CONVECTIVE MOISTURE ACCUMULATION IN STRUCTURES WITH ADDITIONAL INSIDE INSULATION

Tuomo Ojanen **Carey Simonson**

ABSTRACT

In cold climates, inside insulation often is added to improve the thermal performance of old building structures that have high U-factors when compared to the current requirements or building practice. The objectives of this research are to analyze the moisture performance of such structures under Finnish weather conditions. In practice, it is likely that there are air leakage routes at the interfaces of the old structure and the new insulation layer. Temperature difference may cause a natural air convection loop so that the indoor air enters the structure at the top, cools down while flowing down along the interface, and finally flows back to the indoor air space through the bottom joint of the additional insulation. Depending on the airflow rate, temperature conditions, and indoor air humidity, there may be hygroscopic moisture accumulation or even condensation conditions in the structure.

The analysis of these walls was performed both numerically and experimentally. Experiments with constant +22°C, 40% relative humidity (RH) interior and −18°C exterior conditions showed moisture accumulation between the new 50-mm-thick insulation and the old structure. In many cases it was possible to reach moisture content values that exceeded those considered safe for wood-based building materials after 50 days' exposure to these conditions. Experiments also were used for validation of the numerical simulation model. Numerical simulation was done to study the yearly moisture behavior of some typical structures with additional inside insulation in the Finnish climate. A sensitivity analysis changing the airflow rate and the thermal resistance of the new insulation layer was done to find out the limits for critical moisture behavior and to give guidelines for the thermal renovation of structures with inside insulation.

INTRODUCTION

The structures studied in this research are typical of single-family houses in Finland built during the 1950s and 1960s. They have 100-mm wood framing with sawdust or mineral fiber insulation. These structures do not meet the current requirements for thermal comfort or U-factor for cold climates. The thermal performance of these structures typically is improved by installing an additional thermal insulation layer on the inside surface of the wall. The old wall usually is left without any changes. It may have old vapor retarder and it is not usually perfectly straight. Also, the inside covering may have an uneven and rough surface caused by timber sheathing or the joints of other sheathing boards. The same problems also apply for the floor and ceiling. Therefore, the contact conditions between the old structure and the new inside insulation layer typically are far from ideal and it is possible to have air leakage cracks both at the vertical and horizontal interfaces of the old and new construction layers.

The additional interior insulation decreases the temperature level of the old wall during the heating period. The temperature differences between the inside air and the interface of the old and new parts of the structure may cause natural air convection. When there is air leakage at the joints of the additional insulation layer, the indoor air flows to the upper part of the wall, down by the interface (and also through the new insulation layer), cools down while in contact with the structure, and flows back to the inside air space through the joint with the floor. Convection brings moisture into the structure, and, depending on the temperature field at the interface and the humidity of the indoor air, hygroscopic moisture accumulation may occur in the material layers or even water vapor condensation.

The objective of this study was to analyze the moisture performance of timber-framed wall structures with added interior insulation. The analysis was made both experimentally and numerically. The experimental results also were used in verification of the numerical simulation model.

Numerical simulation was done to study the hygrothermal performance of structures during a one-year period using the hourly averaged values of real weather data. The natural convection airflow rate varied according to the temperature variations. The indoor air humid-

Tuomo Ojanen and **Carey Simonson** are with VTT Building Technology, Espoo, Finland.

ity conditions were set assuming constant moisture production that gave varying values for relative humidity. Two thicknesses of the inside insulation were studied.

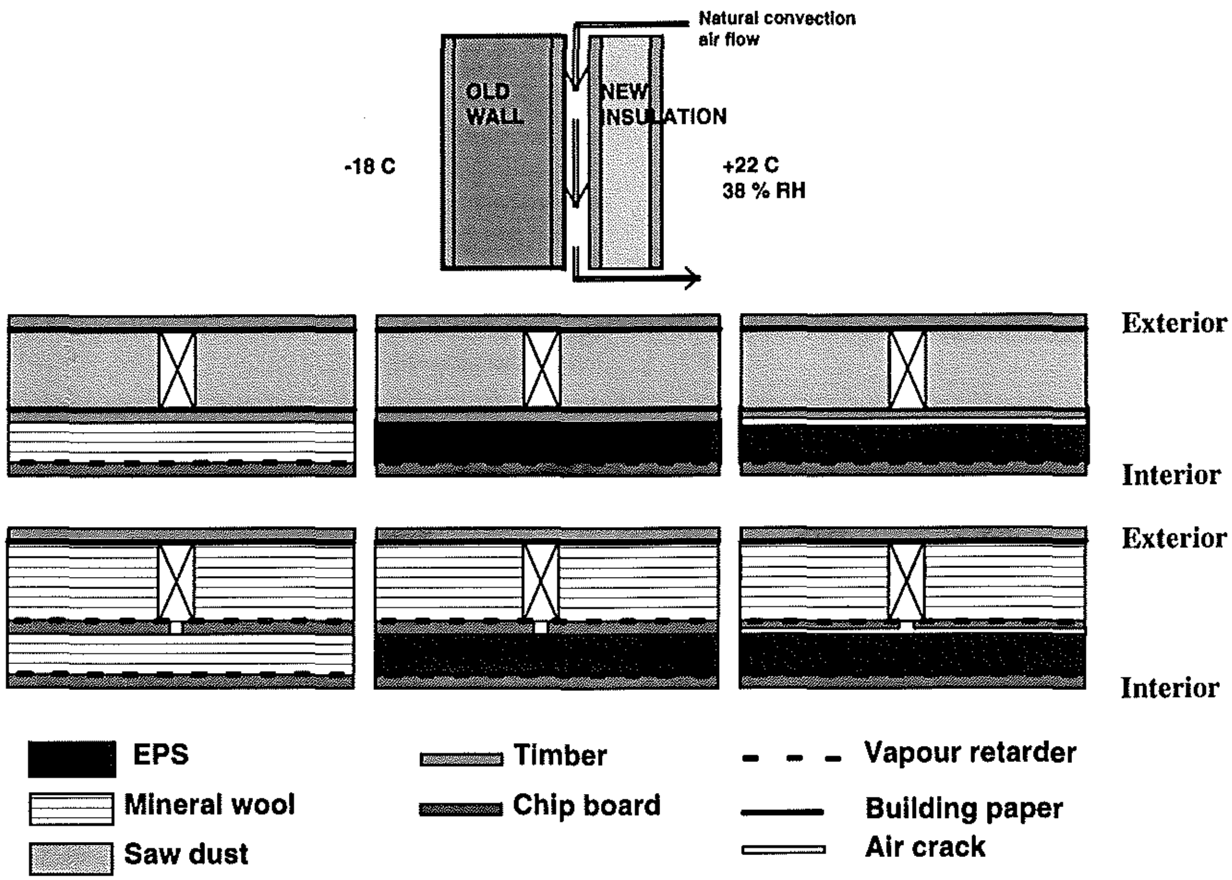
In both experiments and numerical simulation the building envelope was assumed to be airtight so that there was no air infiltration or exfiltration. The temperature difference caused natural air convection of the indoor air only along the leakage routes between the old structure and new insulation layer.

EXPERIMENTS

These laboratory experiments were done to study moisture accumulation in structures with additional inside insulation under constant temperature and moisture load conditions. The conditions used in the experiments were extreme when compared to typical real outdoor and indoor climatic data during the winter in Finland. The objective was to study the effect of natural air convection on moisture accumulation and to produce data for model validation.

Structure and Boundary Conditions

In these laboratory experiments the moisture accumulation within additionally insulated walls was measured during a 50-day period. Two different wall structures that needed additional insulation were studied. These structures, referred to later as "old," had a 100-mm wood framing insulated with either sawdust or mineral wool. The new 50-mm-thick inside insulation layer was made of mineral wool or expanded polystyrene. There were two kinds of contact conditions between the old structure and the new insulation layer: the new insulation was mounted so that an air crack was intentionally left at the interfaces or the layers were in contact with each other.



Wall	Old Insulation	Old Vapour Retarder	Old Wall, Inside Sheathing	New Insulation	Measured Air Flow Velocity m/s
A	Sawdust	No	Timber 22 mm	Min. wool	Not measurable
B	Sawdust	No	Timber 22 mm	EPS	Slight
C	Sawdust	No	Timber 22 mm	EPS	0.1
D	Min.wool	Yes	Chipboard 12 mm	Min. wool	0.1
E	Min.wool	Yes	Chipboard 12 mm	EPS	0.1
F	Min.wool	Yes	Chipboard 12 mm	EPS	0.15

Figure 1 *A schematic presentation of the airflow caused by natural convection and construction of the experimental walls shown from the top view; the measured airflow velocities are presented in the enclosed table.*

A schematic presentation of the construction and the material layers in the six experimental walls can be seen in Figure 1. The original (old) walls—A, B, and C—had sawdust insulation and walls D, E, and F had mineral wool insulation. All the walls were provided with a polyethylene vapor retarder located on the inner surface of the additional insulation. Walls D, E, and F already had an old vapor retarder located between the old insulation and the sheathing board. The cold-side sheathing for all the structures was 22-mm-thick timber siding. Moisture accumulation was expected to be the greatest at the thermal bridge caused by a 50-mm by 100-mm wood stud in the center of the old wall.

When insulating existing structures, there are almost always cracks in the construction due to irregularities in the existing wall. Each wall was assumed to have cracks between the new insulation layer and the old floor and roof structures. To observe the effects of nonideal vertical contact conditions, 2-mm to 3-mm cracks were left behind the additional insulation in walls C and F. Walls D, E, and F had an additional vertical air crack (5 mm by 12 mm) at the joint of the wood chipboard (interior sheathing) of the old construction. Natural air convection caused airflow mainly along these air leakage routes (cracks), affecting the hygrothermal performance of the wall. Walls A and B had no air cracks, only locally nonideal contact conditions between the old structure and the new insulation.

The temperature in the warm room during the 50-day-long test was +21.8°C ±1°C and the cold-room temperature was −18.2°C ±2°C except for five defrost cycles. The average relative humidity in the warm room was 37.5% ± 5%.

The temperature and moisture fields were measured. The moisture contents at the interface between the old and new walls were determined using small wooden samples. These samples were placed between the internal sheathing of the old wall and the additional insulation. They were in the center of the wall at the stud and distributed along the height of the wall. The moisture content of the test samples was determined using a weighing-and-drying procedure. The moisture content of the wooden samples at the beginning of the test was about 5% by weight.

Experimental Results

In all cases, the temperatures at the interface between the old and new construction at the top of the wall were about 7°C to 15°C higher than those at the bottom. This indicates that the warm air entered at the top of the wall and cooled while flowing down the structure along the air leakage route.

The airflow rates were not exactly known. The airflow velocities were estimated by using tracer smoke, and the approximate values are given in Figure 1. They are based on measuring the time that passed when the smoke flowed through the air leakage route in the structure. The airflow rates are not presented because the dimensions of the leakage routes were not fully defined.

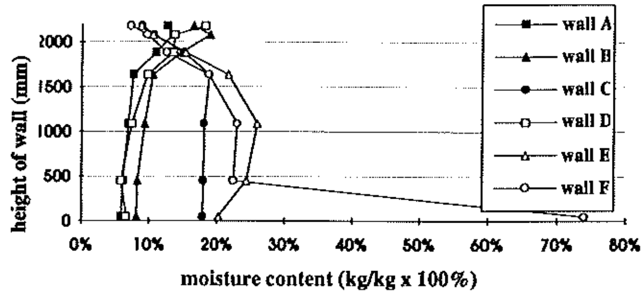


Figure 2 Moisture content of the wood samples for all the experimental walls at the end of the 50-day testing period.

The measured moisture contents of the wood samples at the end of the experiment are presented in Figure 2. Wall F had the highest moisture content level, as expected, because this wall also had the highest airflow velocity. The wood moisture content near the bottom of the wall after the 50-day period was 74% by weight. At the bottom of the wall, free water was visible and the nails in the structure had begun to rust. The second highest moisture content (26% by weight) was in the middle of wall E. Both of these walls had wood moisture contents that exceeded the critical moisture content for wood rot, 25% by weight (Viitanen and Ritschkoff 1991a). Wall C also had a relatively high moisture content (18%) throughout the bottom three-quarters of the wall. At this moisture content the wall is unlikely to rot but may experience biological growth in the form of mold. The critical conditions for mold growth are when the moisture content is 16% and the temperature exceeds +5°C (Viitanen and Ritschkoff 1991b). Walls B and D also had local moisture contents above 16%. Wall A had the lowest moisture content and appeared to be safe.

The moisture measurements presented in Figure 2 were obtained at the stud (thermal bridge) and, therefore, indicate the local maximum moisture contents. At the end of the test, the moisture content in all of the construction materials was measured by taking samples from these materials and drying them. The average moisture content of the wood stud was in the range of 9% to 12% and that of the old inside sheathing board was 5% to 12% by weight. Despite the moderate average levels of moisture content, the high local values indicate risks caused by moisture.

According to the experimental results, it is possible that the local moisture contents at the interface between the old and new constructions exceed critical values for wood rot. This can happen if the workmanship leads to convection air cracks on the order of 2 mm to 3 mm in the construction and if there is a long, cold winter. Those walls that had vapor retarder in the old construction (D, E, and F) had typically higher local moisture contents at the interface between the old and new construction than walls having old hygroscopic sawdust insulation without vapor retarder.

Although these extreme conditions showed moisture accumulation, the yearly moisture performance with varying temperature and humidity conditions needs further analysis. Also, the effect of the indoor air humidity on moisture accumulation should be studied separately.

MODEL USED IN SIMULATIONS

A computer program was used for the calculations. This program was developed at a research center in Finland (Ojanen et al. 1989), and has been used in the analysis of several different studies concerning heat, air, and moisture transfer in structures (Ojanen and Kohonen 1989, 1995; Ojanen and Kumaran 1992). This model can solve the transient heat, air, and moisture transfer in two-dimensional multilayer building structures. An ordinary finite-difference method is used in the numerical solution. Heat is transferred by conduction and convection, and moisture by diffusion and convection. The airflow can be caused by natural or forced convection through porous materials or cracks. The material properties that are needed in simulations are dry density, thermal capacity, thermal conductivity, air permeability, vapor conductivity, and sorption isotherms. Transport properties can be functions of temperature and moisture content. Weather files can include hourly values of ambient temperature and relative humidity, solar radiation intensities, and wind velocity and direction.

MODEL VERIFICATION

The simulation model was first used to predict the temperature and moisture content fields of the experimental cases. In this simulation the airflow rates were set to have a constant value corresponding to the approximate values that could be derived from the measured airflow velocities and crack dimensions. After this validation of the model, numerical simulation was used to study moisture accumulation in structures with additional inside insulation under real weather conditions.

The verification was done by setting a constant airflow rate through the air leakage route between the old and new parts of the wall construction. After a 50-day simulation period, the temperature fields and moisture content distributions were compared to the measured ones. Two slightly different airflow patterns were used. In the first case (a), the airflow at the bottom of the structure had a steep 90-degree turn from vertical downward flow to horizontal flow back to the indoor air; in the other case (b), the air flowed vertically out from the structure. The comparison of the measured and calculated moisture content distributions for walls C, E, and F is presented in Figure 3.

When using the airflow rates solved with the measured airflow velocities and a 3-mm air crack, the calculated moisture content levels corresponded relatively well with the measured levels. The highest differences between the measured and calculated moisture distributions were detected in the bottom part of the structure. The liquid moisture flow along the interface in case F could not be analyzed numerically. Airflow pattern (a)

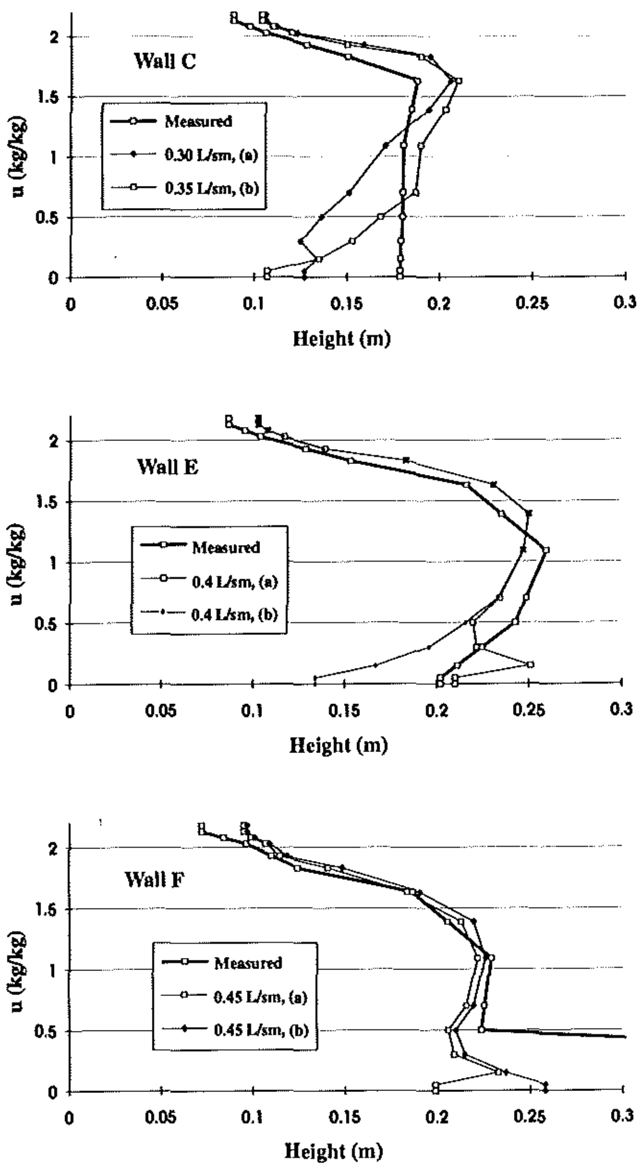


Figure 3 *Calculated and measured vertical moisture content distributions of the wooden samples at the interface of the old structure and the new insulation layer for cases C, E, and F after 50 days exposure to +22/−18°C conditions. Airflow pattern (a) corresponds to the experiments, and in pattern (b) the air flows in a vertical direction out from the structure.*

showed locally lower temperatures and higher moisture contents at the bottom of the structure. The distribution was not as smooth as what was measured, which may be due partly to the relatively coarse network used in the simulations. The airflow pattern was used later in the simulations because it corresponded to the real airflow route and, despite the local differences, the average results were closer to the measured results.

NUMERICAL SIMULATION USING REAL WEATHER DATA

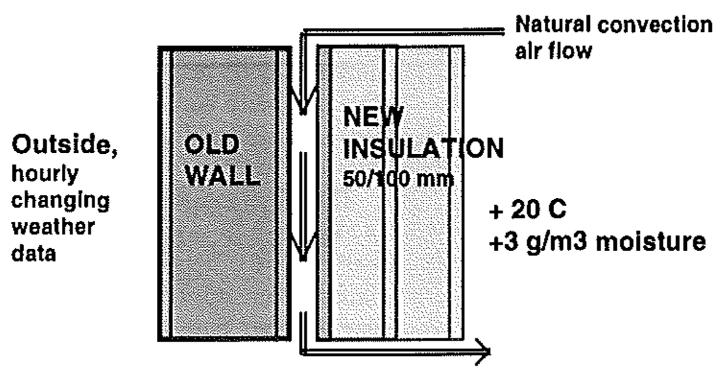
The objective of numerical simulation was to analyze the yearly moisture performance of structures with additional inside insulation under real, hourly changing weather data. Also, sensitivity analyses changing the airflow rate and the thermal resistance of the new insulation layer were done. The airflow rate between the structure and the inside air depends to some extent on the temperature difference. Numerical simulation makes it possible to simulate the hygrothermal performance of a structure during the changing airflow and boundary conditions.

Numerically Analyzed Cases

The analyzed wall structures were similar to those used in the experiments. The old structure was 100 mm thick and having either mineral wool or sawdust insulation. There were both old and new vapor retarders in the wall with old mineral wool insulation. Walls with old sawdust insulation had no vapor retarder. This assumption was made to study the worst-case scenario for the walls insulated with sawdust. The height of the structure was 2.5 m and the new insulation was either 50-mm-thick or 100-mm-thick mineral wool. The simulation was done for a two-dimensional cross section at the wood framing. The analyzed cases are presented in Figure 4, and the numerically solved results are shown in Figure 5

The airflow routes along the structural leaks were presented by adjusting the air permeability properties of the new insulation layer at the surface of the old structure. These air permeabilities were set so that the "basic" airflow rates calculated using temperatures +22/−18°C over the wall structure corresponded to the values determined in the experiments. The analysis was done using four different air leakage properties for the structures and, as a reference case, a totally impermeable inside surface also. In the four cases (Figure 4) the airflow rate varied in the range of 0.02 to 0.46 L/s·m, with a 40°C temperature difference between the indoor and outdoor air spaces.

The yearly average airflow rates are presented in the table in Figure 4. In the wall with old mineral wool insulation, the temperature of the interface was higher than that in the sawdust-insulated wall; therefore, the airflow rates were about 10% smaller.



Old Insulation	Vapor Barrier	Old Inside Sheathing Board	New Insulation	Airflow Case	Air flow Under $\Delta T = 40°C$ 50 mm New Insulation L/(s·m)	Yearly Average Air flow Rate 50 mm New Insulation L/(s·m)	Yearly Average Air flow Rate 100 mm New Insulation L/(s·m)
Sawdust	No	Timber siding (22mm)	Mineral wool 50 mm / 100 mm	1	0	0	0
				2	0.02	0.016	0.023
				3	0.10	0.036	0.045
				4	0.31	0.13	0.18
				5	0.46	0.19	0.24
Mineral wool	Old + New	Wood chipboard (12mm)	Mineral wool 50 mm / 100 mm	1	0	0	0
				2	0.02	0.014	0.022
				3	0.09	0.03	0.047
				4	0.27	0.11	0.16
				5	0.41	0.17	0.28

Figure 4 Numerically analyzed cases. Additional interior insulation thicknesses were 50 mm and 100 mm. The yearly average airflow rates for both insulation thicknesses are shown in the table.

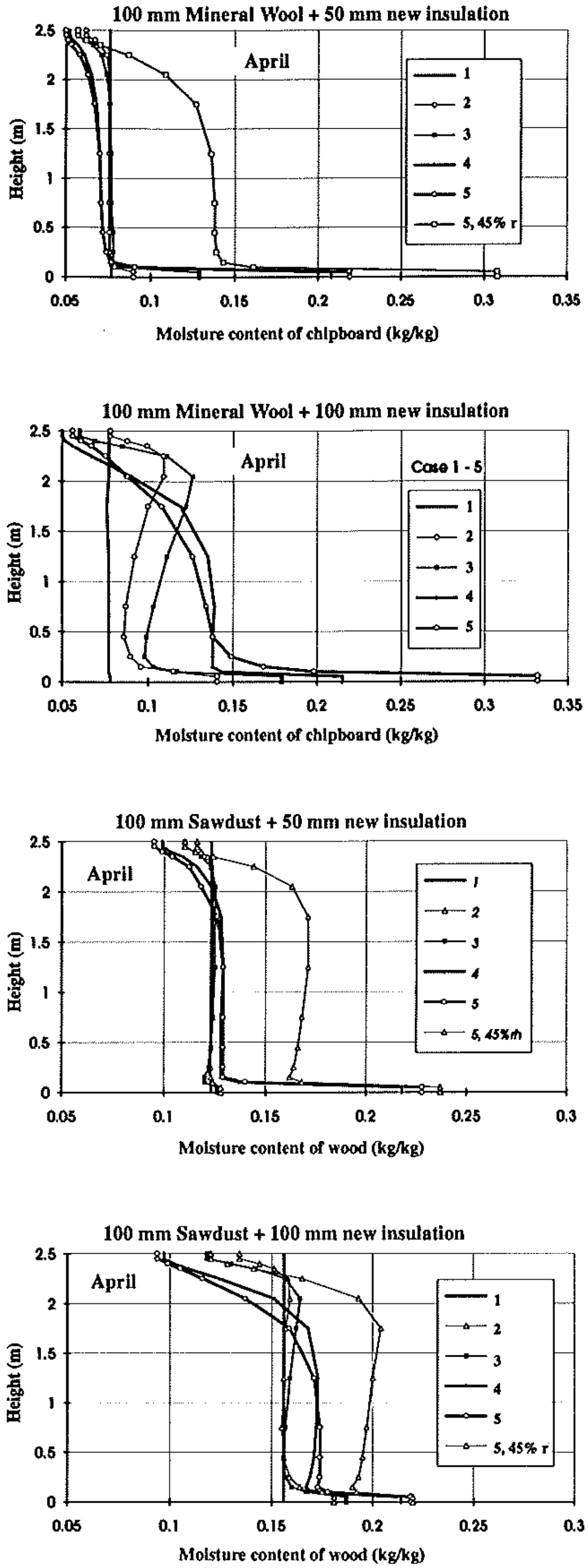


Figure 5 *Numerically solved vertical moisture content distributions of the old inside sheathing at the end of April.*

To take into account the three-dimensional heat flow by the wood framing and the old insulation, two-dimensional analyses of the temperature fields of horizontal cross sections were done under the pure heat conduction case. In this analysis the thermal conductivities were as follows: wood framing, 0.13 W/K·m; mineral wool, 0.035 W/K·m; and sawdust, 0.085 W/K·m. The solved temperatures of the interface of the wood framing and new insulation were used to define the apparent thermal conductivity for the wood framing layer in a vertical two-dimensional cross section. When using these thermal conductivities (0.074 W/K·m for the structure having old mineral wool insulation and 0.106 W/K·m for the sawdust structure) instead of the real material properties, the calculated temperatures corresponded better to the real three-dimensional case.

The indoor air temperature was set to have a constant value +20°C. When the outdoor air temperature exceeded this value, the indoor air temperature also was assumed to have this higher value because no air conditioning was assumed. In cold climates, the relative humidity of the indoor air may vary in a large range during the year. Therefore, constant moisture load is a more realistic assumption than a constant relative humidity value. The indoor air relative humidity was presented in two different ways. All the cases were solved using a 3-g/m^3 increase in the moisture content from that of the outdoor air. This assumption often is used to present the moisture production in residential houses. During cold winter periods, the 3-g/m^3 increase in the moisture content may correspond to only about 20% indoor air relative humidity. Some cases also were solved using a constant 45% relative humidity to study the sensitivity of the indoor air humidity to moisture accumulation.

The initial moisture content of the wooden boards was 0.12 kg/kg (old sawdust wall) and that of the wood chip boards was 0.075 kg/kg (old mineral wool wall). The simulations were done using the hourly averaged reference year weather data of Jyväskylä in central Finland. The simulation period was one year starting from the September 1. The walls were assumed to be north facing without any solar or diffusive radiation. The heat transfer coefficients were 15.0 and 7.5 W/K·m^2 for the outside and inside surfaces, respectively.

Simulation Results and Discussion

Moisture accumulation levels in these structures were found to be the highest at the end of the heating period. Figure 5 presents the numerically solved vertical moisture content distributions of the inside covering board at the end of April. Results are presented for the walls having old sawdust and mineral wool insulation, 50- or 100-mm new inside insulation, and five different air permeabilites (cases 1 through 5) for the air leakage flow route. All the cases, except one with new vapor retarder and no airflow, showed an increase in local moisture content values.

The numerically solved moisture content values were always less during the one-year simulation period than the values measured in the experiments with constant, extreme boundary conditions. Also, the varying boundary conditions and airflow rates changed the moisture distributions in the structures from those determined experimentally.

Effect of the Inside Insulation Thickness

A thicker (100 mm) interior insulation layer increased the natural convection flow in the structure when compared to the case with 50-mm-thick insulation. The increase of the airflow rate varied in the range from 25% to 60% (Figure 4). Due to increased convection and lower temperatures at the interface, the risks for moisture accumulation increased significantly with 100-mm-thick additional inside insulation when compared to the case with 50-mm-thick insulation

Effect of Indoor Air Relative Humidity

Figure 5 shows the results solved using constant 45% indoor air relative humidity with airflow case 5. In all the cases solved using interior 45% RH, the average moisture contents were significantly higher than those solved using the +3 g/m^3 assumption. When the indoor air has low humidity, it is possible that convection, at intervals, also dries out moisture from the structure during the heating period. The maximum local moisture contents in the sawdust-insulated walls were at the same levels in both cases, but with the old mineral wool structure the maximum value had increased from 0.22 kg/kg to 0.31 kg/kg. Moisture accumulation is sensitive to indoor air relative humidity. When the humidity increases, the moisture accumulation also increases highly. Low moisture capacity (old vapor retarder and mineral wool insulation) leads to higher local moisture accumulation than sawdust-insulated old walls.

Sensitivity to the Airflow Rate

Figure 6 presents the correlation between the maximum local moisture content of the inside covering board of the old part of the structure and the yearly average airflow rate between the structure and the indoor air. The yearly average airflow rates were about 50% to 60% smaller than those defined in +22/−18°C conditions (Figure 4).

The acceptable yearly average airflow rates can be defined from Figure 6 by setting values for the critical moisture contents. The lowest critical value for the moisture content of wood is 16% by weight when the possibility for mold growth is selected to be the criterion. In cases with 50-mm inside insulation, the maximum moisture content reached this value when the yearly average airflow rate exceeded 0.06 L/s·m. According to the experiments and their numerical analysis, the yearly average

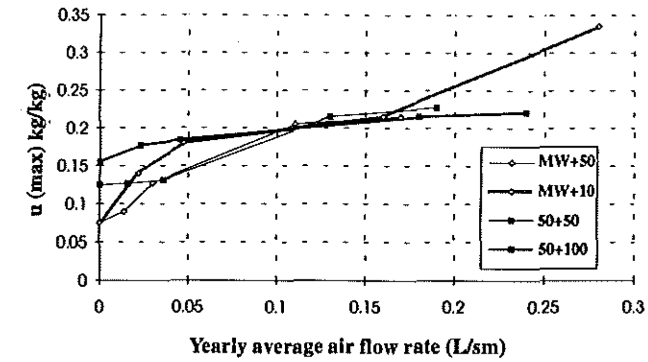


Figure 6 Correlation between the maximum local moisture content of the inside covering board of the old part of the structure and the yearly average airflow rate between the structure and the indoor air. MW corresponds to the case with mineral-wool-insulated old wall and SD is the case with sawdust-insulated old wall. Additional insulation thicknesses are 50 mm and 100 mm.

value, 0.06 L/s·m, corresponds to an airflow rate of approximately 0.12 to 0.15 L/s·m under constant +22/−18°C temperature conditions. In the experiments, an airflow rate of approximately 0.30 L/s·m was reached in all the experimental walls that had uniform vertical air cracks at the interface of the old structure and new insulation—either an air crack set intentionally during installation or those caused by the vertical joints of the old sheathing boards.

In the analysis, the old sawdust wall had no vapor retarder. New vapor retarder would decrease the diffusive moisture load. In this case, the convective moisture load is dominant and vapor retarder would only have a marginal effect on the correlation between maximum moisture content and the airflow rates. The conclusion is that any continuous vertical air crack may cause risks for high moisture accumulation due to natural air convection.

In a case with 100-mm-thick inside insulation without vapor retarder, the pure diffusive moisture transport caused 0.15 kg/kg maximum local moisture content. Therefore, there should always be a new vapor retarder when using such thick additional inside insulation layers.

The critical moisture content for the wall with 100-mm new insulation and with vapor retarder was reached with the yearly average airflow rate of about 0.03 L/s·m. This sets high requirements for the airtightness of the inside interfaces of the wall. In practice, the contact conditions between the old and new structures should be as ideal as possible and there should be no air cracks contributing to air convection along the interfaces. Even natural convection through a porous mineral wool layer with no vertical air cracks may cause extremely high airflow rates. This means that airflow through the horizontal joints of the additional insulation and the old structure should be prevented by sealing the joints.

CONCLUSIONS

Natural air convection can transport moisture from indoor air into a structure with additional inside insulation if the joints between the new insulation and the old structure are not sealed. Typical workmanship leads to air cracks, even on the order of 2 mm to 3 mm, that contribute to the airflow. If the structure and climatic conditions allow natural convection, it is possible that moisture contents at the interface between the old and new construction can get high enough to cause mold growth or even wood rot.

Convection and moisture accumulation depend on the structure and climatic conditions. In the Finnish climate, the safe upper limit for the yearly average airflow rate for a structure with 50 mm additional inside insulation is 0.06 L/s·m. According to the experiments, cracks on the order of 2 mm to 3 mm and even the cracks between the joints of the old sheathing boards may cause airflow rates of about 0.3 to 0.45 L/s·m when the temperature difference between the indoor and outdoor air is 40°C. Numerical simulation showed that these peak airflow rates correspond to yearly averages of about 0.16 to 0.19 L/s·m, greatly exceeding the given limit value of 0.06 L/s·m.

Vapor retarder in the old wall increases the risks for high local moisture contents, while hygroscopic insulation without old vapor retarder decreases these risks.

A structure that has 100-mm old sawdust insulation can be insulated from inside with 50-mm-thick new insulation, even without a vapor retarder, if the air convection through the joints can be kept at a level that corresponds to natural convection through the insulation material only.

For a wall with 100-mm-thick additional insulation, the critical limit value for the yearly average airflow rate is as low as 0.03 L/s·m. This value can be reached even without any cracks at the vertical interface. Natural air convection through the horizontal joints and the new mineral wool insulation may cause high convective moisture transport into the structure. Any wall having 100 mm additional inside insulation should have a new vapor retarder and contact conditions between the old wall and new insulation that are as ideal as possible. The horizontal joints should especially be sealed to prevent airflow into the structure.

The presented results are valid for relatively cold weather conditions only, typical for northern European and most Canadian locations. The dependence on indoor climatic conditions also is strong; separate analyses should be done for cases that are different from those presented.

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