Due to ASHRAE's late receipt of this paper, its contents (which includes text, figures, and equations) were not edited according to ASHRAE Special Publications standards.

Investigation of Warm Weather Condensation in New and Insulated Basement Walls

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ABSTRACT

The Institute for Research in Construction has undertaken an investigation into the cause and potential solutions to the problem of basement wall condensation during the first spring and summer after construction. The research involved the implementation of a computer model to test a hypothesis on the mechanisms involved and to evaluate strategies that would defeat the condensation mechanism. The detailed computer simulation tool used was the FSEC model, originally developed by the Florida Solar Energy Center. The model was adapted by IRC to investigate 2-dimensional, dynamic heat and moisture flow in the basement wall, floor slab and surrounding ground.

The investigation involved close collaboration with a provincial builders association to determine typical construction practice and to characterize case studies of basement condensation problems.

The simulation results suggest that conditions exist for moisture to accumulate and condense in freshly poured and finished basement walls during warm periods of the year, by way of a vapour-diffusion mechanism which would redistribute the moisture from the concrete to the insulated cavity of the finished wall. As well, building the insulated cavity without building paper between the concrete and the insulation makes this wall particularly susceptible to the vapour diffusion mechanism. Other means to control the mechanism were explored. The results suggest that there may be a better way to assemble a basement wall and operate the house to minimize the risk of this type of condensation.

INTRODUCTION

The sporadic problem of condensation and pooling of water during the first spring and summer of freshly poured basement walls insulated on the inside has plagued builders and new homeowners in many parts of Canada for at least a decade. A detailed field investigation had previously been undertaken to document basement condensation problems in new Winnipeg houses (Unies 1987). At the time, it had been postulated that a number of factors could make new basements prone to condensation and pooling of water:

- cold weather construction followed by warm summer weather conditions
- full height insulation placed on the interior of the concrete wall
- higher than ambient relative humidity of basement air, combined with concrete surface temperatures at the dew point of that air
- poor air barrier detailing, which would allow moist basement air to circulate in the insulated cavity
- fresh concrete, which would have little or no capacity to absorb and store excess moisture from the air

The following construction practices had been proposed as possible solutions:

- insulate the exterior of the concrete instead of the interior, or
- for interior insulation:
  - leave the wall open for up to a year before insulating
  - take measures to lower interior humidity levels
  - properly seal the air barrier to prevent convective flows from transporting moist air into the cavity

In spite of these proposed solutions, rashes of problems continued to be reported - many in central Canada this year. It is felt that the solutions offered have not been fully proven and have been viewed as too restrictive, expensive or impractical by builders. A broader range of effective and inexpensive solutions were needed to address the problem. Review of the documented field work (Unies 1987) and of reported cases of basement condensation has suggested a new explanation for the mechanisms involved, first formulated in 1990 (Swinton 1990).

Hypothesis

It is hypothesized that a two-dimensional vapour diffusion mechanism is contributing strongly to the basement condensation problem in the first spring and summer. The mechanism is believed to redistribute excess water in the concrete through the interior insulation to the vapour barrier surface and to the bottom of the concrete wall, as a result of inward and downward temperature gradients in the saturated wall in spring and summer. Water would accumulate and eventually drip to the floor, manifesting itself as pools of water. This mechanism

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would take place in an unimpeded fashion, in the absence of any form of vapour diffusion retarder at the surface of the concrete.

The Institute for Research in Construction has undertaken an investigation into the cause and potential solutions to the problem of basement wall condensation during the first spring and summer after construction. The following reports the results of our computer modelling investigation of this problem.

OBJECTIVE

The objective is to confirm that the mechanism of vapour diffusion induced by inward and downward temperature gradients in the wall in late spring and summer is a contributing factor in the warm-weather condensation problem and to suggest what strategies might be taken to defeat the mechanism.

APPROACH

Two-dimensional combined heat transfer and vapour diffusion in a basement wall was modelled to assess whether or not condensation could be predicted under the conditions reported in case studies. As well, the model was used to evaluate strategies devised to defeat the vapour diffusion process.

The investigation consisted of several tasks including data collection, computer model selection, adaptation of the model and implementation for analysis. These tasks are described below.

Data Collection

The data collection consisted of a review of current construction practice and of case studies of reported summer condensation problems reported for basements.

Current Construction Practice

Typical construction practices involved in problem cases were established by a representative of a provincial builder association who was a member of the project team (Gagné 1993). Characteristics of the poured concrete walls were provided by an industry representative (Hajduk 1993).

Typical Canadian basement construction consists of a full depth basement with 200 mm (8") concrete wall, insulated on the interior to either 600 mm (2 ft) below grade (part height) or to the floor slab (full height). The concrete typically has a water-cement ratio of 0.6 at pouring. This quickly drops to 0.5 after pouring due to spillage and drainage through the form work, and eventually to 0.3 to 0.4 when fully cured. The difference between the water-cement ratio of 0.5 after pouring and ratio when fully cured is attributed to evaporative drying - which is believed to be one of the sources of the moisture. The density of the finished and cured concrete ranges between 2000-2400 kg/m3.

Basement walls are typically insulated on the interior, either with rigid insulation or with an assembly consisting of batt insulation placed in the cavity formed by 38 x 64 mm studs (2x3 studs) @ 400 mm (16") on center. The studs are installed out from the wall to accommodate the thicker batt. A dampproofing coating is applied onto the exterior face of the concrete, from grade down. Building paper can be used on the interior face of the concrete from grade to slab, as required by code, but can be omitted when wood framing is not used or when the framing members are not in direct contact with the concrete. Polyethylene is used as the vapour barrier applied to the inner face of the studs and batts. The interior walls are finished with gypsum board.

Typical Scheduling

Building the poured concrete basement wall typically features the following schedule:

- forms are removed within 24 hours after pouring of the concrete
- exterior dampproofing and backfilling can occur within 5 days of pouring
- interior framing, insulating and finishing can occur within 45 days

Pouring the concrete wall in March or April can result in the basement wall being closed-in and finished in May or June.

Example Cases Reported

Of the several cases reported directly to investigators, three did not fit the usual description of the problem and are worth noting:

1. Severe condensation problems were reported in summer for a "roll bag" installation, where the insulation was applied to only 600 mm (2 ft) below grade. There was no building paper, nor polyethylene separating the batt and the fresh concrete. The most seriously affected wall was south facing, which had no shading from the sun. On one warm sunny day, the surface temperature of the concrete wall exposed to the sun was measured to be 27°C, whereas the inner surface of the concrete was at 20°C. Residual moisture which had condensed on the polyethylene over the summer was observed as late as mid-September. Before this case was recorded, it had been previously thought that the full height application of insulation and vapour barrier was somehow a cause of the problem.
2. New homeowners that had already gone through an episode of basement condensation with a previous house, instructed the builder not to close-in the basement wall in their new house for 3 months. This was done, but two weeks after closing-in the wall in July, extensive condensation occurred on the polyethylene. Apparently, relying on drying time alone may not be enough to avoid the problem.
3. In another case, severe condensation problems were reported in spring shortly after the basement wall was retrofitted with full height insulation, installed on a 30 year old concrete block basement wall. The concrete blocks had previously been sealed and painted with a vapour barrier paint. The source of the moisture was

postulated to be the green lumber used, although this could not be verified. Once released to the cavities, the moisture apparently condensed on all cool, low permeability surfaces and pooled at the bottom. This case highlights that although the excess moisture in curing concrete is suspected to be the main source of moisture in most cases, the moisture in green lumber is also a likely contributing source.

The information gathered was used to define the configuration and simulation conditions needed to model the phenomenon. A general conclusion that emerged from the data collection was that a diversity of conditions were involved in the summer condensation problems, and singling out or ruling out contributing factors could not be done by simply reviewing case studies. Consequently, the modelling would have to be as detailed as possible to as many of the contributing factors as possible.

Model Selection and Adaptation

A number of candidate models were reviewed for the task, including:

- the TCCC2D - Transient Coupled Convection and Conduction 2-Dimensional model (Ojanen 1992)
- a detailed and more comprehensive model currently under development at the National Research Council of Canada - LATENITE, (Karagiozis 1993)
- a generalized solver of multi-dimensional, heat, air and moisture flow problems developed at the Florida Solar Energy Center - FSEC. (Kerestecioglu 1992)

After detailed review of all model capabilities, it was determined that the FSEC model was most suited for adaptation to our research project, primarily on the basis of its flexibility.

Model Attributes

The FSEC model is a 3-dimensional general purpose software package specifically designed to simulate complex building science problems. The program offers unique features, including an ability to solve user-defined systems of governing equations. Up to 250 coupled differential equations and their boundary conditions may be either selected from libraries or defined by the user. The use of finite elements allows the model to accommodate very complex structures and geometries, which is a very important feature in the basement condensation project.

Moisture Transport and Storage

The moisture transport modules use the evaporation and condensation theory, assuming:

- moisture travels due to water vapour density gradients; i.e. due to differences in the partial pressure of water vapour
- local thermodynamic equilibrium exists
- the total pressure is constant, and
- the solid matrix is rigid.

In a control volume (element), the net amount of water increase in the control volume is equal to the amount of water vapour brought to the control volume by diffusion minus the amount of liquid water accumulated. Since thermodynamic equilibrium prevails at all times, the amount of liquid water at any given point is calculated through the equilibrium sorption isotherm using the temperature and water vapour density at that point.

Heat Transport and Storage

Additionally, the net amount of energy stored in the same control volume is equal to the amount of heat conducted plus the energy liberated during the phase change.

Air Flow (not modelled)

For the purposes of this first simulation of this phenomenon, the effects of air flow and circulation through the basement wall system were not modeled. It was felt that, for the sake of simplifying an already complex model, and the fact that air flow was not needed to test the vapour-diffusion hypothesis, air flow could be left for future investigation, should the vapour-diffusion explanation prove not to be the apparent mode of vapour transport.

The FSEC model has been applied to several moisture problems and good agreement has been found with analytical solutions (Kerestecioglu 1988, 1990).

Implementation

The FSEC model was implemented to represent a typical basement wall in two dimensions, as depicted in Figure 1. Several of the elements were varied in the analysis, such as the depth of the water table (4.28 and 8.28 meters), and the basement temperature (15 & 25°C). As well some of the moisture controlling elements were removed to see the effect; e.g., the building paper and the polyethylene.

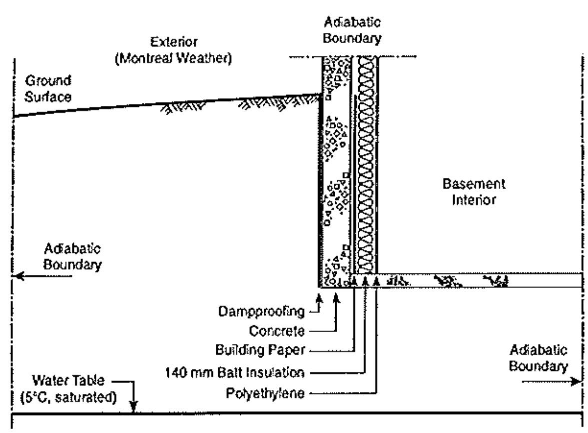

Figure 1 Representation of the Heat and Moisture Flow System of the Basement.

Several simplifications were made to the model:

- wood studs were not included in the model, as this would require a three dimensional analysis. Based on some of the anecdotal evidence cited above, the initial moisture content of the wood studs could have a major impact on the moisture balance in the cavity. The impact of the initial moisture content of the studs has been left for future investigation. Nevertheless, the roll-bag example, which featured no wood studs, is evidence that the summer condensation problem can occur without wood studs.

- the concrete of the basement wall and slab was assumed to be uniformly just below saturation when the wall is closed-in and when the simulation begins. Current limitations in modelling prevent us from initiating the simulation with super-saturated concrete.

The boundaries of the heat and moisture flow system are also shown in Figure 1. The key boundaries are the ground surface and the top portion of the concrete wall which are exposed to weather. For this study, hour-by-hour weather for Montreal was used(AESC). The weather data included ambient air temperature, relative humidity, and incident solar radiation. Physical properties of materials used in the simulation (IEA 1991) are recorded in Table 1, along with material thicknesses.

Table 1 Properties of Materials and Thicknesses Used in the Simulation

Material	Effective Vapour Diffusivity (m^2/s @ 30% RH)	Material Thickness (mm)
dampproofing	1.0 E-13	2
concrete	1.2 E-6	203
building paper	1.0 E-9	1
glass fibre insulations	1.82 E-5	140
vapour barrier	1.0 E-12	1
soil	1.25 E-6	—

Description of the Simulations

The cases listed in Table 2 were performed with varying conditions to explore the sensitivity of condensation potential to different basement wall characteristics and boundary conditions. The cases and conditions are listed in Table 2. Five simulations were run for approximately 1200 simulated hours - about 50 days to study emerging trends. For these runs, it was assumed that the basement wall was closed-in on May 1. Two simulations, A1 & A2, involved a full year. For these runs, the walls were closed-in earlier, on April 6, but with the same initial conditions. For each case, all temperatures and moisture contents were calculated by the model.

Table 2 Cases and Conditions Investigated Through Simulation

Case	Start date / Hours of Simulation	Basement Temp.	Basement RH (approx.)	Depth of Water Table	South Solar Gains?	Membrane Between Insul. & Con.	Vapour Barrier
A1	April 6 / 8760	15°C	60%	4.28	yes	none	none
A2	April 6 / 8760	15°C	60%	4.28	yes	bldg pap.	bldg pap.
B1	May 1 /1200	15°C	60%	4.28	no	bldg pap.	poly
B2	May 1 / 1200	15°C	60%	4.28	yes	bldg pap.	poly
B3	May 1 / 1060	15°C	60%	4.28	yes	none	poly
B4	May 1 / 1200	25°C	33%*	4.28	yes	none	poly
B5	May 1 / 1200	15°C	60%	4.28	yes	bldg pap.	bldg pap.
B6	May 1 / 1200	21°C	41%*	4.28	yes	none	poly

* represents the same absolute humidity (and vapour pressure) as 60% @ 15°C

RESULTS AND ANALYSIS

Temperature Response

Figure 2 shows the temperature profiles in a vertical plane within the insulation in the basement wall, next to the vapour barrier. The wall warms progressively through this period, responding to exterior weather patterns. The temperatures at the top part of the wall fluctuate due to weather, whereas the mid and bottom parts of the wall lag in temperature due to the mass effect of the earth. Since the temperature of the basement air is cooler at 15°C, temperature gradients in the insulation are, for the most part, inward to the basement and downward to the bottom of the insulation - as hypothesized.

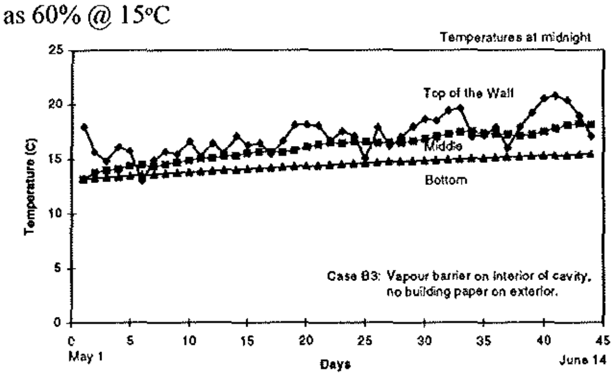

Figure 2 *Simulated Temperature Response of the Insulated Basement Wall Cavity.*

Confirmation of the Hypothesis with the Model

Case B3 includes characteristics and conditions that are hypothesized to lead to condensation problems in the wall: the above-grade concrete is exposed to warm spring-time conditions, including strong solar radiation on sunny days; as well, the basement wall has no building paper separating the concrete and insulation from grade down and includes the polyethylene vapour barrier on the inside surface of the insulation. Figure 3 shows the predicted relative humidity of the air at a vertical plane in the insulation, 35 mm inside the polyethylene. As can be seen, the relative humidity in the insulation fluctuates widely at the top of the insulation, momentarily reaching 100% towards the end of the simulation. The RH at mid-height and bottom of the insulation tends more steadily towards 100% throughout the simulation period. The point of steady condensation (RH > 100%) is reached at mid-height after 1000 hours from the start date of May 1. The bottom part of the wall appears to be heading towards the saturated condition as well. This indicates that the conditions exist in this wall for moisture to accumulate into condensation at about the second week in June.

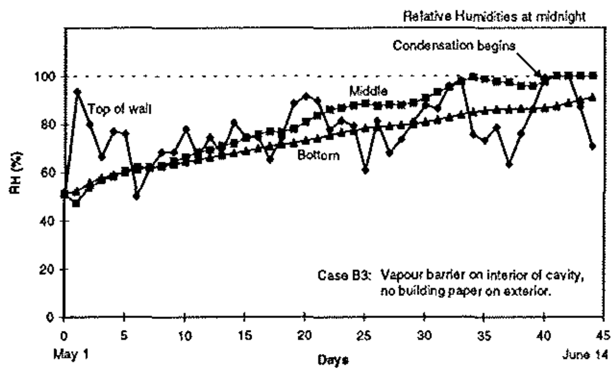

Figure 3 Simulated Relative Humidity Response of the Insulated Basement Walls Cavity.

The periods of rapid rise in relative humidity of the air in the insulation correspond to periods where the above-grade portion of the basement wall is exposed to warming influences from outdoors. It should be noted that RH is only an indirect indication of the amount of moisture in the cavity air. However, in these simulations, the RH of the cavity air increases with warmer temperatures, suggesting that the absolute moisture increases considerably as well. (If the absolute humidity of the cavity air had remained constant, the RH would have dropped with higher temperatures).

These modelling results suggest that the hypothesis is correct: vapour diffusion, driven by inward and downward temperature gradients in the basement wall, can cause condensation in the insulation for Montreal weather conditions that prevail as early as the second week in June, given a close-in date of May 1.

Sensitivity to Design and Operating Conditions

Four other simulations were undertaken to evaluate the potential for moisture accumulation in the basement wall cavity for different wall constructions and different boundary conditions, over the same time period. These variations in constructions and conditions are listed in the above table for the series of simulations labeled "B".

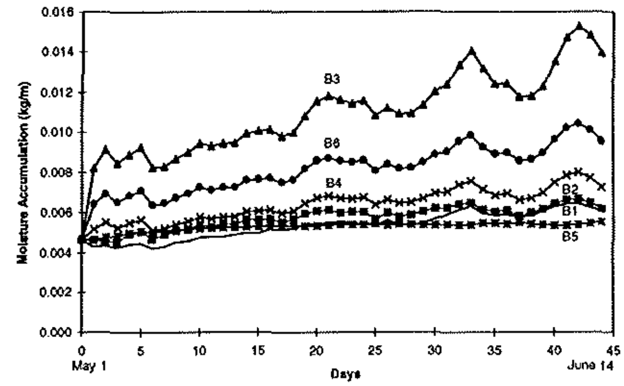

Figure 4 Simulated Accumulation of Moisture in the Insulated Basement Wall Cavity.

The total amount of moisture in the insulation was plotted over this period, as shown in Figure 4. The case used to test the hypothesis (case B3 with solar gains on the above-grade wall, no building paper) shows a much more rapid increase in the total amount of moisture in the insulation over this period than any other case tested. All other cases have at least one feature that works against the mechanism:

Case	Strategy
B1	- addition of building paper, shaded from solar gains
B2	- addition of building paper
B4	- setting the basement temperature to 25°C
B5	- addition of building paper and substituting building paper for polyethylene
B6	- setting the basement temperature to 21°C

Relative to case B3, the other strategies appear to have a similar effect; however, there are differences. Although the strategy of keeping elevated basement temperatures (B4 & B6) results in a reduced moisture load compared to case B3, these cases appears to be more susceptible to warmer exterior temperatures than the other measures. This measure works by keeping the insulation and polyethylene above the dewpoint of the cavity air, which is not as easily achieved in warmer weather. Cases B1 and B2, both with building paper added, perform even better throughout the simulation period, suggesting that vapour diffusion control could be the most effective solution to the problem. Shading the exposed wall from solar radiation (B1) appears to have some advantage over leaving it exposed to solar gains; however, as can be seen with the merging graphs, the advantage is short-lived. This suggests that over prolonged periods of warm weather, differences between shaded and unshaded walls may not be significant.

Balancing the permeability of the two sides of the cavity with building paper (B5) results in a steadier moisture content in the insulation that eventually falls below those resulting from other strategies. This suggests that a very low permeability vapour barrier may not be the ideal material for moisture protection in basement walls.

Full Year Simulations

Full year simulations were performed to further investigate the effect of reducing the vapour resistance of the vapour barrier and eliminating it. The simulation period was extended to a full year to investigate whether the emerging solutions for summer condensation would increase the probability of winter condensation. Case A1 was run to investigate the effect of removing the air barrier as well as the building paper promotes fast spring and summer drying; however, as would be expected, the outer layers of insulation at the top of the wall do become saturated in the next winter. The results of this case also suggests that delaying the placement of the vapour barrier to late summer or early fall could help address both condensation seasons.

Case A2, which is a full year run of case B5 (building paper on both sides), was performed to assess whether the greater overall permeability of this wall system, which assists the cavity in the summer, does not result in saturated conditions in the outer part of the insulation in the next winter. The results, shown in Figure 5 indicated that the relative humidity in the cavity fluctuates within a relatively narrow band with changing season and does not reach saturation in winter. This configuration thus shows some promise for more detailed investigation.

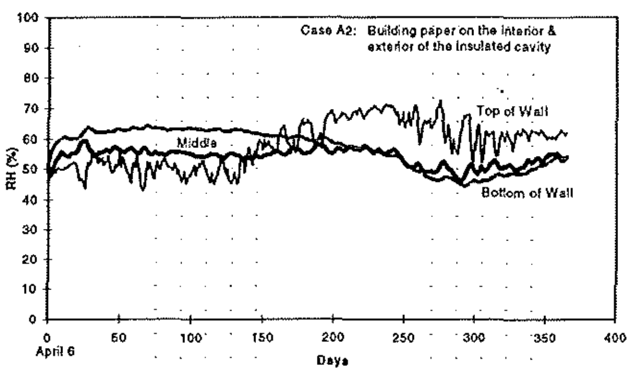

Figure 5 Simulated Relative Humidity in the Basement Wall Cavity over One Year.

DISCUSSION

The following principle emerges from this investigation:

In an enclosed cavity that has saturated materials in contact with the cavity air; i.e. in contact with the air in the insulation, the dew point of the cavity air tends to be the same as the temperature of the warmest saturated material. If the saturated material (the concrete) reaches 20°C for example, then the dew point of the air in that cavity becomes 20°C as the air comes into vapour equilibrium with the material. Any other impermeable member exposed to the cavity that is less than 20°C; e.g., the polyethylene in contact with 15 °C basement air, or the lower part of the concrete wall in contact with the cold ground, will be susceptible to accumulate moisture, as long as the saturated material remains saturated at the higher temperature.

The presence of the building paper below grade apparently offers enough resistance to vapour flow into the cavity that the air in the cavity doesn't have a chance to come into vapour equilibrium with the warmer, saturated concrete. The concrete dries out and/or the temperature gradients in the wall change with the season before the cavity vapour pressure has a chance to fully respond. As well, the fact that the building paper is apparently effective even without being placed above grade suggests that the above-grade concrete dries outward during cooler weather and is not contributing greatly to the cavity moisture load. Rapid drying of the above-grade portion of the concrete was observed in the simulations.

Finally, with building paper placed instead of the polyethylene, the cavity air is able to rid itself of additional moisture during the warm periods, reaching some equilibrium that is well below saturation.

CONCLUSIONS

An investigation of the mechanism and potential means of controlling summer condensation in new, insulated basement walls was undertaken using a combination of case studies and computer simulation. The case studies indicated that there are probably several potential sources of moisture and varied conditions that lead to the summer condensation problem. In particular, the documented occurrence of this problem with part-height basement insulation suggests that the full height interior placement of insulation is not the cause in itself.

The simulation results confirm that the postulated vapour diffusion mechanism driven by inward and downward temperature gradients in the wall is a probable contributing factor to the problem; however, this does not rule out other factors. As well, the simulation identified that basement wall assemblies built without the building paper between the concrete and insulation are particularly susceptible to moisture accumulation in the cavity during warm weather. This is supported by the fact that the majority of previously documented cases and the part-height case documented in this paper shared that common characteristic.

Various strategies including interior temperature control and the use of different materials with different permeabilities were investigated. The results suggest that a better balance in permeability of materials on either side of the insulated cavity could offer better protection from this type of condensation. Improvements in assembly design should be investigated more systematically, both through modelling and testing, before a recommendation can be made.

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