LBL-13436

Paper to be presented at the Third International Symposium on Energy Conservation in the Built Environment, Dublin, Ireland, March 30-April 1, 1982.

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OCTOBER 1981

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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ABSTRACT

There are many ways of calculating the dynamic thermal performance of walls and many ways of measuring the performance of walls in the laboratory, relatively few field measurements have been made of the dynamic performance of wall in situ. Measuring the thermal performance of walls in situ poses two separate problems: measuring the heat fluxes and surface temperatures of the wall, and reducing this data set into usable parameters. We have solved the first problem by developing the Envelope Thermal Test Unit (ETTU). ETTU consists of two specially constructed polystyrene blankets, 1.2m square, placed on either side of the test wall that both control and measure the surface fluxes and surface temperatures of the wall. To solve the second problem we have developed a simplified dynamic model that describes the thermal performance of a wall in terms of its steady-state conductance, a time constant, and some storage terms. We have used ETTU in the field to measure the thermal performance of walls, and have applied our simplified analysis to calculate simplified thermal parameters from this data set. In this report, we present the in-situ measurements made to date using ETTU, and the resulting model predictions. The agreement between measured and predicted surface fluxes demonstrates the ability of our test unit and analytic model to describe the dynamic performance of walls in situ.

RESUME

Il existe de nombreuses manieres de calculer la performance thermique dynamique de murs ainsi que de nombreuses facons de mesurer en laboratoire la performance de murs, mais relativement peu de campagnes de mesures ont ete entreprises en vue de determiner la performance de murs in situ. Mesurer la performance thermique de murs in situ pose deux problemes distincts: mesurer les flux de chaleur ainsi que les temperatures de surface, et ensuite reduire ces donnees en parametres utilisables. Nous avons resolu le premier probleme en developpant une Unite de Test Thermique d'Enveloppe (ETTU). ETTU est compose de deux couvertures de polystyrene specialement construites, de 1,2m x 1,2m, situees sur chacun des cotes du mur a tester, de telle maniere que chacune puisse controler les flux surfaciques ainsi que les temperatures de surface du mur. Pour resoudre le deuxieme point nous avons developpe un modele dynamique simplifie qui decrit la performance thermique d'un mur suivant sa conductance (etat stationnaire), une constante de temps, et des termes relatifs au stockage. Nous avons alors utilise ETTU sur le terrain de facon a mesurer la performance thermique de murs, et nous avons applique pour les donnees recueillies notre methode d'analyse simplifiee en vue d'obtenir les parametres thermiques simplifies. Dans cet article, nous presentons les mesures in-situ, effectuees a ce jour en utilisant ETTU, ainsi que les resultats provenant du modele. La concordance entre les flux surfaciques mesures et predits montrent la capacite de l'unite de test ainsi que du modele analytique a decrire la performance dynamique in-situ de murs.

INTRODUCTION

The thermal performance of building walls in situ is largely unknown. Most measurements of wall performance have been done in laboratories, typically with large hot boxes. Measuring actual performance in the filed is considerably more difficult, largely because the experimenter usually has little control over temperature conditions and solar radiation; wind effects. The task of accurately measuring surface temperatures and heat fluxes over time is not easy. Furthermore, assuming this data set can be gathered, the problem remains of how to analyze it. Most existing models contain numerous parameters that make them too unwieldy for direct data analysis. (See a review of measurement techniques and wall performance models has been compiled by Carroll.[1])

The work described in this report was funded by the Assistant Secretary for Conservation and Solar Applications, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under contract No. W-7405-Eng-48.

In order to test the dynamic thermal performance of wall sections in-situ, we have designed and built the Envelope Thermal Test Unit (ETTU) which will be able to measure the surface temperature and heat fluxes of a wall section driven with a known amount of heat. To quantify the characteristics of a wall from measured surface temperatures and heat fluxes, we have developed a simplified model of dynamic thermal performance which uses a set of Simplified Thermal Parameters (STPs) to characterize the thermal performance of walls regardless of their temperature history. In this paper, we discuss the theory of measurement technique, describe ETTU, and demonstrate the usefulness of our dynamic model for in-situ measurements.

MEASUREMENT TECHNIQUE

To measure the steady-state properties of the wall (i.e. its U-value) all that is required is a long-term average of the temperature drop across it and one heat flux. However, for many applications (e.g. structures having massive walls, or passive-solar features, or those in mild climates) the steady-state conductance is insufficient to describe the thermal behavior of that component — hence, the need for determinating the dynamic thermal properties of envelope components.

The measurement of dynamic properties implies an understanding of the relation between time-varying heat fluxes and time varying surface temperatures on the surfaces of the test component. The dynamic thermal performance of walls is tested at several laboratories (e.g. National Bureau of Standards, Owens Corning Fiberglas, Portland Cement Association), using hot boxes. These test generally provide a high degree of accuracy stemming from the high degree of experimental control that can be exercised in a laboratory setting (i.e. over the boundary conditions of temperature and heat flux).

For field applications no measurement tools and strategies of comparable scope have been developed. Yet, only field measurements can tell us about deterioration of walls with age, about the role of construction quality in wall performance, and about the heat losses associated with air leakage through walls. To this purpose, we have recently developed the Envelope Thermal Test Unit (ETTU) designed to perform dynamic field measurements. Because of constraints regarding control systems in any devise designed for field application, we opted for a design in which heat flow is applied on one or both sides of the wall, to effect changes in the surface temperatures; in our system, the temperatures are measured in response to regulated heat fluxes whereas in most hot box methods heat flux is measured in response to regulated temperatures.

ETTU has been described in detail in other reports[2,3] and here we will present only a schematic diagram showing the two blankets as they are placed on the wall, one on each side (See Fig. 1).

DATA INTERPRETATION

Regardless of the source or character of the data, we must be able to use measured temperatures and fluxes to characterize the thermal performance of a wall. This is the reverse of the more common problem of finding the flux response of a wall from the known properties of each component layer. There, one may use response factors, which are weighting factors used to calculate the flux at a particular time from a weighted sum of previous temperature. Although a large body of knowledge exists on the subject of response factors[4-10] the response factor approach will not work for reducing measured temperature and flux data, because of the large number of independent parameters. Our simplified model of wall behavior expresses the performance of the wall in terms of a few pertinent characteristics of the wall as a whole, rather than in terms of the many parameters that characterize individual layers within the wall. The complete derivation of simplified thermal parameters (STPs) is presented elsewhere;[11] the results obtained with this model are given in the sections that follow.

WALL MODEL

The simplest kind of distributed system is one in which the parameters are homogeneous — that is, they are independent of position within the wall. Although the problem of the homogeneous wall has been solved exactly[12] but the results are not usually expressed in the form we have used:

$$\underline{J}^1(t) = U\,(T^1(t) - T^2(t)\,) + 2U \sum_{n=1}^{\infty} F_n^1(t) - (-1)^n F_n^2(t) \qquad (1.1)$$

$$\underline{J}^2(t) = U\,(T^2(t) - T^1(t)\,) + 2U \sum_{n=1}^{\infty} F_n^2(t) - (-1)^n F_n^1(t) \qquad (1.2)$$

where: $\underline{J}(t)$ are heat fluxes (W/m^2) of the homogeneous wall,
$T(t)$ are temperatures (K) at wall surface,
$F_n(t)$ are the normalized temperature filters (K) of degree n,
U is the conductance of the slab (W/m^2-K),
$\dot{\tau}$ is the time constant of the homogeneous wall.

Note that we have defined the surface heat fluxes to be positive when they flow into the wall, and that the superscripts 1 and 2 refer to a specific side

of the wall (e.g. $T^1(t)$ refers to the surface temperature on side one of the wall). The filters are defined below:

$$F_n^{(1,2)}(t) = \frac{n^2}{\tau} \int_0^{\infty} e^{-\frac{n^2 t'}{\tau}} \left(T^{(1,2)}(t) - T^{(1,2)}(t-t') \right) dt' \qquad (2)$$

In the special case of a homogeneous wall, the time constant can be calculated from the thermal and physical properties of the wall:

$$\tau = \frac{L^2}{\alpha \pi^2} \qquad (3)$$

where: L is the thickness of the wall[m] and
α is the thermal diffusivity of the material [m^2/s].

Note the factor of π^2 ($\simeq 10$) in the above expression may differ in other definitions of the time constant.

The above derivation is an exact solution for the problem of a homogeneous wall; however, because few actual walls are homogeneous, we must generalize our model further. Since there is no analytical form to describe a wall of arbitrary composition, we must find a semi-empirical generalization of the model for the inhomogeneous wall. We have elected to do this by modifying the coefficients in front of the filters, $F_n^{(1,2)}$; that is, we assume each of the filters keeps the same relationship to every other filter but vary their coefficients. In this way our general solution for a non-homogeneous wall has additional filters added to the homogeneous solution:

$$J^1(t) = \underline{J}^1(t) + \sum_{n=1}^{n_o} a_n F_n^1(t) \qquad (4.1)$$

$$J^2(t) = \underline{J}^2(t) + \sum_{n=1}^{n_o} b_n F_n^2(t) \qquad (4.2)$$

where: J^1, J^2 are predicted fluxes (W/m^2) for an inhomogeneous wall,
$\underline{J}^1$, $\underline{J}^2$ are fluxes (W/m^2) for the equivalent homogeneous wall,
a_n, b_n are the new thermal parameters (W/m^2-K) and
n_o is the order of the model.

An inhomogeneous wall is completely described by its conductance, time constant and a small number (two or three) of pairs of correction terms (a's and b's) which express the deviation from homogeneity. These coefficients have a physical interpretation; for example, a large positive a_1 (for side one) or b_1 (for side two) implies that the wall is very massive on that side and a negative value implies that the side was resistive.

FIELD RESULTS

In order to test our equipment and our model in a field situation, we took ETTU to a typical, wood-frame, ranch style California house; to measure the insulated exterior stud-cavity walls of the structure. One of the most stringent tests of the analysis system is a run in which neither the temperatures nor the fluxes are controlled by ETTU; that is, a completely passive run which is driven by naturally occurring temperature differences. We collected data in this way for several days and used the center 24 hour period in our analysis. The plot of the surface temperatures and heat fluxes as recorded by ETTU during that run is given in Fig. 2.

We then used our model to find the set of simplified thermal parameters that best described the data, and used these parameters to predict a set of surface heat fluxes to compare with the measured ones. Figure 3 shows the predicted and measured surface fluxes for both sides of the wall. For this set of data we have chosen to use six STPs; their values are as follows:

U	$\div$	a_1	b_1	a_2	b_2
0.92	1.64	1.23	-0.29	6.40	-1.99

(The conductance and all the storage factors have the units of W/m^2-K and the time constants has the units of hours.)

We can compare these results to a calculation of the thermal parameters of the wall based on response factors:

	Off-stud	On-stud	Weighted Average
U	0.40	1.23	0.48
$\div$	0.19	2.64	

Since the calculation of the combined time constant is not a well defined concept, we have not shown a weighted average value; nevertheless the combined time constant must be between the on-stud and off-stud values.

That the calculated average conductance (from ETTU) is significantly higher than the estimated conductance (from the response-factor calculation), suggests that of the insulation within the wall cavity is degraded. For example, assuming that insulation degraded over time to about half of its nominal value and contains 1% moisture content, the estimated thermal conductance increases from a weighted average of 0.48 to 0.96. This measured data set validates our assumption that the insulation has degraded. In a study we conducted several years ago[13] a wall in the same structure was measured using long-term average temperatures and heat fluxes. The combined conductance from that study was U=1.23.

CONCLUSION

The model presented herein, used in conjunction with ETTU, affords an effective mean of evaluating the dynamic thermal characteristics of walls in-situ. Furthermore, the applicability of the model is not restricted to field measurements, nor is the data acquisition system restricted to ETTU. Data measured using heat-flowmeter arrays or hot boxes (both portable and laboratory-based) can be readily analyzed to derive the STPs of a wall, or even of a roof or a floor section.

The first set of field measurements has shown that the thermal performance of a wall can degrade significantly over time because of the deterioration of the insulation in the wall cavity. Our measurements show that the conductance of the wall was 90% greater than that estimated from the construction details.

In the future, we plan to use ETTU on a representative sample of existing walls to compile a catalogue of STPs that can be compared to their theoretically calculated counterparts. In addition, field measurements will be continued in order to shed some light on the effect of different kinds of insulation retrofits and the age of the wall on its thermal performance, since either may cause measured and theoretical performance to differ markedly.

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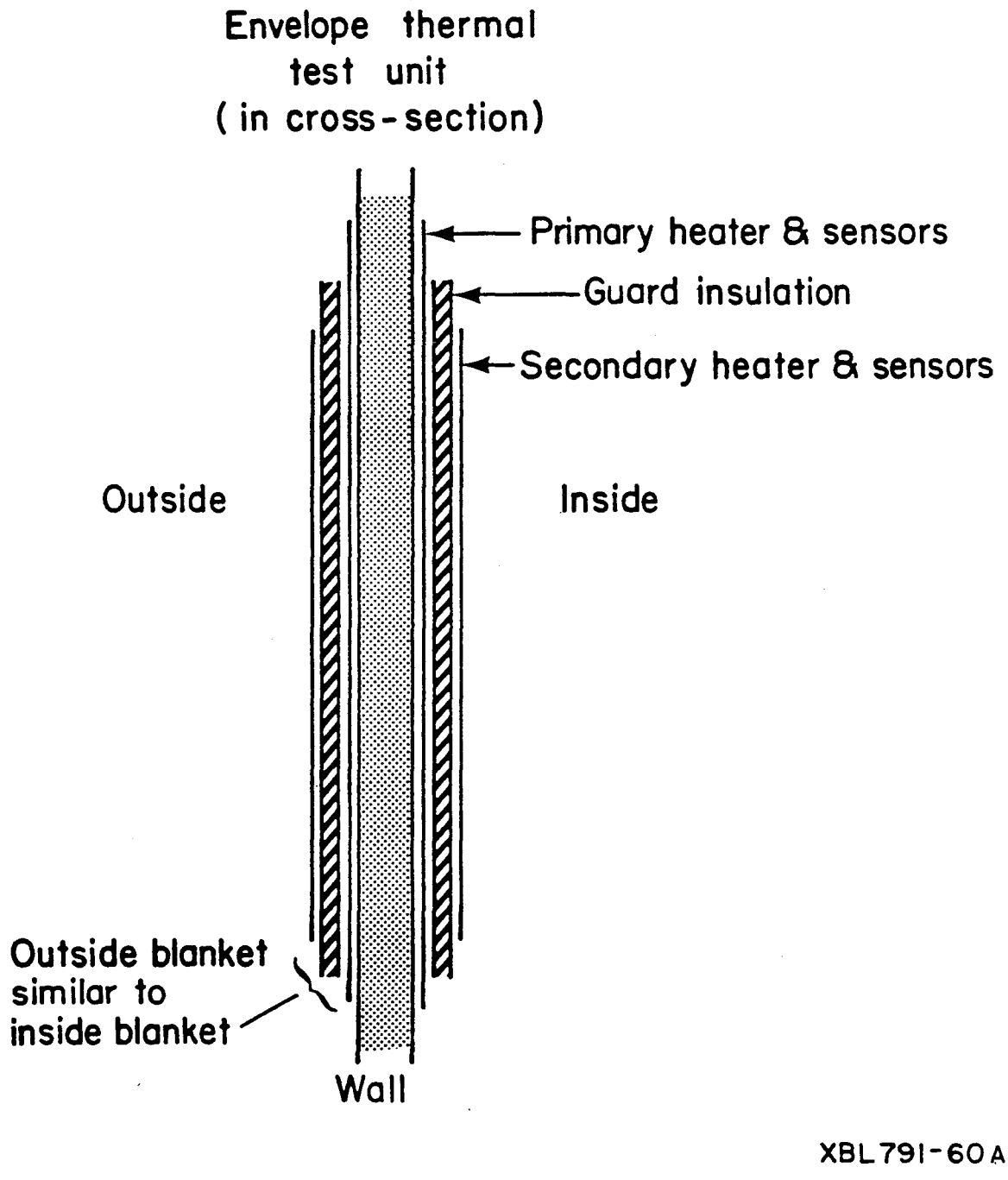

Figure 1. Schematic of Envelope Thermal Test Unit (cross-section).

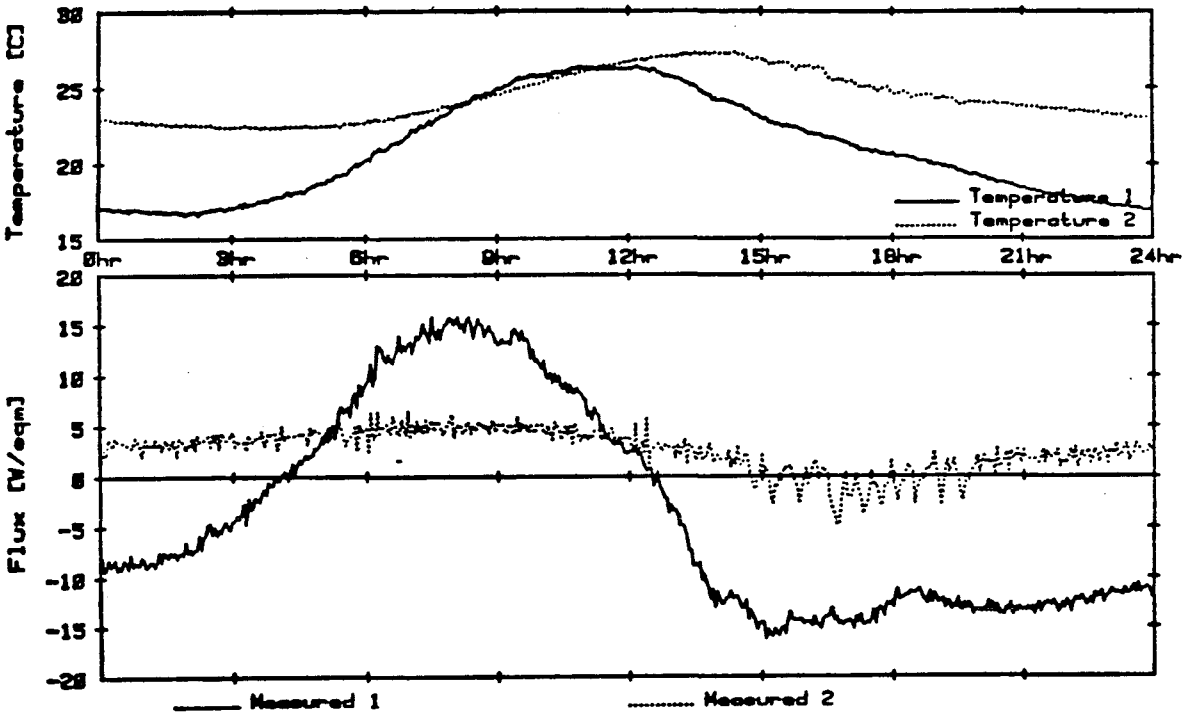

Figure 2. Surface Temperature and fluxes as measured by ETTU.

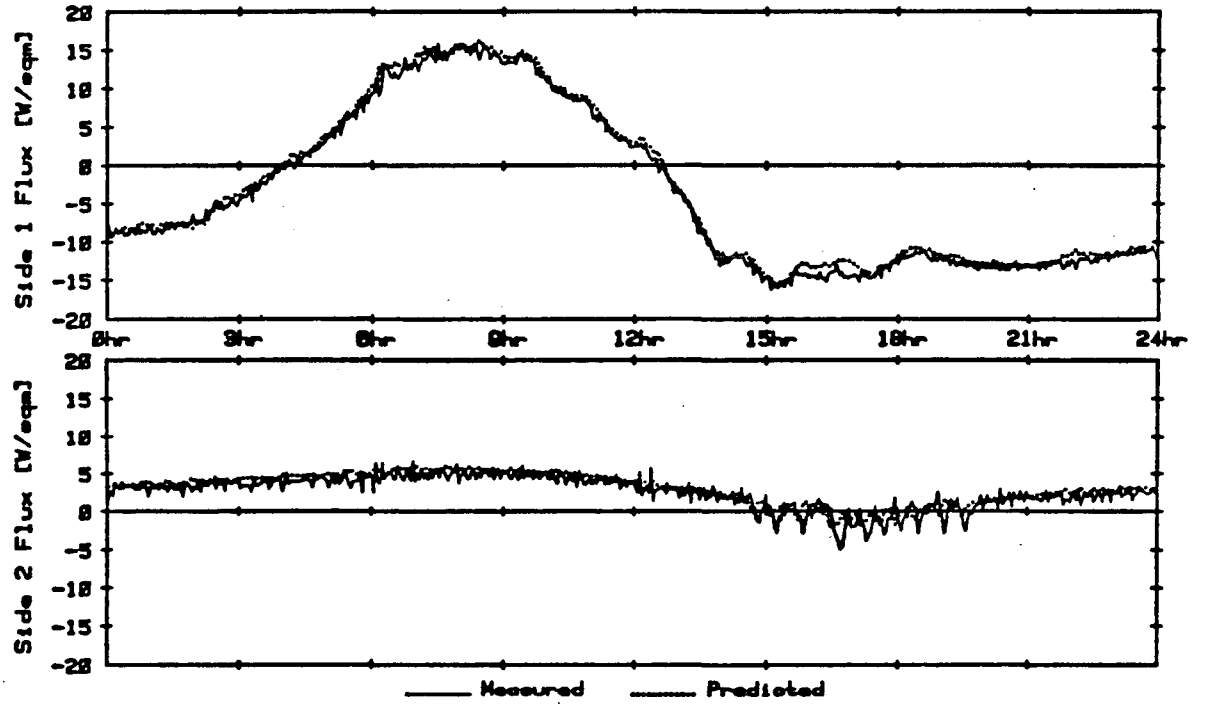

Figure 3. Predicted and measured heat fluxes.