ENERGY CONSERVATION DESIGN GUIDELINES FOR INCLUDING MASS AND INSULATION IN BUILDING WALLS

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ABSTRACT

In the design of energy efficient buildings, it is necessary to optimize wall insulation and thermal mass. The benefits of insulation in light-weight walls are well understood. However, the effects of mass for energy conservation are grossly overestimated by many while being completely neglected by others. Insulation and mass can be combined in different ways to achieve different results as desired in heating, heating/cooling, and cooling climates. Special consideration must be given to internal loads and occupancy profiles (daytime only vs. 24 hour occupancy) and how the walls can help reduce building loads rather than impose building loads. Guidelines are presented here for applying mass and insulation for energy conserving wall design.

INTRODUCTION

Significant efforts have been expended recently to understand the energy impact of most of the major loads in buildings. As glazing and lighting loads have become better understood, attention is now turning to some of the finer points of building shell design for energy conservation. This includes optimal selection of thermal mass and insulation for exterior walls.

Exterior walls offer unique opportunities for energy conservation and peak load control. The designers have greater control over wall loads than most other thermal loads. Other loads are generally determined by constraints outside the control of the designers. Table I lists the major thermal loads in buildings and the major factors (other than first cost and operating cost) which determine these loads. The table indicates that the designer has a great deal more flexibility to select or optimize wall and roof loads than other loads.

Furthermore, these other loads are essentially instantaneous in most cases. Thus, load management beyond proper building orientation is difficult. For these reasons, the wall heating and cooling loads offer unique conservation opportunities for the designers. The designers have a great deal of control over the insulation level and the thermal mass of a wall. Thus, the magnitude and time of occurrence of wall loads can be selected.

This paper discusses the characteristics of thermal mass and thermal insulation which influence heating and cooling loads of walls. Also discussed is the potential for both energy savings and peak load reduction due to wall mass and insulation in buildings with moderate internal heat gains and either night setback or mechanical system shutdown at night (e.g., typical office buildings). The paper does not present exact procedures for calculating optimal mass and insulation, but rather discusses issues to be considered and general characteristics of different walls. The discussions and guidelines presented here are equally applicable to roofs as to walls. However, they do not necessarily apply to buildings with high radiant internal heat gain (e.g., direct-gain solar heated buildings).

CHARACTERISTICS OF THERMAL MASS AND THERMAL INSULATION

Thermal mass has only one characteristic - it increases in temperature as it absorbs heat (phase change materials are not considered here). It does not resist the steady-state flow of heat, but rather delays the development of a steady-state condition. Under the cyclic loading conditions present at the outside surface of a building wall, thermal mass delays heat gain and loss and reduces diurnal variations in heat gain and loss to a room of constant temperature. Figure 1 shows the influence of mass on design day heat gain from walls in New York City. The ASHRAE cooling load temperature difference (CLTD)[1] is shown on the vertical axis and time of day on the horizontal. Table II gives the thermal mass and average CLTD of the 7 wall sections plotted. The more massive walls have smaller diurnal variations in heat gains with lower peak loads (peak CLTD) occurring later in the day. But, average heat gain is essentially equal for all wall sections, as mass does not affect average heat flow.

Massive exterior walls can be used to absorb intermittent internal heat gains to prevent space overheating and to stablize resulting cooling loads. However, this effect is generally minor except where the internal heat gain is by radiation directly onto the mass. The benefits of mass in direct-gain solar heated buildings cannot be overstated. However, that situation will be left for discussion by others and this paper will address itself to more conventional buildings.

Like thermal mass, thermal insulation has only one characteristic - it increases the time required to pass a given quantity of heat across a given temperature difference. As a result, it reduces peak and average heat flow. Under the cyclic loading conditions present at the outside surface of a building wall, thermal insulation reduces diurnal variations in heat gain and loss to a room of constant temperature. The influence of insulation on wall heat gain is shown in Figure 3 which gives design day heat gain on the vertical axis and time of day on the horizontal. Heat gain was calculated using the response factors presented in Reference 1 for four similar frame walls. Properties of these walls are given in Table III along with the peak and average heat gain of each. Figure 2 and Table III show that insulation reduces both peak and average heat gain but does not affect the time of occurrence of heat gains.

POTENTIAL SAVINGS FROM THERMAL MASS

Maximum savings in average and peak energy consumption and in peak equipment sizing could be realized by having wall loads occur 180 degrees out of phase with the building loads. This will actually allow the walls to provide useful heating and cooling to a building during days with moderate ambient conditions. This generally means that peak heat gain through a wall would occur about 6:00 A.M. (approximately 15 hour delay) and peak loss about 2:00 P.M. - 5:00 P.M. (approximately 9 hour delay). However, even the most massive conventional walls of Figure 1 delay peak heat gain only 11 hours and peak heat loss only 7 hours. Thus, the maximum theoretical savings from mass cannot generally be realized in practice. Still, substantial savings due to thermal delays can often be realized, particularly during mild and hot weather.

One design strategy for energy savings due to thermal mass is to delay much of the wall heat gain until after the building occupants have left and the air conditioning system has shut down. This will generally mean that wall peak heat gain occurs during the unoccupied period, so the walls might not comprise a significant portion of the building peak cooling load. Much of the delayed heat gain could then be removed by the air conditioning economizer operating on a night flush cycle or by mechanical refrigeration at night when the ambient temperature is low and cooling efficiency is high.

Figure 3 shows percent of summer wall heat gain occurring between 7:00 P.M. and 6:00 A.M. for the 7 wall sections of Table II. The figure is for a building with its long axis East-West so the east and west wall area is small compared to north and south wall area. Calculations were made for the months of June through September in New York City[2] using the cooling load temperature difference method. The figure shows that more than 60% of the summer heat gain of walls A-D occurs between 7:00 P.M. and 6:00 A.M., while only 10% of the heat gain of wall G occurs during this period. Since cooling can be accomplished very efficiently during this period, significant potential exists for cooling energy savings through proper selection of wall mass.

Savings in winter, however, are generally less impressive. Peak heat loss from a room to a wall occurs during extended periods of cold, cloudy weather which brings the inside wall surface to its lowest temperature. Then early in the morning when the room thermostat is raised from the night setting to the day setting, the peak heat loss occurs. As owners of adobe homes know, the cold, massive walls absorb a significant amount of heat as the room temperature is raised to the daytime setting. This same performance is observed in exterior zones of large buildings with massive walls if the wall mass is placed at the inside surface. But, if wall mass is outside the insulation, the amount of mass has very little influence on peak heat loss from the room to the wall.

The potential for heating energy savings due to wall mass is also generally small. As previously mentioned, this is primarily because the wall cannot delay heat gain from afternoon until early morning. An existing study by Arumi[3] discusses heating energy savings in detail. One of his conclusions is that mass will provide less than 5% savings if $r>1$, where:

r	=	$(T_h - T_m)/DT$,
T_h	=	winter thermostat setting,
T_m	=	mean annual temperature, and
DT	=	amplitude of daily temperature oscillation (0.5* Daily Temp Swing).

Most U.S. cities with significant heating loads have $r>1$ for winter, so mass in building walls, does not generally provide heating energy savings. In fact, wall mass can actually increases the heating energy consumption required to maintain comfort conditions in many buildings. Consider the case where the mass is placed between the wall insulation and the conditioned space of a building (the insulation is outside the mass) which uses night setback. The wall will often be cold in the early morning when the heating system turns on. The mass will then absorb a portion of the heat supplied to the room and, thus, cause the heating system to run longer at peak load before meeting the room comfort conditions. This can use more energy than a building with mass outside the insulation or a building with no mass at all. In these last two cases, sunshine and interior lighting provide some "free" heating to offset space heating loads after night setback. This effect is diminished when mass is closely coupled to the conditioned space, so intermittently heated buildings with moderate interior heat gains (e.g., typical office buildings) should generally not have mass close-coupled to the conditioned space.

The savings potential of mass depends very strongly on the weather conditions of a particular location. A quick, visual indication of the savings potential can be seen from a plot of average daily maximum and minimum temperatures over the course of a year. This is given in Figures 4, 5 and 6 for San Diego, New York and Minneapolis. The savings potential of mass is greatest when the ambient temperature varies in the neighborbood of the comfort zone. Thus, San Diego has significant potential savings, New York has less potential and Minneapolis has still less potential for energy savings due to mass.

It is important to note that the relationship between heating and cooling energy consumption and wall mass is nonlinear. There is often a specific mass which yields minimum energy consumption. This is demonstrated in Figure 3. Thus, it is not always true that "if a little mass is good, a lot is better".

POTENTIAL SAVINGS FROM THERMAL INSULATION

The effects of insulation are much more straightforward than are the effects of thermal mass. This is because insulation has an essentially linear influence on heat gain and loss through walls. Insulation reduces detrimental heat gain and loss on an instantaneous basis. Savings in mechanical equipment sizing, peak heating and cooling demand, and total heating and cooling energy consumption are all realized as insulation is increased in building exterior walls.

The savings potential due to insulation, like the potential of mass, varies with climatic conditions. Savings are greatest in areas with large inside-outside temperature differences. Figures 4, 5 and 6 indicate that savings will be greatest in Minneapolis and least in San Diego.

Walls with insulation inside the thermal mass perform somewhat different from walls with insulation outside the mass. For maximum energy savings, the insulation placement should be determined by the hours which the building is conditioned. If the building is conditioned 24 hours per day, the insulation should generally be placed outside the mass. The mass is then adjacent to the conditioned space and helps to stabilize loads by storing heat or cooling within the conditioned space. However, buildings conditioned less than 24 hours per day should generally have insulation near the inside wall surface with any mass outside the insulation. This is because energy savings due to night temperature setback are greatest if the space temperature is quite responsive. The temperature of responsive buildings drops quickly at night when the thermostat is set back and rises quickly in the morning when the thermostat is set up to the daytime value. Buildings with insulation near the inside wall surface are more responsive than buildings with thermal mass at the inside surface. Thus, the ideal position for insulation is generally at the inside surface of walls of buildings which are intermittently conditioned.

GUIDELINES FOR APPLYING INSULATION AND THERMAL MASS

The following points should be kept in mind when selecting wall sections in energy conserving buildings:

1. Thermal mass does not reduce average heat transfer. It simply delays heat gains and losses and reduces diurnal variations in heat gain and loss. Thermal mass can be used to delay as much as 60% of annual wall heat gain until after 7:00 P.M. when many buildings are shut down. This delay also reduces building peak cooling load.

2. Wall mass generally provides negligible savings in average heating loads. Levels of mass in exterior walls should be selected to benefit the cooling system rather than the heating system when night setback is used.

3. Savings from mass are greatest in climates where the ambient temperature is within the comfort zone for a portion of the day throughout much of the year. This is the case in mild climates and climates with long cooling seasons.

4. Wall insulation should generally be maximized if the walls impose significant loads on the heating and cooling systems. This is the case in severe heating and/or cooling climates. Insulation should be selected to benefit both heating and cooling systems.

5. Insulation should be outside the mass of walls in buildings conditioned 24 hours per day. It should be inside the mass in buildings conditioned less than 24 hours per day.

REFERENCES

1. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Handbook of Fundamentals, 1977.

2. National Oceanic and Atmospheric Administration, "Local Climatological Data", 1978.

3. Arumi, F., "Thermal Inertia in Architectural Walls", National Concrete Masonry Association, 1976.

4. Yellott, J., "International and Historical Perspective", DOE Third National Passive Solar Heating and Cooling Conference, San Jose, 1979.

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TABLE I - MAJOR FACTORS DETERMINING BUILDING LOADS

LOAD	DETERMINANT
OCCUPANCY	BUILDING PROGRAM
APPLIANCE	BUILDING PROGRAM
GLAZING	DAYLIGHTING, THERMAL CONSIDERATIONS
LIGHTING	BUILDING CODES, DAYLIGHTING
VENTILATION	BUILDING CODES, ECONOMIZER DESIGN
WALLS & ROOFS	THERMAL CONSIDERATIONS

TABLE II - AVERAGE WALL CHARACTERISTICS FOR FIGURE 1. BASED ON DATA FROM CHAPTER 25 OF REFERENCE 1.

WALL SYMBOL	A	B	C	D	E	F	G
WEIGHT (KG/M^2)	640	510	410	320	240	180	50
RESISTANCE ($M^2 \cdot C/W$)	1.48	1.22	0.76	0.83	0.79	0.62	1.24
AVERAGE CLTD (C)	9.6	9.2	9.6	9.6	9.6	9.6	9.6

TABLE III - CHARACTERISTICS OF FRAME WALLS OF FIGURE 2

WALL SYMBOL	A	B	C	D
INSULATION THICKNESS (MM)	75	50	25	0
U-VALUE ($W/M^2 \cdot C$)	0.46	0.63	1.00	2.40
PEAK HEAT GAIN (W/M^2)	7.6	10.4	17.0	43.0
AVERAGE HEAT GAIN (W/M^2)	2.4	3.2	5.3	12.8

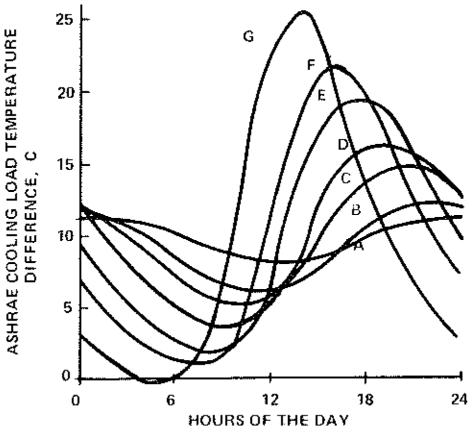

FIGURE 1 – COOLING LOAD TEMPERATURE DIFFERENCE VS. TIME FOR SOUTH FACING WALLS OF TABLE II

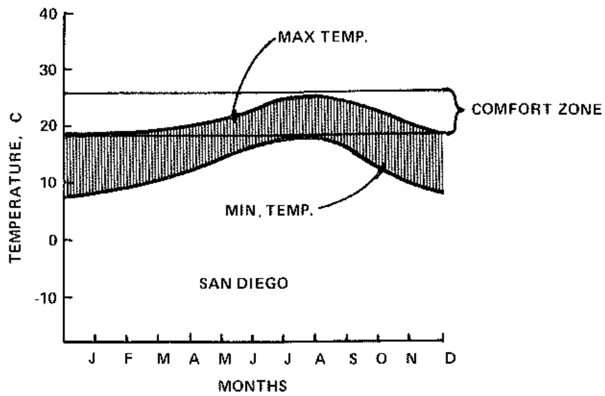

FIGURE 4 - AVERAGE DAILY MAX. AND MIN. AIR TEMPERATURES OVER THE YEAR

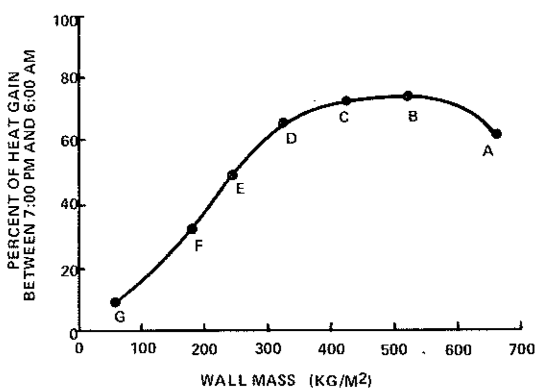

FIGURE 2 - HEAT GAIN VS. TIME FOR SOUTH FACING WALLS OF TABLE III

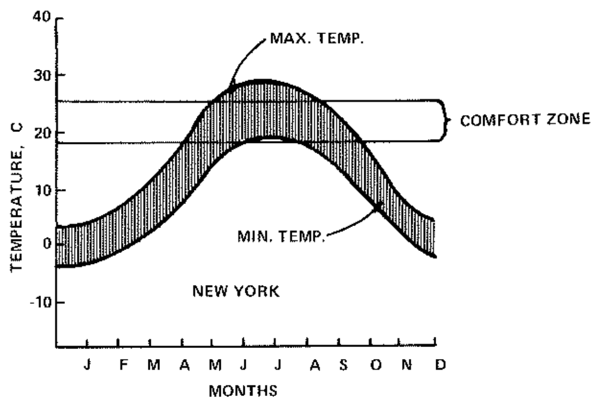

FIGURE 5 - AVERAGE DAILY MAX. AND MIN. AIR TEMPERATURES OVER THE YEAR

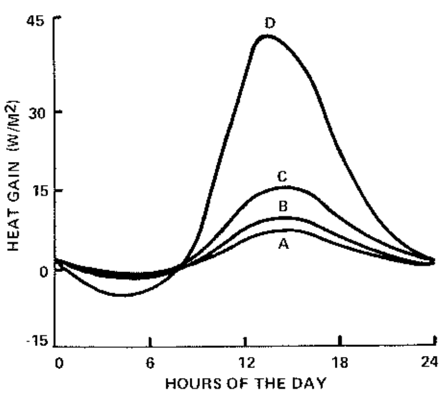

FIGURE 3 - PERCENT OF WALL HEAT GAIN WHICH OCCURS BETWEEN 7 P.M. AND 6 A.M. FOR DIFFERENT WEIGHT WALLS IN NEW YORK CITY

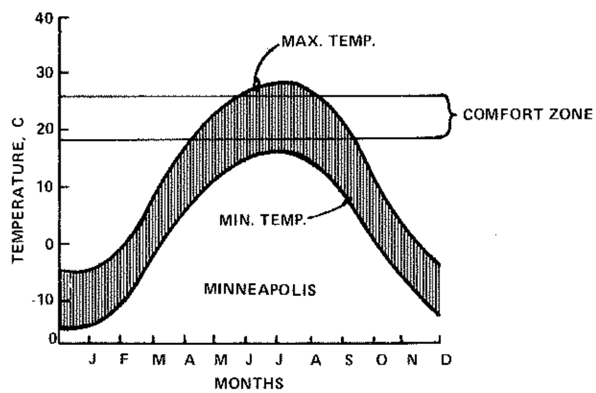

FIGURE 6 - AVERAGE DAILY MAX. AND MIN. AIR TEMPERATURE OVER THE YEAR