Thermal Mass and R-Value: Making Sense of a Confusing Issue

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Understanding Heat Transfer

Heat flows by three mechanisms: **conduction, convection, and radiation**.

Conduction is the transfer of heat through a solid object. When one part of an object is heated, the molecules within it begin to move faster and more vigorously, when these molecules hit other molecules within the object they cause heat to be transferred through the entire object. The handle on a cast iron skillet gets hot as heat is transferred from the bottom by means of conduction.

Convection is the transfer of heat by the movement of a fluid (water, air, etc.) Hold your hand above the stove and you feel the heat as the hot air rises by means of Conduction. Inside of a wall air removes heat from a hot exterior wall, then circulates to the colder interior wall where it loses the heat. Forced-air heating systems work by moving hot air from one place to another.

Radiation is a direct transfer of heat from one object to another, without heating the air in between, the same process in which the Earth receives heat from the Sun or a wood stove supplies heat to its surroundings.

With buildings, we refer to heat flow in a number of different ways. The most common reference is "R-value," or *resistance* to heat flow. The higher the R-value of a material, the better it is at resisting heat loss (or heat gain). U-factor (or "U-value," as it is often called) is a measure of the flow of heat--thermal transmittance--through a material, given a difference in temperature on either side. In the inch-pound (I-P) system, the U-factor is the number of Btus (British Thermal Units) of energy passing through a square foot of the material in an hour for every degree Fahrenheit difference in temperature across the material (Btu/ft^{2}hr◦F). In metric, it's usually given in watts per square meter per degree Celsius (w/m^2◦C).

R-values are measured by testing laboratories, usually in something called a *guarded hot box*. Heat flow through the layer of material can be calculated by keeping one side of the material at a constant temperature, say 90°F (32°C), and measuring how much supplemental energy is required to keep the other side of the material at a different constant temperature, say 50°F (10°.C)--all this is defined in great detail in ASTM (American Society of Testing and Materials) procedures. The result is a *steady-state* R-value ("steady-state" because the difference in temperature across the material is kept steady). R-value and U-factor are the inverse of one another: U = 1/R. Materials that are very good at resisting the flow of heat (high R-value, low U-factor) can serve as insulation materials. So far, so good.

Materials have another property that can affect their energy performance in certain situations: *heat capacity*. Heat capacity is a measure of how much heat a material can hold. The property is most significant with heavy, high-thermal-mass materials such as solid concrete. As typically used in energy performance computer modelling, heat capacity is determined per unit area of wall. For each layer in a wall system, the heat capacity is found by multiplying the density of that material, by its thickness, by its specific heat (specific heat is the amount of heat a material can hold per unit of mass). Water has a heat capacity of 1 Btu/lb.°F (4.2 kJ/kg°K), while most building materials are around 0.2 to 0.3 Btu/lb.°F (0.8 to 1.3 kJ/kg°K).

If there are various layers in the wall, total heat capacity is found by adding up the heat capacities for each layer (drywall, solid concrete, masonry block, and stucco, for example). In the following section, we will examine how the heat capacity of materials can affect the energy performance of buildings.

Thermal Mass

Thermal Mass is a property that enables building materials to absorb, store, and later release significant amounts of heat. Buildings constructed of concrete have a unique energy saving advantage because of their inherent thermal mass. These materials absorb energy slowly and hold it for much longer periods of time than do less massive materials. This delays and reduces heat transfer through a thermal mass building component, leading to three important results. First, there are fewer spikes in the heating and cooling requirements, since mass slows the response time and moderates indoor temperature fluctuations. Second a massive building uses less energy than a similar low mass building due to the reduced heat transfer through the massive elements. Third, thermal mass can shift energy demand to off peak time periods when utility rates are lower.

Thermal Bridging

Thermal bridging is the transfer of heat across building elements, which have less thermal resistance than the added insulation. This decreases the overall R-value.

Wall frames and ceiling joists are examples of thermal bridges, having a lower R-value than the insulating material placed between them. Because of this the overall R-value of a typical construction element can be reduced. For example, adding R2.5 bulk insulation between ceiling joists will actually only achieve an overall R-value for the ceiling of R2.2.

Overall R Value or Whole Wall R Value

The **overall R Value or Whole Wall R Value** is the total resistance of a building element such as a wall or ceiling. It takes into account resistance provided by construction materials, internal air spaces, insulation materials and air films adjacent to solid materials.

"Mass-Enhanced R-Value"

When people refer to the "mass effect" or "effective R-value," they are generally referring to the ability of high-mass materials, when used in certain ways, to achieve better energy performance than would be expected if only the commonly accepted (steady-state) R-value or U-factor of that material were considered. Let's take a look at a typical use of one of these high-mass materials in a wall system. When one side of the wall is warmer than the other side, heat will conduct from the warm side into the material and gradually move through it to the colder side. If both sides are at constant temperatures--say the inside surface at 75°F (42°C) and the outside surface at 32°F (18°C)--conductivity will carry heat out of the building at an easily predicted rate. As described above, this steady-state heat flow is what most test procedures for determining R-value measure.

In real-life situations, however, the inside and outside temperatures are not constant. In fact, in many parts of the country, the driving force for conductive heat flow (remember, heat always moves from warmer to colder) can change dramatically or even reverse during the course of a day. On a summer afternoon in Albuquerque, New Mexico, for example, it might be 90°F (32°C) outside, and the outside wall surface--because it has a dark stucco--might be even hotter. It's cooler inside, so heat conducts from the outside surface of the wall inward. As night falls, however, it cools down outside. The air temperature may drop to 50°F (10°C). The driving force for heat flow changes. As the temperature difference across the wall is reversed, the heat flow is also reversed--drawing heat back towards the outside of the building. As a result of this modulating heat flow through a high-heat-capacity material, less heat from outside the building makes its way inside. Under these conditions, the wall has an ***effective thermal performance*** that is higher than the steady-state R-value listed in books (such as ASHRAE's *Handbook of Fundamentals*). This dynamic process is what some people call the "mass effect."

Another common scenario is when the outside temperature fluctuates but never crosses the indoor set point temperature. In this case, the direction of heat flow never changes, but the ***thermal lag*** or ***time delay*** in heat flow can still be beneficial by delaying the peak heating or cooling load. For example, if the outdoor temperature in Miami peaks at 95°F (35°C) at 5:00 on a summer afternoon, but it takes eight hours for the heat to travel through the wall, the effect of that peak temperature won't be felt inside the building until the middle of the night. Because most cooling equipment operates at higher efficiency if the outdoor air temperature is lower and because night time thermostat settings may be higher (at least in commercial buildings), potentially significant savings can result. Not only can total cooling energy be reduced, but peak loads can also be reduced. This can lead to smaller (and less costly) mechanical systems and lower demand charges for electricity. This time lag effect can save energy and money, but note that it does not affect the total amount of heat flowing through the wall.

As noted above, the amount of heat flow through a wall is reduced by the use of thermal mass when the temperatures fluctuate above and below the desired indoor temperature, so under these conditions a material might have a "mass-enhanced" R-value that is greater than its steady-state R-value. To estimate this mass-enhanced R-value for a given high-mass material in a particular climate, researchers at Oak Ridge National Laboratory measure the thermal performance of a high-mass wall under *dynamic* conditions, in which the temperature on one side of the wall is kept constant and the temperature on the other side is made to fluctuate up or down. With this measured heat flow under dynamic conditions as a basis, they then use computer modeling to arrive at steady-state wall R-values that would be required to achieve comparable overall energy performance under various climate conditions. Those results are what we are calling the "mass-enhanced R-values" for the high-mass material under the modeled conditions.

When is Mass-Enhanced R-Value Significant?

The mass effect is real. High-mass walls really can significantly outperform low-mass walls of comparable steady-state R-value--i.e., they can achieve a higher "mass-enhanced R-value." BUT (and this is an important "but"), this mass-enhanced R-value is only significant when the outdoor temperatures cycle above and below indoor temperatures within a 24-hour period. Thus, high-mass walls are most beneficial in moderate climates that have high diurnal (daily) temperature swings around the desired indoor setpoint.

Nearly all areas with significant cooling loads can benefit from thermal mass in exterior walls. The sunny Southwest, particularly high-elevation areas of Arizona, New Mexico and Colorado, benefit the most from the mass effect for heating. In northern climates, when the temperature during a 24-hour period in winter is always well below the indoor temperature, the mass effect offers almost no benefit, and the mass-enhanced R-value is nearly identical to the steady-state R-value. The ASHRAE *Handbook of Fundamentals* lists "mean daily temperature range" data for hundreds of U.S. climates in the chapter on climate data. These values can be helpful in figuring out how significant mass-enhanced R-value might be for a particular climate, but they do not tell the whole story; also significant is the percentage of days during the heating and cooling seasons when the outdoor temperature cycles *above and below* the indoor temperature.

Do We Need Mass-Enhanced R-Value Ratings?

Clearly, high-mass materials used in exterior walls perform better than would be expected based solely on their steady-state R-values. But the actual thermal performance is highly dependent on where the building is located. Manufacturers of these materials rightly want to take credit for this improved performance, but how can that be done in a way that doesn't exaggerate performance for parts of the country where the mass effect benefit just isn't there? "Right now, we don't have a system that forces people to deal with calculations in a constant way," says Bruce Wilcox, P.E., of the Berkeley Solar Group, who has done extensive modelling of mass effects for the Portland Cement Association and others.

All sorts of claims are being made about mass-enhanced R-value (usually called "effective R-value") with little standardization. The first step needs to be consensus on how the mass effect should be accounted for in testing and modeling. Jeffrey Christian at Oak Ridge National Laboratory has been developing and refining the method of dynamic thermal analysis and simulation described above. This is the most extensive effort to date to quantify the mass effect. Christian's group, with the help of Bruce Wilcox and others, also developed thermal mass tables for the Model Energy Code in the late 1980s that can be used to account for the thermal mass benefits of high-mass building materials in wall systems.

The next step, suggests Christian, might be to formalize the testing and simulation procedures through development of ASTM standards. Establishment of an ASHRAE committee to address the mass effect may also be in the works. To ensure that such standards would be applied in a consistent manner, Wilcox suggests that applicable industries might have to set up some sort of council, perhaps modelled after the National Fenestration Rating Council (NFRC), which enforces consistent reporting of window energy performance. Such a "Thermal Mass Rating Council" might oversee standards relating to how mass effect and mass-enhanced R-value are reported. Wilcox remains leery of the whole concept of mass-enhanced R-value--not that the effect exists, but whether it can be used clearly with building materials. "I don't know if there's any way to make it a property of the material," he told *EBN*, "It's a property of the system." There are a lot of questions to sort out, such as how many climates need to be modelled: are six enough, as Oak Ridge researchers have used, or do we need 20? Would such a system take credit for time delays in heat transfer, or just actual reductions in the amount of heat that moves through? Who will pay for all the research to make this happen? Are the industries that sell high-mass materials large enough to support a Thermal Mass Rating Council and the additional research needed on these issues?

R-Value is not the Total answer to insulation.

Heat naturally flows from warm areas to cooler areas, regardless of direction. In winter, heat flows from the inside of a building to the outside and in the summer high heat from roofs and walls travels from outside to inside. This flow of heat can never be stopped completely, but the rate at which it flows can be reduced by using materials which have a high resistance to heat flow.
(R value= resistance)

Obviously an important step in the creation of an energy efficient house or building is to control heat loss or gain, which accounts for 75% of the total energy loss of a home.

As was previously stated, heat will flow in any direction where a temperature difference occurs. Therefore all areas which separate the interior of a house or building from the outside or which separate heated spaces from unheated (or air conditioned) spaces need to have a high resistance to heat flow, in other words, they should be insulated!

How does insulation work?
Insulation is any material that slows the rate of heat flow from a warm area to a cooler one. The more the rate is slowed, the better the insulative qualities of the material. Its ability to resist heat flow is measured as an R or RSI (metric) value, the higher the R -value, the more the material will resist the flow of heat. In order to be effective, insulation materials must be able to reduce the transfer of heat by the three ways we just discussed, conduction, convection and radiation

Choosing an insulation

The R - value is not the only consideration when choosing insulation yet it is the first thing most consumers ask, "What is the R value"

Conventional insulation materials like fiberglass, cellulose, rock wool and Styrofoam, no matter how thick, have almost no ability to block radiant heat energy which can account for as much as 93 percent of summer heat gain and up to 75 percent winter heat loss in conventional structures.

These products are only designed to slow down (resist) conduction heat energy only. Insulation once saturated with heat will simply allow remaining heat to pass through. Ever notice in the summer, its 10 PM or so and you touch one of the walls in your home that butts up to the outside, the sun has been down for hours but the wall is still Hot! That's because the wall has been absorbing heat all day and is passing it through the wall to the inside of your home.

Remember... R-value means "resistance", if a product resists, it does not stop radiant heat transfer. R-value material only deals with conductive heat transfer. Other factors to consider when choosing insulation are the materials fire, mold, insect, vermin and moisture resistant properties, as well as its cost and ease of application.

The R values required by Standard 90.1 are based on equivalent energy performance. For example, in Tulsa, OK, Standard 90.1 requires an R 8.3 frame wall or an R 4.3 mass wall for some buildings. These requirements are based on the fact that an R 4.3 mass wall is as energy efficient on an annual basis in an occupied building as an R 8.3 frame wall, in this particular climate. The benefits of mass walls vary by climate and can be influenced by factors such as temperature "swings" (differences between the high and low outdoor temperatures during the day), by solar radiation and wind near the building, and by how the building is designed, operated, and maintained for comfort to be energy efficient.

Final Thoughts

Wall systems with significant thermal mass, have the potential to reduce building annual heating and cooling energy requirements, depending on the climate, below that required by standard wood-frame construction with similar steady-state R-value. High-mass building materials can offer significant energy benefits in exterior walls. The benefit may be primarily in the shifting of peak load conditions ***thermal lag*** or in an actual reduction in overall heat gain or loss through ***effective thermal performance***. These benefits are highly dependent upon where the building is located, how it is designed, and how it is operated. How we should give credit--in terms of energy performance--for high-mass building materials is still very much open for debate.