Chapter

3

Insulation Fundamentals and Principles

Heat-Transfer Mechanisms

It is no secret that a house will lose heat in the winter and allow heat in during the summer. Heat, or thermal energy, flows continuously through materials and space, taking the path of least resistance and flowing from the warmer object to the colder object. Insulation attempts to keep thermal heat where it is wanted. To understand how thermal insulation works, it helps to understand the three mechanisms of heat energy transfer: convection, conduction, and radiation.

In winter, the heat in a family's living room invariably flows by air movement to spaces that are not heated, such as the basement, attic, or garage. This is an example of heat flowing through moving air, known as *convection.* Another example is when heat is transferred from hot coffee, through the cup, to the hand holding the cup. This is known as *conduction,* or the process by which heat transfer takes place in solid matter. A third example can be found when a rooftop is warmed by the energy of the sun. This an example of the transfer of heat through space via electromagnetic waves (radiant energy), known as *radiation.*

Convection

Convection is the transfer of heat by physically moving the molecules from one place to another. Convection takes place when a fluid, such as gas or a liquid, is heated and moved from one place to another. When warm air in a room rises and forces the cooler air down, convection is taking place. For example, air, when heated, expands and rises. If this air movement is created mechanically by a floor register, fan, or the wind, it is called *forced convection.* When the sun heats the warm air and it rises, causing the cold air to settle to create a convection loop, it is termed *free convection.* Free convection also occurs when the sun, shining through a window, heats the air inside a building.

Conduction

Conduction is the process by which heat transfer takes place in solid matter, such as the direct flow of heat through a material within a single or two separate bodies in direct contact. Scientifically, it is the molecule-to-molecule transfer of kinetic energy. One molecule becomes energized and, in turn, energizes adjacent molecules. A cast-iron skillet handle heats up because of conduction through the metal from the heat energy provided by the burner on the stove. This also occurs when a person touches a sun-warmed window or when the handle of a poker gets warm after the other end has been placed in a fire for a few minutes.

Convection and conduction are functions of the roughness of surfaces, air movement, and the temperature difference between the air and surface. Mass insulations, because of their low densities, are designed to suppress conduction and convection across their sections by the entrapment of air molecules within their structure. Convective air currents are stilled by the surrounding matrix of fibers or cells, and the chances of heat transfer by the collision of air molecules are reduced. Foam insulations operate under the same principle, although gas is used instead of air within their structure.

Radiation

The third way energy is transferred is through *radiation.* This is evident in the way the sun warms the surface of the earth, which involves the transfer of heat through electromagnetic waves and absorption of that energy by a surface. A person sitting in the sun by a window absorbs radiant heat. Inside a home, surfaces may exchange heat with other surfaces through radiation, which can have some impact on indoor ambient temperature. Heat energy from radiation is most relevant to home comfort in the summertime, however, when the roof and exterior walls absorb heat from the sun. (This heat subsequently enters the interior space through conduction and convection.) This process is more critical in hot climates.

Radiant heat transfer between objects operates independently of air currents and is controlled by the character of the surface (emissivity) and the temperature difference between warm objects emitting radiation and cooler objects absorbing radiation. *Emittance* (or *emissivity*) refers to the ability of a material's surface to emit radiant energy. All materials have emissivities ranging from 0 to 1. The lower the emittance of a material, the lower is the heat radiated from its surface. Aluminum foil has a very low emittance, which explains its use in reflective insulation. This will be further explored in Chap. 12.

Reflectance (or *reflectivity*) refers to the fraction of incoming radiant energy that is reflected from a surface. Reflectivity and emissivity are related, and a low emittance is indicative of a highly reflective surface. For example, aluminum with an emissivity of 0.03 has a reflectance of 0.97.

The resistance of these modes of heat transfer may be retarded by the elements of a building wall section. Elements include

1. *Outside surface films.* The outside surface traps a thin film of air, which resists heat flow. This film varies with wind velocity and surface roughness.
2. *Material layers.* Each layer of material contributes to the resistance of heat flow, usually according to its density. A layer of suitable insulation is normally many times more effective in resisting heat transfer than the combination of all other materials in the section.
3. *Airspace.* Each measurable airspace, as well as its thickness, also adds to the overall resistance. Foil-faced surfaces of low emissivities that form the boundaries of the airspace can further reduce the rate of radiant transfer across the space (provided the airspace is at least $^3/_4$" to 1").
4. *Inside surface film.* The inside surface of a building section also traps a thin film of air. The air film thus formed is usually thicker because of much lower air velocities.[1]

Heat Flow

It is important to point out again that heat (thermal energy) always flows from a warmer object to a colder object. In terms of buildings, we refer to heat flow in a number of different ways. It is the measurement of this heat flow that allows for the mathematical analysis of wall, floor, and ceiling assemblies. U-value and R-value are the most common methods used.

U-value

The flow rate of heat through a building product is known as the *U-value.* The U-value (or U-factor) 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 British thermal units (Btu) of energy passing through a square foot of the material in an hour for every degree Fahrenheit difference in temperature across the material ($Btu/ft^2 \cdot h \cdot °F$). In the metric system, it is usually given in watts per square meter per degree Celsius ($W/m^2 \cdot °C$).

Since the U-value is a measurement of heat flow, the lower the U-value, the more slowly does the material transfer heat in and out of the home. The U-value typically is used in expressing overall thermal conductance, since it is a measurement of the rate of heat flow through the complete heat barrier, from room air to outside air. The lower the U-value, the better is the insulating value. U-value is the customary unit used by the fenestration industry to quantify conducted heat gain or loss. With other building materials, such as insulation, roofing, and flooring materials, the R-value is frequently used for conducted heat gain or loss.

R-value

Another mathematical expression used in thermal quantification, and the most common reference used by the insulation industry, is *R-value,* or resistance to heat flow. Since the R-value is the measurement of a product's resistance to heat flow, the higher the R-value, the better is the resistance to the flow of heat (expressed in British thermal units). Insulation is rated in terms of thermal resistance, called *R-value,* which indicates the resistance to heat flow. The higher the R-value, the greater is the insulating effectiveness of mass-type insulations.

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). [This process is defined in great detail in American Society of Testing and Materials (ASTM) procedures. The result is a steady-state R-value. It is called *steady state* because the difference in temperature across the material is kept steady.[2]]

To ensure that consumers are provided with accurate information regarding R-values, the Federal Trade Commission (FTC) in 1980 established a rule that mandates that specific R-value information for home insulation products be disclosed in certain ads and at the point of sale. The purpose of the FTC R-value disclosure requirement for advertising is to prevent consumers from being mislead by certain claims that have a bearing on insulating value.[3]

In the flow of heat through a solid body to air, it was observed that the passage of heat into the air was not accomplished solely through conduction. Instead, it occurred partly by radiation and partly by free convection. A temperature difference existed between the hot solid and the average temperature of the air. In this case, the resistance to heat transfer cannot be computed using the thermal conductivity of air alone. Instead, the resistance has to be determined experimentally by measuring the surface temperature of the solid, the temperature of the air, and the heat transferred from the solid to air. The resistance computed is the combined resistance of conduction, free convection, and radiation.

R-value requirements for a specific house design in a certain locale are mandated by the IECC, formerly the *Model Energy Code*. Many state agencies simplify this process for residential design by outlining general rules of thumb. Manufacturers often provide general planning guidelines as well (Fig. 3.1). Always verify specific thermal requirements with the aforementioned organizations or local building officials.

R-values are reported for 1" of thickness and are not necessarily per inch of thickness (for residential construction only). R-values usually are reported at mean temperatures of 75°F per FTC regulations. The R-value per inch of a specific material is not necessarily always the same. It can be affected by several factors, including temperature, density, and thickness.

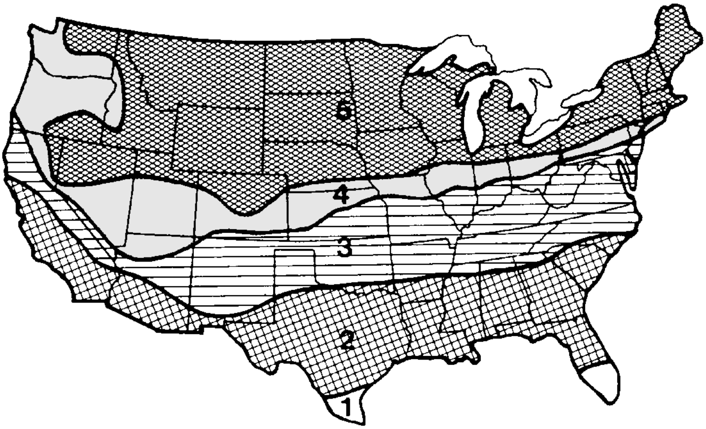
Temperature

Test results at 75°F are adequate for controlled comparisons when choosing materials, but most insulation materials have a higher R-value at lower temperatures. The variation in value is caused by changes in the conductivity of air within the insulation and by changes in radiant heat transfer.

In some cases, this variation can be significant. For example, in winter, the outside temperature may be 0°F and the inside temperature 70°F, resulting in a mean temperature of 35°F. Alternatively, for summer conditions, particularly in southern climates, mean temperatures of 90 to 110°F can be experienced. The variation in R-value between these two extremes can be as much as 27 percent.[4]

Thickness

Generally, R-value increases linearly with thickness. For example, a 2" thickness of a material will have twice the R-value of a 1" thickness of the same material. Recent advances in thermal insulation technology, however, have shown a phenomenon known as the *thickness effect* in low-density materials. Simply stated, the thickness effect is an



Zone	Attic Floor (Ceilings)	Sidewalls	Floors
1	R-19	R-12	R-11
2	R-30	R-19	R-11
3	R-38	R-19	R-13
4	R-38	R-19	R-19
5	R-49	R-19	R-25

R-values on the chart represent CertainTeed recommendations based on the latest Model Energy Code and DOE recommendations. The wall R-values include those for both insulation and sheathing. R-values of individual products can be added to achieve recommended R-values. For example, R-38 added to an R-11 results in R-49. Wall R-values include length, insulation and sheathing.

Figure 3.1 R-values. (*CertainTeed.*)

apparent decrease in R-value per inch with increased thickness. Many examples suggest that conduction is actually taking place, compromising the R-value.

Density

The R-value of certain insulation materials can vary considerably with density. This has important implications in the use of blown-in insulation, the installed density of which is under the direct control of the contractor. For example, blown-in fiberglass is usually listed as having an R-value of about R-2.2 per inch. But this is measured at its "settled" density of about 0.7 lb/ft^3; if that same material is forced into walls at a density of 2.0 lb/ft^3, the R-value jumps to almost R-4.0 per inch. The same effect does not hold for cellulose, which decreases in R-value as its density increases.[4]

Blanket insulation is also affected by density. Stuffing a thick batt (or roll) into a narrow stud cavity will result in a more densely installed material. R-13 batt insulation is designed for proper placement into 2 × 4 wood frame wall. However, if an R-19 fiberglass batt, which is designed for a 2 × 6 wood frame wall, is stuffed into a stud cavity that is only 3.5", the total R-value of the batt will be less than R-19. This is simply due to the fact that the fiberglass batt insulation R-value relies on air as part of the resistance equation. Compressing the batt reduces the airspace between the fibers, which in turn reduces the R-value per inch.

This explanation of density is not to be confused with insulations that have different *design densities*. Typically specified in units of pounds per cubic foot, different products can be optimized for certain locations and higher R-values when manufactured with different densities.

Technically, any air-based insulation material such as fiberglass batt cannot exceed a theoretical maximum R-value of R-5.5 per inch because 5.5 is the R-value of still air. Plastic foams such as urethane and polystyrene sometimes exceed this value by using a fluorocarbon gas instead of air within the insulation cells. These factors will be discussed in greater detail later in the book. Other exceptions to the preceding maximum are experimental air-based insulation materials that contain very fine powders. These materials increase R-value by virtue of extremely small powder particles that interfere with conduction through air. Although they are not available commercially at present, they may appear on the market some time in the future.

As mentioned earlier, U-value is the customary unit used by the fenestration industry to quantify conducted heat gain or loss. With other building materials such as insulation, roofing, and flooring materials, the R-value is used frequently for conducted heat gain or loss. There is a simple relationship between u- and R-values, namely,

$$U = 1/R \qquad \text{or} \qquad R = 1/U$$

For example, a U-value of 0.25 equals $\frac{1}{25}$, or an R-value of 4. Conversely, in order to establish the R-value from the U-value, divide 1 by the U-value, that is,

$$R = 1/U \qquad \text{or} \qquad U = 1/R.$$

Whole-Wall System

Currently, most wall R-value calculation procedures are based on experience with conventional wood frame construction, and they do not factor in all the effects of additional structural members at windows, doors, and exterior wall corners. Thus they tend to overestimate the actual field thermal performance of the whole-wall system.[5]

Clear-wall R-value (Rcw) accounts for the exterior wall area that contains only insulation and the necessary framing materials for a clear section, with no windows, doors, corners, or connections between other envelope elements, such as roofs and foundations.

Center-of-cavity R-value (Rcc) is the R-value estimation at the point in the wall that contains the most insulation. This uses a 0 percent framing factor and does not account for any of the thermal short circuits that exist through the framing.

Whole-wall R-value (Rww) is an R-value estimation for the whole opaque wall, including the thermal performance of both the clear-wall area and typical interface details such as all typical envelope interface details [e.g., wall-wall (corners), wall-roof, wall-floor, wall-door, and wall-window connections]. The whole-wall R-value is a better criterion than the clear-wall R-value, and much better than the center-of-cavity R-value methods used to compare most types of wall systems. The value includes the effect of the wall interface details used to connect the wall to other walls, windows, doors, ceilings, and foundations. Taking into account the interface details can have an impact on as much as 50 percent of the overall wall area. For some conventional wall systems, the whole-wall R-value is as much as 40 percent less than the clear-wall value.[5]

With the increasing use of alternatives to dimensional lumber-based systems (such as metal-frame and masonry systems) for residential construction, this procedure highlights the importance of using interface details that minimize thermal shorts. Local heat loss through some wall interface details may be double that estimated by simplified design calculation procedures that focus only on the clear wall.

The effect of extensive thermal shorts on performance is not reflected accurately in commonly used simplified energy calculations that are the current bases for consumer wall thermal comparisons. Consequently, the marketplace does not currently account for the thermal shorts that exist in building walls. Computer software for modeling is available, but is beyond the scope of this text.

References

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