FIELD MONITORING OF HYGROTHERMAL PERFORMANCE OF ATTIC VENTING SYSTEMS IN EXTREME COLD CLIMATE

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ABSTRACT

Attic ventilation is typically recommended for the removal of moisture built-up caused by air leakage from indoors in cold climates, however, it may also increase the amount of snow, wind, rain and dirt penetration into the attic, especially in the extremely cold regions of Canadian North. In northern regions, extremely cold temperatures can cause snow particles to become very fine like "icing sugar", which will penetrate vents and/or unsealed openings. The snow accumulated in the attic would then melt at temperatures above zero and penetrate to indoors through the ceiling and cause moisture problems. One of the solutions is to add filter membranes along a ventilation cavity behind the façade to prevent snow from entering the attic. There have been also attempts to use un-ventilated cold roofs. Un-vented attics prevent snow accumulation but do not allow for effective removal of moisture, which could be risky and prone to moisture damages. The ventilated attics with filter membrane had some success but there were instances with reported water leakages and moisture damages. There is very limited information on how to design the attic properly for this particular climate to ensure durable wood-frame constructions.

This paper presents a field study of the hygrothermal performance of three attic venting systems. Three houses with different attic designs built in Canadian North were monitored: two houses with a ventilated attic but different strategies controlling snow entry and one Structural Insulated Panel (SIP) house with an un-ventilated cold attic. Data analysis shows that in general the ventilated attics with filtering membrane managed to maintain the attic at an acceptable condition. For the un-ventilated attic, the sheathing moisture content levels remained above 25% through the summer, which indicates that without ventilation the initial built-in construction moisture and moisture accumulated through winter time won't be able to be removed.

INTRODUCTION

Northern Canadian communities face many challenges to sustain themselves and housing is one of the major ongoing problems. Developing and maintaining wood-frame housing in the arctic is much more demanding than in the south. All the material needed to construct wood frame houses cannot be obtained locally and must be shipped from southern Canada. There is a lack of skilled labor and an almost complete dependence on fossil fuels for energy since diesel generators are used to produce electricity. Residential construction costs are 1.3 to 3.6 times higher than in larger southern cities (NRCC, 1997). Consequently, housing shortages and crowding are common issues in many communities (Statistics Canada, 2008). Existing houses have exhibited numerous issues caused by poor design and construction. Accelerated deterioration of these houses is caused by a number of factors including the harsh climatic conditions, culturally inappropriate housing designs, and overcrowding. To help provide a sustainable future for the remote Arctic areas, affordable, energy efficient, and durable housing is needed.

A survey made by Canada Mortgage and Housing Corporation (CMHC) in the early 1980s showed that attic moisture problem always appeared in far northern climates, which have a prolonged period of extreme cold weather (Buchan et al., 1991). The extreme cold temperatures can cause snow particles to become very fine like “icing sugar”, which will penetrate vents and/or unsealed openings (AHFC, 2000). To avoid the penetration of fine snow particles into roofing systems, unventilated cathedral roof is typically built in higher latitudes of the north with smaller snow loads. This design ensures that high winds will not infiltrate the attic space and displace the insulation or allow any fine snow particles to enter and accumulate. However, this type of roof reduces the amount of insulation thickness and generally has a higher construction cost. Un-ventilated cathedral roof needs to be built very air tight, in case any air leakage from the interior space entering in the roof, it will be difficult to remove the moisture.

The unconditioned ventilated attic roof construction is typically used in cold climate regions that are subjected to snow accumulation on the roofs to prevent unwanted ice damming. Having an unconditioned attic space also provides extra room for insulation above the ceiling and typically results in an overall lower cost for the roofing system. The purpose of introducing attic ventilation into roof construction is to minimize condensation and moisture accumulation in attics due to air leakage from the interior space (Rowley et al., 1939, and Rose, 2002). This venting has three primary functions: (1) avoid ice-damming along the attic eaves; (2) remove extra moisture out of attic; and (3) cool down the attic during summer period (Blom et al., 2001; Roppel et al., 2013). Adequate ventilation of the attic is important to ensure its performance. Through field measurements, Hagentoft and Kalagasidis (2010) found that if suitable ventilation was provided to cold roof, moisture risk can be reduced effectively. Arfvidsson and Harderup (2005) concluded that inadequate amount of ventilation reduced the capacity of moisture removal in attic area and adding thermal insulation on the exterior sloped roofing surface contributed to moisture accumulation.

Because of the advantages of being inexpensive and allowing for more insulation, the unconditioned ventilation attic construction has been adopted in extremely cold regions as well. However, the main issue with ventilated attic in extreme cold climates is the snow accumulation in attic spaces. The snow accumulated in the attic would then melt at temperatures above zero and penetrate to indoors through the ceiling and cause moisture problems such as wood decay, mold growth and damages to interior finishes, etc. (IAQ, 2013). One of the solutions to deal with the snow accumulation in ventilated attics is to use a polyester filter membrane at the bottom of ventilated cladding and/or at the entrance of the attic to catch snow before it enters the attic. This strategy has been employed for several years in the Nunavik territory of northern Quebec. The design has been somewhat successful, however, from empirical evidence collected from occupants there have been reports about moisture problems, and concerns of blown-in attic insulation displacement, which could be attributed to excessive attic venting. As well, there has been no extensive testing or research conducted to verify the success of this system.

Another strategy to prevent snow from infiltrating attic spaces is to seal the attic such that it is not ventilated. This design has been attempted in a high-performance SIP Duplex constructed in Iqaluit, Nunavut (Baril et al., 2013). The main issue with the unvented attic is that they are very sensitive to air leakage from the house (Fugler, 1999). The moisture added to the attic spaces by air leakage from indoors escapes mainly via diffusion through the roof, which is very slow process. Existing research shows that an unvented attic can perform well in cold climates given that air leakage is minimized (CMHC, 1993; Rose, 1992; and Samuelson, 1998).

To address the issue that there is limited information on the proper design of attics in extreme cold climates, a research project was carried out to investigate the hygrothermal performance of ventilated and un-ventilated attics through laboratory testing, field monitoring and modeling. This paper reports a field study of the hygrothermal performance of three attic venting systems. The following sections include experimental setup, hygrothermal performance analysis including RH and temperature profiles in attic spaces and moisture content of plywood sheathing followed by discussion and conclusions.

EXPERIMENTAL SETUP

Attic Constructions under Investigation

Three houses with cold attics built in the Nunavik territory of Northern Quebec and Nunavut territory were monitored. Two of them have ventilated attics with different filter membrane designs (Figure 1a and Figure 1b) and the third house is a Structural Insulated Panel (SIP House) Prototype House (Figure 1c) with an unventilated attic.

a) House I

b) House II

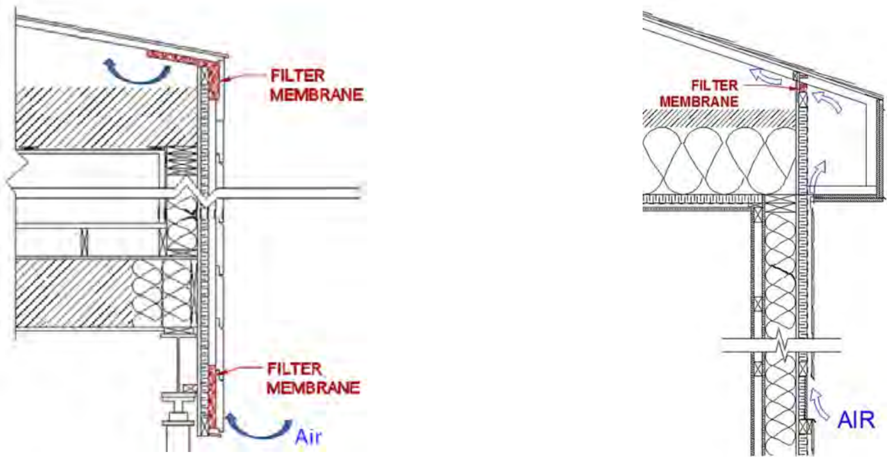
c) House III (SIP)

Figure 1: Photos of the Three Houses Monitored

House I is a single-story duplex with two 92 m2 (1000 ft2) units and a shared mechanical room located in between. This house is owned by Kativik Municipal Housing Bureau House and built in Kuujjuaq in 2012. This single story, two bedrooms' social housing design is currently being constructed throughout the territory to catch up with the housing shortage. Figure 2a shows the venting system in House I. The filter membrane is located at both the bottom of the ventilated cladding and the entrance of the attic space to catch snow.

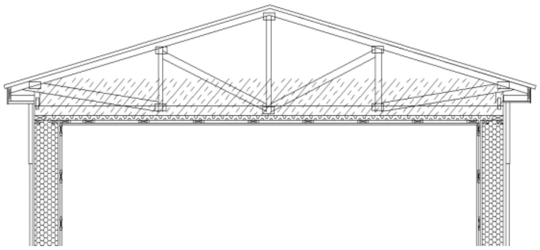
House II is a two-story duplex built in Kuujjuaq, consisting of two 148 m2 (1600 ft2) units with a shared mechanical room built in 2008. It has a ventilated attic with a cold roof, but the design of filter membrane is different from House I. Outdoor air directly enters the air cavity behind the cladding and goes to the eaves area before finally enters in the attic space through the filter membrane, as shown in Figure 2b. This house is owned by the Kativik School Board and is used to accommodate teachers and their families.

House III is a two-story house built in Iqaluit, Nunavut in 2012, consisting of two 157 m2 (1700 ft2) units with a shared mechanical room. This house is a prototype SIP house that has the potential to be used to rapidly construct durable, energy efficient homes for the housing shortage. This passive system uses an unventilated cold roof (Figure 2c), which relies on an airtight ceiling assembly that will keep the warm moist interior air from entering the unconditioned attic space. The unventilated attic means that there is no chance of fine snow particles infiltrating the attic space from outside, if built properly. However, extensive research has also not been conducted on this type of attic system to determine whether it will have sufficient drying potential and will be suitable for the extreme northern climates.



a) Venting System of House I

b) Venting System of House II



c) Un-ventilated Roofing System of House III (SIP)

Figure 2: Venting Systems of the Three Houses

Instrumentation

To remotely monitor the hygrothermal conditions of the attic, indoor occupied space and outdoor conditions, wireless data acquisition systems were installed. Moisture content (MC) sensors were installed to monitor the wood moisture content levels on the roof sheathing and top chord of the trusses. The resistance type of MC sensors has built-in thermistor, which allows the MC correction for temperature and can operate under temperature within -40 ºC to 125 ºC. Relative humidity and temperature (RH/T) sensors were installed to monitor the conditions in the attic air above the access hatch as well as in the ceiling insulation and can be used to determine the amount of moisture in the air at these locations. RH/T sensors were also installed outside the houses to monitor outdoor conditions as well as inside the living space to monitor the indoor conditions. The RH accuracy is ±3%~5% between 10%~95% and can be operated within -30 ºC to 70 ºC. The operating temperature range of thermistor is between 55 ºC and 125 ºC.

a) **b)**

Figure 3: a) Moisture Content Sensor and b) Wireless Multi-Channel Data Logger

The sensors are connected to battery operated multi-channel data loggers, which has an extreme low power usage and can perform long term monitoring from a three AA battery pack without the need for the installation of external power cables. It has three to five-year battery life depending on sampling rate and operating temperature of 0 ºC to 40 ºC. To preserve the battery life, these data loggers were placed below the attic insulation on the warm side where built in RH/T sensors monitoring the insulation conditions. Collected data is wirelessly sent to an internet connected laptop located in the mechanical room of the houses. The data is then synchronized hourly to an analytical website where readings can be monitored remotely as well as downloaded and analyzed at Concordia University in Montreal, Quebec. An uninterrupted power supply (UPS) was installed to extend the battery life of the laptop and provide power to the modem during electrical interruptions.

Field Observation and Sensor Locations

House I

House I is a duplex with two units (Unit A and Unit B) and only the hydrothermal conditions of Unit A were monitored. Field observation found no obvious signs of moisture on building materials and no rust on roofing nails (Figure 4a). Dead bolt locks were installed to ensure hatch pulled tight onto weather stripping (Figure 4b). Figure 5 shows the sensor locations installed in the attic space. Seven MC sensors were installed, two in truss, four on plywood roofing sheathing, and one on OSB gable wall sheathing. One RH/T sensor for attic air was installed over the attic hatch and three RH/T sensors for insulation were buried beneath the cellulose insulation beside the attic hatch.

a) **b)**

Figure 4: Field Observation in the Attic of House I: a) No Signs of Moisture on Building Materials and Roofing Nails not Rusted; and b) Dead Bolt Locks Installed to Ensure Hatch Pulled Tight onto Weather Stripping

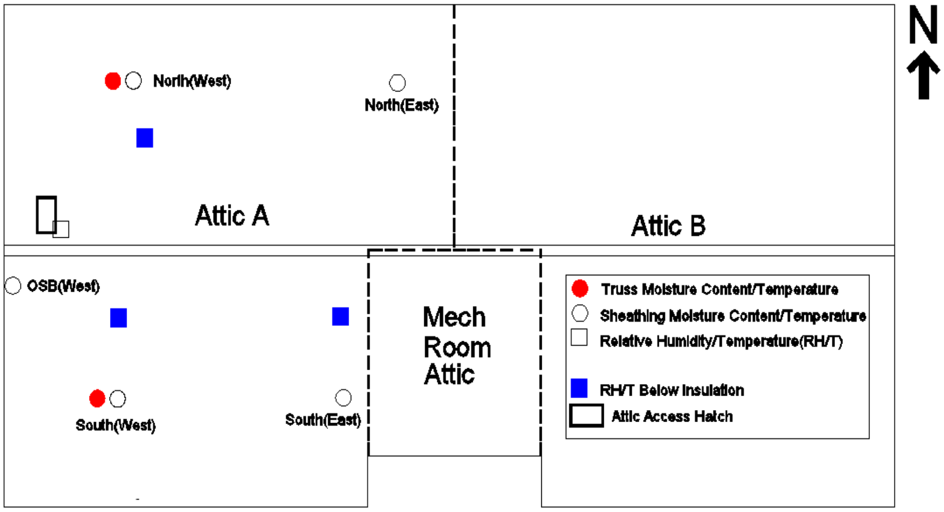


Figure 5: Sensor Locations in the Attic of House I

House II

Same as for House I, only the hygrothermal conditions in the attic of Unit A were monitored in House II. Site observations found no signs of moisture on building materials and roofing nails had no rust (Figure 6). Seven MC sensors were installed, two in truss and five on the plywood roofing sheathing. One RH/T sensor for attic air was installed over the attic hatch and three RH/T sensors were buried beneath the cellulose insulation beside the attic hatch. Figure 7 shows the sensor locations installed in the attic space.

a) b)

Figure 6: Field Observation in the Attic of House II: no Signs of Moisture on Building Materials and no Rusted Roofing Nails

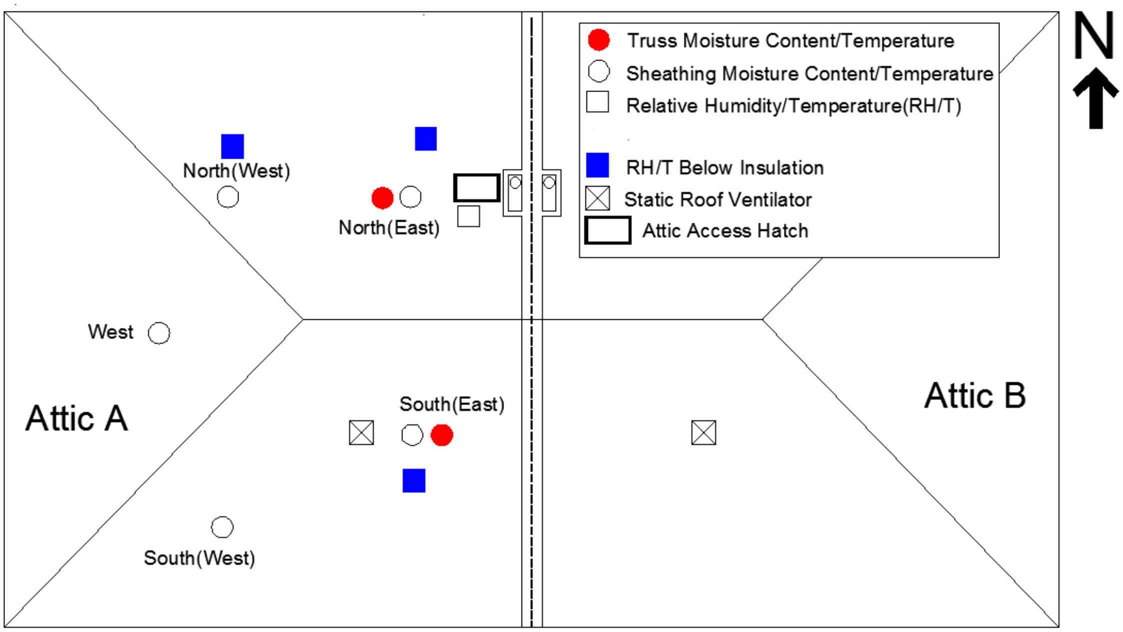
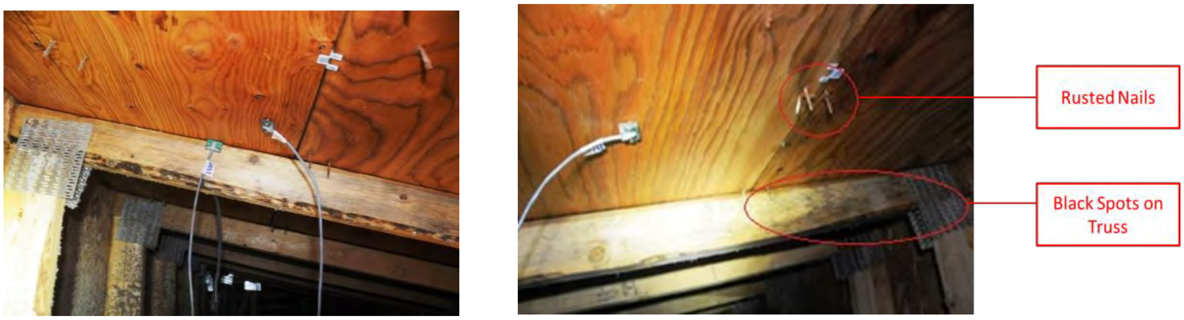


Figure 7: Sensor Locations in the Attic of House II

House III (SIP Un-Ventilated)

The SIP Prototype House has four attic spaces. They are Unit A upstairs (UA-US), Unit A downstairs (UA-DS), Unit B upstairs (UB-US) and Unit B downstairs (UB-DS). All four attics were monitored. Field observation found that weather stripping as an air sealing was used to seal off the attics from indoor space. Closed cell sponge rubber tapes were installed around the openings for the hatches in all four attic units to ensure an airtight unventilated attic construction. However, gasket systems around all attic hatches opening were not installed during construction. Upon opening of all attic hatches, areas of moisture were discovered on plywood sheathing and trusses (Figure 8). Wet plywood sheathing was observed on all four attic spaces on both south and north slopes. Rusty nails were found on sheathing and black spots and signs of wood decay were noticed on wood trusses.



a) **b)**

Figure 8: Field Observation in the Attic of House III: a) Wet Plywood Sheathing; b) Rusty Nails and Black Spot on Truss

Figure 9 shows the sensor locations in the attic spaces. The same number of sensors was installed in each attic space. Four MC sensors were installed, one in truss and three on plywood sheathing. One RH/T sensor for the attic air was installed over the attic hatch and one RH/T sensor for insulation was buried beneath the cellulose insulation beside the attic hatch.

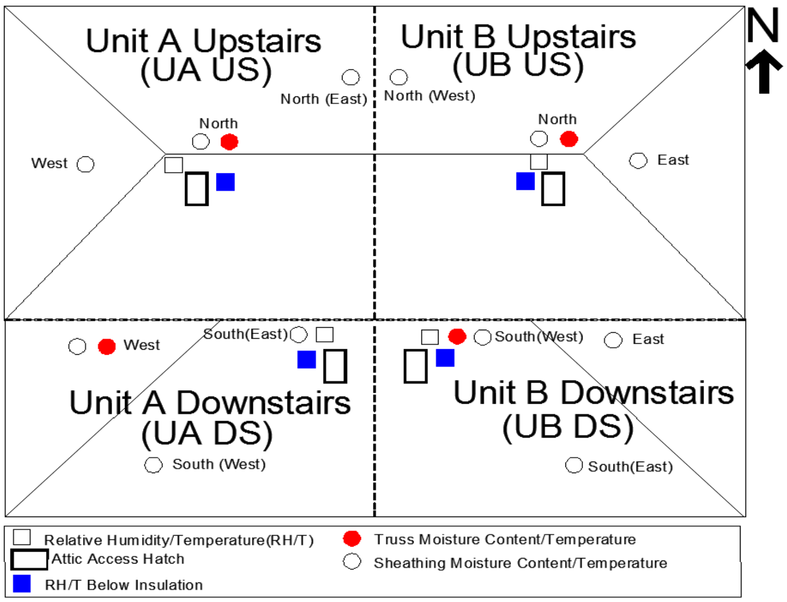


Figure 9**:** Sensor Locations in the Attic of House III (SIP Unventilated)

RESULTS AND DISCUSSION

The hygrothermal performance of attics is analyzed based on the temperature and relative humidity of the attic air, and MC levels in plywood sheathing. The performance for each house is presented in the following section separately.

House I

Figure 10 shows the MC and temperature measured on the plywood sheathing in House I during the monitoring period from July 2013 to January 2015. Seasonal variation in MC and temperature can be observed during this one and half year period. In general, the sheathing temperature was higher than the outdoor air in a range of 10-15 ºC with occasions as high as 30 ºC especially during summer with high solar radiation due to the thermal mass effect. The difference in sheathing temperature of the five locations is not significant although the maximum temperature on the south-orientation was typically about 5ºC higher than that on the north orientation (49 ºC versus 44 ºC).

The MC levels varied between 10% and 25% for the five locations monitored on plywood sheathing. In general, the MC levels in plywood sheathing were low in the summer time between 10% and 15%, while gradually increased during the fall and winter and peaked at around 16% for the three locations NE, NW and West and about 25% for the SE and SW locations. For the SW sheathing, MC levels increased starting from the beginning of Nov. 2013 and reached above 20% in Jan. and peaked at 25% in the middle of Feb. 2014 and maintained till March and started to decrease with greater daily fluctuations. The MCs were able to drop to around 10% during the summer. As for the SE sheathing location, MCs had greater fluctuations than the other locations, while the average MC was lower than that of SW sheathing and was similar to other locations. The high MC level above 20% lasted only for a short period as well in SE sheathing. Nevertheless, a MC level above 20% is considered reaching the risky zone for biological degradation of wood-based materials.

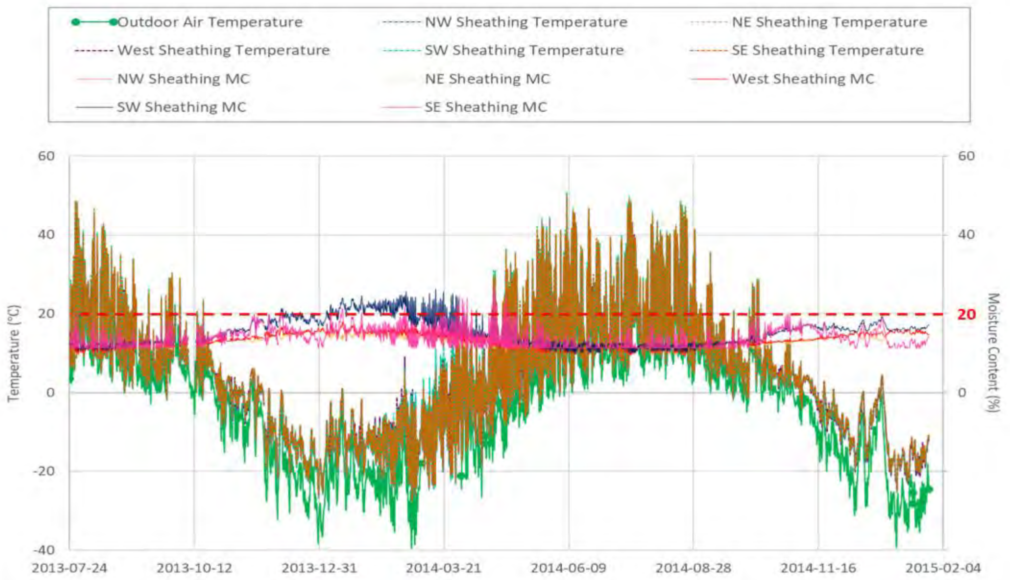


Figure 10**:** Moisture Content and Temperature of Plywood Sheathing in House I Measured During the Monitoring Period from July 2013 to January 2015

Figure 11 shows the comparison of relative humidity and temperature in the attic air and outdoor air. It can be seen that the outdoor air temperature varied between -40 ºC to 25 ºC with a long winter period. The attic air temperature followed a similar trend as the outdoor air and typically higher than outdoor air temperature in a range of 5-15 ºC with occasions as high as close to 30 ºC especially during summer with high solar radiation due to the thermal mass effect. During the summer time, there were also occasions with attic air temperature being lower than outdoor air temperature due to clear sky radiation. In the winter time, the difference was within 10 ºC.

There were slightly seasonal variations in RH level of outdoor air but generally the outdoor RH was high with an annual average of 80% and the maximum RH can get as high as close to 100% in spring and summer time. In winter time, RH level of the attic air remained around 90%, which was higher than the outdoor air. In the summer time, attic RH was significantly lower than outdoor RH due to the much higher attic air temperatures.

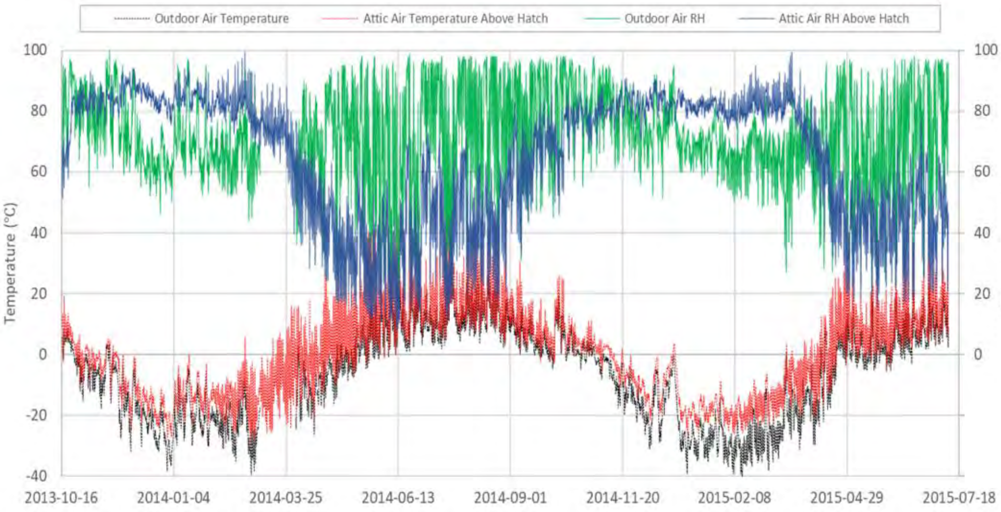


Figure 11: Attic Air RH/T in House I Compared to Outdoor Air RH/T

In general, the attic ventilation system in House I seems working except for one location on SW plywood sheathing as shown in Figure 10, which had moisture content level reaching risky level (above 20%) during the spring time, however it was able to dry to a safe level during the summer time. The temperature and relative humidity differences between attic and outdoor air indicate that some level of attic ventilation induced by wind and stack effect existed.

House II

Figure 12 shows the MC and temperature measured on the plywood sheathing in House II during the monitoring period from Aug. 2013 to January 2015. Seasonal variation in MC and temperature can be observed during this period. The sensor installed on SE sheathing was malfunction, therefore, only the data collected at the four locations on plywood sheathing are shown.

Similar to what has been observed in House I, in general, the sheathing temperatures were higher than the outdoor air in a range of 10-15 ºC with occasions as high as 30ºC especially during summer with high solar radiation due to the thermal mass effect. The differences in sheathing temperatures of the four locations were not significant although the maximum temperature on the south-orientation was typically about 6ºC higher than that on the north orientation (49ºC versus 43ºC).

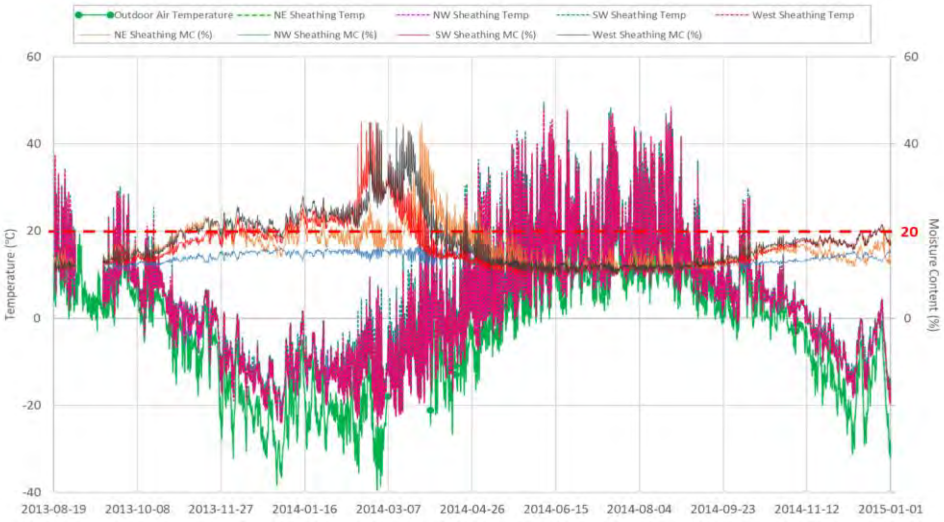


Figure 12**:** Moisture Content and Temperature of Plywood Sheathing in House II Measured During the Monitoring Period from Aug. 2013 to January 2015

The MC levels varied between 10% and 45% for the four locations on plywood sheathing. In general, the MC levels in plywood sheathing were low in the summer time between 10% and 15%, while gradually increased during the fall and winter and peaked at around 15% for the NW location. For the other three locations, the MCs increased gradually and reached about 20% at the end of Oct. 2013 for the West and NE locations and at the end of Nov. 2013 for the SE location and maintained over 20% until mid-March 2014 for the SW location, end of March 2014 for the West location, and end of April for the NE location, respectively. Starting from mid-Feb. 2014, the MC levels at SW and West locations abruptly increased to over 40% and then started to drop and dried to below 20% by the end of March for SW location and by early April for West location, respectively. For the NE location, the abrupt increase in MC started from mid-March, peaked at the end of March, and dried to below 20% by the end of April. The MCs were able to drop to around 10% during the summer for all these locations. The quick increase in MC in plywood sheathing during the period of Feb. to April was most likely due to the availability of solar radiation and warming up of the air temperature that allowed the moisture frozen in the wood structure to melt, therefore, elevated MC sensors' readings.

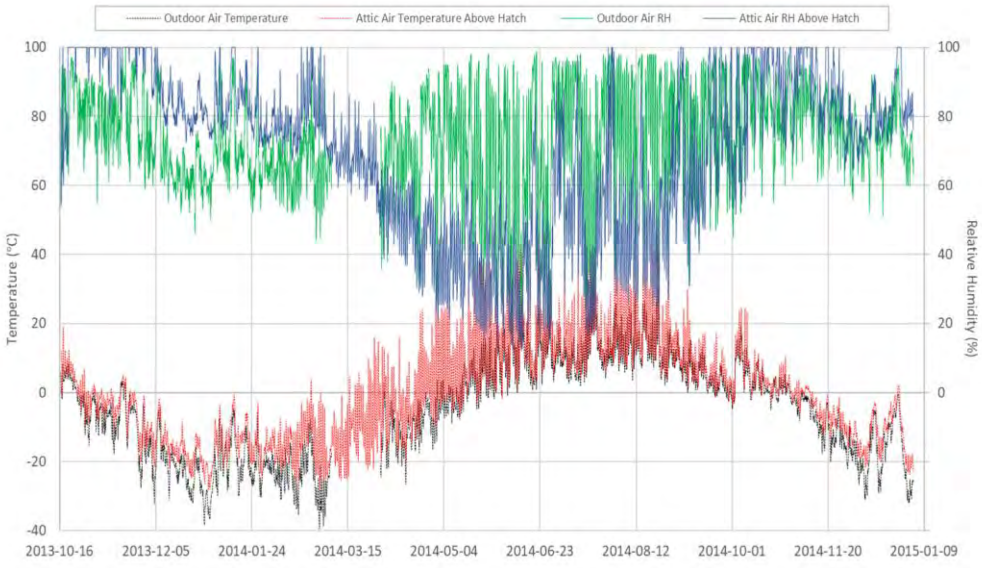


Figure 13: Attic Air RH/T in House II Compared to Outdoor Air RH/T

Figure 13 shows the comparison of relative humidity and temperature in the attic air and outdoor air for the monitoring period from October 2013 to January 2015. Similar to what have been observed for House I (Figure 11), the attic air temperature followed a similar trend as the outdoor air and typically higher than outdoor air temperature in a range of 5-15 ºC with occasions as high as 30 ºC, especially during summer with high solar radiation due to the thermal mass effect. During the summer time, there were also occasions with attic air temperatures lower than outdoor air temperatures due to clear sky radiation. In the winter-time, the differences were smaller within 10 ºC.

There were slightly seasonal variations in RH level of outdoor air but generally the outdoor RH was high with an annual average of 80% and the maximum RH can get as high as close to 100% in spring and summer time. In winter time, RH level of attic air remained above 90% and sometime reached 100%, which was higher than the outdoor air. In the summer time, attic RH was significantly lower than outside RH due to the much higher attic air temperatures.

House III (Un-Ventilated SIP)

Figure 14 shows the MC and temperature measured on the plywood sheathing in SIP house during the monitoring period from July 2013 to Aug. 2014. The sensors installed in Unit A downstairs lost power, therefore, only data collected at the other three locations are shown in Figure 14. Seasonal variations in MC and temperature can be observed during this one year period. The differences in sheathing temperature of the three locations were not significant.

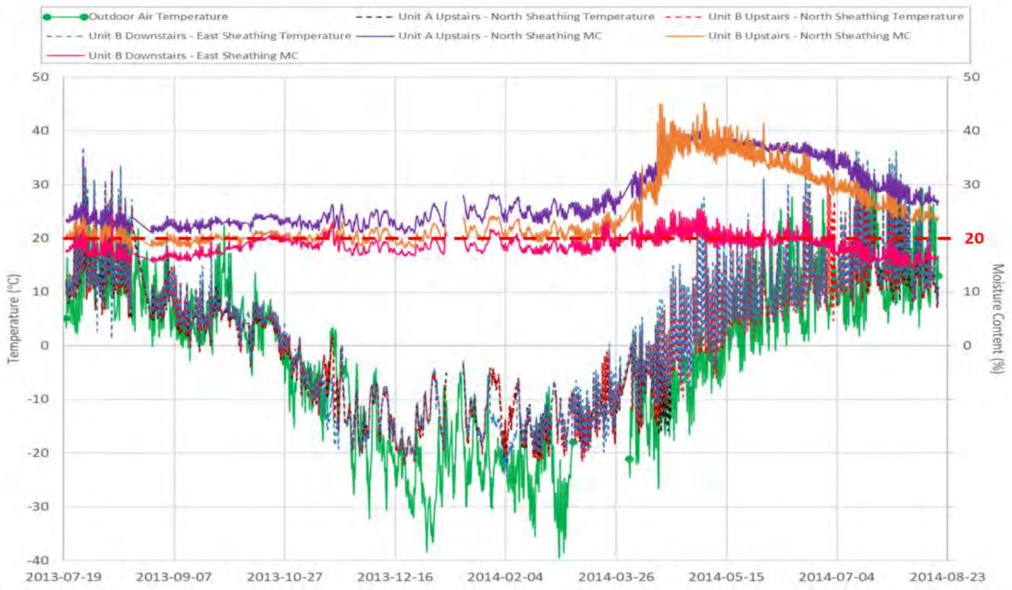


Figure 14: Moisture Content and Temperature of Plywood Sheathing of House III Measured During the Monitoring Period from July 2013 to Aug. 2014

The MC levels varied between 18% and 45% for the three locations monitored. The initial moisture contents of plywood sheathing were high, at around 18% for East sheathing in Unit B, slightly above 20% for north sheathing in Unit B, and 23% for north sheathing in Unit A, in July 2013. The MC levels fluctuated with slight increase over the winter time. Starting from the end of March, 2014, there was a significant increase of MC at upstairs Unit A and B North sheathing and the MC levels reached over 40% by the end of April and remained at that high level till June, and then gradually decreased but still remained at above 25% by mid-Aug. 2014. For the sheathing location at the downstairs Unit B, the MC levels remained between 20% to 24% through the spring and dried to 18% towards the mid-Aug. 2014. Although the MC at this location did not increase significantly, the MC reached a risky level for biological degradation of wood-based materials.

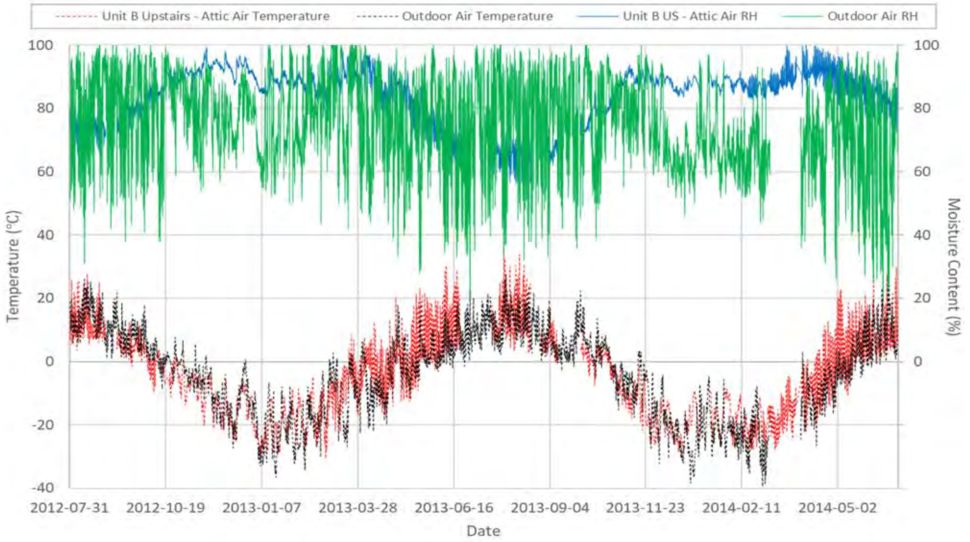


Figure 15: Attic Air RH/T in Unit B Upstairs in House III Compared to Outdoor Air RH/T

In general, there is no significant difference in relative humidity among the four attic spaces monitored in SIP house with slightly higher RH levels in the upstairs attic spaces. Therefore, data analysis obtained for upstairs Unit B attic for the period from August 2012 to June 2014 is presented as an example (Figure 15).

The attic air temperature followed a similar trend as the outdoor air and typically higher than outdoor air temperature in a range within 10 ºC with occasions as high as close to 20 ºC, especially during summer with high solar radiation due to the thermal mass effect. During the summer time, there were also occasions with attic air temperatures being lower than outdoor air temperature due to clear sky radiation. In the winter time, the difference was within 5 ºC.

There were slightly seasonal variations in RH level of outdoor air but generally the outdoor RH was high with an annual average of 80% and the maximum RH can get as high as close to 100% in spring and summer time. In winter time, RH level of attic air remained above 90%, while in the summer time, attic RH remained above 60%, which was much higher than the attic RH levels in House I and House II with ventilated attics.

In general, the RH level in attic air and the MC levels of sheathing in the un-ventilated SIP house were higher than that in Houses I and II with ventilated attics. The MCs of sheathing reached levels for risks of mold growth and decay.

DISCUSSION AND CONCLUSION

The hygrothermal conditions of three houses with different venting systems in remote Arctic regions were monitored and the hygrothermal performance of these attics were evaluated based on measured relative humidity and temperature, and moisture content of plywood sheathing. The difference in hygrothermal performance of these three attics is summarized in Table 1.

Table 1: Comparison of three venting systems

	RH (Attic air)	**ΔT (attic air-outdoor air)**	**MC of plywood sheathing**
House I (ventilated attic with filter membrane at both the bottom of the cladding and the entrance of attic space)	Average: 65.2% Min: 8.8% Max: 99.5%	Average (positive): 8.4 ºC Average (negative):-3.2 ºC Min: -22.5 ºC Max: 37.9 ºC	**NW, NE, W**: below 16% throughout the year **SE and SW**: above 20% from Jan. to March, peaked at 25% in Feb., dried to 10% during the summer months.
House II (ventilated attic with filter membrane at the entrance of attic space)	Average: 69.9% Min: 12.4% Max: 100%	Average (positive): 5.4 ºC Average (negative):-2.9 ºC Min: -13.7 ºC Max: 35 ºC	**NW**: 10-15% throughout the year **SW**: peaked over 40%, dried to below 20% by end of March **W**: peaked at over 40%, dried to below 20% by early April **NW**: peaked over 40%, dried to below 20% by end of April

House III (un-ventilated attic)	Average: 75% Min: 20% Max: 100%	Average (positive) 5.9 ºC Average (negative):-5.2 ºC Min: -18 ºC Max: 23 ºC	**Unit A N**: initial MC of 23%, slight increase during winter time, abrupt increase at end of March, peaked over 40%, remained high level till June and slowly dried to 27% at the end of Aug. **Unit B N**: initial MC of 20%, slight increase during winter time, abrupt increase at end of March, peaked over 40%, remained high level till June and slowly dried to 25% at the end of Aug. **Unit B E**: initial MC of 18%, slight increase over winter time, above 20% from March to June, dried to about 18% at end of Aug.

The analysis shows that in general the ventilated attics with filtering membrane managed to maintain the attic in an acceptable condition except for one location in House I and three locations in House II with sheathing MC levels reached above 20% to 45% for a short period. The MC levels at these locations were able to decrease to around 10% during the summer months. In general, the attic RH level in House II was slightly higher than that in House I and the maximum MC levels in sheathing in House II was higher than that in House I, peaked at 45%. In addition to the difference in venting strategies, other factors such as the moisture loads from indoors, the airtightness of the ceilings, and local weather conditions may have also attributed to the difference in hygrothermal performance.

For the SIP house with the un-ventilated attic, the attic RH levels were higher than those in House I and House II, especially during the summer months, a RH level of above 60% remained through the summer. The sheathing MC levels remained above 18% throughout the entire one-year monitoring period with the sheathing MC in the upstairs attics reached over 40% and remained above 25% through the summer, which indicates without ventilation the initial built-in construction moisture and moisture accumulated through winter time won't be able to be removed. The initial MC level of the plywood sheathing in SIP house was higher at about 18-23% compared to that in House I and House II. The application of weather stripping around the attic hatches may have limited the air leakage from indoor space to attic, which did not increase the MC of sheathing significantly as indicated by the slight increase of MC in sheathing over the winter time. However, without active attic ventilation, even slight accumulation of moisture in the attic won't be able to be removed out of the attic. Attics without ventilation may pose durability issues. Further investigation of the appropriateness of unventilated attic under extreme cold climates through continued field monitoring and modeling is required.

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