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Introduction

Infrared thermography is a technology that allows infrared or heat radiation to be transformed into a visible image. It has found applications in forestry, medicine, mechanical and electrical systems maintenance, search and rescue, and building maintenance. In the last it is used primarily to locate and identify areas of heat loss caused by design and/or construction deficiencies. In heritage buildings, it is also used to assess the integrity of masonry cladding materials.

The successful use of thermography for building applications depends not only on a thorough knowledge of building construction and the principles of heat, air and moisture transmission, but also on an understanding of infrared radiation and the factors that can affect its detection and measurement.

This digest provides a brief introduction to infrared theory and its application in building analysis, and describes some typical building faults that may be identified by thermographic inspection.

Infrared Detection and Temperature Measurement

All objects emit electromagnetic radiation in the wavelength range of 0.1 micrometres (μm) to 100 μm. This band occurs just beyond the visible range and is referred to as the infrared or IR range.

IR detection systems detect radiative power, the intensity of which depends on the temperature of the object and its surface characteristics. The warmer an object, the greater will be the rate of heat flow from its surface. Surface characteristics are described in terms of emissivity or the ability to emit IR radiation. The higher the emissivity of a surface, the greater the rate of heat flow. The reciprocal of emissivity is reflectivity. Thus, a highly reflective surface such as aluminum would be a poorer emitter than a less reflective surface such as brick.

These relationships form the basis of IR detection and measurement. Given two surfaces of known or equivalent emissivity and the temperature of one of them, it is possible to determine the temperature of the other.

Factors Affecting Data Collection and Interpretation

Although the basic relationships between radiative power, temperature and emissivity are quite straightforward, there are a number of factors that complicate the collection and interpretation of thermographic data. The emissivity of a surface, for example, is not stable. The deposition of dust, rainwater or other foreign matter will alter the surface and its emissivity.

Thermographic detectors used in building surveys are sensitive in either the 2.0 to 5.6 or the 5.6 to 8.0 µm range, and the emissivity values used in the relationship to calculate temperature or power must correspond to the average emissivities over these ranges. In addition, the emissivity of a surface within a wavelength range may change as the temperature of the surface changes.

Other factors that affect data collection and interpretation are discussed briefly below. Some of them are characteristic of all thermographic surveys while others are peculiar to building investigations.

Angle of vision -- As with a photograph, a thermograph of a building taken at an acute angle presents less information than one taken at right angles. In a thermograph, however, the information may be further distorted depending on the surface material and its ability to radiate in different directions.

Distance -- The resolution of the thermographic image decreases with distance. That is, since each point on the thermographic image corresponds to a specific area of the subject surface, an increase in distance implies that each image point must represent a larger surface area. As a result, the radiation emitted from that area is averaged and detail is lost.

Atmosphere -- The complex mixture of gases, liquids and solids that comprise air has an effect on the amount of radiation received from the subject by the IR detector. In building surveys, reflection and emission of IR radiation from air pollution and precipitation cause the most interference.

Ambient Temperature -- Ambient temperature can affect both the performance of the thermographic equipment and the amount of IR radiation emanating from the surface of the subject. At very high or very low temperatures, IR detection systems become less stable. High ambient temperatures can mask thermal information, especially when the subject has a reflective surface.

Extraneous Heat Sources -- Reflection or absorption and re-emission of radiation from extraneous heat sources can also distort a thermal image. In building surveys, the most obvious and intrusive source is the sun. On a clear day, the heat that radiates from the sun to the exterior surfaces of a building will completely mask the more subtle thermal patterns that result from the transfer of heat through the building envelope. The information from an interior survey could also be misleading because the heating of the exterior surface will alter the normal flow of heat from the inside to the outside. Even on a cloudy day, diffused solar radiation will affect the thermal patterns on the exterior of the building. For these reasons, exterior surveys are generally conducted at night, and interior surveys, at night or on heavily overcast days.

Objects exposed to solar radiation will store heat for some time after the heat source has been removed. A thermographic survey should not, therefore, commence immediately after sundown. The time allowed for the stored heat to dissipate will depend on the heat capacity of the materials in the enclosure system as well as the temperature difference between the surface and its environment. A light wood frame wall with wood or aluminum siding may require as little as 2 hours to release stored heat. Heavier construction with brick or precast cladding may require more than 6 hours. Massive masonry construction may require 24 hours, and in this case, a survey will produce valid data only if the sky is overcast during the day.

Extraneous heat can also be produced by radiators, lights, vehicles and people. The extent of the interference caused by these sources depends on their radiative power and the reflectivity of the surface of the subject. Radiation from people is not generally a problem except where the subject is highly reflective. Radiators and lights should be turned off well before the survey begins or otherwise be taken into account in the analysis of the thermographic data.

Temperature Difference -- Thermal patterns on the surface of an object depend on the rate of heat flow to and from the surface. Assuming no extraneous heat sources, the temperature at the surface of a building envelope depends to a large extent on the temperature difference across the envelope and the thermal resistance of its components. The greater the temperature difference, the higher will be the rate of heat flow and the more obvious will be those areas of lower resistance. Temperature difference must therefore be taken into account in the interpretation of the thermographic data.

Convection -- Convective air flow in, through and around buildings is primarily caused by localized heating or cooling, stack effect and wind. Warm air flowing upward from radiators or hot air registers, or cold air washing downward from windows can cause serious distortion of surface temperatures. Stack pressure encourages infiltration on the lower floors of a building and exfiltration on the upper floors. This results in cooling of the walls at the lower levels and warming at the upper levels. Wind can affect surface temperatures in the same manner as stack pressure. positive pressure developed on the upwind side of a building will encourage infiltration; negative pressure on the downwind side will encourage exfiltration. The air need not pass completely through the enclosure system to distort the surface temperature; air flow over the exterior surface of the enclosure will decrease the thermal resistance of the surface air film and cool the enclosure surfaces.

Pressurization -- Mechanical pressurization or depressurization of a building will distort the thermal patterns in the same manner as wind and stack effect. That is, pressurization will exaggerate defects when they are viewed from the exterior and make them less apparent when viewed from the interior. The opposite occurs when a building is depressurized. Measuring the pressure difference across the enclosure is therefore important. In some cases, buildings may be pressurized or depressurized purposely to exaggerate deficiencies and make them easier to detect.

Mechanisms Causing Variations in Surface Temperature

The three mechanisms that cause building envelope defects and deficiencies to manifest themselves as surface temperature variations are 1) variations in thermal conduction, 2) air flow, and 3) temperature reversal.

Conduction

The rate of conductive heat flow across a building envelope depends on the temperature difference across the envelope and the thermal resistance of the system. In this context temperature difference is defined as the difference between the ambient indoor temperature, which is maintained by the heating system, and the ambient outdoor temperature, which is determined by the weather. Where the difference in the ambient temperatures across an area of the envelope surface is the same for the whole area, variations in the rate of heat flow and the resultant variations in surface temperature indicate variations in thermal resistance. This may in turn indicate a defect in the enclosure design or construction. From the exterior, areas of lower than normal thermal resistance will be warmer than surrounding surfaces. From the interior these areas will be colder.

Air Flow

Defects that allow air to pass through all or most components of an envelope can easily produce temperature variations 10 times greater than those resulting from a high rate of conductive heat flow. These defects manifest themselves when subjected to wind, stack effect, or pressurization as discussed previously.

Temperature Reversal

Temperature reversal occurs when heat is added to or removed from the vicinity of an object. Assuming identical surface characteristics, variations in the rate of heat loss or gain depend on the mass or heat capacity of the object. That is, a more massive building component will gain and lose heat more slowly than a less massive component. During heat gain, the surface of a massive component will remain cooler than the surrounding surfaces; during heat loss, it will be warmer. With any discontinuity in the massive component, due, for example, to missing material or incipient spalling, the rate of temperature change in that area will differ from surrounding areas. In this manner, when a supposedly uniform, homogeneous building component is being heated or cooled, variations in the surface temperature may indicate defects.

Identification of Building Envelope Anomalies

Walls

Most defects or deficiencies in walls are identified as a result of differences in the rate of conductive heat transfer through the wall, heating or cooling by convective air flow, or a combination of the two. A few typical wall defects are discussed below.

Lack of insulation -- A wall area where insulation is missing will conduct heat faster than an insulated area. The void in the building envelope left by the missing insulation will also be subject to convective air flow. The transfer of heat from one side of the cavity to the other will therefore be somewhat higher than that due solely to conduction. Where convection occurs, the cavity will be colder at the bottom than the top.

If the insulation consists of batts or boards, uninsulated areas will usually appear as rectangular patches that are warmer or colder than the surrounding wall surface, depending on the direction of heat flow. If the insulation was blown in, voids may be caused by failure to completely fill the cavity, settlement of the insulation or interruption of the cavity by fire stops or cross bracing. In all cases, the area of higher heat flow will be in the shape of the uninsulated portion. If foam insulation has been used, uninsulated areas tend to have a much less regular shape. Gaps may be of any shape and occur anywhere in the cavity. Shrinkage of insulation may increase the rate of heat flow over all the surface and allow convective air flow to transfer heat by bypassing the insulation.

Displaced insulation -- In frame walls with insulation in a cavity, displaced or improperly installed insulation can result in air circulation around the insulation or between the insulation and the interior sheathing. Even a very small space between the insulation and the interior sheathing can significantly affect the inside surface temperature.

Where the attachment of a rigid insulation board to a block infill wall has failed and the board has fallen into the cavity away from the block and rests against the back of the cladding, cold air circulating in the cavity will move between the insulation and the exposed portion of the block wall. From the interior, this area will appear as one without insulation. From the exterior, however, the area will be colder than the surrounding surface and will thus appear as a more highly insulated area.

Wet Insulation -- Because water has a relatively high thermal conductivity, wet insulation will transfer heat more rapidly than dry insulation and will affect the IR patterns accordingly.

Thermal bridging -- A thermal bridge is a component in an enclosure system with a thermal conductivity significantly higher than that of adjacent components. For example, a floor slab that penetrates an exterior wall and supports brick cladding or extends to form a balcony provides a direct thermal bridge from inside the building to the outside. Metal studs in an insulated wall also constitute thermal bridging. When dealing with high levels of insulation, even wood studs and nails may be considered as thermal bridges. As with uninsulated areas, thermal bridges may be identified by warmer or cooler surfaces in the shape of the lower resistance component.

Air leakage -- As mentioned previously, the direct transfer of warm or cold air through the enclosure produces the most obvious thermal patterns. Infiltration is evident when viewed from inside the building and exfiltration when viewed from the outside. The thermal patterns produced on the wall surfaces flare out from the point of leakage. Air exfiltration is accompanied by the transfer of moisture from inside the building to colder surfaces within the enclosure system. Exfiltration therefore often results in condensation. This may or may not affect surface temperatures depending on the rate of condensation and the materials in the enclosure system. In the most extreme case, condensation may saturate the insulation, leading to a significant reduction in thermal resistance.

Roofs

The procedure used to identify defects and deficiencies in roofs depends initially on the type of roof being examined. In most housing the roof systems consist of a sealed, insulated ceiling, a vented attic space and the roof itself. In these cases, the vented attic space provides a thermal buffer between the ceiling and the roof. The radiation transmitted from the roof can provide only a reduced and distorted image of deficiencies in the ceiling components that resist air, moisture and heat transfer. Detailed investigations of these roof systems must therefore be conducted from the interior. Defects and the resultant thermal patterns are similar to those for walls.

Barring suspended ceilings or other buffering elements, flat roofs may be investigated from the interior or exterior in the same manner as walls, although during the heating season, exterior surveys may be limited by the problem of snow cover. Because many roof defects result in wet insulation, which has a higher heat capacity than dry insulation, they may be identified by temperature reversal, thus enabling the season for conducting roof surveys to be extended into the summer months.

Masonry and Concrete

The mechanism of temperature reversal also permits the identification of delamination or incipient spalling of masonry or concrete. Where spalling is imminent, the surface material is separated from the rest of the mass of material by small cracks. These cracks resist heat flow and effectively reduce the heat capacity of the material in that area. Incipient spalling may therefore be identified by areas of lower heat capacity.

Conclusion

Infrared thermography has been proved to be very useful in detecting and identifying defects and deficiencies in building enclosure systems, but because of the complexities of building construction and performance and of IR detection and measurement, considerable care must be taken both in collecting and interpreting thermographic data.