Drying Capabilities of Wood Frame Walls with Wood Siding

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ABSTRACT

The hygrothermal performance of wood siding and exterior sheathing and the need of cavity ventilation for wood frame wall systems has been investigated. The aim of this preliminary study was to investigate various design strategies to improve the drying performance and capabilities of wood frame wall systems. A moisture engineering approach was undertaken by conducting a combination of laboratory experiments and advanced computer simulations. The intent of the work was to investigate the heat and moisture performance as affected by variations in the wall design.

Several different walls systems with wood siding were constructed that included different material layers as exterior sheathing, different insulation materials, and wall systems that incorporated air cavity ventilation and others that did not incorporate a cavity between the wood siding and the exterior sheathing. Laboratory experiments were carried out to examine the hygrothermal performance of the walls exposed to different exterior and interior boundary conditions. The drying capabilities of the walls and their ability to recover from moisture loads caused by vapor convection and diffusion were investigated.

The information generated from the laboratory experiments was subsequently analyzed by advanced computer modeling, and additional simulations were performed to determine the response of various wall systems using realistic environmental conditions. The experiments were also numerically simulated for the same laboratory conditions. In general, when comparing the numerical and experimental results, good agreement was observed, both indicating similar trends in the hygrothermal behavior. But at the same time, some anomalous results were also found that were initially believed to be due to anomalies within details of the wall structures but were later found to be caused by spurious values in the prescribed boundary conditions. The different requirements due to actual climatic boundary conditions were addressed by selecting exterior data from a cold climate. The analysis developed preliminary information in terms of guidelines and practices for acceptable thermal and moisture performance of wood frame walls.

The hygrothermal performance of exterior sheathing materials, their effect on wall moisture performance, and the ability of the structure to dry out moisture from possible leaks (or initial construction moisture) need further research to establish guidelines applicable for a wider range of climates. Even today, many examples of moisture-related problems exist in the literature, some of which have been attributed to improper design of the cladding system. This paper attempts to shed some light on the issues and concerns of the drying performance of wood frame wall systems exposed to cold climates.

INTRODUCTION

One of the main reasons for having a wall cladding system is to protect the interior wall from exterior moisture loads (i.e., water sources such as wind-driven rain and air moisture content), while at the same time, the wall must allow any moisture originating from the interior side of the wall to escape through the wall cavity and to dry to the exterior. Material layers in wall structures that are exposed to exterior climatic conditions can have large yearly variations in moisture content and relative humidity. These variations depend on the materials' sorption and moisture transfer characteristics and the way the layers are assembled (i.e., the system characteristics). Moisture in structures is one of the key factors affecting the durability and service life of materials and building components. Wall cavity ventilation and its effects on air leakage through the wood frame walls, heat loss, and moisture performance have been studied by TenWolde et al. (1995). They

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concluded that wall cavity ventilation may have an inconsistent effect on wall moisture performance if the airtightness of the inner wall is poor.

In order to achieve near perfect protection against moisture from the exterior (rain penetration, vapor transfer), a building envelope designer may choose to make the exterior layer perfectly watertight by using a façade material that is liquid moisture tight and making sure that the joints and flashing do not allow unintentional water leaks. If the exterior cladding is also vapor tight, the moisture has no other way to dry out except via air exchange between the space in the midst of the exterior sheathing and cladding. In cold climates, a general rule is to position construction layers with higher permeance at the cold (exterior) side of the insulation layer rather than at the warm side of the insulation. A rule of thumb in Finland is to employ exterior permeance/interior permeance > 5. The cladding vapor diffusion permeance is normally not included in the calculation of the moisture permeances if an air cavity is present between the cladding and the exterior sheathing. The underlying assumption is that in the presence of an air cavity, an adequate amount of air exchange exists between the wall and exterior air to allow fast drying of moisture in the wall. Currently, no design guidelines exist to address the various requirements for an air cavity (except that it is usually required), to provide a method to dimensionally design the cavity, and to determine if one is needed in the first place. Generally speaking, the only guideline found in Finland is one that simply recommends that it should be present, whereas in countries with a similar climate such as Canada, some walls are still constructed without air cavity ventilation.

LABORATORY EXPERIMENTS

A hut that is 2.8 m long by 2 m wide by 2 m high was built inside a cold laboratory room. The frame of the hut was made of 120 mm thick extruded polystyrene sheets. The frame was sealed to be airtight. Openings 1.73 m high and 0.46 m wide were cut in the walls to accommodate 12 test walls. The walls were assembled inside the openings in the polystyrene sheet without any wall studs.

Description of Wall Structures

The purpose of the experiments was to investigate the hygrothermal behavior of different exterior sheathings in walls employing wood siding as cladding. The main interest was to study the effects of different moisture transfer properties of the sheathing materials (highly permeable vs. moderately permeable) and wall cavity ventilation between the siding and the sheathing. The moisture contents and temperatures on the warmer interior surface of the exterior sheathing were measured as a function of time. The walls were exposed to constant interior conditions and nearly constant exterior (representing cold weather) conditions. Twelve test walls were investigated simultaneously. Some were analyzed in more detail than others by an advanced hygrothermal numerical model. The differences between the 12 test walls were basically the following:

a. the selection of either employing a polyethylene vapor retarder or building paper,
b. the presence of a wall cavity open for air exchange between the cavity and exterior air or no cavity,
c. the presence of controlled air leakage (no leakage vs. 0.15 L/s) through a 1 mm gap at a location 50 mm from the top of the wall,
d. the choice of exterior sheathing: porous wood fiberboard or spun-bonded polyolefin air barrier plus dense mineral wool, and
e. the choice of the stud cavity insulation: mineral wool or cellulose fiber insulation.

Gypsum board (12 mm thick) was used in each wall as interior sheathing. No paints were applied, either on the gypsum board or on the exterior sheathing and cladding. The test walls had the following layers and details (abbreviations are used to make the identification of structures in Table 1 shorter).

Description	Abbreviation
• Vapor retarder, polyethylene (PE), 0.2 mm	VR
• Building paper (BP), 0.35 mm	Building paper
• Gap in the interior sheathing on top	Gap
• Insulation, glass fiber, 17 kg/m^3, 100 mm	MW
• Insulation, loose-fill cellulose fiber, 45 kg/m^3, 100 mm	LCFI
• Exterior sheathing, porous wood fiberboard, 12 mm	PWFB
• Exterior sheathing, spun-bonded polyolefin air barrier + glass fiber insulation, 45 mm	T-MW
• Wall cavity (open from bottom and top), 22 mm	Cav
• Cladding, horizontal tongue and groove board, 18 mm	Wood
• Cladding, steel plate, 0.7 mm	Steel

The cases investigated in the laboratory and their structural differences are listed in Table 1.

Boundary Conditions

The interior air temperature was kept constant at +20°C. The interior relative humidity was also kept constant at 25% and 50% during the simulated winter and spring season, respectively. The humidity in the air was controlled with a nozzle-type humidifier. The amplitude was occasionally measured to be ±5% (relative humidity), as shown in Figure 2.

The exterior air represented a winter season (75 days) and a spring season (40 days). During the winter season, the exterior air was kept at approximately −10°C and during the spring season at +5°C. The relative humidity of the exterior air was

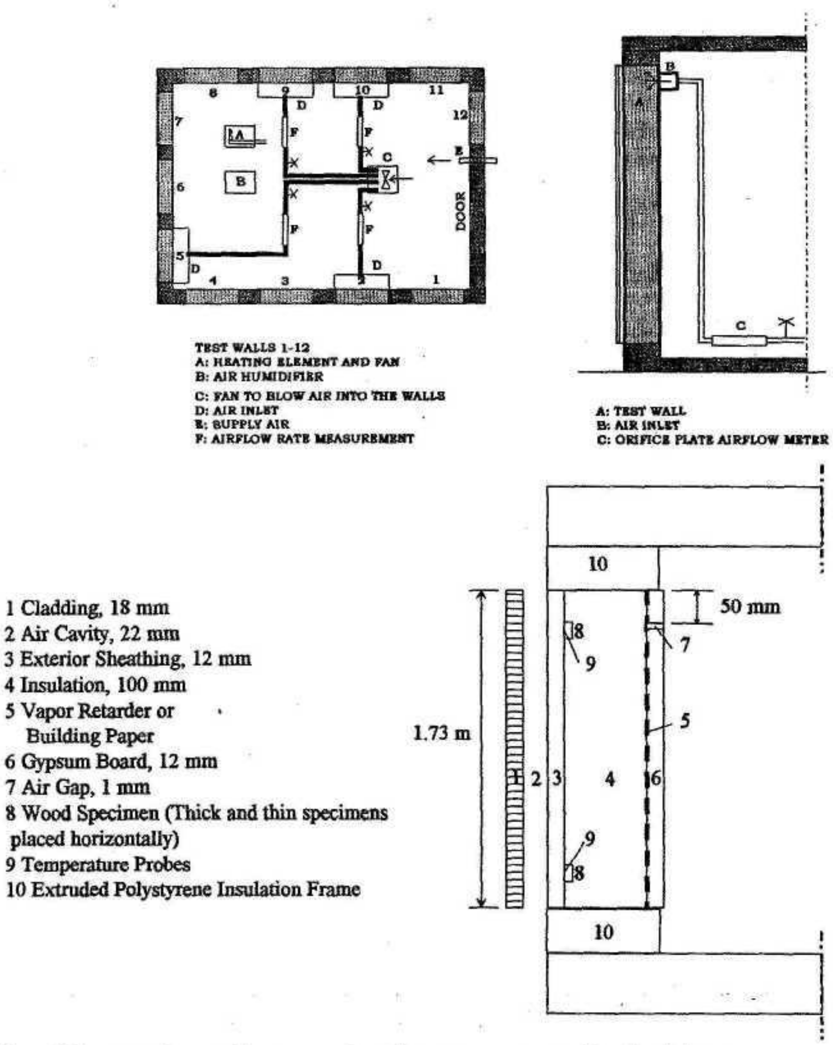

Figure 1 *Schematics of the experimental setup and wall structures tested in the laboratory.*

TABLE 1
Wall Structures in the Laboratory Experiments, Layer Numbers in Parentheses (Figure 1)

Wall #	VR/BP (5)	Gap (7)	Insulation (4)	Exterior Sheathing (3)	Wall Cavity (2)/ Cladding (1)
1	PE	–	MW	PWFB	Cav/Wood
2	PE	Gap	MW	PWFB	Cav/Wood
3	Building paper	–	MW	PWFB	Cav/Wood
4	Building paper	–	MW	T-MW	Cav/Wood
5	PE	Gap	MW	T-MW	Cav/Wood
6	Building paper	–	MW	–	– /Steel
7	Building paper	–	LCFI	–	– /Steel
8	Building paper	–	LCFI	PWFB	Cav/Wood
9	Building paper	Gap	LCFI	PWFB	Cav/Wood
10	PE	Gap	MW	PWFB	– /Wood
11	Building paper	–	MW	PWFB	– /Wood
12	Building paper	–	LCFI	T-MW	– /Wood

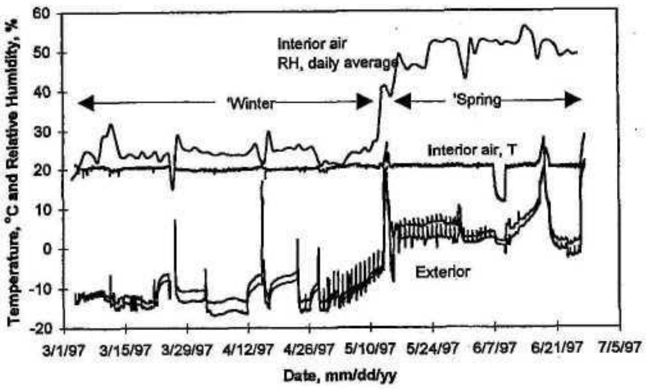

Figure 2 *Interior humidity and interior and exterior air temperatures as a function of time.*

not measured but was estimated to be approximately 60% because the temperature of the cooling coil was 4° to 6°C lower than the exterior air and moisture was condensing and freezing on the cooling coil. On occasions, the cooling coil had to be defrosted, which caused short periods when the temperature in the exterior air was higher than intended. Two fans were used to recirculate the air in the climate chamber in order to maintain equal conditions around the test wall setup.

The walls with an air gap on top were assembled with a chamber around the air gap. The chamber was connected to a fan with a duct. The airflow rate through the wall structures was set to 0.15 L/s. This corresponds to an effective leakage area of $58 \cdot 10^{-6}$ m^2 at 4 Pa pressure difference, which is well within the range measured in real walls (TenWolde et al. 1995). The airflow rate was monitored with an orifice plate flowmeter.

Material Properties

The heat and moisture transfer properties of the construction materials are given in Table 2. The properties are given as a range because most of the properties are not single valued but, instead, functions of moisture content and temperature.

Methods to Measure Moisture Contents and Temperatures

Small wood (pine) chips (130 mm × 40 mm × 2 mm) were placed 50 mm from the bottom and top of the walls between the exterior sheathing and the insulation layer in such a way that they could be quickly taken out without disturbing the experiment. The exterior sheathing had been cut in order to form a small door at the location of the wood pieces. The gaps around the "door" were taped to make sure that there were no airflows in the middle of the wall except through the porous material. Thicker wood pieces (145 mm × 45 mm × 19 mm) were also placed in the same locations. Copper nails were installed in these pieces, and the electric resistance between the nails was measured manually at frequent intervals. Moisture content was determined from the correlation between the moisture content and electric resistance. However, these wood pieces were found to be too thick to estimate short-term variations in moisture contents of surfaces (time constant for moisture accumulation/drying), and the accuracy of the method has been found to be rather poor at moisture contents outside the range of 7%-30% weight for wood (the range being dependent on wood species). The wood specimens used in the moisture measurements were cut from the same board, and the correlation between moisture content and electric resistance was calibrated at +20°C and at known moisture contents determined by weighing the wet and dry wood specimens. The dependence of the measured moisture content on temperature was approximately –0.02% ... 0.05% weight/K at different levels of relative humidity. The uncertainty in the moisture content measurement under steady-state conditions is approximated to be ±1% weight. However, under rapidly varying

TABLE 2
Thermal and Moisture Transfer Properties at +20°C of Construction Materials Used in the Experiments

Material	Thermal Conductivity λ, W/m·K	Property Vapor Permeability δp, ng/m·s·Pa*	Moisture Diffusivity D_w, m^2/s
Gypsum board, 620 kg/m^3	0.26	15 - 65	$0 - 3.4 \cdot 10^{-7}$
Polyethylene vapor retarder*, 0.2 mm	–	0.75	–
Building Paper*, 0.36 mm	–	2,000 - 10,000	–
Glass Fiber Insulation, 17 kg/m^3	0.034	150	$1...100 \cdot 10^{-8}$ (at moisture contents above 4% vol)
Cellulose Fiber Insulation, 45 kg/m^3	0.041	40 - 150	$0.3...100 \cdot 10^{-8}$ (at moisture contents above 6% vol)
Porous Wood Fiberboard, 310 kg/m^3	0.055	16 - 61	$0 - 10 \cdot 10^{-10}$
Pine Wood, 425 kg/m^3	0.09 - 0.19	2.8 - 10	$0 - 3 \cdot 10^{-10}$

* Permeance ng/m^2·s·Pa

dynamic conditions, the moisture content will be different on the surface and in the middle of the specimen and, thus, the method's accuracy under dynamic conditions is likely to be worse than ±1% weight. Thermocouples were installed on the exterior surface of these pieces between the exterior sheathing and insulation. The uncertainty of the temperature measurements is approximately ±0.1 K.

Results from Laboratory Experiments

Moisture content of the small wood pieces was determined by weighing the samples after 25, 46, and 68 days (winter period) and 89, 104, and 114 days (spring period) from the start of the experiments (Table 3). Moisture contents of the thicker wood samples were measured electrically. The moisture contents in the thin and thick wood pieces differ significantly at times (especially at the beginning of the experiment), which is due to the slower response of the average moisture content in the thick wood specimens during wetting and drying periods.

TABLE 3
Moisture Contents (% weight) of the Thin Wood Specimens (Measured by Weighing)

Wall, Location	Date (Days from the Start of the Experiment)					
	25 Mar (25)	15 Apr (46)	13May (68)	28May (89)	12 Jun (104)	26 Jun (118)
1 B (Bottom)	8.4	9.2	9.8	6.5	7.1	8.7
1 T (Top)	8.0	7.8	8.8	6.4	6.5	6.7
2 B	15.4	13.5	14.1	8.3	10.4	10.9
2 T	18.4	15.3	15.5	13.6	14.9	20.3
3 B	12.4	12.9	13.2	9.7	10.7	11.6
3 T	14.1	12.5	13.5	10.5	11.6	13.2
4 B	10.6	11.6	12.5	7.8	9.2	9.9
4 T	12.2	11.1	13.6	8.7	9.9	11.1
5 B	12.5	11.7	12.8	8.3	8.1	9.1
5 T	13.9	12.9	15.0	10.0	10.8	10.4
6 B	20.2	25.1	45.5	75.1	78.6	80.4
6 T	31.0	40.4	61.5	65.3	72.4	96.6
7 B	26.4	29.4	34.1	47.2	87.1	75.3
7 T	25.9	45.8	51.5	43.8	77.2	77.3
8 B	14.0	14.3	15.4	11.5	11.6	12.2
8 T	13.1	13.3	13.3	10.8	10.8	12.7
9 B	13.0	11.8	13.3	10.6	11.6	12.7
9 T	16.2	14.5	14.7	12.2	12.5	15.1
10 B	14.7	15.6	16.8	14.9	17.4	19.9
10 T	17.0	16.5	15.6	16.3	18.4	20.7
11 B	13.7	13.3	14.2	14.0	12.6	15.8
11 T	16.0	15.4	16.1	15.3	16.0	19.2
12 B	14.0	15.0	15.4	15.4	13.0	15.5
12 T	14.4	15.0	15.8	13.2	13.0	14.5

Some selected laboratory experiments were also simulated using the hygrothermal model in order to investigate whether the performance of the walls could be predicted using a computer model. This comparison was needed in order to be able to extend the investigations to simulate the behavior of the wall structures under real environmental conditions using weather files. Due to uncertainties in both the large-scale experiments and assigned material properties, an exact match between the measured and simulated results was not expected but, rather, the same tendency of behavior. The boundary conditions on the exterior side of the wall were not well enough known even though the measurements were carried out under laboratory conditions. The vapor pressure in the exterior air as a function of time and the airflow conditions in the wall cavities were found to be critical factors affecting the results of analytical analyses by numerical methods.

Temperatures on Top and Bottom. In all the walls, the temperature at the top location of the wood pieces was higher than at the bottom location of the wood pieces. The temperature difference between top and bottom was naturally the highest in the cases where air was exfiltrating through the wall (cases 2, 5, 9, and 10). On average, the temperature difference during the measured period was 1.1°C-5.0°C and 4.1°C-8.9°C without and with air exfiltration, respectively. The temperature difference was slightly higher in walls with mineral wool insulation than with cellulose fiber insulation. The temperature difference between the top and bottom was noticeably smaller in walls employing mineral wool during the "spring" season than during the "winter" season. The exterior air temperature was raised from −10°C to +5°C at the beginning of the spring season. This decrease in temperature difference is likely due to the reduction of natural convection activity within the insulation layer.

Moisture Contents in the Exterior Sheathing

Walls with Building Paper or with Vapor Retarder. Walls with a vapor retarder and without air exfiltration experienced moisture contents not higher than 10% weight during the winter period in the experiments. Significantly higher moisture contents, up to 14% weight, were measured both electrically and by weighing when the vapor retarder was replaced in the wall by building paper (permeance approximately $0.5 \cdot 10^{-9}$ kg/m^2·s·Pa [8.7 perm]).

The moisture contents at the top and bottom of the wood specimens are shown in Figures 3 and 4 for a wall with cellulose fiber insulation (wall 8) and a wall with mineral wool insulation (wall 3). The difference between the top and bottom moisture contents is much higher in the wall with mineral wool insulation, which is due to natural convection within the

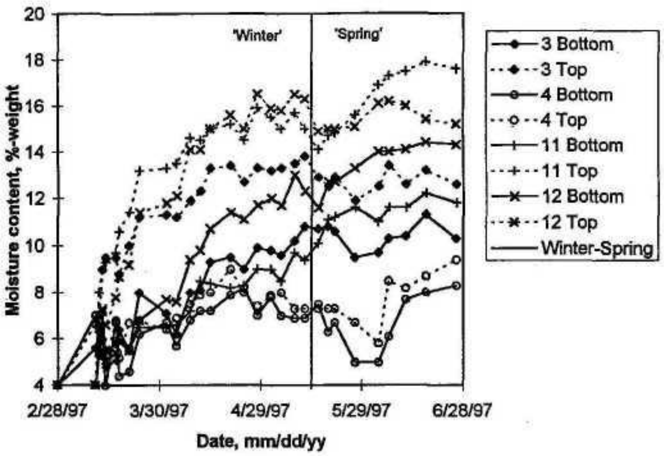

Figure 3 *Electrically measured moisture contents in the wood specimens on top and bottom of walls 3, 4, 11, and 12.*

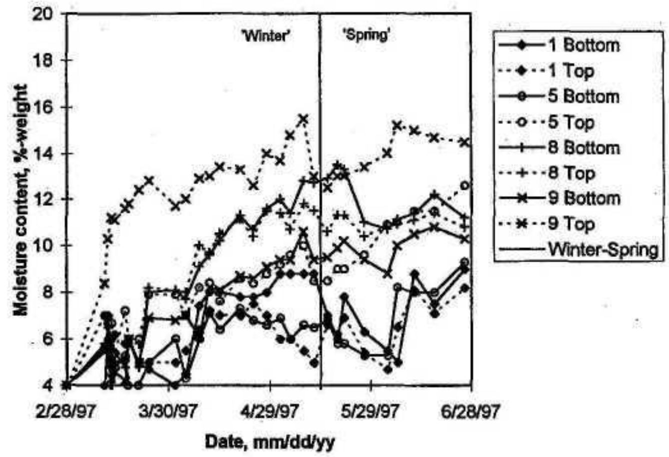

Figure 4 *Electrically measured moisture contents in the wood specimens on top and bottom of walls 1, 5, 8, and 9.*

insulation layer, whereas in the wall with cellulose fiber insulation, the moisture contents are much closer to each other. The air permeability of mineral wool insulation is higher than that of cellulose insulation, which is most likely the cause for the effect. According to the two spot measurements (top and bottom) of the wall, the moisture behavior of the wall with cellulose fiber insulation and with air exfiltration (wall 9) is very similar to the behavior of the mineral wool wall without air exfiltration (wall 3). Moisture distribution present in a wall having air exfiltration is studied more in numerical simulations and is presented later.

Exfiltration with or without Wall Cavity Ventilation. The effect of wall cavity ventilation can be seen by comparing case 2 (cavity ventilation) and case 10 (no cavity ventilation). The measured results are shown in Figure 5. Both cases employ mineral wool insulation, a vapor retarder, and a path for exfiltration. At the beginning of the "winter" period, the

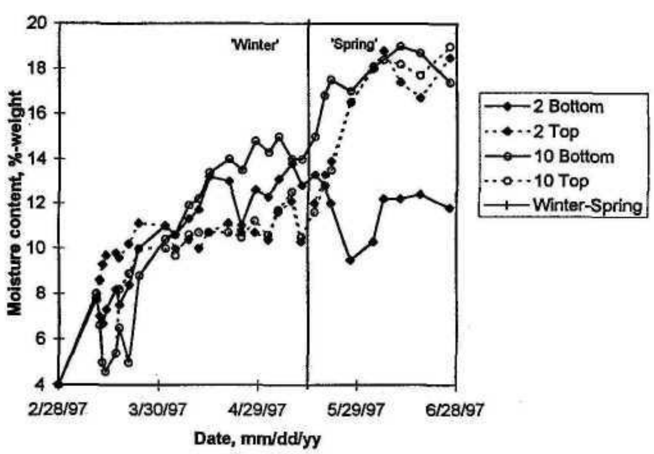

Figure 5 *Electrically measured moisture contents in the wood specimens on top and bottom of wall 2 (with air cavity behind the siding) and wall 10 (without air cavity).*

moisture content on the top increases (likely due to the airflow from interior air), but later on the moisture content in the bottom part becomes higher than that on top. The top of the wall seems to reach a stage of quasi-static steady state. Exfiltrating air keeps the temperatures on top high enough to ensure that no further condensation occurs. During the "spring" period (after 75 days), the moisture contents in the wood specimens increase up to 19% weight both on top and bottom in the wall that has no wall cavity ventilation (case 10), whereas in wall 2, with cavity ventilation, the bottom part slowly dries out. The difference between these walls is in the airflow distribution. In wall 2, the exfiltrating air can flow out of the wall through the opening between the cladding and exterior sheathing, thus leaving the bottom part of the wall intact. In wall 10, the air flows more evenly through the exterior cladding, carrying interior moisture both to the top and bottom parts of the wall.

No Exfiltration, with or without Wall Cavity Ventilation. Wall systems 3 and 11 do not have a path for air exfiltration present, but, instead of a vapor retarder, these walls include building paper. Wall 3, which included air cavity ventilation, experienced significantly lower moisture contents on the top part of the structure than wall 11, which did not include air cavity ventilation (Figure 3). Wall 1 is also shown as a reference case, as it includes a polyethylene vapor retarder and air cavity ventilation.

According to previous studies (CMHC 1988a, 1988b, 1988c), the selection of exterior sheathing produced large differences in the moisture performance of the sheathing if the cladding layer (with or without air cavity) had low vapor diffusion resistance and low or high cavity ventilation. Higher vapor diffusion resistance of the sheathing layer resulted in lower moisture loads from the inner wall into the cavity and lower requirements for cavity ventilation. Wall 3 employed porous wood fiberboard as the exterior sheathing and wall 4 employed dense mineral wool with an air barrier as exterior sheathing. Both of these materials have adequate vapor permeability to dry out moisture, but the difference in the moisture behavior is still apparent. The higher vapor permeance of the mineral wool allows less moisture accumulation. Wall 12 is the same as wall 4 except that it has no cavity ventilation present. The drying capability of the wall system by diffusion from interior air is greatly reduced. However, under these conditions, the performance of all of these walls is still satisfactory and was confirmed by measured spot checks of the moisture content.

Wall systems 6 and 7 accumulated large amounts of water during the experiment, which is expected since these walls incorporated a vapor impermeable exterior sheathing (steel) without an air cavity present. Wall 6 used mineral wool for stud cavity insulation, while wall 7 employed cellulose fiber insulation. Wall 7 displayed slightly lower moisture contents in the wood chips at the measured spots than wall 6, but the differences were insignificant—both walls perform unsatisfactorily. The measured lower moisture content in wall 7 is due to different spatial distribution of moisture resulting from the higher moisture capacity of cellulose fiber in comparison to mineral wool.

The effective vapor permeance of the cladding is a combination of vapor diffusion and air exchange between the interior side of the cladding and ambient environment. Wood siding has air gaps between the panels, reducing the airtightness of the siding. Even without a wall cavity with openings at the top and bottom, there most likely exists air exchange through the siding. In real buildings, air exchange may be unexpectedly high in walls with wood siding due to pressure fluctuations on the exterior surface that are caused by blowing wind. This behavior could not be tested in laboratory conditions. There may be some drawbacks, however, if the pressure difference between the exterior surface and the interior side of the siding is high—pulsating pressure may push wind-driven rain through the siding into the wall cavity.

Comparison Between Walls with or without Air Exfiltration. Larger differences between top and bottom moisture contents were experienced in walls with air exfiltration than in walls without the airflow (Figure 4, walls 8 and 9). Accurate conclusions, however, are difficult to make according to these experiments because the boundary conditions and airflow patterns in the wall and cavity are not well known. According to the simulations, many parameters, such as wall cavity ventilation, humidity of the exterior air, and internal airflow patterns in the walls, affected the results significantly. Those parameters should have been measured in order to verify the numerical simulations against the measurements, and, with hindsight, we would have made fewer experiments with more measured parameters.

COMPARISON BETWEEN MEASURED AND NUMERICALLY ANALYZED LABORATORY EXPERIMENTS

The measurement data were partly insufficient for comprehensive verification between measurements and numerical simulations. The measured moisture contents present only local values from a few selected spots in the walls, but the moisture distribution within the wall remained practically unknown. Some of the parameters affecting the moisture accumulation and distribution during air exfiltration had been numerically studied earlier (Ojanen and Kumaran 1992). These and the present numerical simulations show how the maximum moisture accumulation in the exterior sheathing is very local, depending strongly on the air exfiltration flow rate. In the present experimental large-scale testing, only the top and bottom moisture contents were measured, while the simulations conducted after the tests were performed showed highest moisture accumulation with the same airflow rates at about one-third from the top of the wall. Because the obvious moisture accumulation in the critical spots was not measured, a complete comparison between measured and simulated results could not be done.

Another important unknown is the airflow field in the ventilation cavities of the walls. In the experiments, special arrangements were done to have uniformly distributed temperature fields in the cold chamber. The varying forced convection around the test walls and in the wall cavities was not measured. According to the simulations, the variations in the airflow rates and patterns may create vast differences in the microclimates on the top and bottom part of the wall. Depending on the air pressure conditions caused by the wind in real buildings or by the air fans in the experiments, the airflow in the ventilation cavity may be upward, downward, or fluctuating, and there may also be possible leaks through the siding. In real buildings, the pressure gradients along the wall cavity may be positive or negative depending on the wind direction and velocity (Uvsløkk 1996). Only approximated flow fields in the ventilation cavities could be used in the simulations. The humidity conditions of the cold-side air were also unknown, but some approximations could be done based on the temperature level of the cooling coils.

Despite the lack of complete information about the boundary conditions and moisture content distribution fields, the experiments were studied numerically using the best approximations for the unknown parameters. The objectives of this comparison were to find out what effect different parameters have on the moisture performance of the wall and wood siding. The numerical analyses also have shown conclusively the importance and need of detailed planning and instrumentation of even rather simple experiments, especially when these are to be used for verification of simulation models.

Numerical sensitivity analyses were then performed to parametrically determine the effects of ventilation airflow rate and direction and the cold-side humidity conditions on the total moisture performance of the walls. Some experimentally studied cases were selected and analyzed numerically, and some of the most interesting results are presented in the following.

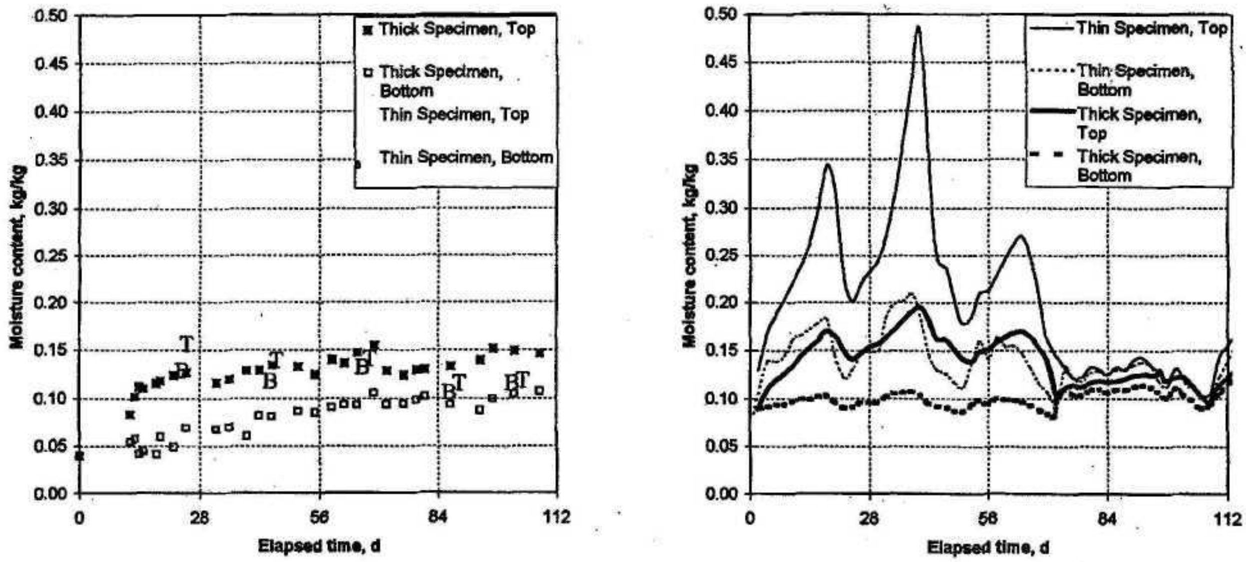

Figure 6 *The mass capacity (thickness 2 mm or 19 mm) effect of the size of the wood specimen on the measured and simulated moisture content of wall 9.*

Effects of the Thickness of Wooden Moisture Probes

The size of the calibrated wood specimens used to measure moisture accumulation at the interior surface of the exterior sheathing may give misleading data about the moisture performance of the wall. The moisture capacity of thick wood specimens flattens out rapid changes of the moisture contents near the surfaces of the wall layers. The slow response of the thick wood pieces in the bottom of wall 9 in comparison to the thin wood pieces is depicted in Figure 6. The simulated results for the wall show that the moisture contents would vary within a large range (0.1-0.5 kg/kg) in thin specimens and within a smaller range (0.1-0.2 kg/kg) in thick specimens. The variations were due to the temperature changes in the room representing exterior climate. Unfortunately, the thin specimens seemed to have been measured at times when the moisture contents were not at the highest according to the simulations, and the peaks remain unnoticed in the collected measurement data. When compared to electrical measurements, the simulated moisture contents of the thick specimens show the same behavior as in measurements (ups and downs). Changes in the humidity conditions on the surface of materials are important when determining the risk for mold growth.

Parametric Analysis of Cavity Ventilation

Depending on the direction and magnitude of the airflow in the air cavity behind the siding, the moisture contents of the siding as well as the inner wall structures behave differently. Figure 7 shows the simulated moisture contents in the thin wood pieces in wall 3 at different air cavity ventilation rates: 9 mm/s downward (negative values), 10 mm/s or 100 mm/s upward (positive values). The top moisture contents are significantly higher than the bottom moisture contents in the case when air is flowing upward at 10 mm/s in the cavity. When the air velocity increased to 100 mm/s upward, it affected the pressure distribution inside the wall insulation, and the natural convection inside the insulation changed, which, in turn, affected the vertical moisture content distribution on the interior side of the exterior sheathing. As a result, the moisture content became higher at the bottom than at the top. When the air was flowing downward in the cavity at 9 mm/s, the top moisture content was distinctly lower than when the air was flowing

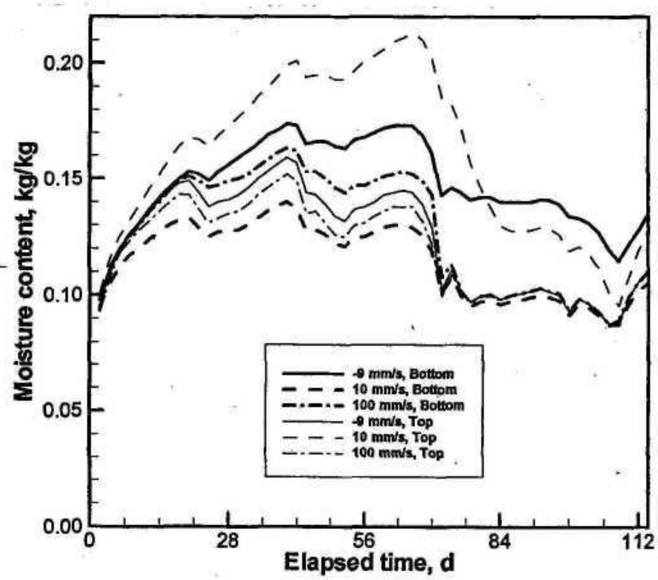

Figure 7 *The effect of airflow rate and direction on the moisture contents in the bottom and top wood specimens in wall 3. Velocity in the air cavity −9 mm/s (downward), 10 mm/s or 100 mm/s (upward).*

upward at 10 mm/s. The air that enters the cavity is in these cases drier than the surfaces of the cavity, and while flowing in the cavity, the air gains moisture. Natural convection inside the insulation layer tends to make the top moisture contents higher than the bottom ones. Dry air that enters the cavity, flows along the cavity, and exits at the other end has a tendency to make the moisture contents higher near the exit. When air is flowing downward in the cavity, this effect and the natural convection in the insulation layer have opposite impacts on the moisture content distribution, which is why the difference in the top and bottom moisture contents is notably smaller with downward airflow. An air velocity of 100 mm/s upward resulted in the lowest difference between the top and bottom moisture contents, and the magnitude of the moisture content is acceptable for proper moisture performance of the wall under these conditions. This airflow rate (100 mm/s) is still very small for a wall with an open air cavity. The effect of cavity ventilation rate on the moisture performance is further studied in yearly simulations.

SIMULATED YEARLY HYGROTHERMAL PERFORMANCE OF WALLS WITH AIR EXCHANGE IN WALL CAVITY

Discussion of Simulation Model

A detailed model description of the two-dimensional LATENITE hygrothermal model is given by Hens and Janssens (1993) and Salonvaara and Karagiozis (1994). Only a brief overview is presented in this paper. The moisture transport potentials used in the model are moisture content and vapor pressure; for energy transport, temperature is used. The porous media transport of moisture (vapor and liquid) through each material layer is considered strongly coupled to the material properties (i.e., the sorption-suction curves). The corresponding moisture fluxes are decomposed for each phase and are treated separately. Energy and moisture conservation equations are coupled via phase changes of moisture (latent heat of evaporation, freezing of liquid). Hourly weather data can be used to create the boundary conditions. A typical weather data file used in the simulations includes ambient temperature and relative humidity, wind speed, wind direction, hourly precipitation, direct and diffuse solar radiation, and cloud cover index. The program has a built-in material property database for common building materials (Karagiozis et al. 1994).

Description of Wall Structures

Two different walls were numerically analyzed with three different cavity ventilation rates. The wall structure was 2.4 m high and the layers and thickness, starting from the exterior, are listed in Table 4.

On the top and bottom of the insulation cavity were 2 in. by 4 in. sill and cap plates.

TABLE 4
Material Layers in the Simulated Walls

Material Layer	Case 1	Case 2
Wood Siding, 18 mm	X	X
Air Cavity Open from Bottom and Top, 22 mm	X	X
Exterior Sheathing		
OSB, 12 mm	X	
Porous Wood Fiberboard, 12 mm		X
Glass Fiber Insulation	X	X
Vapor Retarder, Polyethylene 0.15 mm	X	
Building Paper, 0.36 mm		X
Gypsum Board, 12 mm	X	X

The main difference between the walls is the interaction between the structure and the indoor air. In the wall with building paper (case 2), there is moisture diffusion from the interior air into the wall (or vice versa), whereas in the wall with a vapor retarder, the moisture flow from indoors is practically zero.

Cavity Ventilation Rates

The air cavity ventilation was set to a constant velocity: 0.001 m/s, 0.01 m/s, and 0.1 m/s. In buildings, the air cavity ventilation depends heavily on the wind pressures at the bottom and top of the wall as well as the temperature difference between the cavity and exterior air. The ventilation rates for different wall configurations are not well known, and the effect of the magnitude of the ventilation on the hygrothermal performance of the wall is not yet clearly understood. Whether the wall cavity ventilation can isolate the moisture performance of the siding and the inner wall from each other—and at what ventilation rate—is still an unanswered question. Isolating the siding from the inner wall would prevent possible moisture leaks into the wall cavity from indoor air or from exterior sources (wind-driven rain) that could damage the siding. The durability of the wood siding depends on the moisture content variations and the moisture content gradient in the wood at different times of the year. On the other hand, wall cavity ventilation is disadvantageous in terms of the fire safety of wood frame buildings.

Wood siding is commonly not airtight even if the air cavity behind the siding is not open to outside on top and bottom. The tongue and groove planks have been measured to have 19.12 L/s per m^2 air leakage at 75 Pa pressure difference (CHBA 1995). When the air cavity is ventilated, i.e., is open to the outside on top and bottom of the cavity, the airflow rates have been measured within the range of 0-10 m/s in the air cavity (Geving 1998). Assuming the cavity is closed at the top and bottom of the wall, the average air exchange between the cavity and the exterior environment can be estimated by making the following assumptions:

- The maximum difference between the wind pressure coefficients at the top and bottom of the wall (height 2.4 m) is ≤1.0.
- The wind pressure on the exterior surface of the siding is linearly distributed along the height.
- The pressure in the cavity is the average of the pressure on the exterior surface of the siding.
- The average wind speed in Helsinki is 4.0 m/s.
- Fluctuations of the wind are not taken into account.

The average pressure difference between the bottom and the top of the wall would be

$$\Delta p_{wind} \le \frac{1}{2}\rho_{air} v_{wind}^2 \approx 0.6 \cdot 4^2 \text{ Pa} = 9.6 \text{ Pa} \quad (1)$$

where Δp_{wind} is the pressure difference (Pa) between the bottom and top of the wall, ρ_{air} is the density of the ambient air (kg/m^3), and v_{wind} is the wind speed (m/s).

The pressure in the air cavity (which has little resistance to airflow along the height of the wall) would be 4.3 Pa (above atmospheric pressure). The air flows into the cavity through the bottom part and out of the cavity through the top part of the wall. If we further assume that the pressure distribution is linear along the height of the wall and that the airflow through the wood siding is laminar and proportional to pressure difference, we get the following average air exchange between the cavity and the exterior environment:

$$q_V = Av = (0.5 \cdot 2.4 \text{ m} \cdot 1 \text{ m}) \cdot \left(19 \cdot 10^{-3} \frac{\text{m}^3}{\text{s,m}^2} / 75 \text{ Pa}\right) \cdot (0.5 \cdot 4.3 \text{ Pa}) = 0.65 \cdot 10^{-3} \text{m}^3/\text{s} = 2.4 \text{ m}^3/\text{h} \quad (2)$$

where q_V is the volumetric rate of air exchange (m^3/s) between the cavity and the exterior environment, A is the exterior area of the wall (m^2), and v is the velocity (m/s) across the wall area.

The volume of the air cavity per width of wall is 0.0528 m^3/m (thickness of the cavity is 22 mm and height 2.4 m). Thus develops an effective air exchange rate, n = 45 L/h (the total volume of the air in the cavity will be changed 45 times in an hour). The velocities selected in the simulations develop air exchange rates that are lower and higher than this value; these are 1.5 L/h, 15 L/h, and 150 L/h with corresponding velocities of 0.001 m/s, 0.01 m/s, and 0.1 m/s, respectively.

Boundary and Initial Conditions

The hourly climate of Helsinki, Finland, was used. The orientation of the walls was facing south. The initial conditions of the material layers were +22°C and 60% relative humidity (except exterior sheathing and sill plates). The indoor air conditions were:

- temperature +22°C or outdoor air temperature if higher than +22°C;
- indoor air moisture content $\rho_{vapor,in}$ was outdoor air moisture content $\rho_{vapor,out}$ + 3 g/m^3, but indoor air relative humidity was limited to 30% ≤ relative humidity ≤ 70%.

The simulations were carried out for a 14-month period starting June 1.

The initial moisture contents in the OSB/porous wood fiberboard and sill/cap plate corresponded to 95% RH (which in wood corresponds to approximately 25% weight moisture content) in order to enable us to analyze the drying efficiency of the walls. The rest of the materials were initially at 60% RH.

Results from Yearly Simulations

The moisture contents in the wood siding at the bottom, top, in the middle of the siding (9 mm from the surfaces), and 1 mm deep from the interior surface (cavity side) are shown in Figure 8 as a function of cavity ventilation rates. The results showed that as the ventilation rates increase, lower moisture content is present in the top siding. However, at the bottom, the wall cavity ventilation has little effect on the moisture contents (Figure 9) and the moisture performance follows the exterior humidity conditions quite closely. The ventilation rate associated with an air velocity of 0.01 m/s is not enough to convect moisture from the air cavity and to dry the inner surface of the wood siding (moisture gradient in the siding is outward). The wall system with the building paper and velocity of 0.1 m/s is found adequate enough to change the direction of the moisture gradient. In the wall with a vapor retarder (polyethylene) present, a lower velocity is sufficient to dry out the initial moisture, which is due to lower vapor permeability of OSB and a lower evaporation rate of moisture into the cavity.

The simulation results presented so far deal with the moisture distribution present in the wall assembly under different combinations of the investigated parameters. The next step was to determine the probable durability consequences of the various combinations of the wall systems. A state-of-the-art wood damage model was used to assess the durability consequences. The model and damage results will be described briefly in the following section.

Estimation and Description of Mold Growth Analysis. Mold growth in the structures was estimated using a model equation that employs temperature, relative humidity, and exposure time as input. The mold growth model and the mathematical equations involved are presented in detail in another paper (Hukka and Viitanen 1998) and only a short introduction is given here.

Quantification of mold growth in the model is based on the mold index used in the experiments for visual inspection. The mold growth model is based on mathematical relations for the growth rate of the mold index in different conditions including the effects of exposure time, temperature, relative humidity, and dry periods. The model is purely mathematical in nature and as mold growth is only investigated with visual inspection, it does not have any connection to the biology in the form of modeling the number of live cells. Also, the mold index resulting from computation with the model does not reflect the visual appearance of the surface under study because traces of mold growth remain on wood surface for a long time. The correct way to interpret the results is that the mold index represents the possible activity of the mold fungi on the wood surface.

The model makes it possible to calculate the development of mold growth on the surface of small wooden samples exposed to fluctuating temperature and humidity conditions including dry periods. The numerical values of the parameters included in the model are fitted for pine and spruce sapwood, but the functional form of the model can be reasoned to be valid also for other wood-based materials.

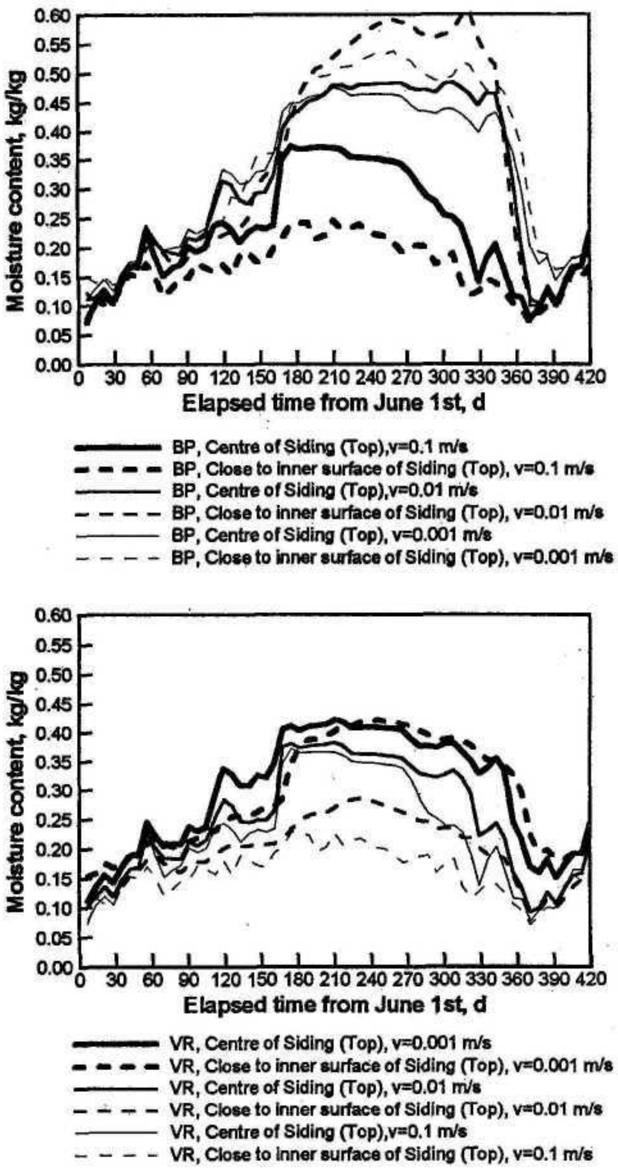

Figure 8 *Moisture contents on top of the wall 11 mm (in the center) and 1 mm from the inner surface of the wood siding. Wall with building paper (top) and vapor retarder (bottom).*

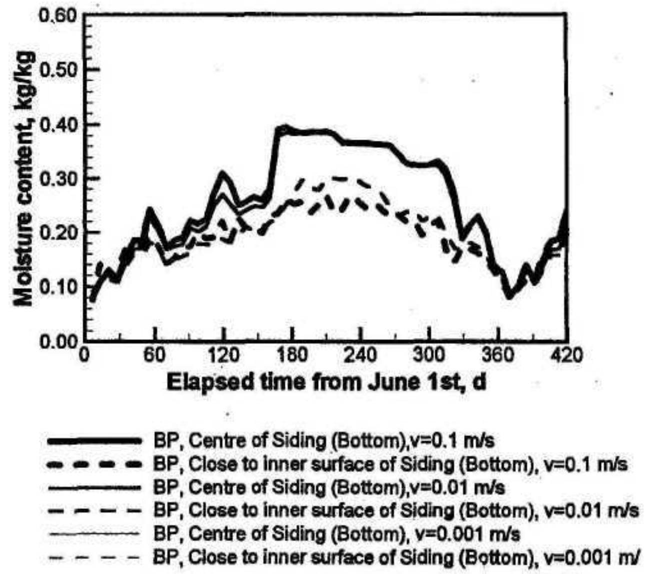

Figure 9 *Moisture contents at the bottom of the wall 11 mm (in the center) and 1 mm from the inner surface of the wood siding. Wall with building paper. Wall with vapor retarder is not shown here; the results were almost the same.*

The calculation method is briefly as follows. The critical relative humidity above which mold growth is possible is a function of temperature. At temperatures below 0°C and above 50°C, mold growth is not possible. The critical relative humidity lies between 100% (at 0°C) and 80% (at ≥20°C). The growth rate of mold increases as temperature and relative humidity increase, and it is also dependent on the mold index itself: a higher mold index enables faster mold growth. During dry periods, when relative humidity is below the critical humidity or when temperature is outside the range of temperature enabling mold growth, the mold index decreases at a constant rate.

The mold index scale assumes the values in Table 5.

The estimated mold growth index on the exterior surface of the exterior sheathing is depicted in Figure 10 as a function of cavity ventilation rate. Results are shown for the wall

TABLE 5
Mold Index Values and Their Meaning

Index	Descriptive Meaning
0	No Growth
1	Some Growth, Detected only with Microscope
2	Moderate Growth Detected with Microscope
3	Some Growth Detected Visually
4	Visually Detected Coverage More than 10%
5	Visually Detected Coverage More than 50%
6	Visually Detected Coverage 100%

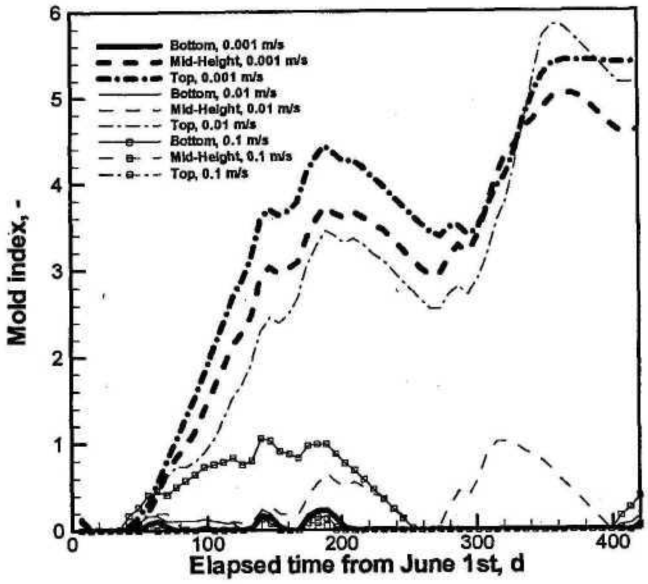

Figure 10 *Mold index on the exterior surface of exterior sheathing (porous wood fiberboard) at different heights of the wall as a function of different cavity ventilation rates. Results for a wall with building paper.*

that employed building paper. This wall system exhibited higher humidities in the cavity for a longer period of time. Results conclusively show that a cavity ventilation rate of n = 150 L/h (velocity in the cavity, v = 0.1 m/s) is adequate to prevent moisture conditions that could allow mold growth. Air cavity velocities of either 0.001 m/s or 0.01 m/s developed a mold index that gradually increased as a function of time. Indeed, the damage model predicted the occurrence of more than 50% visually detected mold growth for low cavity ventilation rates.

CONCLUSIONS

Both the laboratory experiments and the simulated results clearly show the effect of wall cavity ventilation on the moisture performance of the walls.

The need for cavity ventilation is still unresolved for a wide range of climatic conditions and wall material combinations. It is well known though that wall cavity ventilation can improve drying of walls. Moisture from interior sources (e.g., exfiltration) or other leaks may be found in the insulation cavity. Slow drying may create conditions favorable for mold growth and rotting. In order to improve the drying capacity of a wall, the exterior sheathing requires a high enough vapor permeance. This, in turn, requires that the exterior wall cavity have the ability to dry out the moisture diffusing through the exterior sheathing. Wall cavity ventilation cannot improve the drying out of moisture present in the insulation layer if the exterior sheathing has low vapor permeance. High humidity conditions may be found in the wood siding if the exterior cladding has low vapor and air permeance and details that may occasionally allow wind-driven rain to penetrate into the wall cavity. Open wall cavities reduce the fire safety of wood frame structures; thus, it would be advantageous to be able to design the walls in such a way that the air exchange is high enough to allow fast drying of wall cavities but low enough not to assist in spreading a possible fire in the building. In testing the double-stud wall configuration (partition walls separating dwelling units) without the specific fire-stop material in place, the flame spread in the wall cavity was found to be highly dependent on the width of the air space: the flames were stopped very effectively by the lack of oxygen when the air space was 13 mm, but with an air space of 38 mm, flames spread quickly throughout the wall (NRC 1998). The situation is similar in the exterior wall configurations.

The effect of wall cavity ventilation on the moisture performance of the walls depends on the climate and moisture loads into the wall from different sources. The ability of the wall to survive these moisture loads depends on its ability to dry out that moisture.

The deterioration of wood siding depends on the temperature and humidity conditions to which it is exposed. Wood siding can be isolated from moisture loads to which the inner wall layers are exposed by arranging adequate wall cavity ventilation behind the siding. In the cold climate of Helsinki, a rate of 150 air exchanges per hour in the wall cavity was found to be adequate for the investigated walls. This ventilation rate could be obtained even without a wall cavity that is open at the top and bottom of the wall. Air leaks through the gaps between the planks may be adequate. According to some air leakage measurements for tongue and groove planks, the average air exchange over a year might be 45 L/h in an air cavity in the Helsinki climate. This air exchange might be adequate in many wall structures. Further attention should be paid to designing wood sidings with ventilation holes similarly to the way it has been done for some impermeable siding materials such as vinyl.

The unique approach presented in this paper, of coupling hygrothermal modeling and durability damage modeling, can assist in the development of moisture engineered wall systems for any combination of critical elements. The integration of experimental investigation, hygrothermal modeling, and durability damage analysis is an approach that can provide the development of wall design guidelines that will permit the building designer to optimize building envelope wall systems.

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