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THE EFFECT OF WALL MASS ON THE ANNUAL SPACE HEATING AND COOLING LOADS OF RESIDENCES

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1. Introduction

The National Bureau of Standards carried out field studies (1,2) using six one-room test cells in Gaithersburg, MD, to investigate the effect of wall mass on space heating and cooling loads. The test cells were extensively instrumented and monitored over a one-year period.

The study (1) pertaining to space heating found that wall mass did not have a measurable effect on space heating loads during the cold part of the winter in Gaithersburg, MD. However, during mild spring heating days, when the internal heat gains caused the indoor temperature to rise above the thermostat set temperature, a significant thermal mass effect was observed. The heavyweight masonry and log buildings consumed less space heating energy than essentially identical lightweight buildings having building envelopes of equivalent thermal resistance. Wall mass was found to be more effective when it was placed inside, as opposed to outside, the wall insulation. The study (2) pertaining to space cooling found that wall mass had a significant effect on space cooling loads of these test buildings during the entire summer season in Gaithersburg, MD.

While the field study results conclusively demonstrated the existence of a thermal mass effect, they were found to have limited applicability to real houses because the test cells were small, the solar gains through windows were small, and the top surfaces of the floors were insulated.

A limited series of tests were conducted with a partition wall installed in two of the test cells (3). However, both the field measurements and computer predictions indicated that the effects of a partition wall in the test cells was very small. This was because the direct solar gains through windows did not enter the test buildings during periods when a thermal mass effect would normally be expected. The present computer study examines the effect of partition walls and interior furnishings in a house under conditions when direct solar gains contribute in a normal way to the internal heat gains.

2. Description of computer program

The Thermal Analysis Research Program (TARP) is a computer program that predicts either the indoor temperature or space heating/cooling loads of a building under a dynamic set of boundary conditions. TARP uses a detailed heat-balance method to determine heating/cooling requirements from the predicted heat losses and heat gains. The computer algorithms are partly based on subroutines from the Building Loads Analysis and System Thermodynamics (BLAST) Computer Program. In using TARP, a detailed description of the building including the heat-transfer parameters for all materials comprising the building envelope, an operation schedule for the building, and hourly outdoor climatic data are specified as input for the program. Further information on TARP may be found in ref. (4).

Space heating and cooling loads predicted by TARP have been compared to corresponding measured space heating and cooling loads for the six thermal mass test cells with good agreement (5). In these comparisons, TARP predictions accurately followed the general trends of the measured data. TARP predicted peak space heating and cooling loads within 15% and 18%, respectively. This level of agreement was considered to be reasonable in view of the uncertainty in the heat-transfer properties of the building materials specified as input for the program and the simplifying approximations in the computer algorithms. The level of agreement is comparable to, and in most cases better than that for other similar computer programs cited in the literature. A strong case for the validity of the TARP program relative to the thermal mass studies (1,2) is that during climatic periods when a thermal mass effect was experimentally observed, the TARP program predicted the correct relative cumulative space conditioning loads. That is, the ranking of the test cells and the relative magnitudes of the predicted thermal mass effects were the same as those for the actual test cells.

3. Description of house used in the analysis

The house considered in this study, was a wood-frame rambler having a floor area of 110 m^2. This house was similar to the house specified by Hastings (6). It had a pitched roof and ventilated attic with R-3.3 $m^2 \cdot K/W$ ceiling insulation. The wall constructions analyzed included: insulated wood frame; insulated masonry with mass on the exterior; and insulated masonry with mass on both sides of the insulation. A description of these wall constructions is given in table 1. The wall constructions were the same as those for the field test cells, except that the overall thermal resistances were made to be identical by slightly adjusting the thermal conductivities of the wall insulations.

For this house, the windows were double pane and had a surface area of 13.1 m^2, or 12% of the floor area. For each orientation, the ratio of window area to gross wall area was constant. The roof overhung the windows by 0.61 m along the north and south walls.

The floor consisted of 25 mm wood and R-1.9 $m^2 \cdot K/W$ insulation placed over a ventilated crawl space. A floor plan and elevation are given in fig. 1. Further information on the house is given in ref. (3). For the analysis, the rate of infiltration was taken to be constant at one air change per hour.

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Table 1. Description of wall constructions

Insulated lightweight wood frame

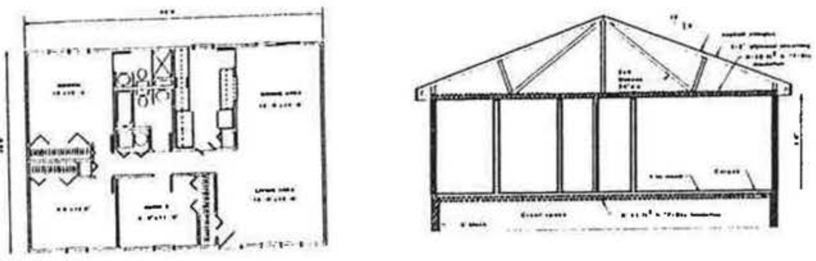
13 mm gypsum board
0.05 mm polyethylene film
50 x 100 mm studs placed 0.41 m on center with R-1.9 $m^2 \cdot K/W$ blanket insulation installed between the studs
16 mm exterior plywood

Insulated masonry with interior insulation (mass on outside)

13 mm gypsum board
0.05 mm polyethylene film
51 mm thick extruded polystyrene insulation placed between 38 mm wide wood furring strips placed 0.6 m on center
6 mm air space
102 mm 2-core hollow concrete block at 1680 kg/m^3
102 mm face brick

Insulated masonry with insulation sandwiched between inside and outside mass

13 mm plaster
200 mm 2-core hollow concrete block at 1680 kg/m^3
89 mm perlite insulation in cavity
102 mm face brick



A. Floor Plan. B. Elevation.

Figure 1. Floor plan and elevation for the house.

4. Description of computer model

Each house was simulated as three zones including a living space, an attic, and a crawlspace. Space heating and cooling was provided only for the living space. The air temperature within each zone was assumed to be uniform. Partition walls and interior furnishings were included as surfaces within the living space. The radiant exchange among the surfaces within each zone was computed by the mean-radiant-temperature network method. This method is equivalent to putting all surfaces on a hypothetical sphere permitting each surface to have some view of every other surface. Compared with other contemporary computer programs, TARP is one of the few programs that handles the radiation exchange among interior surfaces.

Each of the partition wall surfaces consisted of 50 x 100 mm framing with 13 mm gypsum board attached at opposite sides. The surface area of the partition wall surfaces was identical to the actual partition walls of the Hastings' house.

Interior furnishings were modeled as a 50 mm slab of wood having a surface area of 86.6 m^2. The total weight of interior furnishings was 3200 kg, and its specific heat was taken to be 1200 $J/kg \cdot K$. The weight of interior furnishings included not only the weight of movable furniture but also fixed furnishings such as appliances and fixtures.

For the computer simulations, the thermostat was set at 20°C for space heating and 24°C for space cooling. Within a 4°C range between the setpoints, space conditioning was not provided. A constant internal load of 8.1 W/m^2 of floor was used to simulate heat release associated with occupancy.

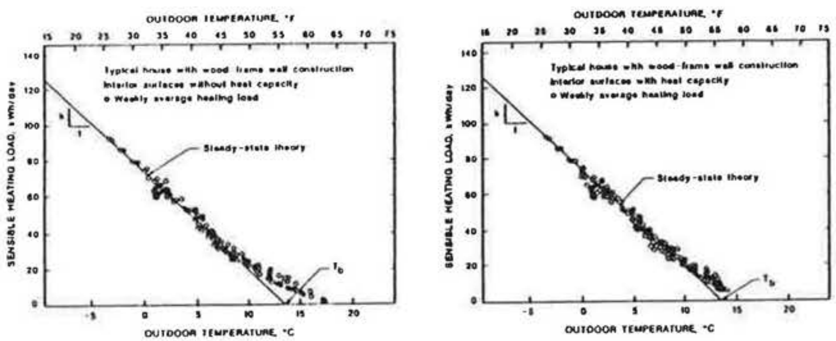
5. Results

Using climate data from WYEC (Weather Year for Energy Calculations), annual space heating and cooling loads were predicted for the following cities: Madison, WI; Lake Charles, LA; Washington, DC; Los Angeles, CA; and Charleston, SC. These cities were selected to represent the climates of the Northern, Gulf Coast, Mid-Atlantic, southern West Coast, and Southern regions of the U.S., respectively.

Weekly average winter heating loads expressed in kWh/day for the house with lightweight wood-frame wall construction exposed to Washington, DC, climate are plotted as a function of weekly average outdoor temperature in fig. 2. The special case of interior surfaces without thermal storage is given in fig. 2a. Here the interior surfaces participate in the radiant exchange within the living space, but they do not store heat. Note that the majority of the heating loads are correlated by a linear relationship obtained by the method of least squares. As the outdoor temperature becomes warmer, the heating loads rise above this linear relationship. The larger heating loads during mild heating periods are caused by an inability of the house to utilize all of its internal heat gains. The indoor temperature rises above the thermostat set temperature, and thermal energy is rejected to the environment. This means that some energy is not utilized compared to a week with steady outdoor temperature. In extreme cases of overheating, the indoor temperature actually rises above the setpoint for space cooling, and cooling loads occur. The effect of adding thermal heat capacity to the interior surfaces is illustrated in fig. 2b. Here it is seen that the addition of thermal heat capacity to the interior surfaces causes the house to utilize a larger portion of its internal heat gains. As a result, the heating loads near the balance-point temperature closely approach the linear relationship. Here the term balance-point temperature denotes the average outdoor temperature at which the space heating load vanishes.

The linear relationship functions as a "high-mass limit." That is, the space heating loads approach this limit as thermal mass is added to the house. Heating load correlations for the house with insulated masonry wall constructions are given in fig. 3a for the case of mass on the outside and in fig. 3b for the case of mass on the inside. These results indicate that wall mass has a small effect on space heating loads in Washington, DC, because the presence of interior surfaces caused the space heating loads to approach closely the "high-mass limit." Under this condition additional mass provided in the walls had a small effect. The linear relationship is shown in ref. (7) to coincide closely with a variable-base heating-degree-day model.

Reductions in annual heating load achieved by using masonry instead of wood-frame wall construction for the five climates analyzed are summarized in table 2. Here it should be emphasized that the houses compared have equivalent steady-state envelope heat-transfer coefficients. From table 2, it is evident that inside mass is considerably more effective than outside mass. That is, percent reductions in annual space heating loads are generally about 3-5 times

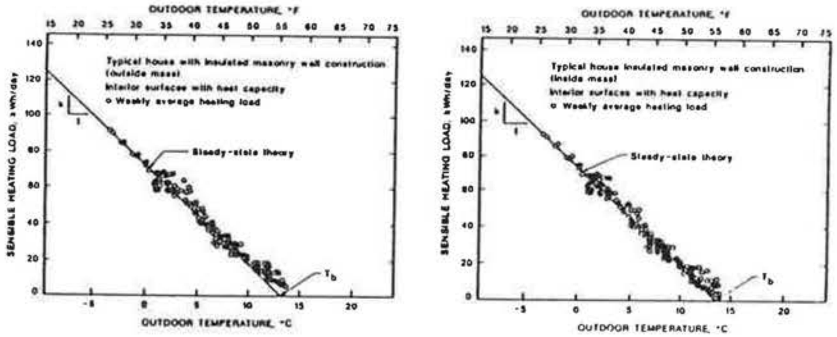


a. Interior surfaces without heat capacity.

b. Interior surfaces with heat capacity.

Figure 2. Heating load correlations for houses with wood-frame wall constructions located in Washington, DC.

larger. Both the percent and absolute reductions for cases of inside and outside mass are larger in the mild climate regions because the majority of the heating days are near the balance-point temperature. At an electric rate of $0.06/kWh, the largest observed absolute reductions of 294 kWh for Charleston, SC, represents an annual monetary savings in heating cost of $18. This reduction is 9.9% of the annual heating load.



a. Mass on outside.

b. Mass on inside.

Figure 3. Heating load correlations for the house with masonry wall construction located inWashington, DC.

Reductions in annual space cooling loads for the house are summarized in table 3. Here the same trends as given for annual heating loads are apparent. That is, absolute and percentage reductions are largest in mild climates, and mass is more effective when it is positioned inside, as opposed to outside, the wall insulation. As in the case of reductions in space heating load, the absolute reductions convert into rather small monetary savings. For instance, at an electric rate of $0.06/kWh and for air conditioning equipment with a seasonal average coefficient of performance equal to 2.4, the largest reduction (found in LA) of 469 kWh represents an annual monetary saving in cooling costs of $12. This reduction is 12.3% of the annual cooling load.

As part of this study, an analysis was conducted of a house with large solar gain. Thermal mass effects were shown to be more important in instances where the internal heat gains were large, the mass was located inside the insulation, and the house operated predominantly near its balance-point temperature (7).

The effect of thermal mass on peak space heating and cooling loads is addressed in ref. (8). The effect of thermal mass on night temperature setback savings is given in ref. (9).

6. Summary and conclusions

The computer program TARP was used to predict the space heating and cooling loads of a house. This house contained representative interior surfaces including partition walls and interior furnishings.

Weekly space heating loads were correlated with weekly average outdoor temperature. The presence of partition walls and interior furnishings caused the space heating load correlations of the house to approach a linear relationship that coincided with steady-state theory. Under this condition, the presence of additional mass, such as wall mass, was found to have a small but beneficial effect on space heating and cooling loads, except for climates where the house operated predominantly near to its balance-point temperature. Similarly, wall mass was found to have a small effect on space cooling loads in the house with partition walls and interior furnishings.

Table 2. Reductions in annual space heating loads achieved by masonry wall construction compared to wood-frame wall construction

Region	City	Annual Heating Loads, 10^3kWh: Wood Frame	Masonry (Mass) Outside	Masonry (Mass) Inside	Reductions: Mass Outside kWh	Mass Outside %	Mass Inside kWh	Mass Inside %
Northern	Madison, WI	15.7	15.6	15.5	41	0.26	158	1.0
Mid-Atlantic	Washington, DC	8.01	7.98	7.88	26	0.33	135	1.7
Gulf Coast	Lake Charles, LA	1.94	1.88	1.71	55	2.9	227	11.7
Southern West Coast	Los Angeles, CA	0.651	0.591	0.416	60	9.2	235	36.
Southern	Charleston, SC	2.98	2.88	2.68	93	3.1	294	9.9

Table 3. Reductions in annual space cooling loads achieved by masonry wall construction compared to wood-frame wall construction

Region	City	Annual Cooling Loads, 10^3kWh: Wood Frame	Masonry (Mass) Outside	Masonry (Mass) Inside	Reductions: Mass Outside kWh	Mass Outside %	Mass Inside kWh	Mass Inside %
Northern	Madison, WI	3.07	2.97	2.79	108	3.5	286	9.3
Mid-Atlantic	Washington, DC	6.14	6.06	5.96	88	1.4	188	3.1
Gulf Coast	Lake Charles, LA	10.4	10.3	10.2	105	1.0	255	2.4
Southern West Coast	Los Angeles, CA	3.80	3.61	3.33	193	5.1	469	12.3
Southern	Charleston, SC	8.27	8.16	8.01	105	1.3	258	3.1

7. References

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