COMPUTER SIMULATION OF MOISTURE TRANSPORT IN WALLS OF RESIDENCES

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ABSTRACT

Well insulated walls of residences experience temperature depression in their outer layers during cold weather, causing moisture to condense on the surfaces. A predictive model capable of identifying the conditions that potentially lead to condensation or high moisture levels has been developed. The model utilized includes both moisture storage and distribution effects by utilizing the general form of the thermal energy and moisture conservation equations for each layer of a wall of typical residential construction, utilizing materials such as wood siding, insulation, and gypsum board. A finite difference numerical solution produces the transient temperature and moisture profiles for each material. The model predicts that the wood layers offer most of the storage capacity for moisture, exhibiting large delays between changes in the external conditions and response of the moisture content. When walls are exposed to various outdoor climates, the wall moisture content is greater for mild and moist climates than for cold and dry climates. Simulation of an air leak in the wall, such as that found around an electrical outlet, show that the wood moisture in the region adjacent to the leak is substantially greater than with no air leak.

INTRODUCTION

The trend toward the construction of more energy efficient buildings in recent years has increased the concern about the presence of moisture in wall cavities. The addition of wall insulation lowers the temperature of those material layers external to the insulation during cold winter conditions. As moisture from within the house migrates outward, either by diffusion or leakage convection, it will condense on any surface whose temperature is below the dew point. If moisture were to accumulate at these sites, subsequent mold or wood decay could potentially occur.

Methods were developed to predict the occurrence of moisture condensation within walls based on steady state moisture diffusion theory (ASHRAE 1985). However, under conditions whereby these models predicted moisture to accumulate, it was not observed in field studies (Tsongas 1979, Tsongas 1985). The consensus seems to be that under such conditions, even though condensation may occur, it either does not accumulate at high enough levels to induce problems, or it evaporates during the warmer, drier summer months.

These findings point out the deficiency of a steady state model to usefully predict transient phenomenon such as the wetting and drying of wall materials. Transient models have subsequently emerged and are currently in various stages of development (Cunningham 1983, Kohenen 1984, Spolek et al. 1985, Thomas and Burch 1990). These models, with adequately defined transport and material properties, would be capable of testing a wide range of constructions and exterior conditions in a relatively short time. The primary difficulty to date is measurement of the transport properties for these materials.

The purpose of this paper is to describe the development of one of those transient models, the numerical methods employed, and present some of the predictions when subjected to actual weather data. While the critical need for accurate transport property data has not been circumvented here, the model relies on well established properties. The findings point out that structural effects are as important as the property data.

MODEL

The wall of a typical house in America consists of layers of materials (such as sheathing, siding, gypsum board, and insulation) which are hygroscopic to some degree. Each layer has the potential for conducting and storing thermal energy, and for diffusing and storing moisture.

Heat and mass transport are driven by gradients in the temperature and moisture concentration, respectively, plus convection due to bulk flow when it is significant. Following arguments presented elsewhere (Spolek et al. 1985, Oosterhout and Spolek 1988), convection through construction materials is negligible, so the governing equations for heat and mass transport can be written as

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{1}$$

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial x^2} \tag{2}$$

where α and D are the effective thermal and moisture diffusivities, respectively, for each material layer. Constant values for diffusion coefficients were used for the first approximation, although it was recognized that both coefficients are actually dependent on both moisture content and temperature.

The innermost (indoor side) and outermost (outdoor side) layers were subjected to convective boundary conditions. The boundary condition for heat transfer is:

$$h\ (T_\infty - T_{surf}) + \dot{m}\ h_{fg} = -\ K\ \left.\frac{\partial T}{\partial x}\right]_{surf} \qquad (3)$$

The second term of this equation accounts for the latent heat of vaporization as moisture evaporates or condenses on the surface. This term arises only at the convective surfaces because the moisture is assume to be effectively bound throughout the structural materials. Since adsorption and desorption were assumed to occur only at these surfaces, the surface mass flux term was represented as:

$$\dot{m} = \rho\ D\ \left.\frac{\partial M}{\partial x}\right]_{surf} \qquad (4)$$

The convective mass transfer boundary condition was written in terms of the single dependent variable M as:

$$h_m\ (P_{wv,\infty} - P_{wv,surf}) = -\ \rho\ D\ \left.\frac{\partial M}{\partial x}\right]_{surf} \qquad (5)$$

The sorption isotherm was used to relate the moisture content at the surface to the water vapor partial pressure at the surface (via the relative humidity). The convective mass transfer coefficient was derived from the convective heat transfer coefficient by using the Lewis analogy.

At the interface between the layers, a diffusive boundary condition was assumed. For heat transfer, this relationship is straightforward since temperature is a continuous variable. However, a discontinuity in moisture content exists at the interface because of the definition of M, which was the ratio of the moisture density to the material's dry density. The abrupt density change between, say, wood and fiber glass causes a discontinuity in M. By assuming that the moisture content at each interface was in equilibrium with the water vapor pressure as predicted by the sorption isotherm, then the moisture content discontinuity could be handled. This assumption was key to allow the use of a single dependent variable, namely moisture content, to be used for the mass continuity equation. While this variable may not be the most convenient, it is the one that is traditionally used in the measurement of effective diffusion coefficients.

A fully implicit finite difference numerical method was used to solve the governing equations. The program was written in the Pascal programming language and employed the Crout Reduction Algorithm to solve the tridiagonal matrices. The computer program read data from an external file to incorporate a variety of materials and their geometric and thermophysical properties. The finite difference solution used a fixed time step of one hour, and was typically run to represent one year of exposure. A variable spatial increment utilized seven computational nodes per material layer.

The wall that was modeled for this preliminary study was a simple 3-layer wall as illustrated in Figure 1. The base wall configuration had a 2 cm. wood layer on the outside, a 9 cm. layer of fiber glass insulation, and a 1 cm. layer of gypsum board on the inside. The inside of the wall was exposed to constant conditions of 22°C and 50% relative humidity. The outside of the wall was exposed to hourly temperature and relative humidity data representing the Typical Meteorological Year for Portland, Oregon, USA. The convective coefficients for each surface were those recommended by (ASHRAE 1985).

Additional simulations were performed on a wall with an assumed leak, also shown in Figure 1. The leak extended through the gypsum board and insulation layers, but not through the wood. This type of leak is representative of the pathway around an electrical outlet, for example. For purposes of simulation, the heat transfer was assumed to be unaffected by the leak, implying that the convection was negligible and that the temperature distribution was the same as it would be for pure conduction. The moisture transfer, on the other hand, was assumed to be affected such that the leak imposed negligible resistance to the transfer of moisture. This combination of assumptions probably constituted the "worst case" conditions to investigate whether the presence of leaks are important in wall moisture transfer.

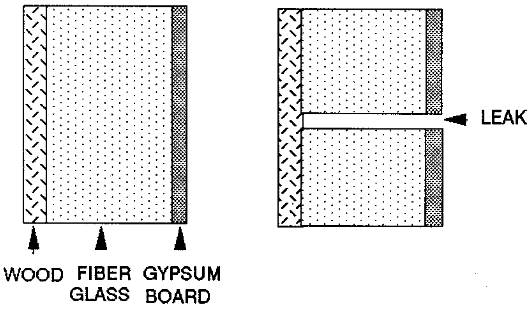

Figure 1. Model of a layered wall with and without a leak.

RESULTS

The computer simulation predicted the moisture and temperature distribution through each material for each hour for the entire year. As reported previously (Spolek et al. 1985, Oosterhout and Spolek 1988), the characteristic time constant for the redistribution of thermal energy is on the order of one day while that for moisture distribution is on the order of 50 days. To some extent, therefore, the energy and mass transfer equations are decoupled by the phenomena.

The wood layer of the wall is capable of storing significantly greater moisture than the insulation or gypsum board layers. The effective diffusion coefficient for wood is also much lower than those of the other materials. Hence, the wood layer acts as a moisture capacitor. This result is illustrated in Figure 2. For this case, the wood was assumed to be uniformly at 22% moisture while the fiberglass was at 4% and the gypsum board was at 0%. The starting time was January 1 of the Typical Meteorological Year. The wood began to dry out immediately and had experienced significant drying during the first 11 weeks, with the maximum moisture at about 17% in the center of the wood layer. During the remainder of the year, the wood's moisture fluctuated somewhat in response to the changing ambient conditions. The surface of the wood in direct contact with the outdoor climate showed wide swings in moisture content, varying from 7% to 26%. But the variation was reduced just slightly inside the wood, ranging from only 12% to 20%. At the inner wood surface, the fluctuation of moisture was negligible and remained at essentially 10% throughout the year. This moisture prediction reflects the constant indoor conditions and the high relative permeability of the other materials; actual walls would likely exhibit greater fluctuation due to indoor variations. The insulation and gypsum board layers showed little change in moisture throughout the year.

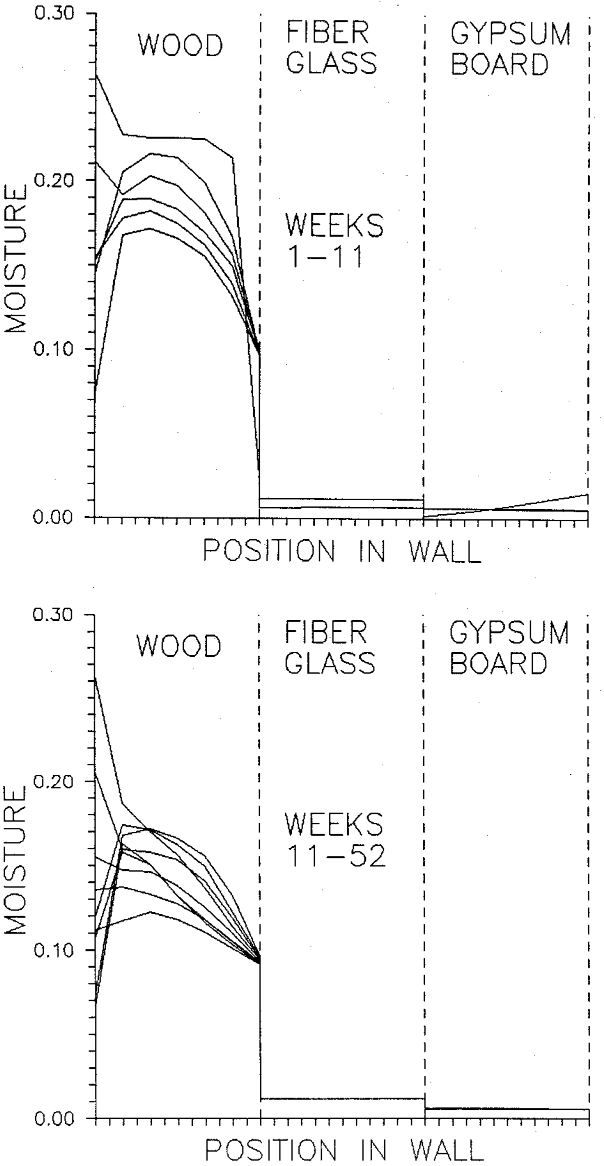

Figure 2. Moisture distribution in a layered wall for one year.

Since the "most interesting" prediction of wall moisture occurred at the outer surface in response to the ambient conditions, the same wall with the same indoor conditions was exposed to the simulated weather for a different climate. It has been speculated that a cold climate will reduce the temperature of the wood which would enhance condensation and increase wood moisture. The climate for Spokane, Washington, USA is much colder than that of Portland, Oregon. But the air's humidity is also lower, and that effect causes the wood's moisture to remain lower throughout the year, as illustrated in Figure 3. The outer surface of the wood in Spokane is predicted to be considerably drier during the summer and remain somewhat drier in the cold winter months. This finding would suggest that homes built in warm, moist climates would be more susceptible to moisture problems than those built in cold, dry climates. Field investigations have corroborated this conclusion (Tsongas, 1987).

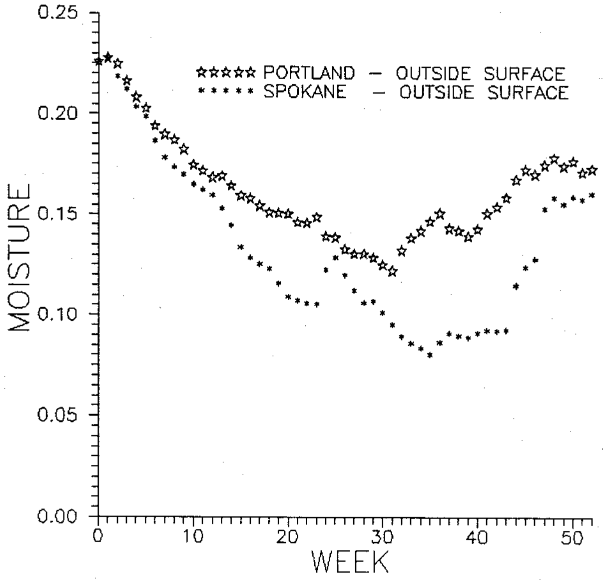

Figure 3. Wood Moisture for Cold and Warm Climates.

The predictions of the moisture history adjacent to a leak was quite interesting. Again, the leak was defined as illustrated in Figure 1: original heat transfer with enhanced mass transfer. As the warm, moist air from the living space was brought in direct contact with the inner surface of the wood, which became very cold in winter, the water vapor condensed on the wood and locally increased its moisture content. See Figure 4. Local values were predicted to reach 50% - 60% in the neighborhood of the leak. These results are very similar to results obtained from measurements of wood moisture taken in actual houses during winter. Moisture in wood siding directly behind electrical outlets and other leak sites were measured in the range 40%-60% (Tsongas 1987). Measurements removed from the leaks were typically in the range of 15%-20%; the model prediction was 10% for those sites. The model also predicts that the outside wood surface would be affected by the leak, but to a much lesser extent. As seen in Figure 4, the outer wood's surface for the two cases (leak and no leak) are quite similar. This implies that moisture problems may be hidden from outside inspection.

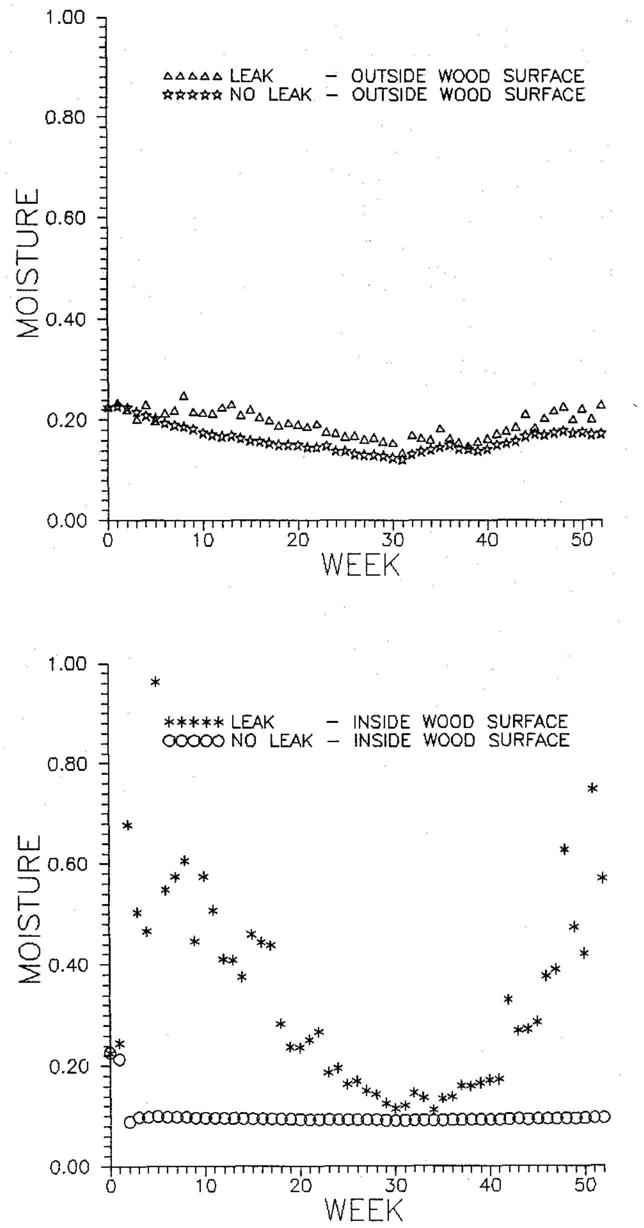

Figure 4. Effect of a Simulated Leak on Wood Moisture.

The logical extension of this finding for walls with leaks is that greater insulation layers would further depress the temperature of the wood and cause even greater moisture buildup. The same leak was modeled with 27 cm of fiber glass insulation (R-33) rather than the original thickness of 9 cm (R-11). As seen in Figure 5, the wood moisture was predicted to be greater but not substantially so.

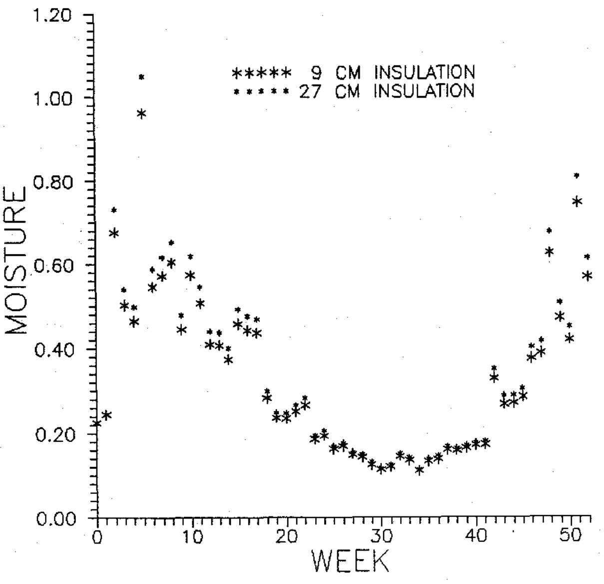

Figure 5. Effect of Increased Insulation.

It must be noted that many simplifying assumptions have been employed to develop this simulation model. Some of these must next be examined to evaluate their impact on the results. Other wall configurations must also be tested, including such effects as paint and vapor retarders. But the model does appear to predict the correct trends observed by field studies, demonstrating the potential value of transient models.

CONCLUSIONS

A computer simulation of the transient heat and moisture transfer in a the layers of a typical residential wall was developed. The model was applied to a variety of ambient conditions and structural configurations. It was found that only the wood contributes significantly to moisture storage. Normally, the moisture of the wood surface exposed to the outdoor conditions would fluctuate with the weather, but the remainder of the wood remained constant. The wood moisture was higher for a warm, moist climate when compared to a cold, dry climate over the duration of a year. A leak through the inner layers, such as that developed around electrical outlets, allows wood moisture to dramatically increase during cold winter months. Although it dries during the summer, it may remain high enough on average to allow degradation of the wood, even though it may not show visibly on the outer wall surface.

REFERENCES

ASHRAE. 1985. "Vapor Migration by Diffusion." *ASHRAE Handbook - Fundamentals*, ASHRAE, Inc., 21.3-21.7.

TSONGAS, G.A. 1979. "A Field Study of Moisture Damage in Walls Insulated Without a Vapor Barrier." *ASHRAE/DOE-ORNL Conference Proccedings, Thermal Performance of the Exterior Envelopes of Buildings*, 801-815.

TSONGAS, G.A. 1985. "The Spokane Wall Insulation Project: A Field Study of Moisture Damage in Walls Insulated Without a Vapor Barrier." *ASHRAE/DOE/BTECC Proceedings, Thermal Performance of the Exterior Envelopes of Buildings III*, 556-569.

CUNNINGHAM, M.J. 1983. "A New Analytical Approach to the Long Term Bahavior of Moisture Concentration in Building Cavities - I. Non-Condensing Cavity." *Building and Environment*, V. 18(3): 117-124.

KOHENEN, R. 1984. "Transient Analysis of the Thermal and Moisture Physical Behavior of Building Contructions." *Building and Environment*, V. 19(1): 1-11.

SPOLEK, G.A., Oosterhout, G.R., and Apfel, R.I. 1985. "Transient Heat and Mass Transfer in Walls." *ASHRAE/DOE/BTECC Proceedings, Thermal Performance of the Exterior Envelopes of Buildings III*, 634-662.

THOMAS, W.C. and BURCH, D.M. 1990. "Experimental Validation of a Mathematical Model for Predicting Water Vapor Sorption at Interior Building Surfaces." *ASHRAE Transactions*, V. 96, Pt.1.

OOSTERHOUT, G.O. and Spolek, G.A. 1988. "Transient Heat and Mass Transfer in Layered Walls." *Proceedings of Symposium on Heat Transfer in Insulation Systems*, ASME.

TSONGAS, G.A. 1987. "A Field Study of Moisture in the Exterior Walls of New Northwest Energy-Efficient Homes." *Proceedings of the ASTM Conference on Insulation Materials, Testing and Applications* STP1030, (Bal Harbour, FL, Dec. 6-10).

NOMENCLATURE

D	effective mass diffusivity, m^2/s
h	thermal convection coefficient, W/m^2-K
h_m	effective mass convection coefficient, s/m
h_{fg}	enthalpy of phase change (fluid to vapor), J/kg
K	thermal conductivity, W/m-K
$\dot{m}$	moisture mass flux, kg/m^{2}s
M	moisture content, mass of water/mass of material
P_{wv}	water vapor pressure, Pa
T	temperature, Kelvin
t	time, s
x	spatial variable, m
α	effective thermal diffusivity, m^{2}2/s
ρ	density, kg/m^3
∞	ambient conditions

BIOGRAPHY

Graig Spolek is Professor and Chair of the Mechanical Engineering Department of Portland State University in Portland, Oregon, USA. His educational background includes B.S. and M.S. degrees from University of Washington, and the Ph.D. degree from Washington State University, all in mechanical engineering. At Portland State, Spolek teaches courses in thermodynamics, heat transfer, HVAC, and experimental design. His research areas include both numerical simulation and experimental testing of heat and moisture transport in building systems. He is an active member of ASHRAE and the energy conservation community.