A COMPARISON OF SEALED AND VENTILATED ATTIC SPACES: A CASE STUDY OF RESIDENTIAL ATTIC DESIGN

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ABSTRACT

Two attics were constructed as part of a building renovation project at the University of West Florida. The first attic is described as a traditional ventilated attic, with openings in the soffits and a small dormer vent on the roof. The second attic is described as a sealed attic (with no ventilation), and open-cell spray foam insulation installed on the underside of the roof deck. The study was undertaken to demonstrate hypothesized performance differences between attic types. Thermal and relative humidity sensors were installed to measure the condition of the air in the two attics spaces, and measurements were taken at 15 minute intervals. Measurements of relative humidity were later calculated as dew point and specific humidity. Similar studies are often conducted by comparison of attics in separate buildings under different use conditions. This project offers a unique opportunity to explore data collected from a single structure, and provides support for existing research on attic design in southern regions. The resultant data show significant differences in attic temperatures, with the sealed attic exhibiting a much more thermally stable pattern. There were also significant differences in attic dew points and specific humidity, although these differences appear to be much less pronounced. Data were analyzed using independent t-tests to establish significant differences between means. Overall, the sealed attic performed better than the ventilated attic, although dew point and specific humidity remain concerns.

KEYWORDS

energy efficiency, sealed attic, ventilated attic, roof design, residential construction, cool roof

INTRODUCTION

The energy efficiency of residential structures is heavily dependent on the design of roofing systems (Huberman et al 2015; Nahar et al 1999; Jain 2006), particularly in the hot, humid climate of the Southeastern United States (Miller et al 2015). In Florida for example, it is not uncommon for attic temperatures to reach 130 °F (54 °C) during the summer months

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(Parker and Sherwin 1998). In contrast, indoor air conditions are generally kept within the parameters of psychrometric comfort, with dry bulb temperatures ranging from 70 to 82 °F (21 to 28 °C). This results in a delta of up to 60 °F (16 °C) and air conditioning loads of substantial proportions.

In an effort to minimize attic temperatures, traditional design has relied on various forms of ventilation (Block 1980; Lien and Ahmed 2011; Al-Obaidi et al 2014). Passive ventilation systems induce air movement by creating pressure differentials between different types of vents, including soffit, ridge and spinning turbine. However, it has been shown that attic ventilation may increase latent loads within the building envelope, particularly so if infiltration is high between the ceiling and attic (Rose and TenWolde 2002), a condition commonly encountered in older residential construction (Chan et al 2005). Although ventilated attics have had varying degrees of success in reducing air conditioning loads, high attic temperatures are a persistent problem and an important design consideration.

A considerable amount of research has been devoted to the structure of roof and attic spaces, as this influences both convection (Kamiyo et al 2010; Anderson et al 2010; Saha et al 2010; Saha 2011; Saha and Kahn 2011; Wahlgren 2007) and the angle of incidence (Wang and Shen 2012). Roofing material is also an important design consideration. The installation of roofs with high solar reflectance and high thermal emittance (cool roofs) results in much lower roof surface temperatures and cooling loads (Levinson et al 2005; Bozonnet et al 2011; Zinzi and Agnoli 2012; Romeo and Zinzi 2013; Kolokotroni et al 2013), and is often employed as a passive design feature (Jain 2006; Nahar et al 1999; Ong 2011). Indeed, cool roofs have been recognized as essential design elements for energy efficient structures, and codified as such (California Energy Commission 2005).

Radiant barriers offer another approach to reducing attic temperatures (Medina 2000; Al-Hamoud 2005), and have been used with varying degrees of success since 1994. According to the Florida Solar Energy Center (FSEC), radiant barrier roofing "could cut annual cooling loads by 4–8% depending on attic ventilation." (Fairey 1994).

Insulation systems and air tightness have also been examined with respect to energy efficiency (Wilkes and Rucker 1983; Hung et al 2002; Al-Hamoud 2005), and designs have evolved during the last 50 years, with increasing levels of insulation and air tightness (Gann et al 1998). These gains in energy efficiency have been accompanied by important revisions to indoor air ventilation and quality requirements (Redlich et al 1997).

Expandable, spray-applied foams have been used as a method for achieving higher levels of both insulation and air tightness. More recently, research has been dedicated to the ideal placement of spray-applied insulation. Traditional methods have placed insulation in between, or directly above ceiling joists, and directly adjacent to the conditioned space (Ong 2011). Insulation types have included rock wool, fiberglass batts and blown cellulose. Spray foam insulation allows application on the underside of the roof deck, and may eliminate the need for ventilation. Lstiburek refers to this type of attic design as "conditioned" (2015). The concept of sealed (or "conditioned") attic spaces has been promoted as a means of reducing both attic temperatures (Parker et al 2002) and humidity levels (Bjaløv et al 2016). Additionally, the relocation of insulation to the underside of the roof deck permits the location of ductwork in sealed ("conditioned") space, which minimizes losses due to leaks.

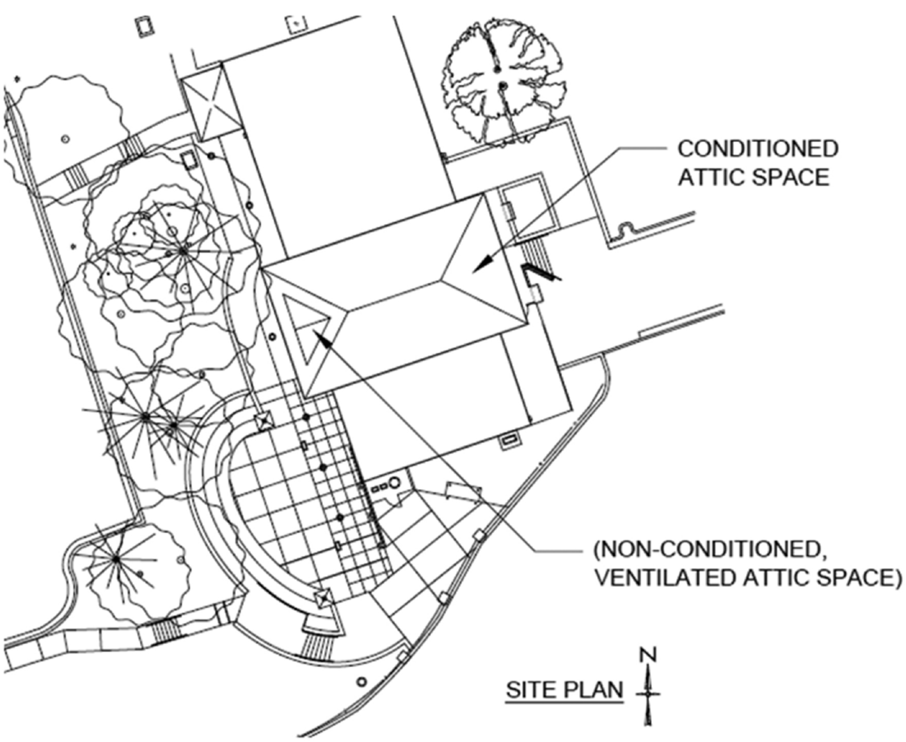
The efficiency of sealed attics depends largely on location. For instance, it has been shown that sealed attics have a relatively small impact on cooling energy usage in hot, dry climates such as Nevada and Arizona. By comparison, duct leakage, thermal conductance, attic air exchange rates and the type of roofing material have a greater influence on energy savings, independent of climatic variables and attic configuration (Hendron et al 2002). In Florida, humidity is a major concern, as the summer rainy season brings considerable amounts of latent heat. Shreyans (2011) reported normalized results for a study in Florida, of 27–49% reduction in cooling energy after the installation of closed-cell foam insulation. The degradation of insulation and the growth of mold are also important considerations for attic design in this climate (Ezeonu et al. 1994; Nik et al. 2012; Shreyan 2011).

This study was initiated with the purpose of comparing two different types of attic design: a traditional ventilated attic, and a contemporary sealed attic. Based on previous studies, it is believed that the sealed attic will exhibit greater thermal stability and result in lower cooling and heating loads during the summer and winter months respectively. The question of dew point and specific humidity is less clear, however. Miller et al. (2016b) examined attic moisture levels in sheathing and foam insulation in sealed attics, where 80–90% humidity levels were detected between 12:00PM and 8:00PM on hot and humid days. As such, this study will analyze outdoor air dew point and specific humidity levels, and compare them with those present in the sealed and ventilated attics. Similarly, this study will examine the relationships between outdoor air dry bulb temperatures, and those present in the sealed and ventilated attics.

METHOD

Two attic spaces were constructed as part of the Community Outreach, Research and Education (C.O.R.E.) laboratory on the University of West Florida campus (Figure 1). The C.O.R.E laboratory is a pre-fabricated metal building, approximately 40 ft. × 100 ft. (12.2 m × 30.5 m).

FIGURE 1. Site Plan of the CORE building on the University of West Florida campus



The building was renovated in 2012. The structure and roof were modified, including two attic spaces (sealed and ventilated). Each attic space was constructed under a 25 ft. (7.6 m) section of a hip roof (4:12 slope) with wood truss construction.

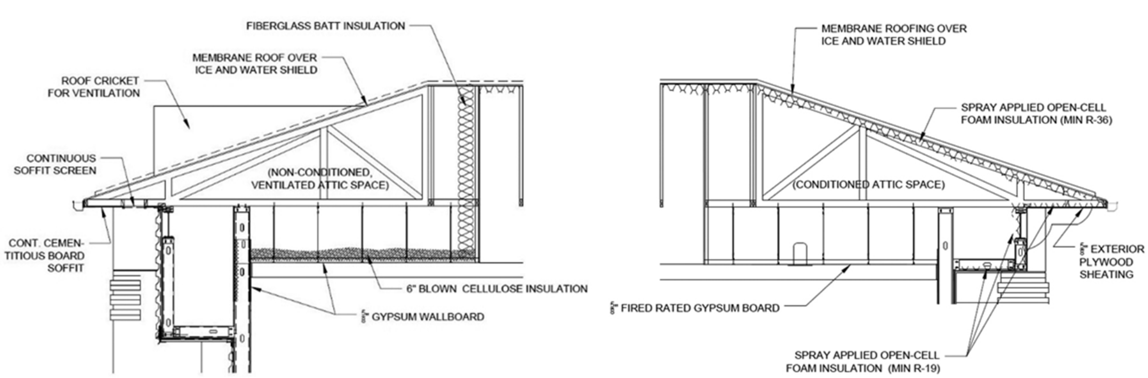
Both attic spaces were constructed under a single-ply, extruded PVC membrane roof, with a Solar Reflective Index (SRI) of 64. Each attic space is 25 ft. (7.6 m) in length and 15 feet, 8 inches (4.8 m) deep, from the fascia board to the interior knee wall. There is additional attic space below the trusses. In total, there are roughly 1,300 ft^3 (36.8 m^3) of volume in each attic, as represented in Figure 2. The ventilated attic space included R-38 fiberglass batts installed in the knee wall, and blown cellulose above the ceiling. Soffit vents were coupled with a small dormer vent to induce air movement. No vents were installed in the sealed attic space, and R-20 open-cell polyurethane foam was applied to the underside of the roof deck, across the soffits and down to the exterior walls. Initially, cooling was provided by existing mechanical systems, which were replaced with newer equipment in June and July of 2016. Both attics were equidistant from the existing and retrofitted air handlers, and were therefore subject to the same interior air flow and condition at all times.

A 16 ft. (4.87 m) serpentine thermal sensor was installed in each attic space to measure dry bulb temperatures. Serpentine sensors were selected due to their flexibility and capability of capturing an average of temperatures across the space. The specified tolerance for these sensors is indicated as $\pm(0.54\ °F + (0.005 \times |T_{°F} - 32|)$, or $\pm\ (0.3\ °C + (0.005 \times |T_{°C}|)$. Additionally, relative humidity sensors were installed in each attic space. The specified tolerance of these sensors is ±5% in high humidity, but with increased accuracy in areas with lower temperatures and humidity. Each meter reported temperature and relative humidity readings at 15 minute intervals. In order to get a better understanding of the air condition in the two attics, measurements of relative humidity were later calculated to measures of dew point and specific humidity, and the influence of temperature was effectively negated. The following formula was used to convert measurements of relative humidity to dew point:

$$\text{Dew Point} = (RH/100)^{1/8}(112 + 0.9\ C°) + \left[(0.1\ C°) - 112\right]\left[(9/5) + 32\right]$$

Some of the dew point measurements proved to be invalid, as values were negative or not recorded. As such, certain values were removed as "outliers" from the dataset, and attributed

FIGURE 2. Cross section of the Ventilated and Sealed Attic Spaces



to errors in instrumentation. Outliers were identified using the interquartile range (IQR) and formulae as follows:

$$\text{IQR} = \text{Q3} - \text{Q1}$$
$$\text{Lower Bound} = \text{Q1} - 1.5\ \text{IQR}$$
$$\text{Upper Bound} = \text{Q3} + 1.5\ \text{IQR}$$

Initially, 25,401 measurements were taken from the dataset. Following the removal of outliers, a total of 24,786 measurements remained. It is understood that this formula can be used with multipliers of 2.2 or 1.5. In this study, we opted to use the multiplier of 1.5 to remove any possible errors resulting from the aforementioned problems with instrumentation.

The data were again converted to measure the specific humidity of the outdoor air and attic spaces. The following formula was used:

$$v_p = 6.112e^{[(17.67\ Td)\div(Td+243.5)]}$$
$$q = (0.622e) \div \left[p - (0.378e)\right]$$

v_p = vapor pressure in mb

Td = dew point in degrees Celsius

p = surface pressure in mb

q = specific humidity in kg/kg

Data were further converted to show specific humidity in grains of moisture per pound of dry air, as follows:

$$\text{Specific Humidity} = \left[(q1{,}000{,}000) \div 64.799\right] \div 2.2$$

To determine the normality of distributions and any significant differences between means and levels of variance in the outdoor air, sealed and ventilated attic spaces, independent t-tests were performed for dry bulb temperature, dew point, and specific humidity. Statistical Package for the Social Sciences (SPSS) software was used for the analysis and these tests were performed on the entire dataset (N = 24,786). Measurement began on November 26, 2015 and continued through August 18, 2016. As such, the results of the independent t-tests reflect the full range of Florida seasonal weather characteristics.

RESULTS

As shown in Table 1, the mean dry bulb temperature was 70 °F (21 °C) for the sealed attic and 71.7 °F (22 °C) for the ventilated attic. Although this difference seems negligible, it is important to note that, in Florida, the cooling season is much longer than the heating season, such that a cooler attic is preferred. The range of temperatures is perhaps more revealing. For the ventilated attic, dry bulb temperatures ranged from 36 °F to 110 °F (2 °C to 43 °C). In the sealed attic, the range was considerably smaller, from 43 °F to 96 °F (6 °C to 36 °C). As residential, interior air temperatures often range between 70 °F and 76 °F (21 °C and 24 °C), extreme attic temperatures correspond with higher heating and cooling loads, such that a narrower range is preferred. Independent t-test results confirm that there are significant differences between the means of the two datasets. A standard deviation of 9.26 was observed in the sealed attic. In the ventilated attic, a standard deviation of 13.49 was observed. The results of the analysis were determined to be significant ($p < 0.001$), with $t = -16.37$ ($df = 43{,}890$), and the 95% Confidence Interval (CI) = [−1.9046, −1.4973], as shown in Table 2.

A second independent t-test was performed for the dew point readings in the attics. The mean dew point of the sealed attic was 55.36, with a standard deviation of 12.05. The observed mean dew point of the ventilated attic was 55.71, with a standard deviation of 14.20. The difference was determined to be significant ($p < 0.004$), with $t = -2.9$ ($df = 48{,}297$), with the 95% Confidence Interval (CI) = [−0.57, −0.11], as shown in Table 1.

A third independent t-test was performed for the specific humidity readings in the attics. The mean specific humidity of the sealed attic was 70.21, with a standard deviation of 29.57. The observed mean specific humidity of the ventilated attic was 72.84, with a standard deviation of 31.92. The difference was determined to be significant ($p < 0.001$), with $t = -9.5$ ($df = 49{,}570$), with the 95% Confidence Interval (CI) = [−3.17, −2.08], as shown in Table 2.

The normality of data distribution should also be noted. Dry bulb data for the sealed attic space exhibited negative skewness (−0.258) and slight platykurtosis (−0.083). Similarly, the distribution of the ventilated attic exhibited slight negative skewness (−0.068) and platykurtosis (−0.249), as shown in Figure 3. Dew point data for the sealed attic showed a negative skewness value of −0.343, and kurtosis of 0.144. The distribution for the ventilated attic was considerably less normal however, with a skewness value of −0.693 and kurtosis of −0.286, as shown in Figure 4. Similarly, specific humidity data for the sealed attic exhibited skewness (0.836) and leptokurtosis (1.074), whereas the ventilated attic exhibited slight skewness (0.036) and platykurtosis (−1.018). These data are shown in Figure 5.

It should be noted that all of these distributions still fall within acceptable parameters, and for all intents and purposes, are normally distributed. Although the dew point levels in the ventilated attic are moderately skewed, it is possible that further data collection will tend toward

TABLE 1. Group statistics for dry bulb temperature, dew point, and specific humidity for both sealed and ventilated attics.

		Group Statistics			
		N	Mean	Std. Deviation	Std. Error Mean
Dry Bulb Temperature	Sealed	24786	70.00	9.26	0.06
	Ventilated	24786	71.70	13.49	0.09
Dew Point	Sealed	24786	55.36	12.05	0.08
	Ventilated	24786	55.71	14.20	0.09
Specific Humidity	Sealed	24786	70.21	29.57	0.19
	Ventilated	24786	72.84	31.92	0.20

TABLE 2. Independent t-test results for dry bulb temperature, dew point, and specific humidity

Independent Samples Test										
		Levine's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Dry Bulb Temperature	Equal variances assumed	3024.95	0.001	−16.37	49570.00	0.00	−1.70	0.10	−1.90	−1.50
	Equal variances not assumed			−16.37	43890.11		−1.70	0.10	−1.90	−1.50
Dew Point	Equal variances assumed	1196.00	0.001	−2.90	49570.00		−0.34	0.12	−0.57	−0.11
	Equal variances not assumed			−2.90	48296.53		−0.34	0.12	−0.57	−0.11
Specific Humidity	Equal variances assumed	761.64	0.004	−9.50	49570.00		−2.63	0.28	−3.17	−2.08
	Equal variances not assumed			−9.50	49283.56		−2.63	0.28	−3.17	−2.08

FIGURE 3. Sample distributions for dry bulb temperature for sealed and ventilated attics.

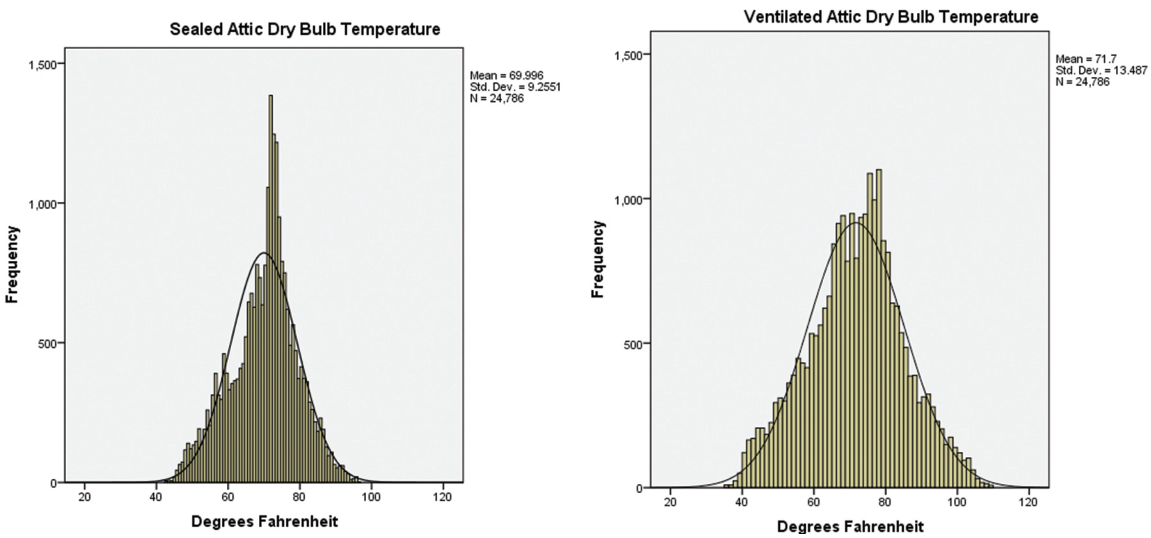
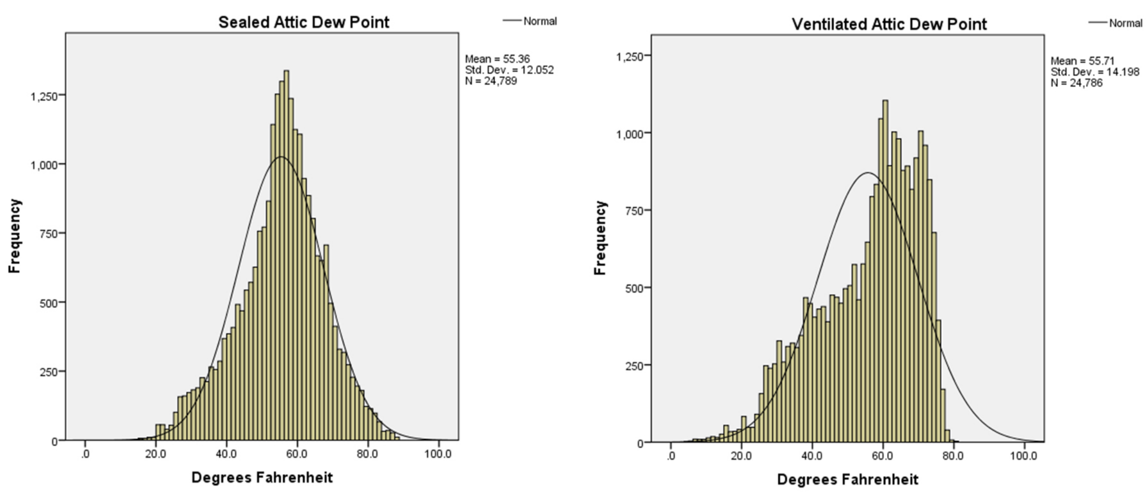


FIGURE 4. Sample distributions for dew point for sealed and ventilated attics.

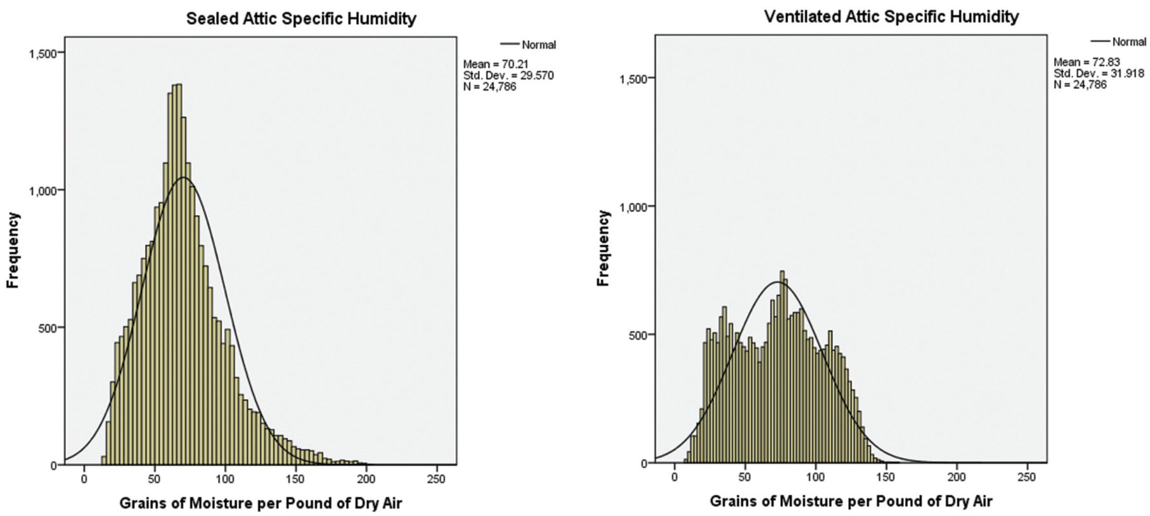


a more normal distribution, along with the recurrence, of cooler, drier air. The skewness of the specific humidity distribution for the sealed attic is less clear, but have values consistently lower than those of the ventilated attic distribution.

LIMITATIONS AND DISCUSSION

This case study was undertaken as a means of comparing two attic types—sealed and ventilated. As the attics were built as part of a renovation project in an existing building, flexibility and attic layout was somewhat limited. The long axis of the building runs slightly off of a true North-South bearing. Additionally, a hip roof was used to test the two attic types, and portions of these roof surfaces faced East and West respectively. Typically, the hottest daytime temperatures in

FIGURE 5. Sample distributions for specific humidity for sealed and ventilated attics.



Florida will occur in the early to midafternoon, such that the angle of incidence may have been slightly more direct for the ventilated attic at these times. It should also be noted that mechanical systems for the building were updated in June and July respectively. During the first part of data collection, older mechanical systems serviced the entire building. Air conditions since July have improved with perceptibly lower humidity, and this may have affected the observed measurements in each attic. Even so, both attics were subject to identical exterior and interior air conditions throughout the study. Any differences in dry bulb temperature, dew point and specific humidity were therefore directly attributable to the design of the attics, as these were the only variables.

As stated by Lstiburek (2015), sealed attics are often referred to as “conditioned,” as there is often a direct transfer between the interior space and the attic. Aside from a single access door, the sealed attic design in this study excluded any direct transfer grill, instead relying on infiltration between the building interior and attic to “condition” the space. It is believed that this, in combination with the ageing mechanical system prior to July 2016, may have contributed to the unexpectedly high specific humidity levels in the sealed attic space. However, as noted by Miller (2016a), sealed attics are often susceptible to high levels of specific humidity, and sheathing degradation is still a major concern with respect to moisture movement in a sealed attic. Although attic humidity remains a concern, Prevatt and Miller (2017) reported to the Florida Building Commission (FBC) that their field data study and analysis indicates that section R806.5 of the FBC provides adequate protection against moisture affecting the durability of roof sheathing. Future assessments of sealed attic spaces should consider the parameters outlined in the Prevatt and Miller (2017) sensitivity analysis regarding parameters for peak moisture contents in sheathing, which show that interior heat and moisture generation as well as cooling set points have the greatest influence on moisture content.

The enhanced structural performance of sealed attics should also be examined, as the application of spray-applied insulation to the underside of the roof deck reinforces the structure in many ways. These questions are particularly relevant to the coastal areas of Florida, where severe weather is relatively common.

It is possible that longitudinal data may reveal further differences between the attics, something that may not have been revealed during the first nine months of data collection. On another level, subsequent studies should take note of the preferred orientation of attics and thermal isolation measures as described in Parker and Sherwin (1998).

It is believed that further comparisons between attic types warrants investigation. As noted in this study, there are significant differences in the thermal stability of each attic, and these have a noted effect on the energy efficiency of the structure. On a larger scale, these impacts affect facility managers and home owners, power distribution companies, natural systems, and should be foremost in the minds of policy makers everywhere.

CONCLUSIONS

Based on nine months of data collection, it is clear that the sealed attic is more thermally stable than the ventilated attic. This can be determined from the mean temperature readings and standard deviations listed in Table 1, the independent t-tests in Table 2, and the histograms of data distribution in Figure 3. With regard to dew point, apparent differences between attics were less pronounced (as shown in Table 1), although determined to be statistically significant via independent t-test (Table 2). It should also be noted that the skewness of the distribution for the ventilated attic was moderate, indicating a trend toward more humid air conditions. For specific humidity, differences were also noted between the sealed and ventilated attics (Table 2). As with the measurement of dry bulb temperature and dew point, there was a significant difference between the two means, and variance was higher for the ventilated attic.

Ultimately, the results of this study corroborate those of other studies, particularly with respect to the passive design potential of sealed attic spaces and higher humidity levels in sealed attic spaces. Dew point readings in the sealed attic, although lower, are a cause for concern and future research should explore mitigation efforts. It has been noted that materials will degrade in hot, humid climates (Ezeonu et al. 1994; Nik et al. 2012; Miller et al. 2017), such that any gains in energy efficiency may be offset by decreases in the service life of the materials. The data in this study indicate that the sealed attic is the preferred option with respect to temperature, dew point and specific humidity, which supports literature concerning condition attic construction in humid regions.

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