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# DYNAMIC MEASUREMENT OF NIGHTTIME HEAT LOSS COEFFICIENTS THROUGH TROMBE WALL GLAZING SYSTEMS*

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## ABSTRACT

A Trombe wall presents a unique opportunity to measure the heat-loss coefficient through the glazing system because the wall itself can be used as a heat meter. Since the instantaneous heat flux through the outer wall surface can be determined, the heat loss coefficient at night can be calculated by dividing by the wall surface-to-ambient temperature difference. This technique has been used to determine heat-loss coefficients for Los Alamos test rooms during the winter of 1980-81. Glazing systems studied include single and double glazing both with and without night insulation used in conjunction with a flat black paint, and both single and double glazing used in conjunction with a selective surface.

## 1. INTRODUCTION

The U-value for heat loss from the surface of a double-glazed Trombe wall to ambient has been reported by Palmiter, et al. The method relies on the use of a heat flux meter attached to the Trombe-wall surface. The measured U-value reported for a wall with a selective surface foil attached to the outside surface is 0.32 Btu/F-hr-sq ft. The measured U-values are reasonably steady, indicating that the wall can be accurately modeled using a constant heat loss coefficient[1].

A method of determining heat fluxes from temperature measurements made in massive walls was developed by Balcomb and Hedstrom[2]. This method does not rely on heat flux meter data. The process consists of solving the heat diffusion equation in one dimension using finite difference techniques given two measured temperatures as input. The method is fast and accurate and also allows for an in-situ measurement of wall thermal diffusivity if a third temperature is measured. Once the outer-wall heat flux is known the heat-loss coefficient at night can be calculated by simply dividing by the wall surface-to-ambient temperature difference. The technique has been applied to data taken from Los Alamos test rooms during the unusually mild winter of 1980-81 during which several different configurations were under test. The resulting U-values have good internal consistency, are in good agreement with both handbook values and Palmiter et al. results, and clearly show pronounced differences between the various options.

## 2. TEST ROOMS

For this study data were used from test rooms 1 and 2 at the Los Alamos National Laboratory passive solar test room facility. These test rooms are an adjacent pair having a building heat loss coefficient (excluding the south wall) of 26.3 Btu/F-day. Electric backup heating was used in the test rooms to maintain a minimum temperature of 65 F. The temperature control system was modified midway during the year to provide more accurate control although this has no particular effect on the results presented in this paper. Robert McFarland at Los Alamos is in the process of preparing a comprehensive report on the results of the passive test rooms for the 1980-81 winter and it is anticipated that this report will be forthcoming in the near future.

The test rooms have been modified since the 1979-1980 configuration to provide for a smaller solar collection aperture. This results in a larger value of building Load Collector Ratio in order to achieve a more representative comparison with actual buildings. The glazing is a standard 46" x 76" 3/16 in. tempered glazing unit. The Trombe walls are constructed by stacking 5.63" x

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*Work performed under the auspices of the US Department of Energy, Office of Solar Applications for Buildings.

7.5" x 15.5" solid concrete blocks to form a 15.5" concrete wall. The Trombe walls are unvented and all cracks between blocks have been well caulked to prevent air leakage. The test rooms are intentionally of very low mass construction with a fiberglass-filled 4" frame stud wall lined on the inside with 1" of polystyrene foam. A forced infiltration rate is maintained at three air changes per hour.

During the entire winter the Trombe walls themselves were not modified. The outside surface of the wall of test room 1 was painted flat black and test room 2 had a selective surface metal foil glued to the outside surface. The selective surface used was manufactured by Berry Solar Products and consists of black chrome electroplated on copper foil.

## 3. ANALYSIS TECHNIQUE

Energy flow through the wall is assumed to be one-dimensional and in accordance with the heat diffusion equation. The solution method is numerical, using finite difference techniques. Inputs to the calculation are values of the wall inside and outside surface temperatures measured at hourly intervals. Temperatures are then calculated hourly for a series of points between the two measurements. An initial temperature distribution is assumed but the effect of this assumption dies out after 20 or 30 time steps. The heat fluxes can then be inferred from the temperature gradients at the surfaces. Six nodes were used so that the spacial differencing is 2.58 inches. The technique is described in detail in Ref. 1.

The thermal diffusivity of the wall material was adjusted in order to obtain a good match between the measured and calculated temperature at the wall center. The value which gives the best agreement is 0.0423 $ft^2$/hr. The value of thermal conductivity used is 1.0 Btu/hr-ft-F and the volumetric heat capacity used is 23.6 Btu/$ft^3$ F. Measured density is 145 lb/$ft^3$.

Figure 1 shows the measured temperatures at the outside wall surface, inside wall surface, wall center, and outside ambient on a sunny day. Also shown on the figure is the calculated temperature at the wall center in excellent agreement with the measured value. The fact that the shape of this calculated curve is identical to the measured curve indicates excellent internal consistency of the technique.

The heat fluxes at the inner and outer wall surfaces calculated by this technique are shown in Fig. 2. Note that the outside heat flux is peaked in the daytime, as

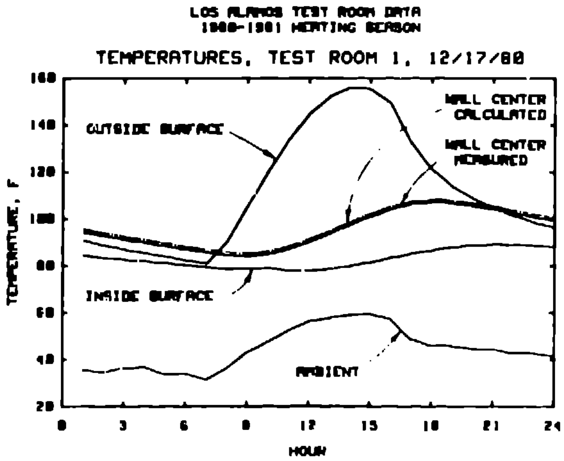

Fig. 1. Temperatures measured within the Trombe wall (solid lines). Dashed line is the calculated temperature at the wall center.

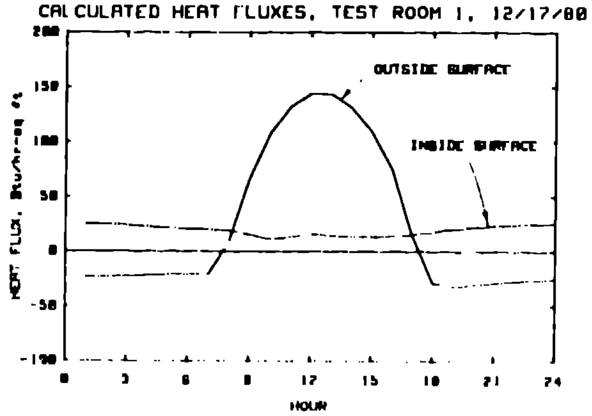

Fig. 2. Calculated heat fluxes at the two wall surfaces for the same day as Fig. 1. (Positive values indicate heat flow toward the room.)

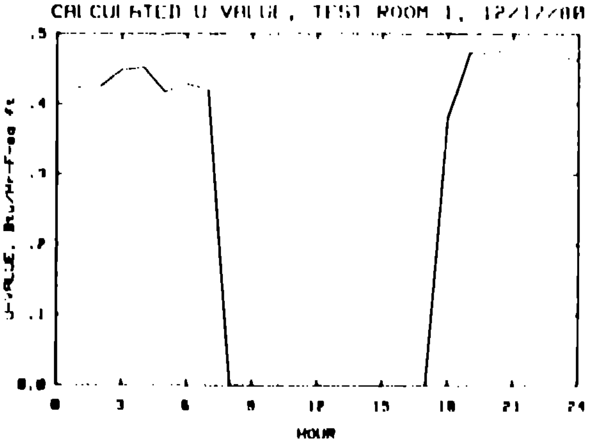

Fig. 3. Calculated U-value between the wall surface and outside ambient, based on the information in Figs. 1 and 2. Only the values at night are meaningful.

expected, but the flux into the room surface is relatively constant throughout the 24-hour period dipping only slightly during the midday. One sees that the Trombe wall is an ideal moderator of the highly-peaked solar radiation profile transforming it into a smooth, comfortable, and uniform building heater.

The apparent U-value of the Trombe wall glazing, measured from the wall surface to outside ambient, can be determined by dividing the outside wall heat flux by the wall surface-to-ambient temperature difference. The result of this calculation is shown plotted in Fig. 3 for the same day. During this time test room 1 was being operated with double glazing and without the use of any night insulation. Note that the value is relatively steady at night varying between 0.43 and 0.48. During the daytime when there is a strong solar flux present this calculated U-value is meaningless and becomes negative. Only the values between 8 p.m. and 6 a.m. have been used in the U-value calculations presented in this paper. These eleven hourly values are averaged in order to provide a nightly average apparent U-value for the glazing system and then many nightly values are averaged to obtain the final results reported.

The hourly U-value calculated by this technique seems to vary somewhat due to conditions. Figure 4 shows calculated U-values for the period December 15 through January 3 for both test rooms 1 and 2. During this entire time period both rooms were operated double glazed with no night insulation. There is a clear and marked difference between the calculated U-value for the test room 2 which has flat black paint and for test room 1 which has a selective surface. It is an unmistakable conclusion that the apparent U-value of the wall with the selective surface is markedly less than the U-value for the flat black wall. The ratio is 0.65.

The hour-to-hour and night-to-night variations in the apparent U-value are partly due to the effect of wind changing the outside film coefficient of the glazing. The average wind speed during these nights was a relatively low 2.9 mph. Correlations were made between wind speed and apparent U-value, both on an hourly and a night-average basis and although there is an evident correlation showing increased loss coefficient with increased wind velocity, the scatter is quite large. Apparently there are other effects which lead to variations in the apparent U-value. These may be associated with changes in the nature of the convection mechanism between the glazing and the wall. Note especially the dip on Dec. 19 20, a night with average wind following a cloudy day.

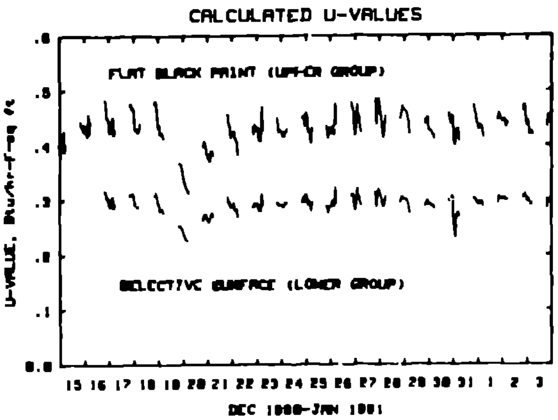

Fig. 4. Calculated U-values for 20 consecutive nights. The upper group are for Test Room 1 (flat black surface) and the lower group are for Test Room 2 (selective surface). Both walls are double glazed and unvented.

## 4. RESULTS

A total of 92 nights of data were analyzed for cell 1 and for cell 2 representing six different glazing configurations. Nightly averages were included only for nights when the data were consistent and steady. This resulted in dropping out a few nights of data. The resulting effective U-values are shown in Table 1. The values given are an average over the number of nights shown in the table.

## 5. INTERPRETATION

The data shown are all based on measurements made in the center of the wall and thus the assumption of one-dimensional flow should be quite reasonable. The U-values calculated should be representative of the center region of the wall but one might expect to see some small variation toward the edges. The measurements are quite consistent as indicated by the standard deviation shown. The standard deviation calculated for each group of 11 points for a single night is generally about one-half these values indicating that the night-to-night variation is significant, probably due to different wind speeds. As expected, the variation is larger for the cases with single glazing.

The accuracy of the average U values given is probably about plus or minus 5 percent. The largest potential source of error is inadequate knowledge of the thermal conductivity of the wall material. (The measured U-values scale directly with wall thermal conductivity.) Although the thermal diffusivity is measured in-situ, individual values of specific heat and

TABLE 1

MEASURED NIGHTTIME U-VALUES

| Time Period | No of nights used | Cell | Glazings | Other* | Average U-value | $\sigma$** | Average wind speed, mph | Average Night-time Ambient Temperature, F |
|---|---|---|---|---|---|---|---|---|
| 12/15 - 1/4 | 20 | 1 | 2 | - | 0.430 | .031 | 2.9 | 33.6 |
| 1/8 - 2/2 | 23 | 1 | 2 | NI | 0.124 | .026 | 2.4 | 27.2 |
| 2/6 - 3/4 | 23 | 1 | 1 | NI | 0.138 | .020 | 3.1 | 32.0 |
| 3/6 - 4/1 | 26 | 1 | 1 | - | 0.663 | .087 | 4.8 | 32.5 |
| 12/17 - 1/30 | 42 | 2 | 2 | SS | 0.281 | .023 | 2.6 | 30.4 |
| 2/6 - 4/2 | 50 | 2 | 1 | SS | 0.359 | .037 | 4.1 | 32.3 |

*NI refers to night insulation, SS to selective surface.

**Standard deviation of the hourly measurements. The number of points used in calculating the averages and standard deviations is 11 times the number of nights used.

thermal conductivity are less well known. The value of k = 1 which was used is representative of the high end of values for thermal conductivity for concrete given in handbooks.

The U-values determined for both single glazing and double glazing are in good agreement with values given in the ASHRAE Handbook of Fundamentals[2] after correcting for the fact that the conditions are not identically the same. For example, the U-value for single glazing is given as 0.73 in still air and 1.1 at 15 mph on the outside surface. However, the heat transfer from the Trombe wall surface to the glazing is different than from ordinary room air to a window surface. Correcting for a wall air film coefficient of 1.46 and assuming that half of the energy flow is by radiation and half by convection, the modified single glazing coefficients become 0.60 for still air and 0.86 for 15 mph. The measured value of 0.66 given in Table 1 is made for an average wind speed of 4.8 mph. This compares favorably with the interpolated value of 0.68 based on the handbook numbers. Likewise, the measured value for double glazing of 0.43 is in good agreement with the adjusted handbook value of 0.435. This good agreement gives credibility to the other numbers in Table 1.

### 5.1 Effect of night insulation

As expected, the effect of night insulation is to reduce the nighttime U-value of the glazing system markedly. The night insulation system employed was not intended to represent a practical solution for a passive building but rather a simple configuration which can be well characterized. It consisted of a 2-inch polystyrene sheet with a sheet of plywood glued to one surface and cut to fit the window opening size. It was held tightly against the outside glazing surface at night. The dramatic effect of the night insulation can be seen in Fig. 5 which shows the calculated U-values for eight consecutive nights. The application of the night insulation was initiated at the end of the day on January 5 and one can easily observe the factor-of-3.5 reduction in calculated U-value which occurs at this time.

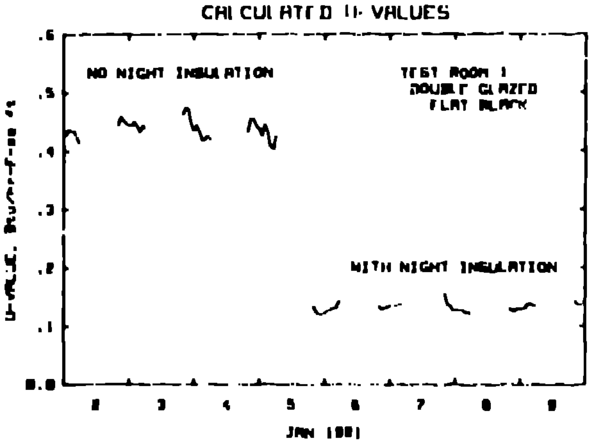

Fig. 5. Calculated U-values for eight consecutive nights in January. Application of night insulation was initiated on January 5.

The effective resistance of the night insulation can be inferred from the difference in the reciprocals of the U-values measured with and without night insulation. This calculates to be R = 5.7 for both the single glazing and double glazing configuration. The consistency between the two is encouraging.

The manufacturers' stated R-value of the insulation is 5 per inch resulting in an expected overall R-value of 10. However, one would expect that the effect of heat losses through the wood sections surrounding the window, which are unaffected by the night insulation, might reduce this substantially. Thus the implied night insulation R-value of 5.7, although lower than might have been anticipated, is not particularly surprising.

### 5.2 Effect of the selective surface

As shown in both Fig. 4 and Table 1 the selective surface has the effect of reducing the nighttime loss coefficient through the glazing system by a significant amount. The ratio of U-values with and without selective surface is 0.54 for single glazing and 0.65 for double glazing. It is especially interesting to note that the measured U-value for a selective surface and single glazing is less than for a flat-black surface and double glazing. Clearly the selective surface is very effective in reducing nighttime losses.

The other part of the evaluation of the selective surface concerns its performance during the daytime. Some results concerning overall performance have been presented previously by Hyde[3] showing a significant performance increase with a selective surface. Further evaluations have been done by both the author and by McFarland at Los Alamos based on the 1980-81 test room experience. Preliminary indications from this analysis indicate that the selective surface wall, although showing a significant increase in performance consistent with the results reported by Hyde, may not be living up to the full potential indicated by the dramatic reduction in loss coefficient. It is not yet known whether this is due to a wall absorptance which is less than predicted or a small contact resistance between the metal foil and the wall surface. Either effect or a combination could explain the observed results.

After the conclusion of the testing season the glazing was removed and several samples of selective surface foil were peeled from the wall. The wall had been prepared and the foil applied using a procedure recommended by the manufacturer using a rubber-based cement. The adherence of the metal foil to the wall seemed to be reasonably good.

One problem noted, however, is that the concrete blocks which were used to construct the wall had a significant amount of small surface voids which resulted in air pockets being formed behind the selective foil. These pockets have typical dimension of about 1/4 inch and make up about 15 percent of the surface area. This might explain an apparent contact resistance.

If the effects seen are indeed due to a contact resistance between the wall surface and the foil, then such a resistance can be included in the model. When this was done good agreement with the observed daytime conditions was obtained with a contact coefficient of R = 0.28.

The best one can say at the present time is that although the effect of the selective surface is to significantly increase the performance of the wall it may not be living up to its full performance potential. The full potential would be achieved if the U-values indicated in Table 1 pertain throughout the 24-hour period, the solar absorptance is equal to the optically-measured value of 0.93, and the contact resistance is negligible.

A contact resistance of R = 0.28 has a very minor effect on the nighttime loss coefficient values given in Table 1. If the contact resistance were reduced to zero, then the U-value would be increased to 0.30 for double glazing and to 0.40 for single glazing.

The Los Alamos results are in good agreement with the value of 0.32 measured by Palmiter, et al. (with double glazing)

## 6. ACKNOWLEDGEMENTS

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4. J. C. Hyde, "Performance of Night Insulation and Selective Absorber Coatings in LASL Test Cells," Proceedings 5th National Passive Solar Conference, Oct. 12-19, 1980, Amherst, MA