Moisture Transport by Convection in Lightweight Exterior Facades

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ABSTRACT

This paper presents the experimental setup, a computer model, and simulation results of a recent Ph.D. project that focused on the effect of convection in lightweight exterior facades on moisture transport. First, the paper presents measurements of air velocity in the wall cavity by tracer gas and thermal anemometer. It is found that tracer gas can be used for air velocity measurement. Secondly a computer model is validated against measurements. Finally, using the computer model, a set of different yearly simulations with weather data from a design reference year were used to study the effect on cavity moisture levels of (1) insulation thickness, (2) presence or absence of vapor barrier, and (3) the degree of cavity ventilation.

INTRODUCTION

Convection is known to be a dominant type of moisture transport, and it may be important to protect the different parts of the building envelope from undesirable effects of convective moisture transport by ensuring airtight construction. However, in ventilated facades, the exterior cladding can function as a rain screen. The space behind the cladding may be kept dry by the passage of outdoor air, thus exploiting the potential of convection to disperse excess moisture that may have entered from the outside or has migrated from inside the building.

This paper will focus on the function of the ventilation behind the exterior rain screen. The term "ventilation" will be used for the flow of outdoor air that passes in the cavity between the rain screen and the sheathing. Wood-based building structures such as lightweight walls, attics, and crawlspaces are often designed with ventilation openings to dry out moisture that may have exfiltrated from the indoor climate or come from the outdoor surroundings. Both stack effect and wind force influence the air change rate.

Both the advantage and disadvantage of ventilation of building envelopes on the moisture load in a building envelope are discussed in the literature. Ventilation of building envelopes for residential houses with outdoor air is the accepted method for controlling moisture accumulation at an acceptable level (Walker and Forest 1995). Traditionally, it is assumed that ventilation is the way to prevent moisture content from rising to a critical level in wood-based building envelopes. Recommendations of, for example, opening area for ventilation can be found in a guideline from the Danish Building Research Institute (Andersen et al. 1993).

The ventilation air will, for some periods of the year or day, increase the moisture content and, for other periods, it will decrease the moisture content. For some structures and in some climates, the increase of moisture content due to ventilation can result in an unacceptable moisture load for a longer period. The ventilation of the structure is therefore recommended in some cases and deprecated in others. For instance, in cold climates, ventilation is generally thought to prevent the moisture content behind the exterior cladding of attics and wood-based walls from increasing to critically high levels since the outdoor air will, for most of the time, have a lower dew point than that of the cavity. Examples of when ventilation could be deprecated are: in constructions where the exterior cladding can be subjected to significant undercooling by long-wave sky radiation or in roofs where the ventilated cavity will have an underpressure relative to the indoor climate such that exfiltration of humid air from the indoors is exacerbated by the ventilation of the cavity. Finally, the ventilation with outdoor

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air into a cavity in the building envelope may not be desired under circumstances when the dew point of the outdoors is high in relation to the temperature in the cavity, such as in hot-humid climates or by ventilation of basements in summer.

In October 1999, an amendment to the Danish building regulations from 1995 accepted wood-based exterior claddings up to four stories high, provided that there is no cavity behind the cladding. The required absence of ventilation is due to fire safety reasons, but little attention has been given to the moisture conditions in such building envelopes without ventilation. Also, a requirement concerning energy savings has increased the insulation thickness. This will, to some extent, influence the temperature in the ventilated cavity such that it comes closer to the outdoor air temperature, and this will, in turn, reduce the stack effect as one of the driving forces for the ventilation of the cavity, and it may lead to new considerations about needed opening area for ventilated cavities.

It is generally recognized that convective moisture transport from the indoor climate has a significant impact on the moisture load when it takes place. Several researchers (Ojanen and Kumaran 1996; Hagentoft and Harderup 1996; TenWolde and Rose 1996; Condren 1982) have found that the convective moisture transport from the indoor climate must be prevented and suggest that the moisture transport be controlled, to some extent, with an airtight layer between the indoor climate and the warm side of the insulation so air transport from the indoor climate into the building envelopes does not occur. Also, the Danish guideline stipulates that airtightness between the indoor climate and the warm side of the insulation has the highest priority.

In practice, moisture transport from the indoor climate to the building envelope still takes place by diffusion and by unintended leakage, such as through electrical joints and missing sealing of the vapor retarder, etc. This moisture is removed from the envelope by airflow of outdoor air that carries moisture from the building envelope to the outdoors. The focus of this paper, however, is restricted to the airflow and convective moisture transport in exterior ventilated cavities behind the rain screen.

AIR VELOCITY MEASUREMENTS IN A WALL ENCLOSURE

In order to investigate the effect of convection on hygrothermal performance, it was desired to measure the actual air change in the exterior cavity of some walls of a small test hut (see Figure 1). However, a suitable method for outdoor measurement had to be devised. The choice was to use tracer gas, but the method had to be validated against another method—thermal anemometers. The tracer gas technique (TG) enables determination of the directional average air velocity over the cross section of the cavity. However, TG has a long response time.

A thermo-anemometer (TA) typically has a high sampling rate, i.e., short response time. Therefore, it is appropriate for point measurements in the flow and, thus, determination of average air velocity as well as more detailed investigation of the airflow.

The detailed measurements can be used for investigation with regard to uniformity of the airflow distribution in the cavity and its characteristics (mean velocity, standard deviation of velocity, turbulence intensity, frequency of velocity fluctuations, etc.).

Measurement of Air Velocity in Cavity by Thermo-anemometer

Multi-channel low-velocity thermal anemometers were used to measure the airflow velocity. The system consisted of eight identical velocity probes, eight transducer units, and a multi-channel power supplier. The velocity probe had a spherical (omnidirectional) velocity mass sensor of 2 mm (0.08 in.) in diameter, made of enameled copper wire molded into a sphere. The overheating temperature of the sensor was 25°C (45°F). The velocity probe also had an unheated sensor, which measured the air temperature. The specifications for the sensors are listed in Table 1.

The sensors were individually calibrated by the manufacturer. The analogue signal of instantaneous velocity and

Table 1. Manufacturer's Specifications for the Thermal Anemometer

Thermal anemometer	
Type of velocity sensor	Omnidirectional, spherical
Velocity range	0.05 - 5 m/s (0.16 - 16 ft/s)
Repeatability	0.02 m/s ±2% (0.07 ft/s)
Temperature range	0 to 50°C (32 to 122°F)
Accuracy of temperature measurement	0.3°C (0.5°F)

Figure 1 *Test hut used for testing of measuring principles for determination of airflow in outdoor ventilated air cavities.*

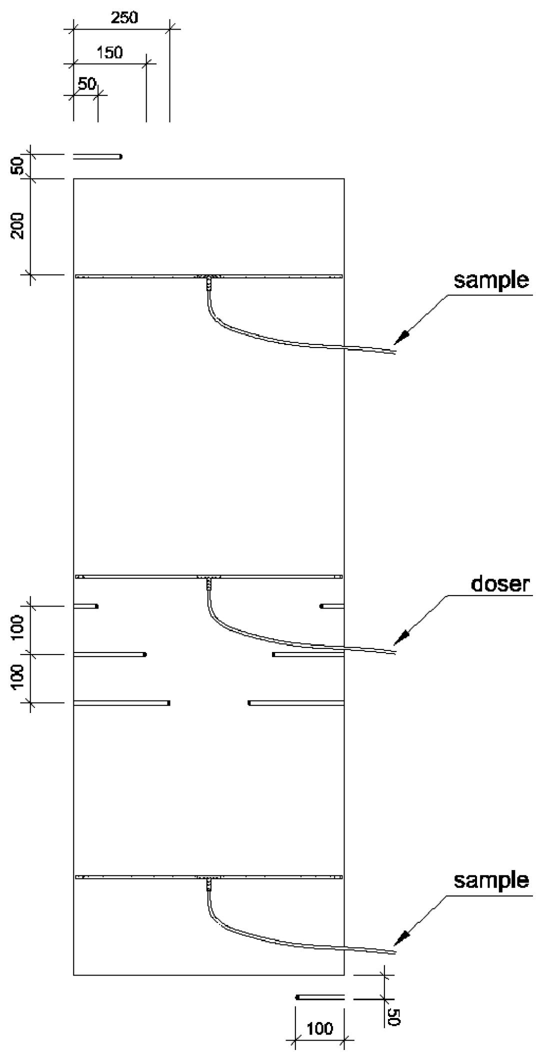

Figure 2 *Thermo-anemometer probes inserted from the sides into the cavity and tubes for tracer gas dosing and sampling. The tubes have decreasing distance between the drilled holes in the tracer gas tubes in order to distribute and sample uniformly over the cross-sectional area.*

temperature measured by the sensors was logged on a computer with a frequency of 5 Hz.

Six of the probes were used to measure the airflow in the cavity. They were placed symmetrically in the cavity, three on each side of the center line (see Figures 2 and 3). The probes were inserted in the vertical posts through holes and were positioned by a specially designed device. In order to avoid disturbances between the probes due to the natural convection flow generated by the heated sensor, the probes were positioned 100 mm apart from each other in the vertical direction. Further, two more probes were used to measure the air velocity near the ventilation openings, one at each opening.

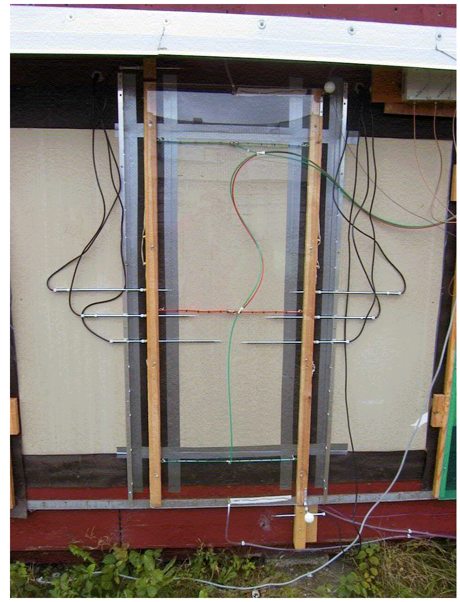

Figure 3 *Photo of the instrumented exterior wall cavity. The rain screen is Plexiglas.*

The average velocity through the ventilation cavity was calculated assuming that the thermo-anemometer probes did not influence the airflow. The cross-sectional area of the cavity was constant and equal to the area of the ventilation opening.

Air Velocity and Moisture Content Measured with Tracer Gas Equipment

Tracer gas measurements were performed with a gas analyzer, based on the photo-acoustic infrared detection method. The instrument quantifies the concentration of any gas that absorbs infrared radiation. In a given air sample, it makes individual measurements of the concentration of a maximum of five gases, and water vapor, with optical filters. Dinitrogenoxide (N_2O) was used as a tracer gas during the present measurements. The choice of N_2O instead of the normally used sulphurhexaflouride (SF_6) was due to a density close to density of atmospheric air.

The gas analyzer can measure N_2O in the range 0.03 to 30,000 ppm, with a repeatability of 1% of the measured value of a 140 mL (8.5 in.^{3}) sample (see Table 2). Cross-compensation between the measured gas and water was included in the calculation of the measured N_2O concentration. The gas analyzer was used in conjunction with a multi-point doser and sampler, which enables measurements in up to six points.

A constant dose of tracer gas was added to the flow in the cavity through the doser tube. The dosing valve delivers approximately 0.5 mL/s (0.03 in.^{3}/s), depending on the chosen nozzle. The dosage is calculated with ±2% accuracy (see Table 3).

Table 2. Manufacturer's Specification for Multi-Gas Monitor

Multi-gas Monitor	
Response time	~30 s per gas
Measurement range (N_2O)	0.3 ppm to $3 \cdot 10^5$ ppm
Repeatability	1% of measured value
Operating temperature	5-40°C (41 - 104°F)
Relative humidity	up to 90% at 30°C (at 86°F)
Volume of air required	140 mL/sample (8.5 in^3 pr. sample)

Table 3. Manufacturer's Specifications for the Multipoint Sampler

Multipoint Sampler and Doser	
Dosage	0.5 mL/s, 3.0 mL/s or 15 mL/s
Accuracy of calculated dosage	±2%
Sampler volume flow rate	15 mL/s(0.91 $in.^3$/s)

In order to distribute the tracer gas uniformly in the flow, a horizontal tube with nine drilled holes was used. The seven holes nearest to the middle had diameters of 1 mm (0.04 in.), and the two at the end had diameters of 2 mm (0.08 in.). The uniformity of the tracer gas distribution through a tube with drilled holes in the width of the cavity was tested by observing that smoke came out of all nine holes in each side (Gudum 2000a). The tracer gas was supplied in the middle of the tube through the outer wall of the cavity. The analyzed result from the air sample downstream to the dosing tube was used for calculation of the air velocity. The flow direction in the cavity was determined by sampling both upward and downward from the dosing tube. The two sampling tubes placed in the cavity, at a distance of 200 mm (8 in.) from the openings (see Figure 2), were identical to the dosing tube.

Further, a sample of the outdoor air collected to the west (the dominating wind direction) of the test hut was analyzed to compensate for background N_2O concentration, and one sample inside the test hut was analyzed for safety reasons during operation of the instruments. The sampling and analysis of the four air samples (one from each tube in the cavity, outdoor air, and indoor air) were performed one by one in a loop of about eight minutes, as the time for sampling and analysis was about one to two minutes for each sample.

The uncertainty of the average air velocity determined with the tracer gas method depends on the accuracy of determination of the cross-sectional area, the accuracy of the concentration measurements, and the accuracy of the calculation of tracer gas dosing. In the velocity range of 0.02-1.4 m/s (0.07-4.6 ft/s) the uncertainty was estimated to be 0.003-0.17 m/s (0.01-0.56 ft/s) (Gudum 2000b), assuming uniform distribution and complete mixing of tracer gas.

Theoretical Consideration

Tracer Gas. The tracer gas method was calibrated under laboratory conditions using a separate experimental model, with dimensions similar to the outdoor model. In the laboratory, the measurements with tracer gas of vertical air velocity inside a cavity were compared to measurements of the volume flow rate (Gudum 2000b). Here it was found that the mean air velocity, u (m/s), over the cross-sectional area of the ventilation opening area, including an empirically found constant A_{eff}, is

$$u = \frac{F}{A_{eff} \cdot b_{corr} \cdot (c_c - c_b)}\ , \tag{1}$$

where

A_{eff} = cross-sectional area, m^2;
b_{corr} = experimentally found correlation factor;
c_c, c_b = gas concentration in the cavity and background (surroundings) respectively, mg/m^3;
F = dose of tracer gas, mg/s.

The airflow by volume, Q (m^3/s), through the vents was assumed to be equal for inlet, outlet, and over the cross-sectional area.

$$Q = u \cdot A \tag{2}$$

where

A = cross-sectional area, m^2, and
u = average air velocity over the cross-sectional area, m/s.

Thermal Anemometers. The horizontal average velocity through the ventilated cavity was calculated from the six point measurements, assuming that the thermal anemometer probes did not influence the airflow. The cross-sectional area of the cavity was constant and equal to the area of the ventilation openings.

A number of experiments were run. Data were logged in five-minute intervals, except in experiment #16, where the logging interval was three minutes (see Table 4). According to Andersen (2000), the mean velocity across the cavity depth is equal to two-thirds of the maximum velocity for laminar flow. The present measurements identified a nonlaminar airflow in the cavity with large velocity fluctuations and moderate variation across the cavity width. Nevertheless, the two-thirds criterion was applied to estimate the average velocity in the cavity from the time-averaged velocity in the middle of the ventilated cavity where the velocity probes were placed.

$$u_{average} = \frac{2}{3} \cdot \frac{\sum_{1}^{n} u_{time,average}}{n} \tag{3}$$

where

$u_{time,\ average}$ = mean velocity in the cavity during the three- or five-minute periods, determined from the measurements by the six velocity probes, m/s;
n = number of probes.

Since the cross-sectional area of the cavity is assumed to be the same at the opening and at the position of the thermo-anemometers, the following equation can be used to determine the volume flow rate, Q (m^3/s):

$$Q = u_{average} \cdot A \tag{4}$$

where

A = cross-sectional area, m^2;

$u_{average}$ = mean of the time average velocity of the six probes.

Comparison of Tracer Gas Technique Against Thermal Anemometer. To compare TG against TA, 16 preliminary experiments were performed with the outdoor model of the ventilated cavity. Some of the results are shown in Table 4. The measurements were performed in five-minute intervals between 9:00 and 14:00 on August 11 and 14, 2000, for experiments #1-15, and on October 16, 2000, for experiment #16. Mean velocities for TG and TA are listed in Table 4. The turbulence of the air velocity is defined as the standard deviation divided by the mean velocity ×100 %, which tells how even the velocity has been during the experiment.

The horizontally averaged value of the six inside thermal anemometer probes was used with Equation 3 to calculate the mean air velocity TA in Table 4. The turbulence was calculated for the horizontally averaged velocity and listed in Table 4. The mean air velocity TG from tracer gas measurement was calculated with Equation 1. The wind velocity and wind direction were measured simultaneously, and the mean values and the standard deviations were calculated for each run. The airflow direction in the cavity was observed with smoke and was also defined from the tracer gas measurements.

The air velocity was measured similar to Figure 1 in six positions in parallel with the wall. The collected data were analyzed in order to identify the mean velocity, the standard deviation of the velocity, and the turbulence intensity in the cavity flow (Table 4). For the rather narrow range of wind speed and direction, the mean velocity measured in the cavity was in the range 0.12-0.22 m/s (0.39-0.72 ft/s) with thermal anemometers and the range 0.08-0.32 m/s (0.26-1.05 ft/s) with tracer gas, while the turbulence intensity for the mean velocity (thermal anemometers) was from 17% to 80% (for the individual thermal anemometer probes the turbulence intensity was measured from 36% to 102%).

Table 4. Velocity Measured Inside Ventilated Cavity with Thermal Anemometers (TA) and Tracer Gas (TG).*

Measurement #	Mean Air Velocity, TA [m/s]	Turbulence of TA [%]	Mean Air Velocity, TG [m/s]	Mean Wind Speed [m/s]	Standard Deviation, Wind Velocity [m/s]	Mean Wind Direction [°]	Standard Deviation, Wind Dir. [°]	Airflow Direction
1	0.17	17	0.19	1.77	0.69	268	26	upward
2	0.21	60	0.16	1.32	0.88	251	86	upward
3	0.18	59	0.18	0.91	0.61	287	37	upward
4	0.21	52	0.32	1.45	0.80	275	59	upward
5	0.19	45	0.19	1.71	0.66	265	22	fluctuating
6	0.19	47	0.23	1.79	1.01	262	69	fluctuating
7	0.22	46	0.22	1.98	1.03	265	25	upward
8	0.16	37	0.18	1.96	0.80	250	51	upward
9	0.18	44	0.24	1.90	0.87	252	50	upward
10	0.15	42	0.22	2.02	1.31	258	26	upward
11	0.12	37	0.17	0.69	0.52	148	59	upward
12	0.13	58	0.08	1.50	0.96	154	63	upward
13	0.13	66	0.08	1.48	0.85	156	53	upward
14	0.13	59	0.13	1.41	0.94	153	80	upward
15	0.14	61	0.3	1.20	0.68	157	71	upward
16†	0.17	80	0.08	2.12	1.21	98	57	fluctuating

* Wind data measured 1.8 m (5.9 ft) above roof height. The flow direction is observed from smoke that is spread near the openings and from tracer gas measurements.
† Experimental period of three minutes

The results in Table 4 show that the outdoor conditions during the present experiments did not change in a wide range. The mean wind speed during the measurements was in the range of 0.7-2.1 m/s (2.3-6.9 ft/s), while the mean wind direction was either around 260° (west) or 150° (southeast). The standard deviation of the wind direction during the experiments was from 22° to 86°. The airflow direction was mostly upward, with three observations of fluctuating direction.

The average air velocities measured with the thermal anemometer and with the tracer gas are compared in Figure 4. The comparison shows a good agreement between the two measurement methods. Only for some of the experiments—#4, #15, and #16—the agreement was poor. The differences were large, especially for experiments #4 and #15, where the average velocity determined by the tracer gas technique was more than 50% higher than with the thermal anemometer. The discrepancy between TG and TA #16 could be due to fluctuating air direction, where the thermo-anemometers were expected to estimate higher velocity than the tracer gas method. A reasonable explanation for the divergence in #4 and in #15 was not found.

Nevertheless, the systematic difference and the standard deviation of the difference in the average velocity determined by the two methods was low—0.03 m/s (0.10 ft/s). Thus, it seems that the assumptions made for the determination of the average velocity by the thermal anemometer, the two-thirds criteria, and the location of the maximum velocity in the middle of the cavity cross section may be used in practice.

Both the tracer gas method and thermo-anemometers are methods that can be applied for air velocity measurements in a ventilated cavity. The tracer gas method can detect recirculation of cavity air and the directional air velocity, but constant changes in air direction can be wrongly estimated as high air velocity due to a long response time of the method. The tracer gas method is appropriate for long time measurements (days), where the average air velocity for a longer period and not the instantaneous air velocity is required. Besides, the tracer gas analyzer also measures the moisture content of the air, which can be used for estimation of the convective moisture transfer.

Thermo-anemometers measure the instantaneous point air velocity with a high frequency. This is appropriate for investigation of fluctuations in the air velocity, as well as for investigation of the velocity distribution in the flow field. The instruments are sensitive to moisture and rain and are only appropriate for short time measurements (hours) in a dry weather period. The thermo-anemometers are nondirectional, and several measuring points are needed to estimate the horizontal average air velocity.

The two methods are supplemental to each other, where the tracer gas method is appropriate for long-term measurements of the average velocity, and the thermo-anemometers are appropriate for detailed investigations of the air velocity in the flow field.

Here the tracer gas method was tested under a narrow range of wind direction, wind velocity, and temperature. Even though the method was tested in the laboratory for air velocity in the range 0.02 to 1.4 m/s (0.07 to 4.6 ft/s), it is recommended that the tracer gas method be further tested under a variety of wind directions, wind speeds, and temperatures.

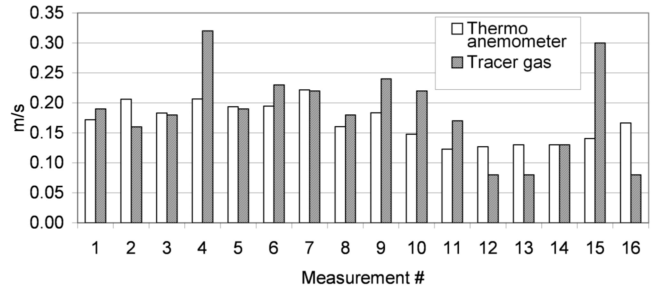

Figure 4 *Mean air velocity inside the cavity measured by tracer gas and thermal anemometer.*

SIMULINK COMPUTER MODEL

A computer model for simulation of the heat and moisture transport in a building envelope with ventilation was conducted, using the Simulink code in MATLAB. The model was built from smaller subsystems, which could be combined, in general, for description of hygrothermal conditions in virtually any kind of building envelope. For the present study of a ventilated wall, the toolboxes were used to simulate the hygrothermal conditions in the wall material and cavity of a ventilated facade in order to find the yearly moisture transport by convection in the ventilated cavity and to find the period length with critical moisture load for the sheathing, for different insulation thicknesses, and different airflow rates.

Description of the Computer Model

The basic model of the ventilated facade consists of an inside finish (gypsum board with paper), a vapor retarder (if present), insulation material, sheathing (gypsum board), ventilated air cavity, and a rain screen (see Figure 5). The basic model is modified by, for example, excluding the vapor retarder or not having the ventilated cavity.

The simulation model describes the coupled heat and moisture transport in a multi-layer wall in one dimension, with a ventilated air layer on the outside. The moisture transport through the wall is considered by diffusion only and moisture transport in the ventilated cavity by convection only. Radiation between the sky and the surface and between the cavity sides are included in the model. The simulation node was placed on the surface in order to calculate the radiation exchange between surfaces and the convection moisture transport correctly. In order to retain the simplicity of linear equations, a radiation heat transfer coefficient was used. The radiation heat transfer coefficient varied linearly from 3.4 to 4.9 W/m^2K

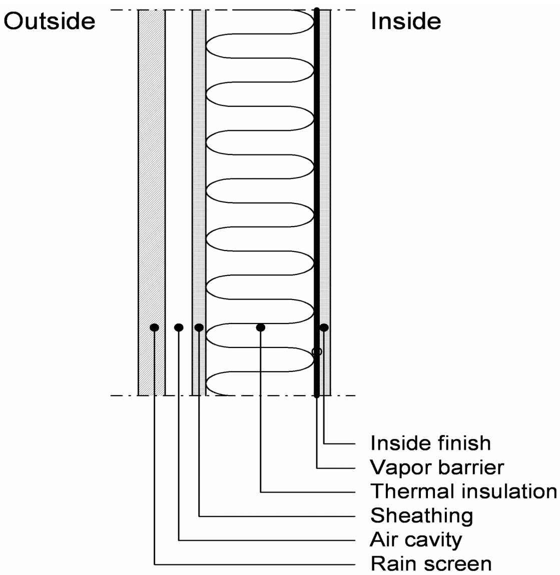

Figure 5 *The material layers in a ventilated wall, which have been an object for modeling the coupled heat and moisture transfer using Simulink.*

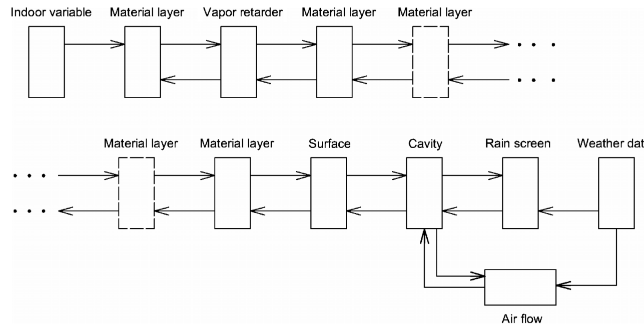

Figure 6 *Subsystems in a Simulink model of a ventilated wall where the arrows show the data streams. Each physical part of the ventilated wall was described by at least one subsystem.*

(0.60 to 0.86 Btu/h·ft^2·°F) for temperatures between –10°C and 25°C (14 and 77°F).

The heat and moisture transfer coefficients between the inner surface and the cavity air were simulated as a function of the air velocity, assuming that the airflow was laminar, driven by forced convection.

The temperature and moisture content in the cavity was lumped and localized in a single node to represent the temperature and moisture content for the cavity air, and they were calculated from an energy and moisture balance, respectively.

The mean temperature of the air cavity was found from a thermal balance of the cavity. The balance includes energy entering and leaving the cavity by the volume airflow, as well as heat transfer by convection from both the rain screen and the sheathing. The heat conduction in the air was considered negligible.

Similar to the heat balance, a moisture balance was used to calculate the moisture content of the cavity air. The transport phenomena were the convective moisture transfer between the air and the rain screen, as well as between the air and sheathing, and, furthermore, the difference in moisture content for air entering and leaving the cavity; from these, the moisture balances were made. It was assumed that airflow in the wall layers did not take place, and that rain was not present behind the rain screen.

The temperature of the rain screen was simulated as a balance between the radiation to the cavity side and the outdoor surroundings, where the outside heat transfer coefficient was simulated as a function of the wind velocity. The heat transfer coefficient to the cavity side was the same as for the sheathing, meaning that it depends on the air velocity in the cavity. The radiant temperature of the surroundings was the mean temperature of the air and the sky, both taken from the weather file that was used.

The model uses detailed calculations of the wind pressure and requires detailed wind pressure coefficients from measurements, qualified estimates, or from computer calculations. Here, computer-calculated wind pressure coefficients in intervals of 5° were used. Both wind and stack effect were included in the simulation of the airflow.

The simulation model of the wall was created by subsystems of the different physical parts of the wall. Each material layer was represented by at least one subsystem, in which the heat and moisture transport equations were solved. The thermal insulation layer, for example, was simulated as two separate material layers, and the surface of the sheathing was in a subsystem different from the subsystem of the sheathing material. In connection, there were other subsystems for the ventilated cavity, the rain screen, and the boundary conditions (see Figure 6).

The simulation of exposure of the building envelope to outdoor weather conditions was modeled by using a file with test reference year data with hourly values for the outdoor climate. Inside climate was simulated by two sinusoidal expressions of temperature and relative humidity with a yearly cycle.

The model is further detailed by Gudum (2003).

Test of Simulation Model Against Field Measurements

Field measurements from a test building (Figure 7) were compared with simulation results. Measurements of temperatures and relative humidity from five different facades were compared to Simulink simulations. The measurements were made for different examples of ventilated walls and a compact wall (Nicolajsen and Hansen 2001). Measurements of moisture content and temperatures were taken at different locations in the different lightweight facade walls. Data were logged

Photo: Jan Carl Westphal

Figure 7 *Test building used for field measurements of wood-based, lightweight outer walls with ventilated facade systems. The facade is facing north.*

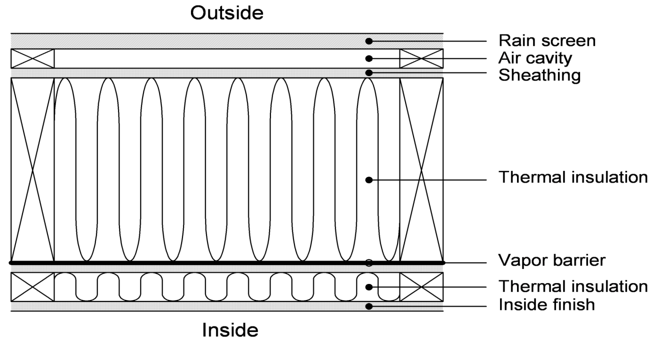

Figure 8 *Horizontal section of test wall 1V from the field test building. From the inside, it consisted of 13 mm (0.5 in.) gypsum, 45 mm (1.8 in.) rock wool, 13 mm (0.5 in.) gypsum, PE-foil, 240 mm (9.6 in.) rock wool, 9 mm (0.4 in.) gypsum as sheathing, 25 mm (1.0 in.) ventilated cavity, 20 mm (0.8 in.) pine bevel lapped siding. The points show where thermistors and dowels were placed.*

every 12 hours during a long period. Measurements from one year were compared to simulations.

For the comparisons, the simulations used measured weather data as outdoor boundary conditions. The initial conditions for the simulations were the available measured values, or 10°C (50°F) and 50% RH.

Simulink simulations were compared with five variations of north-facing facades. Four walls were with a ventilated cavity, and one was a compact wall without air cavity.

The moisture contents were measured by wood dowels of beech, and the temperatures by thermistors. The moisture content measurements were temperature compensated, and the corresponding relative humidity was found by a sorption curve for beech.

It should be noted that the wood dowels have a time constant of 12 hours, and special attention must be paid for thin hygroscopic materials due to the dowels' physical size of 1 × 2 cm (0.4 × 0.8 in.). The dowels give an average value and change their moisture content in a way similar to the hygroscopic building materials they are supposed to represent. A hole was drilled, and the dowel was inserted in the 9 mm (0.35 in.) thick gypsum material that made up the sheathing. Thus, the measurement was performed for the whole sheathing material and parts of the neighboring material behind (here referred to as "behind the sheathing"). Moisture content below 11 weight-% was not registered, as the measurement technique has a high uncertainty below this level (Andersen et al. 2002). The uncertainty of the moisture content of the dowels is approximately 5% by weight (Peuhkuri 2003).

The simulated and measured relative humidity behind the sheathing were compared for each of the test walls. The sheathing was assumed to be the best measuring place for the comparison. The rain screen was affected by driving rain, which was not considered in the simulation model; the air was changing rapidly compared to the time constant for the dowels, while the measuring behind the sheathing was found to be of preference for comparison.

The wall "1V" (Figure 8), was ventilated through an open slide at the bottom and one at the top. The top slide was protected from direct rain by a projection cap of metal some few centimeters above the slide. In the bottom of the slide was an asphalt felt to drain driving rain. The rain screen was a pine bevel lapped siding.

The discharge coefficient, C_D, is the reduction of airflow across openings due to contraction of the flow and friction and turbulence losses. The discharge coefficients—or the friction factor for different vents and orifices—used for ventilation systems can be found in the literature.

Figure 9 shows a good agreement between measurement and simulation of the relative humidity behind the sheathing until May, where the measured and simulated results seem to diverge. At this time, the data logger for recording weather data was changed and it was later discovered that it was measuring with a constant error of about +2-3°C (4-5°F) and +2-3% relative humidity. The simulations have therefore been performed with wrong weather data from May to October. The results showed that the simulation of the relative humidity behind the sheathing was in accordance with the measurement when the correct weather data were used until May, but the correspondence became poorer for the rest of the period simulated with the wrong weather data.

STUDY OF THE EFFECT ON CAVITY MOISTURE LEVELS BY SIMULATIONS

The optimum airflow for a ventilated building envelope was here defined as the airflow giving the shortest time of crit-

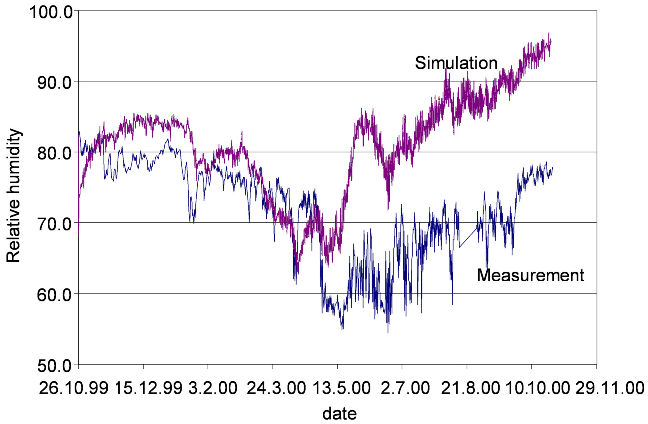

Figure 9 *Relative humidity behind the sheathing, simulated and measured for the ventilated wall 1V. Discharge coefficient of 0.03.*

ical moisture conditions inside the materials of the structure. The critical moisture condition was defined as a combination of temperature and relative humidity in a material, which is favorable for mold growth. The most critical position with respect to moisture has been determined from other recent experiments also carried out on lightweight ventilated facade systems exposed to the Danish climate (Nicolajsen and Hansen 2001). These measurements have shown that such facades have the highest moisture content just behind the sheathing. Therefore, the relative humidity and temperature in the sheathing were used for comparison of different variations of a lightweight facade.

When the relative humidity is higher than 80% and the temperature is above 5°C (41°F), mold growth may occur (Hukka and Viitanen 1999). The occurrence of mold growth also depends on the length of time with critical moisture conditions and temperature level. A study by Sedlbauer (2001) shows that the conditions for mold growth highly depend on the fungus species. However, it also seems that the criteria by Hukka and Viitanen (1999) were on the safe side, and they were applied here.

The acceptable length of a period with critical moisture conditions also has to be defined. Swedish studies of ventilated attics found that plywood sheathings in traditional attics—before the energy crises in the 1970s—had a moisture content at its highest between 15% (73% RH) and 17% (80% RH) by weight during 25% of the time (Larsson 2001). The attics were dry and safe to mold growth due to heating from the dwelling. Such poorly insulated attics tend to have fewer problems than modern attics with heavy insulation. This indicates that, in a Nordic climate, we might accept a continuous period of 8 to 10 weeks (15% to 20% of the time), where the relative humidity is above 80% and the temperature higher than 5°C (41°F). Sedlbauer (2001) finds that with the optimum conditions, the fungus growth may start after only a few days, but that for a common species, such as Aspergillus, the temperature should be above 10°C (50°F), and the relative humidity higher than 90% for 64 days for start of mold growth. In accordance with both Larsson (2001) and Sedlbauer (2001), Viitanen (1997) finds that around the boundary for critical conditions allowing the mold growth, several weeks or months of exposure can be accepted. Thus, in reality, the critical condition would depend both on the species of mold and on the material that is substrate for the mold growth, and it would depend on the dynamics of the hygrothermal conditions. In this study it was desired to apply a rather simple criterion not being specific to particular mold species or substrates, and it was therefore decided to use a maximum period of 10 weeks exceeding the 80% RH and 5°C (41°F) limits as criterion.

For general use of the present Simulink model of a ventilated facade, the actual wind load and the pressure drop through the vents are often unknown, meaning that a simulation of moisture content often will be too inaccurate to determine whether a structure passes or fails a certain durability criterion. However, the simulations will be used for investigation of whether a building structure can benefit from increased insulation thickness and/or changed ventilation rate.

The simulation estimates the hours of critical moisture load in the gypsum sheathing. The period will rarely be continuous. However, the results will be analyzed as if they were continuous, i.e., the worst case.

The optimum airflow rate, which keeps the moisture content at a minimum, is expected to be individual for each structure, depending on the indoor moisture load, the material layers, and their thickness, but poor workmanship will also have a major influence on the actual heat and moisture transport. However, in practice, some guidelines are needed, and some general rules of thumb for the ventilation of facade walls should be given, even though it might not be the optimum for a specific facade.

ANALYTICAL PARAMETRIC VARIATION

The facade studied was north facing and was, in principle, made from the inside of 13 mm (0.5 in.) gypsum board, vapor retarder of 0.1 mm (4 mil) PE-foil (if included), mineral wool insulation 100 mm-300 mm (4-12 in.), 13 mm (0.5 in.) gypsum board, 25 mm (1 in.) air cavity (if included), and a wood-based rain screen (see Figure 3 for case #1). The different cases analyzed in the parametric study varied by insulation thickness (100, 200, or 300 mm [4, 8, or 12 in.]), the presence or not of a vapor retarder in the construction, and by the discharge coefficient for the cavity inlet (see Table 5). The discharge coefficient was either 0.47, corresponding to 25 mm (1 in.) full open; 0.26, corresponding to a scattered situation or the opening width reduced to one quarter; or it was 0 (closed). The total yearly convective moisture transport within the ventilated cavity and the moisture content in the gypsum sheathing are the analyzed results. The intention is to investigate the effect of:

Table 5. Parameter Variations of the Different Simulated Cases

Case #	Insulation Thickness [mm]	Discharge Coefficient	Vapor Retarder
1	100	0.47 max open	Yes
2	200	0.47 max open	Yes
3	300	0.47 max open	Yes
4	200	Closed	Yes
5	200	0.26 scattered	Yes
6	300	Closed	Yes
7	200	Closed	No
8	200	0.47 max open	No
9	300	0.47 max open	No

Table 6. Simulation Results of Yearly Convective Moisture Transport out of a Ventilated Cavity, Time of Relative Humidity above 80%, and Time of Critical Moisture Load in Sheathing for Different Facades, Case 1-9. The Time Is Given as the Number of Hours and Percentage of Time

Case #	Convective Moisture Transport out of the Cavity in kg/year	Hours per Year, Where the Relative Humidity Is Above 80%, for the Outer Gypsum Layer (% of time)	Hours per Year, Where the Relative Humidity Is Above 80% and Temperature Is Above 5°C (% of time)
1	0.114	1217 (14%)	715 (8%)
2	0.113	3463 (40%)	1358 (16%)
3	0.113	4132 (47%)	1563 (18%)
4	-	3987 (46%)	846 (10%)
5	0.113	3408 (39%)	1304 (15%)
6	-	4066 (46%)	853 (10%)
7	-	8040 (92%)	4611 (53%)
8	10.192	6028 (69%)	2961 (34%)
9	8.295	5920 (68%)	2740 (31%)

a. insulation thickness (case 1+2+3, case 8+9)
b. ventilation opening area (case 2+4+5)
c. absence of vapor retarder (case 7+8+9)
d. absence of ventilation (case 2+4+6)

The results of the parametric analysis are given in Table 6. The convective moisture transport out of the cavity is the amount of water (in kg) per year that was carried out of the cavity by ventilation air. A positive value means that the ventilation reduced the moisture content of the structure more than it wetted it.

The results from cases 1, 2, and 3 in Table 6 are for cases with a perfect vapor retarder and insulation thickness of 100, 200, and 300 mm (4, 8, or 12 in.). It is seen that the total convective moisture transport was limited but positive, which means that the structure was dried due to convection. The moisture source in the walls with vapor retarder was mostly outdoor air wetting the structure, which was later dried out. The period of critical moisture conditions was found to increase with the insulation thickness, which was due to lower temperature of the sheathing and ensuing higher relative humidity. The total length of time with critical moisture load had its worst case for thick insulation (300 mm, 12 in.), where the critical moisture load occurred 18% of the time.

Comparison of case 4 (no ventilation), case 5 (limited ventilation), and case 2 (normal ventilation) in Table 6 shows the effect of reducing the discharge coefficient for a normal (200 mm) insulated structure with perfect vapor retarder. This means that the wind effect was varied. It is seen that the time with critical moisture conditions decreased with decreasing ventilation for a ventilated facade with perfect vapor retarder, although the difference between case 2 and 5 was minor. The ventilation had a negative impact on the moisture load on the facade. This was due to a rather low inside moisture load, which meant that the average water vapor pressure at the sheathing was lower than for the outdoor air in the ventilated cavity, and that the sheathing was actually wetted by the ventilation air for some periods of time.

Table 6 shows that the moisture load and the time of critical moisture load on the sheathing were much higher when there was no vapor retarder in the wall (cases 7, 8, and 9).

Further, it can be seen that the ventilated design had considerably less hours of critical moisture conditions (case 8) than the nonventilated model (case 7), meaning that for a wall with heavy moisture load, the ventilation was of benefit. Table 6 also shows that without vapor retarder, the increased insulation thickness was positive for the facade (cases 8 and 9), while it was negative for the wall with vapor retarder. The results also show that the convective moisture transport was high and positive out of the cavity.

A comparison of cases 2, 4, and 6 in Figure 10 shows that the absence of ventilation dampened the variation of the moisture content, i.e., it reduced the effect of exposure to the weather. The ventilation in case 2 dried the air barrier in winter and spring below the condition for case 4 and case 6 without ventilation, but, on the other hand, the ventilation increased the moisture content in the fall. The moisture contents were on similar levels during summer but with more fluctuation for the situation with ventilation (case 2).

SUMMARY AND DISCUSSION

Airflow Measurements

It was proposed to use the tracer gas method as an alternative to thermo-anemometers in order to measure the directional air velocity in a ventilated cavity and in order to measure recycling air. By the use of tracer gas, both the velocity and the direction of airflow were measured.

From laboratory measurements of low air velocity, the tracer gas showed to be valid and accurate. It was also found to be difficult to measure the low velocity with alternative methods due to uncertainty of the instruments on the market that were robust for outdoor weather exposure. The thermo-anemometers used did measure accurately, but these were sensitive and not robust to humid weather.

Changes in mean wind velocity over a short period seem to be correlated to poor performance of the tracer gas method. Here the tracer gas was unreliable and measured extremely high velocities, but these were believed to be an artifact due to directional changes.

The tracer gas method had a long response time, which was found inappropriate for short time measurements for analysis of the influence of wind fluctuations on air velocity. The thermal anemometers had, however, a short response time, which enabled measurements with the frequency of the wind fluctuations.

Simulation Model

In the simulation model developed, the liquid transport was not included. Further, the wind pressure was estimated from hourly mean wind data. This was due both to missing weather data on the turbulence and frequency of wind but also due to a missing mathematical model.

Material data are missing for some materials, and very detailed information is available for others. The data are most often from laboratory conditions with constant gradient where only one parameter is changed at a time. An example of this is how to model the moisture hysteresis. Discussions on how to model the scanning curve between absorption and desorption are, for example, described in Time (1998).

The developed simulation model showed good accordance with measurements (Nicolajsen and Hansen 2001). Simulation results, however, have their limits. Due to theoret-

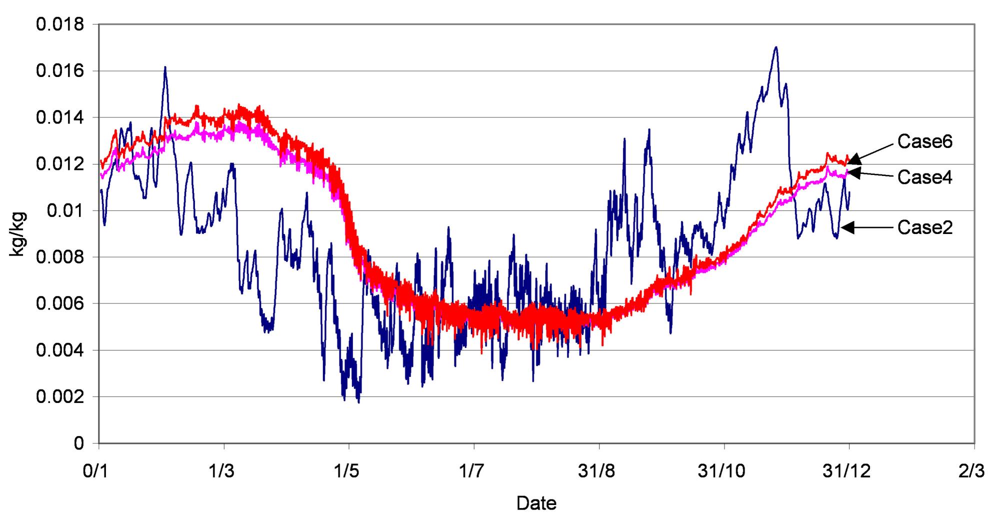

Figure 10 *Simulated moisture content in the gypsum air barrier for three different wall models. Case 2 with 200 mm insulation, vapor retarder, and maximum vent opening. Case 4 was also with 200 mm insulation and vapor retarder but without ventilation. Case 6 had vapor retarder like cases 2 and 4, but it had more insulation (300 mm) and is without ventilation.*

ical limitation, the available data, and the assumptions of unimportant effects, some phenomena were excluded from the model. In the analysis of results, both the physical phenomena and the model should be considered when conclusions are made on the basis of the simulated results. That means that a new phenomenon should be carefully analyzed with respect to the scope of the model. The typical power of simulations is to compare different variations of a model and less to give exact results.

Simulation Results

It was found that the ventilation would wet a structure for long periods and dry it for other periods. The convection removes moisture coming from the inside and can, to a limited extent, compensate for an imperfect vapor retarder. The simulation showed that increasing insulation thickness increased the time of critical moisture load. However, the period of critical moisture load did not exceed a critical length of eight to ten weeks when there was a vapor retarder.

The results from simulations with parameter variation showed that the wall without air cavity would be able to resist the moisture load, provided that the inside lining was vapor-tight and airtight, and that there is no other moisture source, such as from rain. Comparing cases 2, 4, and 5, it can be seen that walls with perfect inside lining were exposed to a higher moisture load in periods when the sheathing temperature is above 5°C when the cavity is ventilated than if it is not. So ventilation will, in fact, increase the moisture load. In this conclusion, the rain screen pressure equalization effect was not included.

Increasing the ventilation for a perfectly sealed wall will increase the time of critical moisture load for highly insulated walls. The cooling effect of ventilation with outdoor air, together with heat loss by radiation, may cause the temperature to be lower than the dew point temperature of the outdoor air, which will therefore condensate when it passes the envelope. Here, more ventilation increases the potential for condensation. However, the simulations also show that the ventilation decreases the time with critical moisture conditions when the moisture load is high, due to, for example, lack of vapor retarder. This means that a wall might be able to resist the moisture load with an imperfect inside lining if the outside is ventilated with outdoor air.

The simulations showed more time with critical moisture conditions for thicker insulation with vapor retarder and less time of critical moisture conditions for thicker insulation in the absence of vapor retarder. Even though the difference between cases 8 and 9 was minor—about 1% difference in time with critical moisture load—the simulated phenomenon was discussed. Furthermore, when the criteria of temperature above 5°C (41°F) was included, the difference in hours with critical moisture load was increased to 3% for case 8 compared to case 9.

The ventilation of lightweight wall is not required, but it is recommended. The wall with both a vapor-tight and airtight lining does not require ventilation to stay dry; in this case, it was shown that the ventilation actually wetted the wall. However, for the non-perfect wall, the ventilated cavity helps to dry the wall and reduce the moisture load. So wood-based facades, without an air cavity behind the rain screen, are possibly durable. However, choosing this requires special care with the workmanship of making the vapor barrier both airtight and moisture-tight.

This paper has analyzed ideal situations with no auxiliary moisture sources. Thus, if constructions are left with construction moisture or could be subjected to minor leaks, it may be most appropriate to have a ventilated cavity that could provide a pathway for removal of the excess moisture. Also, it must be realized that the ventilated cavity is a good way to protect against water entry from driving rain since it relieves the build-up of a wind pressure differential over the exterior cladding that meets the rain. This issue also has not been addressed by the analysis of this paper.

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