# Hygrothermal performance of ventilated attic in marine climate under different ceiling air tightness

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## Summary

An indoor to attic air leakage and vice-versa significantly affect indoor air, thermal comfort and the hygrothermal performance in both living space and unconditioned space. In cold and marine climates an air leakage from living space to an attic brings a relatively high relative humidity to the attic space. This effect is primarily responsible for condensation in attic structural parts such as roof sheathings. In this paper, the hygrothermal performance of a ventilated attic in wet costal climates under different ceiling air leakage is studied. A benchmarked whole building Heat-Air-Moisture model named *HAMFit* is used to study hygrothermal performance of ventilated attics in marine climates. The attic is modelled as 2-dimensional geometry with coupled heat transfer, moisture transport and a turbulence Computational Fluid Dynamics through attic space and porous structural parts of the attic. A vent ratio of 1/300 and three types normalized leakage area (tight, normal and leaky) are used to analyse how the moisture transport behaves in ventilated space. A winter weather data of city of Vancouver, BC is used to represent a wet marine climate. Our findings show specific locations in the attic structure are more exposed to moisture related problems and the air circulation and temperature distribution due to ventilation under multiple ceiling air leakage scenarios are presented.

## PRACTICAL IMPLICATIONS

The indoor air leakage to the attic and an outdoor air, which enters through vents, mix inside the attic space. In this study, a 2-dimensional hygrothermal modelling is used to study the moisture transport throughout the attic structure.

## KEYWORDS

attic, CFD, indoor air leakage, moisture transport, ventilation.

## 1 INTRODUCTION

Attic ventilation is a popular practice which is used to enhance the thermal performance of an attic space and reduce the moisture content of the attic structural elements. The two main sources of moisture in cold and coastal climates are: (i) the condensation created in the attic structure which is caused by a leaked air from leaving space through ceiling and (ii) rain / snow driven through vents.

Ventilation induced cold roofs can prevent ice damming by keeping the entire roof as cold as the outside temperature. Even though, attic ventilation is considered in many building codes as a champion practice in minimizing moisture related problems caused by ice dams and condensation from indoor air that escapes the living space, it does not come without a penalty. Ventilating an attic in cold and coastal climates can cause snow and rain to enter into the attic space which may result in mold and rot. In addition, the moisture carrying capacity of the cold air entering the attic space can be very low.

Several researchers have conducted hygrothermal performance assessment of ventilated attics (Schumacher 2008, Lstiburek and Schumacher 2011, Nik et al. 2012). Most of these studies assume a fully mixed air circulation in the attic space. This assumption provides a generalized and constant hygrothermal measurement throughout the attic space. In this study a Computational Fluid Dynamics (CFD) study of the air movement inside the attic space and porous structure is incorporated to observe the air and moisture movement and locate spots which are more susceptible for moisture related damage.

This study aims to investigate the hygrothermal performance of ventilated attic in coastal climate under different ceiling air leakages using benchmarked heat-air-moisture (HAM) model called *HAMFit* (Tariku et al 2008, Tariku 2008, Tariku et al. 2010).

## 2 Mathematical Model and Description of *HAMFit*

The HAMFit model solves, simultaneously, the three interdependent transport phenomena of heat, air and moisture in a building component.

### 2.1 Governing Equations

The mathematical model is based on building physics and comprises a set of partial differential equations (PDEs) that govern the individual flows. The corresponding governing equations are as shown below:

$$\theta \frac{\partial \emptyset}{\partial t} = \nabla.\left(D_{\emptyset}\nabla\emptyset + D_t\nabla \mathrm{T}\right) - \nabla.\left(\mathrm{D}_t\rho_w\vec{g} + \rho_a\vec{u}C_c\hat{P}\emptyset\right) \quad (1)$$

where $D_{\emptyset} = \left(+D_t\frac{\rho_w RT}{M\emptyset}\right)$, $D_r = \left(\delta_r\frac{\partial\hat{P}}{\partial T} + D_t\frac{\rho_w R}{M}\ln(\emptyset)\right)$ and $C_c = \frac{0.622}{P_{atm}}$

**<u>Heat Balance</u>**

$$\rho_w C_{Peff}\frac{\partial T}{\partial t} + \nabla.(\vec{u}T)\rho_a\left(C_{pa} + \omega C_{pr}\right) + \nabla.\left(\lambda_{eff}\nabla T\right) = \dot{m}_c h_{fg} + \dot{m}_c(Cp_v - Cp_l) + \dot{Q}_s \quad (2)$$

where $C_{Peff} = Cv_m + y_l C_{Pl}$ and $\dot{m}_c = \nabla.(\delta_v\nabla P_v) - \rho_a\nabla.(\vec{u}\omega)$

**<u>Air mass balance</u>**

$$\nabla.(\rho_a\vec{u}) = 0 \quad (3)$$

**<u>Momentum balance (Darcy equation)</u>**

$$\vec{u} = \frac{k_a}{\eta} \nabla P \quad (4)$$

$$-\nabla . \left( \rho_a \frac{k_a}{\eta} \nabla P \right) = 0 \quad (5)$$

where: $\rho_w$ : density of water (kg/m$^3$), $\rho_a$ : density of air (kg/m$^3$), $\theta$ : sorption capacity (kg/m$^3$), $\emptyset$: relative humidity, $\vec{u}$: air velocity (m/s), $\dot{m}$ : mass flow rate of dry air (kg/s), $h_{fg}$ : latent heat of evapouration/condensation (J/kg), $\hat{P}$: saturated vapour pressure (Pa), $\delta_v$: vapour permeability (s), $\omega$: humidity ratio (kg/kg air), $k_a$: air permeability (m$^2$), $\eta$: dynamic viscosity (kg/ms).

The governing partial-differential equations (PDEs) of the three transport phenomena (Equation 1, Equation 2 and Equation 5) are coupled and solved simultaneously for temperature, relative humidity and pressure using a finite-element based software called COMSOL Multiphysics 5.1. This commercial software is found to be beneficiary for solving non-standard coupled-multiphysics problems because of its open provision for implementing user defined PDEs and its smooth interface with MatLab/SimuLink 2015a. The model accommodates non-linear transfer and storage properties of materials, moisture transfer by vapour diffusion, capillary liquid water transport and convective heat and moisture transfer through multi-layered porous media. The transient HAM model is successfully benchmarked against published test cases (Tariku et al 2008, Tariku et al. 2010). The test cases are comprised of an analytical verification, comparisons with other models and validation of simulation results with experimental data.

Most building materials are porous, and composed of solid matrix and pores. In the pores, moisture can exist in any of the three thermodynamic states of matter, i.e. gas (vapour), liquid, and solid (ice) states. However, moisture movement is possible only in the vapour and liquid states. The main mechanisms of moisture transfer can be by vapour diffusion, capillary suction, or combination of both, depending on the moisture content of the material. A Darcy's model is used to study the moisture and air movement inside the porous attic insulation. The general gas law defines the thermodynamic state of the air, water vapour and the water vapour-air mixture in the pores. The contact surfaces between two adjacent layers are assumed to be in perfect contact, consequently, the profiles of vapour pressure, suction pressure and temperature are continuous at the interface. More detailed information on the development and application of *HAMFit* model can be found in Tariku (2008).

### 2.2 Boundary Conditions

A weather data of Vancouver, BC is use to represent a cold coastal climate. Weather data of the year 1975 is selected and used in this study based on 10% hot / cold climate criteria (TenWolde 2009). The outdoor temperature and relative humidity, solar gain and rain fall data are retrieved from Environment Canada (2015). The indoor temperature and RH values for the residential building is set in accordance with ASHRAE 160 class model (2009).

## 2.3 Initial conditions

In any hygrothermal simulation, the user defines the initial moisture content of each wall component at the beginning of the simulation period. In this study a three month moisture and heat transfer computation is conducted using November 1st to December 31st weather data. The last hour (December 31st, 11:00PM) computed values of temperature and relative humidity are used as initial values for the main model.

## 2.4 Geometrical and computational model

A 2-dimensional CFD model coupled with moisture and heat transfer model is used to study the air, moisture and temperature distribution inside the attic space for different ceiling air leakage configurations. The CFD model uses a single phase turbulence flow in the attic space and a Darcy's flow for the porous attic insulation.

The attic geometry is characterized by a 9 meter ceiling width and 4/12 pitch roof. Three different ceiling air leakage values are used to study how the air flow distribution and temperature profile affects the moisture distribution. The three different Normalized Leakage area (NLA) values are calculated based on ASHRAE Handbook – Fundamentals (2013)

The three ceillings, under this study, are classified as (i) sealed ceiling, (ii) ceiling with medium leakage (iii) leaky ceiling. The painted ceiling board is assumed to have a permeability of 5-9 perm. These leakage values are selected based on the data presented by Sheltair (1997) and Morrison Hershfield (2014). Table 1 shows the type of ceilings and their respective NLA used.

Table 1. Ceilings and their Normalized Leakage area

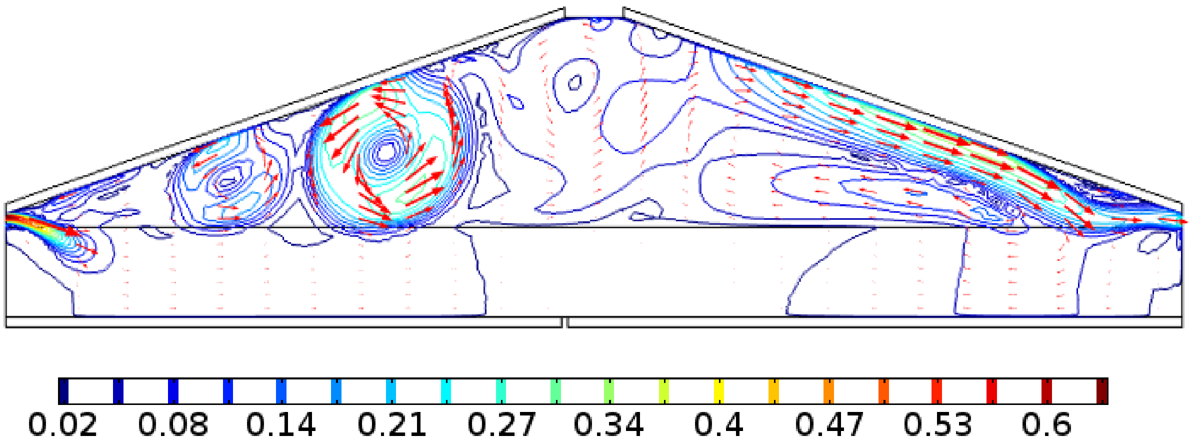
| Type of ceiling | NLA |
|---|---|
| Sealed Ceiling | <0.2 |
| Ceiling with medium leakage | 0.7 |
| Leaky ceiling | 2.4 |

## 2.5 Material properties

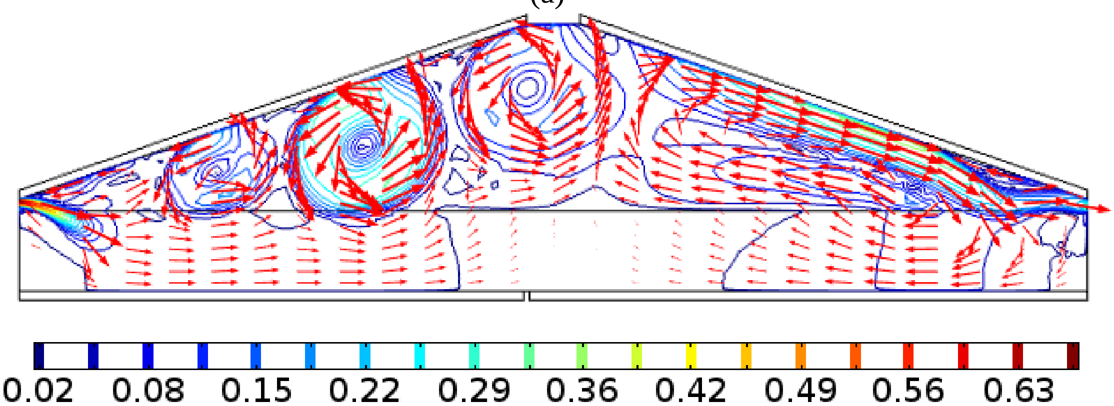
The attic structure comprises of painted gypsum, low density fiberglass insulation and OSB sheathing. The effects of the exterior roof material are taken into account by adjusting the exterior thermal and mass transfer coefficients. In this study the basic material properties required for the input file of *HAMFit* are taken from the ASHRAE research report (Kumaran 2002).
Eight sets of material properties are required for *HAMFit* simulation, which are: (i) Dry density, (ii) Air permeability, (iii) Thermal conductivity, (iv) Heat capacity, (v) Sorption and water retention characteristics, (vi) Water absorption coefficient, (vii) Vapour permeability and (viii) Liquid permeability.

## 3 RESULTS AND DISCUSSION

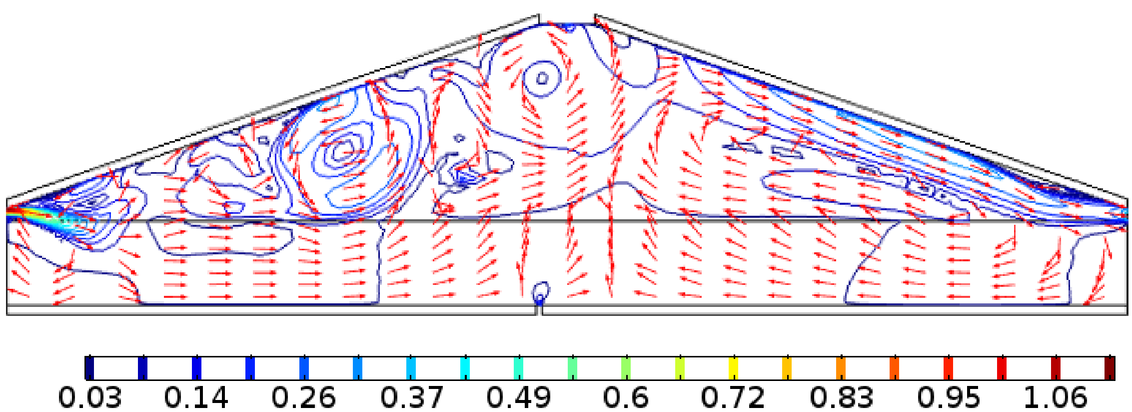
The air distribution inside the attic and the fiberglass insulation for the three different ceiling air leakage values (in accordance to Table 1) are shown in Figure 1 (a) to (c). As expected the air flow has increased proportionally to the ceiling air leakage. However, in all three scenarios the air that enters through vents overwhelms an air that comes through the ceiling leakage.




(a)




(b)




(c)

Figure 1.Velocity (m/s) profile of the air flow inside the attic and insulation. (a) NLA<0.2, (b) NLA=0.7 and (c) NLA=2.4.

Figure 2 shows the temperature distribution in the attic structure with a higher ceiling air leakage (NLA= 2.4). The ventilation kept the attic space and the roof sheathings cold. The temperature near the top of the attic insulation is nearly equal to outdoor temperature near the air vents. The temperature of the insulation has a slightly higher value near the ceiling air leakage area.

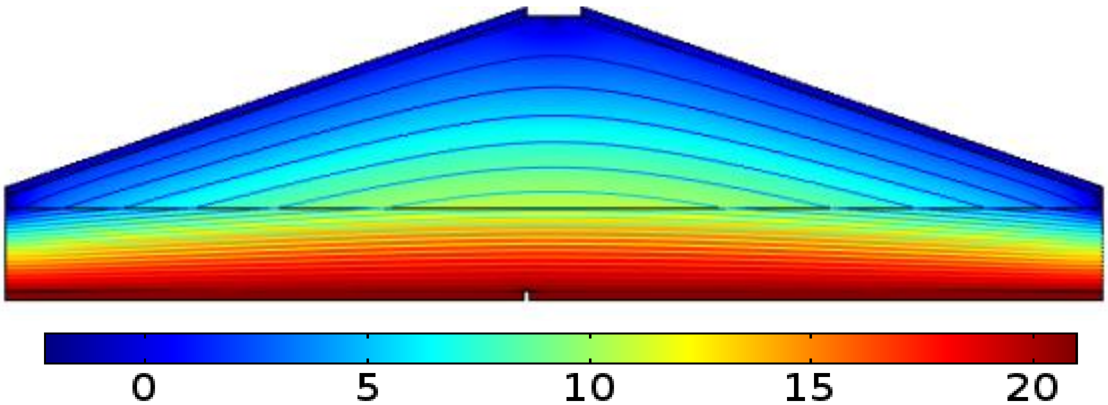



Figure 2. Temperature distribution

As shown in Figure 4 (a) to (c), the relative humidity has increased as the air leakage area increases. The lower side of the sheathings and the roof top area exhibited a higher value of relative humidity. This is due to the combined effect of wet air entering through soffit vent (a vent through exterior ceiling between wall siding and roofline) and condensation created due to the warm air escapes the living space.

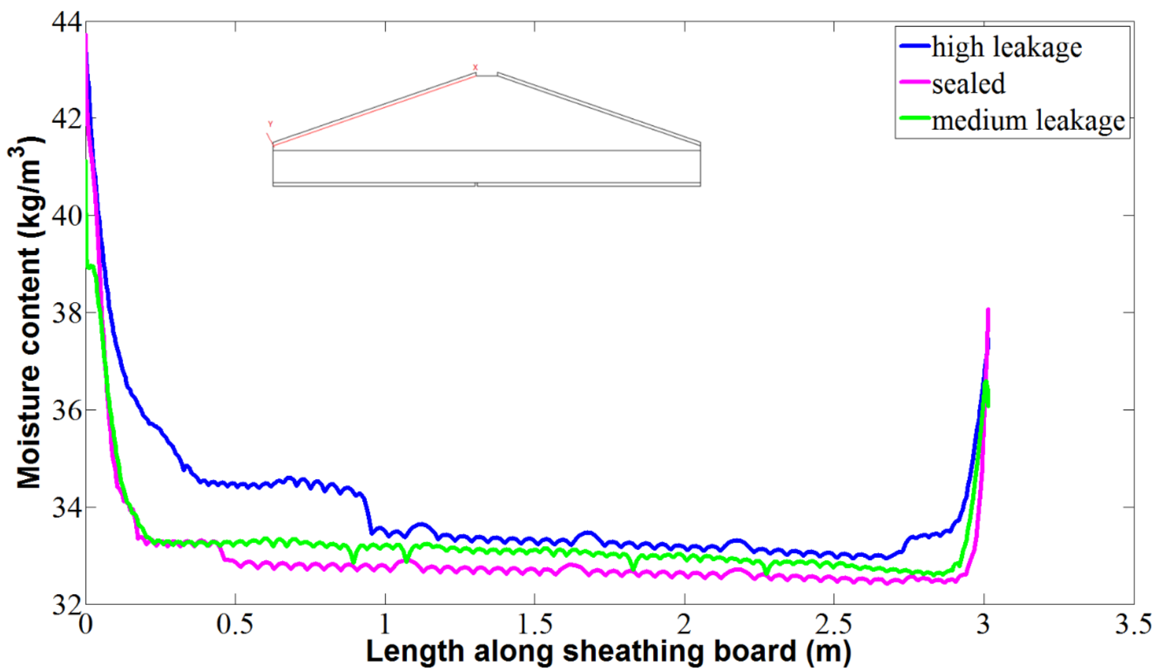



Figure 3. Moisture content of the roof sheathing for different NLA values.

Figure 3 shows the moisture content on the sheathing board. The horizontal axis of the graph represents the distance in the direction of the sheathing board (shown in red in the inset picture). The moisture content is higher near the lower end of a roof sheathing as shown in Figure 3. The sealed attic roof sheathing maintains a lower moisture content by 7.28 % and 11.82 % in comparison to ceilings with medium and high air leakage.

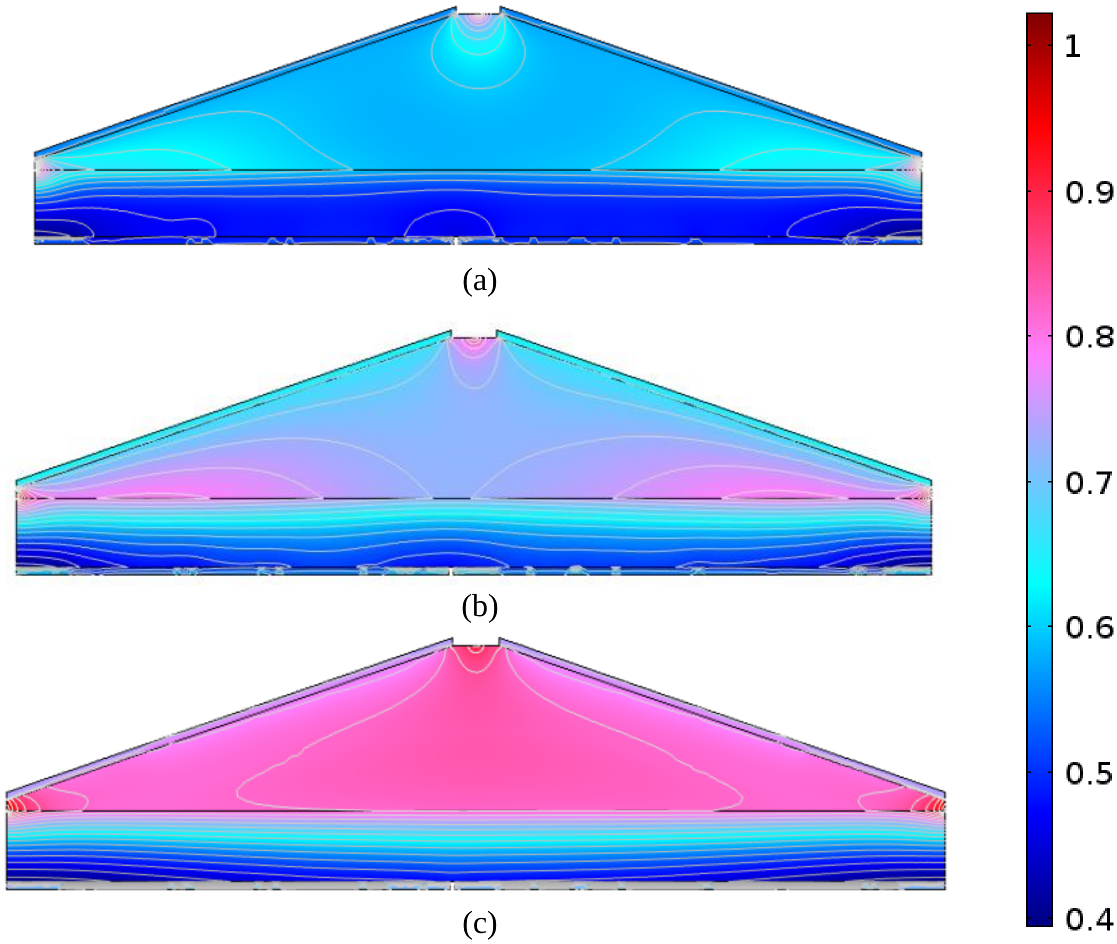



Figure 4. Relative humidity of the attic (a) NLA<0.2, (b) NLA=0.7 and (c) NLA=2.4.

## 4. CONCLUSION

A coupled heat, air and moisture modelling is conducted to study the hygrothermal performance of ventilated attics. The variation of relative humidity and temperature values of the attic space and structure due to ventilation and indoor air leakage, with three different normalized leakage areas, are investigated. Results show that the lower side of roof sheathing and the ridge area are more susceptible to moisture accumulation. The moisture content in both nearly sealed ceiling and ceiling with NLA of 0.7 has not reached a critical value. Whereas in the leaky ceiling case, the relative humidity surpass 80% at lower side of the sheathings and near the attic ridge.

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