ABSTRACT
Ventilation can be important in maintaining proper attic hygrothermal conditions. In Arctic climates, however, fine blowing snow can infiltrate and accumulate in the attic space, causing serious moisture problems. By using filter membranes along a ventilation path behind the cladding of a building, attics can be ventilated without the risk of snow infiltration. To determine the attic ventilation rates under such a configuration, CFD (Computational Fluid Dynamics) simulation is used. Typical wind speeds found in Iqaluit, Nunavut are used to develop the exterior boundary conditions in the model. The effects of two types of cladding are compared: conventional cladding and BIPV/T (Building-Integrated Photovoltaic and Thermal) cladding, which generates electricity while preheating air for the attic and the building as needed. The results from this study will be used to evaluate the hygrothermal performance of attics in the Arctic with various ventilation strategies.

INTRODUCTION
The remoteness and extreme climates of the communities in the Canadian North create many challenges to live there. Early attempts to establish wood frame housing in those communities saw many houses failing under the extreme conditions as they were not designed with that specific climate in mind. Because of this and the growing population, there is also a housing shortage, leaving many homeless. It is therefore crucial that houses built for the north are made to endure the local climate.

One of the important issues concerning these houses is if and how the attic should be ventilated. Ventilation can remove moisture build-up caused by air leakage from the indoors, but it can also introduce moisture and snow from the exterior. Unvented attics prevent snow accumulation, but do not allow for removal of built-up moisture. In northern Quebec, polyester filter membranes are used along a ventilation cavity behind the façade to prevent snow from entering the attic (Baril et al., 2013). Determining the ideal design is therefore not trivial, so an in-depth study is warranted.

There are many ways to ventilate an attic. Listed below are some attic configurations relevant to Arctic housing:

- Natural ventilation: Ventilation occurs due to wind and buoyancy forces.
- Mechanical ventilation: A fan is used to ventilate the attic at a constant flow rate.
- Adaptive ventilation: A fan ventilates the attic only when the outdoor air can remove moisture from the attic.
- BIPV/T mechanical ventilation: A fan ventilates the attic with air preheated with a BIPV/T system.
- BIPV/T natural ventilation: Ventilation occurs due to wind and buoyancy forces, while the air is preheated by a BIPV/T system.

BIPV/T technology has been shown to be effective in cold climates (Chen et. al, 2010; Yang & Athienitis, 2015; Chen et. al 2012), generating electricity for buildings while preheating air that is used for ventilation by removing heat accumulated in the BIPV, which in turn increases its efficiency. The preheated air can also be used to ventilate the attic, since warmer air has a greater ability to absorb moisture and dry the attic.

Air in buildings is displaced via three pressures: wind, stack effect, and mechanical systems. For the cases of natural and BIPV/T natural ventilation, the attic ventilation rates are not known, though ventilation is driven mainly by wind, then stack effect (Walker & Forest, 1995). Ventilation rates can be approximated based on the wind speed, direction, and vent design using various models (Walker & Forest, 1995). Because this configuration involving filter membranes is very particular, it warrants the use of CFD simulation to determine the ventilation rates.

SYSTEM DESIGN
For this project, a building with characteristics typical of a northern house is designed and used as the basis for the simulation. A section of the house is shown in Figure 1. The house has one floor and is raised off the ground to prevent melting of the permafrost. The roof slope is (15º), which is sufficient for arctic climates.
since the snow load is actually quite low. The roof itself is composed of metal roofing over plywood. The attic is insulated at the ceiling level with cellulose insulation and polyisocyanurate insulation. The walls are heavily insulated, in this case it is a structural insulated panel (SIP) wall but it can be any other well-insulated wall for the purpose of this study. To the exterior of the insulated wall is an air space and then wood siding as the cladding. In the configuration with the BIPV/T, the cladding on the south side is replaced with a BIPV such that it generates electrical energy and heats the air in the cavity. At the bottom of the cladding on either side of the building are the vents for the attic. The air entering first goes through a polyester filter media at the bottom of the air cavity and travels up the air cavity into the attic space. The polyester batting is located 25 mm (1") from bottom of the cavity, just above the plane of the vent opening. The batting is 356 mm (14") in height. There are 25 mm (1") ridge vents as well on either side of the roof. They are each located 25 mm (1") away from the ridge.

**SIMULATION SETUP**

ANSYS FLUENT (ANSYS, 2011) is the CFD platform used in this study. The simulation involves both fluid flow and heat transfer, so both these balance equations are used. To simulate attic ventilation, the attic space and the wall air cavities are modeled as one enclosure. Openings are placed at the bottom of the air cavities and at the ridge of the attic. At these points, there would be a specific value of air pressure depending on the wind speed and direction. Heat transferred from the indoor space to the attic and air cavities is also simulated, as well as effects of solar radiation. Ideally, this study would encompass a transient hour-by-hour simulation spanning an entire year to determine the ventilation rate throughout the entire year. This approach would, however, be too computationally demanding and not worthwhile. Alternatively, the steady state ventilation rates can be obtained for particular wind speeds and directions, within range of what is experienced in the arctic. The lack of a transient study is seen as acceptable because the airflow in the attic in one hour will not have a significant effect on the airflow in the next hour.

**Geometry**

The attic space and the wall air cavities are the main focus of this study, so they are modeled as one continuous space and represent the system boundary. Figure 2, Figure 3, and Figure 4 show the modeled geometry of the attic and wall cavity spaces, with the porous zones. The model of the attic is in two dimensions, since the focus is on the overall flow of air in the attic rather than the edge effects at the gable ends. There are small 25 mm (1") openings at the bottom of the wall cladding, north and south, as well as the attic ridge.
For the two cases of standard cladding and BIPV/T cladding, the geometry is essentially identical; the south cladding is simply substituted with a more heat absorbing material in the case of BIPV/T.

The mesh size is restricted to 5 mm in the wall cavities and at all the openings. The growth rate used is 1.08. In total, there are 26,777 nodes in the mesh.

**Porous Material**

To simulate the porous polyester filter membrane in the air cavities, specific properties must be entered.

FLUENT requires the following: the permeability of the material ($\alpha$), the pressure jump coefficient ($C_2$), and the porosity. These can be obtained if the pressure drop and velocity relationship is known for the material. The air permeability properties of the polyester batting are not known, and there is generally a lack of literature on the air permeability properties of this form of polyester. Therefore, a relationship of pressure drop and velocity for a polyester filter intended for HVAC applications is used as a base (Raber, 1986). Polyester batting is significantly more permeable than a HVAC polyester filter, so the pressure drop is reduced by a factor of 100 for the purposes of this study:

$$\Delta P = 27.3V + 8.5V^2$$  \hspace{1cm} (1)

Where $\Delta P$ is the pressure drop and $V$ is the velocity. The equation is in the form

$$\Delta P = B V + A V^2$$  \hspace{1cm} (2)

The coefficients $A$ and $B$ are related to the FLUENT variables for permeability and pressure jump coefficient as follows, where $\Delta n$ is the thickness of the tested medium (1 m).

$$A = \frac{C_2 \rho \Delta n}{2}$$  \hspace{1cm} (3)

$$B = \frac{\mu}{\alpha} \Delta n$$  \hspace{1cm} (4)

Where $\rho$ is the density of air and $\mu$ is the viscosity of air. Therefore, the values of $C_2$ and $1/\alpha$ are $1.27 \times 10^2$ and $1.58 \times 10^6$, respectively. The porosity of the polyester is assumed to be 0.9, which is within the typical range.

**BOUNDARY CONDITIONS**

A number of boundary conditions that affect the flow of air in the attic are imposed, including wind, indoor and outdoor temperatures, and solar radiation. The building is assumed to be in Iqaluit, Nunavut, the largest Inuit community in Canada. Hourly data on the temperature, wind speed and direction, and solar radiation is obtained from a weather file and used as the basis for the simulations. No slip conditions are considered for all surfaces.

**Wind Pressures**

The average hourly wind speeds for Iqaluit range from 0 to 16.4 m/s throughout the year while the annual average is 4.4 m/s, and the wind can be coming from
any direction though northern winds are prevailing. Since only steady-simulations are done, the wind speeds and directions must be specified for each simulation. To get enough data to interpolate, several speeds and directions must be simulation. Figure 53 shows how often the various wind speeds occur.

Figure 5 Occurrence of wind speeds in Iqaluit, Nunavut over a year

The wind speeds must be converted to the height of building to determine what the building is exposed to. The following equation from ASHRAE (2013) is used for this purpose:

\[ U_{\text{HF}} = U_{\text{met}} \left( \frac{\delta_{\text{met}}}{H_{\text{met}}} \right)^{1.0} \left( \frac{H}{\delta} \right)^{0.22} \]  

(5)

Where \( U_{\text{HF}} \) is the local wind speed at the top of the building of height \( H \) (4 m), \( U_{\text{met}} \) is the wind speed recorded at height \( H_{\text{met}} \), \( \delta \) (370 m) and \( a \) (0.22) are the atmospheric boundary layer thickness and exponent at the building, respectively, and \( \delta_{\text{met}} \) (270 m) and \( a_{\text{met}} \) (0.14) are the same properties at the meteorological station. The value of \( U_{\text{HF}}/U_{\text{met}} \) is therefore 0.59, so the wind speeds at the building are reduced by that factor.

Based on this data, typical wind speeds are chosen for this study. They are: 2, 4, 6, and 10 m/s. Accounting for symmetry, 3 directions in increments of 45° from normal will be simulated as well.

For these simulations, wind speed cannot be used directly as a boundary condition. Wind data must be converted to air pressures at the opening and air cavities. This conversion relies on a number of assumptions and empirical data. For example, Swami and Chandra (1987) provide the average wall pressure coefficient for low-rise buildings for all wind angles. Therefore for the wind speeds and angles dealt with in this study, the values of the pressure at the opening can be found.

Table 1 lists values for the pressure coefficient (\( C_p \)) on the windward wall, leeward wall, and roof ridge of single story houses with low sloped roofs from multiple sources, which are indicated in the table.

<table>
<thead>
<tr>
<th>Angle</th>
<th>South wall</th>
<th>South roof ridge</th>
<th>North roof ridge</th>
<th>North wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° (south)</td>
<td>0.6( ^{1} )</td>
<td>-1.3( ^{1} )</td>
<td>-0.9( ^{1} )</td>
<td>-0.4( ^{1} )</td>
</tr>
<tr>
<td>45°</td>
<td>0.25( ^{2} )</td>
<td>-0.9( ^{2} )</td>
<td>-0.7( ^{2} )</td>
<td>-0.7( ^{2} )</td>
</tr>
<tr>
<td>90°</td>
<td>-0.3( ^{3} )</td>
<td>-0.6( ^{3} )</td>
<td>-0.6( ^{3} )</td>
<td>-0.3( ^{3} )</td>
</tr>
</tbody>
</table>

\(^1\)Swami and Chandra, 1987  
\(^2\)Jing and Li, 2013  
\(^3\)Holmes, 1994  
\(^4\)TPTU, 2007

Table 1 Pressure coefficient values for various locations on a low-rise building at different angles from multiple sources

From the range of values obtained, one single value for each pressure coefficient is selected, which is an average of the values. The values obtained from Holmes (1994) is given a greater weight in the averaging process since it is based on a house that is elevated off the ground, which is almost always the case in the North. For the value of \( C_p \) on the windward wall (South), the Holmes (1994) value is used directly. Table 2 shows the final values used in this study. The effect of the polyester filter membrane on the ventilation rates is also studied.

<table>
<thead>
<tr>
<th>Angle</th>
<th>South wall</th>
<th>South roof ridge</th>
<th>North roof ridge</th>
<th>North wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° (south)</td>
<td>0.9</td>
<td>-0.7</td>
<td>-0.7</td>
<td>-0.3</td>
</tr>
<tr>
<td>45</td>
<td>0.3</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.6</td>
</tr>
<tr>
<td>90</td>
<td>-0.3</td>
<td>-0.6</td>
<td>-0.6</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

Table 2 Pressure coefficient values used in this study

Conduction

The temperature difference between the indoor and outdoor encourages buoyancy driven forces to ventilate the attic. The effect is isolated in this study to investigate its significance. In this case, heat transfer into the air cavities and attic is considered for the walls and the ceiling. Typical winter conditions (-30°C) are taken into account since they will produce the high temperature differences, and, therefore, high heat losses.

The temperature of the surfaces in the cavities and attic are the required boundary conditions in FLUENT. Since those temperatures are themselves dependent on
In the case of having no outdoor wind, the temperatures of the surfaces in the cavity can be estimates using the steady-state conduction equation. The thermal resistance of the wall components is 8 m²K/W for the wall (the portion inside with respect to the cavity), 0.2 m²K/W for the still air in the cavity (ASHRAE, 2013), and 0.2 m²K/W for the outdoor heat transfer resistance (considering almost no wind). The cladding is assumed to have no thermal resistance, which is a common assumption. Using the standard heat conduction equation and assuming the indoor temperature is 22ºC, we obtain the temperatures on the surfaces: the exterior face of the cavity is -29.3 ºC and the interior face is -28 ºC. These values are also used for the interior of the roof and exterior of the ceiling, respectively, for simplicity.

In the case where there are higher outdoor wind speeds and higher cavity flow rates, the temperatures can be quite different, so it worthwhile to check using another calculation method that accounts for heat transferred by air movement through the cavity. The equation below (Athienitis et al., 2004) is applied to determine the air temperature in a cavity of finite length and width.

\[
T_a(x) = \frac{T_w + T_b}{2} + \left[ T_o - \frac{T_w + T_b}{2} \right] e^{\frac{-x}{A}} \tag{6}
\]

\[
A = \frac{M_r f}{W h_o} \tag{7}
\]

Where \(T_a\) is the temperature of the air in the cavity, \(T_w\) is the BIPV/Cladding temperature, \(T_b\) is the back plate/sheathing temperature, \(T_o\) is the outdoor temperature, \(x\) is the upward vertical distance from the bottom of the vented cavity, \(M\) is the volume flow rate, \(c\) is the specific heat of air, \(\rho\) is the air density, \(W\) is the width of the wall (1 m), and \(h\) is the cavity surface convective heat transfer coefficient. An initial guess is made for the cavity wall temperatures execute the equation and find the average air temperature in the cavity. That value is used in an energy balance equation to check if the initial guesses for wall temperatures are reasonable, making this an iterative process. The simulations are part of this iterative process since the cavity flow rates, obtained by simulation, are dependent on the surface temperatures. The value of \(h\) is determined using correlations for calculating the Nusselt number for BIPV/T system, obtained by Candanedo et al. (2011), shown below:

\[
N_u = 0.052 Re^{0.78} Pr^{0.4} \tag{8}
\]

The value of \(h_o\) is obtained using correlations provided by Test et al. (1981):

\[
h_o = 8.55 + 2.56 V_{wind} \tag{9}
\]

Radiative heat losses are not explicitly considered in this study, but it is important not to neglect the effect of radiation at low wind speeds, especially in extreme cold climates. To compensate, a minimum value of 12 W/m²K for \(h_o\) is considered. Therefore the value of \(h_o\) is prescribed by the equation above unless it is below 12 W/m²K.

Using this formulation, it was found that the temperature differences are simply reduced with higher wind speeds, and the range of the temperature difference between the interior and exterior faces of the cavity is between 1.3 ºC to 0.5 ºC. The temperature difference is highest at low wind speeds, where the buoyancy forces are more significant, and lowest at high wind speeds, where buoyancy forces have less significance. For simplicity and to be conservative in considering the buoyancy forces, the larger temperature difference of 1.3 ºC is considered in all cases, such that the exterior face of the cavity is -29.3 ºC and the interior face is -28 ºC.

**Solar Radiation**

The heat gains from solar radiation can be obtained by first calculating the total incident solar radiation on a surface, and then by accounting for the absorptance of the BIPV and its electrical efficiency, which is temperature dependent. Only in this scenario would the choice of cladding have an impact on the results since BIPV/T cladding is generally much more absorptive than standard cladding. Therefore, for this case, a BIPV system with an absorptance of 0.95 is considered. The electrical efficiency of the BIPV system is that of typical poly-Si panels (PikeResearch, 2012) which is temperature dependent:

\[
\eta = 0.15 \left[1 - 0.45(T_w - 20)\right] \tag{10}
\]

Where \(\eta\) is the electrical efficiency of the BIPV. The solar properties of a sunny winter noon would be used in the simulation, therefore 600 W/m² of incident solar radiation is assumed. The equation by (Athienitis et al., 2004) presented earlier is used at all wind speeds to determine the temperatures of the surfaces. Of course, this is an iterative process as mentioned earlier. The final input parameters are shown in Table 3.
Table 3 Convection and temperature boundary conditions for BIPV/T cavity

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>h (W/mK)</th>
<th>h (W/mK)</th>
<th>T_h (ºC)</th>
<th>T_t (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12</td>
<td>4.12</td>
<td>6.35</td>
<td>2.35</td>
</tr>
<tr>
<td>2</td>
<td>13.67</td>
<td>5.73</td>
<td>0.55</td>
<td>-4.15</td>
</tr>
<tr>
<td>6</td>
<td>23.91</td>
<td>13.30</td>
<td>-15.35</td>
<td>-21.15</td>
</tr>
<tr>
<td>10</td>
<td>34.15</td>
<td>20.72</td>
<td>-20.25</td>
<td>-25.05</td>
</tr>
</tbody>
</table>

Summary of Simulations

The table below summarizes the simulation cases performed for this project.

<table>
<thead>
<tr>
<th>Simulation Description</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attic subjected to wind speeds 1, 2, 4, 6 and 10 m/s, at 3 directions</td>
<td>15</td>
</tr>
<tr>
<td>Attic subjected to normal wind at speeds 1, 2, 4, 6, 10 m/s, without polyester filter membrane</td>
<td>5</td>
</tr>
<tr>
<td>Attic subjected to normal wind at speeds 0, 1, 2, 4, 6, 10 m/s and considering effects of heat losses through the ceiling and walls in winter</td>
<td>6</td>
</tr>
<tr>
<td>Attic subjected to normal wind at speeds 0, 1, 2, 4, 6, 10 m/s considering above conditions and solar radiation on BIPV/T Wall</td>
<td>6</td>
</tr>
<tr>
<td>Total number of cases</td>
<td>32</td>
</tr>
</tbody>
</table>

Aside from the simplifications and assumptions mentioned previously, the following is a list of general assumptions for this study:

- The influence of snow accumulating in the filter membranes is not accounted for.
- Moisture in the air is not considered.
- No air leakage from the interior to the attic is considered.
- The SIMPLE scheme is used to handle pressure-velocity coupling.
- K-epsilon model used.
- Air is assumed to be an incompressible ideal gas.
- Radiation is not accounted for in the FLUENT model, only in the hand calculations to obtain the surface temperatures.
- Solar radiation on the roof is not considered since there is an open air layer between the roofing and the underlay.

RESULTS

The results are divided up into three sections. First, the influence of wind speed and direction are examined. Second, the influence of removing the porous material is investigated. Third, the effect of heat conduction and solar radiation is compared with the first results.

Wind Speed and Direction

A summary of the ventilation rate results can be found in Figure 64. The flow rate is in the unit kg/ms because the simulation is in two dimensions. As expected higher wind speeds correspond to higher ventilation rates of the attic space. As the wind direction deviates from normal (0º) to 90º, the ventilation rate decreases. This is understood because the wall openings are on the south and north sides of the house and so winds perpendicular to the opening exhibit less pressure on the openings. This makes the relationship between wind speed and ventilation rate rather interesting.

Figure 6 Effect of wind speed and direction on attic ventilation rates

Figure 75 is a representation of the data where the wind direction is on the x-axis. Considering symmetry, the data is extended to 180º, though it can be further extended to 360º. As can be seen in the figure, the plot points for each wind speed can approximated by sin curves. Therefore, empirical equations can be developed to express the relationship between wind speed, direction, and ventilation rate.
Figure 86 shows a sample of how the velocity vectors appear when the wind speed is 6 m/s and the direction is 0°. The highest air velocities are found in the windward wall cavity as expected. High velocities can be seen in the other wall cavity and at the roof ridge openings too. The velocity vectors looks quite similar in most cases, so they are not displayed here in this paper; contact the authors for more information.

Figure 8 Velocity vectors for case with 6 m/s wind speed

The wind speed range of 1 – 10 m/s therefore translates to a cavity air speed range of 0.08 – 1.62 m/s. Data collected by Baril (2013), though not yet published, shows that the range of air speeds observed in wall cavities of northern houses is 0.1 – 1.0 m/s. This indicates that the conditions obtained with simulation are within a realistic and plausible range.

With and Without Porous Material

Figure 97 shows the effect of the porous filter membrane in the wall cavity on the attic ventilation rates. Generally, the ventilation rates are reduced by a factor of 3 with the porous material, based on the assumed characteristics of the material. This is quite significant and can have a significant impact on the hygrothermal performance of an attic.

Heat Conduction and Solar Radiation on BIPV/T wall

When considering energy, the effects of buoyancy forces are clear, especially at low wind speeds. Figure 119 shows the velocity vectors in the case where there is no outdoor wind. The air is moving only because of temperature differences. It can be seen that the velocities are very small, especially compared to what is experienced with wind.

Low wind speeds almost completely override the effect of buoyancy, as shown in Figure 1311 where the wind speed is 2 m/s. This shows that unless there is almost no wind at all, buoyancy driven air movement is not very significant, at least with regards to the patterns of air movement.
When, along with heat conduction, solar radiation on a BIPV/T panel is considered, the results change quite dramatically. Figure 16 shows the velocity vectors in the attic space when there is no wind. The high temperatures in the southern wall cavity cause buoyancy forces to move the air significantly: The air speed in the wall cavity is about 0.2 m/s. Within the attic, air speeds of about 0.1 m/s are observed, which is much more than seen in the case of just heat conduction.

The temperature profile, shown in Figure 17, demonstrates the heating effect of the BIPV/T on the rising air in the wall cavity. In turn heating the entire attic some 10 °C, which is quite significant.

With 6 m/s winds, the air velocities are quite similar to those observed with heat conduction and without, as shown in Figure 18.
The temperature profile with 6 m/s winds, shown in Figure 19, demonstrate how the warm air is propagated in the attic space. A clear separation of cold and warm zones can be seen. This because of the high air speed in the attic, where the air is driven from the wall cavity almost completely to the ridge vents.

The overall ventilation rates of the attic comparing the effect of considering heat and solar radiation are shown in Figure 20. Consistently, accounting for heat transfer in the system increases the ventilation rate in the attic. Adding solar radiation increases it even further. However, in both cases the increase is very marginal if there is wind. If heat conduction is considered without solar radiation, the ventilation rates are also marginally increased. The one interesting condition is when the wind speed is below 2 m/s while heat conduction and solar radiation are considered. The high temperatures achieved in the wall cavity, because of lack of wind, drive the air significantly and a ventilation rate of almost 0.074 kg/ms is observed with no wind and 0.084 kg/ms with 1 m/s wind. This shows that solar driven ventilation should be accounted for at very low wind speeds. However, it must be investigated how often it occurs that the wind speed is low while it is sunny. In Iqaluit, wind speeds lower than 3 m/s overlapping with direct solar radiation higher than 300 W/m² occur less 8% of the time.
CONCLUSION

CFD simulation allows the investigation of physical phenomena that may be difficult to measure in the field, or that there is little information on. In this study, a house in the arctic, fitted with an attic ventilated at the bottom of the cladding, is subjected to typical wind behavior, solar radiation, and temperature differences to determine the ventilation rate of the attic. It was observed, as expected, that higher wind speeds increase the attic ventilation rates, while wind direction deviating from normal decrease ventilation rates. The porous material has quite a significant effect on the ventilation rate, decreasing it by at least a factor of 3 at the properties assumed. When heat conduction is considered, ventilation rates increase slightly but not significantly. The same goes for considering solar radiation on a BIPV/T wall. Only in the cases with low wind speeds (<2 m/s) and peak solar radiation that significant increases in the ventilation rate is observed.

Many assumptions were used in this study. The largest being the properties of the porous membrane because they affect the ventilation rates significantly. However these assumptions are reasonable since the cavity air speeds observed are similar to those observed on the field in a similarly designed house. Continuations of this study would need to include a parametric study on the effect of the porous membrane properties. There are some parameters, like air leakage, that have a large impact on ventilation rates but are very difficult to consider in CFD because the geometry of the cracks and openings in the building are not simple. It is safe to conclude, however, that wind is primary driver for attic ventilation in all cases, but that solar radiation on BIPV/T does have a significant influence on attic ventilation rates at low wind speeds.

The information will allow researchers and builders to know if this design including filter membranes is beneficial in maintaining healthy attic conditions. The results from this study will also be used as part of a larger study to investigate the effectiveness of various ventilation strategies removing moisture build-up in attics.

ACKNOWLEDGEMENT

Financial support from an NSERC Scholarship and the Concordia University Graduate Doctoral Fellowship is acknowledged. Financial support from the ecoENERGY Innovation Initiative and the NSERC Smart Net-zero Energy Buildings Strategic Research Network is also gratefully acknowledged.

NOMENCLATURE

- $a$: Atmospheric Boundary Layer exponent at Building Location
- $a_{\text{met}}$: Atmospheric Boundary Layer exponent at Meteorological Station
- $c$: Specific Heat of Air
- $C_p$: Pressure Coefficient
- $C_\gamma$: Pressure Jump Coefficient of Porous Material
- $h$: Cavity Surface Convective Heat Transfer Coefficient
- $h_o$: Exterior Surface Convective Heat Transfer Coefficient
- $M$: Volume Flow Rate
- $\Delta n$: Thickness of Tested Porous Material
- $\Delta P$: Pressure Drop Across Porous Material
- $T_a$: Air Temperature in Cavity
- $T_b$: Sheathing/back plate temperature
- $T_w$: Cladding/BIPV temperature
- $U_{\text{ld}}$: Local Wind Speed at the Top of a Building
- $U_{\text{met}}$: Wind Speed Recorded at Meteorological Station
- $V$: Air Velocity through Porous Material
- $V_{\text{wind}}$: Wind Speed
- $W$: Width of Façade
- $x$: Vertical Distance from Bottom of Cavity
- $\alpha$: Air Permeability of Porous Material
- $\delta$: Atmospheric Boundary Layer Thickness at Building Location
- $\delta_{\text{met}}$: Atmospheric Boundary Layer Thickness at Meteorological Station
- $\eta$: Electrical Efficiency of BIPV System
- $\mu$: Air Dynamic Viscosity
- $\rho$: Air Density

REFERENCES

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