The thermal dual-probe: its application to the *in situ* measurement of building envelope moisture content

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1. Introduction

Buildings must be designed and built to achieve low energy consumption and predictable service life. In order to achieve these goals, the effects of combined heat, air and moisture (HAM) transfer must be understood. A suitable moisture measurement technique is thus required. There does not exist at present a technique for the measurement of moisture content within building fabrics which fulfils all of the following criteria. Ideally, such an instrument should be:

- Capable of providing *in situ* measurements.
- Capable of producing *transient* measurements.
- Capable of producing moisture *profiles* through the fabric of a building envelope.
- Capable of providing measurements without the need for field calibration (or if calibration is required then it should be non-complex and reliable).
- Accurate.
- Robust.
- Portable.
- Inexpensive.
- Non-complex.

Certainly, techniques do exist for moisture measurement (e.g. NMR[1], gamma attenuation[2], thermogravimetric analysis (TGA), electrical resistance etc.) but all exhibit a failure in at least one of the above requirements. Recent work[3] has shown that the thermal dual-probe technique appears to be applicable to *in situ* moisture measurements in typical building fabrics. Such an approach offers significant benefits over existing methods. This paper deals with the optimisation and testing of the design of such a probe. Firstly, the use of a one-dimensional heat and moisture transfer model to investigate the impact of the instrument on any moisture movement within a sample is described. Secondly, the results of simulations using proven two and three-dimensional finite element (FE) models are detailed. Finally, some initial comparisons with measured data from built probes are provided. A brief description of the theory behind the probe will provide an insight into issues that need to be addressed in order to develop a viable instrument.

2. Theory

A dual-probe heat-pulse instrument with a temperature sensor positioned a fixed distance from a line heat source can measure the volumetric heat capacity of soil (ρc_p) (J m^{-3} K^{-1}) as:

$$\rho c_p = \frac{q}{\pi e r^2 \Delta T_m} \qquad [1]$$

where q is the amount of energy applied per unit length of heater (J m^{-1}), e is the base of the natural logarithms, r is the distance between the heater and the temperature sensor (m), and ΔT_m is the maximum rise in temperature (K) that occurs at the distance r from the heater[4]. This model is for an idealised heater that is infinitely long and releases heat (q) in an instantaneous pulse. It has been determined[5] that for soil applications for typical probe geometry and heating times, the errors in ρc_p associated with this model are negligible (<1%). For a moist material:

$$\rho c_p = \rho_0 c_0 + 4187.w \qquad [2]$$

where ρ_0 is the density of the dry material, c_0 is the specific heat capacity of the dry material and w is the moisture content (kg m^{-3}) [6]. The relationship assumes that the heat capacity of water is constant at 4187 J kg^{-1} K^{-1}. Therefore, if we can measure $\rho_0 c_0$, knowing ρc_p from the probe measurements, we have:

$$w = \frac{\rho c_p - \rho_0 c_0}{4187} \qquad [3]$$

Thus an accurate, absolute, determination of w is possible. Note importantly, that even if $\rho_0 c_0$ is not known then *changes* in w with time can still be accurately determined. Calibration of the probe for specific materials is then no longer necessary. In order to be able to use the probe in building fabrics, any sources of 'error' must not result in significant departures such that eqn. [1] does not hold. Potential sources of error must therefore be examined carefully.

3. Sources of error

Significant issues regarding sources of error are as follows:

1. Moisture movement within the sample as a result of the heat input.
2. Probe spacing.
3. Probe dimensions.
4. Heating times.
5. Probe material.
6. Thermal contact resistance at the probe/wall interface.
7. Errors in the measurement of q and ΔT_m.
8. Errors due to inappropriate assumptions of material homogeneity.

Modelling and experiments can provide an insight into these sources of error. Previous work by the authors[3] provided evidence that none of issues 1-5 are barriers to the design of a successful probe for use in a range of building fabrics. Via further modelling, this current paper begins to deal with the *optimisation* of the design of such a probe in order to reduce any errors to a minimum. It is clear, for example, that if the probes are too close together then one is not sampling the building fabric but merely the probe material (i.e. stainless steel). In the other extreme, probes at too great a spacing will result in low temperature increase (unless excessive heat is applied which may cause moisture migration) compromising accuracy. Issues 6-8 are also being investigated via modelling and this will be reported in a later paper. Here, the results of initial comparisons with experimental data are provided as preliminary evidence that such issues are not obstacles to a successful probe design.

Material	**Density ($kg\ m^{-3}$)**	**Thermal conductivity ($W\ m^{-1}\ K^{-1}$)**	**Specific heat capacity ($J\ kg^{-1}\ K^{-1}$)**
Cast concrete (dense)	2100	1.4	840
Brickwork (outer leaf)	1700	0.84	800
Aerated concrete slab	500	0.16	840
Stainless steel AISI 304	7900	14.9	477

Table 1. Material properties

Table 1 provides details of the relevant thermal properties of these materials that were used in the modelling work including the stainless steel of the needles themselves. A schematic probe design is shown in figure 1.

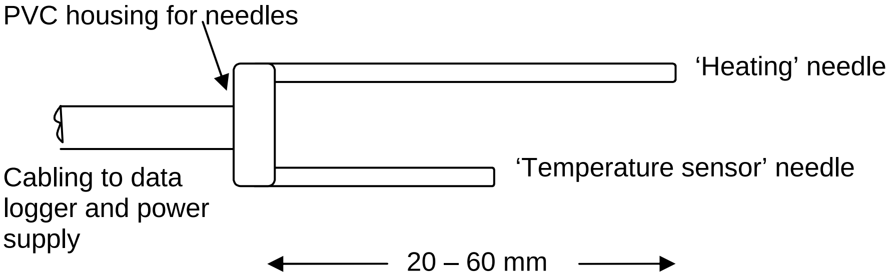

Figure 1. A conceptual dual-probe (not to scale)

4. Heat and moisture transfer model

In order to address the first of the issues regarding sources of error that were noted above, modelling has been undertaken of the moisture migration within a sample when the pulse of energy is applied. Such migration is undesirable and, if significant, will place an upper limit on the energy input at the heater probe. A one-dimensional transient heat and moisture transfer model was used for this purpose[7]. The layer of material was divided into a grid with nodes at 0.2mm intervals. The simulated temperatures and relative humidities at the sensor location were recorded. This work was reported in more detail by the authors in previous paper[3].

5. Finite element (FE) modelling

An extensive programme of FE modelling has been undertaken to study the impacts of heat impulse duration, the dimensions of heating and temperature sensor needles, wall thickness, real wall boundary conditions, transient temperatures etc. on the performance of the probe. The CAE package 'I-DEAS' (supplied by SDRC) was used in this study. Previous work by the authors[3] describes how this FE modelling work was initially used to provide evidence that no major barriers existed to the design of a successful probe for use in a range of building fabrics. The overall aims of the numerical modelling with regards to this current paper were to begin the process of optimising the design of the probe. For this current paper, the 2D work was intended to provide design candidates for more accurate inspection with the 3D models. A typical 3D FE model is shown in Figure 2 with an example of a simulation result (temperature contour plot at 10 seconds).

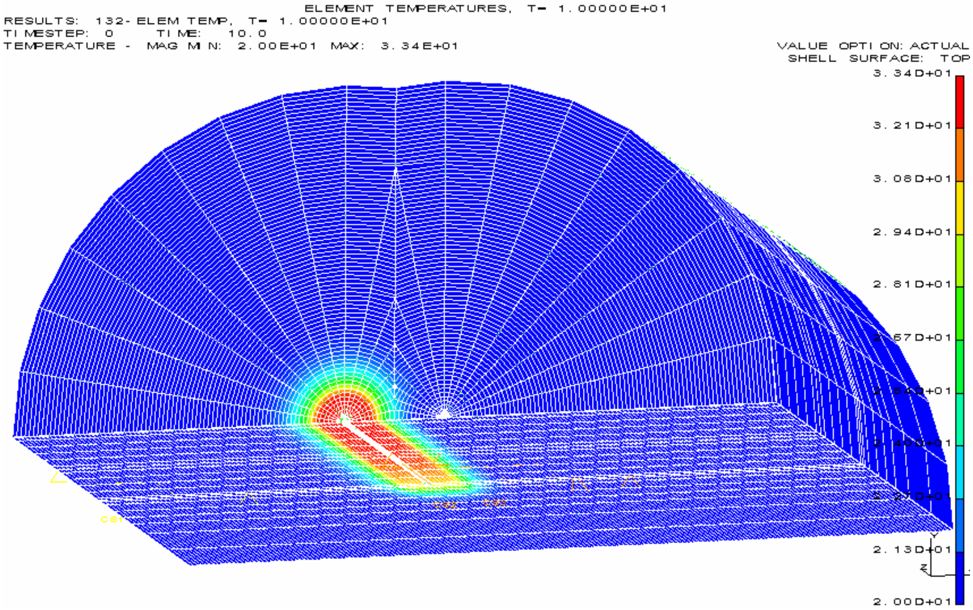

Figure 2. Temperature contour plot for the 3D FE model at 10 seconds

Note that it was sufficient to model only the upper half of the actual domain due to symmetry considerations. The model was relatively complex, consisting of 51585 elements and 39090 nodes.

6. Experimental work

A detailed programme of experimental work has been undertaken to test the probe designs which the FE modelling work indicated would be successful. The initial work has concentrated on one type of building fabric thus far - aerated concrete. As series of aerated concrete cubes (of side 10cm) were dried in an oven. The dry samples were then tested with the probe and $\rho_0 c_0$ thus measured. The results were compared with the concrete manufacturer's data[8].

Note that the samples are currently being conditioned to various moisture contents. These moisture contents will be gravimetrically determined. The moisture changes from the dry samples will also be measured with the probe and compared with the gravimetric results - the full results will be presented in a later paper. In this paper only the interim dry results are presented. The probe measurement system essentially consisted of the probes, a data logger (Campbell CR10X) and a power supply system. The amount of energy applied to the heating needle was measured by placing a precision resistor (1Ω, ±1%) in series with the power supply and the dual-probe heater. The voltage drop across the precision resistor was used to determine the current applied to the heating needle. The thermocouples (type T) used in the probes were calibrated against a quartz reference thermometer and a system accuracy of +/- 0.07 deg. C was achieved for all 4 probes.

7. Results

7.1. Heat and moisture transfer model

As described in more detail in by the authors elsewhere[3], in general, it has been proven that the RH does not change significantly for the building fabric materials tested under typical conditions and pulse energy inputs. For brick, for example, the maximum change was from 60% to 60.3%. Thus the impact of moisture movement was insignificant.

7.2. FE analyses – summary of results

Depending upon the building fabric material, optimal probe lengths and spacings range from approximately 20-50mm and 10-20mm respectively. A selection of 3D modelling results (for aerated concrete in these cases) is shown in table 2. Note that suitable designs are those that show acceptable agreement between the FE predicted temperature rise and the analytically determined temperature rise. A shorter probe is preferable to a longer probe due to increased ease of insertion into the building fabric.

Spacing (mm)	**Heating needle length** (mm)	**FE predicted Δ T_m** (deg C)	**Analytical Δ T_m** (deg C)
16	50	1.10	1.22
16	60	1.12	1.22
18	50	1.10	1.22
18	60	1.13	1.22
20	40	1.03	1.22
20	60	1.12	1.22

Table 2. Summary of a selection of modelling results

7.3. Comparisons with experimental data

Table 3 shows a set of initial results obtained for one block and one probe. Measurements were spaced by at least 90 minutes. It is clear that good agreement was achieved with the manufacturer's data.

Expt. No.	**Max. ΔT_m** measured	**ρc** measured	**ρc** manufacturer's data
	(deg C)	(J/m^3K)	(J/m^3K)
1	1.25	667000	651000
2	1.25	667000	651000
3	1.26	664000	651000
4	1.25	667000	651000
5	1.25	667000	651000
6	1.25	667000	651000
7	1.25	667000	651000
8	1.25	667000	651000
9	1.25	667000	651000
10	1.25	667000	651000
11	1.25	667000	651000

Table 3. Summary of a selection of experimental results

8. Conclusions

This paper has shown the following:

- Any moisture migration within the building fabric, under typical conditions, was found to be insignificant for the materials investigated in this study.
- This work has successfully demonstrated that, depending upon the building fabric material, optimal probe lengths and spacings range from approximately 20-50mm and 10-20mm respectively.
- Good initial agreement with experimental results have been obtained

As a result of the work that has been undertaken, the authors are very confident that the dual probe approach is indeed applicable to typical building fabrics – it is claimed that this is an important and significant advance. Future papers will report on the further optimisation and testing of the instrument.

9. References

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