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A Comparison of the Measured and Simulated Thermal Response of a Simple Enclosure

E. R. HITCHIN*
S. R. DELAFORCE*
C. J. MARTIN†

Dynamic thermal simulation programs are increasingly used as a research tool and as building services design aids. Their limitations are, however poorly understood; mainly because of the difficulty of obtaining sufficiently robust experimental data. New techniques, developed by British Gas and our contractor, The Energy Monitoring Co. Ltd., have permitted testing which is sufficiently powerful to show weaknesses in some aspects of a particular program. These weaknesses occur in a section of the program which is virtually identical in all similar programs. Collaboration with universities to overcome these newly found difficulties is planned.

1. INTRODUCTION

DYNAMIC thermal simulation models have been used as research tools for over a decade now. Since they are of most value in situations which are difficult to examine experimentally, lack of information on their accuracy is a perennial cause of concern. In the past, "validation" of dynamic thermal models has often taken the form of making measurements in buildings and then attempting to reproduce them from the model. This is, at best, a weak form of validation which provides very little information which can inform the model builder or user of which components of a model are strong, and which are weak. We have attempted to test specific aspects of model behaviour by designing experiments which exercise particular features. Carefully designed and analysed experiments in outdoor test cells have proved to be a powerful means of setting up "benchmarks" against which simulations can be compared. This paper reports results from tests undertaken by British Gas plc and the Energy Monitoring Company Ltd. (EMC) from a series which now stretches back a number of years.

Unlike most test cell researchers, our focus is on the dynamic thermal behaviour of buildings and heating systems in general, and not on solar-driven processes. Thus our cell has no window, but has extensive monitoring of air and surface temperatures and surface heat fluxes. The absence of internal short-wave radiation increases our confidence in the accuracy of these measurements.

Many of the earlier experiments in this series were carried out with intermittent heating regimes which deliberately mimic those of occupied buildings [1, 2]. Superficially, these were straightforward to analyse: but in reality it was extremely difficult to separate the effects of heater operation from those resulting from changes in outdoor temperature, solar radiation etc. The responses of air and surface temperatures and surface heat fluxes to changes in heater output are fundamental characteristics of the behaviour of a model. They are difficult to measure directly because the observed temperatures and heat fluxes are influenced by variations of other, uncontrolled, variables such as outdoor air temperature and solar radiation (in this case impinging only on external surfaces, since we have chosen to have no window). The "stochastic" experimental technique described here combines randomized five-minute pulses of heater operation—which ensure that heater output is not correlated with other variables—and an analysis technique which extracts the temperature and heat flux responses to a pulse of heater operation.

From these responses, it is straightforward to construct the more easily visualized responses to a step change of heater output. These are then compared with the equivalent responses predicted by the model.

The paper first outlines the basis of the experimental design, then reports the results of a particular set of experiments, before finally comparing the results with the predictions of the simulation program HTB-2 [3].

2. BACKGROUND THEORY FOR EXPERIMENTAL STOCHASTIC RESPONSE ANALYSIS

This section presents an outline of the theoretical background to the experiments. The use of randomized heater operation to characterize the thermal response of a test room was pioneered by Letherman [4]. A more detailed explanation of the theory, and a further example of its application to model testing can be found in [5].

* British Gas, Watson House Research Station.
† Energy Monitoring Co. Ltd.

2.1 *Impulse response for linear time invariant systems*

A system consists of three items: a set of possible inputs, a set of possible outputs, and a set of rules which map the inputs to the outputs. In our particular case, inputs will be driving forces such as heater power and outputs will be resulting temperatures and test cell surface heat fluxes. In simple terms the impulse response of any system is simply the system output over a period of time for the given input: specifically the temperature and heat fluxes which result from a 'pulse' of heating.

A linear system is one for which outputs can be superposed to generate the responses to the corresponding superposed input. A system is time invariant if the responses that it provides to a given input is always the same.

If the system is time invariant the response to the impulses occurring at different times is simply the impulse response shifted to that time. If the system is further linear, the total output can be obtained simply by adding up these responses to the individual inputs. For further information on response analysis and how it may be related to pulses of finite lengths see [6]. The process described above can be expressed more formally by the convolution sum, which gives the output of any linear time invariant system in terms of the system impulse response and the input sequence:

$$o(k) = \sum_{j=0}^{\infty} i(k-j)h(j)$$

where $o(k)$ is the system output at time k, $i(k)$ is the system input at time j, and $h(j)$ is the system impulse response sequence. For a more comprehensive discussion of the convolution sum see [7] or [8].

2.2 *Covariance functions*

The covariance function of two sequences of numerical data I (input) and O (output) of length $n+1$ is defined as (%)

$$r_{io}(k) = \{1/(n-k+1)\} \sum_{j=0}^{n-k} \{i(j)-\hat{i}\}\{o(j+k)-\hat{o}\}$$

where $\hat{i}$ and $\hat{o}$ are the mean values of the sequences I and O respectively.

The covariance of a sequence with itself is defined in the obvious way and is termed the sequence autocovariance. The covariance function gives a measure of whether the two data sequences are related in any way. In fact it is a measure of the linear association of the sequence at all possible time delays.

By substituting the covariance function defined above into the convolution sum presented in 2.1 [9] it is possible to derive an important property of linear time invariant systems:

$$r_{io}(k) = \sum_{j=0}^{\infty} h(j)r_{ii}(k-j).$$

This is the discrete form of the Weiner-Hopf equation, and it states that the covariance between input and output of a linear time invariant system is given by the convolution of the autocovariance of the input sequence with the system impulse response function. Used in reverse this relationship provides the basis of the technique which is used to derive impulse response from experimental data.

In general the autocovariance function of the input will be quite complex, and obtaining the impulse response from the Weiner-Hopf equation will involve deconvolving this from the observed covariance between input and output. However there is a special class of input sequences which are uncorrelated with themselves in time, and their resulting autocovariance function is simply an impulse function of magnitude given by the variance of the process. In this system, impulse response is given directly by the covariance of the output sequence with the input divided by the input sequence variance. For further details see [10].

3. DESCRIPTION OF TESTCELL

The test cell in question was constructed for BG under contract by EMC to a design that was influenced by both parties. The testcell is well insulated and has internal dimensions of 2.034 m^2 plan and height of 2.334 m. Details of construction and instrumentation together with diagrammatic layout are given in [11].

4. IMPLEMENTATION OF EXPERIMENT

In order to carry out the experiment it was decided to introduce heat using a fanned convector heater to achieve the operating conditions which are close to those assumed in simulation programs: low mass heater with stirred air. Also the results from purely convective heating were expected to be easier to handle than "mixed" heat transfer. The heater was operated in such a way as to produce an impulse power input. The impulse response of every other quantity measured in the testcell to this power input was then directly available from the covariance function of that quantity with the power delivered.

A sequence of five-minute pulses, in which each five-minute period was randomly either "heater-on" or "heater-off" was generated and tested for compliance with the statistical requirements described in section 2.2. The five-minute pulse duration is determined by several factors: the pulse length must be significantly longer than the heater time constant, it must be of sufficient duration to generate temperature and heat flux changes which can be measured accurately, it must be sufficiently shorter than any characteristic time constant of the response to be measured. An advantage of the on/off approach as opposed to modulation of heater power is that the maximum value of input sequence variance is obtained (sequence variance being one of the quantities required for determining the response function).

For further details of test implementation see [10].

5. RESULTS AND DISCUSSION

In the following discussion the term "measured response" is used as a convenient shorthand term for the unwieldy but literally more accurate "response constructed from the measurements". One consequence of the use of random heater operation, is that the precision of the derived response function declines for long time delays. In these experiments, the responses up to about a half-hour delay are very well defined, while those beyond about two hours are of doubtful value. It is therefore not possible to extract, from these experiments, reliable information about those room components which have small, long-delayed responses. Results are presented for three sets of responses: mean (space-averaged) air temperature, ceiling surface temperature, ceiling surface heat flux.

5.1 *Impulse response*

Figure 1 shows the impulse response of the mean internal testcell air temperature to a 5 minute burst from the heater at a rate of 1 Watt. During the test the power output from the heater was set to 0.5 kW and the results have been scaled down accordingly. The mean air temperature has been obtained by averaging the results from the 17 sensors located within the testcell space. For details of sensor positions see [12].

Note that the response shown has a non-zero value at time zero which implies that there is an instantaneous change in room air temperature when power is applied. In fact the temperature data gathered are actually spot readings at the end of each sampling interval, whereas the power values recorded are averages over the whole sampling interval. This feature of the curve means that if power is applied to the room for five minutes the room temperature will have started to rise by the end of that period and is thus physically reasonable. For consistency with the convention adopted in most simulation programs, the time scale on Figs 1–3 should be shifted to the right by one pulse-width (5 minutes).

Like other simulation programs, HTB-2 represents indoor air temperature at any moment by a single uniform value for each zone: we therefore concentrate on the response of the mean air temperature (averaged over 17 measurement points, thus roughly volumetrically). Similarly measured surface temperatures are averaged over 2 points per surface. Heat fluxes were measured only at one point on each surface.

The impulse responses of the air temperature sensors at the various locations within the testcell have not been included in this paper but they are of the same general shape as the mean air response. Inspection of the curves would reveal the range of vertical temperature stratification that builds up; the peak response of the air at the top of the testcell being about twice that of the air at the bottom. It is interesting to note that the temperature stratification is present even when the air is stirred with the fan convector which indicates that the assumption of "perfect mixing" used in models does not hold.

Figure 2 shows the impulse response of the ceiling surface temperature derived in the same way as the bulk air temperature. The ceiling surface temperature shows a pronounced response to heater power. Curiously the peak occurs immediately unlike the air temperature where it was delayed by about 10 minutes. The fact that heater output is almost completely convective rules out the possibility of this being generated by direct radiation from the heater. A more likely explanation is that it is generated by warm air from the heater impinging on the ceiling before other parts of the room: the average temperature, of necessity will lag behind.

Figure 3 shows the response of the surface heat flux

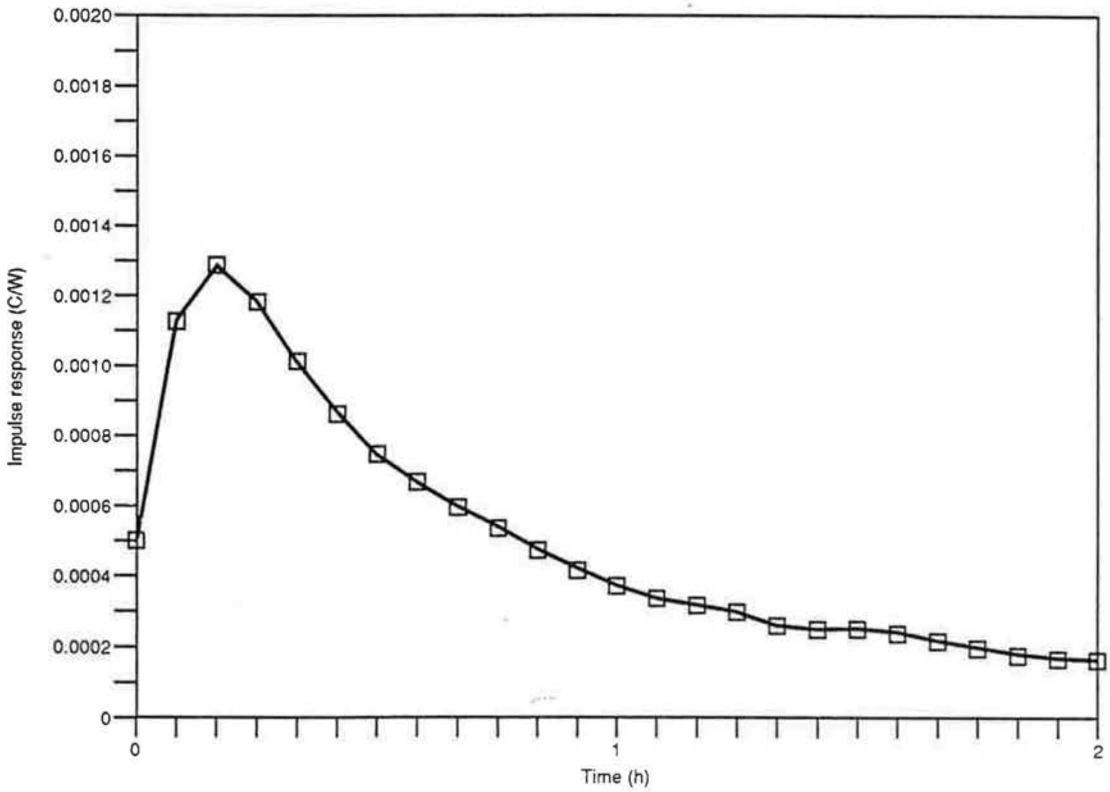

Fig. 1. Heat input vs mean air temperature.

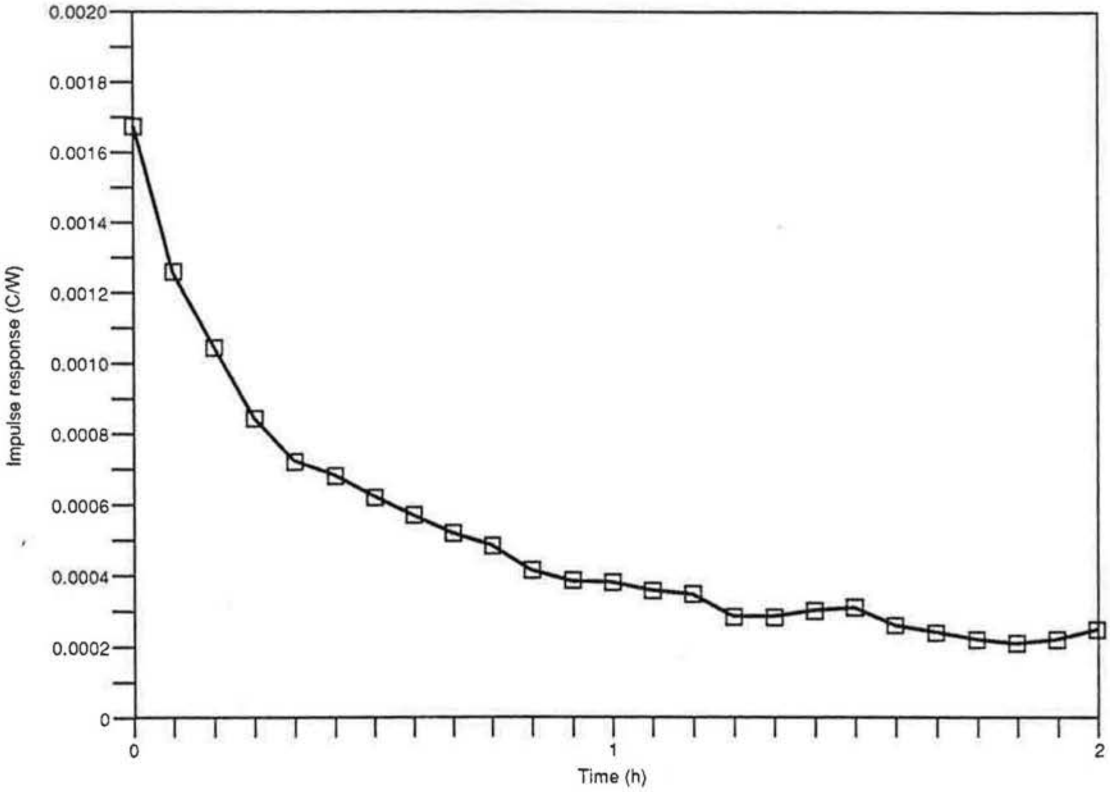

Fig. 2. Heat input vs ceiling surface temperature.

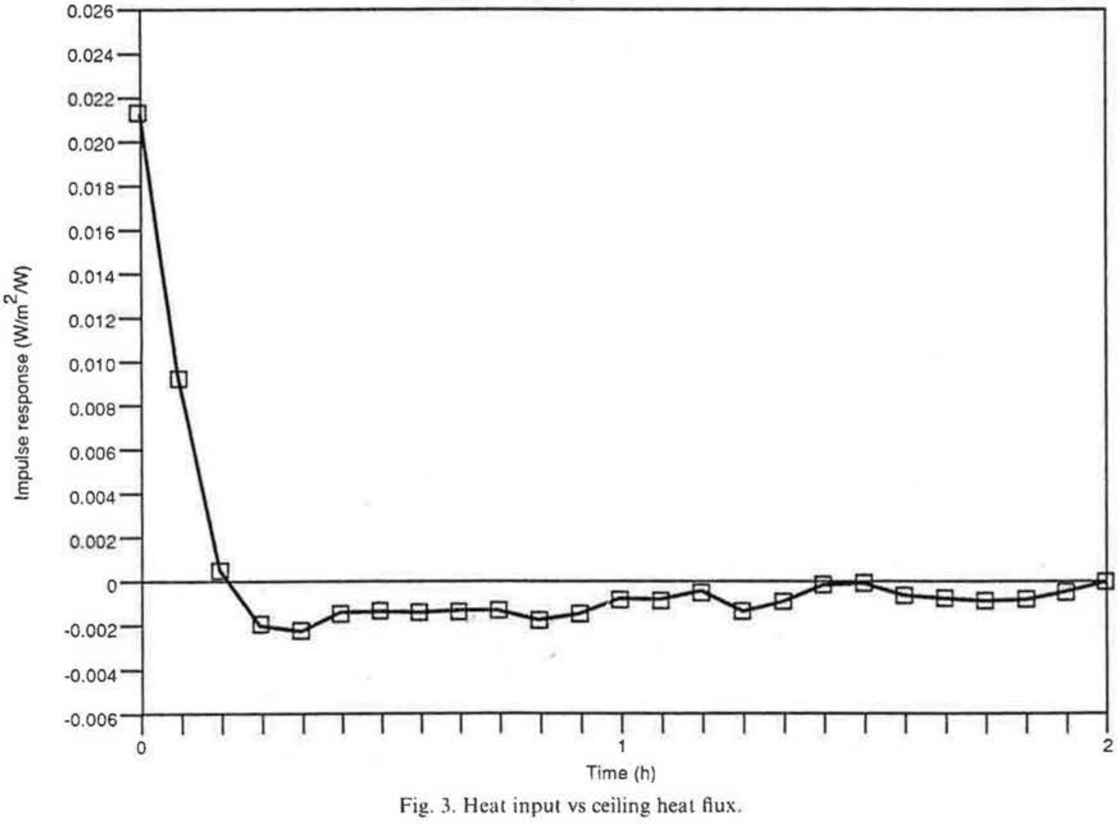

Fig. 3. Heat input vs ceiling heat flux.

at the ceiling, which is of relatively light construction. Following a 5 minute burst from the heater of 1 W the flux rises to about 22 mW/m^2 and remains positive (i.e. heat flow into ceiling from internal air) for about ten minutes. After this period the heat flux response becomes negative indicating that energy begins to flow back out of the surface. The maximum flux return to the testcell is about 2 mW/m^2 which decays after about 2 hours. This is broadly consistent with the evolution of the air and surface temperatures in Figs 1 and 2. Analysis of the heat exchanges between surfaces and between air and surfaces shows that the relatively low thermal capacity ceiling plays an important role in the pre-heating of the space: after a number of minutes, it has become appreciably warmer than the other, higher thermal capacity, surfaces. A significant proportion of the heat received by the walls is by re-radiation from the ceiling—and the floor receives heat from the ceiling and loses it by convection to the air, which because of vertical stratification, is locally cool.

In the case of the north wall and floor, the temperature and heat flux responses were very small and consequently the corresponding plots have not been presented. In practice a five-minutely sequence of heater operations can only yield information about the thermal response over a period of about half an hour. Therefore, it cannot tell us much about the response of high capacity components such as the more heavily constructed brick wall, or the floor which is in a relatively unresponsive section of the testcell. To address these problems a subsequent experiment has recently been carried out in which the heater duration has been increased to 30 minutes and this work will be analysed in the near future.

5.2 *Step response and comparison with computer predictions*

In this section we deal with the comparison of the measured responses with those modelled by the HTB-2 computer simulation. The object of this is to see how well the predictions from computer simulations compare with the measured responses.

We could compare either step or impulse responses, but the former is more useful because this mode of heating is easily understood as that which corresponds to the initial heating of a room from a cold start, i.e. the response to a step change in heat input.

The measured step response can be constructed by integrating the output of a particular impulse response. For example if the impulse response of the mean air temperature to a 5 minute heater burst of 1 W is integrated over a period of time we obtain the mean air step response to a 1 W step input. In this way the step response of the mean air temperature, ceiling surface temperature and ceiling surface heat flux has been obtained and compared with a number of predictions from the HTB-2 computer model.

The computer model was set up using the internal dimensions of the testcell to define both the internal and external measurements. The ventilation rate was set to 1.79 air changes per hour to reproduce conditions within the testcell during the experiment. In order to predict the response of the testcell to a step input, all the external environmental conditions within the model were held constant. At the beginning of each computer simulation all internal and external air and surface temperatures were set to a nominal 10°C. The testcell was then run for 5 simulation days to allow internal equilibrium conditions to be achieved before a step input was applied.

Initially a step input of 1 W was applied to the model but it was found that the resulting output did not stabilize out at an upper bound level but continued to rise at a very small rate. Investigation of model parameters indicated that the long-wave algorithm appeared to cause this instability. Several runs were performed with different levels of cloud cover (a factor which affects the magnitude of the long-wave radiation) but it was not possible to obtain a stable output. To overcome this problem it was decided to increase the step input to 500 W and to scale down the resulting output. In this way the effects of the instability of the long-wave algorithm would become negligible.

5.2.1 *Base case*. In the base case comparison, Figs 4, 5 and 6 show a comparison between the measured response and predicted response of the mean air temperature, ceiling surface temperature and ceiling heat flux respectively for a 1 W step input. The first general point to note is that the step responses which are derived from the measured impulse responses are physically sensible and broadly confirm observations made when the testcell is operated deterministically under intermittent heating patterns.

For the air (Fig. 4) it can be seen that the measured temperature response takes the form of an apparently exponential curve whereas the predicted response is quite different having a two stage response with most of the temperature rise occurring in the first ten minutes. In fact, the "measured" response is similar in form to that previously estimated from a series of conventional experiments [2]: after a delay—in this case, about 4 minutes—the temperature rise is approximately proportional to the square root of the elapsed time. In general it can be seen that the predicted response is much greater than the measured response and after $\frac{1}{2}$ hour operation the predicted air response is still more than twice that of the measured value.

At the ceiling (Fig. 5) it can be seen that the curves are similar in form but with the computer under-predicting the ceiling temperature response. In this case the "measured" ceiling temperature rise is proportional to the square root of elapsed time, with a lag of about one minute. It appears likely that heated air reaches the ceiling within about one minute, while mixing processes delay the rise in average air temperature by about four minutes. After $\frac{1}{2}$ hour operation the predicted air response is 19% lower than measured.

In terms of heat flux through the ceiling (Fig. 6) it can be seen that the two curves are of similar form but with the predicted curve rising more rapidly than the measured curve. The predicted curve has a peak value 13% greater than measured, and this occurs about 10 minutes before the measured peak. It is possible that the differences in ceiling heat flux may simply reflect the differences in air-to-surface temperature difference between observed and simulated values.

There are clearly very significant differences between the observed and simulated responses, especially of the

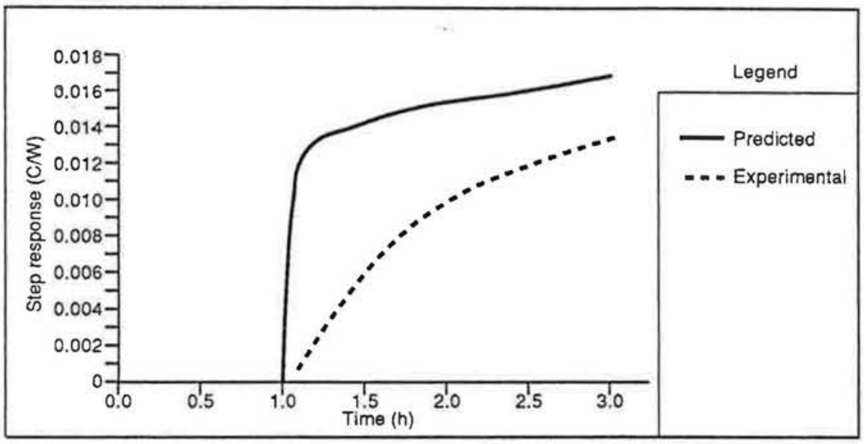

Fig. 4. Air temperature vs time. Base run.

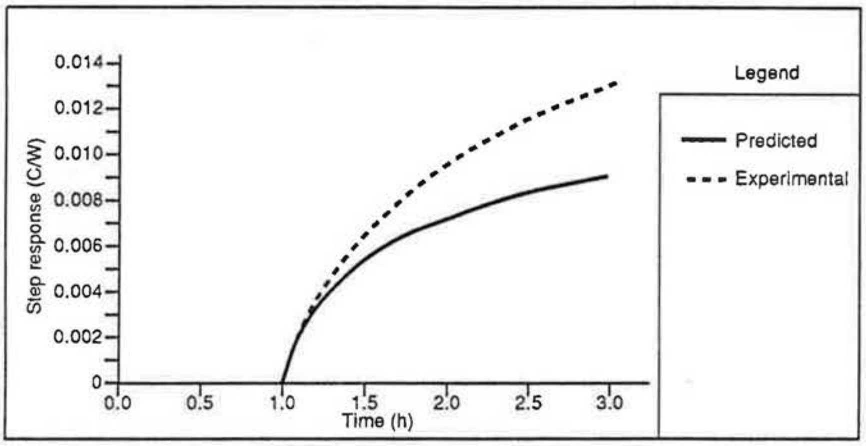

Fig. 5. Ceiling temperature vs time. Base run.

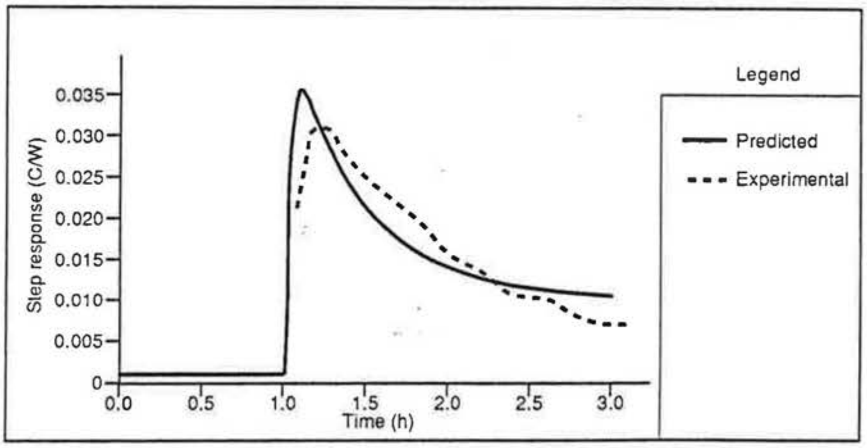

Fig. 6. Ceiling flux vs time. Base run.

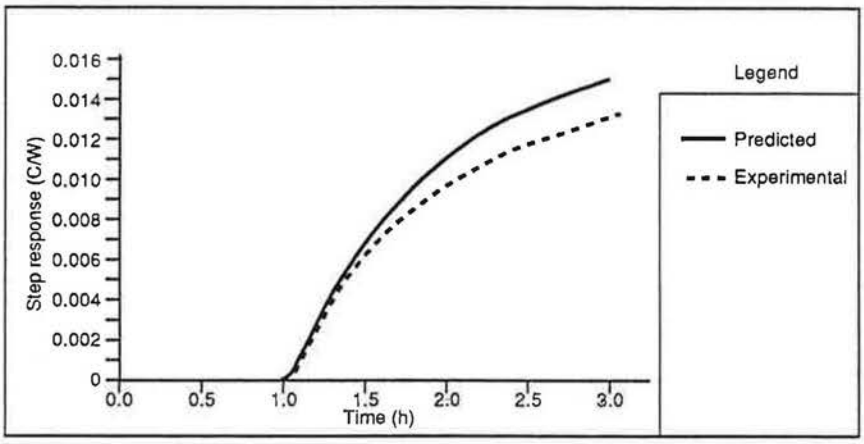

Fig. 7. Air temperature vs time. Heater time constant 40 min.

mean air temperature. In order to explore the extent to which these are sensitive to modelling assumptions, several variations were examined. The changes introduced were not intended to represent physically plausible variations, but rather to determine what magnitude of change was necessary to bring the two sets of results into closer alignment—and to investigate whether the consequences were consistent. The changes include:

Adjustment of HTB-2 heater time constant.
Modification of air specific heat and ventilation rate.
Modification of air density and ventilation rate.
Doubling of internal convective heat transfer coefficients.
Doubling of ventilation rate.

5.2.2 *Adjustment to HTB-2 heater time constant.* The heater was modelled with zero time constant: it had little thermal capacity. This was increased incrementally to a value of 40 minutes, at which point there was a fair measure of agreement in terms of air temperature response.

Figures 7, 8 and 9 show a comparison between the measured response and predicted response of the mean air temperature, ceiling surface temperature and ceiling heat flux respectively for a 1 W step input from a heater with a time constant of 40 minutes.

In the case of the air temperature response (Fig. 7), it can be seen that the measured and predicted curves are fairly similar. However, adjusting the heater time constant causes the ceiling temperature and heat flux to change much more slowly compared to the measured curves (Figs 10 and 11), and also suppresses the predicted peak heat flux to about 50% of the measured value. Also the predicted peak heat flux lags the measured value by about $\frac{1}{2}$ hour.

It is concluded that this change has introduced serious extra discrepancies, and does not improve the lack of agreement between measured and predicted curves.

5.2.3 *Modification of air specific heat and ventilation rate.* The thermal capacity of the air can be increased by changing the assumed specific heat. In order to avoid the complications of changes to the ventilation heat loss, it is also necessary to decrease the simulated ventilation rate in the same proportion as the specific heat is increased.

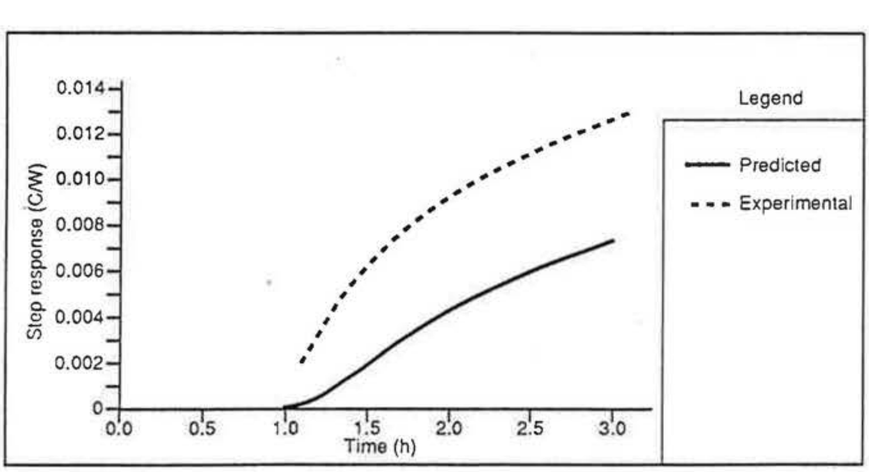

Fig. 8. Ceiling temperature vs time. Heater time constant 40 min.

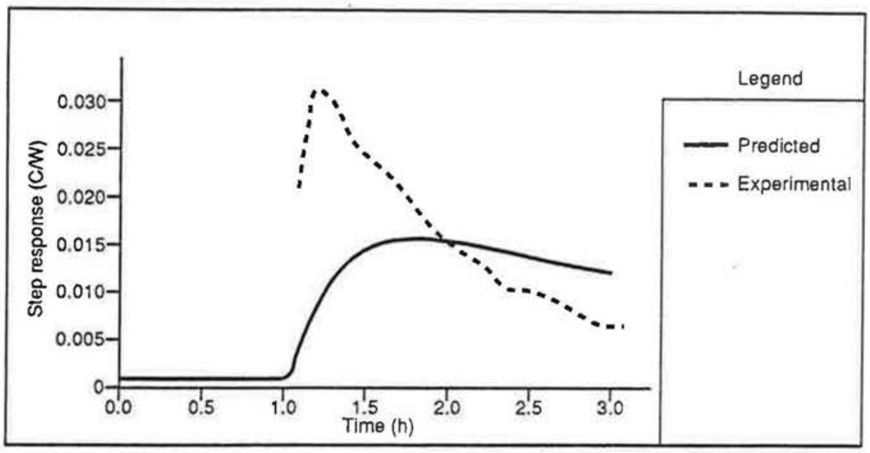

Fig. 9. Ceiling flux vs time. Heater time constant 40 min.

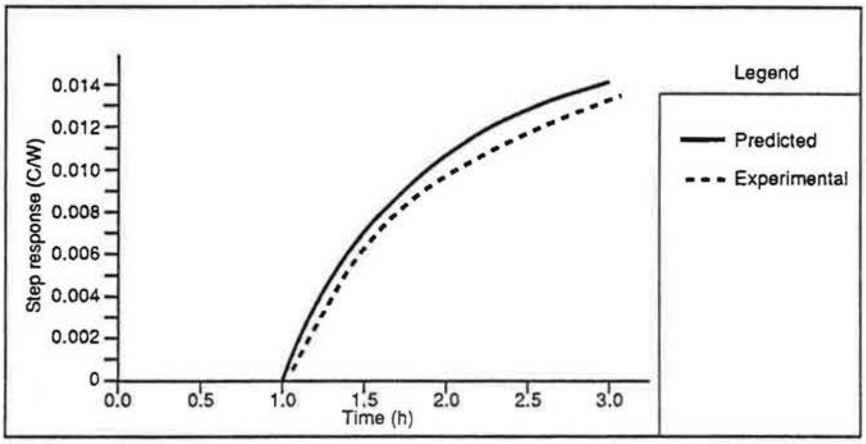

Fig. 10. Air temperature vs time. 16 × specific heat, 1/16 vent.

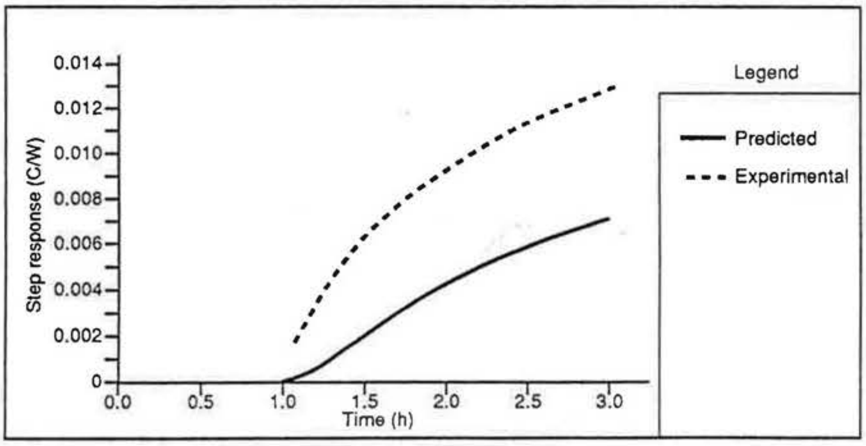

Fig. 11. Ceiling temperature vs time. 16 × specific heat, 1/16 vent.

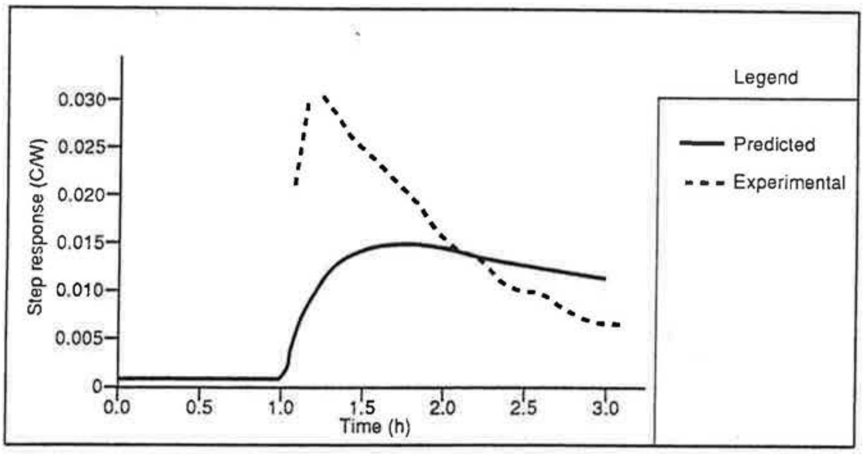

Fig. 12. Ceiling flux vs time. 16 × specific heat, 1/16 vent.

Several computer runs were carried out and it was found that increasing the air specific heat by a factor of 16 (and reducing the ventilation rate to 1/16th) resulted in a fairly good match between the predicted and measured air temperature response and this is shown in Fig. 10. However, there was a mismatch in the predicted and measured surface temperature and heat flux (Figs 11 and 12) of an order similar to that found in the previous case when the heater time constant was increased (section 5.2.2).

5.2.4 *Modification of air density and ventilation rate.* Increasing the air density ought to have an identical effect to increasing the specific heat and hence the air density was increased by a factor of 16 and the ventilation rate was reduced to 1/16th.

Surprisingly, this change in the model had no effect upon the predicted temperature and flux responses which indicates that although there is control over the air density, it does not appear to be taken into account when HTB-2 carries out heat flow calculations. Accordingly no curves for this configuration of parameters are presented.

5.2.5 *Doubling of internal convective heat transfer coefficients.* Earlier studies had thrown some doubt on the reliability of the standard values assigned to convective heat flow coefficients and hence this parameter has been adjusted.

Figures 13, 14 and 15 show a comparison between the measured response and predicted response of the mean air temperature, ceiling surface temperature and ceiling heat flux respectively for the case when the internal convective heat transfer coefficients have been doubled. (Default values of coefficients are 3.08, 4.04 and 0.92 W/m^2K for wall ceiling and floor respectively.)

Compared to the base case (5.2.1) doubling the convection coefficient (Fig. 13) causes a significant reduction in the maximum air response during the initial stages before the knee of the curve is reached. Also the simulated ceiling flux rises and falls more rapidly (Fig. 15) which is to be expected since the energy from the air is being transported to the surrounding surfaces more rapidly due to increased coefficients. The ceiling surface temperature response (Fig. 14) is suppressed slightly.

5.2.6 *Doubling of ventilation rate.* Compared with the base case, doubling the ventilation rate has a small effect on the response of the mean air temperature, ceiling surface temperature and ceiling heat flux respectively and consequently the associated response curves have not been included.

6. CONCLUSIONS

6.1 *Response measurements*

Stochastic testing, using a random sequence of 5 minute periods of heating, has demonstrated that it is possible to extract experimental impulse and step response functions from outdoor test cell measurements.

In particular, it has been possible to examine the response of the internal air temperature, ceiling surface temperature and ceiling heat flux to an impulse of 1 W for 5 minutes. From these measurements, the associated step responses have been determined and it is seen that they are physically sensible and broadly confirm observations made when the testcell is operated deterministically.

It was not possible to obtain satisfactory response curves for the testcell wall and floor. The reason for this is probably due to the short duration of heat input in conjunction with (i) the heavy construction of the wall, and (ii) the fact that the floor is in a relatively unresponsive location within the testcell. Using a random heater sequence with a longer duration (30 minute burst) may enable satisfactory response measurements to be made at the wall and floor surface.

6.2 *Step response and comparison with computer predictions*

The computer model HTB-2 has been used to predict the step response of the air temperature and the ceiling surface temperature and heat flux and has been compared with the experimental response results. The comparison reveals substantial disagreement between measured and

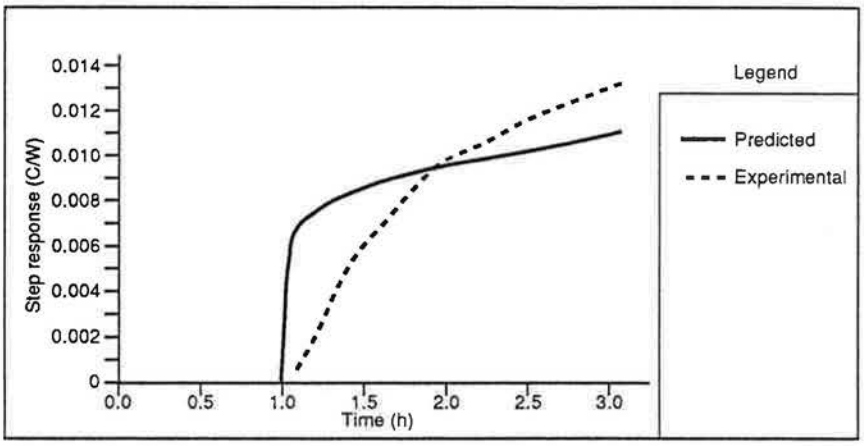

Fig. 13. Air temperature vs time. Double int htc.

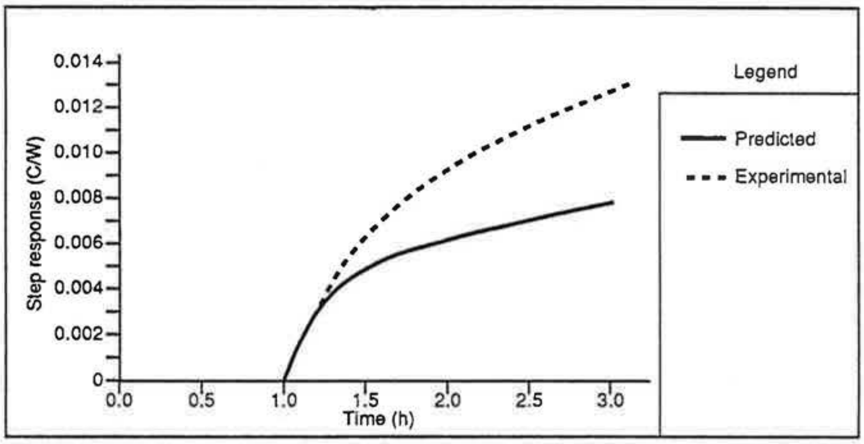

Fig. 14. Ceiling temperature vs time. Double int htc.

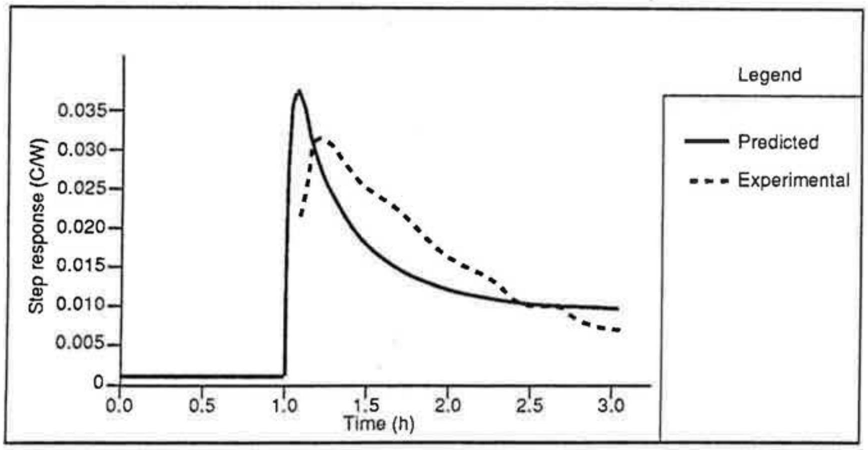

Fig. 15. Ceiling flux vs time. Double int htc.

simulated air temperature responses. It appears that the widely-used "perfect-mixing" assumption not only breaks down, but does so in a manner which has serious consequences when predicting transient thermal response: the actual air temperature response is much slower than that predicted.

By contrast the measured response of the ceiling surface temperature is more rapid than the simulated response—possibly because of rapid local heating from the warm air currents which are implied by variations of air temperature response with position. Air temperature near the ceiling clearly rises faster and further than elsewhere in the cell.

Differences in simulated and observed heat fluxes at the ceiling surface are less marked, and may simply be the consequences of the differences in temperature response remarked above.

Distorting the model parameters to improve the air response is shown to cause serious problems elsewhere.

Three further issues call for examination: the detailed analysis of the measured air temperature response; the extension of the analysis to longer periods, so that the responses of the floor and walls may be obtained; and better air models within simulation programs. The data which will enable the first two of these to be carried out has been obtained, and further studies—including the third issue—are planned, in collaboration with university-based researchers.

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