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AN IN-DEPTH REVIEW TO ESTABLISH GUIDELINES FOR A NEW LIGHT FRAME PANELIZED ROOF MANUFACTURING WITH HIGH THERMAL PERFORMANCE

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ABSTRACT

This study is a summary of previous research work to identify the parameters affecting the hydrothermal performance of pitched roof construction. This in-depth assessment serves as a reference for the new holistic design approach of panelized roofs considering thermal performance and prefabrication factors to manufacture fully panelized homes in North America. Roof design for cold climates requires careful consideration of several factors to avoid moisture build-up in the attic space. Poor design can lead to ice formation near eaves and mold growth in the Oriented Strand Board layer of the roof. It also affects the overall thermal comfort of occupants. The literature review revealed that the following parameters play a critical role in the hydrothermal performance of a roof: a) Attic ventilation ratio, b) Attic baffle size and vent configuration, c) Airflow pattern in pitched roofs d) Internal convection in loose-fill insulations, e) Air leakages around the insulation layer, f) Un-intentional air infiltration rate, g) Type of insulation material and thickness in the ceiling, and h) Properties of roof underlay material. In cold climates, condensation occurs in the attic space of the roof due to the air leakage of the ceiling. To remove this moisture attic ventilation is very effective, however excess ventilation increases the moisture content of roof sheathing whereas low ventilation leads to a negative effect on the moisture removal process. As consequence roof designers must consider optimum attic baffle size and distribution of roof vents since they substantially control the airflow pattern and thus the heat flux of the attic. Based on the literature review and construction practice a possible configuration of roof vent is presented for a case study panelized roof. Finally, a case study gable roof 1/85 ventilation ratio is recommended considering the airflow pattern and temperature distribution as explained in the literature.

Keywords: *Attic ventilation, Attic Airflow, and Panelized Roof Manufacturing*

1. INTRODUCTION

In the North American cold climate, roof venting is provided to obtain a colder attic which prevents ice dam formation on the eave of the roof. However, the roof vent design for a light frame house is not straightforward. Due to the air leakage of the ceiling, condensation occurs in the attic space of the roof. As a consequence moisture build-ups in the cavity insulation and roof sheathing. Although attic ventilation is the most effective design tool to remove this moisture (Bomberg & Onysko, 2002; Essah, 2012; Gutt, 1979; Tobiasson et al., 1994), excess ventilation increases the relative humidity and moisture content of roof sheathing whereas low ventilation leads to a negative effect in the moisture removal process (Blom, 2001; R. Wang, 2018). Therefore, the National Building Code of Canada (NBCC) recommends a minimum 1/300 venting ratio (one square foot of free vent area per 300 square feet of attic floor area) to be a requirement for a light frame pitched roof (Iffa & Tariku, 2015). Typically, a traditional pitched roof fabricated with trusses has vented soffits that act as an air inlet for natural ventilation and the ridge vent acts as an air outlet (Figure 1). The geometry of trusses (Figure 1) makes it easier to design a pitched roof in an on-site stick-built process with a soffit venting option. However, the construction industry is moving toward an offsite construction process to manufacture light-frame homes and it requires a different approach for roof design.

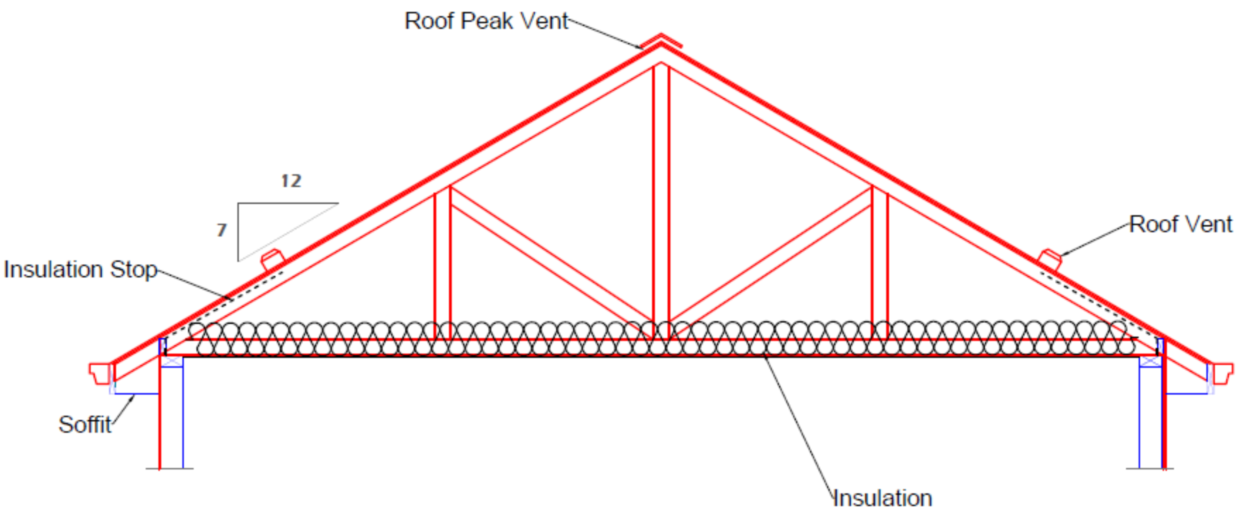

Figure 1: Typical light-frame roof built using trusses

Off-site construction is a manufacturing process where building components, elements, or modules are pre-assembled in a controlled plant environment before installation into their final location (Goodier & Gibb, 2007). Among the several off-site construction approaches, the panelized construction process is broadly used due to its design flexibility and on-site assembly cost savings. This process subdivides a building model into subassemblies such as wall panels, floor panels, and volumetric roof elements, which are manufactured in an off-site facility and then shipped to the site for installation. Although this process is more efficient than stick-built construction, presently, it is classified as partially panelized because of the roof production. Currently, the roof production process is the same as the traditional stick-framing process with the only difference is they are built within factory space and transported to the site as a single-piece module. In order to achieve higher productivity for roof production, a new panelized roof design is proposed (Figure 2). This study is a review of previous research to understand the factors contributing to proper ventilation of the roof. This assessment will provide a guideline for the new holistic design of a panelized roof that considers thermal performance and prefabrication factors to manufacture a fully panelized home in North America.

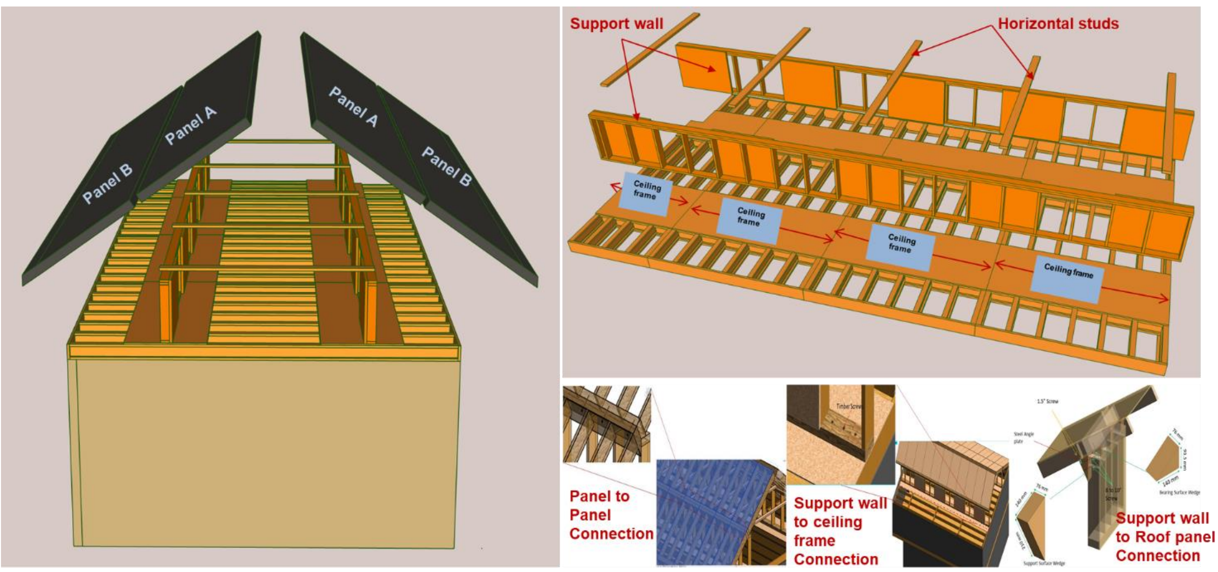

Figure 2: Proposed Panelized roof system

2. PROBLEM STATEMENT AND SIGNIFICANCE

The roof structure is exposed to the most extreme temperature and radiation conditions than any component in the light-frame home (Less et al., 2016). In general, roof design for cold climates requires careful consideration of several factors to avoid moisture build-up in the attic space. Understanding the physics of mass and energy transportation in roof attics is critically important to provide a better hydrothermal performance of the light-frame roof (Bomberg & Onysko, 2002; Gutt, 1979; Less et al., 2016; Tobiasson et al., 1994). It is very common in North America to provide soffit vents for natural ventilation in the attic space. The soffit brings moisture, fine snow particles and cold air into the attic space whereas air leakage from the ceiling provides warm air (Kayello et al., 2017). As a consequence, there is a very complex interaction of heat, air and moisture exchange along with variable outside temperature change in a cold climate. Also, as outside temperature changes with time, heat transferred by radiation, conduction and convection influence the airflow and mass transfer mechanism in the attic space (Less et al., 2016). During winter snow starts to melt if the roof surface temperature raises to a temperature above 32 °F (0 °C) (Yu & Moore, 2015) depending on the solar radiation and precipitation depth (Figure 3). If the roof is not properly ventilated this phenomenon can cause ice dam formation near eaves and moisture accumulates in the Oriented Strand Board (OSB) layer of the roof, thus introducing the risk of mould growth (Blom, 2001; R. Wang, 2018).

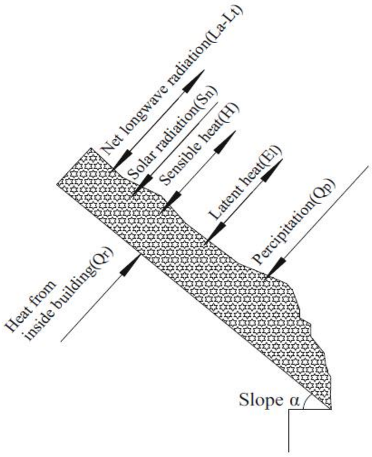

Figure 3: Snow melting process on the roof surface (Zhou et al., 2015)

Furthermore, if the roof is over ventilated excessive moisture is introduced in the roof which increases the attic relative humidity level and moisture content in the sheathing (Tariku & Iffa, 2017; R. Wang, 2018). Additionally, venting the attic in winter minimizes the potential of using solar gain (NBCC, 2015). So, NBCC specifies the passive soffit ventilation ratios of 1:150–1:300 of the unobstructed vent area to the insulated ceiling area. It is common practice to provide proper attic venting outflow in the roof design style so that an equal amount of vent space at the soffit and vent space at the ridge is ensured for traditional truss base light-frame construction (Walker & Forest, 1995; Yu & Moore, 2015). However, there is no clear guideline in the building code on the ventilation opening for any new type of roof construction. Thus, it is required to find out what factors needed to consider while designing the new panelized roof system to avoid ice damming and effective moisture removal from the attic space.

3. REVIEW OF ROOF VENTILATION REQUIREMENT

Temperature, moisture, and airflow pattern are the three important parameters in an attic roofing system that facilitates identifying the vulnerable sections of the roof for ice dam formation. It has been observed that mostly moisture damage and roofing material durability problems are common in the attic roof section (Iffa & Tariku, 2015; Tariku & Iffa, 2017; R. Wang et al., 2020). Blom, (2001) studied temperature and moisture conditions in pitched, insulated wood-frame test roofs for clod climate similar to Canada to quantify the effect of opening in the roof on the temperature and moisture content in the attic. He used two different vent configurations: one roof had an opening area for air ventilation 0.36% (less ventilated roof) while the other roof had 0.75% (more ventilated roof). Temperature and moisture in the roof sheathing were measured for one year. Results from Blom's (2001) test revealed that moisture content in the roof sheathing with the highest air opening area is a dependent variable on venting and moisture infiltration from the living spaces during the winter season, Also, very little venting is necessary to remove excess moisture in the attic (Figure 4) (Blom, 2001). The study also found that a 48 mm (2") vent duct is sufficient in pitched, insulated roof constructions in single-family houses however, a key factor to avoid moisture accumulation and ice dam formation is to provide a continuous thermal insulation layer and prevent air leakage through the insulation.

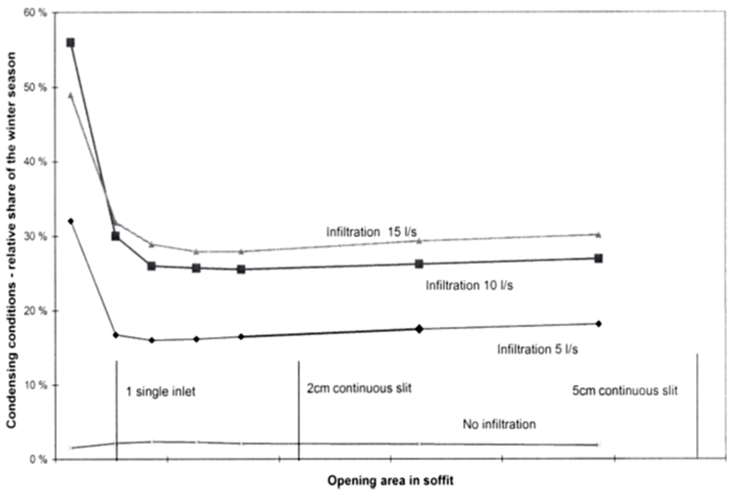

Figure 4: Condensing condition three different levels of attic venting and three different levels of moist air infiltration from the living spaces (Blom, 2001)

International Residential Code (IRC) recommends a clear space between the underneath of the roof sheathing and ceiling insulation which is termed as baffle size must be at least 1" and this gap shall not block the free flow of air. Iffa & Tariku (2015) used three different baffle sizes in a computational model to find out the specific minimum gap that can provide the unobstructed flow of the incoming air in the attic spaces designed in Canada. They developed a computational fluid dynamics model (CFD) for three different baffle sizes and three different locations of the attic vent (Figure 5) to quantify their effect on the airflow pattern and temperature change inside the attic space with a characteristic 30 ft ceiling width and 4/12 pitch roof. Since wind speed is the prevailing factor in the case of attic ventilation both wind-driven air circulation and wind stack effect case were sufficient for the CFD model in that study. Iffa & Tariku (2015) used wind velocity of 2m/s as wind speeds beyond 1.8 m/s the effect of buoyancy on ventilation is very negligible whereas the surface pressure at the inlet is calculated using the following Equation 1:

$$p_s = Cp_I \frac{\rho U_r^2}{2} \qquad (1)$$

Where, U_r wind speed at roof height, ρ air density, p_s surface pressure, Cp_l values are local pressure coefficients which are approximated based on ASHRAE Handbook Fundamentals (ASHRAE, 2013).

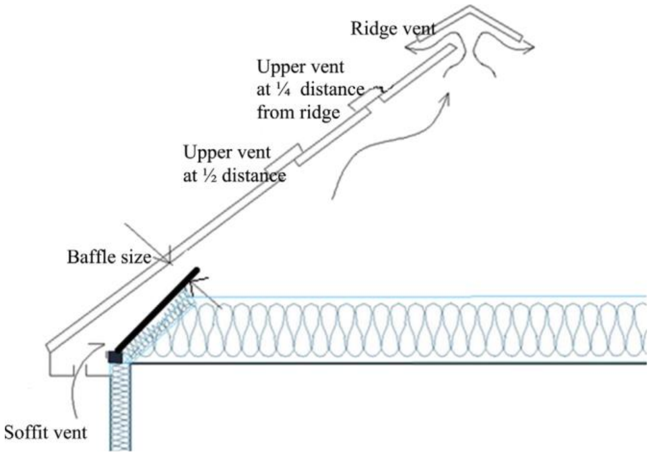

Figure 5: Vent locations in the attic used by Iffa & Tariku (2015)

It was observed by Iffa & Tariku (2015) (Figure 6) with increasing the baffle size positive effect on the air change per hour (ACH) (i.e. 2 inch and 3-inch baffle sizes have 38.5% and 52.49% respectively higher ACH compared to 1 in baffle sized) however the increased airflow does not have a significant effect on the attic air temperature. On the other hand, baffle size does not affect the airflow driven by the stack effect. The most important finding of Iffa and Tariku's (2015) CFD simulation was that the location of the upper vent at ¼ distance from the top ridge had an optimized airflow distribution (a uniform distribution with increased ACH value) as compared with the other two vent locations used in their study.

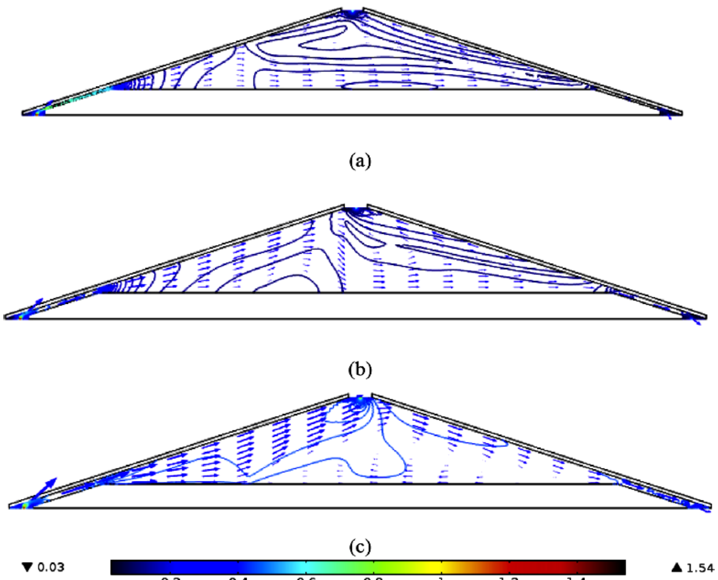

Figure 6: (a)-(c) Airflow streamline variation in wind-driven attic ventilation for baffle size 1", 2" and 3" respectively summer condition in Canada

In contrast to Iffa & Tariku, (2015) CFD model Wang et al., (2012) observed that the airflow and heat transfer inside a vented attic depend on the ambient air temperature under winter conditions for buoyancy-driven turbulent ventilation in the attic space of a gable roof. In fact, ventilation airflow rate is higher on cold days than on warm days and increased vent size has a higher ventilation airflow rate but does not affect the attic heating load significantly. However, the ceiling must have higher insulation (at least R-20). As it can be seen from Figure 7 both the velocity and temperature fields are symmetric with a stabilized airflow because the entering air is colder than both the roof and ceiling during winter; get heated while travelling along the ceiling, and ultimately rises at the midsection of the attic and leaves through the ridge vent (Wang et al., 2012).

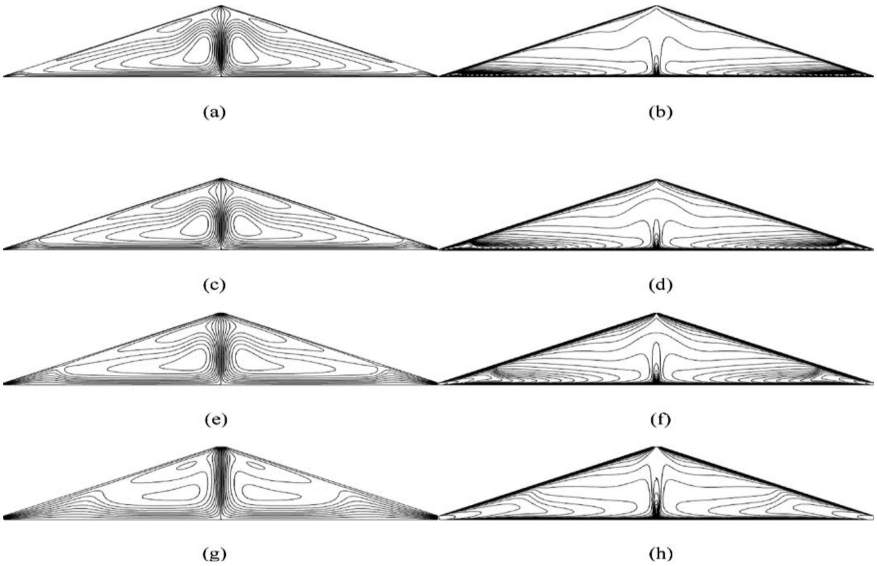

Figure 7: Predicted streamlines (left) and isotherms (right) for the cases of 1 cm (a and b), 2 cm (c and d), 4 cm (e and f), and 8 cm (g and h) soffit vents with T_{in} = 267 K and R-20 ceiling insulation (Wang et al., 2012)

However, a relatively recent study by Tariku & Iffa, (2017) shows that the attic air temperature differences increase with solar radiation gain and reach a maximum of 10°C in winter for the ventilated roof (Figure 8). The study incorporated solar gain with the CFD simulation using Equations 2 and 3 for the boundary condition that represents the winter conditions of Ottawa, Canada in contrast to other studies. The airflow streamlines and attic air temperature pattern (Figure 9) show that ACH is governed by the solar-driven buoyancy force which pulls airflow towards the underneath of the solar-heated sheathing for all wind pressure.

$$Q_l = h_{out}(T_{out} - T) + \alpha Solgain_L \qquad (2)$$
$$Q_r = h_{out}(T_{out} - T) + \alpha Solgain_r \qquad (3)$$

Where h_{out} = combined effects of the convective and long-wave radiation heat transfers using an equivalent surface transfer coefficient; Q_l = heat flux on the left side of the roof; Q_r = heat flux on the right side of the roof; h_{out} = outside heat transfer coefficient; T_{out} = outside temperature; T = attic temperature; $Solgain_L$ = solar gain on the left side of the roof; $Solgain_R$ = solar gain on the right side of the roof; and α = solar absorption coefficient of the outside surface of the roof shingles.

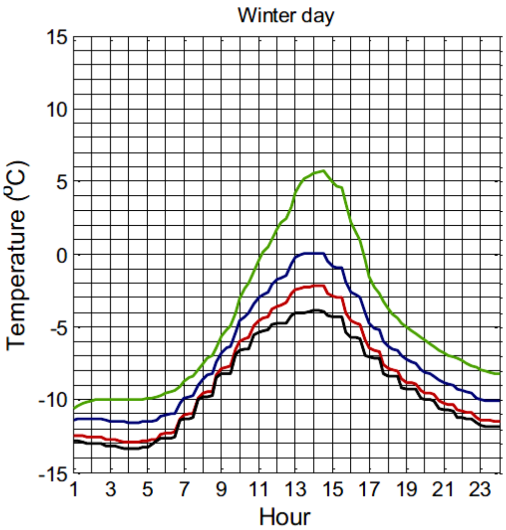

Figure 8: Average attic air temperature for different attic ventilation scenarios during typical winter (Green = sealed; blue = stack effect; red = 0.6-Pa wind pressure; black = 2-Pa wind pressure) (Tariku & Iffa, 2017)

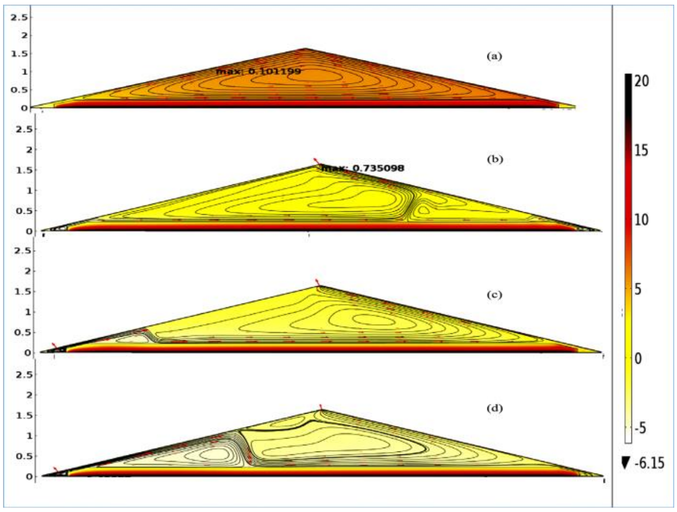

Figure 9: Temperature and airflow fields for different attic ventilation scenarios for a winter day at 2:00 p.m. with solar gain: (a) sealed attic; (b) stack effect; (c) 0.6-Pa wind pressure; (d) 2-Pa wind pressure(Tariku & Iffa, 2017)

Although ventilation is essential for the roof to avoid condensation, an airtight ceiling with a lower-resistance vapour-permeable underlay (VPU) to be the most effective mechanism to avoid mould growth in the roof sheathing (Essah et al., 2009; Lstiburek, 2006). Another way to avoid condensation is to install an air barrier and to dense-pack loose-fill insulation between the floorboards and the ceiling below (Government of Canada, 2020).

4. RESULTS

Based on the above literature review it can be concluded that the following parameters have a significant effect on the hydrothermal performance of a pitched roof:

a) Attic ventilation ratio, baffle size and vent configuration
b) Airflow streamlines velocity distribution in pitched roofs
c) Internal convection in loose-fill insulations
d) Air leakages around the insulation layer
e) Type of insulation material and thickness in the ceiling and
f) Properties of roof underlay material.

The summary of the key findings of the literature review is presented in Table 1. For extremely cold climates like Alberta, roof venting is vital to prevent ice formation at the eaves and to eliminate surplus moisture build-up in the roof sheathing.

Table 1: Summary of key findings from the literature review

Summary of the hypothesis	Literature
The airflow is intended to control moisture in the attic space and ice dam buildup on the roof	(Blom, 2001; Bomberg & Onysko, 2002; Gutt, 1979; Iffa & Tariku, 2015; Tobiasson et al., 1994)
The outside temperature effects on the attic air change are very minimal during wind-driven ventilation.	(Bomberg & Onysko, 2002; Iffa & Tariku, 2015)

Summary of the hypothesis	Literature
When the ventilation is induced by buoyancy the air change is affected by outside temperature, the stack effect for driven ventilation has a higher air exchange rate during hot seasons.	(Iffa & Tariku, 2015; Tariku & Iffa, 2017; S. Wang et al., 2012)
To avoid air flow short-circuiting, it is recommended to place the outlet vents near the ridge	(Walker & Forest, 1995)
Even for the extremely cold climate attic ventilation is required to achieve no mold growth risk	(Wang et al., 2020)
Ventilation may also provide some benefit by prolonging asphalt shingle lifespan.	(Essah et al., 2009)
Higher insulation material in the ceiling and air barrier is required for better performance of the ventilated roof	(Government of Canada, 2020; S. Wang et al., 2012)
Baffle size 2 inch can be used for ventilated roof	(Blom, 2001; Iffa & Tariku, 2015)
Airflow pattern should be considered while providing vents in the roof	(Iffa & Tariku, 2015; Tariku & Iffa, 2017; S. Wang et al., 2012)

It is evident from the review that the above-mentioned factors should be incorporated while designing the vents for the novel panelized roof system. Considering the key findings, a roof vent design is presented for a case study gable roof with a 720 sq. ft footprint area in Figures 10 and 11. In order to ensure proper ventilation for this case study roof, it is recommended to have three types of vents such as a) Soffit vents (at 2′-6" from the edge of the roof as shown in Figure 10), b) Upper vents (at 3′ from the apex of the roof as illustrated in Figure 10) and c) Ridge vent (act as air outlet for incoming air through soffit vent). The design of the roof panel eliminates the use of insulation stop and the location of the soffit vent is governed by the available voids spaces in the support walls. Also, the location and configurations of the vents were determined taking into account the airflow streamline as mentioned in literature and conventional roof construction practice. The location of soffit vents depends on the opening positions of the support wall (Figure 2). In total 16 soffit vents (8 in Panel-A and 8 in Panel-B) are required to ensure the opening alignment with the support wall. Thus ventilation ratio of 1/85 is recommended in this specific case. To ensure uniform airflow in the attic upper vents were provided at a ¼ distance from the apex ridge vent as shown in Figure 10. It should be noted that all the vent holes are 8.5"×8.5" since the most common vent attachment is box type which requires the same hole dimensions to install.

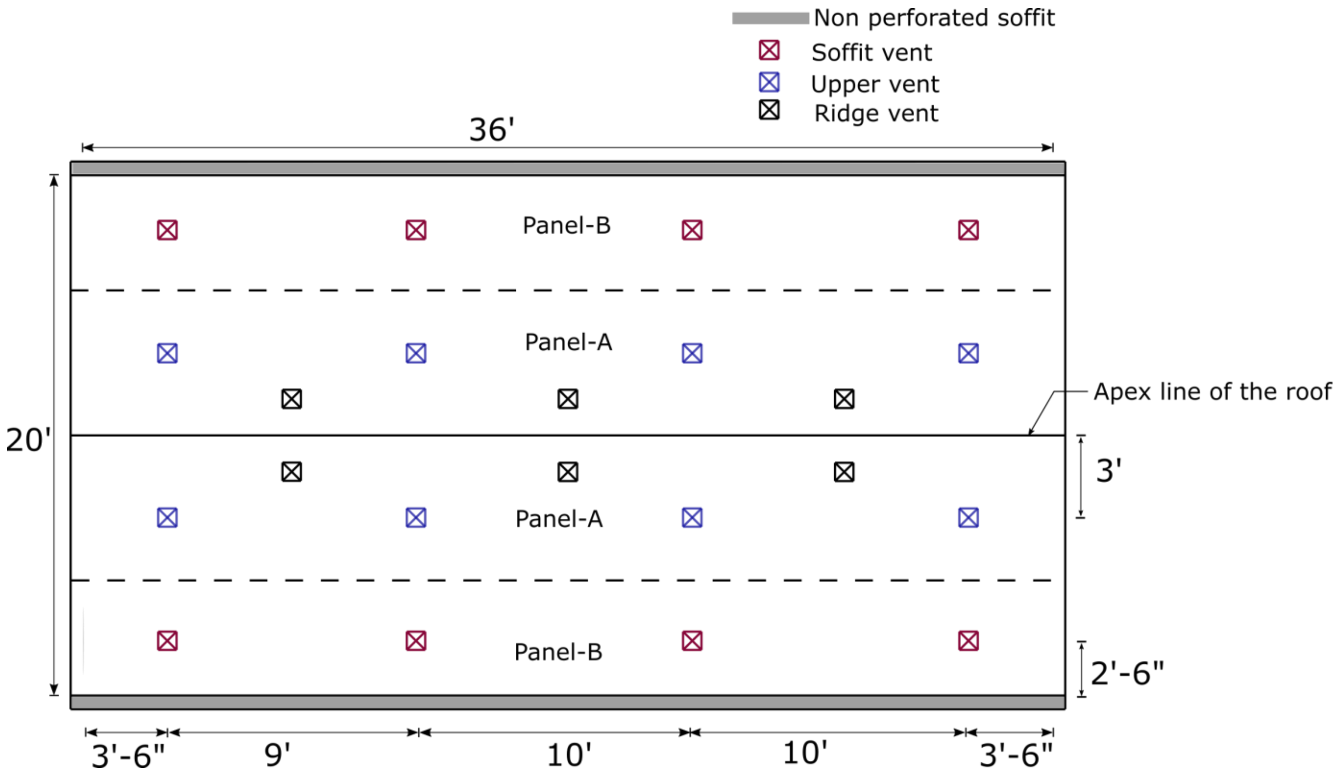

Figure 10: Plan view of possible roof vent configuration for the panelized roof (all vents holes are 8.5" x 8.5")

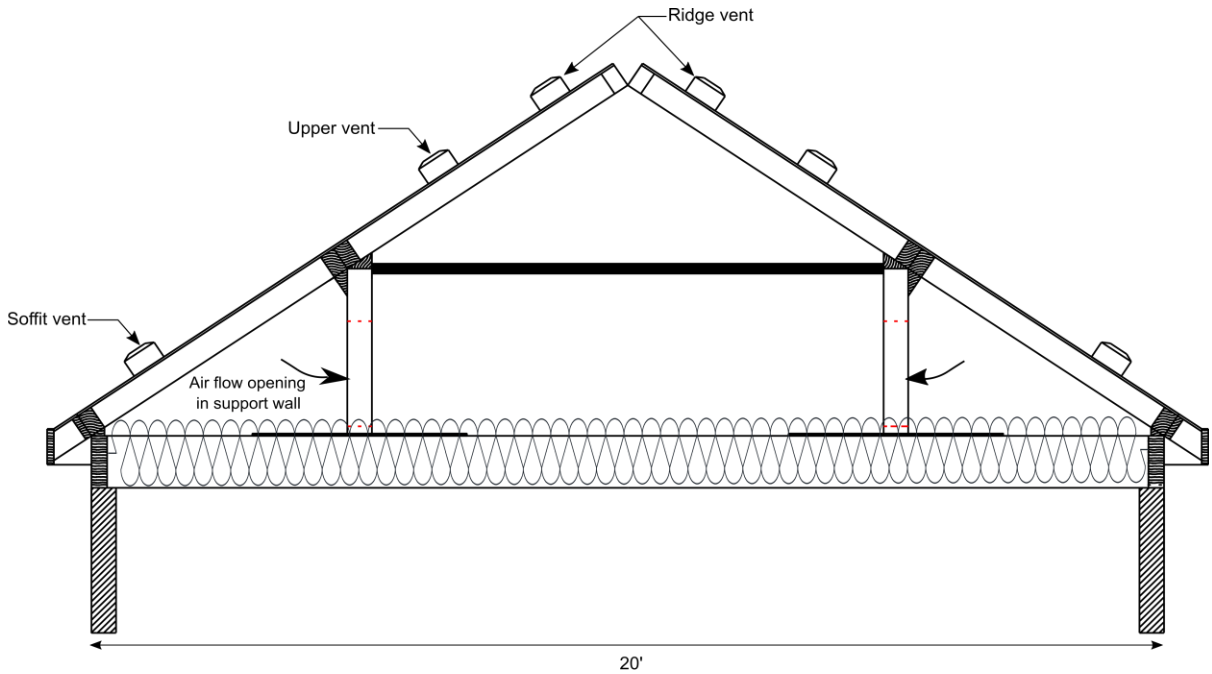

Figure 11: Cross-section of roof vent configuration for new panelized roof

5. CONCLUSIONS

For extremely cold climates like Alberta, roof venting is essential to prevent ice formation at the eave line of the roof. It also eliminates surplus moisture build-up in the attic space of the roof. In traditional pitched roof building, because of the truss geometry (Figure 12), it has less obstruction for natural ventilation in contrast to the panelized roof. So, the ventilation design of the panelized roof must take into account the effect of obstruction in airflow due to the support walls (Figure 2). Although the code minimum for the special case is 1/150, in the case study panelized roof system 1/85 ventilation ratio is provided considering the airflow pattern and temperature distribution presented in the literature review section. The upper vents were provided at a ¼ distance from the apex ridge vent as recommended by Iffa and Tariku (2015). However, hydrothermal simulation is recommended for further study to optimize and improve the vent size and configuration.

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