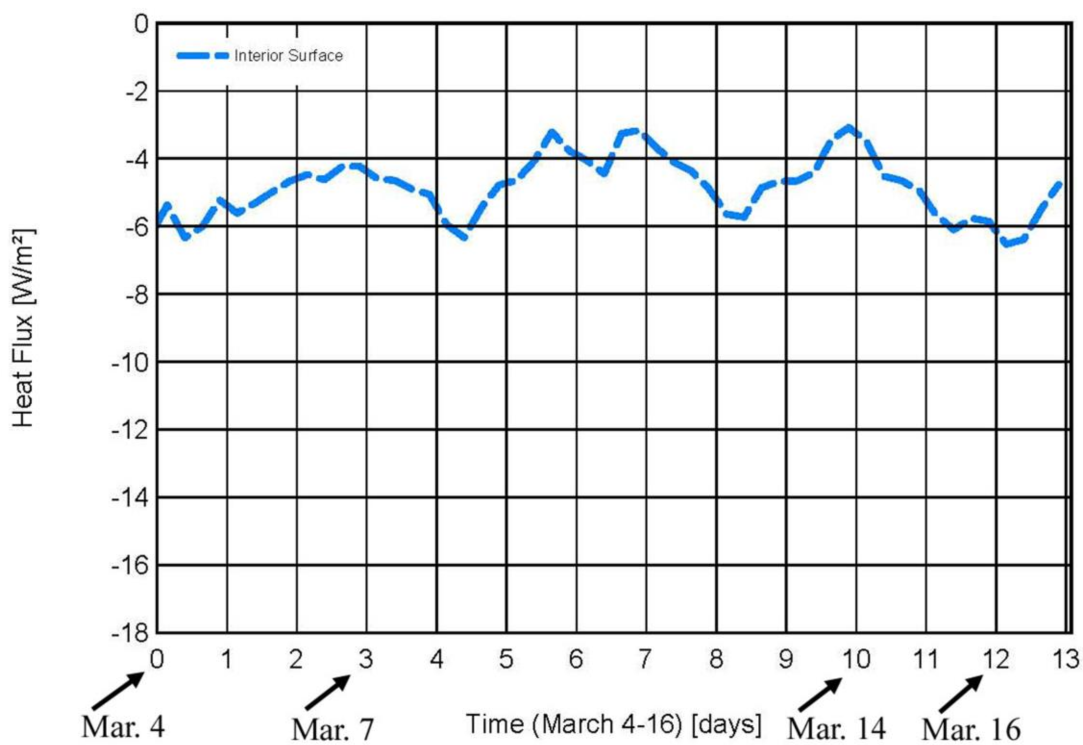

Figure B-6: Daily Heat Flux Density of cha. 2 in fiberglass bldg. (March 4-16)

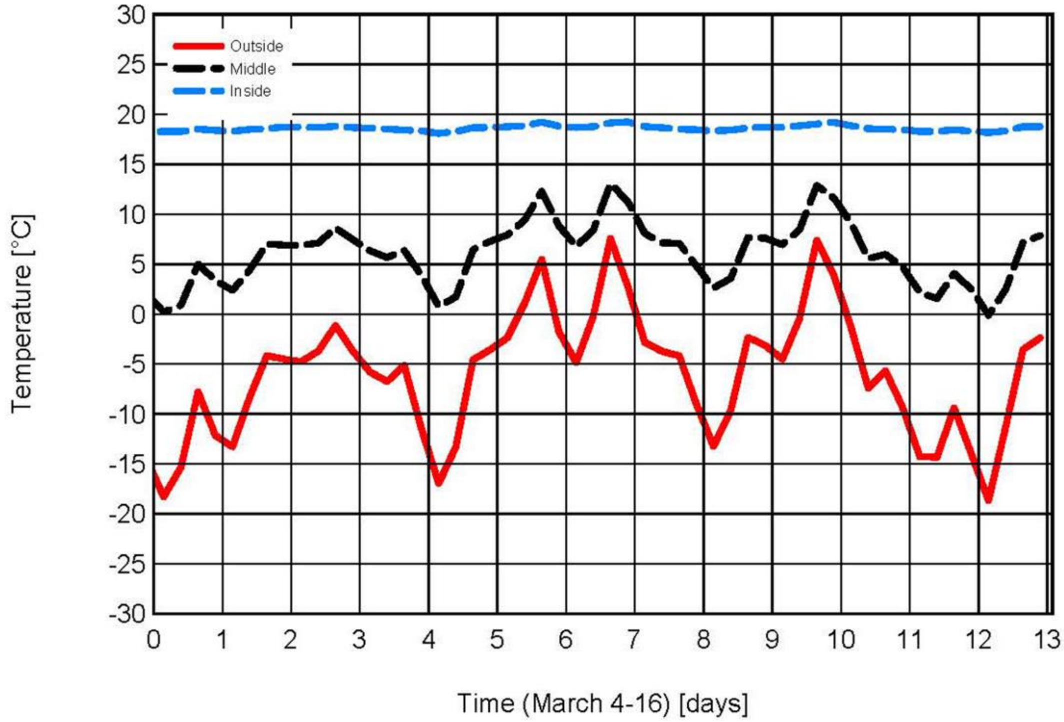

Figure B-7: Daily temp. within wall cavity of cha. 1 in cellulose bldg. (March 4-16)

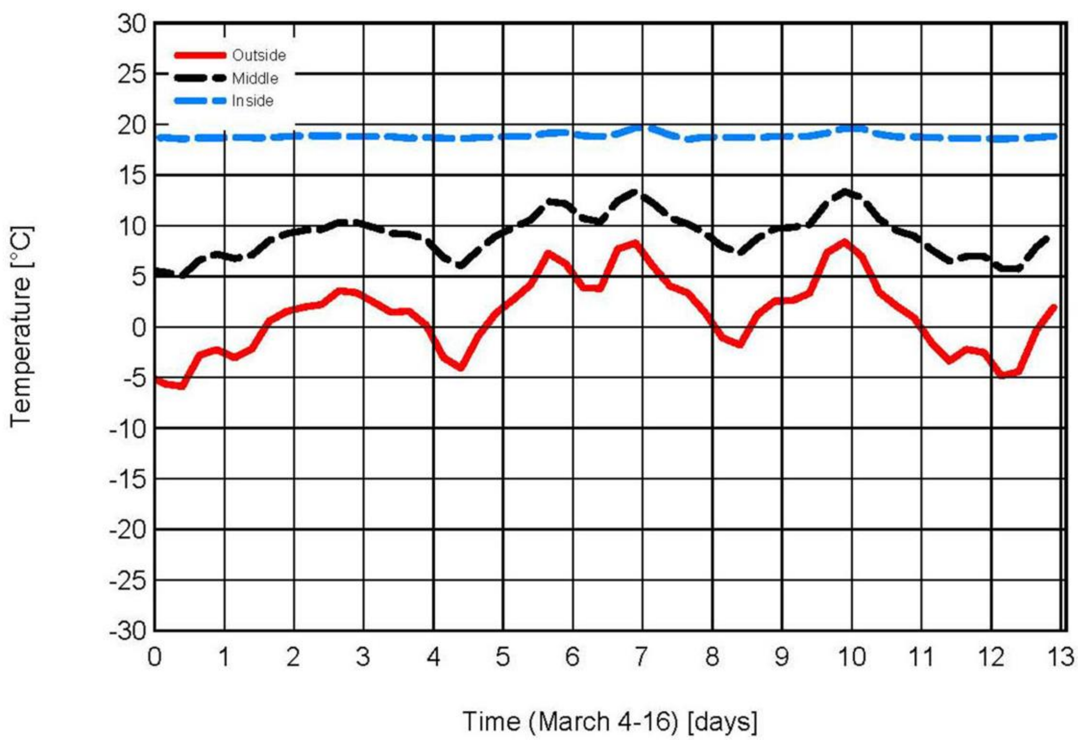

Figure B-8: Daily temp. within wall cavity of cha. 2 in cellulose bldg. (March 4-16)

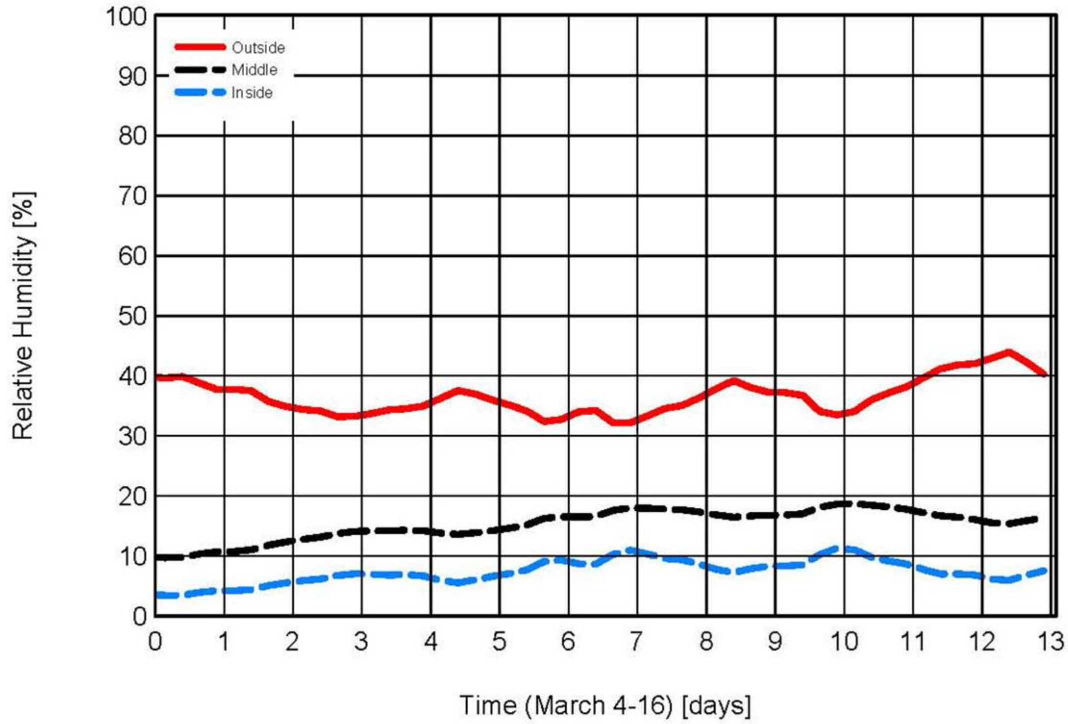

Figure B-9: Daily RH within wall cavity of cha. 1 in cellulose bldg. (March 4-16)

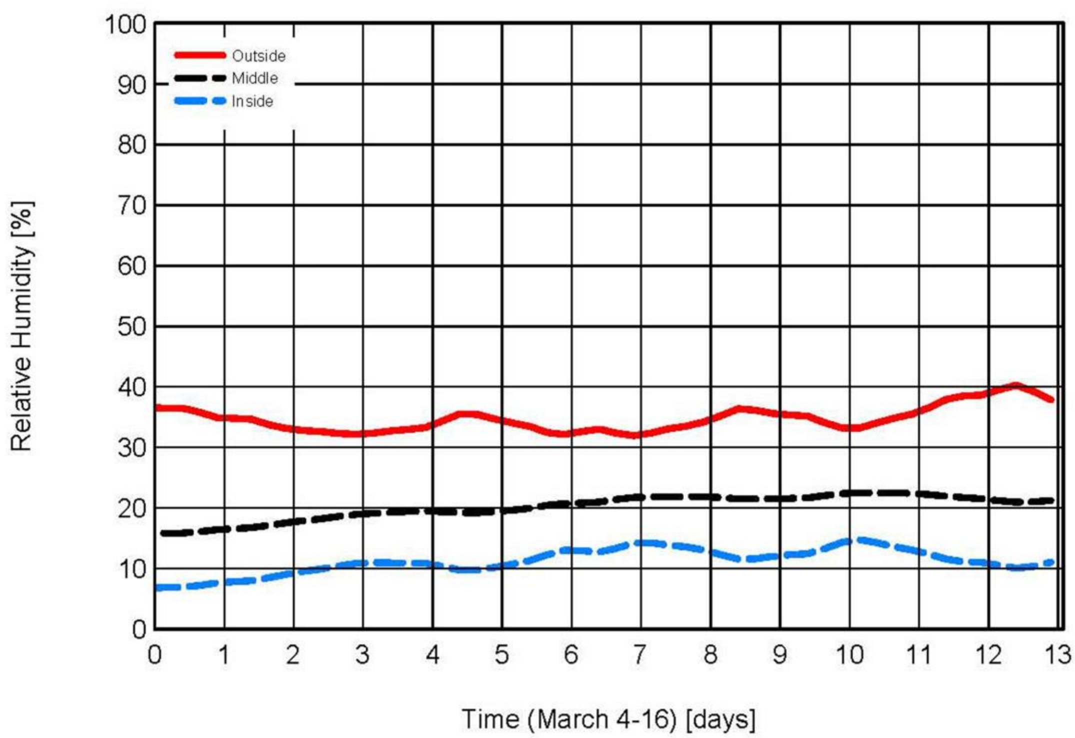

Figure B-10: Daily RH within wall cavity of cha. 2 in cellulose bldg. (March 4-16)

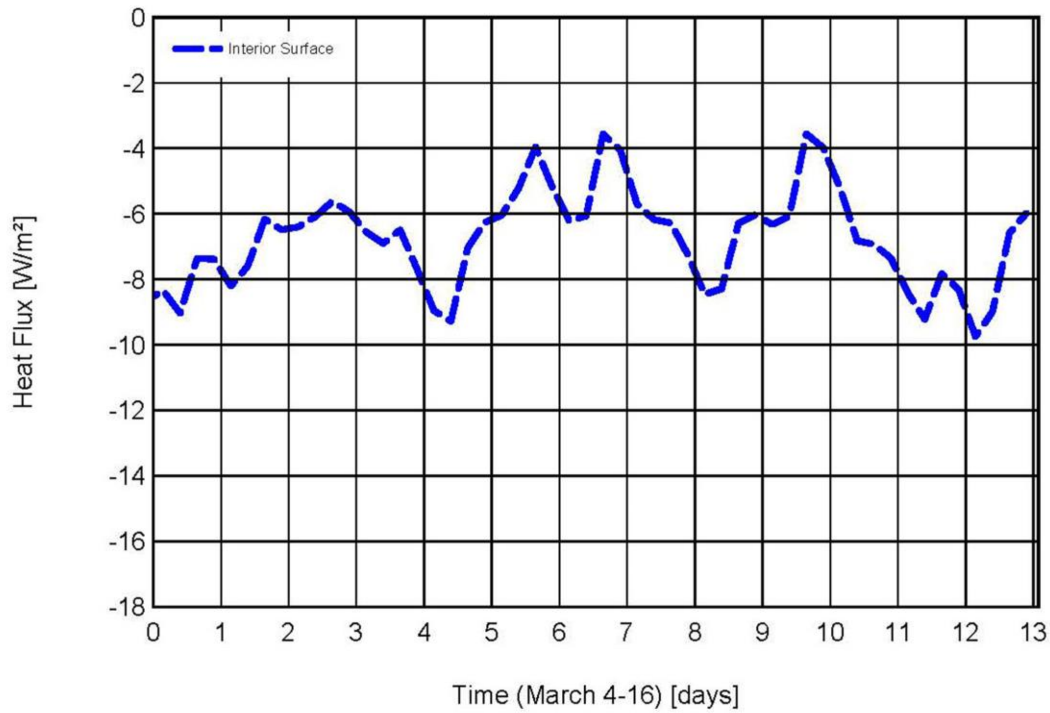

Figure B-11: Daily Heat Flux Density of cha. 1 in cellulose bldg. (March 4-16)

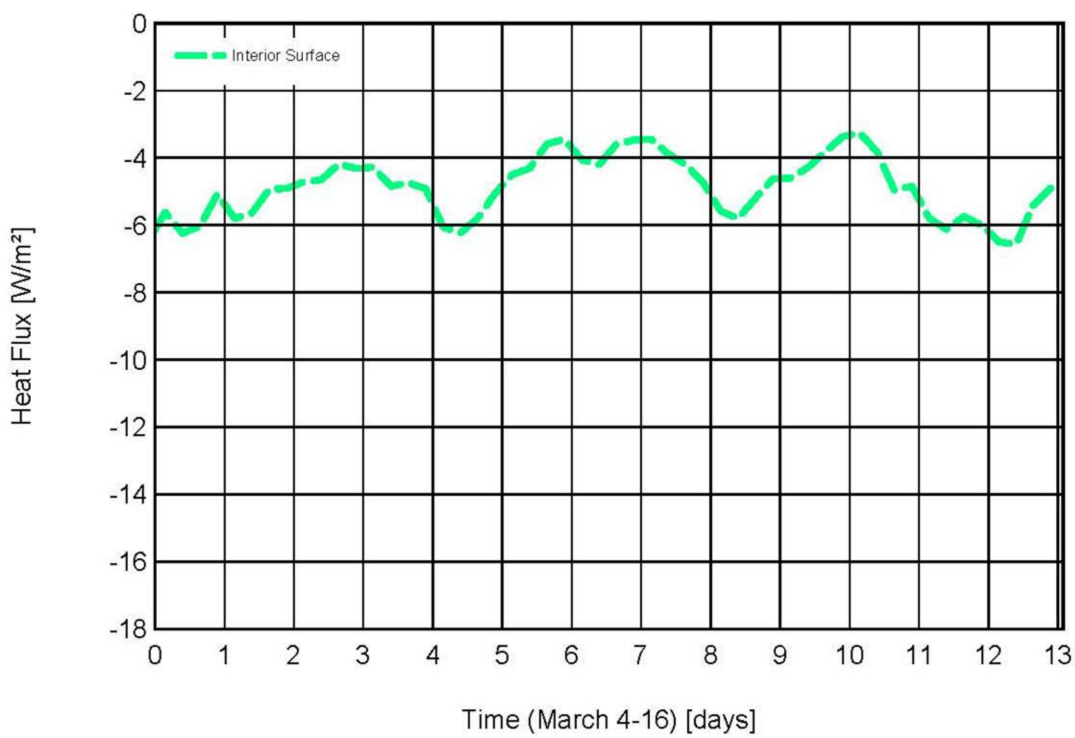

Figure B-12: Daily Heat Flux Density of cha. 2 in cellulose bldg. (March 4-16)