Heat Flow Basics for Architectural Calculations

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Heat always flows from hot cold.

1. DEFINITIONS

Temperature – a measure of thermal energy, units of Kelvin (K) or Celsius (C)

Conductivity – a material property, heat flow per unit area per unit thickness per unit temperature, symbol k (W/m K)

Conductance – a property of a material layer, heat flow per unit area and temperature, symbol C (W/m^2 K) = conductivity k / thickness l (in meters)

Resistance – a property of a material layer or wall measured from surface to surface, equals 1/C , symbol RSI (m^2 K /W)

Imperial value R (ft^2•F•hr/Btu) = 5.678 RSI

Overall heat transfer coefficient – a property of an enclosure assembly, basically the thermal conductance of an assembly, heat flow per unit area and temperature, symbol U, U = $1/R_{total}$, units W/m^2 K.

2. BASIC EQUATIONS

The conductance of a layer, if made of a single material, can be calculated from:

$C = k / l$

where

k is the thermal conductivity of the material, and

l is the length of the heat flow path, that is, the thickness of the layer.

For layers that have complex shapes, such as hollow concrete block, or composites of several materials, the conductance is often derived from physical tests or detailed computer models and reported in tables.

The R-value of a layer is often listed on a material, or calculated from:

$R = 1 / C$ which therefore is l / k.

The thermal resistance of a multi-layer assembly of flat materials (most building enclosures), can be calculated from

$R_T = R_1 + R_2 + \ldots + R_n$

where

R_T is total thermal resistance of the assembly, and

R_1 to R_n is the resistance of each of the building assembly's layers, including air films, air gaps, and solid materials.

The U-value is commonly used to describe the heat transmittance of an assembly, especially windows and non-standard enclosures, and is defined simply as:

$$U = 1 / R_T$$

Example: Given that the thermal conductivity of Type 4 extruded polystyrene (for example, Styrofoam SM) is 0.029 W/mK, find the conductance and resistance of a layer 50 mm thick in both imperial and metric units.

Answer:

Conductance = conductivity k / thickness l (in meters). 50 mm = 0.050 meters so …

$$C = 0.029 / 0.050 = 0.58 \text{ W} / \text{m}^2\text{•K}$$

this means, for example, that a one square meter panel of 50 mm thick Styrofoam SM will allow 0.58 watts of energy to pass through it under a one degree Kelvin (or Celsius) temperature change.

Resistance, RSI = 1 / conductance, so

$$C = 1 / 0.58 = 1.724 \ \text{m}^2\text{•K} / \text{W}$$

Hence, a layer of SM would have a thermal resistance of RSI 1.724. If one were to look in a building supply store, a sheet of 2" SM would be stamped with RSI1.76 or R-10, since 2" sheets are slightly thicker than 50 mm (they are 50.8 mm). By the way, a layer of 100 mm would have a thermal resistance of RSI3.45, eg twice the thickness, twice the resistance (this does not work with conductance).

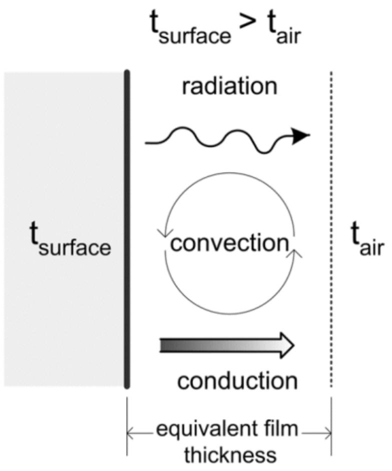
The thermal resistance in imperial R-value would be:
Imperial value R (ft^2•F•r/Btu) = 5.678 RSI
$R_{imp} = 5.678 * 1.724 = R_{imp}\text{-}9.8$

Again, a full 2" thick sheet would have a slightly higher R-value of R10. Thus, one often speaks of an "insulation value" of R5 per inch. Four inches, R20 for this layer, 1.5", R7.5 for the layer.

Most building enclosures include more than just materials – they also include air spaces, which are insulating. The heat transfer from the air next to the enclosure to the surface of the enclosure is also not perfect. Hence, one needs to calculate the impact of this effect. These complications are discussed next.

3. SURFACE FILMS

To account for both the radiation and convection heat transfer modes at the exterior and interior surfaces of building components, radiative and convective heat transfer coefficients are used in the form of an *equivalent conductance* or, alternatively, equivalent resistances. These equivalent coefficients are termed *surface film coefficients.* It is important to recognize that a surface film does not exist in reality. The term film is used simply so that a layer (of indefinite thickness) can be added to a typical conductive heat flow analysis.



The resistance to heat flow at a surface is small relative to the heat flow resistance of most modern wall assemblies and therefore need not be accurately estimated for most purposes. Poorly insulated walls and windows have a lower overall thermal resistance and thus surface effects are more important. Hence, a more precise calculation of surface films is justified for these types of enclosures. The overall equivalent surface conductances, h_o, or resistances in Table 1 can be used to find heat flow without further modification.

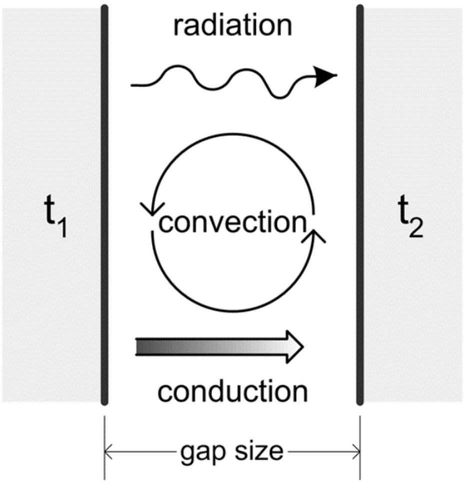
Surface Position	**Flow Direction**	**Resistance**		**Conductance**
Still Air	**(e.g. indoors)**	RSI [m^2K/W]	R (imperial)	[W/m^2K]
Horizontal (i.e. ceilings	Upward	0.11	0.61	9.3
and floors)	Downward	0.16	0.93	6.1
Vertical (i.e. walls)	Horizontal	0.12	0.68	8.3
Moving Air	**(e.g. outdoors)**			
Stormy 6.7 m/s (winter)	any	0.03	0.17	34
Breeze 3.4 m/s (summer)	any	0.04	0.25	23
Average conditions	any	0.06	0.33	17

Table 1: Equivelant Total Surface Film Conductances (h_o)

4. PLANE AIR SPACES

Plane air spaces are commonly used in building assemblies. Heat is transferred across air spaces by a combination of conduction through still air, convection flows, and by net radiation from the warm side to the cold. The modes of heat transfer vary in importance depending on: the emissivities of the surfaces, the thickness of the air space, and the absolute and relative temperatures of the two surfaces.

The heat flow across a plane air space can be found with a reasonable degree of accuracy by using detailed correlations of convection and radiation. However, a high degree of accuracy is rarely necessary or justified in light of the many poorly known variables (e.g. variable cavity widths, blocked cavities, etc.) and the relatively small influence that the airspace has on the thermal resistance of modern enclosure assemblies. Simplified values for most practically encountered situations are presented in Table 2. The values in Table 2 are also given in terms of resistances so that they can be directly used in the heat flow equation.



Heat Transfer Across Plane Airspaces

Situation (non-reflective surfaces)	**RSI Value**	**R-value**
Heat Flow Down (3/4”-4”, 20-100 mm)	0.18	1.0
Heat Flow ***Across*** (3/4”-4”, 20-100 mm)	0.17	0.96
Heat Flow Up (3/4”-4”, 20-100 mm)	0.15	0.87
Reflective Surfaces (low emissivity)		
Heat Flow ***Across*** (3/4”-4”, 20-100 mm)	0.60	3.5

Table 2: Thermal Resistance for non-reflective Enclosed Airspaces (RSI and R-value)

In many practical situations an air space is either intentionally or accidentally vented. Air flow through an air space can change the heat flow characteristics, although significant flows are required to modify the equivalent conductances listed above. In most cases, the effect of venting enclosure assemblies can be ignored, and only in extreme cases does in need to be accounted for. Extreme cases would includes highly ventilated attics (at least 1% venting area) and cladding panels with both at least 2% vent area and cavities over 50 mm in size.

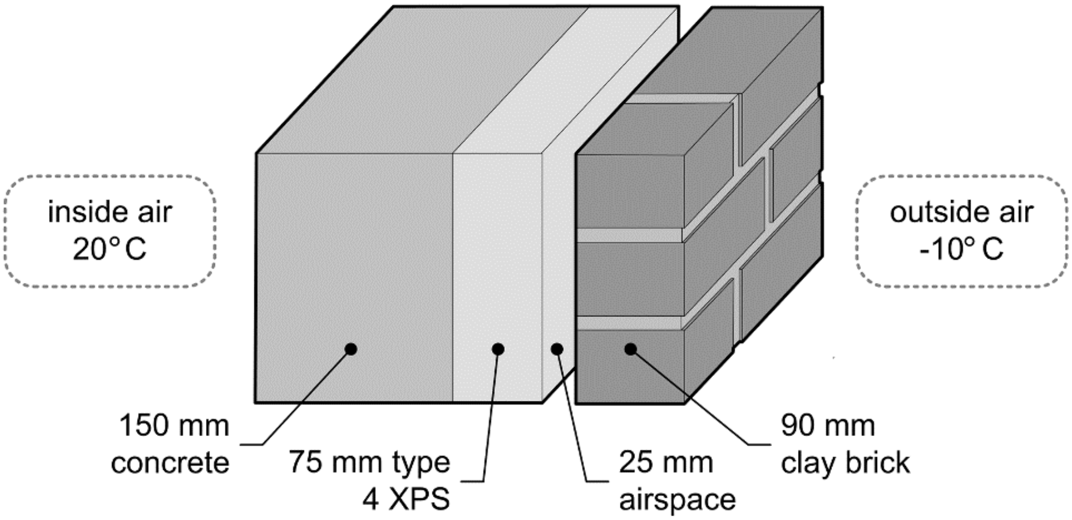
5. HOW TO CALCULATE THE "R VALUE" OF AN ENCLOSURE ASSEMBLY

Remember: one cannot add conductances, you must add resistances

1. List each material in the wall or roof, its conductivity (k) and its thickness (l) in m
2. Calculate the conductance of each layer (C) using C = k / l .
3. Calculate the thermal resistance of each layer using RSI = 1 / C
4. Sum the individual thermal resistances to get the answer.

Usually the thermal resistance of the air films that exist on both the interior and exterior surfaces of an assembly are added to the wall as virtual layers. This makes our calculations more accurate.

Example: Calculate the total thermal resistance (R) and overall heat transfer coefficient (U) of the wall shown below. Use conductivity values from tabulated values.



Answer:

Layer Material	**Conductivity**	**Thickness**	**Conductance**	**Resistance**
Interior film note 1	N.A.	N.A.	8.3	0.120
Concrete	1.8	0.150	12	0.083
Type 4 XPS	0.029	0.075	0.39	2.56
Air space note 2	N.A.	25	N.A.	0.17
Brick	1.3	0.090	14.4	0.069
Exterior film note 1	N.A.	N.A.	34	0.029
		RSI total		**3.04**
		Overall Heat Transfer, U		**0.33**

Note 1: Table 1. Since the interior and exterior films are fictitious, they do not have a thickness, and so no conductivity. Hence, tables typically contain only conductances or resistances for the layer. These values can be quite variable, but as can be seen, the effect of the value of the film resistance on the total resistance of a wall is small if the wall is a modern insulated assembly.

Note 2: Table 2. The flow of heat through an air space is complicated by convection (air flows) and radiation and so tabulated values of conductance are used instead. Like surface films, the values are variable but not important to accuracy in the calculation in most modern walls.

The total resistance is RSI3.04 (or imperial R 17.2), 84%of it provided by the insulation, and heat flow will be 0.33 $W/m^2 K$.

This method can be used to predict heat flow through walls, roofs, or foundations with uninterrupted or “continuous insulation”. If insulation is installed between studs (wood or steel), is penetrated by floor slabs, or extensive steel structure, thermal bridging must be accounted for (see later in this document).

6. HOW TO CALCULATE THE STEADY-STATE HEAT FLOW THROUGH AN ENCLOSURE SYSTEM

Heat flow across an assembly is simply the temperature difference divided by the true R-value times the area. The temperature difference is usually just ($t_{inside} – t_{outside}$).

1. Find the total thermal resistance of the enclosure as described earlier.
2. Find the overall heat transfer coefficient U, using $U = 1/R_{total}$
3. Multiply the temperature difference across the assembly by U, i.e., $U*(t_{inside} – t_{outside})$

Of course if the sun is shining on the wall, the outdoor ***air*** temperature is not the correct one to use, (the actual solar heated surface temperature is more accurate, but difficult to find sometimes – use the table provided later for guidance).

The effect of heat storage, or thermal mass, can be important for some walls since heavy mineral-based materials can store a lot of heat: see the section on thermal mass later.

Example: Calculate the amount of heat flow through the wall of the previous example when it -10 C outside with no sun and 20 C inside.

Heat flow $= U *(t_{inside} – t_{outside})$
$= 0.33 (20 -10) = 0.33 (30)$
$= 10\ W/m^2$

Ans. Heat flow outward would be 10 W/m^2.

7. ASSESSING ENERGY LOSS DUE TO AIR LEAKAGE

If warm/cold air leaks out of the building in winter/summer, it is of course replaced with exterior cold/hot air. This cold/hot air must be heated/cooled to make it comfortable indoors. The energy impact of air leakage is significant and must be considered since it is often an important heat loss/gain component of modern buildings. It can be included by calculating an *equivalent heat loss coefficient* for air leakage. This can be found from:

$U_{air} = 0.3 * n * V$
Where U_{air} is the heat loss coefficient due to air leakage (W/ C)
n is the number of complete air changes per hour (ACH)
V is the total air volume of the building (in m^3)

U_{air} can be included in calculations just like U_{wall} or U_{window}.

8. HOW TO CALCULATE THE STEADY-STATE HEAT FLOW THROUGH A BUILDING SYSTEM

The easiest means of estimating heat flow through an entire building is to

1. Calculate and then list the U-value for each element (wall, roof, window, door) along with the area of that element
2. The product of each elements' area and its U-value is the heat loss coefficient for that enclosure element per unit temperature difference (SI units: W/C)
4. The sum of these products is the overall heat loss coefficient for the building.
5. To find the overall heat loss (or gain) multiply the overall heat loss coefficient for the building by the temperature difference across the assembly.

Example: An industrial "big box" store is 8 m high, 32 m long and 64 m wide.
The enclosure has a lightweight roof (U=0.36 W/m^2/C and) and precast concrete walls (U=0.4 W/m^2/C). The front of the store (which faces west) has a 6 m high by 24 m long glass curtainwall with a U-value of 2.0 W/m^2/C. Six loading doors are at the back, each 5 m high and 3.5 m wide with a U-value of 1.0. The building is estimated to leak at 0.5 ACH under normal conditions.
Ignoring the effect of the floors, sun, and any other doors, find the heating requirements when it is -10 C.

Answer:

See the sketch of the building for details of the areas.

Air leakage Heat loss: 0.3 n V = 0.3 (0.50) (16384) = 2458 W/C.

Enclosure Component	Area (m^2)	U Value (W/m^2/C)	Q Heat Loss (W/C)	% Total Heat Loss
Walls	1287	0.40	515	**13%**
Roof	2048	0.36	737	**18%**
Doors	105	1.0	105	**3%**
Curtain Wall	144	2.0	288	**7%**
Air Leakage		*from above*	2458	**60%**

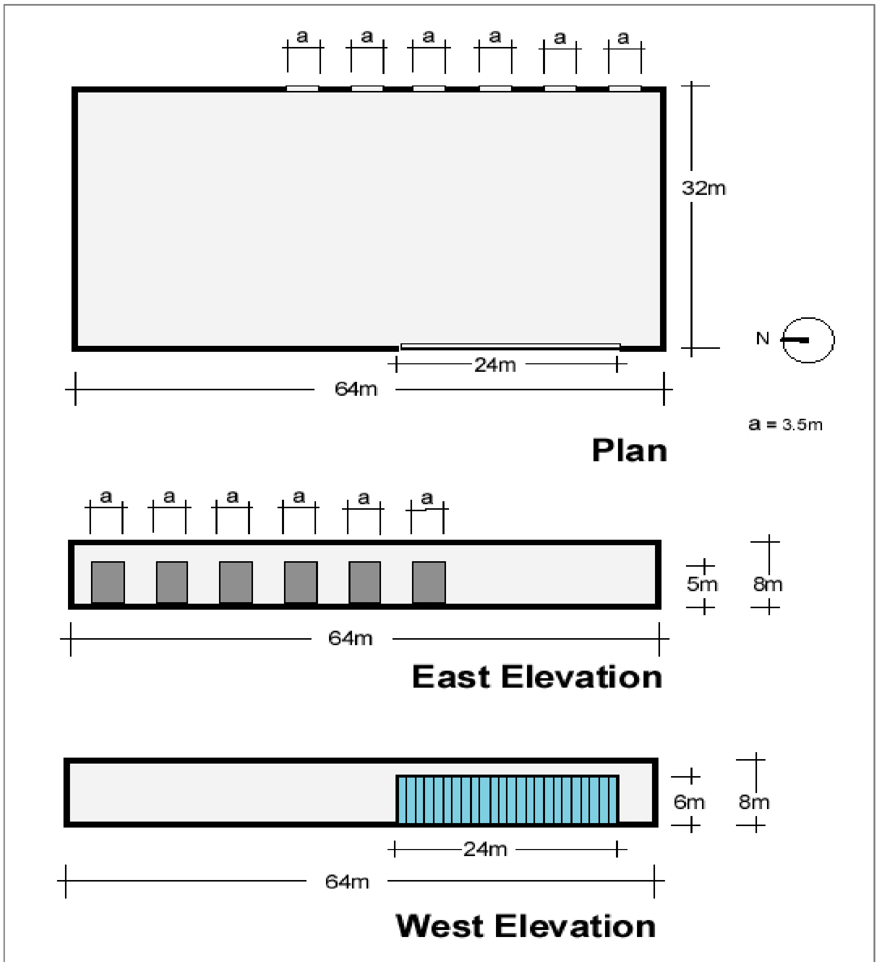
Overall Building Heat Loss Coefficient (U_o) 4103 W/C

Therefore, the total heat loss can be seen to be 4103 W per degree Celsius difference. For an outdoor temperature of -10° C, indoors of 20 °C, the difference is 30 °C, and total heat loss is 123 kW.

The relative impact of each building component can also be seen. For this building type, the U-value of the enclosure is unimportant relative to the impact of air leakage. It should also be noted that the lights and equipment and people in the store may consume 30 W/m^2 of electricity in retail applications, all of which is converted to heat. Hence, if we assume an average energy use of 30 W/m^2, the interior heat gains would be:

$$2048 \text{ m}^2 \times 30 \text{ W/m}^2 = 61440 \text{ W}$$

This energy will offset the losses of 123 kW, but a heating system of some type would be needed to make up the remaining need (123-61) = 62 kW. In normal practice, engineers assume all the energy inside a building is not available to provide heating. This was acceptable in the days of poorly insulated enclosures, with modest interior heat gains, but becomes a questionable assumption in highly insulated buildings.



Building Volume
=32x64x8
=16384

Roof Surface Area
=32x64
=2048 m2

Curtain Wall Surface Area
=24x6
=144 m2

Door Surface Area
=6(3.5x5)
=105 m2

Wall Surface Area
=(64x8)2+(32x8)2-(105+144)
=1024+512-105-144
=1287 m2

Building Surface Area
=2048+144+105+1287
=3584m2

9. HOW TO ESTIMATE ANNUAL HEATING ENERGY

An approximate method, widely used before hourly computer simulations were available, is the Heating Degree Day method. This approach assumes that heating must be provided to a building below some temperature, called the balanced temperature. Above the balance temperature, heat from occupants, lighting, equipment, etc., makes up for heat loss. In the 50's and 60's, the balance temperature of poorly insulated houses was assumed to be 18 °C (65 °F), and that of offices (with the very high lighting use) was assumed to be 10 °C. Today well-insulated houses and offices will tend to have a balance temperature of around 10°C (50 °F). Climate data is widely available for many locations which identifies Heating Degree Days, a number that is the sum of each day of the year of the difference between the balance temperature and the average outdoor temperature for that day.

To estimate annual space heating energy then,

$$E_{annual} = U_o * 24 \text{ hrs/day} * HDD$$

If the units of U_o are in W/°C, then the result will be in Watt-hours per year. If U_o is in Btu/°F, then the results will be in Btu per year.

Material	Density (kg/m3)			Conductivity Range (W/m K)			Conductance Range (W/m2 K)		
Board / sheet products									
Plywood	400	-	600	0.08	-	0.11			
OSB	575	-	725	0.09	-	0.12			
Waferboard				0.1					
Hardboard				0.105					
Vegetable Fiberboard	270	-	300	0.045	-	0.07			
Particleboard	590			0.102					
Particleboard	1000			0.17					
Strawslab	260	-	350	0.085	-	0.11			
Corrugated Metal Deck							negligible		
Finishes									
Ceramic Tiles				1					
Acoustic Tiles - fibreboard				0.065					
Acoustic Tiles - glassfibre				0.036					
Gypsum Board	800	-	900	0.16					
Sand Plaster / Lath				0.71					
Gypsum plaster / Lath				0.16	-	0.35			
Sand :Cement plaster	1570			0.53					
Gypsum plaster w/perlite	720			0.22					
Gypsum plaster w/sand	1680			0.8					
Carpet Fibrous Underlay							2.73		
Carpet Rubber Underlay							4.42		
Terrazzo				1.8					
Hardwood Flooring				0.16					
Siding / Cladding									
Hardboard siding	640			0.094					
Wood Siding - lap				0.1	-	0.12			
Plywood Siding				0.09					
Face Brick - clay	2000			1.3					
Face Brick - concrete	2200			1.9					
Metamorphic Stone	2600	-	3000	2	-	2.8			
Sedimentary Stone	2200	-	2600	2.1	-	2.3			
Metal vinyl clapboard/V-groove							8		
Metal - flush installed				40	-	80	0	negligible	
Cement Stucco	1800			0.7	-	1.4			
Structural Materials									
Softwood lumber	510			0.1	-	0.14			
Hardwood Lumber	720			0.15	-	0.18			
Cedar Logs and Lumber				0.098	-	0.12			
Concrete	2400			1.4	-	2.6			
Concrete (limestone)	1920			1.1	-	1.3			
Concrete (light)	1300			0.5	-	0.7			
Aerated Concrete	400			0.12	-	0.15			
Aerated Concrete	600			0.18	-	0.2			
Carbon Steel	7680			40	-	80			
Aluminum	2800			160	-	200			
Cement Mortar	1800			0.8					
Concrete Block 200 mm							5.1		
Lt. Wt. Concrete Block, 200 mm							2.84		

Concrete Block, 100 mm							8		
Hollow tile, 100 mm							5.5		
Durisol	400	-	500	0.072	-	0.085			
Adobe	1400	-	1800	0.4	-	0.8			
Clay Straw (function of density)	600	-	1400	0.15	-	0.5			
Cement-bonded rice husk	720			0.15					
Wood fibre and cement	1550			0.32					
Insulations									
EPS Type 1	16			0.039					
EPS Type 2	24	-	32	0.034					
EXPS Type 3 and 4				0.029					
Batt Insulation				0.036	-	0.048			
Rigid Mineral Fiber				0.03	-	0.04			
Rigid Fibrous Roof Insulation				0.036					
Rigid Polyurethane				0.024					
Rigid Polyisocyanurate				0.023	-	0.029			
Phenolic Foam (closed cell)				0.017	-	0.02			
Urea Formaldehyde				0.031	-	0.032			
Fibreboard	270			0.052					
Cellulose Fibre	37	-	51	0.039	-	0.046			
Sawdust	145	-	160	0.05	-	0.08			
Strawbale	120	-	200	0.06	-	0.075			
Corkboard	145			0.042					
Sprayed Asbestos				0.05					
Vermiculite, exfoliated	64		130	0.06	-	0.07			
Perlite, expanded	800			0.2	-	0.26			
Perlite, expanded	320			0.07	-	0.08			
Perlite, bonded/expanded	16			0.052					
Eel Grass batt	145	-	215	0.043	-	0.049			
Jute Resin bonded	420			0.065					
Peat slab	240	-	480	0.058	-	0.101			
Sheeps Wool, fluffy	50			0.045					
Roof Materials									
Built-up Bitumen Roofing				0.17					
Asphalt Shingles							12.9		
Wood Shingles							6		
Crushed Stone				1.60					
Thatch-Straw	240			0.07					
Thatch-Reed	270			0.09					
Other Materials									
Fresh Snow	190			0.19					
Compacted Snow	400			0.43					
Ice at -1 and -20 C	920			2.24	-	2.45			
Water at 20 C	1000			0.60					
Earth, dry to damp	1400	-	2000	0.80	-	2.00			
Sand dry	1400			0.30	-	0.80			
Air, still (conduction only)	1.2			0.03					
Glass, soda lime	2500			0.80	-	1.00			
Copper				380					
Lead				35					
Brass				120					
Nickel				60					
Rubber				0.2					

10. Thermal Bridges

Heat flow deviates from one-dimensional at corners, parapets, intersections between different assemblies, etc. When heat flows at a much higher rate through one part of an assembly than another, the term *thermal bridge* is used to reflect the fact that the heat has bridged over / around the thermal insulation. Thermal bridges become important when:

- they cause cold spots within an assembly that might cause performance (e.g., surface condensation), durability or comfort problems
- they are either large enough or intense enough (highly conductive) that they affect the total heat loss through the enclosure

All enclosures should be designed to avoid a large number and large thermal bridges. The most effective solution, exterior layers of continuous insulation (i.e., insulating wall sheathings) are quite useful for "blunting" thermal bridges and also offer improved resistance to exfiltration condensation in cold weather.

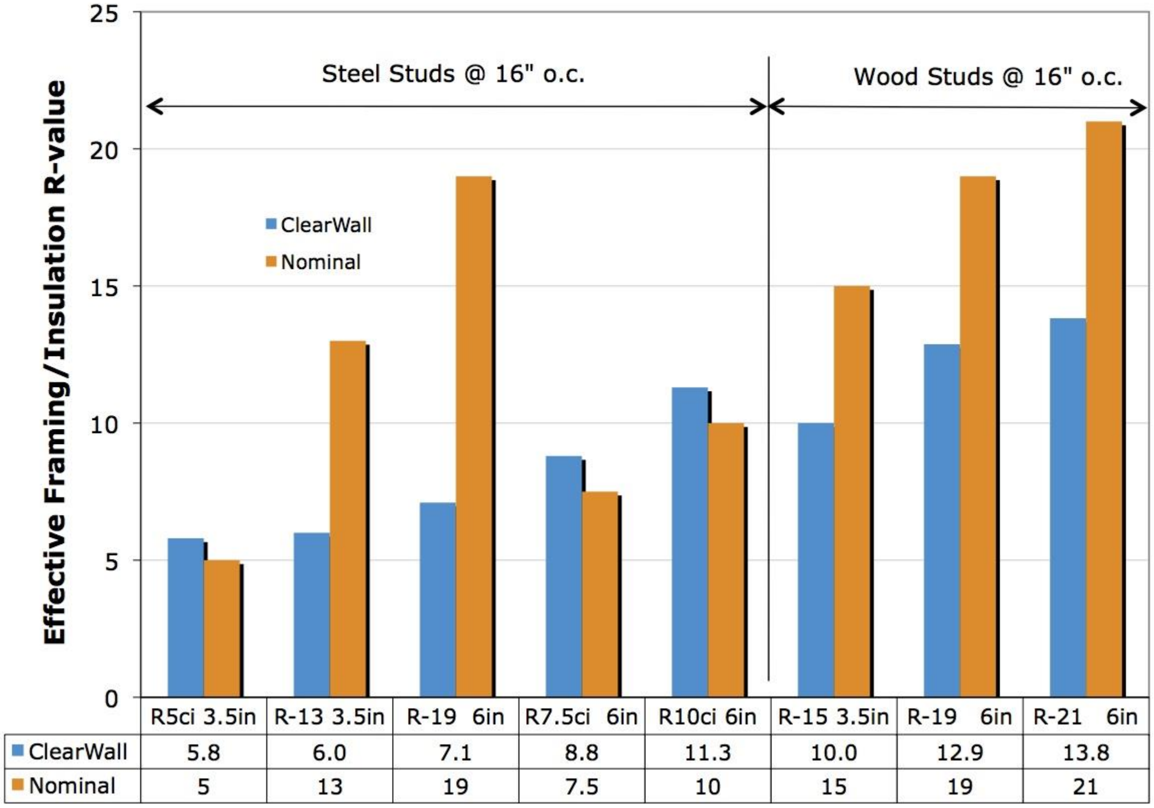
Thermal bridging, especially by steel framing, or at the intersection of wall corners with roofs and floors, projecting structural elements like balconies and perimeter slabs often causes cold interior surface temperatures and thus condensation. Attached figures provide a schematic of how temperatures at studs and near corners can cause low surface temperatures. In the case of the steel framing shown, an exterior temperature of –10 °C can result in interior surface temperatures of 5 to 10 °C at studs, and below freezing at floor to wall corners.

The R-value of walls with insulation (of any type) installed between framing, and penetrated by floor assemblies can be significantly compromised. Wood frame systems will often experience R-value reductions of 25 to 30% compared to the nominal value. Light-gauge steel framed systems regularly experience reductions of 60 to 75%. A commercial steel stud system can be considered to be a single "layer", and the heat flow through the studs calculated. The values for several common steel studs systems are listed below. The thermal resistance of interior and exterior sheathing, finishes, cladding, exterior insulation and air films can be added to these values to predict the overall system R-value.

Cavity Depth (in)	**Rated Cavity R-value**	**Eff R-value @16in centers**	**Eff RSI @405mm centers**
2.5	empty	0.75	0.13
3.5	empty	0.79	0.14
3.5	R-13	6.0	1.06
3.5	R-15	6.4	1.13
6.0	empty	0.84	0.15
6.0	R-19	7.1	1.25
6.0	R-21	7.4	1.31
6.0	R-24 (4" ccSPF)	7.6	1.34

Figure 1: Effective layer Clear-wall R-value for light gauge steel framing

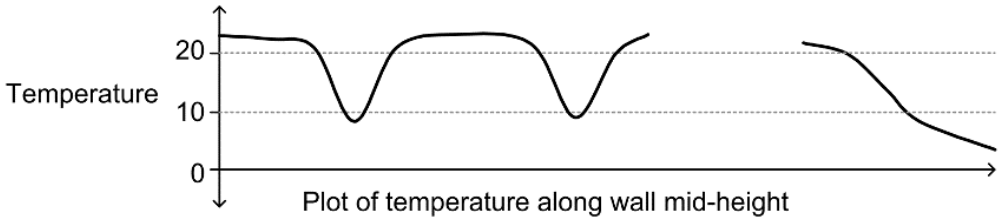
Almost all continuous insulations are, in practice, penetrated by screws, discrete ties, and other point fasteners. Typical use of wire ties for masonry or sheet metal clips degrade performance by perhaps 2 to 5%. However, continuous cold-formed steel Z-girts reduce the performance by 50% or more and should be avoided.

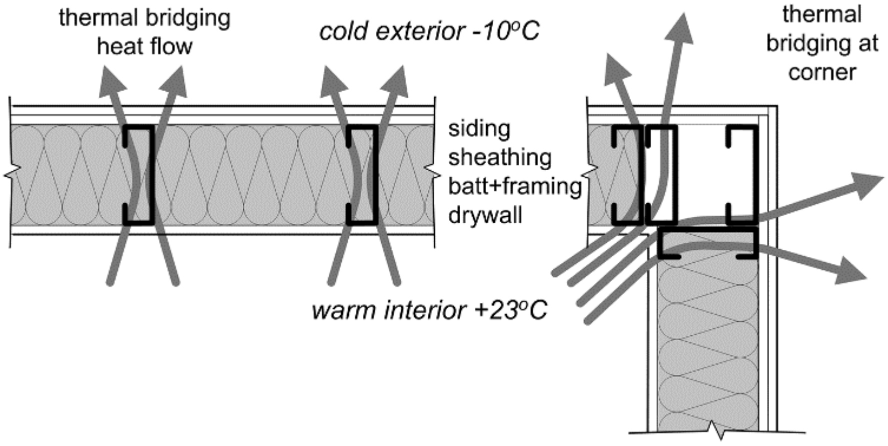


	R5ci 3.5in	R-13 3.5in	R-19 6in	R7.5ci 6in	R10ci 6in	R-15 3.5in	R-19 6in	R-21 6in
ClearWall	5.8	6.0	7.1	8.8	11.3	10.0	12.9	13.8
Nominal	5	13	19	7.5	10	15	19	21

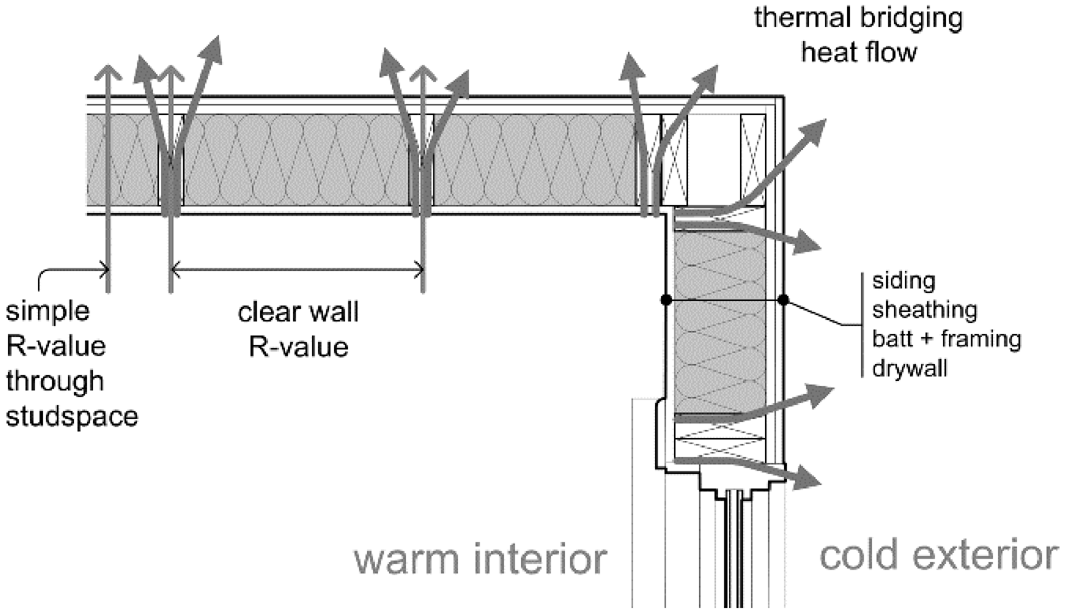
Source: ASHRAE 90.1-2007, Table A9.2B. ci denotes a layer of continous insulation with no framing penetrations

Table 3: The thermal bridging impacts of steel stud vs wood stud

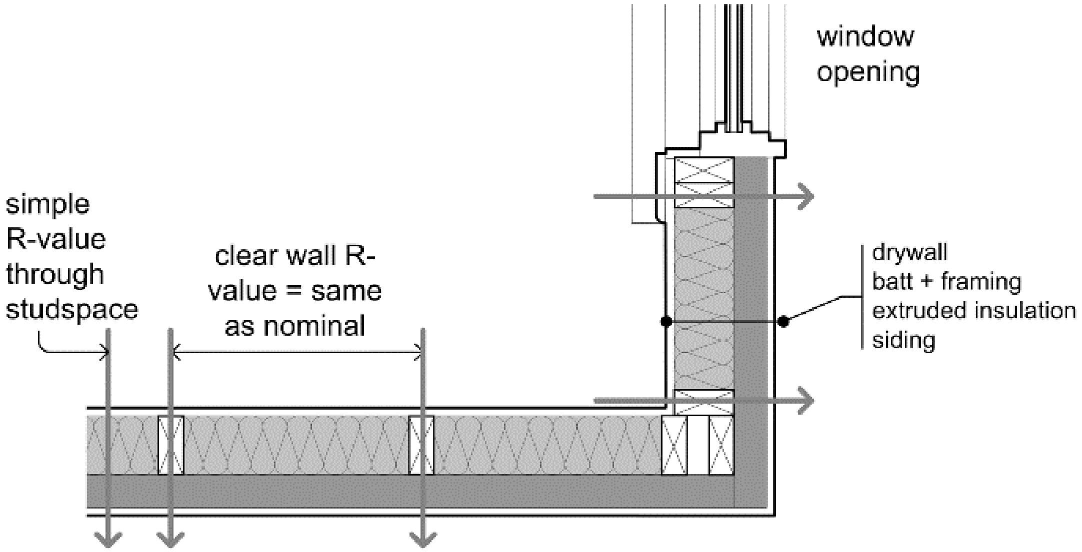

Temperature
20
10
0
Plot of temperature along wall mid-height


thermal bridging heat flow
cold exterior -10°C
thermal bridging at corner
siding
sheathing
batt+framing
drywall
warm interior +23°C

2x6 Framed Wall



2x4 with Exterior Insulation



11. SOLAR HEAT GAIN THROUGH WINDOWS

When analyzing buildings for solar heat gain (beneficial in winter, usually not in summer), solar heat gain is important to assess. Solar heating of surfaces is discussed in Section 11, and this information can be used to predict heat flow through opaque enclosure elements under extreme conditions. This type of heat gain is usually a small fraction of the heat gain through the walls of most buildings. The cooling load of most buildings is controlled by direct solar gain through the windows.

The fraction of incident solar radiation that passes through a window as heat is termed the Solar Heat Gain Coefficient (SHGC). The SHGC is a property of windows that should be specified by the designer, and is readily available from most manufacturers. Hence, the solar heat gain through windows facing one direction is

$$Q_{solar} = A * I_{solar} * SHGC$$

Where A is the area of windows (m^2), and

I_{solar} is the intensity of incident solar radiation on the surface (W/m^2).

Table 4 provides an estimate of the incident solar radiation on a vertical surface for four orientations and four months: detailed values are available from numerous engineering textbooks.

Month	**South**	**North**	**West/East**
Jan 21	870	70	493
April 21	622	131	753
July 21	494	167	722
October 21	829	92	603

Table 4: Representative "Clear Day" Solar radiation on vertical surfaces at their peak hour for 44°N Latitude (W/m^2).

Clear glass, single pane	0.75
Double paned insulated glazing unit	0.66
Double, low-e, argon or air filled	0.55
"Solar Control" low-e IGU	0.25 to 0.40
Reflective coatings, double IGU	0.10 to 0.20
Triple, 2 low-e coatings, passive solar	0.45 to 0.55

Representative SHGC for glazings.

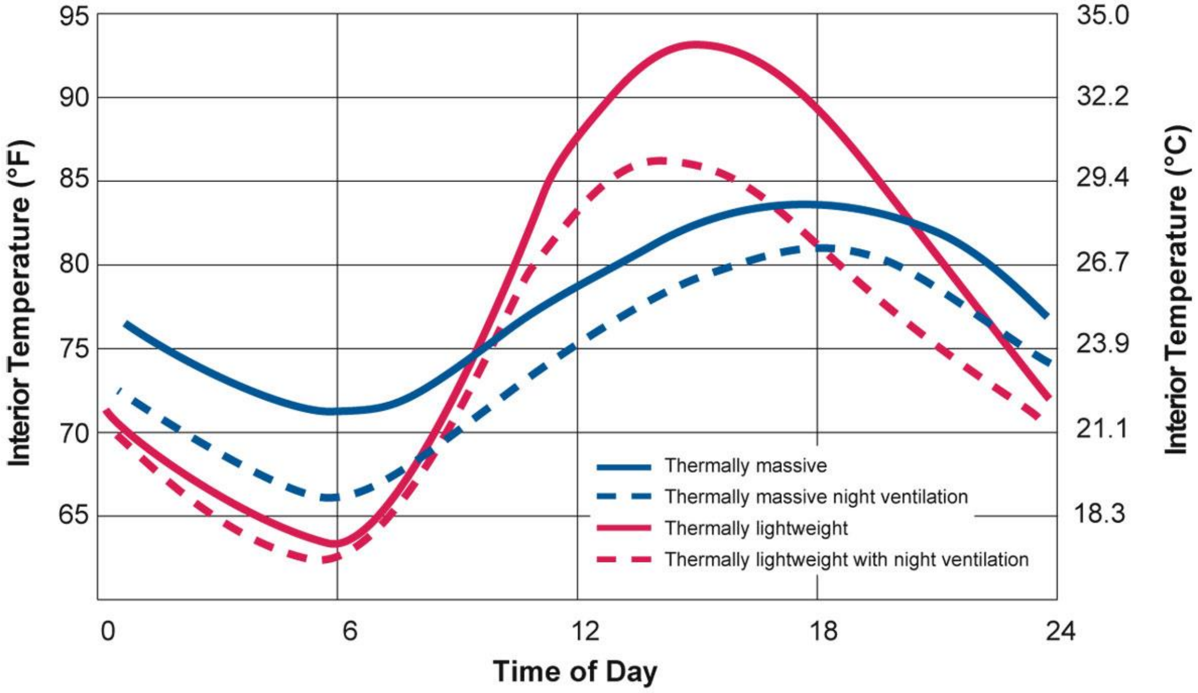
12. THERMAL MASS

Thermal mass acts to store and release thermal energy (heat). Thermal mass is almost always beneficial for buildings with near constant interior temperature. For buildings with aggressive setback temperatures or long periods of unoccupied hours, thermal mass can cause control difficulties and may even increase energy consumption.

For high performance buildings, the overall heat loss coefficient is low enough that the thermal mass of typical construction is quite substantial: if heating is removed it can take hours for the temperature to drop by one degree. In many high-performance buildings setback schedules will not work because the building does not cool down to the setback temperature before the temperature is set up again. This has the major advantage that a super insulated building can survive many times longer than normal buildings in the event of a power outage.

Thermal mass is often desirable to store solar heat gains and internal heat generation from occupancy during the day, and release it during the evening. This is one of the basic tenents of passive solar design. The limit to this strategy in all types of buildings is the rate at which heat gain can be transferred to the thermal mass during sunny period (without overheating) not the amount of thermal mass. Because the heat loss of high performance buildings is so small, increasing thermal mass is often not useful unless the rate of heat transfer to the thermal mass is increased. This latter goal can be achieved by increasing the surface area of mass (e.g mass more than 2 to 4" thick take too long to charge), by ensuring that the mass is not covered by insulating or thermally lightweight finishes, and by encouraging airflow from the heated zone to remote thermal mass in other zones.

For ultra-low energy use buildings, thermal mass can be a powerful and often necessary strategy. However, it is a design strategy that is difficult to use because of the complexity of assessing actual dynamic building use, heat transfer to and from mass, the temperature swing acceptable to the occupants and other poorly characterized variables.



13.RADIATION-INDUCED EXTERIOR SURFACE TEMPERATURES

Radiation, either solar heating by the sun or cooling by radiation to the night-sky, can have a very significant influence on the thermal exposure of the building envelope. Although rarely warranted, detailed procedures can be used to relatively accurately calculate, in terms of energy transfer rates (e.g. W/m^2), the effect of solar heating and night-sky cooling on enclosure surface temperatures.

It is often convenient to have simple equivalent temperatures that can be entered directly into a standard conductive heat flow analysis. When an equivalent air temperature is used, the temperature is termed the *sol-air temperature*. This procedure has the drawback that air temperature is no longer realistic and the advantage that surface films play a role in the definition of the temperature. The value for the overall surface film coefficient is often assumed to be 17 W/m^2·ºC although this coefficient is quite variable, especially if the surface becomes hot. In fact, under solar-heating, the coefficient is likely to be as much as two times larger.

A simple and equally realistic approach is to use *approximate surface temperatures*. Table 5 is a compilation of the most useful approximate surface temperatures based on calculation (using refined surface heat transfer coefficients) and supported by several years of field measurements.

Situation	Thermally Massive	Thermally Lightweight
Roofs: direct sun	$t_a + 42\ \alpha$	$t_a + 55\ \alpha$
roof: sun plus reflected / emitted radiation	$t_a + 55\ \alpha$	$t_a + 72\ \alpha$
roof exposed to night-sky	$t_a - 5\ \varepsilon$	$t_a - 10\ \varepsilon$
walls: winter sun	$t_a + 35\ \alpha$	$t_a + 48\ \alpha$
walls: summer sun	$t_a + 28\ \alpha$	$t_a + 40\ \alpha$
walls exposed to night sky	$t_a - 2\ \varepsilon$	$t_a - 4\ \varepsilon$

Notes: All values are for approximately 35º-55º North. t_a refers to the ambient air temperature, ε is the surface emmittance, and α is the solar absorptance. The emmittance is about 0.90 for most materials. The absorptance varies with colour from about 0.3 for white/beige objects to 0.65 for forest green to 0.95 for flat black.

Thermally massive refers to walls with a significant amount of thermal storage capacity (e.g. brick veneer or equivalent) outside of a low conductance material (e.g. insulation). Walls with significantly more mass (e.g. multi-wythe brick, rubble) or less insulation (U > 1 W/m^2/ºC) will be less affected. Vinyl, metal and EIFS are lightweight walls; other walls can be interpolated based on heat capacity. The values for are for likely clear night or sunny day maximums and apply to east/west orientations in summer and south orientations in the winter.

Table 5: Approximate Radiation-Induced Surface Temperatures (ºC)

Example

> If the example wall in Section 3 were exposed to bright sun on a -10 °C day, the temperature of a very dark, lightweight, south-facing surface would be expected to be as much as 48*1 = 48 C above the air temperature (see Table 5 later in this document). For this example, we will assume dark thermally-massive red brick (absorptance =0.85) and thus estimate a surface temperature of about 35 * 0.85 = 30 C above the air temperature. This means:

Heat flow $= U * (t_{inside} – t_{outside}) = 0.33\ [20 -(-10+30)] = 0.33\ (0)$
$= 0\ W/m^2$

Ans. If the wall were facing south, dark red, thermally massive, and exposed to bright sunshine, the heat flow would be approximately zero.