Emissivity Determination and Temperature Calculation of Fluids in Piping Assemblies

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ABSTRACT

There has been little discussion about infrared ("IR") thermography's ability to determine the temperatures of heating liquids and gas within piping assemblies. Determining accurate emissivity values as related to the curvature of common pipes is critical to accurate temperature determination. It is generally accepted that the emissivity of any non-blackbody object declines as the angle of incidence increases from zero degrees (perpendicular). This fact creates complications with respect to the accurate temperature evaluation of a section of pipe due to the inherent curvature of common piping materials. We will discuss the determination of emissivity for various piping systems and provide explicit directions in order to aid the investigator during infrared inspections/surveys of heated piping assemblies.

INTRODUCTION AND BACKGROUND

The use of infrared thermography in determining the temperature of fluid in pipes is a standard practice in the field of thermographers. The understanding of the geometry of the systems necessary to provide for proper evaluation of the readings is extremely important. It is understood that the emissivity of any object can vary by the inclination or angle of reading. The emissivity does in fact vary by the introduction of angle. The standard tables providing emissivity are provided for an angle of inclination of 90 degree or perpendicular to an object.

In order to provide a better analysis and determination of results with thermography measurements, it is important to understand the relationships of the various products' emissivities. Also, the thermographer should understand the effects of the angle of inclination utilized when conducting thermographic surveys. This paper will deal with the determination of the values of emissivity of such common piping materials and the effect of the angle and distance of view used at the time of the thermographic imaging.

The field use of the infrared camera for this application requires the thermographer to evaluate piping assemblies from various distances. Therefore, the curvature of the pipe introduces an immediate issue: as the perimeter of the pipe draws away from the center line, the angle of inclination is reduced from 90 degrees. The reduction in the angle of inclination will lower the apparent emissivity of the assembly. Because the spot size is essentially averaging an area of differing emissivities, the result is a lower overall emissivity value and an underestimated value for the temperature of the fluid.

If a thermographer performs a thermal evaluation at a distance that minimizes the spot size (i.e., stands closer to the pipe being analyzed), the spot size will be lessened and the angle of inclination will be close to 90 degrees. Conversely, if a thermographer is forced to stand at a greater distance from the subject pipe, the spot size is proportionally increased based on the camera's spot size ratio ("SSR") and the relative size of the piping material. The result is that the thermal image is distorted with the shape of the surface area as the cone of the spot begins to wrap over the cylindrical pipe surface.

The ensuing emissivity "distortion" is inherently nonlinear. That is, the area increases exponentially as a function of the spot size, making the prediction of its effects extremely difficult. Additionally, the angular effects on emissivity are different for every material, as discussed in Professional Investigative Engineer's 2006 Inframation paper, increasing the complexity of a general solution to this problem (materials with low emissivities are greatly affected by this scenario based on their high reflectivity). Figure 1 provides a visual representation of the changing emissivity and its relation to the spot size.

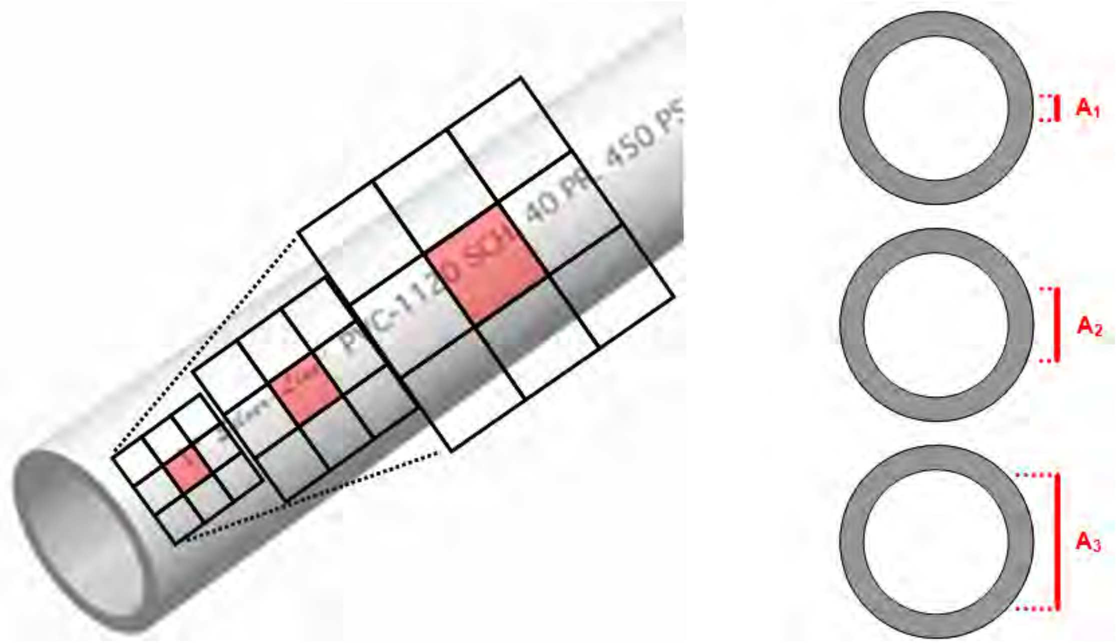

Figure 1. Representation of the increased spot size as a function of the viewing distance. As the thermographer's distance from the pipe increases, the surface area encompassed by the spot also increases. The resulting thermal energy can be misinterpreted by the Infrared camera due to the non-constant emissivity over the curved surface.

CALCULATIONS AND DISCUSSION

In order to evaluate the concept of thermal averaging over a non-constantly emitting surface, it is necessary to understand the geometries that are present in this situation. In the case of the typical IR camera, the "spot" measured is a result of a square grid of pixels which, when analyzed independently, can be interpreted to evaluate a finite amount of thermal energy. On the subject, the curved surface can be represented by a cylinder. The resulting shape created by the intersection of the spot with the cylindrical pipe can be described as similar to the shape that is created as two cylinders pass through each other. This area or volume can be determined by evaluating the integrals of the two cylinders and subtracting them for the area. This shape is known as the Steinmetz Solid, and is shown in Figures 2 and 3. The following images are provided courtesy of Wolfram MathWorld[1]:

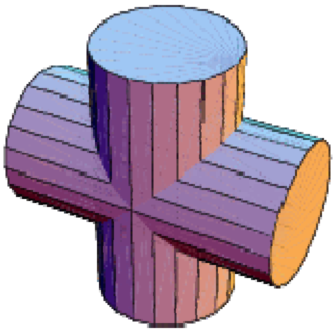

Figure 2. The intersection of cylinders as described by Charles Proteus Steinmetz, an early 20th century American Mathematician and Electrical Engineer. In this case, the shapes are referred to as a one "bicylinder."

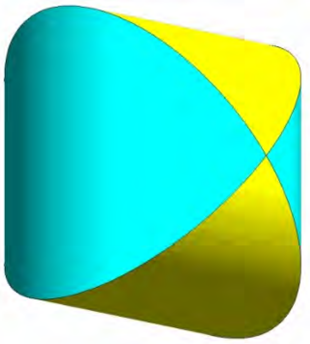

Figure 3. The intersection of the two cylinders results in this intersecting area. This area can be described by the integrals of the two intersecting shapes.

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[1] Weisstein, Eric W. "Steinmetz Solid." From *MathWorld*--A Wolfram Web Resource. http://mathworld.wolfram.com/SteinmetzSolid.html

Review of Figure 3 indicates how the spot size ratio of the camera can produce the net result similar to providing a reading with a low-inclination angle. The shape of this intersection, of course, is dependent on the perpendicular alignment of the two intersecting shapes, and thus assumes that the observer has allowed for a right angle between the pipe and the camera. If the camera operator has projected the camera SSR with an intersecting angle of anything other than 90 degrees, the geometry becomes much more difficult.

The determination of the area of this intersecting surface can be helpful in understanding the process that occurs when shooting cylindrical objects, such as pipes from a long distance. The following derivation is provided at the conclusion of this article for those who have an interest in the mathematical representation of the intersection of the cylinders.

TESTING CONFIGURATIONS

The purpose of this testing was to evaluate the effect of angular viewing on emissivity and accurate temperature measurement when viewing circular piping assemblies. In order to properly evaluate a range of piping products, a system was assembled to include some of the more common materials. The assembly consisted of a heated water basin, a system of piping to feed the three samples, and an electric pump to maintain steady flow of the heated water through the assembly.

This mock-up was assembled solely for the purpose of this testing, and was built to the specifications of the authors. The three piping materials included in the testing are cast iron, polyvinyl chloride ("PVC"), and copper. These materials are commonly found in residential and commercial applications, and are often the subject of thermography. The testing assembly as constructed in the PIE Laboratory can be seen below in Figure 4.

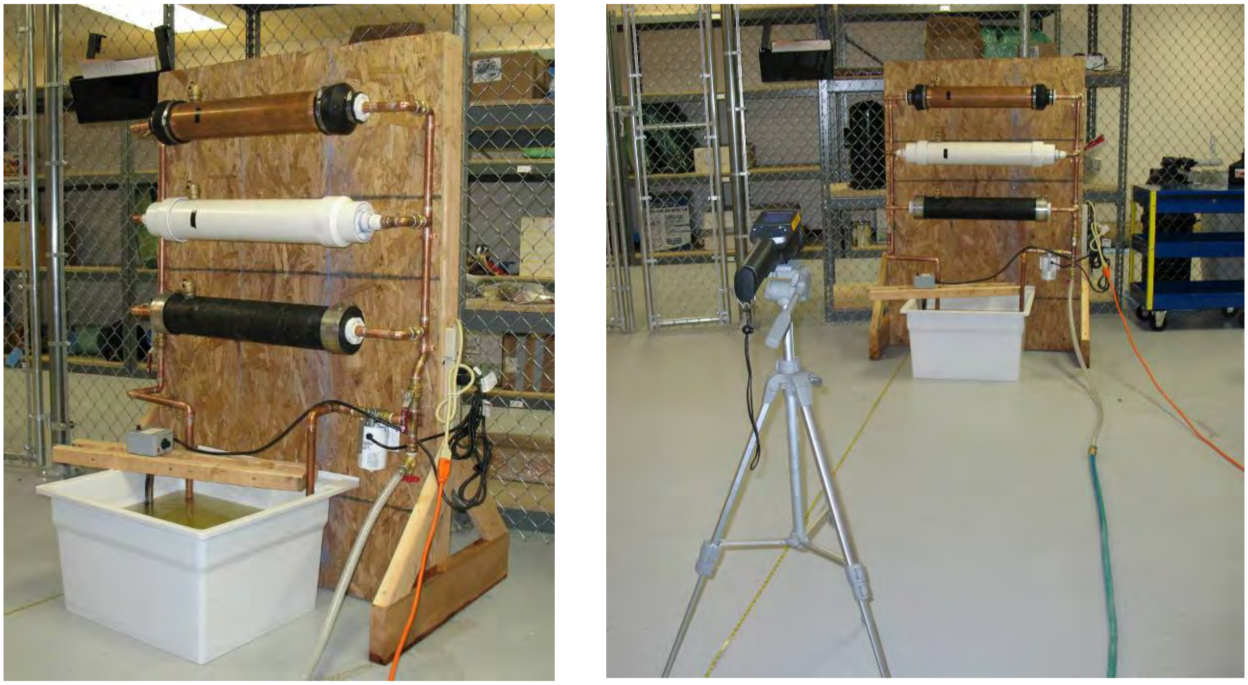

Figure 4. Piping assembly used for laboratory testing. The system consists of a heated water reservoir, a system of pipes, and an electric pump to force the heated water through the pipes. The system was run for two hours prior to testing to ensure that a steady-state pipe temperature had been attained.

In order to ensure a uniform temperature gradient across each of the sections of pipe, it was necessary that the water temperature and flow be consistent and that there was no air in any of the piping. To accomplish this, air purge valves were installed on each of the pipe samples in order to ensure air evacuation and, thus, a uniform pipe temperature. Additionally, the assembly was allowed to run continuously for two hours prior to any thermal imaging in order for the system to reach a steady-state condition with little temperature variation. At the time of testing, the water temperature had reached a steady-state value of 120˚ F. These steps were taken in order to ensure that the pipes exhibit a uniform and unchanging temperature gradient. As this paper does not intend to address the effects of the misalignment of the thermographer (i.e., standing at an angle of inclination other than 90 degrees), the IR camera for the testing was set up perpendicular to the test specimen.

In order to evaluate the angular effects of the circular pipe, it was necessary to divide the pipe into sections and obtain the emissivity at each respective location. For the purposes of this report, the pipe surface was divided as illustrated in Figure 5.

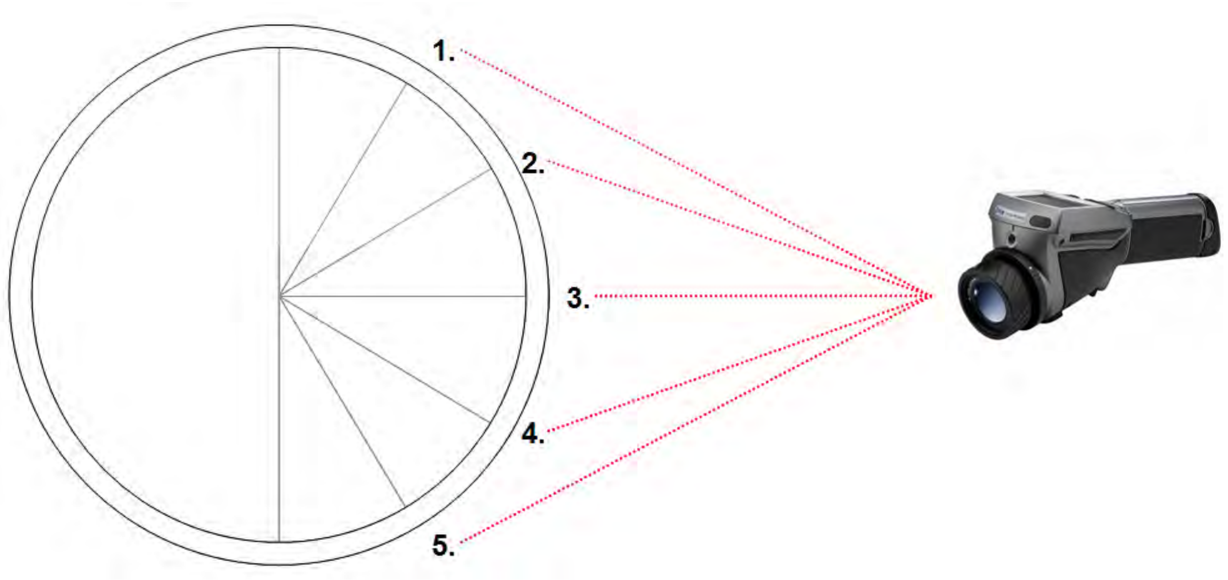

Figure 5. Adjusted Emissivity values were calculated based on an incremental system that represents the piping curvature, where location #3 corresponds to the area of the pipe that is perpendicular to the source camera.

The test procedure followed the outline provided in the FLIR training programs to baseline the readings equally. The room temperature was held constant at 70° F for 12 hours prior to the operation of the laboratory experiment. The sample temperature readings were obtained following the attainment of the steady-state water temperature as described earlier (this allows the sample piping to attain a uniform and non-changing temperature that is necessary for comparative emissivity analysis). The result is a large temperature differential (at least 40° F) between the sample product and the ambient temperature (tamb). For the purposes of this testing, a FLIR ThermaCAM™ EX320 was used for the thermagraphic imaging and emissivity adjustment.

The procedure used to determine the emissivity of the pipe is as follows:

1. The camera was set at 0° (perpendicular to the object of interest).
2. The camera was set to an emissivity of 1.0.
3. The ambient temperature (tamb) was measured (Note: a remote system was used for subsequent readings).
4. The relative humidity of the room was taken.
5. The background temperature is input to the camera parameters.
6. The camera was set to an emissivity of 0.95 for 3M Scotch “Super 88” electrical tape.
7. A sample of Super 88 tape was placed on each of the piping samples and was allowed to reach the same temperature.
8. A thermogram image was taken of the pipe. The image was frozen, and the temperature at the Super 88 tape was measured and recorded. The target product temperature was measured and recorded.
9. The image was saved, and the baseline emissivity of each of the materials was determined. This baseline emissivity was used to determine the emissivity variation at the increased distances.

10. The image was used to determine the spot emissivity necessary to produce the same temperature as the Scotch Super 88 tape. This adjusted emissivity was recorded as the actual emissivity of the sample product
11. The parameters were input into the image set up in the camera settings
12. The target emittance was set in the camera
13. Steps 8 through 13 were repeated for each distance starting at 10 feet and incrementing every 5 feet. The final distance was 65 feet from the test specimen. At each distance, the emissivity was re-calculated at each of the 5 points on the pipe surface as described in Figure 5 above.

The thermogram and corresponding photograph in Figure 6 below are representative of the results found in testing (These particular images were taken at the shortest distance of 10 feet). Note that the water temperatures in all three sections of pipe were identical when these images were taken, but the pipes appear to be different temperatures based on their respective emissivities.

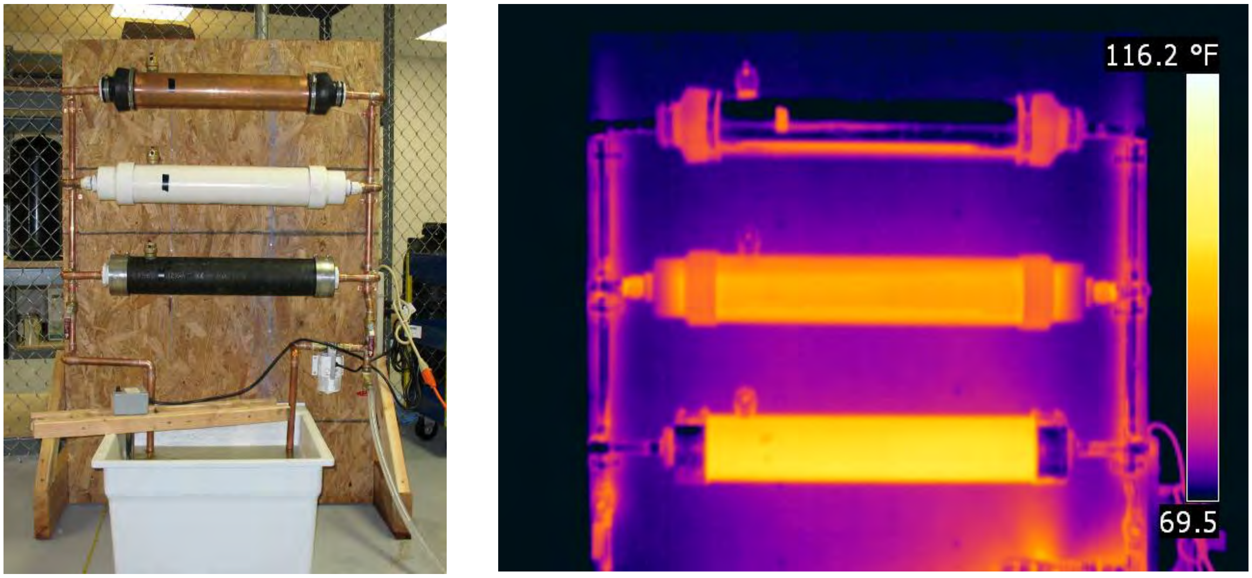

Figure 6. View of the testing equipment as seen from a 10-foot distance, along with the corresponding IR image. Note that all three pipes maintained a temperature of approximately 120˚ F via the floor-mounted water source. The three pipes appear to have different temperatures based on the thermal image.

FINDINGS

In order to evaluate the effect of the cone intersection of the cylinder, a laboratory model was set up. The model included a bath with a heater, valving, and three pipe tube manifolds to allow for multiple measurements of various materials. A series of readings were taken at prescribed distances in order to establish the effect of the radius of curvature on the temperature readings and adjusted emissivities. Those variations are the result of the angular effects of the emissivity.

The effective spot ratio of the IR camera was determined from the manufacturer's data. The subject FLIR EX320 has a spot size ratio of 250:1. For example, the spot size for this camera at a distance of 10 feet is approximately 1/2-inch, and the spot size at the maximum test distance of 65 feet is approximately 3 inches. The spot size in these examples, relative to the diameter of the pipe, would be 12.5% and 75%, respectively. As the spot size increases toward the diameter of the pipe (toward a ratio of 100%), the effects of the angular emissivity variation are increased substantially.

From this testing, the observed temperatures and adjusted emissivities were tabulated based on the material, the angle of reading relative to the pipe curvature, and the distance from the specimen to the IR camera. It should be noted that the emissivity of the Super 88 tape was calibrated for each of the angles prior to testing. This "calibrated" emissivity of the tape was necessary in order to maintain a baseline with which to compare the other materials temperatures and calculate accurate emissivities.

The repeatability of the reported emissivities was also evaluated. A random sampling of the test conditions was repeated at a later date to ensure that the gathered data was accurate. These were compared with the previously calculated emissivities, and they were all within reasonable proximity to the values published in this paper. The following adjusted emissivities, tabulated in Tables 1 through 3, were established from the testing.

Horizontal Distance (Feet)	***Cast Iron emissivity***				
	1	*2*	*3*	*4*	*5*
10	*0.96*	*0.96*	*0.97*	*0.96*	*0.96*
15	*0.96*	*0.96*	*0.97*	*0.96*	*0.96*
20	*0.95*	*0.96*	*0.96*	*0.96*	*0.95*
25	*0.95*	*0.95*	*0.96*	*0.95*	*0.95*
30	*0.94*	*0.95*	*0.96*	*0.95*	*0.94*
35	*0.93*	*0.95*	*0.96*	*0.94*	*0.92*
40	*0.92*	*0.94*	*0.96*	*0.94*	*0.92*
45	*0.91*	*0.93*	*0.95*	*0.93*	*0.91*
50	*0.9*	*0.93*	*0.95*	*0.93*	*0.9*
55	*0.88*	*0.92*	*0.94*	*0.93*	*0.89*
60	*0.86*	*0.92*	*0.94*	*0.92*	*0.87*
65	*0.84*	*0.9*	*0.94*	*0.91*	*0.85*

Table 1. Adjusted emissivity values for the cast Iron section of pipe. Columns 1 through 5 represent the location of the emissivity determination relative to the pipes curvature as illustrated in Figure 6.

Horizontal Distance (Feet)	***PVC emissivity***				
	1	*2*	*3*	*4*	*5*
10	*0.95*	*0.95*	*0.95*	*0.95*	*0.95*
15	*0.95*	*0.95*	*0.95*	*0.95*	*0.95*
20	*0.95*	*0.95*	*0.95*	*0.95*	*0.95*
25	*0.94*	*0.95*	*0.95*	*0.95*	*0.94*
30	*0.94*	*0.95*	*0.95*	*0.94*	*0.94*
35	*0.93*	*0.94*	*0.95*	*0.94*	*0.94*
40	*0.93*	*0.94*	*0.95*	*0.94*	*0.93*
45	*0.92*	*0.94*	*0.95*	*0.94*	*0.93*
50	*0.91*	*0.94*	*0.95*	*0.93*	*0.92*
55	*0.9*	*0.93*	*0.95*	*0.93*	*0.92*
60	*0.89*	*0.93*	*0.95*	*0.93*	*0.91*
65	*0.88*	*0.92*	*0.94*	*0.92*	*0.88*

Table 2. Adjusted Emissivity values for the PolyVinyl Chloride section of pipe.

Horizontal Distance (Feet)			***Copper emissivity***		
	1	*2*	*3*	*4*	*5*
10	*0.02*	*0.04*	*0.06*	*0.04*	*0.03*
15	*0.01*	*0.03*	*0.06*	*0.03*	*0.02*
20		*0.02*	*0.06*	*0.02*	*0.01*
25		*0.02*	*0.05*	*0.02*	
30		*0.01*	*0.05*	*0.02*	
35		*0.01*	*0.05*	*0.01*	
40		*0.01*	*0.04*	*0.01*	
45		*0.01*	*0.03*	*0.01*	
50			*0.03*		
55			*0.02*		
60			*0.02*		
65			*0.01*		

Table 3. Adjusted Emissivity values for the Copper section of pipe. Note that, at the greater distances, the emissivity is effectively zero at every point except perpendicular. This is due to the high reflectivity of the copper pipe, and illustrates the magnitude of the angular effects on emissivity.

Graphically, the results for this testing are displayed below in Figure 7, the adjusted emissivity variation of the Cast Iron section of pipe. As illustrated, the emissivity of the pipe is compromised as the spot size increases in size. If the thermographer is unaware of this condition, an improper emissivity and, therefore, pipe and fluid temperature will be attained.

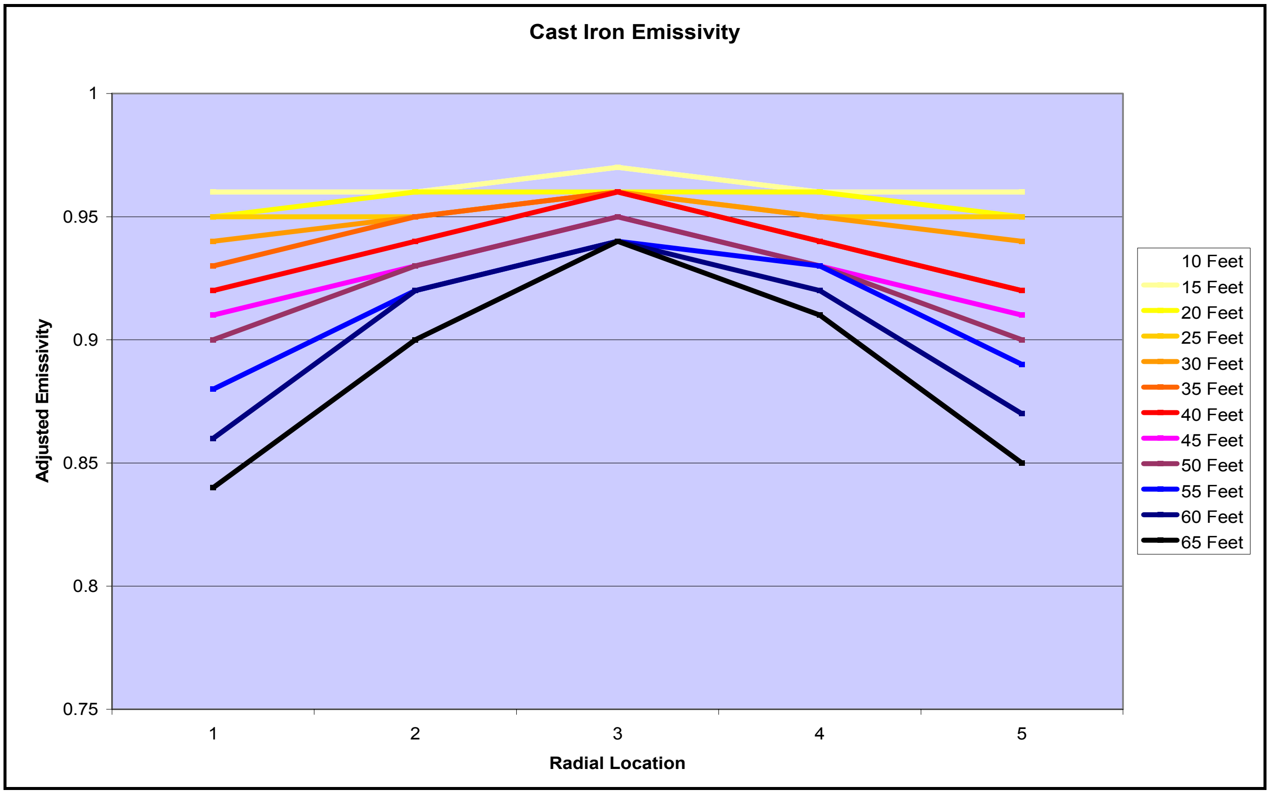

Figure 7. Adjusted emissivity chart for the Cast Iron section of pipe. Note that the emissivity at the edges of the pipe drops off with the increase in distance (and, therefore, increase in spot size).

DISCUSSION OF FINDINGS

The variation in the adjusted emissivities above is evidence that the thermographer needs to be aware of the physical spot size and the distance to the object when preparing a thermal evaluation. Note that the effects of the angular distortion are seen even at a spot size that is less than 25% of the pipe diameter. As a general rule of thumb, the thermographer should attempt to image a pipe as close as possible (within the limits of safety), while being aware of the spot size at that distance. Notably, a larger diameter pipe can be viewed at a greater distance due to the increase in the pipe size as compared to the spot size. The inverse is also true, that a smaller pipe should be viewed from a shorter distance in order to avoid the adverse effects of the angular emissivity distortion. The thermographer should be aware of his/her spot size ratio and be capable of evaluating an adequate spot size and viewing distance while on site.

SUMMARY

The determined emissivity values in Tables 1 through 3 indicate the importance of the thermographer's understanding of their distance to the spot in question and knowledge of the piping product used. Additionally, the user must understand the concept of the angle of inclination and its effects on the emissivity of any emitting surface.

The emissivity of the specular, highly reflective materials was determined to be very subject to the curvature of the piping. However, other materials such as the cast iron had less visual mirror effects due to the surface roughness and were found to have significant variations in the emissivity based on the curvature of the pipe. This laboratory experiment determined that the temperature readings of an IR camera are greatly affected by the "wrapping" of the spot over the cylindrical surface, as predicted in our hypothesis. It is important that the thermographer take temperature readings at the most perpendicular area of the pipe, ensuring that the camera is at a right angle to the piping material and the spot placed at the center and therefore perpendicular, section of the pipe cross section.

The importance of the accuracy of the temperatures needed for the interpretation of the results cannot be overstressed in the review of the site parameters used in the application of the infrared thermography. The use of the camera in tight angles on different materials needs to be evaluated to determine proper temperature measurements. The angular effects, as well as the products, both provide for operator input in the evaluation of the surface temperature determination of the various types of piping assemblies that are under investigation. Improper evaluation of the infrared readings can lead to improper understanding of the systems performance. The operator must have a basic understanding of the angular effect on the readings, as well as the different emissivity values of each product in relation to the angular readings.

DERIVATION OF CYLINDER INTERSECTIONS:

For two cylinders of radius r oriented long the z- and x-axes gives the equations

$$x^2 + y^2 = r^2 \tag{1}$$

$$y^2 + z^2 = r^2 \tag{2}$$

which can be solved for x and y gives the parametric equations of the edges of the solid,

$$x = \pm z \tag{3}$$

$$y = \pm\sqrt{r^2 - z^2}. \tag{4}$$

The surface area can be found as $\int x\,ds$, where

$$ds = \sqrt{1 + \left(\frac{dy}{dz}\right)^2}\,dz \tag{5}$$

$$= \frac{r}{\sqrt{r^2 - z^2}}\,dz. \tag{6}$$

Taking the range of integration as a quarter or one face and then multiplying by 16 gives

$$S_2 = 16 \int_0^r \frac{r\,z}{\sqrt{r^2 - z^2}}\,d\,z = 16\,r^2. \tag{7}$$

Using calculus to provide a simple derivation, however, noting that the solid has a square cross section of side-half-length $\sqrt{r^2 - z^2}$, the volume is given by

$$V_2\,(r, r) = \int_{-r}^{r} \left(2\sqrt{r^2 - z^2}\right)^2 d\,z = \tfrac{16}{3}\,r^3 \tag{8}$$

(Moore 1974).
The volume can also be found using cylindrical algebraic decomposition, which reduces the inequalities

$$\begin{cases} x^2 + y^2 < 1 \\ -L < z < L \\ y^2 + z^2 < 1 \\ -L < x < L \end{cases} \tag{9}$$

to

$$\begin{cases} -1 < x < 1 \\ -\sqrt{1 - x^2} < y < \sqrt{1 - x^2} \\ -\sqrt{1 - y^2} < z < \sqrt{1 - y^2}, \end{cases} \tag{10}$$

giving the integral

$$V_2\,(1, 1) = \int_{-1}^{1} \int_{-\sqrt{1-x^2}}^{\sqrt{1-x^2}} \int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} d\,z\,d\,y\,d\,x = \tfrac{16}{3}. \tag{11}$$

If the two right cylinders are of different radii a and b with $a > b$, then the volume common to them is

$$V_2\,(a, b) = \tfrac{8}{3}\,a\,[(a^2 + b^2)\,E\,(k) - (a^2 - b^2)\,K\,(k)], \tag{12}$$

where $K\,(k)$ is the complete elliptic integral of the first kind, $E\,(k)$ is the complete elliptic integral of the second kind, and $k \equiv b / a$ is the elliptic modulus. The curves of intersection of two cylinders of radii a and b, shown above, are given by the parametric equations

$$x\,(t) = b\cos t \tag{13}$$

$$y\,(t) = b\sin t \tag{14}$$

$$z\,(t) = \pm\sqrt{a^2 - b^2 \sin^2 t} \tag{15}$$

(Gray 1997, p. 204).

The volume common to two elliptic cylinders

$$\frac{x^2}{a^2}+\frac{z^2}{c^2}=1 \quad \frac{y^2}{b^2}+\frac{z^2}{c'^2}=1 \tag{16}$$

with $c < c'$ is

$$V_2(a,c;b,c')=\frac{8ab}{3c}\left[(c'^2+c^2)E(k)-(c'^2-c^2)K(k)\right], \tag{17}$$

where $k = c/c'$ (Bowman 1961, p. 34).

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