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ABSTRACT

An electric coheating experiment was conducted on a double-envelope house in Arvada, Colorado, to determine the total heat loss coefficient (UA) of the double-shelled structure, as well as the heat loss coefficients of the inner and outer shells. Electric coheating is fairly well established as an experimental method for determining the total heat loss coefficient in conventional residential buildings. However, special problems are introduced with passive and double-envelope buildings. A new methodology was developed to meet these problems. That methodology and the results of the experimental investigation are presented and discussed.

1. INTRODUCTION

The double-envelope building (1) has received a great deal of attention both nationally and internationally. Several investigations, both analytical and experimental, have been conducted to determine the thermal performance and underlying thermal mechanisms of the double-envelope building. Ghaffari, Jones, and Dennehy (2,3,4) have instrumented a double-envelope house in Rhode Island and have produced some preliminary performance results, along with a study of energy storage in the ground under the crawl space.

Akridge, Benton, and Abrams (5) present general performance data on a double-envelope house operating over an 8-month period in Georgia. Converse (6) has performed a thermal analysis on the envelope convective loop using measured data from an envelope house in New Hampshire. Sanders, Seaver, and Smith (7), using data from the same New Hampshire house, present general envelope house characteristics based on thermal analyses. Chen et. al (8) have taken a different approach to characterizing the double-envelope performance by constructing and analyzing an envelope test room.

The total thermal performance of any building depends on how well it performs many thermal functions. Examples of these functions for a double-envelope building include allowing solar gains to the inner and outer envelope, conducting thermal energy through inner and outer envelopes, storing thermal energy in the inner and outer envelope, transferring energy around the plenum, and preventing infiltration to the inner and outer envelope. Thus, determining the total performance of the double-envelope building with a single, all-encompassing experimental or analytical investigation frequently necessitates making quite a few assumptions that are difficult to support.

A different approach to determining the total performance is to conduct well-defined, well-controlled, but simpler experiments on the building to determine a single performance parameter of the several that contribute to its total performance. Using this approach, a series of experiments would be generated to determine individually the performance parameters that contribute to total performance. This is the approach we have taken. This report presents one experimental investigation constructed to determine the total heat loss coefficient of the double-shelled structure, as well as the heat loss coefficients of the individual inner and outer shells. The value(s) then can be compared directly to similar values determined by using the same methods on other passive and conventional buildings.

Subsequent experiments will then be conducted to determine the other building performance parameters that are needed to determine the total thermal performance of the double-envelope building.

2. DESCRIPTION OF THE BUILDING

The house that was tested is a double-envelope building (1) located in Arvada, Colo. The living area occupies 180 m^2 (1944 ft^2) on two floors. Figure 1 shows a section view of the building with walls generally of frame construction and batt insulation having the nominal resistance values shown.

The south walls contain 35 m^2 (378 ft^2) of double glazed window on the outside shell, and 23 m^2 (248 ft^2) of double glazed window on the inside shell. The first floor is well shielded on the west

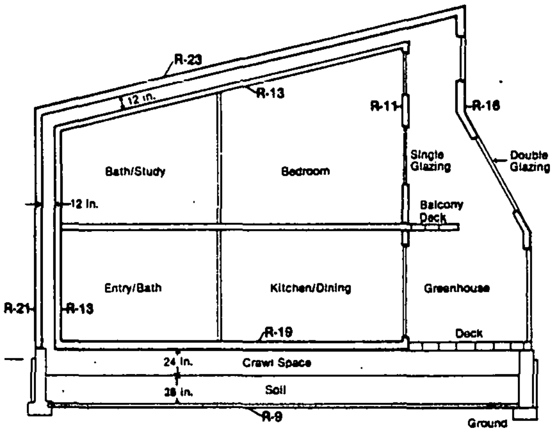

Figure 1. Section View of Double-Envelope House

side by the garage and sewing room. The plenum under the roof and on the north side is 0.3048 m^2 (1 ft) wide, and the crawl space is 0.6096 m^2 (2 ft) high. The dirt immediately under the entire crawl space is separated from the adjacent earth by a layer of 3.81 cm (1.5-in.) styrofoam insulation. The styrofoam extends in a horizontal sheet 0.9144 m^2 (3 ft) below the surface of the dirt, and continues vertically up the outside of the foundation. The total volume enclosed by the inner shell is 534 m^3 (18,865 ft^3), and the volume enclosed by the outer shell is 652 m^2 (23,013 ft^3).

3. METHODOLOGY

The basic premise of a coheating experiment is to measure the heating energy required to maintain the interior of a building at a constant and uniform temperature relative to a constant ambient temperature. This defines a steady-state condition for a two-node thermal representation as shown in Figure 2a. The expected result of the experiment is the total heat loss coefficient for the building, which includes the effects of both conduction and infiltration through the envelope.

Once steady-state conditions are achieved, the energy balance can be written as follows:

$$Q_1 = UA(T_1-T_2) \quad [1a]$$

$$UA = Q_1/(T_1-T_2) \quad [1b]$$

With this equation the total loss coefficient, UA, of the building shell can be determined by measuring the temperature difference between the inside and the outside of the shell, T_1-T_2, and the total heating energy input to the inside zone, Q_1.

The major problem in any coheating experiment is insuring that all of the heating energy is measured. The heating energy must include any energy which is discharged to the inside air from thermally massive components of the building. Conversely, the heating energy values must be decreased by the amount of energy which goes into charging any of the thermal mass.

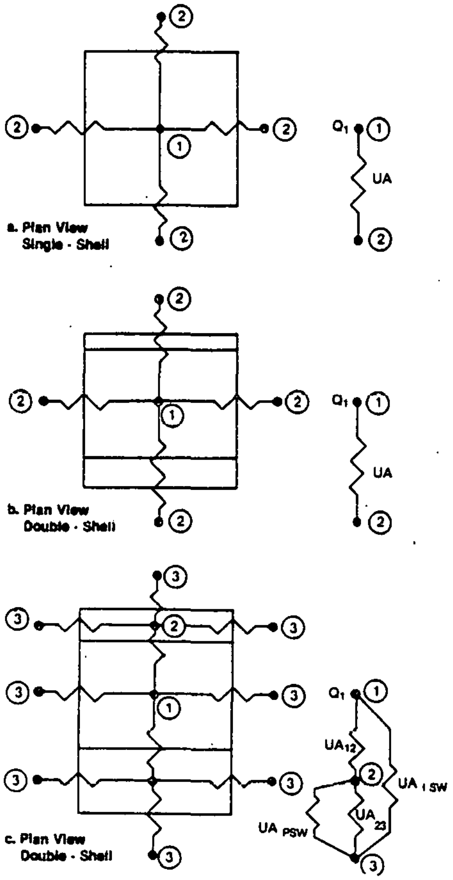

Figure 2. Thermal Network Diagrams for One- and Two-Node Models

There are two possible solutions to this problem. The first is to try to measure all of the energy which goes into charging or discharging the thermal mass. Unfortunately, since this would involve knowing the effective capacitance and temperatures of all of the building components, it is nearly impossible to do with any accuracy. The second solution—which is the one most commonly taken—is to hold all of the interior thermal capacitance at the same temperature as the inside air, and to prevent the capacitative components which are between zones from charging or discharging. This approach eliminates the need to measure energy flows resulting from charging or discharging the building thermal capacitance.

Since conventional frame buildings generally have relatively light construction and small solar apertures, achieving the above stated conditions for a coheating experiment is rarely a problem. Normally the experiment is run at night to avoid any instantaneous energy gains from solar radiation. Well-calibrated heating energy sources—commonly electric strip heaters—are used to maintain the interior temperature within a tight deadband. Since the interior temperature is held essentially constant and there is little thermal capacitance to discharge, steady-state conditions will occur shortly after the outside temperature becomes constant.

In passive buildings, large solar apertures allow significant amounts of solar radiation to enter the shell. To compound the problem, passive buildings are frequently designed to have substantially more thermal capacitance than conventional buildings. Thus, more energy can be stored, and this stored energy can be released over a longer period of time. The technique used here is to prevent this daytime charging and allow the thermal capacitance to come to equilibrium with the air. This is done by covering all the windows for several days prior to the test. With this additional step, the coheating procedure for most passive buildings is much like that for conventional buildings.

In the case of double-envelope buildings, the overall building heat loss coefficient can be broken down into coefficients for each of the shells. Figure 2 schematically illustrates the problem encountered in going from a single-shelled to a double-shelled building. In a single-shelled building, Fig. 2a, the loss coefficient of the building shell can be obtained from a simple two-node thermal representation. This two-node thermal representation is also sufficient to determine the combined loss coefficient of both shells together, Fig. 2b, but it says nothing about the contribution of each shell. To determine the individual coefficients of each shell, a three node thermal representation of the type shown in Fig. 2c is necessary. An energy balance on node 1 and 2 results in the following equations:

$$Q_1 = UA_{12}\,(T_1 - T_2) + Q_{isw} \qquad [2]$$

$$UA_{12}\,(T_1 - T_2) = UA_{23}\,(T_2 - T_3) + Q_{gsw} \qquad [3]$$

where Q_{isw} is the heat flux through the interior side (east and west) walls, Q_{gsw} is the heat flux through the greenhouse side walls, UA_{12} is the loss coefficient between the interior (node 1) and the plenum (node 2), and UA_{23} is the loss coefficient between the plenum and the ambient (node 3). Thus, in order to use equations [2] and [3] to find the individual loss coefficients, the temperatures of all three nodes, the total heating energy input and the heat fluxes through the side walls, Q_{isw} and Q_{gsw}, must be measured. Of these, the temperatures and the total electric power input to the building can be measured directly with the proper instrumentation. However, the heat fluxes through the side walls must be measured at several representative locations on the side walls and windows. The total heat flow through these walls can then be determined by appropriate area-weighted averaging.

It is also possible to define the effective loss coefficients through the side walls, UA_{isw} and UA_{gsw}, in the following manner.

$$UA_{isw} = Q_{isw}/(T_1 - T_3) \qquad [4]$$

$$UA_{gsw} = Q_{gsw}/(T_2 - T_3) \qquad [5]$$

These values represent an effective overall loss coefficient for the entire wall. They can be compared directly with the loss coefficients for the individual shells and the building as a whole.

In this analysis, the conduction losses through the side walls are assumed to represent the only losses that do not occur through the inner and outer shells. This amounts to an implicit assumption that all of the infiltration losses occur through the shells. This implicit assumption is justified on two points. First, the shells contain many more openings than the side walls, and indeed contain all of the doors and most of the operable windows. Secondly, even if the actual infiltration rate were known, it is not apparent how to assign fractions of the total rate to individual walls, windows, or doors. For these reasons all of the total infiltration is assumed to occur through the shells.

4. MATERIALS AND METHODS

Before the test, the house had been instrumented with about 150 temperature and heat flux sensors. Of this total number, 48 sensors were wired up for the experiment, including 39 thermocouples, 8 heat flux transducers, and 1 wattmeter.

The house was heated with seven electric baseboard heaters, which were distributed room by room throughout the house. Each heater was controlled independently by a local thermostat to provide as uniform an indoor air temperature as possible.

The total electric power consumption in the house was monitored by both a Hall-effect watt transducer and by a pulse-initiating wattmeter supplied by the local utility. A comparison of the results from these independent systems showed discrepancies of less than 5%, giving confidence in the accuracy of the measurements.

To prevent solar radiation from entering the house, the windows were covered with foil-backed kraft paper of the type used in the construction industry. The solar reflectivity of the foil side of this paper is 0.86. This paper was fastened to the inside of all the windows with double-backed carpet tape.

Indoor air temperature was monitored with 12 radiation shielded thermocouples. Six of them were distributed throughout the first floor, while the other six were located throughout the second floor. Four shielded thermocouples were located at various heights in the greenhouse, and another three thermocouples were distributed in the top, the north side, and the crawl space to monitor the plenum temperatures. The ambient temperature was monitored by a shielded thermocouple located on a weather instrument tower on the upper southwest corner of the house.

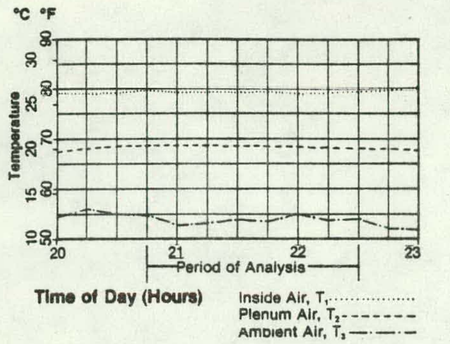

Figure 3. Average Air Temperature

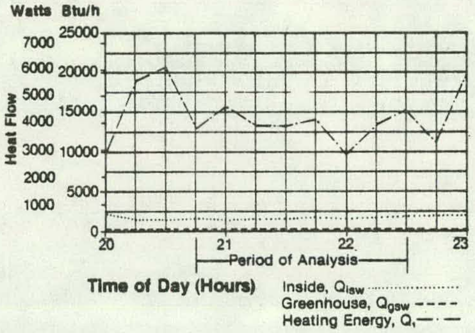

Figure 4. Measured Heat Flows

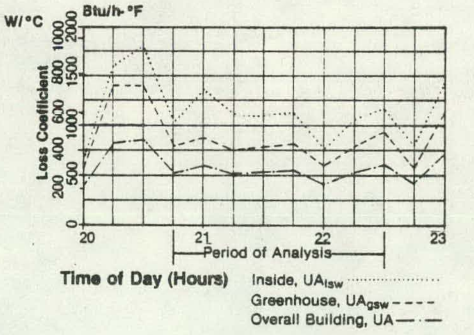

Figure 5. Loss Coefficients

Eight heat flux sensors were used in this experiment. These were located with both air and surface thermocouples in a temperature-heat flux group which was designed to make it possible to back out an effective loss coefficient for the wall (or window) in question.

Temperature-heat flux groups were located so that the heat flows and effective loss coefficients could be measured directly for the east and west walls of the building. One group measured the heat flow through the solid (frame) part of the inside east wall, and another was located on an east facing window. Similarly, groups were placed on the east and west greenhouse walls and windows. On the inside west wall, one group was placed on the first floor to measure the heat flow to the garage, while another was placed on the second floor to measure the heat flow directly to the ambient.

Much of the post-experiment data reduction was directed to providing the values needed to solve Eq . [1] for the overall building loss coefficient, UA, and Eqs. [2] and [3] for the individual shell coefficients, UA_{12} and UA_{23}. To get the inside air temperature, T_1, all twelve inside air thermocouples were averaged together; six temperature readings from the greenhouse, the top plenum, and the north side plenum were averaged together to give the average plenum temperature, T_2. For the outside ambient temperature, T_3, the thermocouple on the weather tower was used. The sidewall loss coefficients calculated from the temperature-heat flux group measurements were area-weighted together to give loss coefficient values for the inside and plenum side walls, UA_{isw} and UA_{gsw}.

5. RESULTS

Despite the warm, sunny weather through the course of this experiment, setting the baseboard heater thermostats up to 27° C (80° F) provided reasonable sized temperature differences between the inside, the plenum, and the ambient. A period of about 2 hours was found on the first night when all of the temperatures were essentially constant. This period occurred between 20:45 and 22:30 on Friday evening. Analysis was concentrated on this period, since no other period of constant temperature could be found in the two nights of testing.

The average indoor, plenum, and ambient temperatures are shown in Fig. 3. The greatest variation in temperature from reading to reading is observed in the ambient temperature, which varied less than 1.7° C (3° F). During the period of analysis the temperature difference between the indoor and the ambient air, $T_1 - T_3$, was 13.9° C (25° F). The temperature difference between the indoor air and the plenum air, $T_1 - T_2$, was about 6.1° C (11° F), while the temperature difference between the plenum air and the ambient air, $T_2 - T_3$, was about 7.8° C (14° F).

The total heating energy input to the house, Q_1, and the heat flows through the inside and greenhouse side walls, Q_{isw} and Q_{gsw}, are plotted in Fig. 4. Although the heat flows through the side walls are quite constant over the period of analysis, the total electric energy input varies by as much as 30%. This is unavoidable, since it occurs because the reading for a particular interval depends on how many of the seven heaters happened to be on for some fraction of that time.

Since the temperature differences are fairly constant, the main cause for the fluctuation in the loss coefficient values plotted in Fig. 5 is the fluctuation in the electric power readings. Averaging the eight readings over the period of analysis gives a value of 279 ± 29 W/°C (529 ± 55 Btu/h-°F) for the overall loss coefficient, UA. Similar averaging on the loss coefficients for the inner and outer shells gives the values shown in Table 1.

Table 1. LOSS COEFFICIENTS

	W/°C	(BTU/hr-°F)	Std Dev.	
Overall building	279	(525)	29	(55)
Inner shell	586	(1100)	83	(157)
Outer shell	413	(786)	47	(90)
Side walls	34	(64)	4	(8)
Greenhouse side walls	10	(19)	0.7	(1.3)

The loss coefficients for the inner and outer shells correspond to effective resistance values of about R3 and R5 respectively. These values take into account losses through solid (frame) sections, through windows, and infiltration losses. The combined average loss coefficient through just the shells in series is 242 W/°C (458 Btu/h-F), which represents about 87% of the total loss coefficient for the building.

6. CONCLUSIONS

The overall loss coefficient of 279 W/°C (529 Btu/h-F) corresponds to a value of 6.5 Btu/degree-day-ft^2. This is the amount of energy this building could be expected to use in the absence of any solar radiation. The actual energy use will, of course, decrease by the amount of useful solar energy collected.

Of the total losses from this building, approximately 87% is lost through the double envelope (including infiltration). This occurs because the double envelope represents the largest surface area in the house, and also because the envelopes contain the vast majority of doors and windows, both fixed and operable.

This building ranks as a reasonably good energy-conserving building when compared on the scale of modern construction. For example, the proposed BEPS (Building Energy Performance Standard) regulation (9) would have allowed the consumption of no more than about 5.1 Btu/degree-day-ft^2 for either conventional or solar-oriented construction.* However, the value reported here for a double-envelope house is only 27% above the BEPS value. It would appear that when solar gains are considered, this house would have little trouble meeting the BEPS standard.

The methodology employed here is a valuable way of experimentally determining a parameter that is quite significant in building thermal performance. Determination of the steady-state loss coefficient is a prerequisite for later dynamic analysis of solar energy gains and storage. As such, it represents a step toward our ultimate understanding of the thermal mechanisms operating in not only the double envelope house, but in all buildings.

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*Based on a gas or oil furnace efficiency of 0.65 in Denver, Colorado.