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Surface Temperature Considerations

“The concept of temperature stems from the idea of measuring relative hotness and coldness and from the observation that the addition of heat to a body leads to an increase in temperature as long as no melting or boiling occurs.”

Engineers are usually taught the basic forms of heat transfer, often with the assumption that surface temperature is an independent variable driving the heat transfer. The reality is, however, that surface temperature is an interface between different forms of heat transfer and responds as a dependent variable. Consequently thermographers, as practitioners in the real world, often have difficulty convincing engineering personnel of the implications of the surface temperature results taken at an instant in time with thermography, and the consequent variance with the other fundamental driving variables controlling conduction, thermal capacity, convection and radiation. This paper will provide an overview of surface temperature as a response to different forms of both internal energy generation and external environment.

What Exactly is Temperature?

Temperature is one of the most frequent and familiar measurements made in the world today. Yet it is probably the least understood of the common measurements such as displacement, time, and mass. Many believe that temperature is a measure of heat energy. If this were in fact true, then one pound of steel at 100°F would have the same heat energy as a 100 pounds of steel at 100°F, or the same heat energy as one pound of styrofoam at 100°F. We know this is not true. In fact if one looks up the definition of temperature from a dictionary the definition is quite abstract. This is one example:

> *“Temperature, in physics, is a property of systems that determines whether they are in thermal equilibrium (see Thermodynamics). The concept of temperature stems from the idea of measuring relative hotness and coldness and from the observation that the addition of heat to a body leads to an increase in temperature as long as no melting or boiling occurs.”*

Physics texts will be a little more precise defining temperature on a macroscopic level as “the average kinetic energy of the molecules.” This definition, however, is not very useful to thermographers either as concept or useful principle. Equilibrium has a lot to do with temperature. Temperature is what drives heat (transfer). This also implies, when there is no net transfer of heat, that two bodies are at the same temperature. And two bodies do not need to be in contact or proximity to ascertain that they are at the same temperature: we simply need a third object that is in equilibrium with the other two. This object is a thermometer.

There really are two fundamentally different types of temperature measurement that we can make: immersion temperature and surface temperature. Immersion implies that the measuring device is totally immersed in the object being measured with the fundamental means of heat transfer between the object and instrument being conduction or convection. An example of an immersion measurement is a meat thermometer taking the temperature of a cooking turkey. In this case, the meat thermometer is equilibrating with the turkey through the process of conduction. A second example of an immersion measurement is an outdoor air measurement using a bulb thermometer. In this case the bulb is immersed in the air and comes to thermal equilibrium through the process of convection.

The idea behind any measuring instrument is that the instrument should not influence the parameter being measured. Since the measurement of temperature is in fact an equilibrium between the instrument and the object then it is essential that very little heat be transferred to/from the measurement instrument in order to bring it to equilibrium. For example, take a very small glass of boiling water at 212°F and place a large meat thermometer in it. The temperature will be much lower than 212°F. The process of measurement has influenced the temperature itself. In general, for accurate thermometry the area of contact should be small, and the thermal capacitance of the thermometer should be much lower than the thermal capacitance of the object being measured.

Before we get to surface temperature we need to think about the energy driving the heat transfer from the internal part of the object (that is measured by immersion) to the object surface. For the sake of simplicity, the following discussions will center around thermal generators that result in heat lost to the environment from the object—that is, the internal temperature is greater than the surrounding temperature(s). All of the principles discussed here apply in reverse, although as thermographers we are often in search of abnormal energy flow from objects rather than energy gained from the surroundings.

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Constant Power Generator

A constant power generator is one that generates internal energy at a constant rate, that is, constant power independent of the environmental conditions. A contact electrical fault is usually considered to be a constant power generator as long as the current flowing through the fault, and the fault resistance, remain constant. The power generated is oblivious to the external environment. The heat transferred to the exterior surface by conduction will be constant. With this type of power generator, the surface temperature will be significantly affected by the external environment.

Constant Temperature Generator

A constant temperature generator will attempt to maintain a constant internal temperature irrespective of the external environment by generating a variable amount of power. Surface temperatures will also respond to the external environment, but not as dramatically as with a constant power generator. A building under heat loss conditions will act like a constant temperature generator since the thermostat inside the building tries to maintain a constant interior temperature. Many processes and mechanical devices with temperature controllers act as constant temperature generators. The heat transferred to the objects exterior surface by conduction will be variable. The extent of the variance will be determined by the thermal conductivity of the material between the generator and the surface. The greater the conductivity, the greater the variance. Thermal capacitance of the material between the generator and surface will not come

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into play until a change takes place. Thermal capacitance and conductivity will determine the response time and volumetric extent of the reaction to the change.

Finite Energy Source

Finite energy sources are ones that have been "charged" to a specific temperature with a finite amount of energy. When this internal temperature is greater than the surrounding temperatures, the amount of heat transferred will vary as the internal temperature declines until equilibrium take place. Here thermal capacitance of the material plays an important role. The rate of heat transfer in this case is totally driven by the environment in which the object is placed. Examples of this type of generator are wet roof insulation, or a motor that has been switched off. In the case of the roof, the sun "charges up" the capacitance of the wet moisture during the day. Thermographers then watch for areas of high surface temperature caused by the slow decay in the evening from that finite amount of energy given to the wet moisture by the sun in the day.

The surface temperature of finite energy sources will be highly sensitive to the convective and radiant environment, even more so than constant power generators. This is due to the fact that their internal temperature falls as the finite amount of heat energy decreases. This results in an ever-decreasing rate of heat transfer and a highly variable rate of surface temperature decline.

For the most part the human body tries to be a constant temperature generator. It tries to maintain a constant internal temperature and varies the rate of energy generation in order to do so. With this type of energy generator the surface temperature is affected much less by the external environment than with a constant power generator, since energy generation goes up proportional to the heat lost to the environment. (At least until hypothermia takes place, and the body forsakes extremities in order to protect internal organs).

So What is Surface Temperature?

Surface temperature is much more complex than the internal object temperature or ambient surrounding temperature. Repeatable surface temperature measurement is only possible if the thermodynamics of the heat transfer to and from the surface is understood at the time of the measurement. Repeatability of surface temperature measurement is often confused with repeatability of the heat transfer.

To begin with, one must know which type of energy generator is driving the heat transfer. Secondly one must know and understand the ambient surroundings to the surface. Ultimately it is both the internal heat or power generation and the surrounding thermal environment that drives the heat transfer through the surface and yields the dynamic of surface temperature.

One side of a surface usually interacts with a fluid immediately adjacent to it (in most thermography applications this fluid is air) simultaneously with a radiant hemispherical environment. The opposite side of the surface (usually) deals with only the process of conduction. According to the Law of the Conservation of Energy, at any control surface (where no other work is being done) there must be an energy balance. Simply stated the sum of the conducted heat transfer plus the convected heat transfer plus the radiation heat transfer must be zero (heat transfer can be either positive or negative).

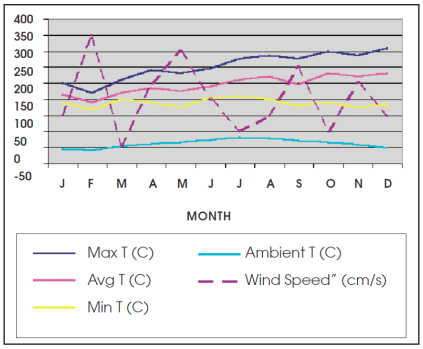

Figure 1

$$Qr + Qcv + Qc = 0$$

Complicating the issue, however, is the radiant interaction, which occurs at the speed of light, the convective heat transfer, which occurs at a much slower rate and the conductive heat transfer, which may be incredibly slow depending on the thermal conductivity and capacitance of the sub-surface material. Notice in this equation that temperature does not enter into it—the balance is an energy balance. Radiation, having the fastest response, is the equalizer for the slower processes of convection and conduction. Because the radiated energy is proportional to the fourth power of surface temperature and surface emissivity, in order for radiation to balance the other two processes the surface temperature must change.

As we have mentioned, with a constant energy generator this change can be dramatic. The energy reaching the surface by conduction from an internal electrical fault operating at constant current is fixed. Under no-wind conditions, a thermographer may measure a good conductor (running near ambient air temperature) to a faulty component surface temperature rise of 100°F. However, if a measurement is made some time later after a 15 mph average wind has acted on the components, the temperature rise from the good conductor to the fault will typically drop by about 2/3, or the rise will only be about 33°F. This rule of thumb is exactly that: it does not apply, for instance, to low-emissivity materials or for objects placed in extremely high or low radiant environments. If the power generated by the fault does not change then the conduction does not change. If the radiant environment does not change then an increase in the convective heat transfer must be met by a corresponding decrease in radiation and consequent surface temperature drop.

For high constant temperature generators, the convective effect is not as dramatic for two reasons. First, the radiant heat transfer predominates over convective heat transfer in industrial ovens, furnaces, and kilns (of which most can be considered to be constant temperature generators). Second, as the convective heat transfer increases, the balance is immediately met by less radiation, causing the surface temperature to drop. It will not drop as dramatically, however, since the radiant energy is a fourth power function, and at higher temperatures the radiant energy decrease does not require as much of a temperature drop than at lower temperatures experienced in building heat loss. However, the lower surface temperature causes an increase in conduction, and as thermal capacitance of the wall is overcome over time, a greater amount of heat will be transferred by conduction. This is a complex time-based relationship, not easily understood by simple surface temperature measurements.

Figure 1(above left) illustrates this point. These are the area temperature statistics taken once a month over the course of the year of an industrial refractory lined process vessel. In order to understand the fluctuations in the surface temperatures, the wind speed has been lotted on the same graph as a dashed line. The vertical (Y) axis has been scaled so that it represents both temperature (in degrees Celsius) for the solid graph lines and wind speed (in centimeters per second) represented by the dashed line. Notice the direct correlation between the inspections times that had a high velocity and lower surface temperatures. The value of long-term trending and statistical analysis of surface temperature becomes quite clear. Only a thermographic instrument is capable of gathering the type of large area-based statistics of surface temperature necessary for such an analysis.

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Engineers and scientists are taught about the different modes of heat transfer independent of one another. While there is certainly an emphasis on ensuring that the laws of energy conservation are obeyed, there is often little practical appreciation of surface temperature as a response to the balance of energy flow, rather than a driver creating the flow.

Indeed, when thermographers and engineers alike are taught about radiation, convection, and conduction, they are taught these concepts in independence of one another. We learn that radiative heat loss increases as the fourth power of surface temperature. We learn that the convective heat transfer increases proportional to the temperature difference between the surface and the fluid times the convective heat transfer coefficient. And conductive heat transfer across a wall increases proportional to the temperature difference from surface to surface times the conductivity of the wall (all of these expression increases are for a unit area). Very seldom do we discuss the heat balance that exists between the heat transferred through the wall to that lost from the surface to the environment.

A significant case in point is the use of the ASHRAE Handbook of Fundamentals in order to obtain “typical” values of the heat transfer co-efficient of the inside and outside air resistance. Many engineers take and use this value for building heat loss and then apply it to check the heat loss from industrial refractory. This is totally inappropriate since the ASHRAE values are in reality not the convective heat transfer co-efficient but the overall heat transfer co-efficient including both radiation and convec-tion from typical wall surfaces inside and out. In buildings heat loss, convection predominates and radiation plays a relatively minor role for insulated walls. In refractory lined vessels, however, radiation predominates and the h value is significantly higher than what the ASHRAE value for building heat loss is stated to be.

To illustrate this point further many refer to the “air film resistance” on the inside and outside of vertical wall surfaces under heat loss or gain. Perhaps familiar to some are the ASHRAE stated values of 0.68 hr·ft2·°F/btu for the inside wall and 0.17 hr·ft2·°F/btu for the outside wall under an average 15 mph wind. First and foremost, these are not the convective surface air film resistance values: these are surface conductance’s and resistances of walls in air. Further they are qualified for specific surface emissivity (0.90) and temperature (inside surface of 70°F with a 10°F surface to air difference). If the surface emissivity changes to 0.05, ASHRAE states that this 0.68 hr·ft2·°F/btu value changes to 0.59 hr·ft2·°F/btu. Why is this important to a thermographer? It’s because many engineers know and take values like these ASHRAE values as gospel without an understanding that the practical application encountered by the thermographer may be entirely different. Calculations may be made that may contradict or make the infrared readings seem unreasonable.

Surface Temperature and Gradients

When analyzing surface temperatures it is useful to perform two types of analysis: first study the heat flow that is occurring through the object from the source of heat generation. Second, look at the impact on the external surface if the balance at the surface changes.

Figure 2A (next page) shows the expected temperatures created through a wall with R-12 insulation compared to R-4 (wood stud). The surface temperature on the inside surface are 66°F and 60°F for the insulation and stud respectively. This means that there is a 6°F

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temperature differential available for detection on the surface. More importantly, however, is that there is a 4°F and 10°F difference between the inside air and these surfaces. This is caused by both the sum total of the radiative and convective heat transfer from the inside air and surfaces. What this mean to the thermographer is that if there are objects placed near to the wall that can interfere with either the radiative or convective flow, then this will be detected with a camera with a sensitivity of better than 0.2°F. As cameras get more sensitive we will observe more and more of this radiative and convective interaction, which can become extremely confusing. The outside surface temperatures in Figure 2A (below) are indicative of a condition of high convection (15mph wind). The temperatures are +0.9°F and +2.5°F for the wall and the stud respectively. Although still detectable with a high resolution infrared camera, it requires an astute operator to ensure that the detail is optimized.

Figure 2B (below) shows the same wall but under a no-wind condition. The inside surface temperatures are almost the same at 66°F and 61°F for the insulation and stud. This is due to the fact that the constant temperature generator has only slightly slowed down the rate of heat transfer (from 5.44 to 5.24 0.68 hr·ft2·°F/Btu) due to the decreased heat transfer coefficient of no wind. Since the heat transfer by conduction through the wall has not really changed but the convective heat transfer away from the wall has decreased significantly, the radiated heat transfer from the wall must increase to maintain the balance. Since it is not capable of changing emissivity, the only way to do so is to have the surface temperature increase. And, in fact, we see the exterior temperatures increase to 3.6°F and 8.9°F for the insulation and stud respectively. An increase from the 15 mph wind conditions is shown in Figure 2A of 2.7°F for the insulation and 6.4°F for the stud. What is important to the thermographer is that difference between the insulation and stud is 5.3°F in the no-wind condition rather than 1.6°F in the 15 mph wind.

Significant problems can arise when measuring surface temperatures with contact devices. There must be good contact with the surface. The sensor must have very low ther-

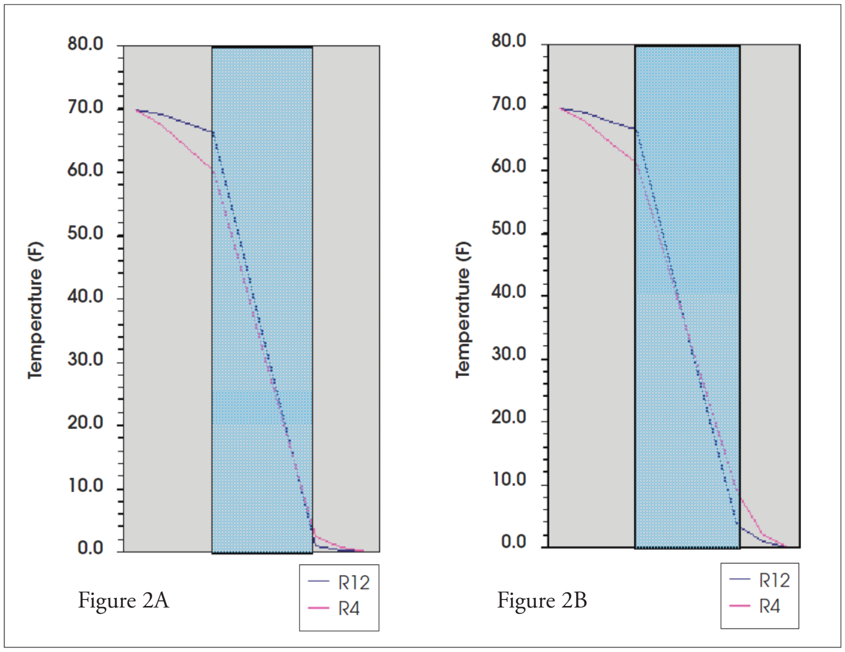

Figure 2A

Figure 2B

More than anything else repeatability of results is paramount to the credibility of thermography.

mal capacitance and very high thermal conductivity. The sensor and its wiring must not influence local convection around the area of measurement. The sensor must not change the surface emissivity, and it's wiring must not create radiation barriers. In some cases, the sensor must have the same broadband absorbtivity as the surface. Radiation devices have their share of difficulties for measuring temperature, not the least of which is that the surface spectral emissivity must be known. The big advantage of radiation thermometry is that it does not contact the surface and therefore has little influence on its thermal balance. The fact that both contact and non-contact sensors have their respective advantages and disadvantages often leads to disagreement between the two and confusion as to what the surface temperature really is. A case in point is internal tube temperature measurements in furnaces and ovens. A thermocouple is often welded to a tube and its temperature reported in the control room to control or monitor the process. The thermal camera will seldom report the exact value as the thermocouple. It is important to establish why this discrepancy exists, and there are many reasons for this—not the least of which is the extreme thermal dynamics of such an environment. Many people tend to believe contact measurements because they are permanent and have a repeatable historical performance rather than an accurate measurement. This is not a bad thing if you can get people to accept the fact that their measurement is wrong but consistent. On the other hand radiation factors such as atmospheric absorption, emissivity variance, and significant background temperature mean that a thermographer must be keenly aware of the instrument settings for these values to obtain an accurate result.

So What Does It All Mean?

Thermographers measure surface temperature at an instant in time (usually a few milliseconds). They report that temperature and someone questions the accuracy of the measurement either because it does not agree with another measurement, or because it does not fit the expectation. In either case a few questions should be addressed:

1. ***Do we really expect that the measuring devices should agree?***
2. ***Is the surface temperature varying with the source?***
3. ***Is the surface temperature varying with the environment?***
4. ***Are we comparing a surface temperature to an immersion temperature?***

More than anything else repeatability of results is paramount to the credibility of thermography. Understanding the dynamics of surface temperature, and educating others that it is a variable dependent on many factors, rather than an entity unto itself should be the goal of every thermographer striving for repeatability in measurement.

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