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The Rapid Thermal Characterisation of Buildings

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The rapid determination of thermal conductivity and U-value measurements

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Abstract

Standard methods for the measurement of the steady state thermal properties of building components are sensitive to the effects of weather. Even when the interior of a building is held at approximately steady state conditions it requires several weeks of time series data to be collected before robust estimates for the thermal transmittance can be obtained.

In this paper, it is demonstrated that novel time series analysis methods can rapidly and accurately characterise the thermal properties of building components. The thermal conductivity of a wall is estimated directly and simultaneously from the time series data. The thermal conductivity was determined for a range of experimental conditions. The estimated conductivity was found to be independent of applied heating and forced convection loads but was found to be dependent of the infiltration rate from the test room used in the experiment. The sample length that is required for an accurate characterisation of the thermal performance of a building component is related to the thermal time constant of its constituent materials. As such, the data can be collected within several hours or days, depending on the materials, and not the several weeks required by other currently used methods.

Introduction

Thermal response factors [1-3] are a well established way of characterising the linear dynamic properties of a building. However, response factor estimation with conventional methods has proved difficult and time consuming to collect suitable data; with typically 50% discrepancies between theory and measurement [4]. The currently available methods for measuring the thermal conductivity of a wall requires the duration of the experiment to be sufficiently long so that the cumulative averages become stable to changes in the weather patterns [5,6].

In the present work, it is shown that consistent and accurate values can be obtained from short sample lengths of data. The actual duration of data required for analysis being chosen to be greater that three times the relaxation time of the thermal conduction process. Time series measurements of the prevailing thermodynamic conditions were analysed for the thermal conduction transport coefficients of the wall of a test room. The estimated thermal conductivity values were compared with the values obtained in the literature and from a previously reported standard hot box experiment. An ordered sequence in time of values of a physical observable, such as a heat flux, is called a time series. The relationship between time series sequences can be characterised in terms of response functions. The test room was situated within an environmental chamber which experienced general meteorological conditions. The test room had a controllable heater within it. In addition the test room was well sealed and had solenoid valves in the ceiling which were used to control the infiltration rate into the test room.

Representation of thermal processes

Equilibrium thermodynamics is concerned with the idea of the local thermodynamic flux being governed by the constitutive equations in terms the local thermodynamic forces. Onsager related the linear steady state thermodynamic fluxes to the local linear steady state thermodynamic forces which motivate the flux. A given thermodynamic flux, $\{Q_k(t)\}$, can be written as a function of the thermodynamic forces, $\{F_i(t)\}$, with

$$Q_k(t) = Q_k(F_1, \ldots, F_A) \tag{1}$$

The linear steady state transport properties can be described by the irreversible thermodynamic equations of Onsager [7,8]. The linear constitutive equations relate the independent thermodynamic fluxes, $\{Q_k(t)\}$, in terms of their conjugate thermodynamic forces, $\{F_i(t)\}$, and a set of linear steady state Onsager coefficients, L_{ik}, with

$$Q_k(t) = \sum_i L_{ik} F_i(t) \tag{2}$$

The most simple case is one dimensional heat conduction where the Fourier law relates the heat flux at a given point to the local temperature gradient, $F_i(t) = \nabla T_s(t)$, at the same point with

$$Q_k(x,t) = -\kappa F_i(x,t) \tag{4}$$

Gurtin and Pipkin [9] developed a realistic theory for heat conduction using constitutive assumptions that lead to finite propagation speeds with the linearised constitutive equation for the heat flux in terms of the local temperature gradient being

$$Q_k(t) = \sum_{\sigma=0}^{t} L_{Q_k \nabla T_s}(t-\sigma)\nabla T_s(\sigma) \tag{7}$$

where

$$\kappa = \sum_{\sigma=0}^{t} L_{Q_k \nabla T_s}(\sigma) > 0 \tag{8}$$

where κ is the steady state thermal conductivity of the solid [10], or more generally the area under the response function is equal to the steady state gain between the processes [11].

At the surface of a solid fluid interface energy and flux are conserved. On the solid side the heat flux is related to the thermodynamic conductive force as described above. On the fluid side the heat flux is related to the convective and radiative thermodynamic forces. The linear form of these relationships can be written as

$$Q(t) = \sum_{\sigma_1=0}^{\mu} L_{Q\nabla T_s}(\sigma_1)\nabla T_s(t-\sigma_1)$$

and (10)

$$Q(t) = \sum_{\sigma_1=0}^{\mu} L_{Q\Delta T_r^4}(\sigma_1)\Delta T_r^4(t-\sigma_1) + \sum_{\sigma_1=0}^{\mu} L_{Q\Delta T_f}(\sigma_1)\Delta T_f(t-\sigma_1)$$

where μ is the finite memory of the transport process.

That is, at the boundary

1) the conductive thermodynamic force is the temperature gradient , $\nabla T_s(\sigma_1)$ °K m^{-1},within the wall and the response function values for the conductive process are $L_{Q\nabla T_s}(\sigma_1)$ W °K m^{-1},

is balanced by

2) the radiative thermodynamic force, $\Delta T_r^4(\sigma_1)$ W m^{-2}, is the Steffan-Boltzmann constant multiplied by the difference between the fourth powers of the surface temperatures of the ceiling and the average of the remaining surfaces and the response function values of the radiative process are $L_{Q\Delta T_r^4}(\sigma_1)$, and

3) the convective thermodynamic force , $\Delta T_f(\sigma_1)$ °K, is the temperature difference across the fluid-surface boundary layer , the response function values of the convective process are $L_{Q\Delta T_f}(\sigma_1)$ W °K^{-1} m^{-2} .

The area under the estimated response function curve for each process is the transport coefficient, or the gain, of that process [11], that is, the gain of the process is the area $A= \sum_{\sigma=0}^{\mu} L_{Q\Delta T_f}(\sigma_1)$ for a given thermodynamic force F(t).

The time series moment equations for the three thermodynamic forces are

$$M_{\nabla T_s Q}(\tau_1) = \sum_{\sigma_1=0}^{\mu} L_{Q\nabla T_s}(\sigma_1)\, M_{\nabla T_s \nabla T_s}(\tau_1,\sigma_1) \qquad (11)$$

$$M_{\Delta T_r{}^4 Q}(\tau_1) = \sum_{\sigma_1=0}^{\mu} L_{Q\Delta T_r{}^4}(\sigma_1) M_{\Delta T_r{}^4 \Delta T_r{}^4}(\tau_1,\sigma_1) + \sum_{\sigma_1=0}^{\mu} L_{Q\Delta T_f}(\sigma_1) M_{\Delta T_r{}^4 \Delta T_f}(\tau_1,\sigma_1) \quad (12)$$

and

$$M_{\Delta T_f Q}(\tau_1) = \sum_{\sigma_1=0}^{\mu} L_{Q\Delta T_r{}^4}(\sigma_1)\, M_{\Delta T_f \Delta T_r{}^4}(\tau_1,\sigma_1) + \sum_{\sigma_1=0}^{\mu} L_{Q\Delta T_f}(\sigma_1)\, M_{\Delta T_f \Delta T_f}(\tau_1,\sigma_1) \quad (13)$$

These moment equations are linear algebra expressions of the form $\underline{c} = \underline{\underline{a}}\underline{L}$, where $\underline{\underline{a}}$ is the auto moment matrix, $\underline{c}$ is the cross moment vector and $\underline{L}$ is the vector of response function values. This formalism can be extended to the non-linear case [13].

In addition to the convolution representation given above the steady state conductivity of the sample materials will be estimated using the ratio of means method. In the ratio of means method steady state conditions are assumed to prevail and the relationship between the local heat flux and the local temperature gradient will be given by the approximation

$$\sum_{t=1}^{N} Q(t) \approx -\kappa_4 \left(\sum_{t=1}^{N} T_2(t) - \sum_{t=1}^{N} T_1(t) \right) \quad (14)$$

where N is the sample length and where it has been assumed that $\Delta x = 1.0$.

So that the steady state conductivity can be written as

$$\kappa_4 = \frac{\sum_{t=1}^{N} Q_k(t)}{\left(\sum_{t=1}^{N} T_2(t) - \sum_{t=1}^{N} T_1(t)\right)} \tag{15}$$

where it is implicit that the heat flux and temperature values are measured in steady state and that the temperature difference used is the actual driving force of the heat flux. This is called the ratio of means method.

The U-value for each case can be determined by multiplying the estimated conductivity by the thickness of the sample in the hot box arrangement.

Facility for the test room experiment

The experiment consisted of a highly sensored test room that was enclosed with in an environmental chamber, see Figure 1. The environmental chamber was allowed to free float and experience the stochastic nature of the meteorological temperature and humidity conditions.

Time series data were collected at thirty second intervals for a duration of two weeks. Sections of this data were then separated for quantitative analysis. The temperature of the air inside the chamber and the surface temperatures of the walls of the chamber were measured. Temperature measurements through the boundary layer of the test room were made at equally spaced intervals on a logarithmic scale. The temperature measurements were made at five different spatial positions both at the surface and embedded 2mm in the surface of the test room walls. The heat flux was measured at four spatial positions at the surface and 2mm embedded within the surface of the wall. The temperature at the centre of the wall of the test room was measured in four different spatial positions.

The walls of the test room consisted of two sheets of gyproc wall board bonded together, all joints were sealed. Within the test room the driving force was provided by a radiant heater supplying 275watts of power. The heater was controlled using a pseudo-random binary sequence which switched it on or off. The switched time interval varied pseudo-randomly from 0-120 seconds.

The natural infiltration rate into the test room was measured to be less than 0.05 air changes per hour. The temperature of the air inside the chamber and the surface temperatures of the walls of the chamber were recorded. A direct air flow path was provided between the test room and the chamber, two valves were used to control the air flow. The first valve was a standard vacuum valve and the second a solenoid operated valve. The vacuum valve was used to seal the test room, the second valve could be driven by a pseudo-random binary sequence with a mean value of 1 air change each hour. Whilst the temperature conditions surrounding the test room were linked to the meteorological conditions, the air flow characteristics were damped by the environmental chamber. To enhance the variation in the external conditions a fan was used in some experiments to mix the air, again driven pseudo-randomly. A computer controlled data logger was used to collect the data from the instrumented test room. The logging interval was 30 seconds and the total duration of the experiment varied between two to three weeks.

Quantitative analysis of the experimental data.

In this section the thermal conduction values are estimated from the time series data. A short section of each data set, typically less than 3 hours duration, were used to obtain estimates of the thermal transport coefficients. In this way it is demonstrated that the steady state representation of the thermal conduction processes can be estimated from a relatively small number of data points. The values being determined firstly under constant infiltration conditions of less than 0.05 air changes per hour and then under unsteady infiltration conditions with a mean value of 1.0 air changes per hour.

Figures 2 and 3 show a sample of the time series data of the temperature difference values measured between the middle of the wall and the surface of the wall and the heat flux flowing at the surface of the wall. In Figure 4 and table 1 the thermal conductivity values determined in the series of experiments are given.

Table 1: estimated conductive thermal transport coefficients W m^{-1} K^{-1}

<0.05 infiltration	response factor value	Ratio of means values	'Hot Box' value	Literature value
	0.130±0.012	0.131±0.012	0.20±0.01	0.16±0.01
heater half power	0.151±0.012	0.153±0.012	0.20±0.01	0.16±0.01
fan on	0.134±0.014	0.143±0.012	0.20±0.01	0.16±0.01
1.0 infiltration				
	0.092±0.011	0.082±0.011	0.20±0.01	0.16±0.01
heater half power	0.115±0.012	0.107±0.012	0.20±0.01	0.16±0.01
fan on	0.098±0.011	0.097±0.012	0.20±0.01	0.16±0.01

It is clear that the thermal conductivity values obtained from the short samples of data are in agreement with the literature value. The values obtained from the response factor analysis are in agreement with those obtained from the ratio of means method. It is also clear that the thermal conductivity values estimated when the infiltration rate was kept to less than 0.05 air changes each hour are in good agreement with the literature value and the value obtained from a standard hot box experiment [13]. There is an obvious lowering of the conductivity, approximately 30% in magnitude, when the infiltration rate is increased to a mean value of 1 air change each hour, but at this time it is not clear how to take account of the extra energy flowpath in the analysis of the data and requires further work.

It can be seen that there are two groupings of the results. These groupings correspond to the 0.05 and 1.0 infiltration rate experiments. Within each grouping there appears to be no discernible effect when the power of the radiant heater was reduced to 50% capacity or when the fan was switched on. In table 1, the conductive thermal heat transfer coefficients estimated are given when the test room experienced artificial forced convective and damped natural meteorological conditions.

Conclusions

In this work the new methodology has been used to estimate the thermal conduction of a standard building material under a range of different experimental conditions. The thermal conductivity being estimated from the time series data using the ratio of means method and the response factor method. These values were compared with those obtained from the literature and from previous hot box work. The analysis in this work was performed on short sections of data, typically each being less than 3 hours duration. The estimated thermal conductivity values are in good agreement with those obtained form the literature for a variety of stochastic experimental conditions. The thermal conductivity results fall into two groupings which correspond to the 0.05 and 1.0 infiltration rate experiments. Within each grouping there appears to be no discernible effect when the power of the radiant heater was reduced to 50% capacity or when the fan was switched on. The effect of increasing the infiltration rate can be clearly seen, with lowering of the conductivity by approximately 30% in magnitude. However, it is not clear how to analyse the effect of infiltration and further experimental and theoretical studies are recommended.

Acknowledgements

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Figure captions

Figure 1. A schematic diagram of the experimental arrangement.

Figure 2. Sample of the surface temperature measured during the first experiment.

Figure 3. Sample of the temperature difference measured between the middle of the wall and the wall surface during the first experiment.

Figure 4. Thermal conductivity values estimated in the series of experiments.

FIGURES

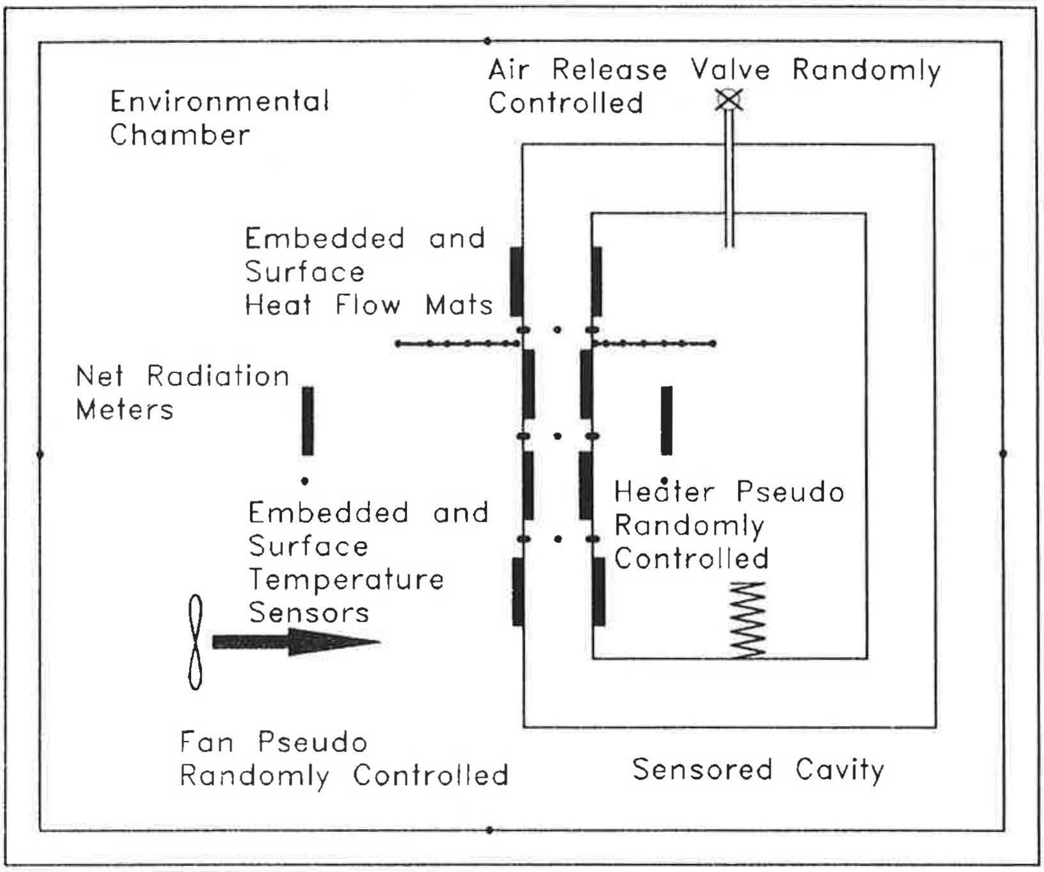

Figure 1 A schematic of the experimental arrangement

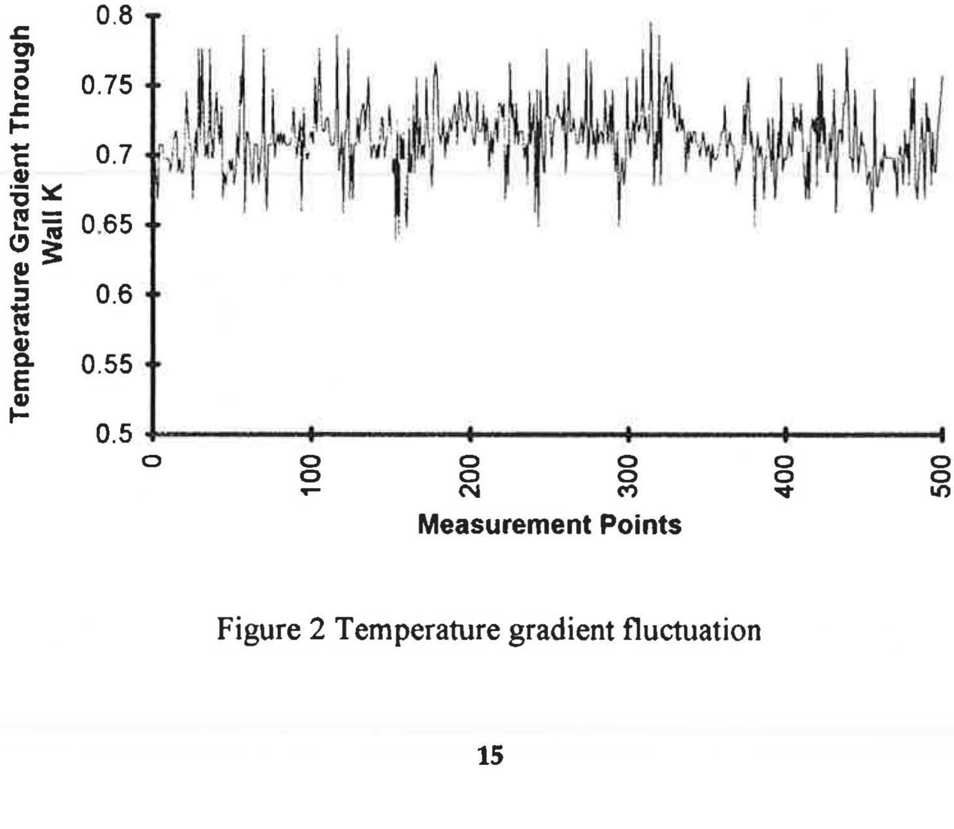

Figure 2 Temperature gradient fluctuation

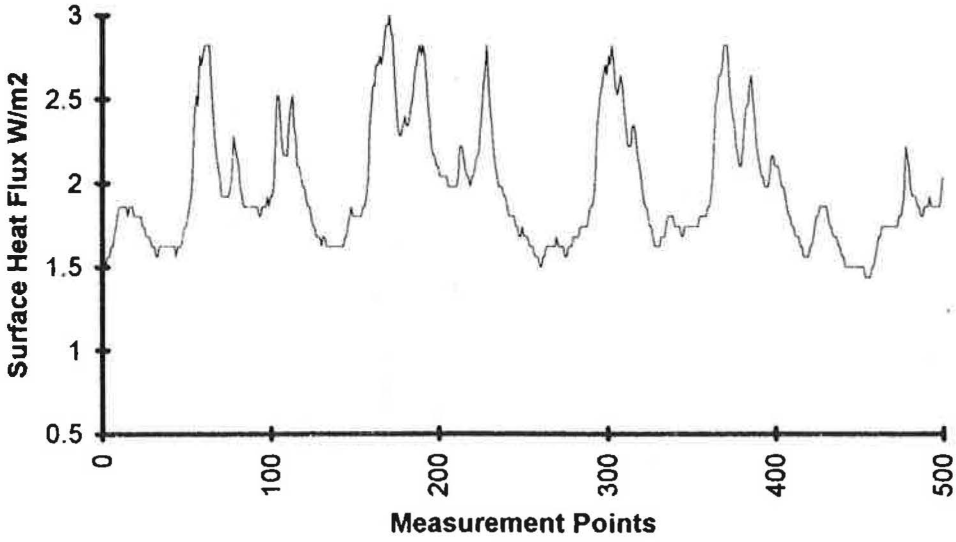

Figure 3 Heat flux fluctuation at the wall's surface

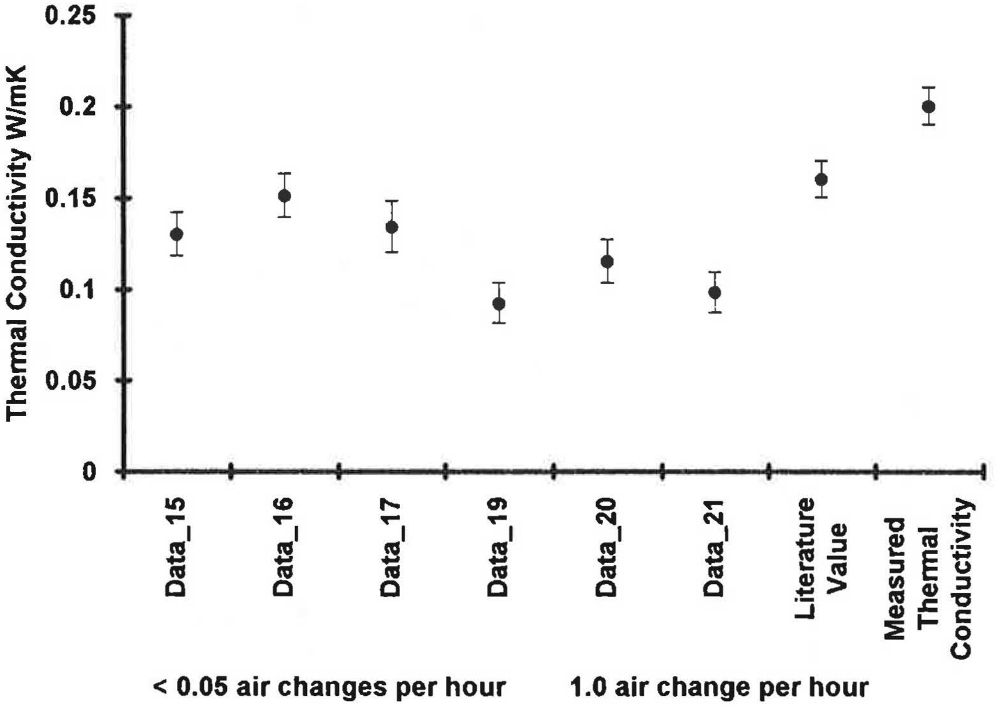

Figure 4 Thermal conductivity valuesestimated in the series of experiments