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CBD 36

Temperature Gradients Through Building Envelopes

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J.K. Latta and G.K. Garden

Please note

The temperature existing at any point in a wall under any given exterior and interior temperature conditions is of great significance in designing problem-free building enclosures. An ability to calculate the thermal gradient permits the designer to forecast the magnitude of the movements caused by external temperature changes, to predict the location of condensation and freezing planes in the wall, and to assess the suitability of any construction. The temperature gradient will not, in itself, give the designer all the information he requires to select and assemble building components, but it is an essential first step. The purpose of this Digest is to show how the thermal gradient can be determined and to indicate why this knowledge is important and how it may be used by building designers.

It is the function of a building envelope when acting in conjunction with heating and ventilating equipment to maintain a more or less uniform internal environment regardless of weather conditions. The first and most obvious effect of a difference of temperature between the inside and outside is that beat flows from the side of high temperature to the side of low temperature; adequate cooling or heating equipment must be provided to counterbalance the over-all gain or loss in order to maintain the desired internal temperature. The determination of the total heat exchange through a wall is accepted as part of the normal mechanical design of any building and will not be discussed further. Emphasis will be placed instead upon the equally important but less obvious effects of the temperature differential that must be taken into account by the building designer.

The warping effect of a bimetallic strip such as that used in a thermostat is well known, but the similar effect which might be produced by a homogeneous material having its opposite faces exposed to different temperatures is not so apparent. Serious distortion can occur in a component subjected to, a temperature differential because the warm side expands relative to the cold side. Since the external surface of the building envelope will be subject to a range in temperature which may be more than 200° whereas the internal surface will be subjected to a much smaller range, there will be a continuing tendency for a solid wall to deflect in and out. In the case of a wall made of many different layers, one layer may slide over the other.

The quantity of water vapour that can be held by air is governed by the temperature of the air. As the temperature drops, the ability of the air to hold water vapour is reduced. Air in contact with a surface that is below its dew-point temperature loses water in the form of condensation on the cold surface. Thus, moisture-laden air circulating in spaces in the wall or passing outward through cracks or other passages in the building envelope will deposit some of its moisture on surfaces within the wall that are below the dew-point temperature. This water often produces stains or moisture accumulations that may cause serious building deterioration.

Interior surfaces of windows, inadequately insulated walls and ceilings and other cold surfaces with temperatures below the dew-point of the air will experience surface condensation. When this occurs, considerable quantities of liquid water can be produced that may in turn cause many forms of damage and deterioration. By calculating surface temperatures the designer can check on the suitability of the proposed enclosing elements of the building.

From the few examples discussed above it is obvious that a knowledge of the thermal gradient will aid the designer to guard against problems that might arise from these causes when the building is placed in operation. The calculation that must be performed to determine the temperature gradient under steady state parallel heat flow is simple and can be performed either arithmetically or graphically. Under these conditions all parallel paths through the wall have the same conductivity and all the components have reached steady temperatures, neither storing nor releasing heat. It follows then that all the heat that enters; the warm side of the wall must flow through each component in turn and be carried away from the cold side. As with many cases of uniform flow such as this, the rate of flow is directly proportional to the magnitude of the driving force and inversely proportional to the resistance. The driving force is provided by the difference in temperature and the thermal resistance is a property of the materials and of the construction of the component being considered, i.e.,

$$\text{Heat Flow} \propto \frac{\text{Temperature Difference}}{\text{Thermal Resistance}}$$

Thus it follows that the temperature drop through each component of the wall is proportional to its thermal resistance.

Thermal resistances (R) for many building materials and combinations of materials are listed in the Guide of the American Society of Heating, Refrigerating and Air Conditioning Engineers; the appropriate chapter of the 1960 edition of this Guide is available as a publication of the Division of Building Research (NRC 5596). It should be noted that the values quoted are for dry materials and that moisture will reduce the thermal resistance. In those cases where a resistance is not given it can easily be obtained by taking the reciprocal of the thermal conductance, $R = 1/C$. The thermal conductance can in turn be obtained for any given thickness of a uniform material by dividing the conductivity (k) of the material by the thickness (n) in inches, $C = k/n$. Alternatively, the resistance per inch of thickness is given by $1/k$ and the resistance for n inches is given by $n \times 1/k$. As more layers of material are added the resistance of each of them must be added to give the total resistance.

Thermal conductivity is a measure of the rate at which heat will flow through a homogeneous material, or materials such as lumber, brick and stone, which may be considered to be homogeneous. The conductivity or k value is the number of British Thermal Units (Btu) of heat that will pass through 1 square foot of a 1-inch thickness of material in 1 hour under a temperature differential of 1°F. Thermal conductance or C value is a term also used to express the rate of heat flow through a material, but it is applied to the specific thickness of the material used in the construction and not to each inch of thickness. It is expressed in the same terms as thermal conductivity, except that the unit temperature difference is across the stated thickness. The term "conductance" is used with materials such as hollow concrete blocks or building papers that are of non-uniform cross-section or are thin; and with air spaces and the air films at the interior and exterior surfaces of constructions.

To illustrate the procedure, using both the arithmetical and graphical methods, the temperature gradient through the wall shown in Fig. 1 will be calculated assuming a monthly average outside temperature of 10°F and a controlled inside temperature of 70°F. To per form the calculation arithmetically a tabular layout is used as shown in Table I. All the components of the wall, including the internal and external air films on the faces of the wall, are listed in sequence with their thermal resistances (R) listed opposite. It is normally necessary to list only resistances and temperatures. Conductivities and conductances have been shown in this example to further clarify some of the text.

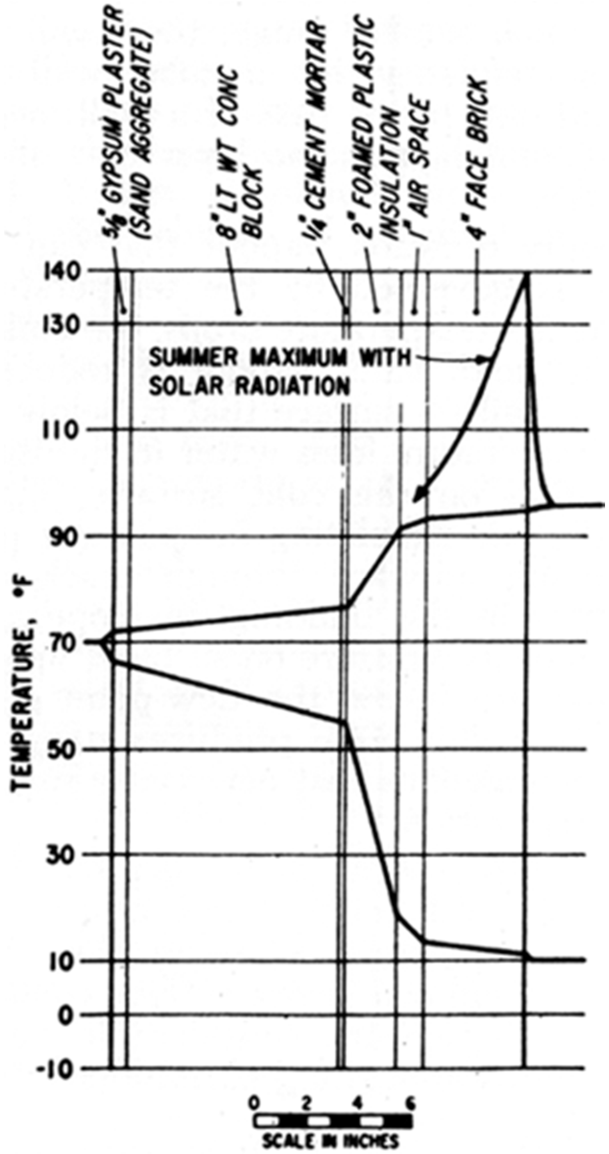

Figure 1. Wall Section to Physical Space

Table I. Arithmetic Determination of Temperature Gradient

Component	Thickness, n, in.	Conductivity, k	Conductancr, C = k/n	Resistance, R = 1/C	Temperature Drop, deg F	Interface Temperature, deg F
Internal Air Film (still			1.46	0.68	4	70

air)						
Gypsum Plaster (sand aggregate)	5/8		9.10	0.11	1	66
Concrete Block	8		0.50	2.00	11	54
Cement Mortar	¼	5.0	20.00	0.05	0	54
Foamed Plastic Insulation	2	0.29	0.145	6.90	36	18
Air Space	1		0.13	0.97	5	13
Face Brick	4	9.0	2.25	0.44	2	
External Air Film (15 mph wind)			6.00	0.17	1	11
TOTAL				11.32	60	

The Over-all Coefficient of Heat Transmission, U = 1/R = 1/11.32 = 0.09 Btu/sq ft/°F/hr

The total temperature drop through the wall in this case is 60°F and can be distributed among the individual components in proportion to their resistances. The interface temperatures can then be determined and recorded in the last column and the temperature gradient plotted as shown on Fig. 1. Should the total heat loss through the wall be required, the over-all coefficient of heat transmission (U) is given by the reciprocal of the total resistance.

The arithmetic determination of the temperature gradient is not a lengthy calculation. It is probably the easier one to use if a wall is being designed to meet fixed internal and external temperature conditions and the components of the wall are selected to suit. On the other hand, if a tentative wall design is chosen and the effects of varying temperature conditions are to be studied, the graphical method may be more convenient.

In the graphical method, a cross-section of the wall is drawn wherein the thickness shown for each component is proportional to its thermal resistance. Then by plotting a temperature scale on the cross-section and a straight line joining the inside and outside temperatures (representing the temperature gradient) the temperature at any point in the construction can be read. This method is illustrated in Fig. 2 for the same wall section as was used in the arithmetical method.

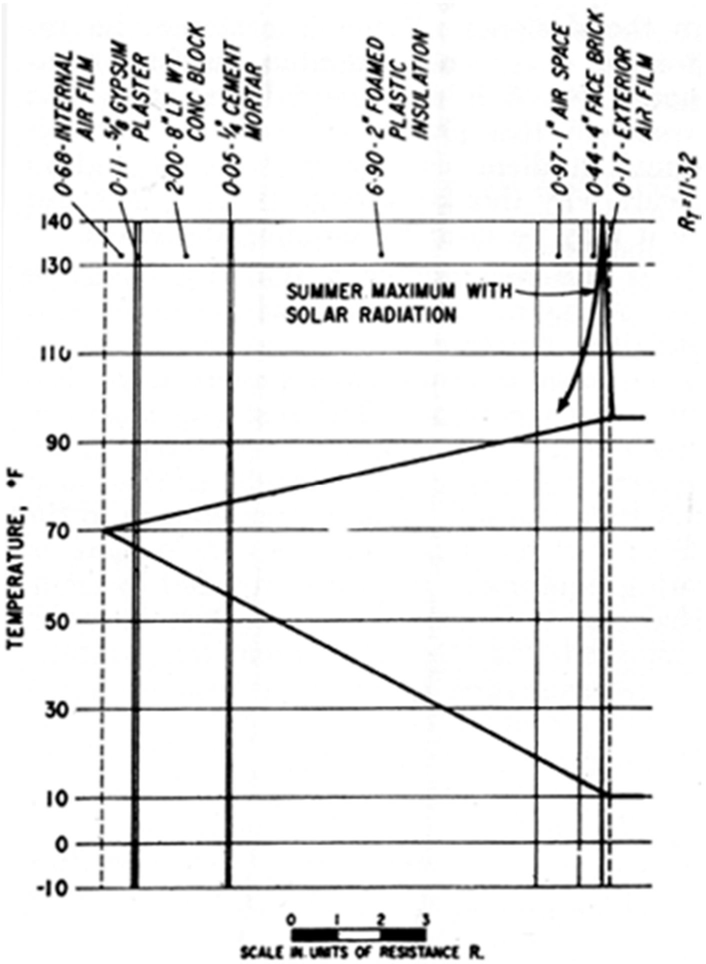

Figure 2. Wall Section to Scale of Thermal Resistance

These methods of calculating the temperature gradient employ conductance values that depend upon the assumption that all components in the envelope, including the air films, have fixed values for their thermal conductivities. In fact, heat is transferred by radiation and convection as well as by conduction. For the conditions involved in any given case, these conductances, C, are not true constants but may actually be functions of temperature, temperature difference, velocity and surface roughness, emissivity and absorptivity. Furthermore, the assumed steady-state conditions are seldom reached owing to fluctuations in the temperatures to which the envelope is exposed and to the heat storage capacities of the material. Unless simplified procedures are followed the solution of practical cases of heat flow through walls and roofs can become very complicated. Some inaccuracies may be introduced by these simplifications, but the results obtained provide a valuable guide for design of walls and roofs. The determination of the interface temperatures to a precision greater than 1°F or 2°F is, however, unwarranted. Paths of high conductivity, called thermal bridges, do produce inaccuracies that often require special consideration.

The selection of appropriate outside air temperatures requires considerable judgement, but much valuable information will be found in the Climatological Atlas of Canada (NRC 3151). The effects of heat storage in materials must be recognized, as must the fact that wall or roof surface temperatures can be higher than air temperature because of "solar radiation" and colder than air temperature because of "clear sky radiation." These temperature modifications vary with the colour, texture, thickness, weight and orientation of the surface materials and with the intensity of the radiation. The effect produced by radiation is indicated in Fig. 2, which shows that the temperature range in a material may be greater than that resulting from the influence of air temperature alone.

It should be emphasized that temperature gradients derived from these simple calculations, although not precise, are of great value in improving a designer's ability to select and locate insulation and vapour barriers and to estimate where freezing may occur in a wall or roof. This information is also of considerable value in analysing a wall or roof construction with respect to water and water vapour behaviour. A designer making these calculations will soon realize that although adding insulation may alleviate some problems it may produce others. An increase of insulation in a wall will raise the interior surface temperature and minimize the risk of surface condensation. A decrease in the insulation value, although increasing the heat loss and lowering the interior surface temperature, will raise the exterior surface temperature, thereby reducing the risk of condensation or freezing within the wall construction. It is important that the services of a consultant skilled in thermal analysis be obtained when the use of a particularly complicated wall construction is contemplated.

The building designer with an appreciation of the temperature variations in wall elements can estimate the magnitude of movements or stresses that may be induced in the components by expansion and contraction. He can then determine the required number and width of movement-control joints or amount of reinforcement necessary to prevent failure.

Determination of the thermal gradient throughout a building element that separates two environments that have different properties is the first step toward designing problem free walls. Information pertaining to thermal bridges, psychrometry, moisture migration, rain penetration and differential air pressures is also necessary for optimum design. Perfection in buildings is not readily achieved and the quest for it is often hampered, for financial reasons. With a good working knowledge of the matters discussed in this Digest, however, a designer can more readily determine the best solution within the limitations established by cost and availability of materials.