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Insulation keeps heating and cooling bills low, but how does it actually work?

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Insulation is the mysterious substance that keeps heating and cooling bills low and falls out of walls and ceilings when drywall is removed - but what is insulation actually, and how does it work?

In simplest terms, common forms of insulation trap air in comparatively small, still pockets and minimize the volume of solid matter within a given space. Since convective heat transfer requires mixing of fluids or gases, keeping air in small, still, discrete quantities effectively stops convective heat transfer within the material (and air is not an efficient medium for conductive heat transfer, with an approximate thermal conductivity varying from 0.0058 to 0.026 Btu/h?ft?°F, depending upon the current air temperature and fraction of water vapor in the air, as opposed to aluminum, with a thermal conductivity of approximately 128 Btu/h?ft?°F). As conductive heat transfer is most efficient (and fastest) in solid matter, minimizing the volume of solid matter severely limits the efficiency of conductive heat transfer through insulation. The most efficient form of insulation is a vacuum (no gases mean no convective heat transfer).

Penetrations of the insulation (often called thermal bridges) are a significant source of heat transfer in many buildings. Joists, studs, door and window openings, utility conduits, plumbing stacks, furnace flues, exhaust vents, and intake vents are among the objects that project through building insulation; carelessly installed insulation, or insulation that has been disturbed during construction or renovation/alteration work may have gaps, which are essentially penetrations by an unconstrained volume of air (while air has a very low thermal conductivity, convective thermal transfer in unconstrained volumes of air can be very rapid). The problem with most penetrations is that the common materials that penetrate insulation have comparatively high thermal conductivities. For comparison purposes refer to table.

As can be seen from the table, many construction materials conduct heat 20, 30, or several hundred times faster than typical fiberglass insulation, and it therefore follows that even comparatively small areas of these substances that are not separated from the interior by insulation can permit significant thermal transfers across the building envelope.

You may be wondering at this point, since it is obvious that low thermal conductivity materials make better insulation than high thermal conductivity materials, why do better insulation materials get high "R-values?"

"R-value" is actually the thermal resistance of the insulation material under steady conditions, which has the unit of measure of °F?ft2?h/Btu. Thermal resistance is useful because thermal resistances in series can be added - which means that the thermal resistance of each layer of a given wall, ceiling, or roof section can be added together.

The inverse of thermal resistance (R) is thermal transmittance (U), which has the unit of measure of Btu/°F?ft2?h. The thermal transmittance of each layer of a given wall/ceiling/roof section cannot be added together to determine the overall thermal transmittance, which is why insulation values are given in terms of R. Note that dividing the thickness of a material by its thermal conductivity produces a thermal resistance value. To determine relative insulation values, compare R-values of the insulation; to determine heat flow perpendicular to a given insulation assembly (i.e. how much heat a building is losing over a given period of time under set conditions), invert the R-value to determine the thermal transmittance and multiply by the assembly surface area to generate a heat transfer rate per degree-hour, then multiply by the temperature difference between the two sides of the assembly to generate a heat transfer rate per hour, and finally multiply by the time period (in hours) to generate a total heat transfer across the insulation assembly.

Of course, determining the R-value of a given building envelope can be complex, because most walls and roofs have several different cross-sections, and determining an overall R-value for the entire envelope becomes an exercise of averaging; under certain conditions, lateral heat flows within the envelope become possible, further complicating the issue.

So, these are the nuts and bolts of how insulation works and how engineers describe how insulation works. A related topic is condensation in insulated assemblies - a topic that relates water vapor, temperature variation through the thickness of an insulated assembly, vapor barriers, and impermeable membranes, and determines why some walls get moldy from water condensation every winter (and why other walls get moldy every summer).

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