A heat and mass transfer analysis of the subfloor cavity of a residential building

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As roof and wall insulation have become a standard inclusion in a residential building’s design, the conditions in the subfloor cavity have gained relative importance to the building’s thermal performance. However, the modelling of heat and mass transfer between a building and the ground is considered a weak point in many building simulation programs. As very little measured data on Australian subfloor conditions exists, this research seeks to investigate the subfloor conditions experimentally. This paper examines measured subfloor climate data and compares it to acceptable limits and prior field studies. Heat and mass transfer relationships connecting subfloor ventilation, ground evaporation and the subfloor and outdoor climate conditions are developed theoretically and investigated using measured data. Ground evaporation is found to have a significant effect on the energy balance in the subfloor. Thus a recommendation is made to include an evaporation model in Australia’s AccuRate building thermal performance simulation program.

Keywords: AccuRate, simulation, subfloor, ventilation, evaporation

INTRODUCTION

New housing built in Australia must meet or exceed minimum energy efficiency standards assessed using accredited building simulation tools. Although it is more important to keep the house energy efficiency assessment consistent across various house designs, these building simulation tools used for predicting the heating and cooling energy demands should be as accurate as possible.

One building thermal performance simulation program used in Australia is AccuRate. AccuRate was developed over decades of research by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Like all building thermal modelling tools, AccuRate is continuously updated and improved. Anecdotal evidence suggests that AccuRate’s subfloor model may be too simplified and further investigations and developments are required to improve its accuracy.

The subfloor model has been the topic of several published papers in recent years. Sequeira et al. (2010) experimentally investigated the relationship between subfloor ventilation and outdoor wind speed, and compared it to theory. Williamson and Delsante (2006) explore the origin of the ventilation requirements with respect to the theoretical predictions of ground moisture evaporation. While these studies are useful and informative, much of the physics of the subfloor is still not well understood.

This research aims to provide an understanding of physics in the subfloor cavity. In this paper the measured moisture conditions in the subfloor of a test cell are investigated and compared to acceptable limits. The rate of ground moisture evaporation is then analysed and compared to the results of other field studies. The effect that this evaporation has on the subfloor climate and energy balance is discussed. The implications of including an evaporation model in AccuRate are discussed.

1. SUBFLOOR CLIMATE CONDITIONS

1.1. Description of test cell

The test cell analysed in this paper is situated in Launceston, Tasmania and is centred between two other test cells. It is a square brick veneer building with a suspended timber floor. There is no under-floor insulation. The subfloor is open to the bare ground with a ground floor area of 33m². A photograph of the subfloor is provided in Figure 1.
The average subfloor height is 0.5 metres. Two 230mm x 165mm vents on each side of the building provide the means for subfloor ventilation. Only natural ventilation is accommodated; the subfloor has no mechanical ventilation. The junction between the subfloor cavity and the wall cavity is blocked, thus minimizing any air flow between the two cavities. There are no walls inside the subfloor other than at the perimeter. Additional information on the test cell, site layout and instrumentation is provided by Sequeira et al. (2010) and Dewsbury et al. (2007).

### 1.2. Subfloor climate data

A weather station capturing temperature, relative humidity, and wind speed is mounted on the north face of the test cell roof. The subfloor temperature and relative humidity measurements are taken from instrumentation mounted on a pier near the centre of the test cell, at approximately mid-height of the subfloor. All data are recorded from the test cell in 10-minute increments. Subfloor and outdoor temperature throughout 2007 are shown in Figure 2, and subfloor and outdoor relative humidity are shown in Figure 3. Note that subfloor temperature is missing for January and February, and that subfloor relative humidity data is missing for December.
The subfloor and outdoor temperature followed the same seasonal trend. Throughout the year the subfloor temperature had a much lower swing range and a higher average than the outdoor temperature. The subfloor and outdoor relative humidity also showed a seasonal trend. They were at their highest values during the winter months, as would be expected due to the lower air temperatures. Throughout the year the subfloor relative humidity had a much lower swing range than the outdoor relative humidity.

The subfloor cavity spent over 1300 hours with the relative humidity over 80%. On three separate occasions in May, July and August the humidity remained above 80% for over 3 consecutive days. The subfloor cavity spent 107 hours with humidity above 85%. Only one instance did not conform to this rule. The one October occasion was when the outdoor temperature was 18.4°C and the outdoor humidity was 77%. The longest continuous time spent at humidity above 85% was 22 hours. This occurred in mid-May. The maximum subfloor humidity reached throughout 2007 was 89%, occurring for 30 minutes in August.

Relative humidity in subfloors is of interest because the subfloor climate is often conducive to mould growth. Williamson and Delsante (2006) report that mould growth is more likely to occur when the subfloor spends a long time – on the order of weeks - at relative humidity of over 80%, and with temperatures above 12°C. The conditions observed in the test cell subfloor are not expected to cause concerns.

2. MOISTURE BALANCE IN THE SUBFLOOR

2.1. Moisture movement through subfloor vents

Once the temperature, relative humidity and atmospheric pressure of air are known, the absolute humidity can then be quantified (Cengel and Boles 2006). Absolute humidity represents the mass of water vapour present per unit volume of air. It is sometimes known as volumetric humidity.

In this study an atmospheric pressure of 101.325 kPa is assumed throughout, as it was not directly measured. Thus, as the subfloor volume, air temperature and relative humidity are known, the total amount of moisture in the subfloor can be calculated as per Equation 1:

\[ m_{v, sf} = AH_{sf} \times V_{sf} \]  

where \( m_{v, sf} \) is the amount of moisture in the subfloor cavity [kg]; \( AH_{sf} \) is the absolute humidity of the subfloor air [kg/m\(^3\)]; and \( V_{sf} \) is the volume of the subfloor [m\(^3\)]. Note that if the volume term in Equation 1 is replaced with a volumetric flow rate [m\(^3\)/hr], then the mass flowrate of moisture [kg/hr] can be calculated.

It is assumed that in the subfloor there are no are leakage paths. Therefore the volumetric flowrate of air entering the vents must equal the volumetric flowrate of air exiting the vents. It is also assumed that the subfloor air is uniformly mixed, except for the air in boundary with the ground surface. Therefore the measured subfloor conditions adequately represent the air entering the vent. Similarly it is assumed that the weather station measurements adequately represent the air entering the vent. Thus, net moisture transfer throughout the vents is:

\[ g_{net, vent} = (AH_{os} - AH_{sf}) \times V_{sf} \times N \]  

where \( g_{net, vent} \) is the net moisture entering the subfloor cavity via the vents [kg/hr]; \( AH_{os} \) is the absolute humidity of the outside air [kg/m\(^3\)]; and \( N \) is the subfloor ventilation rate [air changes per hour, or ACH].
The subfloor ventilation rate is a linear function of the measured wind speed as presented in Equation 3 of Sequeira et al. (2010). Sequeira et al. (2010) derived the relationship between ventilation and wind speed using measured tracer gas data. It is a similar formula to that used in AccuRate. Because wind speed was measured at the weather station, the net moisture transport into the subfloor via the vents can be quantified.

2.2. Ground evaporation

Applying the law of conservation of mass to the moisture affecting the subfloor volume, the following relationship results:

\[
\frac{\partial m_{v, sf}}{\partial t} = g_{net, vent} + g_{evap} + g_{const}
\]  

where \(g_{evap}\) is the rate of evaporation from the ground [kg/hr]; and \(g_{const}\) is the evaporation from the surrounding building constructions of brick walls, concrete piers or plywood flooring [kg/hr]. It is assumed that the rate of absorption by the building fabric is negligible. Thus the \(g_{const}\) term is dismissed, reducing Equation 3 to:

\[
\frac{\partial m_{v, sf}}{\partial t} = g_{net, vent} + g_{evap}
\]  

Equation 4 is essentially identical to the mass balance described by Kurnitski and Matilainen’s Equation 2 (2000). It shows that moisture is introduced into the vent by two means: through the vents or by ground evaporation. What does not get stored in the air as humidity then exits through the vents.

Measured data can now be substituted into Equations 2 and 4 to solve for the ground evaporation rate. No summer data can be used because of the missing temperature or humidity values. Wind speed values are also missing after mid-June. Thus the data set is reduced to 3½ months from March to June, spanning autumn and winter.

The moisture storage term, \(\delta m_{v, sf}/\delta t\) is found to always be negligible. This indicates that the rate of change of absolute humidity of the subfloor air is very small when compared to the other moisture transport terms.

The rate of evaporation is divided by ground area and graphed versus subfloor ventilation rate in Figure 4.

![Figure 4: Ground evaporation versus subfloor ventilation rate between March and mid-June, 2007](image)

As Figure 4 shows, the evaporation values are always positive, as expected. This indicates that the net effect of the vents is to carry away more moisture than they bring in. In fact, in all instances between March and November of 2007 the vents carried away more moisture than they introduced; again, due to missing windspeed values the amount of this moisture transport occurring after June cannot be quantified.

The evaporation values are within the range of what other field experiments have found. Kurnitski (2001) performed a similar study on the crawl space under an apartment building in Finland and calculated average evaporation rates of 3.6-5.7 g/m\(^2\)/hr with both natural and mechanical ventilation, with a peak as high as 12.4 g/m\(^2\)/hr. Trethowen (1994) directly measured ground evaporation under houses in New Zealand using a lysimeter. The average evaporation rate found was 17 g/m\(^2\)/hr, though it is stated that there was large variation. In a separate study Trethowen (1988) reports of directly measured evaporation rates under New Zealand houses averaging as high as 92g/m\(^2\)/hr in summer and autumn.

It is also interesting to quantify the source of moisture entering the subfloor. On average, the amount of moisture entering the subfloor space through the vents is 2½ times that of evaporation. This is much smaller than the results of a field study of a similar subfloor in the UK, where the vent contribution is an order of magnitude greater than the evaporation contribution (Hartless and Llewellyn 1999). This difference is notable, as the UK test house was of
similar construction and experienced ventilation rates up to 29 ACH. Thus, in the current study evaporation plays a more significant role in the subfloor moisture balance.

3. ENERGY BALANCE IN THE SUBFLOOR

3.1. Energy balance at the ground surface
As the ground evaporation is found to be significant, it is prudent to consider the subfloor cavity as an evaporative cooler. The evaporative cooler model is applicable because as Abbott claimed in a 1983 study, subfloor evaporation rates approach that of free water when the soil has ground water at the surface (Williamson and Delsante 2006). In an evaporative cooler, liquid moisture evaporates into a vapour, absorbing energy from both the water body and the air. As a result of this reduced energy, the temperature of both the water and surrounding air are cooled (Cengel and Boles 2006).

To quantify the importance of the evaporation process, the law of conservation of energy is applied to the ground surface, as was done by Kurnitski and Matilainen (2000). This yields an energy balance of:

$$ Q_{\text{cond\_ground}} = Q_{\text{rad\_ground}} - Q_{\text{conv\_ground}} - Q_{\text{evap}} $$  \[5\]

where $$Q_{\text{cond\_ground}}$$ is the heat energy conducted away from the ground surface to the subground [W]; $$Q_{\text{rad\_ground}}$$ is the net radiation absorbed by the ground surface [W]; $$Q_{\text{conv\_ground}}$$ is the convection from the ground surface to the subfloor air [W]; and $$Q_{\text{evap}}$$ is the total enthalpy of vaporization [W]. Equation 5 equates the heat transfer on each side of the ground surface. On one side, heat is transferred to the subground via conduction. On the other side, heat is gained from radiation and lost via convection and evaporation.

The enthalpy of vaporization is the product of the latent heat of vaporization and the rate of evaporation, as shown in Equation 6:

$$ Q_{\text{evap}} = h_{fg} \times g_{\text{evap}} $$  \[6\]

where $$h_{fg}$$ is the latent heat of vaporization [kJ/kg]. $$h_{fg}$$ is itself a function of the ground surface temperature. Thus the $$Q_{\text{evap}}$$ term in Equation 5 relates the mass transfer from evaporation to the heat transfer at the ground surface. This evaporative energy term is not considered in AccuRate.

The ground thermal conduction is driven mostly by heat transfer from the peripheral ground surface and is generally in the order of several W/m². If neglecting ground thermal conduction, then the energy for evaporation must be coming from an increase in convection and/or radiation energy to the ground surface. Assuming a typical under-floor surface temperature of 16°C and a ground surface temperature of 10°C yields a net radiation heat transfer to the ground of 24 W/m² assuming the emissivity of both surfaces to be 0.85. However, an evaporation rate of 30 g/m²/hr would yield an energy loss from the ground surface of 21 W/m². The evaporation energy term is on the same order of magnitude as the radiation term and thus cannot be dismissed as insignificant for the case investigated in this study.

This energy loss at the ground surface due to evaporation lowers the ground surface and nearby air temperature to achieve a state where the saturation pressure of water at the ground surface temperature is equal to the vapour pressure of the subfloor air. This concept is known as phase equilibrium (Cengel and Boles 2006) and the temperature drop can be significant. For the 3½ months of data considered in this study, achieving phase equilibrium would require the ground surface temperature to be an average of 5°C below the subfloor air temperature.

This drop in ground surface temperature directly affects the conduction, radiation and convection terms in Equation 5, with the radiation term particularly affected as radiation is proportional to the 4th power of temperature. This in turn would affect the subfloor air temperature and the underfloor surface temperature and the thermal performance of the zone above.

3.2. Energy balance over the subfloor volume
To further quantify the effect of the evaporation on the subfloor conditions, an energy balance of the subfloor volume is now performed. This yields:

$$ \frac{\partial H_{sf}}{\partial t} = Q_{\text{conv\_ground}} + Q_{\text{conv\_floor}} + Q_{\text{conv\_const}} + Q_{\text{net\_vent}} + Q_{\text{evap}} $$  \[7\]

where $$H_{sf}$$ is the total enthalpy in the subfloor air [J]; $$Q_{\text{conv\_floor}}$$ is the convection from the floor to the air [W]; $$Q_{\text{conv\_const}}$$ is the convection from the other building constructions in the subfloor, such as the brick wall and piers, to the air [W]; and $$Q_{\text{net\_vent}}$$ is the net total enthalpy transfer into the subfloor via the subfloor vents [W]. When the energy transfer due to subfloor constructions is neglected the resulting equation is similar to Kumitski and Matilainen’s (2000) energy balance.
The total enthalpy in a particular volume is a product of enthalpy and mass. The enthalpy of air is a function of temperature, humidity and atmospheric pressure. The mass of air in a particular volume, its density, is a function of its temperature and humidity. Because the subfloor air temperature, humidity and atmospheric pressure are known, the total enthalpy in the subfloor can be calculated.

\[ Q_{\text{net\_vent}} \] represents the difference in the rate of total enthalpy exiting and entering the vents. A positive value for \( Q_{\text{net\_vent}} \) indicates that more energy exits the vents than enters. The calculation is similar to the total enthalpy calculation above, with a term for air density and subfloor ventilation applied. Because all input values are known, \( Q_{\text{net\_vent}} \) can be calculated. Thus, all terms in Equation 7 except for the convection terms can be calculated using the measured data. The terms are then divided by ground area.

It is noted that the enthalpy of the subfloor air is slow to change; the highest rate of change recorded is 0.5 W/m². Therefore at any given instant the \( \delta H / \delta t \) is negligible. It is also noted that in only two instances out of the 2500 measurements considered is the net effect of the vents to actually introduce energy into the subfloor. The amount of energy introduced is minor, never more than 0.5 W/m².

This net ventilation enthalpy is compared with the enthalpy of the evaporated moisture and shown in Figure 5.

Figure 5: Energy movement in the subfloor cavity versus ventilation rate between March and mid-June, 2007

Figure 5 shows that the enthalpy of vaporization is significant compared to the net ventilation enthalpy. On average the enthalpy of vaporization is 57% of the net ventilation enthalpy. This indicates that the role evaporation plays in the energy balance of the subfloor is important.

The difference between the net ventilation enthalpy and the enthalpy of vaporization is the sum of convective heat transfers of Equation 7. As no surface temperature data is available with which to pursue the convection calculations, the energy analysis currently rests here and measurements of the surface temperatures will be included in future studies.

4. IMPLICATIONS FOR ACCURATE

From the current study, it is believed that the effects of ground moisture transfer in the subfloor cavity may warrant its inclusion into the AccuRate program. The next issue then becomes the feasibility of the calculations. It would be desirable to include the calculations without having to include any additional user inputs.

Currently AccuRate requests that the user input building design specifications, building location and terrain. The program then uses the input post code to access representative weather data files. Relevant to this study, the weather data file in AccuRate includes the outdoor temperature, humidity, windspeed and atmospheric pressure.

Still needed are the subfloor temperature and humidity. These were previously shown to be inputs to the rate of evaporation. Currently, AccuRate calculates the subfloor air temperature and humidity without the consideration of evaporation. However, as was shown above, the evaporation in turn has a great effect on the subfloor climate. These values are intrinsically linked. They may be solved for explicitly using simultaneous calculations, however a simpler method would be to use an iterative process. Iterative processes rely on a good first guess of the final value of the parameter in question.

In the case of this test data a good first guess of the evaporation rate would be to simply calculate evaporation as a function of windspeed. As Figure 4 showed, evaporation has a good correlation with subfloor ventilation, with ventilation being a function of windspeed alone. The \( R^2 \) of this correlation is 0.79.

To find a better correlation, a multiple linear regression is used on the entire 2007 dataset to calculate subfloor temperature as a function of outdoor temperature and outdoor absolute humidity. The resulting function has an \( R^2 \) of 0.57. Similarly, a multiple linear regression is used to calculate subfloor absolute humidity as a function of outdoor air temperature and outdoor absolute humidity. The resulting function achieves an \( R^2 \) of 0.76.
The test data is then revisited. Only the outdoor temperature, outdoor relative humidity and windspeed are known. Estimated subfloor temperature and humidity are calculated using the regression results, and ventilation rate is calculated from the windspeed. An estimated ground evaporation rate is then calculated. When this new ground evaporation rate is compared to the originally calculated rate, the R² slightly improves to 0.82.

Though this method is simplified and applies only for this test cell and site conditions, it shows the possibility that a reasonable value for evaporation may be included into AccuRate.

CONCLUSION

In this paper it is found that the relative humidity in the subfloor of a test cell does reach above 80%, though for a period of time not likely to lead to mould or decay problems. The rate of ground moisture evaporation is in the higher end of the range of previous field studies. It is found that the evaporation process may have a significant effect on the subfloor climate, and it is therefore recommended that an evaporation model be included in AccuRate.

The next phase of this research is to experimentally investigate the remaining components of the energy balance, including especially conduction through the ground and the radiation between the ground surface and test cell floor.

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REFERENCES


