Predicting the Effect of Wall-Cladding Ventilation on Condensation due to Sun-Driven Moisture: Comparison of Hygrothermal Simulation with Laboratory Testing

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ABSTRACT

Providing for ventilation airflow behind wall claddings has been shown to reduce the risk of condensation due to sun-driven moisture when rain wets an absorptive exterior surface and solar radiation subsequently drives this moisture toward the building interior. Historically, enclosure designers have relied on rules of thumb or on knowledge of cladding ventilation designs that have worked successfully in various climates. Only recently are some of the widely available commercial hygrothermal analysis programs attempting to model the effect of wall-cladding ventilation. This may provide a way for enclosure designers to accurately model and predict the effect of wall-cladding ventilation.

This paper compares the results of a hygrothermal simulation program with the results of a series of laboratory tests designed to study the performance of wall systems with ventilated wood siding under sun-driven moisture conditions. The amount of ventilation behind the siding was measured, as well as the temperature and relative humidity profiles. Gravimetric measurements were also made of each component to quantify the amount of moisture accumulation and redistribution within the wall system. Conclusions are drawn on how well the hygrothermal simulation program predicts the effect of wall-cladding ventilation on condensation due to sun-driven moisture.

INTRODUCTION

Problem of Condensation Due to Sun-Driven Moisture

Condensation due to sun-driven moisture is a phenomenon that affects walls with an absorptive cladding or where rain has penetrated behind the exterior cladding. When these wetted walls are heated by solar radiation, a strong vapor-pressure difference is created that drives the moisture both outward and inward from the cladding. Inward moisture migration may lead to condensation on an interior vapor retarder (if provided) or on interior wall components, or it may lead to excessive moisture accumulation within the wall system.

The typical design of exterior walls for cold climates requires the use of a vapor retarder on the interior side of the wall assembly to limit the amount of moisture diffusing from the interior into the wall assembly. Without the vapor retarder, there is an increased risk of condensation during winter against the inside surface of the exterior sheathing or the backside of the cladding. However, the use of a vapor retarder, such as polyethylene sheet, can present a problem when there is an inward vapor drive, such as sun-driven moisture. Eliminating the vapor retarder is not always an effective solution, as other vapor-impermeable interior finishes, such as oil paints or vinyl wallpaper, can have similar effects on impeding inward vapor flow.

Mitigating Condensation Due to Sun-Driven Moisture

Condensation due to sun-driven moisture can be mitigated or prevented by various measures, including using nonabsorptive claddings, such as vinyl, metal siding, or an exterior coating that prevents wall moisture absorption. Other measures include using a low-permeance material on the exterior of the sheathing (e.g., board insulation, a sheathing

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membrane, or the sheathing itself) (Southern 1986; Straube and Burnett 1997; Pressnail et al. 2003). However, the use of low-permeance materials or coatings on the exterior of a wall system leads to a higher risk of moisture accumulation or condensation during winter in cold climates when the water-vapor flow is usually from the interior to the exterior.

Both laboratory and field tests have shown that ventilated claddings can reduce or eliminate condensation due to sun-driven moisture (Wilson 1965; Southern 1988; Handegord 1985; Straube and Burnett 1997; Kan 1999; Kan and Piñon 2006). Furthermore, cladding ventilation reduces the risk of moisture accumulation or condensation during winter in walls with low permeance claddings by allowing the water vapor diffusing through the wall from the interior towards the exterior to bypass the vapor diffusion resistance of the cladding (Straube and Burnett 1997). Because of its potential benefits in both winter and summer in a cold climate, cladding ventilation is a good choice for mitigating condensation due to sun-driven moisture.

Predicting and Modeling the Effect of Wall-Cladding Ventilation

Historically, the enclosure designer has had to rely on rules of thumb or on knowledge of cladding ventilation designs that have worked successfully in various climates. The widely available commercial hygrothermal analysis programs have not been able to simulate the effect of wall-cladding ventilation on the overall wall performance. Only recently, are some of the widely available commercial hygrothermal analysis programs attempting to model the effect of wall-cladding ventilation (Kuenzel et al. 2006). This provides a way for enclosure designers to accurately model and predict the effect of wall-cladding ventilation, particularly the risk of condensation due to sun-driven moisture.

Objective

The objective of this paper is to compare how well a one-test hygrothermal simulation program models and predicts the effect of wall-cladding ventilation, particularly the risk of condensation due to sun-driven moisture.

Scope

The discussion and conclusions sections of this paper are limited to a comparison between the hygrothermal modeling of the specific laboratory tests described herein.

Approach

This paper presents the results of a series of laboratory tests designed to study the performance of wall systems with ventilated wood siding in a cold climate that have an interior vapor retarder and are subject to sun-driven moisture conditions. Computer simulations of these walls are run subject to the same conditions as in the laboratory. The modeling results are compared to the experimental results to evaluate the accuracy of the hygrothermal simulation models in predicting the effect of wall-cladding ventilation and reducing the potential for condensation due to sun-driven moisture.

LABORATORY TESTING

Experimental Setup

The author conducted a series of laboratory tests of wall systems from 1996 to 1999 (Kan 1999). The primary objective of the testing was to study the phenomenon of condensation due to sun-driven moisture and to investigate possible solutions to prevent condensation. Wall panels, 0.5 × 0.5 m each (1.64 × 1.64 ft), of various configurations were built and tested in a controlled laboratory environment.

Each wall panel was placed between two rooms with controlled temperature and relative humidity (RH) to simulate an indoor (18°C ± 1°C, 50% ± 10% RH) and an outdoor (20°C ± 1°C, 50% ± 10% RH) environment.

A set of heat lamps were placed in front of the wall panels to produce an evenly distributed temperature on the surface of the wall panels during testing and to simulate the effect of increased surface temperature by solar radiation. Four heat lamps with a total of 600 W spaced approximately 0.25 m (0.82 ft) from each 0.5 × 0.5 m (1.64 × 1.64 ft) wall panel were used to create a sol-air temperature of 28°C–32°C (82.4°F–89.6°F) above ambient temperature. The total radiation measured at the surface of the wood cladding is approximately 1400 W/m^2.

Ontario white cedar panels, 4 mm (0.16 in.) thick, were used to construct the exterior cladding of the walls. Wood siding was saturated to simulate rainwater absorption. Although the moisture gain of the wood siding after immersion in the water tank differed from one panel to another before the experiment, most of the exterior wood panels gained about 280–300 g (0.62–0.66 lb) of moisture during the 24-hour soaking period. This corresponds to a moisture content following soaking of approximately 110%. A wide range of wall configurations were tested in the laboratory. For comparison purposes, only walls with an air cavity are discussed in this paper. Figure 1 shows the elevation and section of these wall panels. Table 1 shows the variations tested.

The following two sets of data were produced from the experiments:

1. *Weight.* Immediately before and after the test, all elements of each wall panel were carefully disassembled and weighed in order to quantify the amount of condensation.
2. *Temperature and RH.* Each wall panel was instrumented with thermocouples and RH sensors to monitor the fluctuation of temperature and RH on the exterior wall cladding, within the air cavity, and on the interior-finish wall surface. Temperature and RH readings were recorded by data loggers every five minutes. The wall panels were

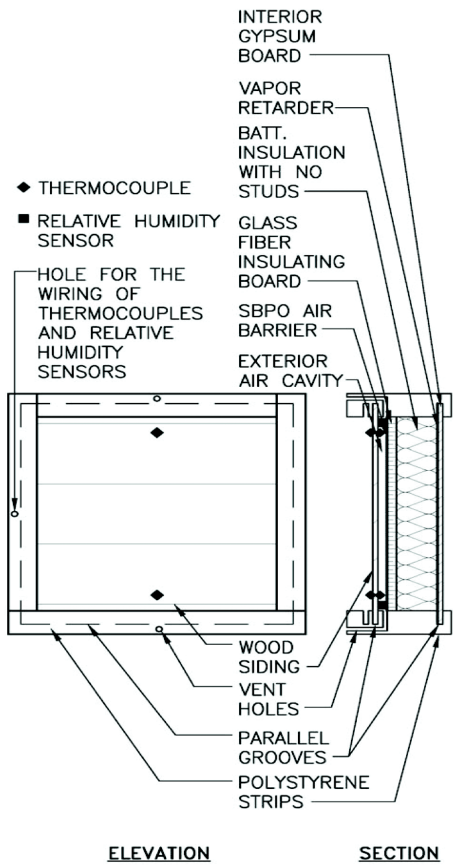


Figure 1 *Elevation and section of the wall panels tested.*

monitored for 24 hours. All test wall assemblies reached temperature equilibrium within 24 hours.

Measured Amounts of Condensation

The experimental results for tested wall panels with various flowrates are shown in Table 2. The results are reported as both amount of condensation and as *percent gain*, which represents the percentage of condensation resulting from every 100 g (0.22 lb) of water evaporating from the wood siding.

The experimental results show that the higher the ventilation provided behind the cladding, the less risk there is of condensation due to sun-driven moisture.

The wall panels with no ventilation or a low natural ventilation flowrate of 0.002 L/s (0.004 cfm) showed significant amounts of visible condensation inside of the wall assembly. We observed a minimal amount of condensation for the wall assembly with a higher natural ventilation rate of 0.03 L/s (0.06 cfm), while a cladding ventilation rate of 2, 1, or 0.5 L/s (4.24, 2.12, or 1.06 cfm) completely eliminated the occurrence of interstitial condensation in this laboratory-created sun-driven moisture scenario.

Table 1. Experimental Variations of Test Panel

Panel	Ventilation	Vent Hole Diameter*		Flowrate	
		in.	mm	L/s	cfm
1	Mechanical	0.5	12.7	2	4.24
2	Mechanical	0.5	12.7	1	2.12
3	Mechanical	0.5	12.7	0.5	1.06
4	Natural	0.5	12.7	0.03	0.06
5	Natural	0.125	3.175	0.002	0.004
6	No ventilation	0	0	0	0

*Two vent holes were provided for each wall panel, one at the top and one at the bottom.

Table 2. Experimental Results of Test Panel

Panel	Ventilation	Flowrate		Measured Condensation		
		L/s	cfm	g	lb	Gain,%
1	Mechanical	2	4.24	0	0	0
2	Mechanical	1	2.12	0	0	0
3	Mechanical	0.5	1.06	0	0	0
4	Natural	0.03	0.06	2.12	0.005	0.7
5	Natural	0.002	0.004	16.22	0.036	5.6
6	No ventilation	0	0	29.48	0.065	10.2

Average Temperature and RH Measurements

The average temperature profiles measured at the outside and inside faces of the exterior wood cladding and inner side of the interior gypsum board for a wall panel with a 0.03 L/s (0.06 cfm) ventilation rate are shown in Figure 2. Figure 2 also shows that temperatures measured at the outside face of the cladding and the indoor face of the gypsum board quickly reached thermal equilibrium soon after the test started. In comparison, it took approximately four hours for the air-space temperature to reach equilibrium.

Figure 3 shows that, for this case, it took approximately four hours for both the air-space temperature and RH to reach equilibrium. Therefore, it is safe to conclude that sun-driven moisture conditions within the wall assembly for this ventilation rate occurred within the first four hours.

The temperature and RH measurements for the same wall with a lower ventilation rate of 0.002 L/s (0.004 cfm) suggest similar profiles (Figure 4) but approach equilibrium at a slower pace, taking about seven hours to reach equilibrium.

We determined that each individual test wall panel can be characterized by two values: t_m, which is the time required to reach maximum moisture content in the air space, and t_e, which is the time required to reach equilibrium moisture content in the air space. These two values, which appear to be intrinsic to each test wall panel, reflect the ability of the wall to handle the sun-driven condensation situation imposed by the experiment.

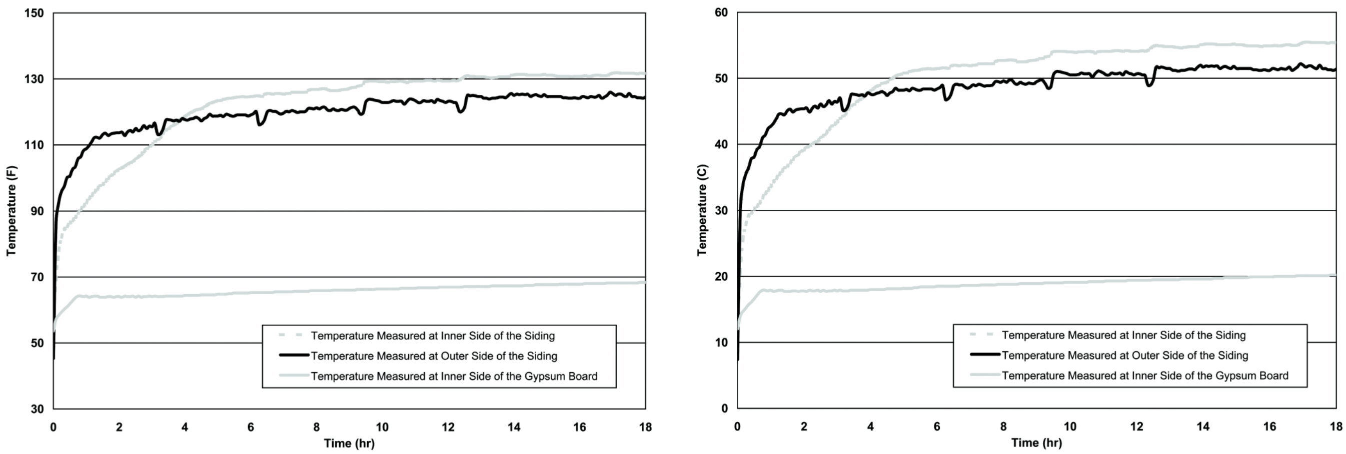


Figure 2 *Experimental results: I-P (left) and SI (right) temperature profiles at outside and inside faces of exterior cladding and inside face of the interior gypsum board for cladding ventilation at 0.03 L/s (0.06 cfm).*

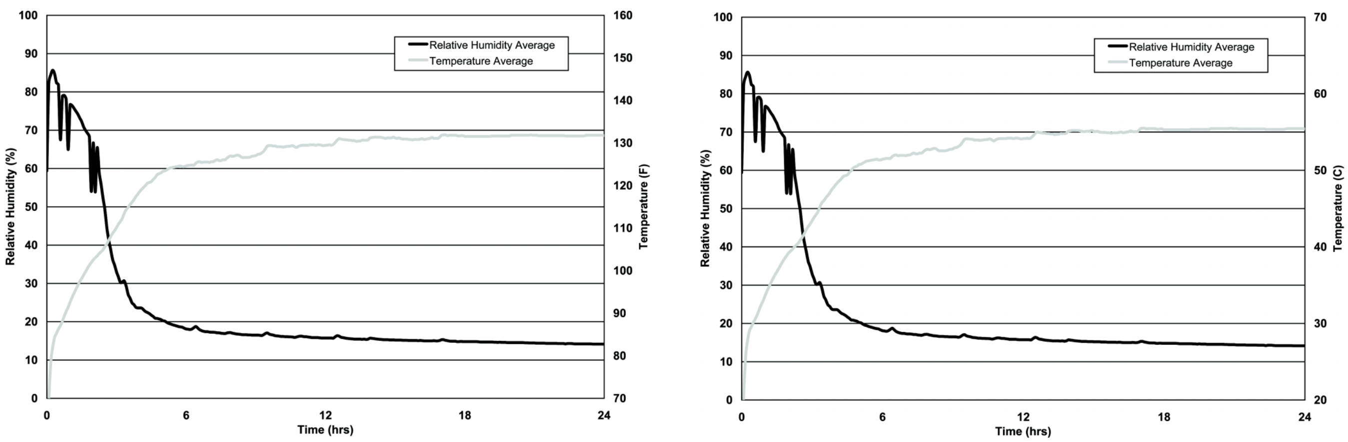


Figure 3 *Experimental results: I-P (left) and SI (right) temperature and RH profiles at inside face of exterior cladding for ventilation at 0.03 L/s (0.06 cfm).*

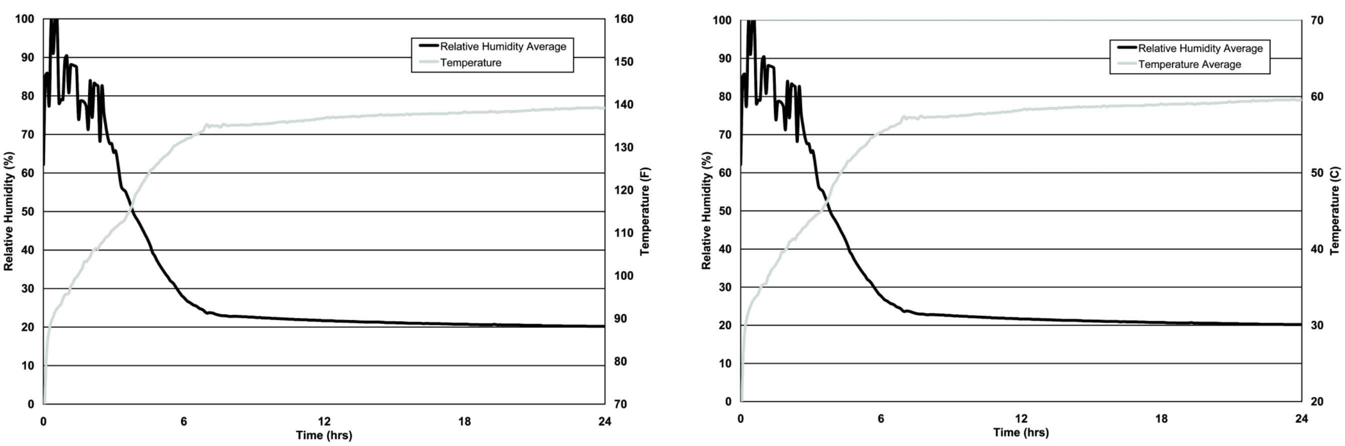


Figure 4 *Experimental results: I-P (left) and SI (right) temperature and RH profiles at inside face of exterior cladding for ventilation at 0.002 L/s (0.004 cfm).*

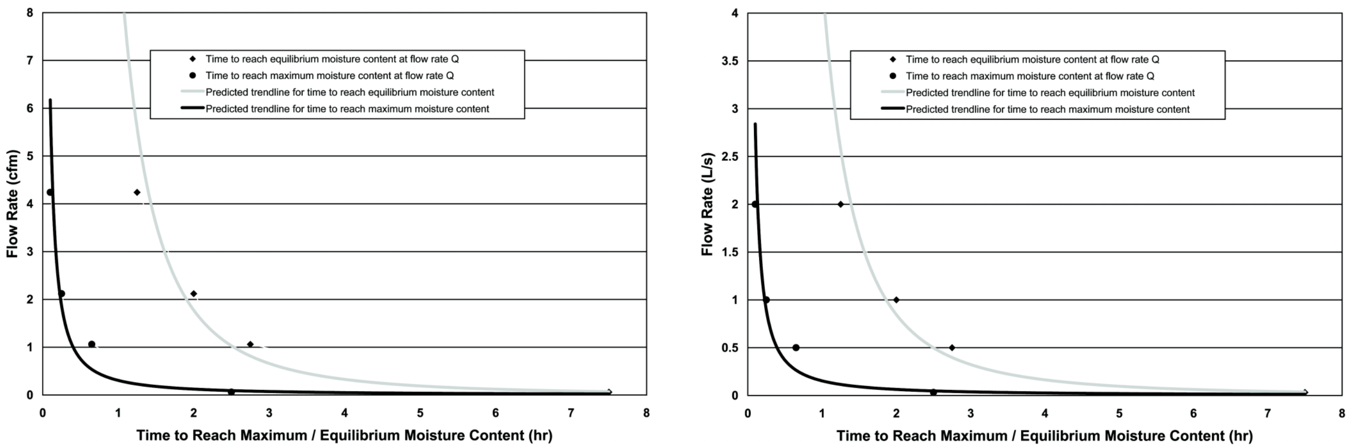


Figure 5 *Experimental results: time to reach equilibrium or maximum moisture content in the air space under different flowrates—I-P (left) and SI (right).*

The relationship of these values, t_m and t_e, with the ventilation flowrate is shown in Figure 5. It is evident that at lower flowrates more time is required for the system to reach either the peak or the equilibrium moisture content. It is also shown that the relationship of these intrinsic values, t_m and t_e, with the flowrate is in a power-law form.

Note that the values representing the wall construction with a 0.002 L/s (0.004 cfm) flowrate were not plotted in Figure 5, since substantial amounts of interstitial condensation occurred in the tests of this wall type. This is a result of substantial amounts of vapor diffusing inward and being of the same order of that carried out by the ventilation drying in the outer-cladding drying process. Furthermore, the lower limit of this flowrate range indicates a point where the ventilation rate is no longer sufficient to dry the air cavity.

Temperature and RH Profiles along Height of Cavity

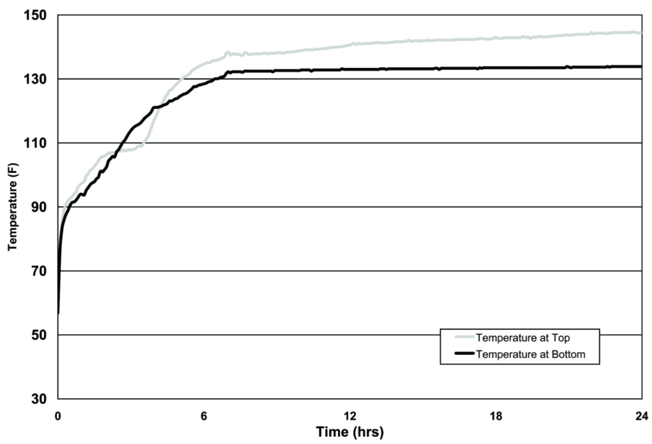
The average temperature and RH readings presented above show the general response of the wall system to cladding ventilation. However, the temperature and RH readings at the top and bottom of the air space reveal the two-dimensional heat and moisture transfer patterns within the ventilated cavity during the sun-driven condensation phenomenon.

Figures 6 and 7 indicate that the temperature and RH profiles measured at the top and bottom of the air space have significantly different patterns. The RH at the bottom of the air space was its highest at zero time and decreased afterward until it reached equilibrium after approximately three hours. The corresponding temperature profile slowly but steadily increased until it reached thermal equilibrium at about the same time when the RH reached equilibrium. The RH at the top of the air space was above 90% from the very beginning for about 2.5 hours. The value sharply decreased after 2.5 hours until it reached equilibrium after six hours from the start of the test. The corresponding temperature profile seemed irregular, however; it can be explained by the following moisture moving mechanisms acting in the air space.

In the experiments, the relatively dry ventilation air entered the air cavity from the vent holes at the base and moved up and out of the air cavity through the vent holes on the top. This ventilation path was similar to what was induced due to moisture and thermal-buoyancy forces caused by solar heating of the cladding. The ventilation air was heated once it entered the air space and absorbed moisture while moving up. The warm, moist air exhausted through the vent holes at the top. The moisture evaporating from the base of the inboard face of the wet cladding was first carried out by the ventilation air. Therefore, the RH at the base of the air space decreased once the test commenced. The moisture evaporating from the top of the wet cladding could not initially be carried outside, because the ventilation air was already saturated when it reached the top. This was reflected in the almost 100% RH profile during the first 2.5 hours. As the bottom of the inboard side of cladding dried out, the ventilation air was able to pick up the moisture evaporating from the higher part of the inboard face of the cladding and, finally, from the top of inboard face of the wet cladding. After 2.5 hours, the RH started to decrease until it finally reached equilibrium.

COMPUTER MODELING OF LABORATORY EXPERIMENTS

For the computer modeling, we used a widely available commercial hygrothermal software tool capable of heat transport calculation (thermal conduction, latent heat flow, direct solar radiation, and night-time long-wave radiation), vapor transfer calculation (vapor diffusion), and liquid transport calculation (capillary conduction and surface diffusion) (Kuenzel et al. 2006). The program we used also accounts for driving rain and the wetting of wall cladding, which is of special importance in modeling sun-driven condensation scenarios.



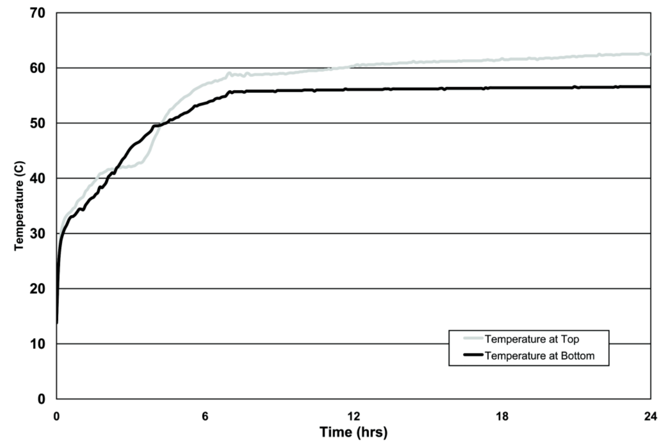


Figure 6 *Experimental results: I-P (left) and SI (right) temperature profiles at top and bottom on the inside face of exterior cladding for ventilation at 0.002 L/s (0.004 cfm).*

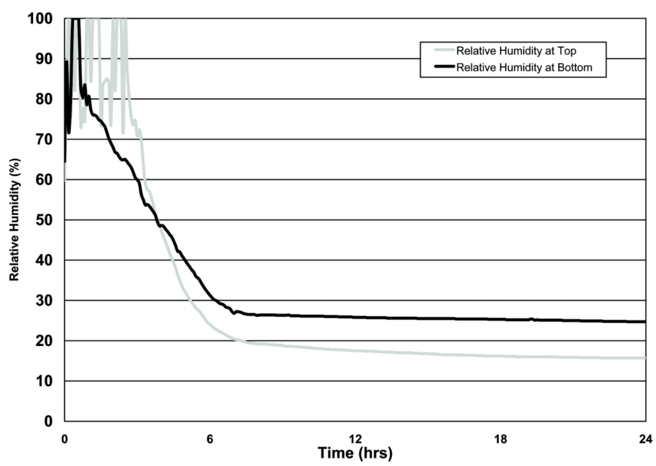


Figure 7 *Experimental results: RH profiles at top and bottom on the inside face of exterior cladding for ventilation at 0.002 L/s (0.004 cfm).*

The recently released test (beta) version of this software (Kuenzel et al. 2006) has been improved to include local heat source, local moisture source, and local air exchange. The local air-exchange feature in the new version enables us to model a wall with cladding ventilation.

Limitations and Assumptions

The program we used has the following limitations with regard to modeling convective airflow:

- Air leakage is not modeled. The program assumes that walls are perfectly sealed so that there is neither air leakage at the perimeter nor air leakage due to joints.
- The specific version of the program we used models only the one-dimensional flow along the height of the cavity; two-dimensional flow is not modeled.
- Cladding ventilation is modeled as air exchange only. As a one-dimensional program, the program does not model air flowing in, along, or out of the cavity; instead, it considers only the exchange of air between the outdoors and the air space. Furthermore, the program does not model the effect of this convective air flow on the surface-film resistances or heat transfer across the air space.
- The recently released test version of the program has a limit on the amount of cladding ventilation you can simulate due to convergence failures.
- Air layers in the program are modeled after a porous material and, as such, the dependence of the moisture content of the air with RH and temperature is not accurately reproduced.

Computer Modeling Results

The computer modeling results include temperature and RH at all specified locations of the wall section and the moisture content of each individual material in the wall assembly. For the simulated walls, the amount of moisture accumulation can be estimated from the change in the moisture content of the layer of fiberglass insulation at the end of calculation. The calculation results are shown in Table 3. The results are presented together with the experimental results for comparison purposes.

Table 3 shows that the hygrothermal simulation produces very similar moisture accumulation quantities compared with laboratory testing results for walls with various cladding ventilation rates. The comparison also shows that the amount of moisture accumulation predicted by the simulation is higher than the amount measured from the experiments—a consistent percent-gain difference of less than 1%. However, the computer simulation never actually predicts the occurrence of condensation. The RH and temperature profiles at the interior side of the fiberglass insulation, where moisture accumulation occurs, are presented in Figures 8 and 9 for 0.002 L/s (0.004 cfm) and zero ventilation respectively. Note that while the RH in the simulation approaches, it never actually reaches 100% RH. Both of these cases showed significant amounts of visible

Table 3. Comparison between Computer Simulation and Experimental Results

Panel	Ventilation	Flowrate,		Moisture Accumulation			
				Experiment,		Computer Analysis,	
		L/s	cfm	g	Percent Gain,%	g	Percent Gain,%
1	Mechanical	2	4.24	0	0	0	0
2	Mechanical	1	2.12	0	0	0	0
3	Mechanical	0.5	1.06	0	0	0	0
4	Natural	0.03	0.06	2.12	0.7	4.4	1.5
5	Natural	0.002	0.004	16.22	5.6	18.48	6.4
6	No ventilation	0	0	29.48	10.2	32.12	11.1

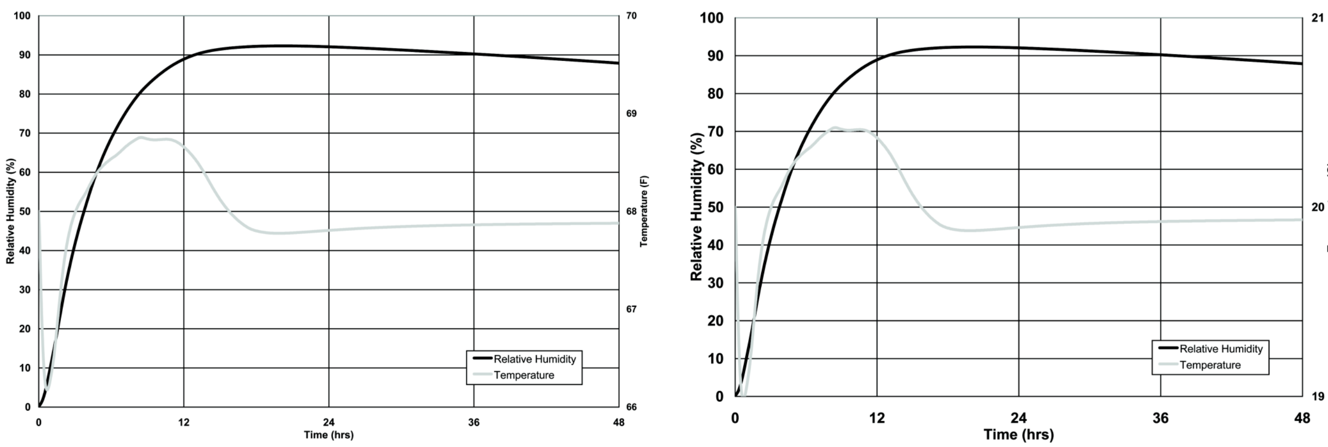


Figure 8 *Computer simulation results: temperature and RH profiles at inside face of fiberglass insulation for ventilation at 0.002 L/s (0.004 cfm)—I-P (left) and SI (right).*

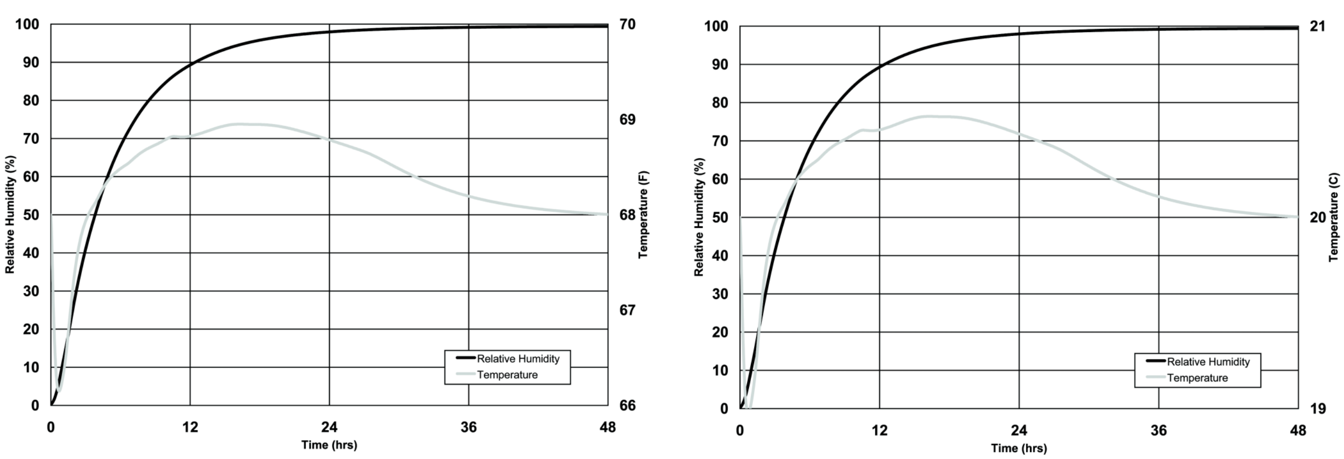
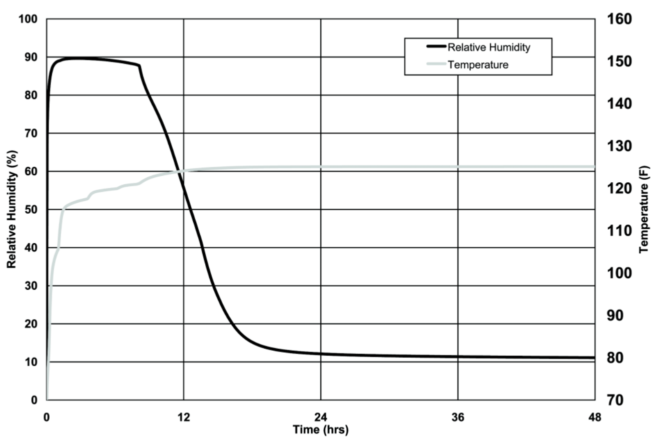


Figure 9 *Computer simulation results: temperature and RH profiles at inside face of fiberglass insulation for ventilation at 0 L/s—I-P (left) and SI (right).*

condensation in the laboratory experiment. Closer examination of Figures 8 and 9 show that while 100% RH is not predicted, the computer simulation does show a drop in temperature in this location as the RH approaches saturation, which likely indicates latent heat transfer for condensation. Also, a comparison of Figures 8 and 10 shows a delay of RH surge, which implies that the evaporation moisture from the interior side of the wet cladding migrates to the interior side of the fiberglass insulation and eventually leads to condensation.

The temperature and RH at the interior side of the wet cladding for the wall with a ventilation rate of 0.002 L/s (0.004 cfm) predicted by the computer modeling are presented in Figure 10. The curve shows a RH of over 90% from the beginning of the test for about seven hours, and then the RH drops rapidly between the seventh and twelves hours to below 10% and reaches equilibrium. The temperature rises correspondingly during the first seven hours and reaches equilibrium at about 65°C (149°F) after twelve hours. It is reasonable to conclude that surface evaporation from the interior side of the exterior cladding occurs mostly in the first seven hours. The temperature and RH readings measured in laboratory testing for the same wall as shown in Figure 4, suggest similar profiles. The experimentally measured RH, however, approaches equilibrium sooner, at about six hours as opposed to almost twelve hours, and the duration of elevated RH is shorter, about three hours as opposed to seven hours as predicted by the computer simulation.

The temperature and RH at the interior side of the wet cladding for the walls with ventilation rates of zero and 0.03 L/s (0.006 cfm) are presented in Figures 11 and 12 respectively. The duration of elevated RH at the interior side of the cladding and approximate time for all tested and simulated cases to reach equilibrium is summarized in Table 4.



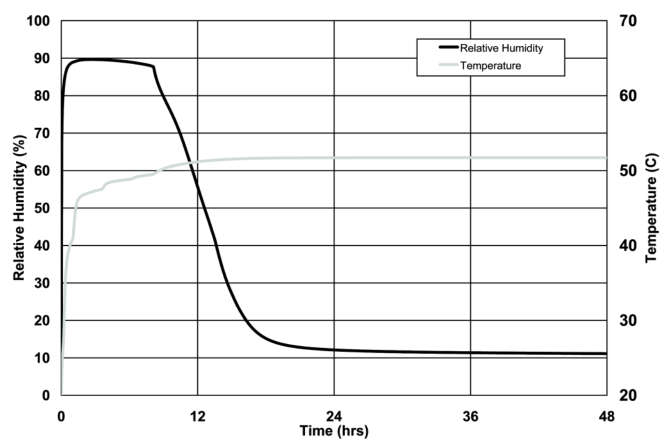
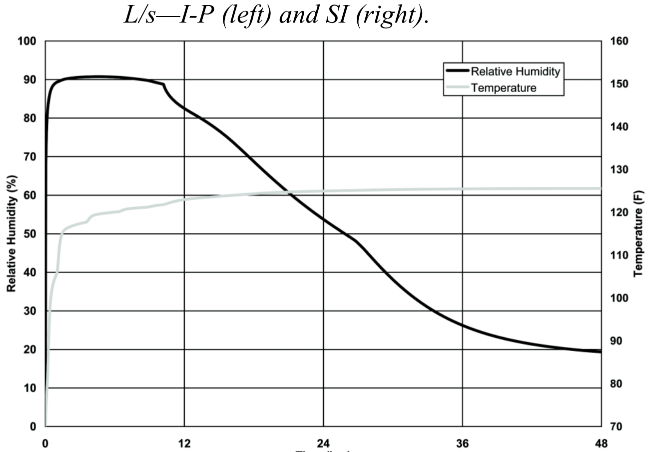


Figure 10 *Computer simulation results: temperature and RH profiles at inside face of exterior cladding for ventilation at 0.002 L/s—I-P (left) and SI (right).*



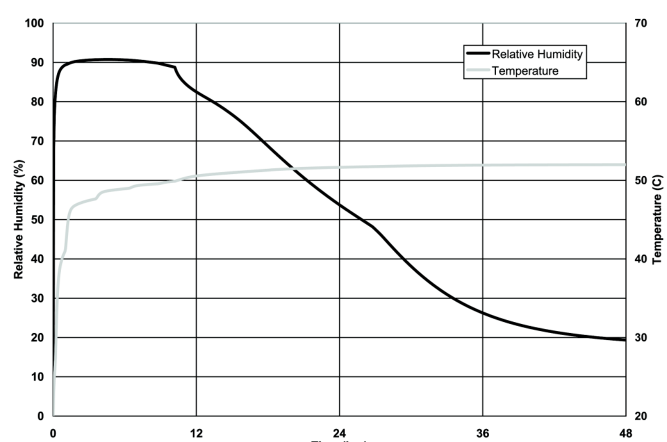


Figure 11 *Computer simulation results: temperature and RH profiles at inside face of exterior cladding for ventilation at 0 L/s—I-P (left) and SI (right).*

DISCUSSION

The amount of moisture accumulation predicted by the computer simulation is in reasonable agreement with the experimental findings. The reason why the simulation consistently overpredicts the amount of moisture accumulation could be due to any of the following effects:

- Two-dimensional convective airflow effects.
- Heating of the ventilation airflow as it travels along the backside side of the heated cladding. This heating of the ventilation air can increase the amount of moisture that the ventilation air can remove from the cavity.
- Error in the amount of moisture content in the cavity and ventilation air due to approximate air space properties in the computer simulation.

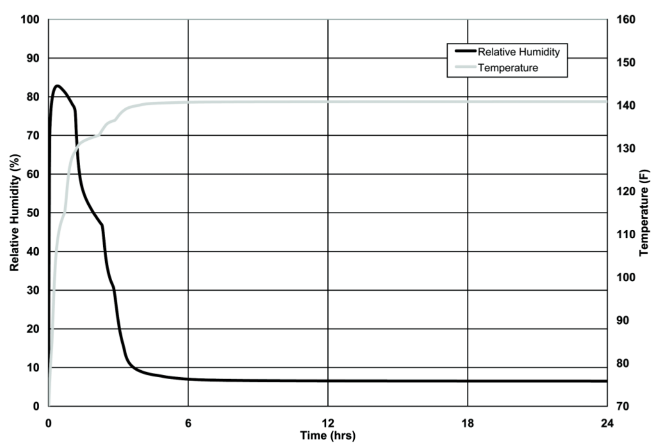
Because the computer program used is a one-dimensional simulation, it is not surprising that the temperature and RH profiles predicted by the computer modeling differ from the experimental results, which include measurements at the top and bottom of the cavity and an average of the top and bottom measurements.

The most significant difference between the experimental results and the computer simulation is that the simulation did not technically predict the occurrence of condensation by an analysis of RH alone. Our comparison has shown that while it is possible to extract the occurrence of condensation by analyzing other factors, such as concurrent temperature changes, extracting an occurrence of condensation would be difficult in a typical transient simulation used for design versus a steady state laboratory analysis.

CONCLUSIONS

Both the laboratory experiments and computer simulations show that cladding ventilation helps reduce or eliminate condensation due to sun-driven moisture.

Computer simulation using a recently released test version of a widely available commercial hygrothermal software tool presents moisture accumulation results that are consistent with those from laboratory testing for ventilated wall assemblies with absorptive cladding under a sun-driven moisture scenario. However, this study did reveal the following limitations with the current test version:



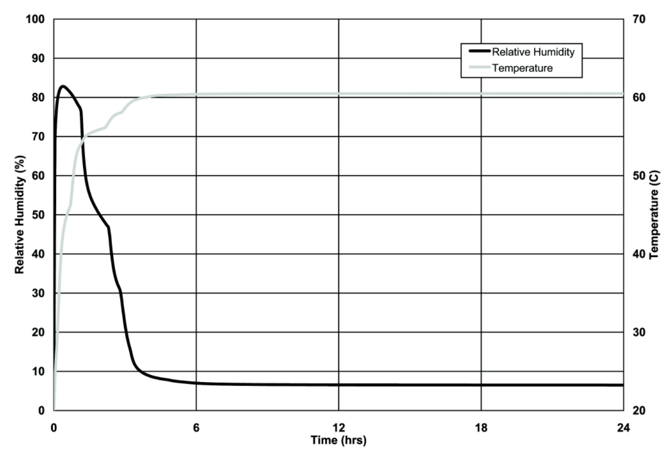


Figure 12 *Computer simulation results: temperature and RH profiles at inside face of exterior cladding for ventilation at 0.03 L/s (0.06 cfm)—I-P (left) and SI (right).*

Table 4. Duration of Inward Moisture Surface Evaporation

Panel	Ventilation	Flowrate, L/s	Flowrate, cfm	Duration of Elevated RH (hrs)/Time to Reach Equilibrium (hrs): Experiments, hrs	Computer Modeling, hrs
1	Mechanical	2	4.24	0.2/1.5	Not able to be simulated
2	Mechanical	1	2.12	0.4/2	Not able to be simulated
3	Mechanical	0.5	1.06	0.8/2.7	Not able to be simulated
4	Natural	0.03	0.06	2/6	2/4
5	Natural	0.002	0.004	3/7	8/16
6	No ventilation	0	0	10/24	10/36

- The computer program did not actually predict occurrence of condensation that occurred in the laboratory. It did predict an elevated RH of 90% or above for those cases that produced condensation in the laboratory. Therefore, we caution designers to conservatively assume that condensation is likely if the simulation results in an RH within the wall assembly of 90% or greater—the amount that can be estimated from the resulting changes in moisture content in the material layer in question.
- The computer program is limited to very low cladding ventilation flowrates and is not able to model the higher flows that proved in the laboratory the most beneficial in eliminating the occurrence of condensation due to sun-driven moisture.

Despite the limitations noted above, the computer program used is a useful tool and one of the few tools available for designers to easily quantify the effect of cladding ventilation in reducing or eliminating the occurrence of condensation due to sun-driven moisture conditions.

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