THE ROLE OF HYGROTHERMAL MODELING IN PRACTICAL BUILDING DESIGN: CASE STUDIES

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ABSTRACT

Several detailed hygrothermal building enclosure simulation tools are now widely available to the practitioner. This paper will demonstrate the challenges and benefits of using three such tools – THERM, HEAT2D and WUFI – for the design of several different enclosure systems. The case studies include a several wall design choices for a high-rise apartment building. Results from these case studies will be presented and their role in the decision-making process discussed. The paper will deal with issues such as material property and weather data sources, selecting interior temperature and moisture conditions, and the role of 2-D and 3-D effects on results of lower dimension. Recommendations for successful and useful hygrothermal modelling will be made.

INTRODUCTION

Design, including the design of building enclosures, is an iterative process. Ideally, design proceeds with the identification of a problem, the choice of a proposed solution, and the assessment of the suitability of the proposed solution. The hygrothermal design of building enclosures has rarely followed this process, primarily because assessing the suitability of a particular design for a particular use was not practical.

Coupled heat and moisture transport through building enclosures can now be calculated for each hour of several years worth of exposure in a few minutes using currently available one-dimensional hygrothermal computer models. This capability can be very useful for the quantitative and qualitative analysis of building enclosure performance. Heat air and moisture analysis (HAM) is, of course, only one small part of the enclosure design process, but it is an emerging, important, and poorly understood part deserving more attention.

This paper examines the role of computerised HAM models in the building enclosure design process. Case studies are used as a vehicle for demonstrating the challenges faced in using such models and the benefits that they can provide. The moisture physics and the numerical methods used in these models are important topics but are not covered in this paper, as the designer using a HAM model assumes that these challenges have been solved.

For design purposes the role of a model is that of a tool in support of decision-making, and they are often used to distinguish between several competing alternatives, not to quantify absolute performance. In some cases, the alternatives being compared are different enclosure assemblies, (e.g., a wall system with or without a vapour barrier, a cathedral ceiling with or without ventilation). In other cases a known successful enclosure design is analysed to assess the influence of different boundary conditions (e.g., the effect of moving a wall system used in Denver to Vancouver, or converting a roof system used for office space to one for a swimming pool). Since comparisons of performance are being examined (relative versus absolute results)., the accuracy of the model is not as critical as is sometimes thought.

MODELLING PROCESS

Different steps are needed if the modelling is used for different purposes (Straube 2001). The modelling process is shown in Figure 1. Each step is discussed below.

1. The first step is the definition of the need. This implies that one identifies why modelling is required and how the results of a model will aid decision making.

2. The *modelling* problem can now be defined in greater detail together with the client. A number of

questions are typically posed, such as: which enclosure cross-sections are to be modelled, which orientation and interior conditions are important, is performance due to rain, air leakage, or energy consumption the focus, how many resources (human, capital, and information) are available.

3. The model is then "built". A major choice at this stage is which model to use. This choice essentially involves the selection of how the physics are to be modelled and how the numerical solution will be generated. For example, choosing a model such as Therm implies that steady-state 2-D heat flow is all that is required. Selecting MOIST means that driving rain absorption cannot be accounted for and hence is not important to the results. Using WUFI limits the analysis of air leakage condensation.

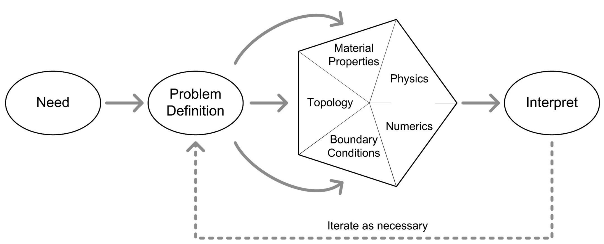

Figure 1: The Modelling Process

The major inputs required from a design user are the topology, the material properties, and the boundary conditions.

The topology includes the geometry and arrangement of materials within the enclosure, including a choice of the number of dimensions. For example, when modelling a framed system, the designer must decide whether to conduct a full 2-D model analysis, or a combination of a 1-D analysis through the stud bay and a 1-D analysis through the framing elements. For many framed systems the critical temperature and moisture conditions occur in the stud bay, since this area is more highly insulated and vapour permeable. Another common choice is whether to conduct an analysis of a vertical or horizontal 2-D section.

Detailed material property information is not widely available for many building materials. Despite this serious limitation, there are many situations where only readily-available material properties need to be defined. By varying the material properties and rerunning the simulation several times, the sensitivity of the results to the variation in material properties can quickly help determine which material properties need to be known accurately and which can be approximated.

The moisture content of materials at the start of a simulation may be important. In most cases beginning the simulation with all materials at room temperature and 70% RH is reasonable. If one years results are desired, simulating for two years and ignoring the first years data is one means of reducing the impact of the initial conditions. To assess the ability of an assembly or material to dry, it is very useful to start a simulation with a specific material at a high moisture content. For example, the ability of an assembly to dry incidental rain penetration (a measure of the assemblies moisture tolerance) can be assessed by adding the moisture from a hypothetical leak (say 1 kg) to a hypothetical area (say 0.5 m^2). This could be done by increasing the moisture content of the sheathing (12.7 mm thick) by 1 kg/0.5 m^2/0.0127 = 157 kg/m^3 above the equilibrium moisture content at 70%RH.

The model is then run for a period of time (often several years) and the results output for interpretation. Most models provide plots of time versus temperature and moisture content or RH (or both) for each material layer. Some allow the user to define an arbitrary location of interest and outputs the hygrothermal state of the location at every time step. This data must be compared to performance thresholds and/or performance targets (i.e. interpretation).

For durability, the most common variables of interest are RH versus time, since the deterioration mechanisms of mould, rot, and corrosion are functions of temperature RH and time. The analyst can select one of the several mould indices that have been developed, most of which are based on RH and temperature (for example see Clarke et al, 1999).

CASE STUDY 1

The first case study involves the design review of a multi-storey residential tower planned for a city in the

Pacific Northwest. The client was interested in choosing the best wall system without expending unnecessary resources. The building had a reinforced concrete frame with light-gauge steel stud infill. The cladding was to be brickwork.

Four basic wall assemblies with several different variations were considered:

Wall A1: 90 mm (3.5") Brick veneer
25 mm (1") Airspace,
Tyvek or building paper,
13 mm (1/2") Dens-glas Gold,
150 (6") Steel Stud with R-19 Fiberglass batt,
Vapor barrier (VB),
13 mm (½") GWB, with two coats latex on primer

Wall A2 As Wall A1 but with VB removed and w/ vapor retarding primer paint (½ US perms).

Wall A3 As Wall A2 but with two coats latex on primer (3 US perms) in lieu of the vapor retarding primer.

Wall B: 90 mm (3.5") Brick veneer
25 mm (1") Airspace,
38 mm (1.5") extruded polystyrene insulation (XPS)
Tyvek
13 mm (1/2") Dens-glas Gold,
150 (6") Steel Stud with 90 mm R-11 Fiberglass batts,
13 mm (½") GWB, w/ vapor retarding primer paint
(permeance= ½ US perms)

Wall C: As Wall B, but with 2" of XPS, peel-and-stick, and no batt insulation but with two coats latex on primer (permeance = 3 US perms) in lieu of the vapor retarding primer.

Thermal Analysis

The thermal performance was studied using the THERM 2.1 two-dimensional steady-state heat flow model. Since a framed system is a 3-D system, the analysis was conducted in two steps. First, the wall was divided along a horizontal section through the wall at mid-height, including double-stud details at windows and doors. Then, a second analysis was conducted through a vertical section through the floor-slab (Figure 2). The U-value results were area weighted and used to calculate an overall effective U-value. Since the system has little thermal mass outside the thermal insulation, steady-state analysis was deemed sufficient for the purposes of comparison.

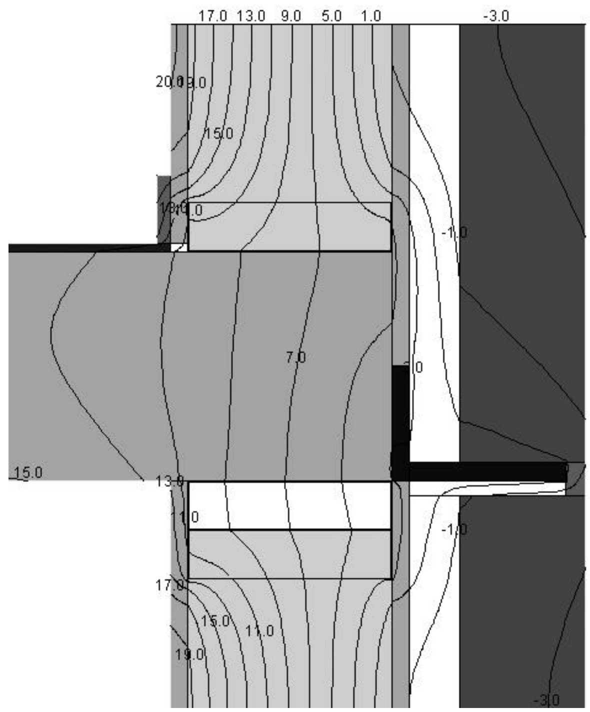

Figure 2: Isotherms through floor slab under –5 C exterior conditions (vertical section)

The results for the three wall types considered are shown in Table 1. Thermally, Wall A is at a clear disadvantage of wall A, whereas Walls B and C both exhibit better thermal performance. The analysis also showed that Wall A suffered from low interior surface temperatures at the slab, especially under the carpet. Several variations of topology were conducted to demonstrate that the results were relatively insensitive to batt R-value, top track nesting, etc.

Wall Type	Steel Stud Section	Floor Slab Section	Total Effective
Wall A	1.3	0.70	1.2
Wall B	2.6	2.2	2.5
Wall C	2.3	2.3	2.3

Table 1: Effective Thermal Resistance of Different Wall Systems (R_{SI})

Moisture Analysis

Two major questions was the need for a sheet polyethylene vapour barrier and insulating sheathing in the moderate climate. The thermal performance of the uninsulated steel stud system was also important.

The climate was first analysed, and using TMY2 files, hourly driving rain records were developed using techniques previously reported [Straube 2000]. Figure 3 shows the distribution of driving rain for the city. This distribution made it clear that the south-facing orientation was critical for rain absorption (and hence inward also vapour drives).

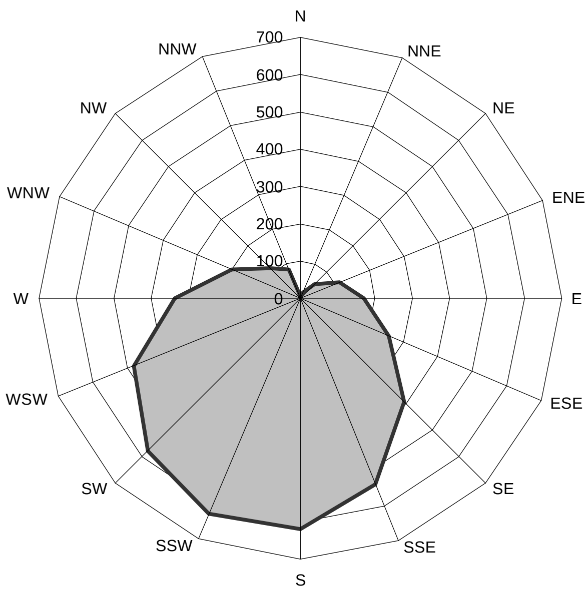

Figure 3: Driving Rain Distribution (mm/yr) for a vertical wall facing different directions

It was assumed that interior conditions varied from 20 Celsius and 40%RH in the middle of winter (January 15) to 24 Celsius / 60%RH in the middle of summer (July 15). It is important that these interior humidity levels be controlled by some means to achieve these targets for the analysis to be relevant. In this case, the building's mechanical design incorporated full-time ventilation with sufficient capacity to maintain a winter time RH at 40% or lower. Summer RH values in this non air-conditioned building would likely fluctuate about 60%RH, but the influence of summer RH levels on the results was small.

The 1-D model WUFI 3.2 Professional was used for the analysis. The choice of most of the material properties was not difficult and was based on the standard values in the WUFI database. The permeance of the interior finishing paint layers were based on published tests and previous testing conducted at the University of Waterloo. Through sensitivity analysis, it was determined that the sorption isotherm of both the brick and the Dens-Glas had an impact on the results. The silicone treatment of the gypsum core and the lack of paper facers were assumed to reduce the moisture storage capacity by adsorption, relative to the material data available for gypsum.

All of the simulations were conducted for 20 months, with the last 12 months being analyzed (it was demonstrated that longer simulations did not change the results).

Initial simulations showed the rainwater absorption of the brickwork was very important for Wall A. Hence, the design team decided that all of the walls would use a clear water-repellent treatment (a common practise in the Pacific Northwest). Previous unpublished water uptake test results for water absorption were used to approximate the liquid diffusivity of the surface layer of the brick using the approximation function provided in WUFI.

Figure 4 plots the resulting RH at both the poly and the Dens-Glas layers. It can be seen that the RH in the Dens-Gas reaches dangerously high levels during the rainy and cool winter period. In fact much of the winter the RH is above 90% at the Dens-Glas. As expected, the latex paint finished wall had a higher winter Dens-Glas RH than the wall with poly, although the difference was quite small. The ability of the painted wall A3 to dry quickly in the spring is evident from the results. Also clear is that the latex paint allowed inward vapour drives to the interior, thereby resulting in somewhat lower RH at the poly layer during the summer.

Figure 5 compares the performance of Wall B with that of Wall C. Although the RH of the Dens-Glas is near or slightly over 80%RH in Wall B, it remains at least 10%RH lower than any of the Wall A scenarios and keeps the RH at the poly to less than 70% for most of the year. For Wall C, the RH at both points is maintained between 50 and 60% all year.

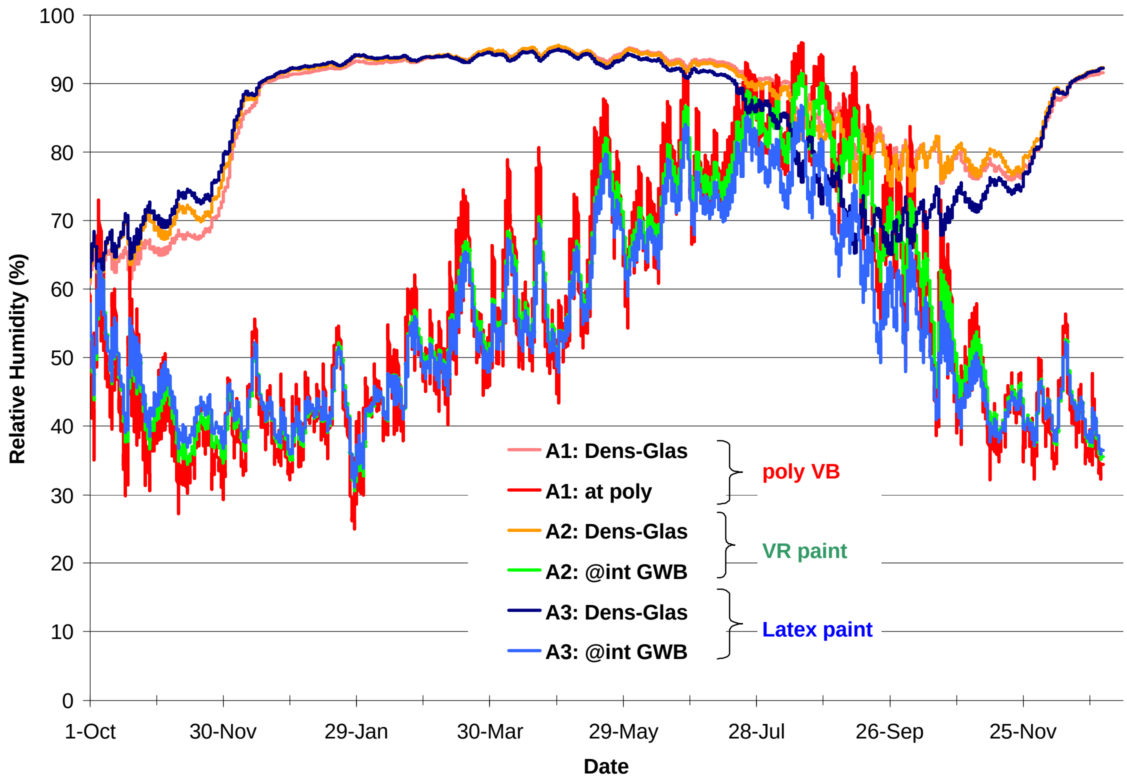

Figure 4: RH in Dens-Glas and at poly layer in Wall A

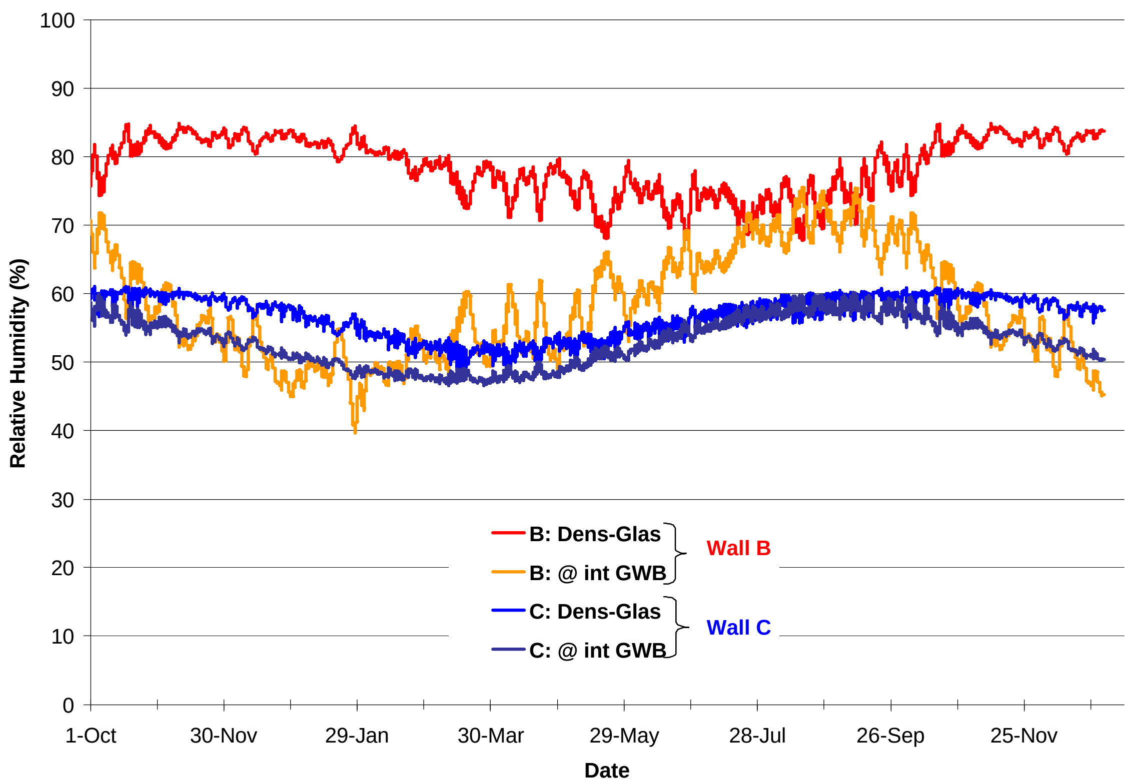

Figure 5: RH in Dens-Glas and at poly layer in Walls B and Wall C

Figure 6 presents a plot of the cumulative number of hours a material (or surface) exceeds a given RH over a one-year period. We have found this type of presentation a useful means of comparing moisture performance. It can be seen that the exterior sheathing of Wall A (Dens-Glas) is exposed to over 95% RH for a large proportion of the year. Wall A, at the poly, is also exposed to a significant number of hours of 80% RH, all of this time over 15 C. The Dens-Glas layer in Wall B spends many hours over 80% RH, but almost none over 84%. The temperature of this layer is also cold (between -5 and 5 C) for most of the time over 80%RH. All moisture sensitive layers in Wall C and the poly in Wall B spend no time above 80%RH.

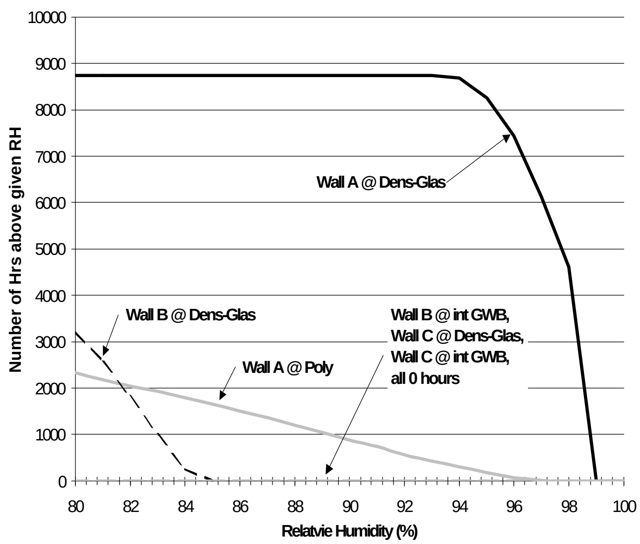

Figure 6: Plot of Cumulative Hours above 80%RH

The results were analysed using a conservative threshold of 80%RH and t>5 C for the onset of mould growth and corrosion. Wall A is clearly unacceptable by this performance standard. Wall A also has almost half the thermal resistance of the other two systems. Wall C is clearly safe. Wall B is marginal. Since the Dens-Glas has no paper to support mould growth and the RH at the studs would be slightly lower (because of thermal bridging), Wall B could be deemed safe, especially if some simple changes were made (such as ventilating the brick veneer, which reduces summer inward drives and increases winter drying slightly).

The simulations supported the construction team's choice of Wall C and eliminated Wall A from contention.

CASE STUDY 2

Radiantly heated house basement slabs are becoming quite popular in heating climates. Standard practise in slab construction is to avoid the placement of insulation below the slab since it is not deemed economically worthwhile.

A study was conducted of several different basement scenarios, with and without insulation below the slab, for a range of soil types (i.e., thermal conductivities).

The two-dimensional dynamic heat flow model, HEAT2D was chosen as the model. BASECALC, a widely available basement heat flow model, was not chosen because it does not allow for heated floor slabs, especially those that vary with time.

Three-dimensional effects could be subsequently accounted for by using the corner correction method [Beausoleil-Morrison 1995].

The first challenge was the choice of exterior environment. A calculation time step of 7 days was chosen for the boundary conditions since the thermal mass of the soil will damp variations of even longer time periods. The outdoor temperature was assumed to vary in a manner representative of a moderately cold climate. The peak summer temperature was fixed at 20 °C and the minimum winter average at –10 °C. The monthly average temperatures of Toronto and Calgary have been plotted alongside the simulated climate in Figure 7. The interior temperature also was assumed to vary sinusoidally, from a minimum of 20 °C on January 21st to a maximum of 24 °C on July 21st. The insulating effect of snow cover and solar radiation were not included, both because these are highly variable and because they are difficult to account for.

Parametric studies revealed that the thermal resistance of the slab finish had a significant impact on the heat loss through the system. The thermal resistance of a ¾” wood floor (approximately RSI 0.18) as the slab floor covering was used for all simulations. Wood flooring is a common finish over radiant slabs and its thermal resistance falls in the middle of the range of values for finishes. The impact of finishes such as carpet and surface films near corners have both been found to have a significant impact on the results (especially surface temperature and hence surface RH) in other simulations and should be carefully chosen.

The thermal conductivity of soil is an important material property for this study. This is a case in which a material property is both poorly defined (or variable) and important to the results. To account for this influence, a wide range of thermal conductivities (0.7, 1.5, and 2.3 W/mK) were included to conduct a parametric study.

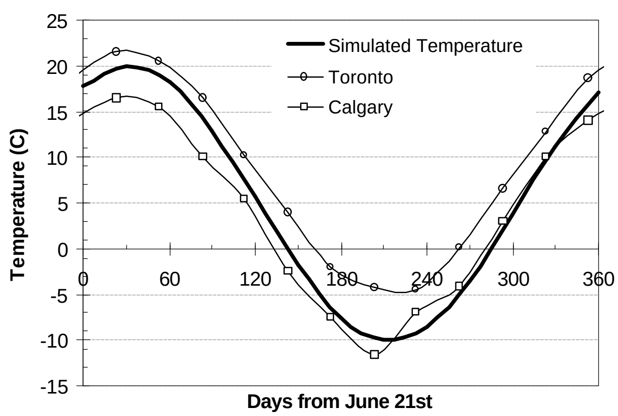

Figure 7: Simulated exterior Temperatures

It was assumed that the slab was heated from late October through to late March with a heat source strong enough to maintain a well-insulated house at comfortable temperatures. A peak weekly average heat flux of 40 W/m^2 on January 21 was chosen, and the flux decreased sinusoidally (much like the exterior temperature) during other times. HEAT2D allows the analyst to "measure" the heat flux across defined boundaries. This facility was necessary in this case, since the same amount of heating needed to be provided to the space above the floor regardless of the interior floor finish or sub-slab insulation. The total annual amount of heat energy delivered *to the house* interior in this study was maintained at about 130 kWh/m^2. Houses with poor insulation or excessive air leakage would require a higher heat flux and thus higher average slab temperature to maintain interior temperatures, and hence heat losses to the soil would also be higher.

Simulations were conducted for systems with and without under-slab insulation, with full height interior wall insulation of RSI2.1 (R12) and exterior insulation of RSI1.4 (R8).

It was found that the temperature and heat flow took 5 years to stabilise within 90% of the difference between the starting conditions (5 C) and the long-term values. This has implications for both actual performance (new houses will loose more energy) and for simulation (many years may be required until a system stabilises).

The results were plotted as temperature isolines and heat flow arrows (Figure 8). The total annual heat loss downward through the slab was summed over the heating season and tabulated.

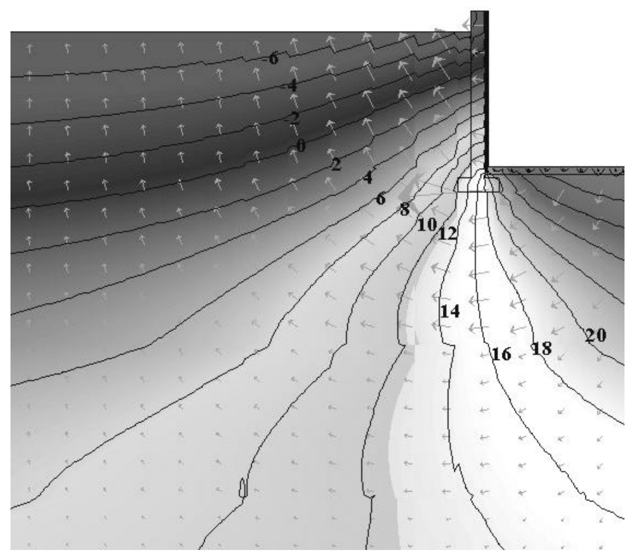

Figure 8: Isotherms and Heat Flux Plot for Uninsulated Slab in January

In general, heat losses through radiantly heated slabs were found to be over twice that of otherwise similar unheated slabs for the conditions considered. The application of RSI 1.4 (R8) of sub-slab insulation reduced peak heat loss through the slab by almost half, and the total energy by as much as 28 kWh/m^2/yr for conductive soil.

Table 2 presents some of the results for a full basement. Many more simulations were conducted to assess the influence of basement geometry, unheated slabs, soil conductivity and insulation levels, but the results are not the focus of this paper.

Soil Conductivity (W/mK)	Wall (RSI)	Slab (RSI)	Annual Energy Use (kWh)
2.3	1.41	1.41	-33.2
2.3	1.41	0.00	-61.5
2.3	2.11	1.41	-35.9
2.3	2.11	0.00	-63.7
1.5	1.41	1.41	-26.1
1.5	1.41	0.00	-42.7
1.5	2.11	1.41	-28.9
1.5	2.11	0.00	-44.8
0.7	1.41	1.41	-16.0
0.7	1.41	0.00	-22.7
0.7	2.11	1.41	-18.3
0.7	2.11	0.00	-25.1

Table 2: Simulation Results for Full Basements

CONCLUSIONS

Hygothermal computer models have reached a level of sophistication that allows them to be useful to building enclosure designers. In most cases, the absolute accuracy of models is not critical, since the models should be used to compare design choices.

The case studies presented above have attempted to show the process that might be followed in practical hygrothermal analysis. The challenges of choosing the correct boundary conditions, material properties and topology are clear. These difficulties can likely be overcome in time as more research is conducted and techniques and data published.

In the authors' opinion, a combination of field experience and an understanding of moisture physics are required to successfully use hygrothermal modelling for the design of building enclosures. While the former is available to many practitioners, the latter is still lacking in industry.

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