THE MEASURED PERFORMANCE AND COMPUTER SIMULATION OF TWO UNHEATED PASSIVE SOLAR TEST CELLS IN THE PACIFIC NORTHWEST

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ABSTRACT - The purpose of this study has been to examine the performance of passive solar structures in the mostlv cloudy climate of the Pacific Northwest. Only a small amount of detailed research has been done to determine the use of passive solar energy in this region. primarily because it has been supposed that building conditioning by solar energy is not practical in this climatic -one. In this study. the measured temperat ure response of two passive solar structures -- a direct gain cell and a Trombe wall cell - has been sought. In general these test cells have performed very much as expected. The direct gain cell has tended to show larger temperature oscillations. whereas the Trombe wall cell has exhibited a delaying (or lagging) effect of heat penetration into the space behind the wall due to the capacitance of the wall mass. Based on the temperature measurements. neither cell has appeared to perform significantly better than the other. The average interior temperatures of the cell have been within the comfort zone. although the temperature swings have sometimes been rather large. IOC (18F). The authors anticipate that improvements in the storage mass may help to reduce these fluctuations. Generally. the heat fluxes have been found to be low in both cells. In addition to the measurements of the thermal performances of these cells, the authors have conducted simulations of the test cells using the program UWEN- The predicted values correlated well with the measured values. There have been some differences in magnitudes. but the form and time dependence of the basic heat transfer processes have shown good agreement with observed behavior patterns. Thereby. the authors have shown a usefull congruence. for the purposes of comparative design analysis in this region. between the meastired and predicted values using a well-constructed simulation device.

INTRODUCTION

The work we will describe here is one of the latest efforts in a decade-long study, which the authors have been conducting, of the thermal performance of buildings in the Pacific Northwest. Much of the early work in which we have engaged concerned the use of simulation programs to predict building performance. Two notable examples of programs developed by us and other collegues for such predictive purposes are UWENSOL [1,2] and UWLIGHT [3], the first for estimating heat transfer rates in multiply-zoned buildings and the second for predicting patterns of natural and electric illumination in buildings.

A primary focus of this simulation work, particularly using the UWENSOL program, has been the investigation of how passive solar-conditioned buildings will behave in the temperate maritime Seattle climate. Initially, we relied on results derived from simulation work because little empirical data were available for passive solar buildings in this region and because the use of simulation programs is a time-saving alternative to the gathering of measured building performance data. Necessarily, we have previously qualified the accuracy of the UWENSOL code by conducting comparisons between measurement data from test cells, built and operated at the Los Alamos National Laboratory and predictions established with UWENSOL. We have previously published results of these comparisions, demonstrating quite good congruence [2]. We have also demonstrated how a simulation program can be effectively used in the design process by parametrically investigating the sensitivity to changes in the built environment [4].

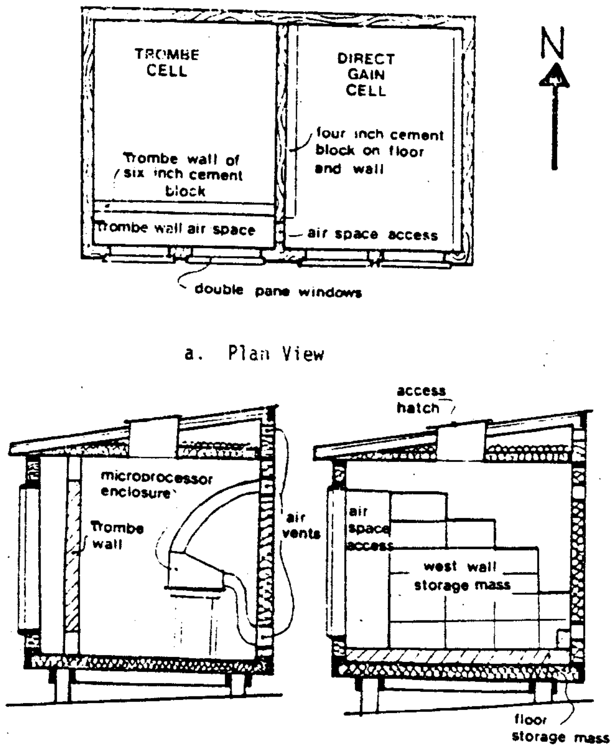
During the last three years, we have been conducting heat transfer measurements in passive solar test cells of our design as an effort, first, to quantify the behaviors of passively-conditioned buildings in this climate and, second, to establish measured data that can be used for the further tuning of UWENSOL and other simulation codes. The remainder of this paper will describe the measurement data taken from two test cells -- one a direct gain structure and the other conditioned by a Trombe wall. Then the paper will discuss comparisons of measured data and subsequent predicted results obtained by exercising UWENSOL.

STUDY PROCEDURE

A. The Composition of the Two Passively-Conditioned Test Cells

The organization of the two test cells is shown in Figure 1. These cells have been build as : two parts of a single building. The cells are composed of traditional wood-frame construction. Batt insulation equalling R-19 is present in the ceilings (underneath a ventilated attic) and floors and R-11 batting is in the exterior and common interior walls. Additionally, the floor has a one-inch thick styrofoam board (R-5) layer placed underneath and in contact with the batting. Each cell has two double-pane, fixed, windows facing south with a total glazed area of 3.1 sq m (33 sq ft) per cell. We believe that the rate of infiltration in the cells is minimal because entrance to either cell occurs through a tight-fitting hatch door on the roof of each cell. The storage mass in the direct gain cell has a surface area of approximately 7.4 sq m (80 sq ft) of the floor and side and back walls. This mass is composed of 10 cm (4") concrete masonry units (with empty cores) and has an estimated weight of 1650 kg (3630 pounds). The Trombe wall in the adjoining cell is constructed of 15 cm (6") concrete masonry units grouted together and the surface left unpainted. The mass surface area of the Trombe wall cell is 5.4 sq m (58 sq ft),

not including the upper and lower vents (with a total area of 5.5 sq m, 6 sq ft).



a. Plan View

b. Trombe Wall Cell Cross-section

c. Direct Gain Cell Cross-section

Figure 1 Test Cell Plan and Cross-Section Views.

Table 1
Passive Solar Building Parameters

	Direct Gain	Trombe Wall
Glazing Area/Floor Area	0.46	0.52
Mass Area/Glazing Area	2.42	1.75
Mass/Glazing Area	537 lb/sq ft	298
BLC (BTU/Deg-Day)	557	553
LCR (BTU/Deg-Day/sq ft)	16.9	16.8

B. Instrumentation

1. Temperature Measurement: Copper-constantan thermocouples have been used in these cells because of their low cost, easy availability, and relatively good accuracy. There are approximately thirty groups of such thermocouples in each cell, each group composed of four thermocouples wired in a parallel circuit with appropriate swamping resistors included to overcome discrepancies due to differential wire length. Thereby, an average value across the four sensors in a group is taken.

These groups of thermocouples have been deployed on the internal surfaces of and within the envelopes of the two cells, as well as on and in the respective storage masses. Air temperature in each cell is measured with three radiation-shielded thermocouples, placed one each about six inches out from the north, east and west walls halfway between floor and ceiling and wired in a parallel circuit. Thermocouples have also been included to measure the air temperature in the direct gain cell and the air temperatures on both sides of the Trombe wall and in the upper and lower vents (when open).

2. Weather Data: As part of the overall building, including the two test cells, a weather station is present. Information about total and diffuse irradiation is gathered using two solarimeters (both deployed horizontally), one mounted with a shadow-band. Wind speed and direction data are measured with a three-cup anemometer and a wind vane. Ambient dry-bulb temperature is determined with a shielded thermocouple placed out from the north side of the building.

3. Data Acquisition System: The temperature and weather data are collected using a microprocessor of our design [5]. This system is based on an Intel SBC 80/24 microcomputer board with an 8085 processor chip. Voltage signals flow from the sensors to terminal strips, which feed into three Data Translation analog-to-digital converters (one "high level", two "low level"). The signals from the A-to-D boards then pass to the processor. For most of the study described in this paper we have set the processor to sample each data channel every minute and to perform hourly averages of the assembled data. These hourly averages are then loaded onto a tape in a cassette recorder for short-term data storage. The contents of the cassette tape are periodically downloaded to the University Cyber 175 mainframe for detailed analysis.

4. Accuracy and Related Instrumentation Qualifications:

The microprocessor has been located in the interior cell space behind the Trombe wall. After some initial observations, we found that the heat generated by the processor (70 watts) was significant and was affecting the measured thermal behavior in the Trombe wall cell (giving an indication of the thermal tightness of the cell). Thus we then enclosed the processor in a shroud and ventilated its interior using outside air (see Figure 1). Secondly, for the signals from the thermocouples to the A-to-D boards, we used a temperature compensator on each board, rather than employing an ice bath. From calibration runs we found that the accuracy of the thermocouple-to-processor assembly was in the range of +/- 0.5C (0.9F). Some of this error is attributable to the fact that the reference temperature for each board is taken at the center of the board. Slight temperature variations are also present away from the center of these boards. Further, these variations were slightly aggravated by the admission of cold air into the processor shroud (i.e., that used for cooling).

MEASUREMENT AND SIMULATION RESULTS

The thermal measurements of these two passive solar test cells, that serve as the basis for this paper, were taken during the period from January through June 1984 by R. D. Kunkle and are described in his thesis [6]. However, the results which we will report in this section will specifically focus on the thirty days of April. Our reasons for limiting consideration strictly to this shorter period are several: (1) the density of the data for the entire study cannot be adequately treated in a paper of this length (we shall follow this paper with one treating other interesting results); (2) we were able to employ additional thermocouples for this shorter period, taking them away from a parallel study; thus, this period presents the fullest data record; (3) this period encompasses much of the "shoulder season" in Seattle (i.e., that time when on consecutive days, buildings may alternately require heating or cooling); and (4) generally, the behaviors shown here are representative of the entire study period.

A. Weather Characteristics for April, 1984

The weather record showing average daily outside air temperatures and total and diffuse horizontally measured irradiation is presented in Figure 2. For the early part of the month these curves display the characteristic cool, cloudy weather of the Seattle winter. Then, during the middle of the month, a period of relatively clear sky and warm days and cool night conditions predominate. Finally, towards the end of the month, there is evidence of the generally warmer, though still overcast, weather that is common during Spring in Seattle. During the month, there was a low value of total daily irradiation of 5 MJ/sq m (440 BTU/sq ft), a high of 22 (1937), a minimum daily change of 3 (260) and a maximum change of 15 (1320). Thus the month is characterized by very abrupt changes in solar irradiation, and thereby represents a severe test of both the performance of passive solar conditioned buildings and of simulation techniques.

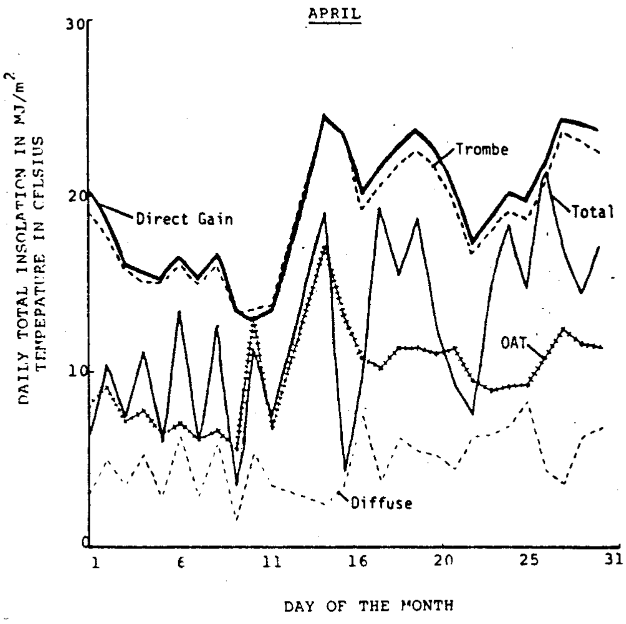


Figure 2 Average Daily Test Cell Air Temperatures, Outside Air Temperature (OAT), and Total and Diffuse Horizontal Insolation

B. General Monthly Temperature Trends in the Two Cells

The average daily air temperatures within the direct gain and Trombe wall cells are also displayed in Figure 2. Statistical analyses of the thermal behaviours of these two cells reveal the following facts: (1) the average air temperatures for this period in the direct gain and Trombe wall cells were 19.4C (67F) and 18.8C (65.8F), respectively; (2) The average daily air temperature swing, (i.e., the difference between the maximum and minimum) for the direct gain and Trombe wall cells were 7.8 (14F) and 7.4C (13.3F); and (3) the coefficients of variation of the inside air temperatures for the direct gain and Trombe wall cells were 0.13 and 0.12. From the graph and these analyses it is apparent that the two cells show similar behaviors. The primary explanation for this would seem to be that both cells have similar construcitons (i.e., in terms of envelope resistance and the amount and type of glazing). A second observation concerning the graph, particularly, is that the temperature patterns of both cells follow the character of the total irradiation more than the outside air temperature (or the diffuse irradiation). However, the direct gain cell appears to respond more promptly to increased irradiation than does the Trombe wall cell, an interesting result given that the ratio of mass-to-glazing area for the direct gain cell is more than twice the ratio for the Trombe wall cell (note that a possible explanation for this result will be presented in Section D below). The lower average air temperatures found in the Trombe wall cell may be explained by the fact that the mass for this cell has a greater radiant view between its surface and the sky than does the direct gain cell mass. Thus, there will be greater nighttime heat loss to the sky, especially during periods of clear skies.

Average Hourly Behaviors of the Two Cells

The average hourly behaviors for these two cells are shown in Figure 3 and 4. The maximum, average, and minimum air temperatures for both cells display clearly sinusoidal profiles. The maximum average air temperatures within the direct gain cell and outside the cell demonstrate almost no time lag, whereas the same maximum average air temperatures for the Trombe wall cell indicate a time lag of about 1-1/2 hours. For the direct gain cell the standard deviation of the hourly air temperatures are greater in the afternoons than in the morning, again presenting evidence that the irradiation drives the direct gain cell air temperature. The corresponding deviation for the Trombe wall cell is lower, both generally throughout the 24 hour day and specifically for the afternoon hours. Further, the direct gain cell shows a larger temperature swing, a greater tendency to overheat, and greater peak temperatures than does the Trombe wall cell. All of these results occur inspite of more favorable mass-to-glazing area ratio present for the direct gain cell; namely, 298 kg/sq m for the Trombe wall cell and 537 kg/sq m for the direct gain cell. We conjecture that the Trombe wall cell is under-massed and that, if additional mass were added (i.e., by filling the cores of the blocks or using a poured-in-place concrete wall) the Trombe wall cell may have out-performed the direct gain cell significantly. We have noted a study based on mulation modeling that showed superior perfor-ances for Trombe wall houses over direct gain houses, each will equal mass/glazing area ratios, using Madison, Wisconsin weather data [7].

D. Measured Surface Mass and Air Temperatues for the Direct Gain Cell

For the remainder of this paper we will focus our attention on the results -- by measurement or simulation -- found for the direct gain cell. In this section we will document the interaction of the storage mass and the air temperatures and the trends present therein. By so doing, we will show when the storage mass operates most usefully, what heat transfer modes appear to be at work, and what parts of the storage mass are effective. The measurements described here result from an alteration in the thermocouple operation protocol. For the following sets of observations, the temperatures measured by the thermocouples in and on the storage mass were not averaged across the four plane quadrants. Rather, the temperatures were measured on a quadrant-by-quadrant basis, so as to establish sub-areal temperatures to assess the effectiveness of the mass areas. The average hourly temperatures for the four quadrants of the top surface of the floor storage mass and for the test cell air are displayed in Figure 5. Additionally, the average hourly temperatures for the east and west wall storage masses, along with the cell air temperature e shown in Figure 6.

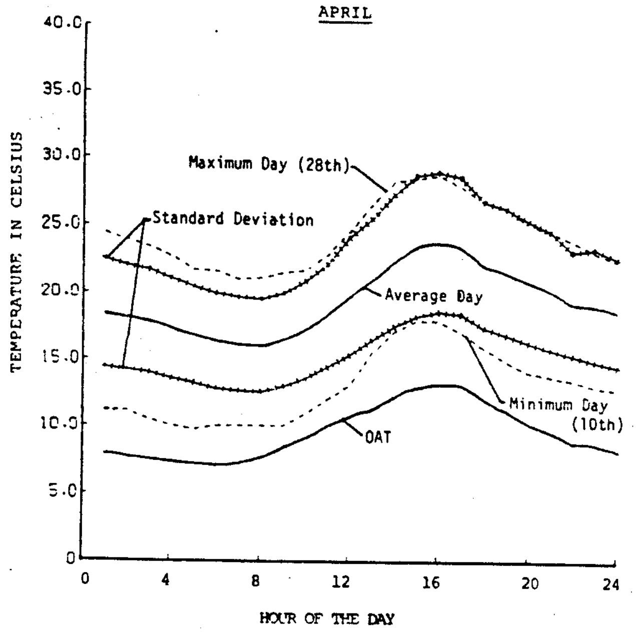


Figure 3 Maximum, Average, and Minimum Direct Day Gain Cell Hourly Temperatures and Outside Air Temperature (OAT)

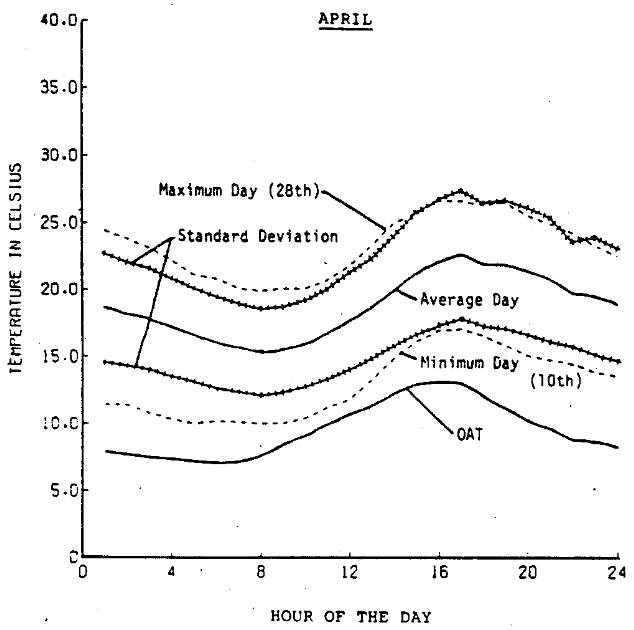


Figure 4 Maximum, Average, adn Minimum Trombe Cell Hourly Temperatures and Outside Air Temperature (OAT)

From the first of these figures it is apparent that only the two southerly quadrants of the floor mass serve as primary storage. The northerly quadrants display a temperature swing of only 2C (3.6F) over the day, whereas the southerly mass quadrant varies at least 10C (18F). That the temperature of the southwest quadrant rises earlier than that of the southeast quadrant is attributable to the diurnal path of the sun. The floor surface temperatures for the southerly quadrants exceed the

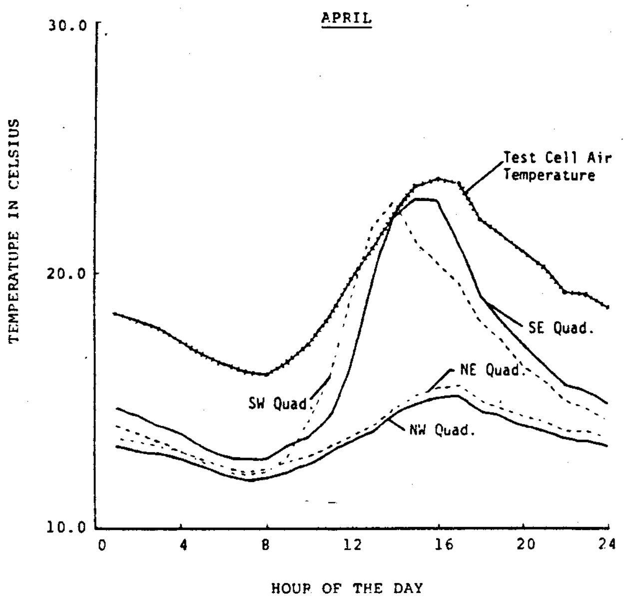


Figure 5 Hourly Average Floor Storage Mass Temperatures for the Top Surface of the Direct Gain Cell

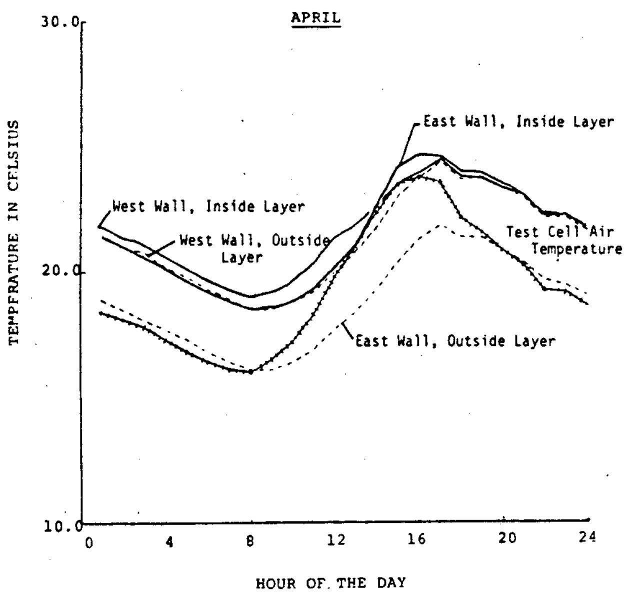


Figure 6 Hourly Average East and West Wall Storage Mass Temperatures for the Direct Gain Cell

test cell air temperature only from 1300 to 1600 hours; otherwise the floor mass surface temperatures are less than the cell air temperature. During the period from 1100 to 1700 hours this mass gains heat. But for the remainder of the 24-hour period, heat flow occurs out of the mass into the test cell.

The presence of higher temperatures at the bottom of the floor mass in comparison to those at the top indicates that the direction of heat transfer is out of the floor mass. For most of the period before 1100 and after 1700 the air temperature of the cell is greater than that of the storage mass. Thus, convection cannot be the effective heat transfer mechanism. Also, the inside surfaces of the test cell -- including the inside surfaces of the windows (which are close to the temperatures of the floor mass at night) -- are warmer than the floor mass surface. The warmth of the cell air combined with that from storage mass on the east and west walls keeps the temperatures of the remaining walls and the windows at relatively high levels. Therefore, radiant transfer from the floor does not seem to be a major factor. Still the temperature distribution in the floor mass indicates heat transfer out of this mass. The only means by which this could be possible would be if there were a comparatively cold stagnant air layer just above the floor and that such an air layer was at a temperature sustantially below the measured cell air temperature.

Comparing the east and west wall mass temperatures (see Figure 6) for the direct gain cell with those of the floor mass, we found that wall masses reach higher temperatures. The surface temperature for the west wall is higher than cell air temperature for virtually the entire 24-hour period. The apparent reason for this is that the west wall mass adjoins the insulated stud wall that is common to the direct gain and Trombe wall cells. We have found a slight heat transfer from the direct gain cell to the Trombe wall cell, but this rate is substantially less than one would expect between interior and exterior surfaces for a similar wall composition. The temperature pattern for the east wall room surface demonstrates the effectiveness of the mass: during the period form 1700 to 10000 hours, the wall surface remains 3 to 4C (5-7F) warmer than the cell air temperature. Only when irradiation is significant does the air temperature increase to a value similar to that of the mass of the east wall. Thus, a substantial amount of heat is convected from the wall to the room air. Necessarily, as the room surface of the east wall is warmer than the surface of this mass adjacent to the exterior wood-framed envelope (and as this intermediate node is at a higher temperature than outside the cell), heat trannsfer occurs through the mass and the envelope to the exterior of the cell.

In summary, it appears that a majority of the irradiation absorbed by the storage mass in this cell serves to match the heat losses experienced through the envelope of the cell. Thereby, little heating of the cell air occurs from the mass. As noted in the previous paragraph, some convective heating of the air occurs from the wall mass. The radiant exchange between the surfaces in the cell seems to be small because most of the wall surfaces -- including the north wall which has no storage mass adjacent to it -- have similar room surface temperatures. Some net radiant exchange from the wall masses to the windows is evident, but this is only appreciable between the sourtherly parts of the east and west wall masses. The anglefactors from these wall sections to the windows likely would approach 0.2 and produce heat losses of perhaps 5 W/sq m. This rate would decrease significantly for elements more than four to six feet from the south wall.

E. Measured and Predicted Air Temperatures in the Direct Gain Cell

In this and the next sections of this paper we will compare results of simulations of the thermal behavior of the direct gain test cell, performed with the UWENSOL program [1,2], with measured values. In these comparisons we wish to demonstrate the degree of correlation between predicted and measured values for a solar-conditioned building and to indicate some of the topic areas for which we feel further work is needed in the development and use of simulation codes. The UWENSOL program employs a finite difference technique to solve the various equations used for describing heat transfer in a building. The program is based on the dual assumptions of one-dimensional transfer between nodes and gray-enclosure radiant exchange between surfaces. UWENSOL can be used to model mutiply-zoned buildings. It conducts hourly calculations and provides results in terms of computed air and surface temperatures, as well as heat transfer rates between elements.

For the simulations of the test cells, we performed the computations as if each cell were independent of the other: this appoach was employed essentially to simplify the use of the program. The predictions for the direct gain test cell we will report here were conducted for the five days of April 6th through the 10th, a period during which the weather was variable (we have done similar comparisons for other weather periods). We acknowledge at the beginning of this comparative work that there is an implicit danger in modeling a structure when measured results are already available. Necessarily, there are a number of input variables which can be adjusted and tuned until the simulated results effectively match measured ones. Whether such tuning is transferable from one user of a code to another is questionable, especially if the structure to be modeled by the latter individual has not yet been constructed. In our work, we conducted two sets of simulations: the first for a "base" case: and the second for a "refined" case. We anticipate that any experienced engineer with some understanding of how a structure might behave would arrive at the base case results. The refined case values, alternatively, have been reached by adjusting the following parameters: the mass capacitance: the mass surface absorptivity; and the heat transfer coefficients from the mass surface to the cell air.

A comparison between the direct gain cell air temperatures, measured and predicted for the "refined" case, is displayed in Figure 7. The basic temperature pattern of daytime increases and nighttime reductions is present for both measured and predicted values and the shapes of the curves are quite similar. The simulation values show about 10% over-shooting of the measured values. This increment then is sustained until the commencement of heat gain from irradiation during the next day, when the measured and predicted values then overlap again. Interestingly, when we compared the

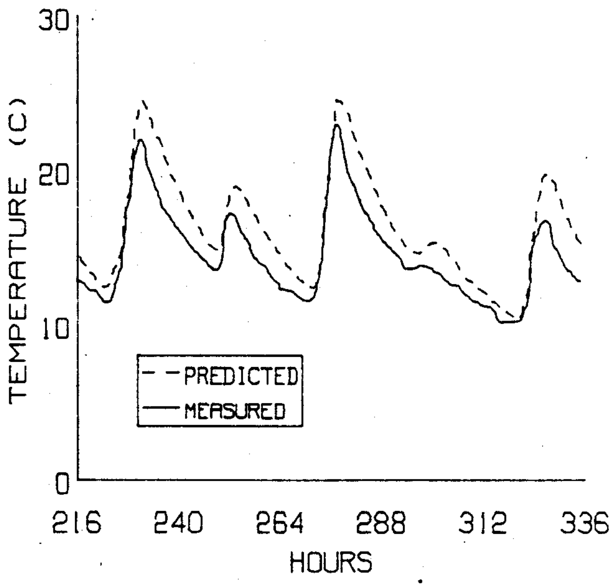


Figure 7 Direct Gain Cell Air Temperatures for the April Test Period for the Refined Case

there were within 2 to 3C (3.6-5F) and the temperature versus time plots had nearly identical forms. Further, the east wall mass surface and that of the floor were shown to be at quite similar temperatures: the temperature of the west wall mass surface was not measured during the February testing. In the "refining" of the predicted results that were adopted after the February comparison of predicted values for the "base" and the "refined" cases for this period (we used the same refining strategy for all of the direct gain cell simulations), we found little difference between the predicted results for the two cases. This lack of difference may suggest that the thermophysical properties that we chose to tune are of less significance than is the rate of irradiation present at the vertical glazing surface.

F. Measured and Predicted Surface Temperatures in the Direct Gain Cell

Figure 8 compares the measurement and prediction of mass surface temperatures within the direct gain cell for the study period in April. The UWENSOL simulation indicates that the east and west wall mass surface temperatures will be the same throughout this period. Further, the floor mass temperature is predicted to be nearly the same as those for the east and west wall masses. But the temperatures measured at the three mass surfaces in the cell show appreciable differences amongst themselves and also between themselves and the predicted temperatures: the patterns of temperature fluctuation are similar, but the magnitudes differ by as much as 100%.

Before suggesting why these differences may be present, we would note that, for similar comparisons performed for a February period (not shown here) we found good agreement between measured and predicted surface temperatures. The discrepancies

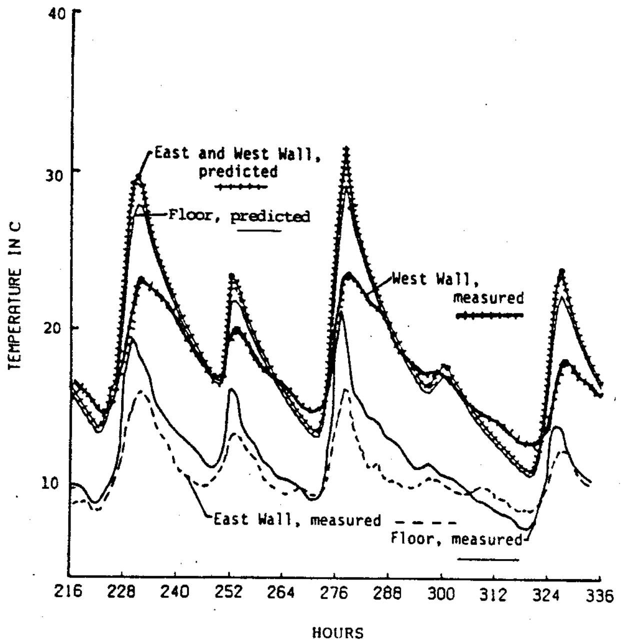


Figure 8 Direct Gain Storage Mass Inside Surface Temperatures for the April Test Period for the Refined Case

measured and predicted results (i.e., to alter the predicted the cell air temperature), we reduced the capacitance of the storage mass and increased the transfer coefficients of the walls and floor. Inspite of these "refinements" we found little change in the "base" and "refined" case surface temperatures and very good agreement between measured and predicted surface temperature values.

Considering now the significant differences between measured and predicted temperatures for the mass surfaces -- as found for the April tests -- we would first note the uneven heating of the floor and wall masses as shown in Figures 5 and 6. For the floor quadrants and the east versus west wall surfaces, we have seen different temperatures present. Then and now, we have ascribed such differences to unequal rates of irradiation: the southerly floor mass surface receives more solar gain than does the northerly half and apparently the west wall receives more than the east wall (i.e., due to higher solar angles and perhaps slightly clearer afternoon skies). Also, the "refinements" employed for the February test comparisons when applied to the April test created little alterations between the "base" and "refined" cases (as was true for the February "refinements"). Finally, that the three primary mass surfaces are predicted to be at essentially the same temperature suggests an averaging of conditions occurring within the simulation technique. Thus, the difficulty in predicting the surface temperature may arise from more than one factor.

DISCUSSION

In this section we will limit our discussion to the results of the comparison of measured and predicted temperatures for the direct gain cell. We believe that the measurement results, by themselves, serve to explain the performance of this cell. Rather, the potentially more interesting feature of the work we are presenting here concerns the degree of congruence found between the measured and predicted temperatures. Throughout the large thesis [6] from which this paper is drawn, the various comparisons between measured and predicted values have shown that the UWENSOL code provides a satisfactory model of the physical processes acting in the cells. The "base" case tests provide reasonable results and the "refined" case tests generally showed better correlations with the measured values. From such agreement, one may have confidence that a simulation code like the UWENSOL program will predict the performance of a solar-conditioned building. But, necessarily, it must be understood that these simulation devices have largely been developed to compare design options, not to predict the exact thermal performance of a structure. Thereby, while serving as a means to conduct trade-off analyses and to examine the sensitivity of design parameters, a simulaton device will have its ultimate utility.

From this comparative study of the congruence of measured and predicted results for a solar-conditioned test cell we believe we have identified a number of study topics whose investigation and resolution are required to ensure that simulation codes will be able to provide predictions that are close to subsequently-measured values. Among these topics we would cite four as requiring further study:

A. More accurate assessment of the effectiveness of mass as a capacitance device, including determining what surface areas are useful and what is the appropriate amount of mass participating in the behavior of the building;

B. Better estimation of the degree of anisotropy of temperatures in room air and across building surfaces, particularly when these parameters are affected by variable conditions such as weather or occupancy effects;

C. Reduction in the uncertainty in assigning magnitudes for many thermophysical properties of materials and building features, including thermal conductivities, convection coefficients, surfce absorptivities and glazing transmissivities;

D. More regionally-accurate irradiation models (i.e., beyond the Liu and Jordan correlations [7]) suitable for predicting irradiation on vertical and tilted surfaces.

CONCLUSION

Our primary goals in undertaking this work were to demonstrate the effectiveness of solar ~gy as a means for conditioning buildings and to ..ess further the accuracy of the UWENSOL code. In terms of the first goal we have shown that temperatures close to or within the thermal comfort range could be maintained in each of the two test cells and that each of the two passive solar operating systems -- the direct gain cell and the Trombe wall cell -- displayed quited similar performances. Second, we have further defined the accuracy of the UWENSOL code and better indicated topics for which additional research is needed to promote the further "fine-tuning" of this simulation code.

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