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CBD 47

Extreme Temperatures at the Outer Surfaces of Buildings

Originally published November 1963

D.G. Stephenson

Please note

It is sometimes taken for granted that the variation in the outer surface temperature of a wall or roof will never exceed the range of the outside air temperature. This ignores the influence of radiation and seriously under estimates the maximum temperatures that building materials must withstand. This Digest discusses the effect on outside surface temperature of solar radiation, long-wave radiation, surface colour, the position and colour of adjacent surfaces, temperature of the air inside and outside the building, and the thermal properties of materials used to form a building envelope.

The most direct way of determining the temperatures that actually occur in buildings is to measure them. This approach is quite impractical, however, when the purpose is to find the extreme temperatures that any wall or roof surface may experience; this would require a long series of observations on structures with every combination of wall and roof construction, surface colour, orientation and location. Instead, the heat exchange at the outside surface of a wall or roof can be analysed and the factors that influence the surface temperature can be studied separately. With these data it is possible to predict the temperatures that will obtain under any specified circumstances.

Thermal Radiation

All objects continuously emit radiation and absorb some of the radiation from other bodies that is incident on them. Emission and absorption of radiation play a large part in the energy exchange at the outer surface of a building.

The wave-lengths of the thermal radiation depend on the temperature of the emitting surface - the higher the temperature the shorter the wave-length at which the maximum energy occurs. The absolute temperature of the outer layers of the sun's atmosphere is about twenty times as great as the temperature of the surface of the earth and terrestrial objects such as buildings. The energy in solar radiation is concentrated, therefore, at much shorter wave-lengths than occur in the radiation from low-temperature bodies. Thus solar radiation is generally referred to as "shortwave" and radiation from terrestrial objects as 'long-wave."

The rate of energy emission from unit area of a surface depends on the fourth power of the absolute temperature of the surface and on the nature of the surface, which is characterized by the value of the emissivity. The value of the emissivity also indicates the propensity of the surface to absorb radiation of the same wave-length as that it emits. The absorptivity of a surface for short-wave radiation, a, is not, in general, equal to its absorptivity for long-wave radiation. The change in absorptivity with wave-length can sometimes be exploited to reduce the maximum temperatures that occur at the surface of bodies exposed to the sun. This is discussed later under the effects of colour.

Heat Balance at a Surface

At every instant the total heat leaving a surface must be equal to the total heat approaching the surface. Figure 1 shows the various components of the heat flow toward and away from an opaque surface. For the surface of a building exposed to solar radiation the various heat flows will be in the directions shown in the figure. The temperature of the surface is always at the value where the heat gains and losses balance. If the solar radiation incident on a surface increases, the surface temperature rises, causing conduction, convection and long-wave radiation to increase just enough to offset the increased rate of energy absorption.

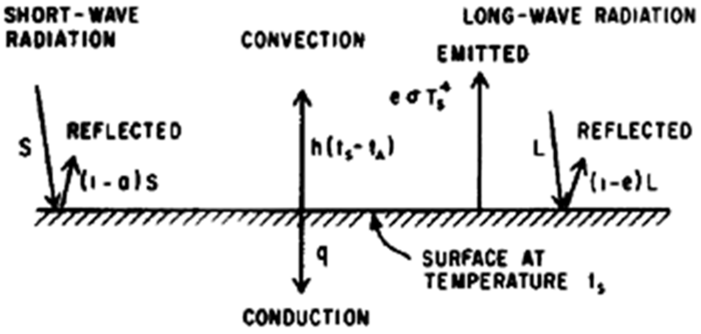

Figure 1. Components of heat balance at an opaque surface.

Calculation of the surface temperature and heat flux can be greatly simplified through the use of the sol-air temperature concept. The S. A. T. is the fictitious temperature of the outside air that would produce by convection alone the same rate of heat exchange at the surface as actually occurs by convection and long and short-wave radiation combined. Thus

$q = h\,(\text{S. A. T.} - t_s)$;

combining this definition of S. A. T. with the energy balance at the surface gives

$$t_A + \frac{aS}{h} + \frac{eL}{h} - \frac{E\sigma T_s^4}{h}$$

The temperature of the outside surface of a wall or roof with negligible heat storage capacity can be determined by the graphical method described in **CBD 36**, using S. A. T. as the outside temperature and *h* as the outside surface conductance. Figure 2 gives the magnitudes of the different components of S. A. T. and shows how the roof conductance and inside temperature affect the outside surface temperature. The values used for this example are appropriate for a dark coloured, flat roof in the region between 40 and 50 degrees north latitude, at a time when the surface temperature would be a maximum. The indicated surface temperature of 190°F represents the highest temperature a dark roof with an unobstructed view of the sky is likely to attain in any part of Canada.

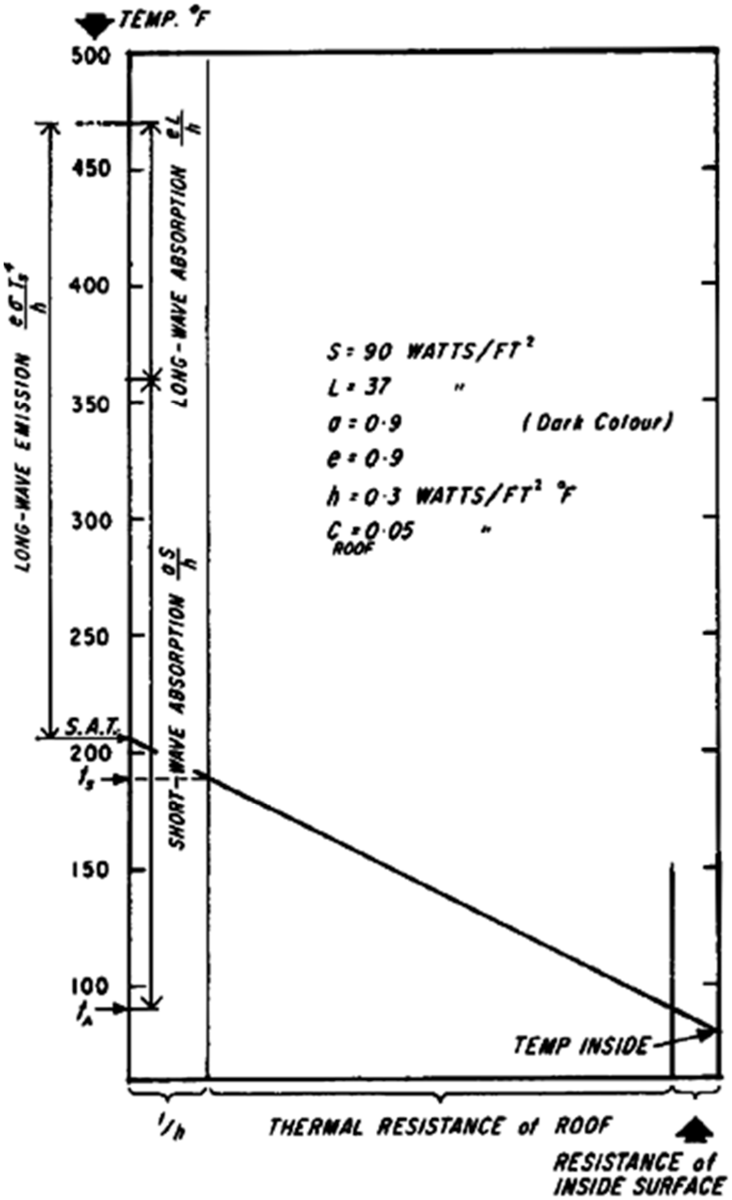

Figure 2. Summer temperature for dark roof with unobstructed view of sky.

The short-wave irradiation S may include reflected radiation from adjacent surfaces, depending on their colour, proximity and the irradiation they receive, as well as the radiation that comes directly from the sun and sky. The value of the long-wave radiation, *L*, is likewise dependent on the surrounding surfaces that can be seen from the surface in question. For example, the roof of a low building situated directly south of a much higher building will receive a considerable amount of reflected sunlight, plus some fraction of the long-wave radiation emitted by the wall of the higher building. The maximum temperature of a dark horizontal roof situated close to the south wall of a very high building could be as high as 230°F.

Vertical Surfaces

The annual maximum insolation is nearly the same for all walls facing not more than 90 degrees from south, regardless of latitude. The hour and date of the maximum depend, however, on the wall orientation and latitude. Walls facing east and west receive their greatest irradiation in the middle of the summer about 4 hours before and after noon, respectively, whereas those facing south receive their maximum at noon about the middle of November.

Walls facing east and west will have higher surface temperatures than walls facing south, other things being equal, because their maximum irradiation coincides with the maximum ambient air temperature.

Walls always receive some reflected shortwave radiation from their surroundings. They also receive more long-wave irradiation than flat roofs because at least half their field of view is below the horizon where the intensity of long-wave irradiation is always greater than that from the sky. Thus the total radiation incident on a vertical surface is just about the same as that shown in Figure 2 for a flat roof. A surface temperature of 190°F, therefore, is the maximum a dark coloured wall is likely to attain.

Effect of Heat Storage

It is commonly recognized that the surface of a thick masonry wall does not become as hot during a clear summer day as the outer layer of a light curtain wall section, if both walls have the same exposure. The difference lies in the heat storage capacity of the walls.

When the radiation incident on a wall or roof surface suddenly changes, as when a cloud moves away from in front of the sun, the S. A. T. increases abruptly, but the temperature of the exposed surface does not reach a new equilibrium value until some time later. The time required depends on the value of the surface conductance and the heat storage capacity of the wall or roof. Lightweight walls reach equilibrium in a fraction of an hour; very heavy walls require more than a day. The temperatures indicated by the straight line on Figure 2 are the equilibrium values. Even on a cloudless day the S. A. T. is never constant, because solar radiation continuously changes from sunrise to sunset. Around midday, when the solar radiation on a horizontal surface is maximum, the S. A. T. changes very little in a period, of an hour so that the surface of a lightweight roof could reach the maximum temperature of 190°F shown in Figure 2. The maximum surface temperature for a massive slab with the same total thermal resistance would be somewhat lower. The precise calculation of surface temperature, allowing for heat storage capacity, is quite involved and a detailed discussion is beyond the scope of this Digest. It is perfectly correct to say, however, that the temperatures at various points throughout a building enclosure will never exceed the values that would obtain at equilibrium with the maximum S. A. T. Thus the straight line on Figure 2 represents the upper limits for the temperatures everywhere through the roof.

The Effect of Surface Colour

The fraction of the solar irradiation absorbed by a surface depends primarily on its colour. A white surface absorbs about 40 per cent, whereas dark green, brown and black surfaces absorb about 90 per cent. Figure 2 shows the extent to which the S. A. T. for a surface depends on the magnitude of the absorbed short-wave radiation. If the roof considered in Figure 2 had a white instead of black surface (i.e. $a = 0.4$ instead of 0.9) the surface temperature would be 130°F instead of 190°F. The difference between the maximum temperatures of black and white vertical surfaces is about 50 F degrees compared with 60 F degrees for horizontal surfaces.

The aptness of these calculated values has been corroborated by measurements made on a building in Ottawa. The opaque parts of the wall were lightweight panels, black on one side and white on the other. They were originally installed with the black side out, but as an experiment two panels in the middle of a south-west wall were reversed so that the white surface was outside. During one summer the observed maximum temperature of the outer black surface was 175°F, while that of the adjacent white panel was 130°F.

Unpainted metal surfaces that are not heavily oxidized reflect about the same fraction of incident short-wave radiation as a white painted surface, but their emissivity is only one quarter the value for a painted surface. Consequently, the radiation emitted by an unpainted metal surface is much less than that for a painted surface and its surface temperature is higher, therefore, than that for a similarly exposed white painted surface. It is for just this reason that most airlines have the upper half of the fuselages of their aircraft painted white and the under surfaces unpainted. An aircraft parked in the sun is significantly cooler when painted this way than if it is completely unpainted or completely painted.

Low Temperature Extremes

The foregoing discussion has been concerned only with the annual maximum S. A. T. and the resultant maximum surface temperature. A building designer also needs to know the minimum temperature that can occur so that he can allow for thermal expansion effects and condensation within the wall or roof. Minimum surface temperature occurs when there is no solar radiation, the ambient air temperature is at a minimum, there is no wind and the sky is clear. Under these conditions the S. A. T. is well below ambient air temperature and the surface of an insulated roof may be about 10 degrees cooler than ambient air temperature. In this case the energy leaving the surface in the form of long-wave radiation is equal to the sum of the heat conducted through the material backing the surface, the convection from the outside air to the surface and the fraction of the long-wave radiation from the sky that is absorbed by the surface. The frost that forms on the windshield of a car left out on a clear calm night is a good demonstration that surfaces exposed to a clear sky do, in fact, fall well below the temperature of the air. As walls receive more long-wave irradiation than flat roofs, they have a minimum outer surface temperature only slightly below the minimum air temperature. The colour of the outer surface has no appreciable effect on minimum surface temperature because all paints have nearly the same value of emissivity. Painted surfaces will always have lower minimum temperatures, however, than similarly exposed unpainted metal.

Conclusion

The maximum temperature of the outer surface of any building depends mainly on its colour and orientation. The colour and proximity of neighbouring surfaces also have a significant effect on surface temperature. Analysis has shown that dark roof surfaces may reach temperatures of the order of 230°F in summer and fall a few degrees below the minimum air temperature in winter. It is important, therefore, to be sure that any proposed roofing system with a dark surface can operate satisfactorily at temperatures varying between -50 and 230°F. If a light coloured surface is used to reduce the maximum temperature it is important to be sure that the surface will retain a low value of short-wave absorptivity over its entire service life.

The maximum temperature for a wall surface is between 140 and 190°, depending on colour and proximity to reflecting surfaces. If external shading devices are used they should have a dark surface that will absorb the radiation incident on them rather than reflect it onto adjacent wall or window surfaces. It is important, however, not to darken the colour of an outer surface until it has been established that its new shade will not cause the temperature of the wall materials to exceed their allowable values.