Selection Criteria for Infrared Thermometers for Glass Temperature Measurement

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Abstract: The infrared thermometer is an optical device which can quantitatively measure the radiance of a blackbody or other radiating object. Various Infrared thermometers are available, each responsive to a different band of wavelengths in the spectrum. Planck's relationship shows that each of these thermometers can be employed to determine the true temperature of the blackbody radiator. This paper emphasizes the selection criteria for Infrared thermometers for glass temperature measurement. The optical properties of soda-lime-silica glass are presented in this paper and are related to the use of infrared thermometers for temperature measurements on glass products. It discusses how the thermometer can be selected to conform to the specific application allowing the user to stress surface or interior temperature measurements. Practical rules are provided to enable the user to avoid the common interferences.

Keywords: *Infrared thermometers, Soda-lime-silica glass, Emittance factor, Spectral transmittance.*

I. INTRODUCTION

Infrared thermometers are without doubt a preferred device for glass temperature measurement. This paper covers the fundamental background of radiation thermometry and discusses important optical properties of soda-lime-silica glass. Specific data is presented for soda-lime-silica glass because of its preponderant use in common glass products such as sheet, plate and bottles. Other silica glasses, though not identical, behave similarly and the principles illustrated are equally applicable. Furthermore, the inclusion of various other constituents in the soda-lime-silica composition in order to color or decolorize the glass does not significantly change the data presented.

II. FUNDAMENTAL BACKGROUND

The Ideal or Blackbody Radiator

A blackbody radiator emits a continuous stream of thermal radiation from its surface. This radiation forms a continuous spectrum though the intensity and varies throughout the spectrum. The radiance (or brightness) at every wavelength throughout the spectrum depends only on the blackbody temperature. The radiance at every wavelength increases with the blackbody temperature. These relationships are quantitatively embodied in Planck's Law of blackbody radiation.

Real object and the Emittance Factor

The simple relationship involved in employing the infrared thermometer to measure the radiance and thus the temperature of a blackbody is somewhat complicated when applied to a real object. A real object, such as a glass bottle, is generally not a blackbody and is characterized by the fact that its radiance may be lower than that of a blackbody at the same temperature. The ratio of these two radiance values is defined as the emittance (ε) of the real object. Since (ε) can vary with wavelength, the spectral emittance (ε_λ) is referred as:

$$\varepsilon_\lambda = \frac{\text{Radiance of real object at wavelength } \lambda}{\text{Radiance of blackbody at wavelength } \lambda}$$

Where, both are at the same temperature.

Furthermore, $0 \le \varepsilon \le 1$.

Clearly, the infrared thermometer responsive at wavelength (λ) can measure the true temperature of a real object only if its correct value of (ε_λ) is known.

For objects of many materials, (ε_λ) must be determined experimentally through direct temperature measurements. Certain other materials are available in such forms that the value of (ε_λ) can be readily determined by simpler, indirect means. Glass is one example of the latter.

Kirchoff's Law

This fundamental law relates (ε_λ) for an object to its spectral transmittance (t_λ) and its spectral reflectance (r_λ) as follows:

$$\varepsilon_\lambda = 1 - t_\lambda - r_\lambda \qquad \text{……….} (1)$$

Glass is readily available in forms suitable for the direct determination of both (t_λ) and (r_λ) using standard laboratory spectrophotometers. The results of such measurements for soda-lime-silica glass are presented in the following section.

III. OPTICAL PROPERTIES OF SODA-LIME-SILICA GLASS

Spectral Transmission Vs. Wavelength:

The curves of spectral transmittance(t_λ) versus wavelength(λ) for several thicknesses of soda-lime-silica glass are shown in figure-1. This family of curves clearly shows the strong dependence of (t_λ) on the thickness.

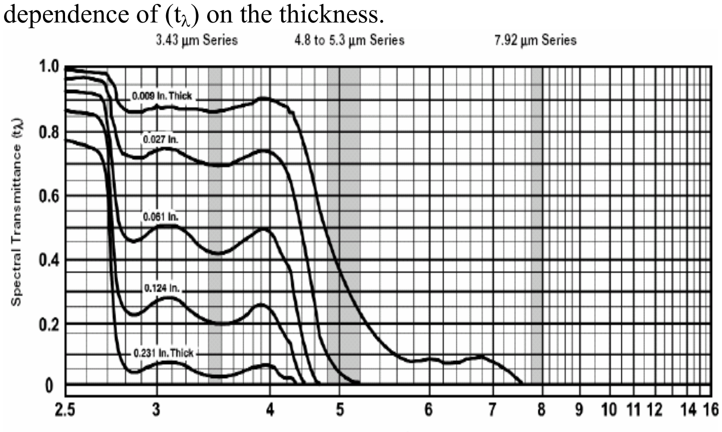

Figure-1: Effects of Thickness on Spectral transmittance Curves for Soda-Lime-Silica Glass

Spectral Transmittance Vs. Thickness:
Figure-2 is a semi-log plot of spectral transmittance (t_λ) versus thickness (x) evaluated for the spectral regions of the model series operating at 7.92µm, 4.8 to 5.3µm and 3.43µm. The data for the latter two series are taken directly from Figure-1, using the center wavelength of the spectral responses. All three curves are straight lines on this plot as predicted by Beer's Law, which states:

$$t_\lambda = \varepsilon^{-k_\lambda x} \qquad \text{……… (2)}$$

Where, (k_λ) is the spectral absorption coefficient. Clearly (k_λ) varies markedly with (λ) for glass.

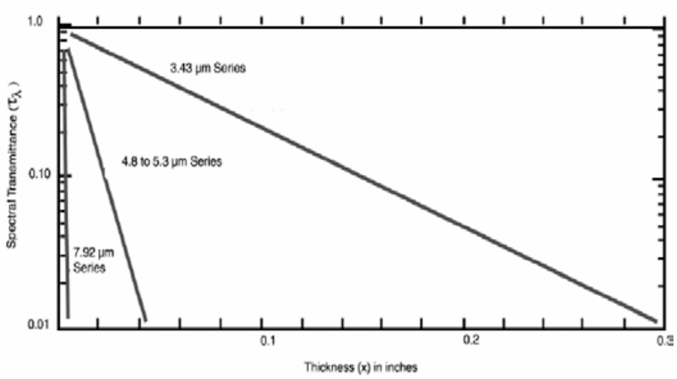

Figure-2: Transmittance Variation with Thickness for Soda-Lime-Silica Glass

Spectral Reflectance Vs. Wavelength:
Figure-3 plots spectral reflectance (r_λ) versus wavelength (λ). This data is for a smooth surface of glass taken at normal incidence. Only a single curve appears here because (r_λ) is independent of glass thickness.
The shape of the curve is typical of all silica glasses. The reflectance starts out low at 2.5 microns and slowly drops to zero near 8 microns before soaring to peak at about 9.5 microns. This reflectance peak is caused by the silica in the glass and is associated with the very strong silica absorption band in this region.

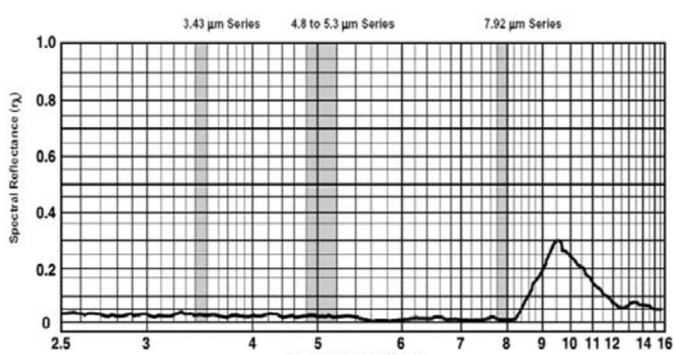

Fig. 3 - Spectral Variation of Reflectance for Soda-Lime-Silica Glass taken at normal incidence

Spectral Reflectance Vs. Angle of Incidence:
Figure-4 represents the variation of spectral reflectivity(r_λ) versus angle of incidence(↓), evaluated at 5 microns. The important consideration here is that (r_λ) is quite constant out to 45° and reasonably constant out to about 50°. However, as the angle increases beyond here (r_λ) increases rapidly and approaches 1.00 as ↓ approaches 90°.

Spectral Emittance Vs. Thickness:
The glass optical properties presented to this point permit the evaluation of spectral emittance (ε_λ) versus thickness (x). Kirchoff's Law (Eq. 1) can be solved using the data of Figure 2 and 3. As an example, consider a sheet of glass 0.125 inch thick. The value for (ε_λ) for each of the three thermometers shown can be evaluated as follows:

$$\varepsilon_\lambda = 1 - t_\lambda - r_\lambda$$
$$\varepsilon_{800} = 1 - 0.00 - 0.01 = 0.99$$
$$\varepsilon_{700} = 1 - 0.00 - 0.02 = 0.98$$
$$\varepsilon_{340} = 1 - 0.16 - 0.03 = 0.81$$

Here, the values for (t_λ) and (r_λ) are estimated to the closest ±0.01 units which is more than adequately close for practical infrared thermometry.
The curves of (ε_λ) versus thickness for various thermometer series can be obtained as shown in figure-5. In each case, (ε_λ) increases rapidly with thickness and levels off at the limiting value of (1– r_λ). It can be noted that, the limiting emittances for the three thermometer series range from 0.97 to 0.99. These unusually high values of (ε) are particularly advantageous in helping to cope with various measurement interferences that can arise in practical applications.

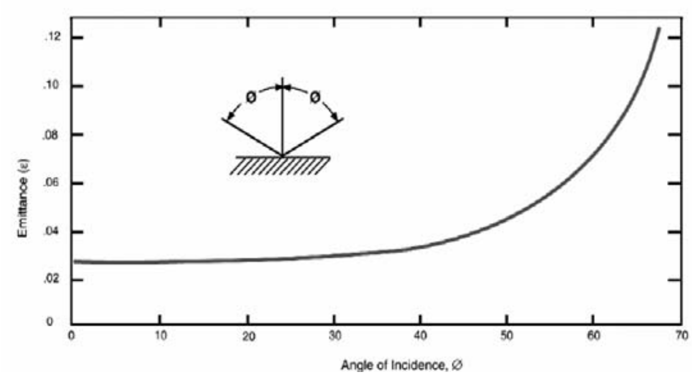

Figure-4: Variation of Reflectivity with Angle of Incidence for Soda-Lime-Silica Glass in the region of 5 microns

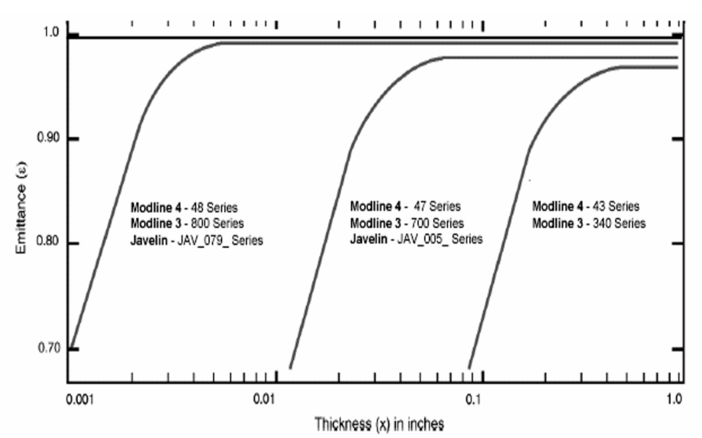

Figure-5: Emittance Variation with Thickness for Soda-Lime-Silica Glass

IV. FACTORS AFFECTING THERMOMETER SELECTION AND USE

Depth of Temperature Measurement:

Glass has a relatively poor thermal conductivity. Consequently, during many phases of processing into finished parts, there exist high temperature gradients extending from the surface into the interior. This fact often prompts the thermometer user to ask questions similar to the following:

"How far under the surface am I measuring?"

"The thermometer indicates 500°C. Is this the surface or the interior temperature?"

For qualitative answers to these questions, we can refer to Figure-2. A thin layer of glass located at a depth (x) below the surface is radiating thermal energy toward the surface at a rate governed by its temperature and its thickness. The portion of this energy reaching the surface is proportional to the transmittance to the surface or $\varepsilon^{-k_\lambda x}$. The closer this thin layer is to the surface, the greater the transmittance to the surface, and the greater contribution it makes to the radiance of the surface as "seen" by the thermometer. Using the example of the 3.43 µm spectrum, it can be seen that for the layer lying right at the surface, 100% of its radiance arrives at the surface; for the equivalent layer lying 0.15 inch under the surface, 10% of its radiance is transmitted to the surface; for the layer at 0.3 inch from the surface, only 1 % of its radiance reaches the surface; and so on.

The radiance of the surface as viewed by the thermometer is the sum of the radiance values of all the thin radiating elements extending from the surface on down into the depths of the interior. The measured radiance and thus the measured temperature, is an integrated average of all the values extending in from the surface. Clearly, the surface layers always contribute more to the measurement than deeper layers.

Again, with reference to Figure-2, it is clearly seen that 90% of the "weight" of the radiance values measured by the 7.92µm, 4.8 to 5.3µm and 3.43µm series thermometers arise from the first .002, .022, and .153 inch thick layers at the surface, respectively.

If the glass temperature is at a constant 500°C from the surface on down, all three thermometers will indicate 500°C If the temperature is 500°C at the surface and it increases with depth into the interior, each thermometer will indicate above 500°C with the 3.43 micron series indicating the highest temperature, followed by the 4.8 to 5.3 micron, and 7.92 micron series in stated order.

Product Thickness Variations:

The effect of the thermometer indicated temperature caused by product thickness variations depends on the thickness and the thermometer series. If the minimum product thickness is thicker than the value required to provide the limiting value of (ε_λ) no error will result. This is because the thermometer does not "see" all the way to the back surface. If the product thickness is below this value, variations in its thickness represent variations in emittance, i.e. temperature errors will result unless the emittance settings are properly adjusted.

For example, consider a process where a continuous strip of sheet glass of thickness (0.10 ± 0.01) inch is passing a thermometer temperature station. Figure 5 shows that the emittance for the 7.92µm and 4.8 to 5.3µm series are completely unaffected, and consequently both the 7.92 µm and 4.8 to 5.3 µm series will indicate the proper temperatures independent of thickness.

However, the emittance for the 3.43 µm series will vary from 0.71 to 0.77 for the extreme thicknesses. Consequently, with the 3.43 µm series and with a sheet temperature of 900°F, these uncompensated thickness variations will cause "apparent" temperature swings of ±10°F. In such cases, the Infrared thermometer, which is not influenced by the expected thickness variations, should only be chosen.

Interfering Sources:

Interfering sources behind the product and hotter than the product can cause high temperature readings if the glass is thin enough to transmit the background radiation. To avoid this, the longer wavelength thermometer can be selected. Interfering hot sources can also reflect off the glass surface viewed by the thermometer. Best practice is to aim the thermometer at a different angle to avoid the bad reflection and/or interpose a cool shield in front of the interference to block it at the source. If these solutions are not available, switch thermometers in the sequence 3.43; 4.8 to 5.3; and 7.92 micron series as the reflectance values decrease in that order. The reflectance values for all three thermometers are quite low and reflection problems are seldom a problem.

However, one special case where reflections can be a serious problem involves the use of high intensity tungsten filament quartz lamps in radiant heating applications. The extreme temperatures of the filaments of these lamps provide radiation levels that can cause severe interference with thermometers operating at wavelengths shorter than about 4.7 microns (See Figure-6). Above this wavelength the quartz envelope becomes opaque, eliminating the source of interference. The 3.43µm series can suffer interference here while the 4.8 to 5.3 µm and 7.92 µm series will be completely immune.

Angle of View:

Figure-4 shows the variation of reflectivity with ϕ at 5 microns. Qualitatively, this behavior also applies to the other spectral regions, too. Best to avoid the higher values of (r_λ) and the consequent lower values of (ε_λ) by viewing the target surface at any angle below about 50° degrees from the normal.

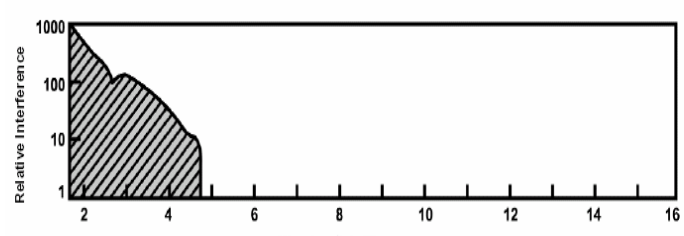

Figure-6: Relative Interference Caused by Quartz Lamp Infrared Heaters

Atmospheric Absorption:

Figure-7 shows the spectral regions covered by atmospheric absorption bands. Atmospheric water vapor and carbon dioxide absorb strongly in these regions and can cause serious errors for thermometers operating therein. So Infrared thermometers should not be operated in any of these regions and should have no atmospheric transmission problem.

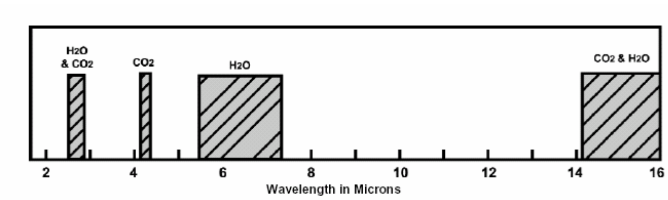

Figure-7: Areas of Significant Atmospheric Absorption over a Path Length of 10 feet

V. CONCLUSION

A wide range of infrared thermometers is available for glass temperature measurement, but the selection of infrared thermometer in a specific application requires attention to some critical parameters. Important optical properties of sold-lime-silica glass are discussed. Other silica glasses though not identical behave similarly and the principles illustrated are equally applicable factors affecting thermometer selection are discussed and practical rules are derived to enable the user to avoid the common interferences.

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