MEASURING AND MODELLING MOISTURE AND TEMPERATURE BENEATH A SUSPENDED TIMBER FLOOR

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ABSTRACT

Temperature and relative humidity have been measured in a BRE test house to investigate the vapour content in the void beneath the timber floor. The void can be ventilated naturally or by means of a fan supplying or extracting air. The results show that air flow into and out of the void is stack dominated. The fan needs to supply or extract large volumes of air in order to disrupt this. Measurements and modelling have shown that the vapour content in the void is generally dependent on the level in external air, and that the contribution from the ground is usually small by comparison. The models are used to calculate rates of soil gas ingress.

INTRODUCTION

BRE has a test house in Devon where a number of radon remedial measures are being tested [1]. This paper examines the subfloor remedial measures and looks at how they affect subfloor moisture levels. The purpose of this work is to evaluate the factors that determine moisture levels beneath suspended floors and to ascertain the most effective methods of control. The research will contribute to guidance on ventilating beneath suspended floors to control emissions of ground moisture as well as other hazardous soil gases (e.g. radon and methane) [2]. It is an extension of BRE's previous work on subfloor ventilation [3,4].

DESCRIPTION OF TEST HOUSE AND SUBFLOOR VOID

A full description of the test house and measuring equipment is given elsewhere [1]. The house was built in the 1930s, is semi-detached and is typical of much of the UK housing stock. It has an internal volume of $200m^3$ ($5m \times 8m \times 5m$), and blower door tests indicate that the envelope leakage is about 17 ach at 50Pa which is slightly higher than the UK average.

The house has a suspended timber floor (tongue and grooved boards on joists) about 0.35m above bare earth. Although the tightness of the floor has not been measured it appears very leaky. The subfloor void has a volume, V, of about $14m^3$ and is split into four zones by 'sleeper' walls. It is ventilated by nine plastic air bricks on the three external walls which can be opened and sealed as required. In addition, a 'Turbo T2 RA22' fan installed at the front of the house can be used to supply air to or extract air from the void. The total equivalent area of the air bricks plus open area of fan when it is not operating is $56{,}000mm^2$. When operating at full speed the fan produces a volume flow rate of 406 m^3/hr (equivalent to a subfloor ventilation rate, n, of 29.0 ach), and at half speed the flow rate is 191 m^3/hr ($n = 13.6$ ach).

MEASUREMENT DETAILS

Room temperatures are measured in all ground floor rooms and the front bedroom using thermistors. The internal temperature, T_i, is the average of these. Below floor temperatures are measured in each of the four zones, and the subfloor temperature, T_f, is the average of these. External temperature, T_o, is recorded in a Stevenson screen and agrees well with data obtained from local weather stations. Relative humidity is measured in the living room, beneath the living room floor and outside in the Stevenson screen. These measurements define the internal (RH_i), subfloor (RH_f) and external (RH_o) relative humidities respectively. Exernal vapour pressure calculated from RH_o and T_o agrees well with vapour pressure calculated using data from local weather stations.

Pressure differences are measured across the floor of each of the four ground floor rooms using a differential pressure transducer. The pressure difference used is the average of these four measurements. A positive pressure difference means air is flowing from the house to the subfloor void, and a negative difference means air is flowing from the void to the house.

Atmospheric pressure, wind speed (U) and direction are also recorded on site. All parameters (except wind direction) are measured every two minutes and stored as half-hour averages.

SUBFLOOR RADON REMEDIAL MEASURES

A range of remedial measures has been tested in the house each for about a month in order to reduce indoor radon levels [1]. Those applied to the subfloor void are summarised in table 1.

Table 1. Summary of subfloor radon remedial measures

Remedy type	No.	Remedy details	Date of test
Natural ventilation	1	'Poor' – air bricks and fan sealed	26/4/96 to 28/5/96
	2	'Enhanced' – air bricks and fan open	23/12/94 to 30/1/95
Supply ventilation	3	Fan on full speed, air bricks open	1/3/95 to 27/3/95
	4	Fan on full speed, air bricks sealed	14/12/95 to 12/2/96
	5	Fan on half speed, air bricks open	30/10/96 to 4/12/96
	6	Fan on half speed, air bricks sealed	20/3/96 to 25/4/96
Extract ventilation	7	Fan on full speed, air bricks open	1/2/95 to 27/2/95
	8	Fan on full speed, air bricks sealed	15/11/95 to 13/12/95
	9	Fan on half speed, air bricks sealed	13/2/96 to 19/3/96

Increasing natural ventilation will help to disperse any radon coming up from the ground. For test 2 the equivalent free area corresponds to a ventilation provision of 3,100 mm^2 per metre run of external wall. Current new-build guidance [2] for dealing with ground moisture beneath suspended timber floors requires a ventilation provision of at least 1,500 mm^2/m on two opposing external walls and a ground cover (e.g. concrete oversite and polyethylene sheet). Comparing the test house with current guidance shows that although it has a high ventilation provision there is no ground cover. Supply ventilation should increase ventilation and possibly create a positive pressure in the void to reduce radon entry. However, it is likely to increase the flow of air up through the floor. Extract ventilation should increase ventilation but could also create a negative pressure in the void that will increase radon entry. This though may be offset because the normal air flow pattern from void to house may be reversed.

RESULTS

Temperature

Aggregating the data for the nine tests shows that T_f ranged from 2 to 15°C and generally changed in response to T_o (range: -5 to 20°C). T_f was greater than T_o for the majority (97%)

of the time since most of the measurements were taken during the winter months. T_f is likely to be lower than T_o during the summer, particularly in the day. The two temperatures can be related through the equation $T_f = 0.52T_o + 6.88$ ($r^2 = 0.59$). Inspection of individual test data showed similar trends, and the highest correlation achieved between T_f and T_o was in test 4 simply because external air was being blown into the void. Correlation of T_f with T_i was poor.

Pressure difference

The measured pressure differences across the suspended floor, ΔP_f, are summarised in table 2.

Table 2. Pressure difference across suspended timber floor

Remedy type	Test no.	Pressure difference (Pa)		
		Average	Maximum	Minimum
Natural	1	-0.31	-0.11	-0.58
	2	-0.91	-0.42	-1.98
Supply	3	-1.71	-0.98	-3.79
	4	-2.42	-2.06	-3.09
	5	-1.11	-0.24	-2.26
	6	-1.62	-1.00	-2.10
Extract	7	-0.05	+0.36	-1.20
	8	+0.43	+0.76	+0.21
	9	-0.05	+0.16	-0.95

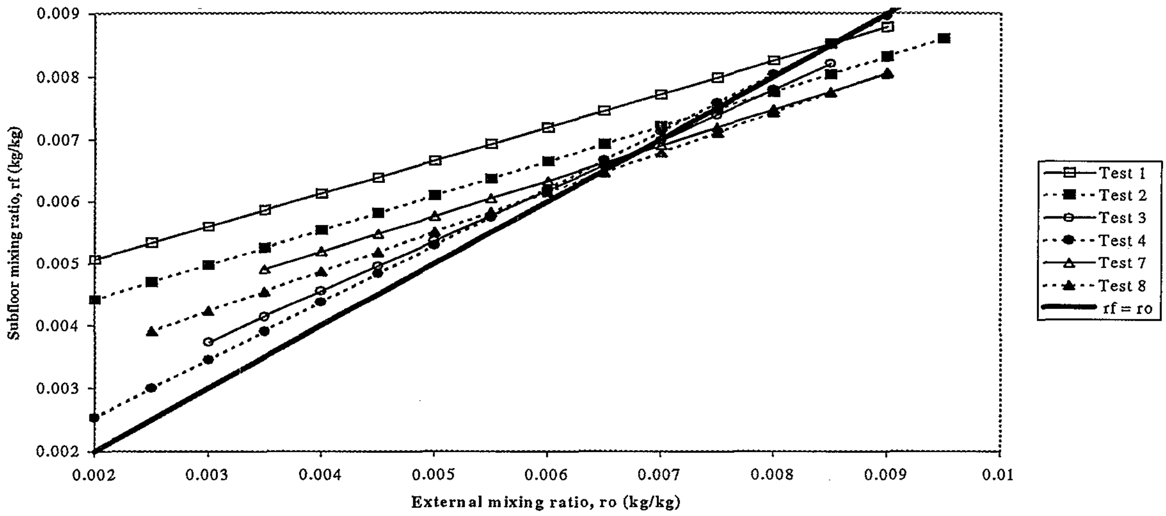
For natural ventilation the normal stack effect is in operation, i.e. air flows through air bricks into the void and then up into the house. ΔP_f (and hence flow rate) is greater in test 2 probably because the open air bricks allow air to be drawn into the void more easily. For test 1 there is a weak negative correlation between ΔP_f and U ($r^2 = 0.11$) and a stronger one between ΔP_f and $T_f - T_o$ ($r^2 = 0.32$). The latter correlation increases considerably ($r^2 = 0.67$) when higher wind speeds ($U > 2$ m/s) are eliminated from the analysis. The trends for test 2 are similar although the negative correlation between ΔP_f and U is stronger ($r^2 = 0.43$) because the open air bricks assist wind driven ventilation. During these tests flow never reversed, i.e. air flowing from house to void. Reversal could possibly occur when $T_o > T_f$ and wind speed was low.

For supply ventilation the situation with natural ventilation is reinforced, i.e. air flow from void to house is increased. With the fan operating at full speed ΔP_f is at its greatest, and sealing the air bricks will increase ΔP_f with respect to open air bricks. Sealing air bricks (tests 4 and 6) minimises the influence of both $T_f - T_o$ and U, i.e. the fan ensures that ΔP_f is relatively constant as shown by its narrow range in table 2. With the air bricks open (tests 3 and 5) the correlations of ΔP_f with $T_f - T_o$ and U are comparable to those seen with natural ventilation.

For extract ventilation the flow up through the floor is reduced (ΔP_f less negative), and for test 8 it is completely reversed. Flow reversal occurs occasionally in tests 7 and 9 but the fan needs to operate at full speed with air bricks sealed to ensure that flow is always reversed. The influence of both $T_f - T_o$ and U appears to be minimal; only when air bricks are open (test 7) does ΔP_f show a negative correlation with U.

The above observations support previous work on subfloor ventilation [3,4].

Graph 1. Subfloor mixing ratio plotted against external mixing ratio



Moisture

Aggregating data for the nine tests shows that RH_f ranged from 45 to 95%, whilst RH_o ranged from 35 to 100%. Generally, RH_f fell between RH_i and RH_o. However, in order to compare the tests with each other it is necessary to calculate the mixing ratio (ratio of mass of water vapour to mass of dry air with which water vapour is associated with) using the appropriate relative humidity, temperature and atmospheric pressure data. Formulae given in BS 1339 [5] were used for this purpose.

Plotting the subfloor mixing ratio, r_f, against the external mixing ratio, r_o, for each of the nine tests shows that the two variables are well correlated ($r^2 > 0.65$). The highest correlations ($r^2 > 0.90$) were achieved with the supply ventilation tests, particularly those with sealed air bricks. This is presumably because in these tests external air is introduced very efficiently into the void and no air is drawn down from the house above. There is no clear pattern to the correlation between the internal mixing ratio, r_i, and r_f for each of the tests. The only discernible trend is that when the correlation between r_i and r_f is good the correlation between r_o and r_i is good and *vice versa.*

The best fit lines for six of the nine tests are plotted in Graph 1 above. The length of the lines represents the range of r_o and r_f for each of the six tests. Also plotted is a line to represent $r_f = r_o$. The graph shows that, as might be expected, test 1 has the highest values of r_f and hence the lowest subfloor ventilation rate. Opening air bricks to increase natural ventilation (test 2) reduces r_f. For short periods of time r_o is greater than r_f during both tests 1 and 2. This occurs because r_o will increase as T_o increases for constant RH_o, and if the difference between T_f and T_o is small r_o can become greater than r_f.

All of the fan assisted tests reduce r_f further, and for tests 3 and 4 the best fit lines lie close to the $r_f = r_o$ line. Supply ventilation is better at reducing r_f when $r_o < 0.007$ kg/kg but extract ventilation is better for higher values of r_o. This is because for supply ventilation moist air is not drawn through the floor from the house above and the flow of moist air from the ground below is reduced. The opposite is true for extract ventilation where air is drawn from the house above and the flow of air from the ground is possibly enhanced. Obviously, for low r_o, r_i is the greater and this leads to an increased r_f. However, as r_o increases it becomes greater than r_i which ensures that extract ventilation is better than supply for higher r_o. Sealing air bricks improves both supply and extract ventilation with respect to open air bricks. Tests with the fan running at half speed show similar trends although not as pronounced.

The above analyses suggest that for the natural and supply ventilation tests the majority of subfloor moisture originates from the outside air rather than the ground. This is also likely to be true for extract ventilation with open air bricks (test 7). Previous work on subfloor ventilation [3,4] and the above analysis of ΔP_f indicate that $T_f - T_o$ is an important driving force for air movement into and out of subfloor voids. This can be confirmed by plotting $r_f - r_o$ against $T_f - T_o$ for each of the tests. For the majority of the tests the correlations were good ($r^2 > 0.60$), the notable exception being test 1 were there was little correlation because sealing the air bricks limits the exchange of subfloor and external air. Plotting $r_f - r_o$ against U generally gave poor correlations, the highest correlations ($r^2 \approx 0.30$) achieved were for tests 1 and 2 because these were the natural ventilation cases.

MODELLING SUBFLOOR MOISTURE

A model of subfloor moisture was developed that incorporated emission from the ground, removal by ventilation and absorption and desorption terms. The equation used was [6]:

$$\frac{dr_f}{dt} = \frac{G}{\rho V} - r_f(n+\alpha) + nr_o + \beta r_{SVP} \qquad (1)$$

The terms not already defined are:

G = Rate of moisture input from ground into subfloor void (kg/h)
r_{SVP} = Mixing ratio of subfloor air at saturation vapour pressure (kg/kg)
ρ = Density of air (kg/m^3). A value of 1.2 kg/m^3 is appropriate.
t = Time (hours)
α, β = Moisture absorption and desorption coefficients for materials in subfloor void (hour^{-1})

Equation (1) assumes that air is not drawn down from the house (i.e. r_i is not present) and so it cannot be applied to the extract tests. As shown above though this equation is likely to represent the situation in most naturally ventilated voids. Many of the variables are known, and suitable values for α and β for wood are 0.6 and 0.4 h^{-1} respectively [6]. However, n in the natural ventilation tests is unknown and so the model can only be applied to the four supply tests where n is both known and constant. The solution to equation (1) assuming that for each half-hour interval G is constant and r_o takes an average value (i.e. $\overline{r_o}$) is then:

$$r_f = \frac{A - \{A - (n+\alpha)r_{f0}\}\exp[-(n+\alpha)t]}{(n+\alpha)} \qquad (2)$$

where,

$$A = \frac{G}{\rho V} + n\overline{r_o} + \beta r_{SVP}$$

r_{f0} = value of r_f at start of half-hour interval.

Equation (2) can be re-arranged in order to calculate G, the main variable of interest. Now, if the volume flow rate of soil gas into the void is Q (m^3/hr) and we assume that the absolute soil gas temperature equals T_f, its vapour pressure is given by [5] $GT_f/(0.217 \times Q)$. This assumption is supported by measurements in another BRE test house with a suspended timber floor where subfloor air and concrete oversite temperatures are very similar. If we also assume that the soil gas is saturated with water vapour its saturation vapour pressure (SVP) can be calculated from T_f using the Magnus formula [5]. Setting the above expression equal to the SVP enables us to calculate Q since G is known. The value of Q calculated in this way is probably an underestimate because the soil gas will not necessarily be saturated with water vapour, although most of the tests were undertaken during the winter months.

The range of average values for Q obtained for each of the supply tests was 10 to 25 m^3/hr, although the maximum calculated value was 70 m^3/hr. Plotting Q against $T_f - T_o$ for each of the tests showed that they were highly correlated ($r^2 > 0.70$). For sufficiently small $T_f - T_o$ soil gas flow is reversed (i.e. from void to ground) so the supply fan is working as intended. (The model can only be used for positive values of Q.) Analysis of the other tests shows a similar picture, although for the half speed fan tests $T_f - T_o$ needs to be negative for flow reversal to take place. The above values for Q and the observations concerning temperature can be used as a guide to likely levels of soil gas ingress into the voids of buildings with suspended floors and no ground cover.

Close inspection of equation (2) shows that it can be simplified further because n is large in comparison to α and β, i.e. for subfloor voids ventilation dominates. This is likely to be true for naturally ventilated voids because measured rates are high (3 to 13 ach) in voids ventilated to current Building Regulations guidance [3]. Using this simplification equation (2) becomes:

$$G = n\rho V\left(r_f - \overline{r_0}\right) \qquad (3)$$

Equation (3) gave comparable values of Q to those obtained from equation (2), and it suggests a way of comparing the tests on the basis of $r_f - r_o$. Mean values of $r_f - r_o$ were calculated for each of the supply tests and differences between them were found to be statistically significant. Further, the percentage increase in the mean value of $r_f - r_o$ going from test 3 to 5 is 59.5% and this is comparable to the corresponding increase in the subfloor fan's volume flow rate (53.0%), i.e. it is a good indicator of ventilation rate. Accordingly, mean values of $r_f - r_o$ were calculated for tests 1 and 2 and were much greater than for the supply tests. These means were then used in equation (3) with values of Q from above to estimate ventilation rates for tests 1 and 2. The estimated rate for test 1 ranged from 4 to 9 ach, and those for test 2 ranged from 7 to 18 ach. These rates accord with the measured rates given above.

Overall, the model can be used to show that for the natural and supply ventilation tests the quantity of water vapour introduced into the void from outside air exceeds that coming from the ground by about an order of magnitude.

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