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HEAT AND MASS TRANSFER IN BUILDING MATERIALS AND STRUCTURES

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Z_m [W/m^2 K] - response factors

Z_g [W/m^2 K] - normalized response factors

ℓ^* [m] - critical wall thickness

τ^* [s] - time of change heat flux sign

a [m^2/s] - temperature conductivity coefficient

P_H [W/m^2 K] - heat flux change during interval τ for the ascending part of the triangle temperature pulse

P_C [W/m^2 K] - heat flux change during interval τ for the descending part of the triangle temperature pulse

D [-] - relative difference of the heat flux increment changes

j,m,n - counters

REFERENCES

/1/ Mitalas,P.G.,Stephenson,G.D.:ROOM THERMAL RESPONSE FACTORS (ASHRAE Transactions,Vol.73,No2019,1967.)

/2/ Kusuda,T.: THERMAL RESPONSE FACTORS FOR MULTI-LAYER STRUCTURES OF VARIOUS HEAT CONDUCTION SYSTEMS (ASHRAE Transactions,Vol.75,Part I,No 2108,1969)

/3/ Hittle,C.D.:CALCULATING BUILDING HEATING AND COOLING LOADS USING THE FREQUENCY RESPONSE OF MULTILAYERED SLABS (US Army-Construction Engineering Research Laboratory,1981.)

/4/JUS U.J5.600 (Yugoslav standard,1987.)

/5/Živković,B.,Marjanović,Lj.: HEAT TRANSFER TIME-LAG IN CONCRETE WALLS USED IN PASSIVE SOLAR ARCHITECTURE (CLIMA 2000: Renewable Energy Sources and Heat Pumps, page 51-56, Sarajevo, 1989.)

/6/Todorović,B.:ACTUAL COOLING LOADS FROM SOLAR RADIATION THROUGH WINDOWS IN THE CORNER ROOM OF A BUILDING (Refrigeration and Science, Technology, published by International Institute of Refrigeration ,Paris, 1969, pg.205-216)

/7/Todorović,B.: COOLING LOAD FROM SOLAR RADIATION THROUGH PARTIALLY SHADED WINDOWS(ASHRAE Transactions,1982)

/8/Todorović,B.:THEORETISCHE GRUNDLAGEN FUR DIE VERBESSERUNG DER KUHLLASTBERHUNG (Klima,kalte,Heizung,Karlsruhc.,No 10/

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A Procedure for Estimation of Building Transfer Functions Coefficients from Experimental Data

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ABSTRACT

The dynamic thermal behaviour of a building in response to external and internal changes is not well-known. The pre-calculated coefficients recommended in the ASHRAE Handbook are based on simplifying assumptions. Moreover, they are only for three types of construction (light, medium and heavy), which do not cover all possible design alternatives.

In this study, the transfer function coefficients for three buildings are determined by experimental identification. The weight level of these buildings are 46, 130, 535 kg/m^2 of floor area. The derived coefficients complement those values given in ASHRAE Handbook.

INTRODUCTION

The ASHRAE Handbook of Fundamental [1] recommends the use of z-transfer function technique for building load calculation. The transfer function method has been used extensively for building load calculations. The precalculated coefficients (response factors) given in the ASHRAE Handbook [1] are valid for typical light, medium and heavy construction which are characterized by 146, 312 and 635 Kg/m^2 of floor area, respectively and do not cover lighter or heavier construction. Several approaches have been used for the derivation of dynamic models to predict the thermal behaviour of buildings. One approach is to develop a set of differential equations that describe the room air temperature as a function of ambient weather conditions, using knowledge of the physical characteristics of building. This set of differential equations could be either deterministic [2,3] or stochastic [4]. This technique requires numerous assumptions and approximations to specify the actual condition.

Another approach is to derive a dynamic model from field measurements using system identification techniques [5-8]. The main advantage of this approach is that it does not require simplifying assumptions and it can take into account the material deterioration and thermal bridges. Most recent experiments performed have shown that heating and/or cooling load calculated by the ASHRAE method is different from the load needed practically [7]. This lack of agreement was also observed when in-situ measurements from three buildings were compared with the predicted results [6,8].

The use of system identification methods to determine parameters of a system is well established [9-11]. These are methods of obtaining a mathematical model for a system on the basis of analysis of input and output signals. This requires both selection of the form of the model (i.e., the equation) and estimation of values for the parameters in the model. The existence of many different solutions for a given system is common. Therefore, the selection of the model depends upon the purpose of the identification and the experience of the user. While system identification techniques may employ non-linear models, the techniques described in this paper are applicable only when linearity can be assumed since the z-transfer function is valid only for linear systems. Heat transfer problems are normally considered linear, but this may be inappropriate in some cases such as when heat transfer is primarily by radiation such as direct gain houses.

The main objective of this paper is to develop a methodology for derivation of a dynamic model for buildings thermal behavior from experimental data. This study also provides a technique for developing a dynamic thermal model of a building for application in energy management systems applications.

THE TRANSFER FUNCTION TECHNIQUES

The transfer function techniques for calculation of thermal loads and room air temperature are described in the ASHRAE Handbook [1] and DOE Manual [12]. This calculation is performed in a two-step process. The block diagram of these two steps is shown in Figure (1). In the first step, the room air temperature is assumed to be constant at a reference value and the instantaneous heat gains/losses are calculated based on the reference room air temperature. These instantaneous heat gains (losses) are solar radiation entering the room through windows, internal heat gains, and conduction through the building envelopes. The transfer function of each component is used to calculate the cooling (heating) load. The total load is the summation of the individual term. This load is defined as the rate of heat which must be removed (added) from the room in order to maintain the room air temperature constant at the reference value.

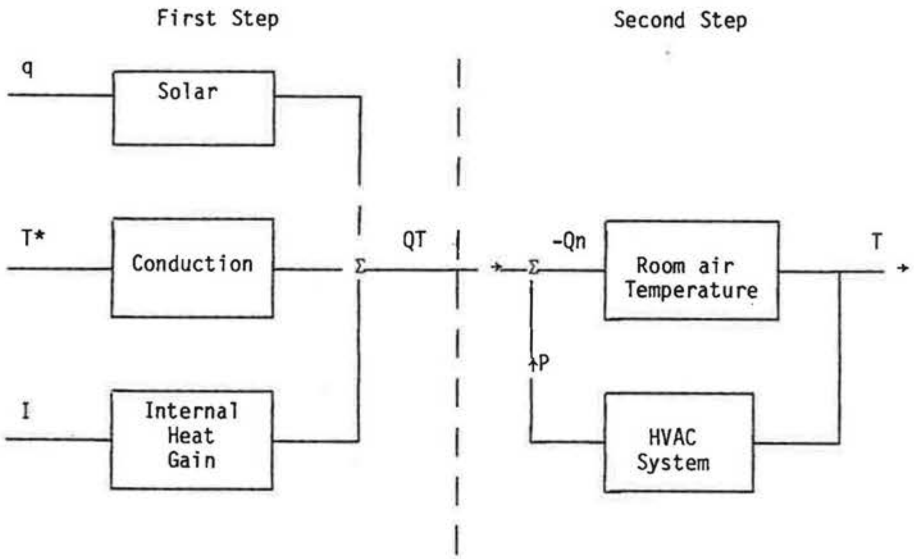


Figure 1. Block diagram of the system

In the second step, as shown in Figure (1), the total load, along with data about the HVAC system, and the information about the room air temperature transfer function are applied to determine the actual heat extraction rate (net cooling load) and the actual room air temperature.

The energy balance for the room air temperature results in:

$$Q_s + Q_e + Q_R = P \tag{1}$$

where Q_s is the cooling load due to solar gain through window, Q_e is cooling load due to heat gain through envelope, Q_R is the heat release by room thermal storage and P is the auxiliary energy required to keep the room air temperature within given limits. The corresponding transfer functions can be written as

$$Q_s(z) = \frac{v_0 + v_1 z^{-1}}{1 + w_1 z^{-1}} \; q(z) \tag{2}$$

$$Q_e(z) = \frac{a_0 + a_1 z^{-1}}{1 + w_1 z^{-1}} \; T^*(z) \tag{3}$$

$$Q_R(z) = \frac{g_0 + g_1 z^{-1} + g_2 z^{-2}}{1 + w_1 z^{-1}} \; T(z) \tag{4}$$

where q(z), T*(z) and T(z) are z-transforms of the instantaneous heat gain, sol-air temperature, and room air temperature deviation. The symbols of a, v, g and w_1 are the z-transfer function coefficients. Now, by substituting equations (2), (3), and (4) in equation (1) we have

$$(v_0+v_1z^{-1})q(z) + (a_0+a_1z^{-1})T^*(z) + (g_0+g_1z^{-1} + g_2z^{-2})T(z) = (1+w_1z^{-1})P(z)$$

or in the time domain

$$P(t) = \sum_{i=0}^{1} v_i \; q(t-i\Delta) + \sum_{j=0}^{1} a_j \; T^*(t-j\Delta) + \sum_{k=0}^{2} g_k \; T(t-k\Delta) + w_1 \; P(t-\Delta) \tag{5}$$

where t is the time and Δ is the time interval.

These coefficients vary from season to season due to deterioration of building components, variation in wind speed and direction, and pattern of air distribution in the space. The coefficients can be derived from actual system performance data, using modern control techniques.

EXPERIMENTAL FACILITY

The buildings selected for this study were three one story insulated wood-frame huts [13]. The field measurements were performed during December 16 - 28, 1980 in the unoccupied huts. These huts are nearly identical in construction, except for their interior finishing. They are 79.6 m^2 and 2.47 m high inside. The details of the huts and the wall construction are given in Figure 2. Each hut consists of a south and north room with a connecting door. The south and north rooms have a window of 2.6 and 1 m^2 net glass area respectively. All the interior wall surfaces of unit 1 (light construction) consist of a single 12.7 mm layer of gypsum board; unit 2 (medium construction) consists of 4 layers of 12.7 mm gypsum board on walls and two layers on the ceiling; and unit 3 (heavy construction) contains a layer of 100 mm of solid cement bricks. All the units are pressurized with corridor air (20°C) to eliminate the infiltration effect. The floors of the units are insulated with a thick layer of insulation (7 m^2C/W) to reduce the basement heat gains/losses. The basement is heated and kept at 21°C and the corridor temperature is kept constant at approximately 20°C. Each test unit is heated to 20°C (low set-point) with an electric baseboard heater. The north zone is kept at 20°C constant, while the control strategy for the south zone consists of temperature set-points in the range of 20° to 27°C. To avoid overheating, the south rooms are equiped with an exhaust fan to cool the room with outdoor air whenever the room temperature exceeds 27°C. This wide range of temperature fluctuation in the south zone provides a wide range of dynamic test conditions for the internal thermal mass.

ESTIMATING TRANSFER FUNCTION COEFFICIENTS FROM DATA

The analysis involves fitting an appropriate transfer function model to a set of the measured data. A standard least-squares technique is used to determine the coefficients in this model from the actual performance data [14]. The estimated transfer function coefficients of the cooling load due to solar gain through window are shown in Table (1) along with the results of other investigators and ASHRAE. In general, the data follows the theoretical direction, which means the coefficient w_1 (decay coefficients) increases as the building weight increases. Figures 3-5 show the predicted hourly heating and cooling load using equation (5) along with the measured data, for three weight levels: light, medium and heavy.

The results indicate that this technique predicts the heating load within 5%, while building simulation program underestimates it by 23% [8].

The cooling load response factors due to the heat gain through the envelope (construction) and the room air temperature response factors were also estimated. The estimated values could not be directly compared with the values given in the ASHRAE Handbook, since T*(t) is not the same for each wall, and also in Eq.(5) values of a include wall overall heat transfer coefficients (UA) and that again is not the same for each wall.

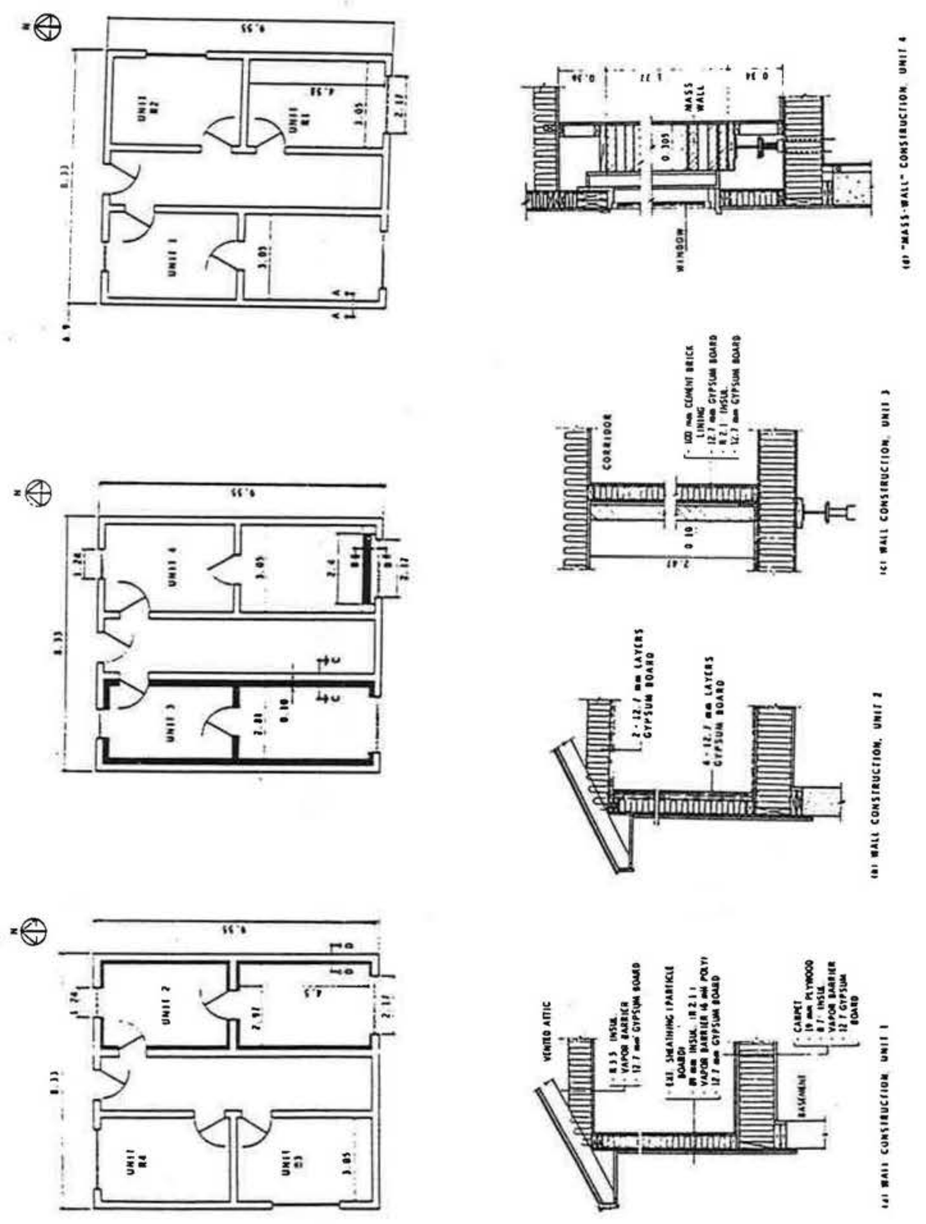


Figure 2. Details of test units and Construction Materials

Solar Transfer Function Coefficients	Weight/floor area (kg/m²)									
	46		130		146	341	535		635	
	Present work	Ref. 6	Present work	Ref. 6	ASHRAE	ASHRAE	Present work	Ref. 6	ASHRAE	Ref. 7
v_0	.64	.635	.52	.400	.224	.197	.28	.335	.187	.32
v_1	-.35	-.240	-.28	-.140	-.044	-.067	-.17	-.205	-.097	-.25
w_1	-.70	-.605	-.76	-.740	-.820	-.870	-.88	-.870	-.93	-.93
f	1	1	1	1	1	1	1	1	1.31	1

Table 1. Response Factors

In this study, the temperature difference is defined as:

$$\Delta T_i^* = T_0 - T_R \quad \text{for outside surfaces} \tag{6}$$

$$= T_i - T_R \quad \text{for inside surfaces}$$

where T_0 is the sol-air temperature, T_i is the adjacent space room air temperature and T_R is the room air temperature. $T^*(t)$ is a weighted temperature difference defined as [6]:

$$T^*(t) = \frac{\sum_{i=1}^{n} A_i \Delta T_i^*}{\sum_{i=1}^{n} A_i} \tag{7}$$

where A_i is the area of each surface. A more accurate result can be obtained if the overall heat transfer coefficient of each surface is known, then the weighted temperature difference is defined by [6]:

$$T^*(t) = \frac{\sum_{i=1}^{n} (UA)_i \, \Delta T_i^*}{\sum_{i=1}^{n} (UA)_i} \tag{8}$$

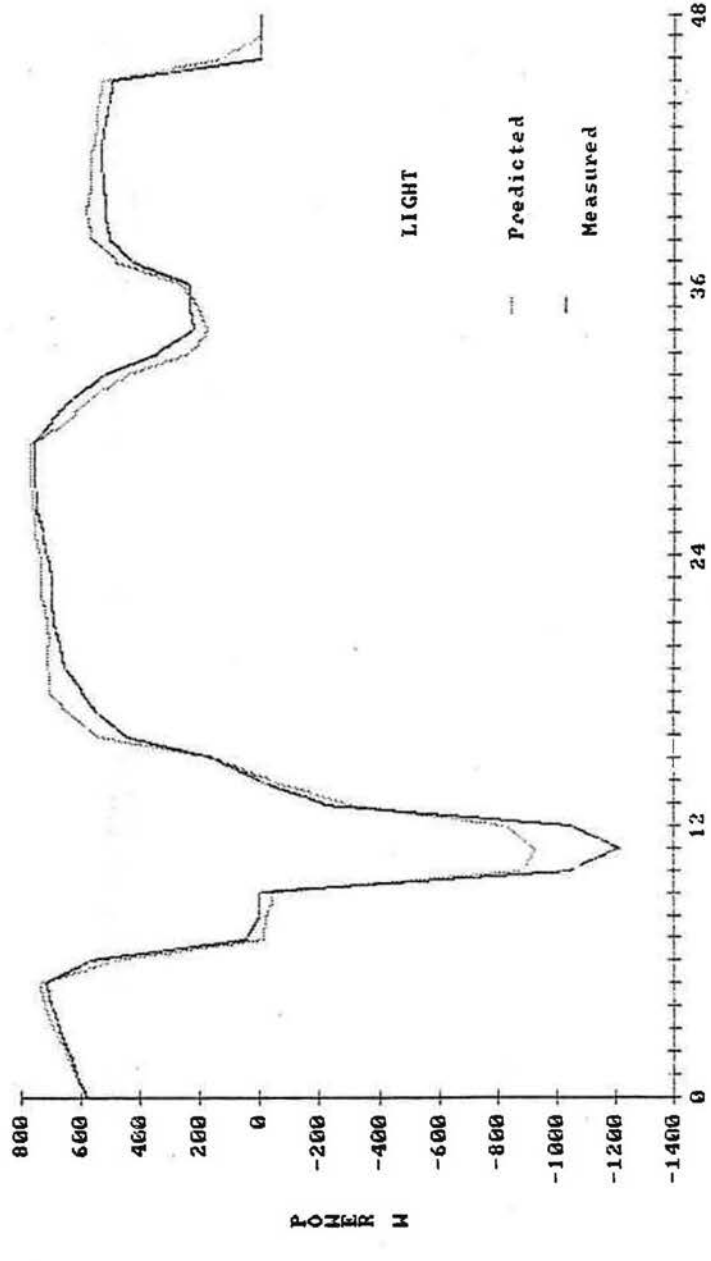


Figure 3. Comparison of measured and simulation using new transfer function coefficients.

Figure 4. Comparison of measured and simulation using new transfer function coeffients.

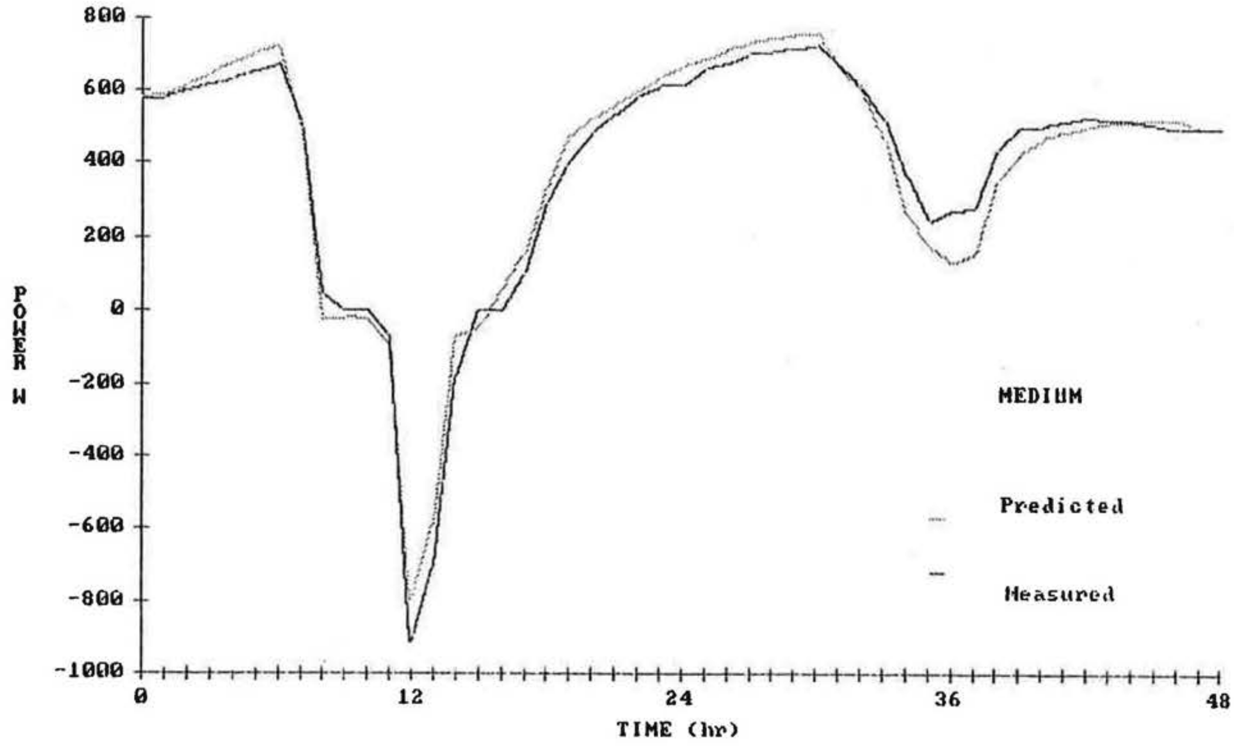
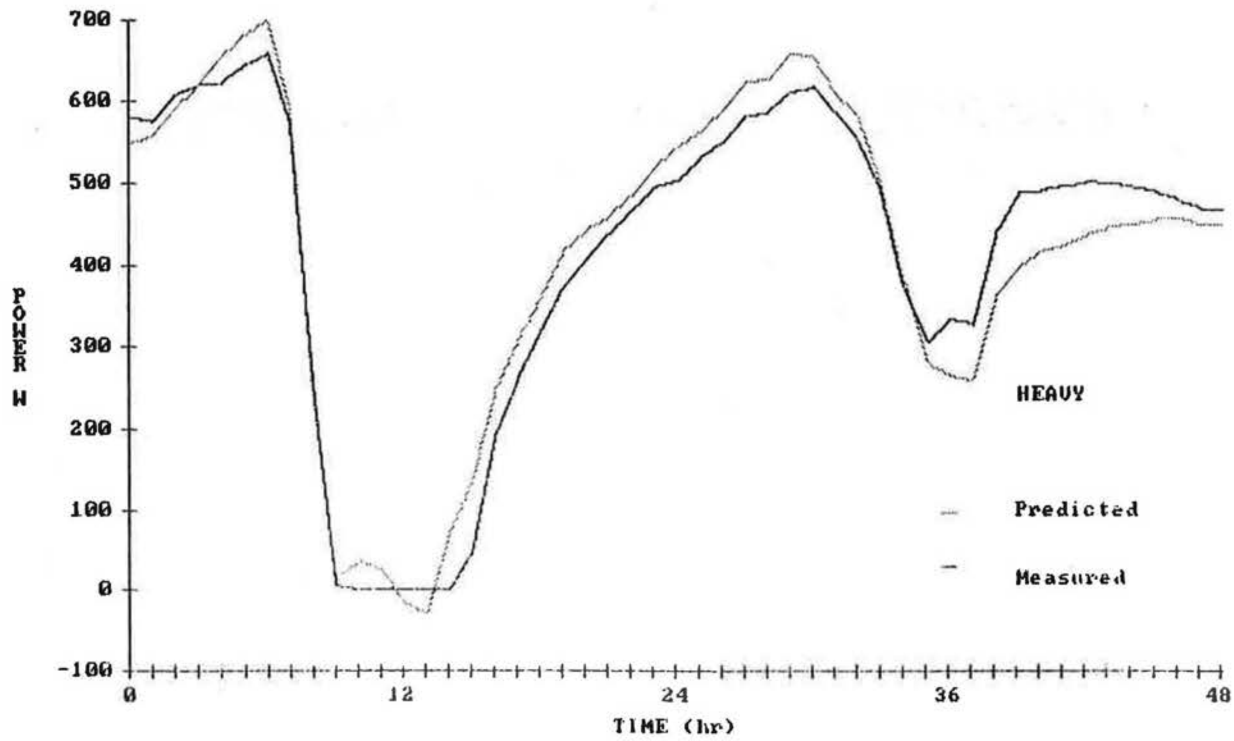


Figure 5. Comparison of measured and simulation using new transfer function coefficients,



For similar reasons, the estimated air-temperature response factors cannot directly be compared with those given in the ASHRAE Handbook due to inclusion of inside film coefficient in calculation of conduction response factors.

SUMMARY AND CONCLUSION

A methodology for determination of the building transfer function coefficients using system identification techniques has been demonstrated. This method involves the following steps: select the form of the model; measure inputs and output variables; fit the model parameters to the measured data.

The obtained results have been demonstrated and compared with the values given in the ASHRAE Handbook and the results of other workers. The method has been shown to be quite applicable and reliable for modelling the dynamic performance of three particular buildings. As mentioned earlier, the values of transfer function coefficients depend on the input and output. Therefore, the transfer function coefficients obtained from this study (solar) can be used in the design of other buildings, and are complementary to those in the ASHRAE Handbook.

The experiment on the three test units indicates that system identification could be a Powerful tool in determining dynamic thermal response. By developing an appropriate test procedure, one could apply it to determination of the other transfer function coefficients of Equations 3 and 4. Since this type of testing has long been used in process industries it could be well suited to determining the dynamic characteristics of the other elements, such as HVAC system components.

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REFERENCES

1. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigeration and Air Conditioning Engineers, 1985.

2. Haghighat, F., Chandrashekar, M., System-Theoretic Models for Building Load Calculation, ASME Journal of Solar Energy Engineering, Vol. 109, pp. 79-88, 1987.

3. Haghighat, F. and Athienitis, A., Comparison Between Time Domain and Frequency Domain Computer Program for Building Energy Analysis, Computer-Aided Design, Vol. 20, No. 9, pp. 525-532, 1988.

4. Haghighat, F., Chandrashekar, M. and Unny, T.E., Thermal Behaviour of Building Under Random Conditions, Applied Mathematical Modelling Vol. 11, No. 5, pp. 121-133, 1987.

5. Haghighat, F. and Sander, D.M., Experimental Procedures for Determination of Dynamic Thermal Response Using Identification Techniques, Thermal Insulation, Vol. 11, pp. 120-143, 1987.

6. Barakat, S.A., Experimental Determination of the Z-transfer Function Coefficients for Houses, ASHRAE Trans. Vol. 93, pp. 146-160, 1987.

7. Shan, J.P., The Development of Researches on Air Conditioning Load Calculations Method of Building in China, Clima 2000, Vol. 2, pp. 377-381, 1985.

8. Haghighat, F., Fazio, P. and Zmeureanu, R., A Systematic Approach for Derivation of Transfer Function Coefficients of Buildings from Experimental Data, Energy and Buildigs, Vol. 12, pp. 101-111, 1988.

9. Astrom, K.J. and Eykhoff, P., System Identification - A Survey, Automatic, Vol. 7, No. 2, pp. 123-162, 1971.

10. G.A. Bekey, System Identification - An Introduction and a Survey, Simulation, Vol. 14, No. 4, pp. 151-166, 1970.

11. N.K. Sinha and B. Kuszta, Modelling and Identification of Dynamic Systems, Van Nostrend Reinhold Co., 1983.

12. DOE-2 Engineers Manual, Technical Informaion Centre, 1982.

13. Barakat, S.A., Passive Solar Heating Studies at the Division of Building Research, ISSN 0701-5232, Building Research Note 188, Ottawa, Canada, 1982.

14. Åke Gjörck, Iterative Refinement of Linear Least Square Solution II, BIT, 8, pp. 8-30, 1968.