Measurement and Analysis of *in situ* Dynamic Thermal Performance of Building Envelopes Using Heat Flow Meter Arrays*

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ABSTRACT

A method is described for determining dynamic thermal performance of building envelopes *in situ*. The method is passive in the sense that only heat flux and temperature measurements are made -- experimental conditions are generated by the natural environment of the wall. Included in the method are procedures for time-averaging of large quantities of data using numerical techniques. This approach makes it possible to collect and analyze digital data rapidly enough to provide essentially a continuous record of performance and, at the same time, store the data in a form convenient for subsequent analysis. Dynamic models are developed, as are methods of correlating them with measured data to determine model parameters representative of dynamic performance characteristics. Sample data obtained from a typical frame cavity wall were measured and fitted to the models. The relationship between the dynamic performance characteristics of this wall and traditional steady-state characteristics is discussed. The method described here avoids many of the limitations inherent in steady-state experimental measurements.

Keywords

building thermal performance; dynamic models of thermal performance; field measurement of thermal performance; passive measurement of thermal performance; thermal performance models.

INTRODUCTION

Because of our current national energy situation, energy conservation has become an important approach for maintaining a balance between supply and demand in a world where new energy supplies are becoming increasingly difficult to find and more expensive. Over one-third of the total energy consumption in the United States is in buildings, and more than half of that amount is expended for heating or cooling [1]. Since the economics of increasing conservation efforts -- as opposed to developing new supplies -- is quite favorable [2], there is a strong incentive to improve the thermal performance of building envelopes. It is thus important to have an ability to accurately and reliably measure the thermal performance of envelope components, both for current practice designs and improvements to them, and for totally innovative designs. We are developing several approaches that will overcome many of the limitations of current testing methods. This paper describes one of them. The advantages of this approach are that it permits dynamic characterization, it can be used to determine *in situ* performance in actual buildings, and it does not require the experimental imposition of any temperature or flux conditions as boundary conditions. The method allows the measurement and characterization of non-uniform walls, without the need for large-area devices. A related method, based on the

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imposition of transient heat fluxes, is described in a companion paper [3].

Basically, the approach described here involves the use of arrays of small-area, sensitive, heat-flow meters and temperature-measurement transducers. Measurements typically made are of air temperatures near the wall (or any other planar envelope system), surface fluxes and temperatures at a number of positions on each side of a wall. Time-series data are collected from each transducer at rates that are large compared to the highest frequency of interest in the dynamic performance of the system. Enough data are acquired to determine dynamic response properties over all frequencies of interest, and they are then averaged appropriately over the entire area of the measurement array. These data are either stored for subsequent processing, or processed on-line using a microprocessor-based computer system, if the data has been acquired in digital form. Although straightforward in concept, this approach had not been developed because of limitations in instrumentation. Presently, however, technologic developments have reached a point where hardware for data acquisition and numerical processing are now available and, thus, such an approach is feasible for the first time. These developments have led to our approach, which lends itself especially well to field applications, as well as laboratory applications.

The processed information leads to a complete dynamic characterization of the wall at all frequencies of interest. It yields steady-state properties in the low-frequency limit, that can be compared with calculated values based on nominal wall design, or with values measured by existing steady-state methods. We feel that this approach is preferable to existing steady-state measurement methods because the properties derived from dynamic measurements are the properties displayed by the wall in its actual thermal environment. Additionally, the effect on heat loss and gain properties due solely to dynamic phenomena, such as thermal storage and mass effects, are directly measured and appear explicitly in the dynamic characterization. This is information that is not available from steady-state tests. We believe this dynamic measurement technique to be superior because, unlike steady-state tests, it provides important information on the properties displayed by a wall in its actual thermal environment. Additionally, the effects of thermal storage and thermal mass on heat loss and gain reflect exclusively on the dynamic properties of a wall, can be measured directly, and thus become an explicit component of the dynamic characterization.

We anticipate a number of useful applications for this information. One example would be the development of response-factor or conduction transfer function time-series coefficients for use in computerized calculations of building heating and cooling loads calculations [4,5]. The measured dynamic characterization could be used in these circumstances to predict thermal performance under any specified thermal environment, such as actual weather conditions different from those during which the measured characterization took place. Another significant application would be the direct comparison of the dynamic properties of various wall designs based on measured data, which would allow us, for the first time, to determine the degree to which actual walls perform in comparison with predictions of performance based on calculations or on the measurement of similar walls in the laboratory. This application thus provides us with some estimate of the effects of materials choices and construction practice on actual performance.

In the remainder of this report, we (1) summarize the analytical basis for the dynamic models used in analyzing the measured data and providing a framework for dynamic characterization; (2) describes in greater detail the data analysis methodology used with the dynamic models; and (3) presents results from a preliminary experiment that highlights the features of this approach.

ANALYTICAL REPRESENTATION OF DYNAMIC PERFORMANCE

The experimental determination of dynamic thermal performance has been inherently more difficult than steady-state methods; accordingly, the amount of work reported in the literature is limited. From a general survey we have made of the literature on thermal performance [6], we find that there have been several approaches to the characterization of dynamic thermal behavior. General approaches, which start from first principles, treat walls as discrete layers of homogeneous conduction media and generally lead to the formulation of a conduction transfer function matrix (see references [7-12]). An approach based on thermal admittance functions is described in references [13-15], and the response factor formulation is described in [16,17]. Laboratory-based studies of dynamic behavior are described in references [18-25], and are relevant because a number of them utilize lumped-parameter models, which are amenable to experimental analysis using electrical analogs. These lumped-parameter models can also be analyzed numerically using digital computers, which we describe in more detail below and utilize in the subsequent analysis of our data. Experimental studies that include measurements based on actual weather conditions are described in references [26-30].

We found it useful to recognize the similarity of a wall to a multiport linear system. From this basis, either a continuous, or a lumped-parameter representation is possible. In the simplest case, the wall can be represented by a linear two-port system. The temperature (T) and heat flow (ϕ) are analogous to voltage and current, respectively, and the two ports represent the exterior and interior surfaces of the wall. From the time-dependent quantities T(t) and $\phi(t)$, we can derive their Fourier transforms T(f) and $\phi(f)$. (Unless otherwise noted, these quantities will subsequently be the transformed quantities.) Working in the frequency domain, there is a transfer function relating T_1, T_2, ϕ_1, and ϕ_2, the temperatures and heat fluxes at ports 1 and 2, respectively. For a compact notation, we write vectors:

$$\underline{T} = (T_1, T_2)^{\dagger} \tag{1}$$

$$\underline{\phi} = (\phi_1, \phi_2)^{\dagger} \tag{2}$$

There is a 2 X 2 impedance matrix $\overline{Z}$ such that

$$\underline{T} = \overline{Z}\, \underline{\phi} \tag{3}$$

The inverse of $\overline{Z}$ is an admittance matrix $\overline{A} = \overline{Z}^{-1}$ such that

$$\underline{\phi} = \overline{A}\, \underline{T} \tag{4}$$

All of the above vectors are complex functions of frequency, f. In the case of a wall, the admittance and impedance matrices have rather smooth and simple dependence on frequency -- a consequence of the fact that heat flow through a material by conduction can be described by a diffusion equation rather than a wave equation. Stated another way, materials have heat capacity and heat-flow resistance, but there is no thermal phenomenon analogous to inductance. Our problem is to find an adequate description of $\overline{A}$ for a wall.

DATA ANALYSIS METHODOLOGY

Because we expect the admittance to be a smooth function of frequency, we attempt to describe the wall thermal performance with a parametric model. This type of model recognizes and exploits the known physical properties of the wall; that is, the wall does not have to be treated as a completely "black box". Models having the desired smooth frequency response can be generated by using lumped elements of thermal resistance and capacitance and connecting them in a way analogous to electrical circuits. The analog of the voltage and current drives and responses are, in our case, the time-series record of the inside and outside temperatures and surface heat fluxes. The admittance matrix, $\overline{A}$, for such a model can be evaluated either algebraically or numerically, using standard techniques of circuit theory. The circuit equivalents of the models used in this study are shown in Fig. 1 in order of increasing complexity. For each model there are a number of resistance and capacitance parameters that must be chosen to achieve a best fit to the data. In addition to the parameters shown in the figure, each model contains several other parameters that are of lesser interest in characterizing the wall, i.e.,

(1) For each capacity, there must be an initial temperature -- in our fits, an adjustable parameter.

(2) We found evidence in our fits that the temperature scales for the inside and outside were offset from each other. To accommodate this offset, we included in some of our fits an adjustable offset parameter, T_0.

(3) During the afternoon, even though the wall was shaded, there was an extra heat input on the exterior surface due indirectly to the sun. We included in some of the fits two direct radiant heat inputs, to the exterior stud and cavity, respectively.

(4) The driving function must also be inferred from the data. The actual temperatures inside and outside are inferred from a weighted combination of temperature and heat-flux measurements. There are two fitted temperatures (inside and outside) for each time step in the data, i.e., 1026 drive function parameters. These drive parameters can be evaluated separately, by linear regression, for each time step, and thus do not add significantly to the complexity of the problem.

The other parameters are found by a numerical evaluation of chi-squared, and a search for the parameter values which minimize chi-squared, both of which were accomplished by using the simplex algorithm of Nelder and Mead [31] and Fletcher's "switching algorithm" [32,33].

Although the models are described in Fig. 1 as resistor/capacitor circuits, what was actually tested as the model were finite-time-step digital filters whose performance was very similar to that of the illustrated circuits but not the same. In all cases, the time step used for fitting and parameter determination was the same as that in the digitized data (168.75 s). By deciding to use digital filters instead of actual lumped-parameter circuit models, we were able to reduce substantially the amount of computation needed. The most complicated model reported here used 21 parameters in addition to the trivial drive function parameters.

EXPERIMENTAL EXAMPLE

For the first test of these ideas, we used an array of four sensors for heat flux and two for air temperature on a wall of a typical residence in this area. The construction of the wall was an insulated frame cavity with a stucco exterior. Figure 2 shows schematically the arrangement of the sensors on a cross-section of the wall. The heat-flux sensors are 5-cm squares having sensitivities of about 30 W/m^2mV. The manufacturer's calibration was used for each of the sensors. The overall thermal resistance of these devices is about .002 Km^2/W. They are model B-185 of International Thermal Instrument Company. The temperature sensors used, Analog Devices model AD590, are solid-state devices that measure temperature through its effect on the voltage-current relation in a PN junction. The air temperature was measured inside and outside approximately 20 cm from the wall surfaces. Heat-flux sensors were placed over a stud and over the center of a cavity section of the wall between studs, both inside and outside. The outside surface of the wall and the associated temperature sensor were shaded from direct sunlight in order to match the exterior heat flux to the maximum range of the recorder and to minimize problems of interpretation in relating heat flux to air temperature. The output of the sensors was recorded on a six-channel chart recorder. After the data were collected, they were digitized manually and stored in a computer for subsequent analysis. In the future, data will be acquired automatically and stored directly in digital form, without human intervention. The time-series data were digitized in time steps of 168.75 s. There are 512 such steps in a day. Data from 513 consecutive steps were digitized for the analysis. In all, we used 3078 independent measurements in regressing this model i.e., there were 3078 - 1026 - 21 = 2031 residual degrees of freedom for the most complicated model. A sample of the original analog data is shown in Fig. 3.

In addition to regressing different models, some computer analyses were made by regressing a single model on different portions of the data, with the temperature offset, T_0, fixed, free, and otherwise adjusted. A summary of the results of these several regressions are presented in Table 1. For comparison, the last line contains the steady-state values for the air-to-air resistances, calculated from nominal materials properties.

Cases 4 and 5 are results using the same model as case 3, but each uses only half the data from the sensors over the stud, where the data collected over the total time period used in the analysis is divided into two sequential time periods, each half the length of the total time period. Case 4 uses the first half of the data for analysis, and case 5 the second half. Cases 8, 9, 10, and 11 use the same model as case 7, with the following exceptions: Case 8 requires that the offsets in temperature and heat flow be fixed at zero. Case 9 smooths the short-term fluctuations by averaging every four sequential data points together. Case 10 includes a simple model for solar radiation on the exterior surface. Case 11 combines the effects of cases 8, 9, and 10, but also allows the temperature offset to be non-zero. Case 13 is the same as case 12 except that the data streams have been corrected for the displacement of the recorder pens, which had the effect of causing a constant time offset for data recorded on each of the channels with the adjacent channel.

Figures 4 and 5 are computer-generated plots from the analysis of case 13. The symbol (0) represents measured data, and (+) the best fit from model IV. (There is no (+) when the fit falls on the same print column as the measured data.) Values in parentheses indicate the size of the standard deviation used in computing chi-squared. Here, size of the standard deviation is about one print column. The fluctuations in Fig.4 are caused by the cycling of the furnace in the house where the measurements were made.

The chi-squared values for the various fits show a progression toward better agreement of the models with the measured data. Fits with a non-zero temperature offset, T_0, are definitely preferred over those for which it is fixed at zero. We draw two conclusions from this relative improvement:

(1) The zero offset on the chart recorder was not set correctly for one or both of the temperature sensors.*

(2) It is possible to determine the thermal resistance of a wall from changes in the temperature across the wall rather than from the absolute temperature difference across the wall. Thus, it is not necessary to have a true zero offset.

We notice that the values of R_{total} and C_{total} do not change much as we add to the complexity of the model. Therefore, we feel that further refinements of the model are unnecessary for making assessments of thermal performance.

DISCUSSION

In order to characterize the dynamic performance of a whole wall, a larger array of sensors than that used in our experiment would be needed. The results of the regression analyses that are presented here encourage us to develop larger arrays, and to have the data acquired automatically by the computer. With an array of perhaps a dozen heat-flux sensors, we should be able to determine the dynamic thermal characteristics of any wall in situ. In this work, the existence of a direct radiant heat input to the exterior surface was inferred from the data. This inference would be considerably strengthened by direct measurement of the surface temperatures and by including such data in the regression. It would mean that solar exposure could be treated as part of the analysis and that shading of walls would not be required, if the dynamic range of the flux sensors and data acquisition instrumentation is large enough.

In addition to models in which we include transverse heat flow over the surface of the wall, we intend to attempt modeling the total heat flow in a larger array by a single digital filter. Because the models are actually the digital filters themselves, we will be able to use them quite directly to compute the experimentally determined response factors for use in computerized building heating and cooling load calculations, as mentioned in the introduction.

CONCLUSIONS

We have used a passive experimental approach for collecting temperature and heat-flow data on a wall in situ. These data have been fitted to several lumped-parameter dynamic models, with good agreement. The parameters calculated from the model fits, which represent dynamic wall performance, are not very model-dependent, suggesting that simple dynamic wall models should suffice. The steady-state wall characteristics derived from the fitted parameters have been compared with values calculated from the wall design and from nominal material properties. Although the differences are significant, independent measurements on this same wall [34] suggest that the nominally calculated values may be in substantial error.

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* Adjusting the offset of the recorder is equivalent to calibrating the zero of the sensor. Since we were using sensors that measure directly in degrees Kelvin, the recorder offset was large.

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TABLE 1. CALCULATED WALL PARAMETERS FOR LUMPED-PARAMETER MODELS

Model[a]	Chi-Sq	Stud R_{total} (Km^2/W)	Stud C_{total} (kJ/m^2K)	Cavity R_{total} (Km^2/W)	Cavity C_{total} (kJ/m^2K)
1. I	11258	.618	79.7		
2. I	8112			1.102	29.0
3. II	6758	.762	97.6		
4. II 1st 1/2	2206	.776	104.3		
5. II 2nd 1/2	4497	.803	100.1		
6. II	4657			1.15	54.1
7. III	9023	.825	96.0	1.076	51.4
8. III T_o,P_o fixed	11099	1.038	111.0	1.306	58.3
9. III and 4 way avg.	7943	1.033	114.4	1.304	59.4
10. III and radiation	7115	1.045	114.3	1.317	58.9
11. III but free T_o	5769	.833	94.4	1.082	47.6
12. IV	5167	.771	109.1	1.119	41.8
13. IV time adjusted	2874	.778	98.7	1.096	41.7
Calculated nominal		1.1		2.3	

a. These model numbers refer to the circuits shown in Figure 1. Entries are missing from the table when the corresponding data were not used in the fit, i.e., for Model I, case 1 refers to a stud resistance and case 2 to a cavity resistance.

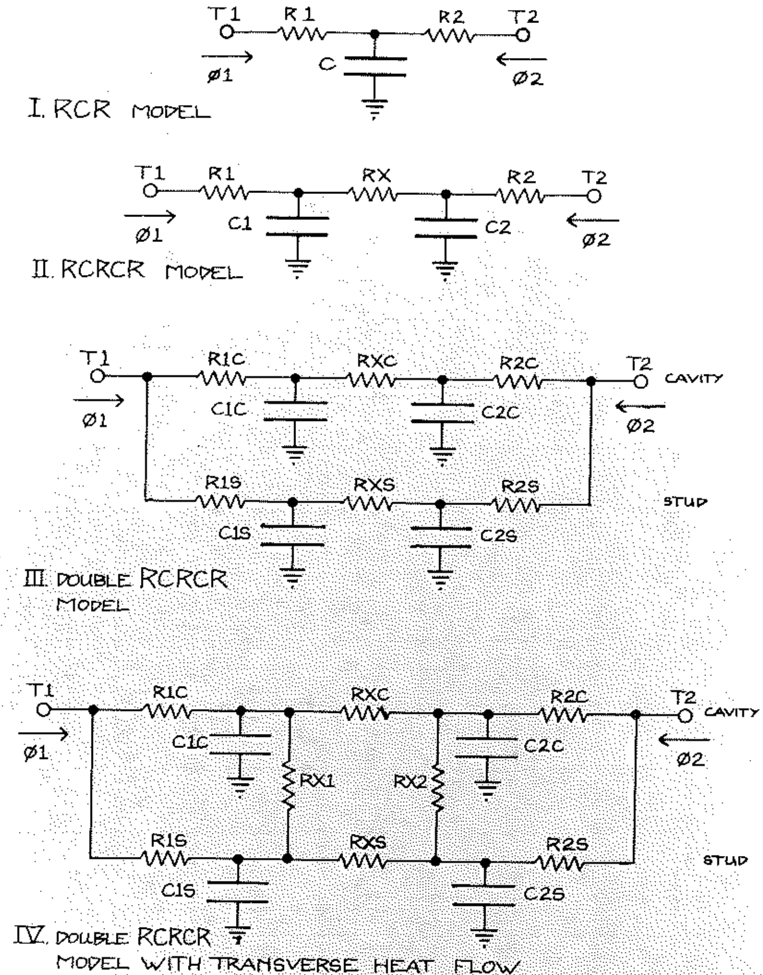

Figure 1. Equivalent circuit representation of lumped-parameter models

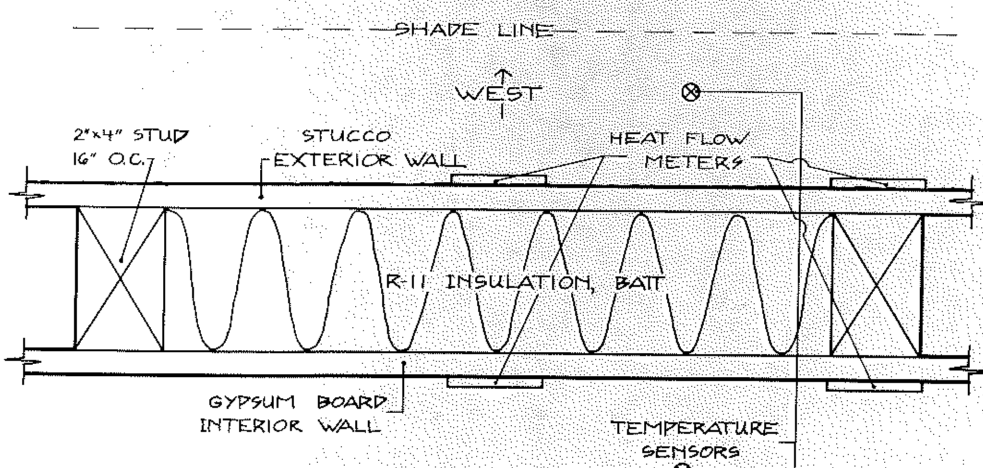

Figure 2. Cross-section of measured frame-cavity wall showing transducer placement

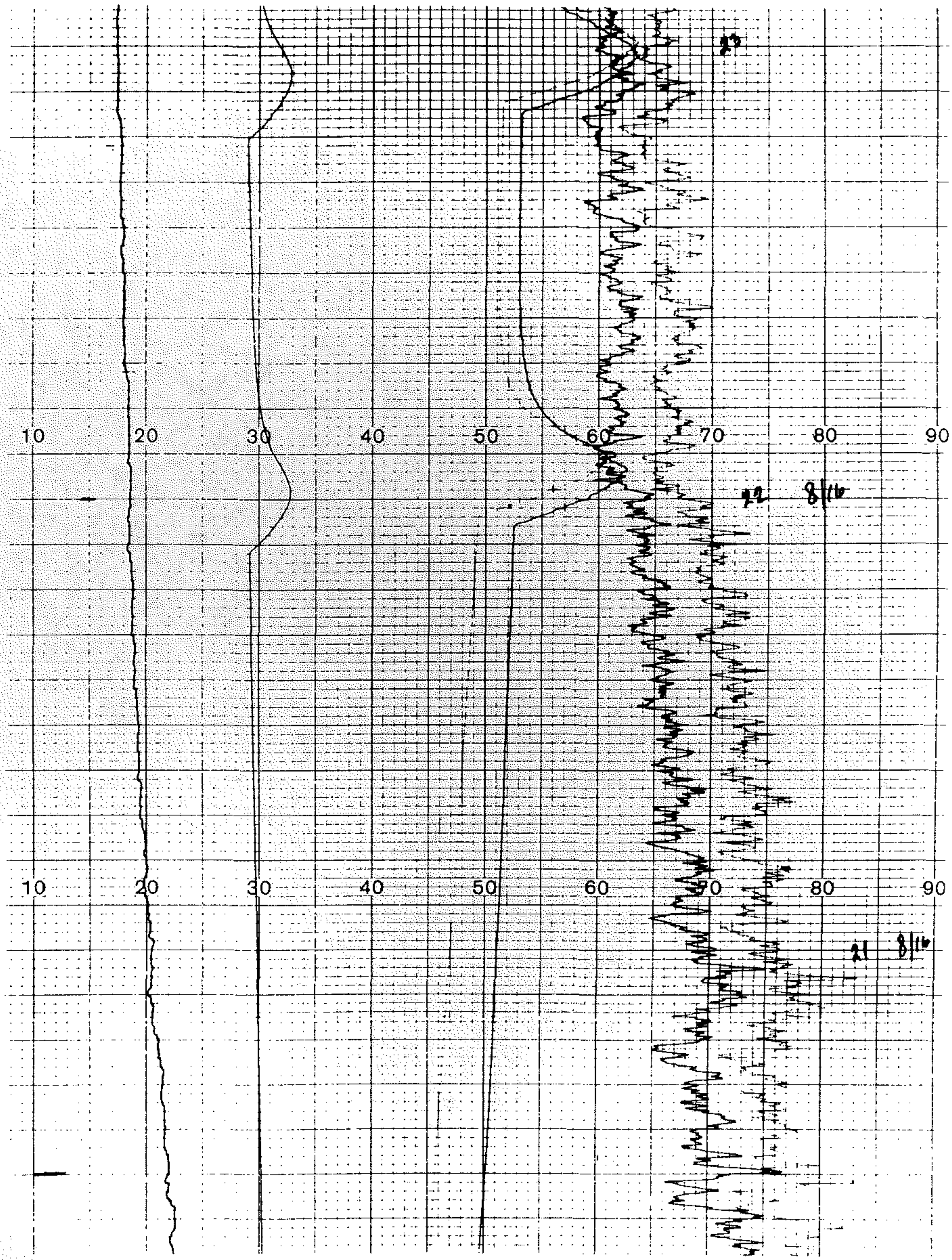

Figure 3. Reproduction of a time-segment of measured data used in the analysis

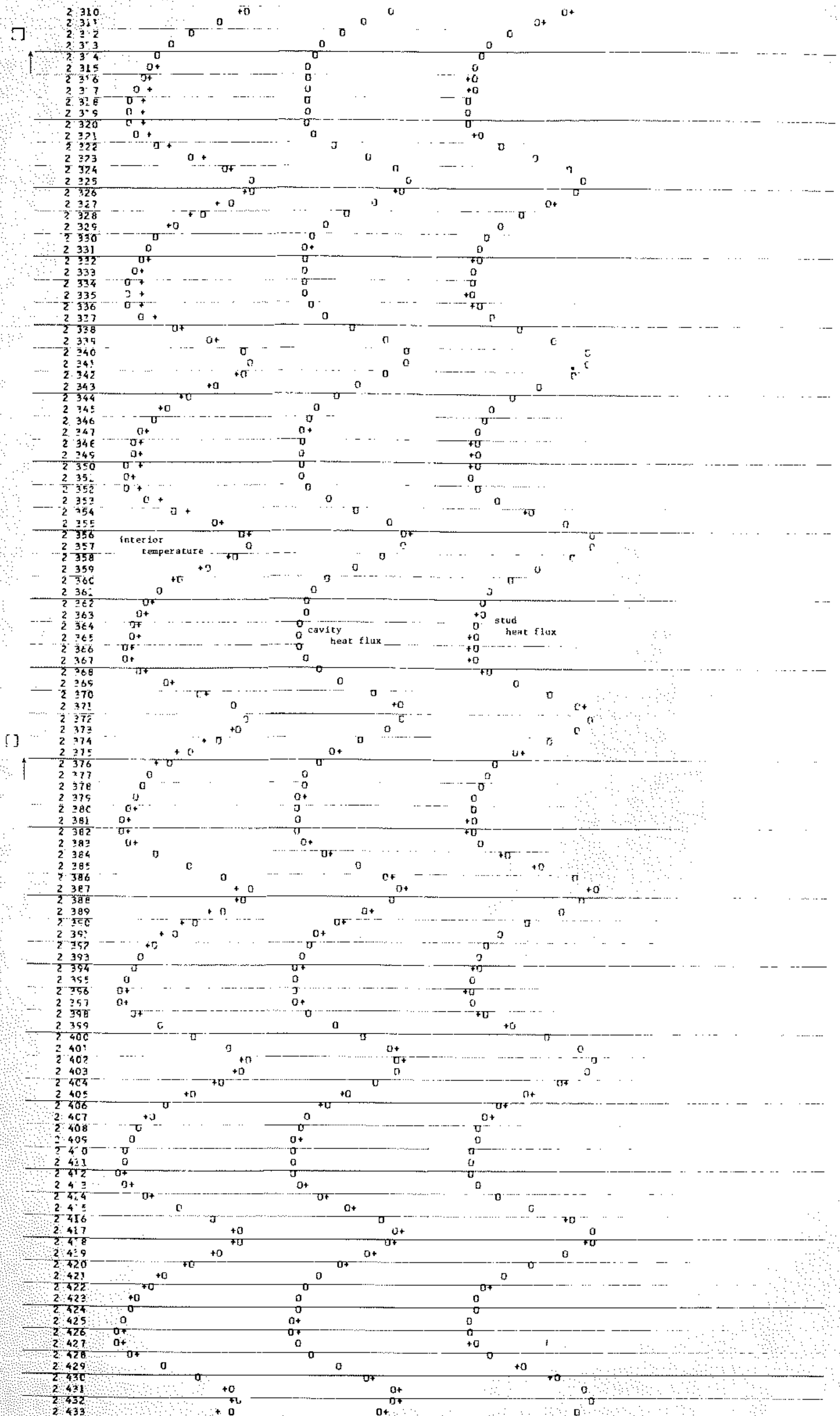

Figure 4. Computer plot comparing measured and fitted values for interior temperature, stud, and cavity heat fluxes

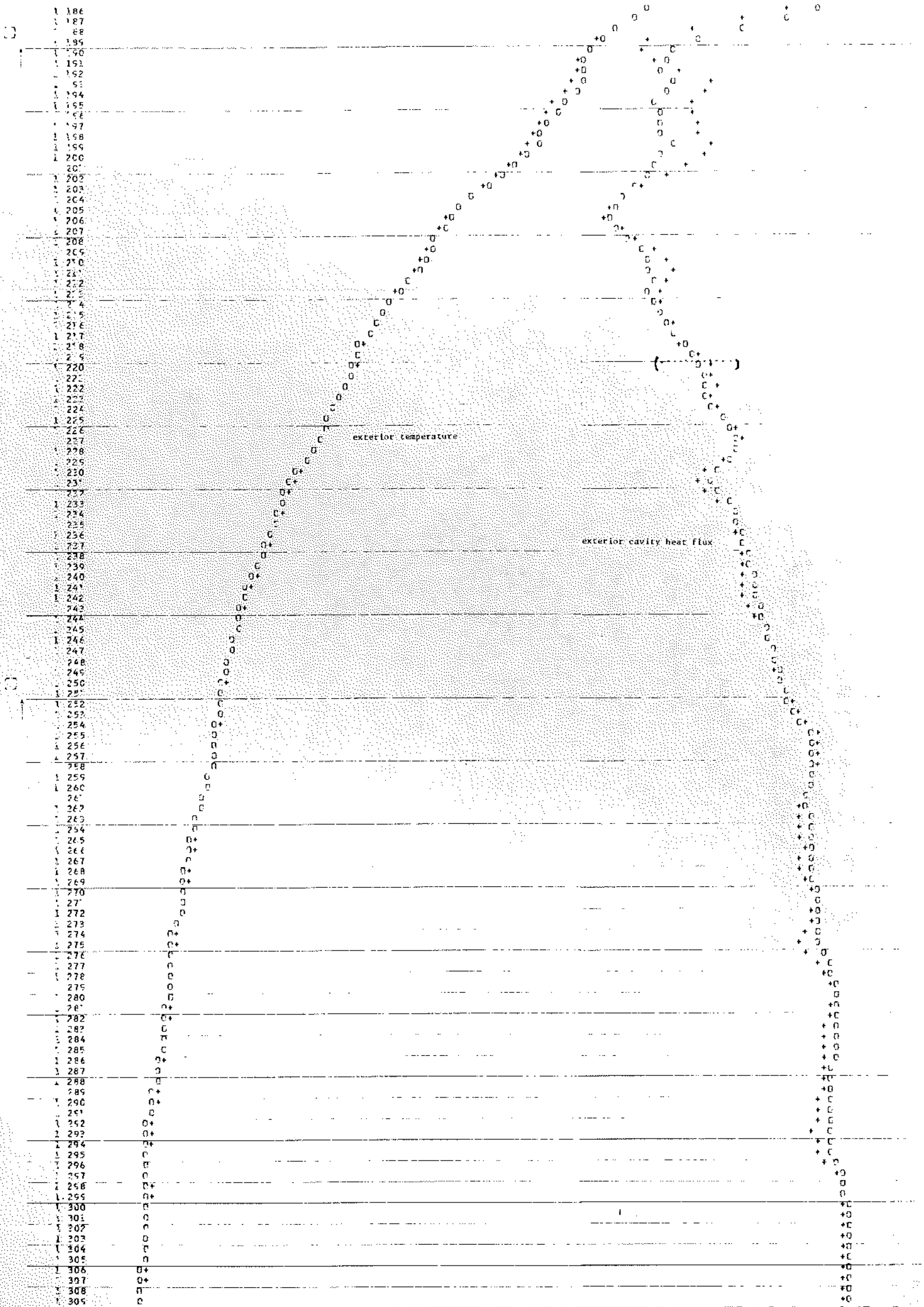

Figure 5. Computer plot comparing measured with fitted values for exterior temperature and heat flux