Emissivity of “Grey” Bodies, Surface Roughness and other Measures

Randy K. Salazar, Cris Lawrence B. Laurente
University of San Jose – Recoletos

Abstract

The Stefan-Boltzmann law quantifies the radiating energy of a body, but this requires knowledge on emissivity. The surface emissivity values more often are determined using instruments in a test or experiments. This procedure may not be practical for large objects that are difficult to mount in a laboratory. This paper reviews the different concepts and dimensions that affect emissivity. This explores the relationship of emissivity with the selected thermodynamic properties, dimensions including the surface microstructure of the material. Thermodynamic properties and surface microstructure images from online sources were utilized as data for the selected materials. Field Emission Scanning Electron Microscope (FESEM) provides the rest of the unavailable images. Fractal image analysis characterized and gave dimension to the roughness of the surface microstructure of the material. Different regression models of the relevant dimensions were tested to determine the statistical relation and the optimum correlation to emissivity. Overall, the calculated values of the emissivity model of the study yields strong correlation with the published emissivity values.

Keywords: emissivity, grey body, surface roughness, electron microscopy, fractal dimension, heat transfer, thermal radiation, regression analysis

1.0 Introduction

Emissivity refers to the ratio of the energy radiated from a material's surface to that emitted by a blackbody at the same temperature and wavelength, and under the same viewing conditions (Cengel, et al., 2008). Gustav Kirchoff, in 1859, equated the emissivity of a surface with its absorption of incident light or the absorptivity of the surface. Emissivity cannot exceed 1; the largest absorptivity corresponding to complete absorption of all incident light by a truly black object is also 1 (Siegel, 2001). The knowledge of surface emissivity for any material is essential both for accurate non-contact temperature measurement and for heat transfer calculations (Thompson, 2010). However, not all objects can be mounted or tested in a laboratory to test its emissivity. This paper explores the relationship of the emissivity values of the different materials, with the selected thermodynamic properties and its surface microstructure roughness.

Objects with temperatures that are significantly above absolute zero emit thermal radiations. For any particular temperature and wavelength, the amount of radiation energy emitted from a surface depends on the material of the body and condition of the surface and temperature (Astarita &

Carlomagno, 2013; Cengel, et al., 2008). Pertinent method for determining surface emissivity values, as suggested by scientific researches, includes measurements using simple devices. An example is the *Leslie's Cube* in conjunction with a thermal radiation detector such as a *thermopile* or a *bolometer*. Other method consists of using a mathematical *multispectral radiation thermometry* (MRT) model for the emissivity model from radiance measurements (Wen & Mudawar, 2006). Studies pertaining to the determination of emissivity include a semi-theoretical equation relating emissivity to the thermal conductivity of the material (Attalah, 1966).

Emissivity is essential to the heat transfer calculations. This dimension quantifies the efficiency of the surface for radiating energy. The internet and various scientific journals have published a credible and accurate values of emissivity of different materials. Experimental researches in radiation are focused on measuring the value of emissivity as a function of certain factors. These factors include the material type, surface condition and temperature. Methods used to measure emissivity also include the use of detectors like the infrared spectrometer, infrared radiometer, and an infrared thermometer (Chen, 1990; Johnson, 1988; Especel, 1996; Siroux, 1998). However, with all these knowledge and technologies, emissivity values often are measured with instruments in a laboratory, and is limited to small mass and laboratory sized objects. Large mass and composite materials like buildings, land mass and the like may not be applicable.

The paper considers the different regression models to define the relationship of emissivity with selected thermodynamic properties of the different materials. Fractal image analysis will measure the surface roughness of the material.

2.0 Design and Methodology

Regression measures the association of one variable to one or more other variables. In this study several statistical regression models are explored to test the strength of relationships of selected properties with the emissivity values of a material. The regressions may be linear $y = mx + b$, exponential $y = e^x$, logarithmic $y = \ln x$, power $y = a^x$, or polynomial $y = a_0x^n + a_1x^{n-1} \ldots + a_{n-1}x^0$. The strength of the relationship is denoted by a correlation coefficient, R or by the coefficient of determination R^2. The software used for the regressions is Microsoft Office Excel.

Material information including images of the surface microstructures were downloaded from online sources (Micrographs : Microstructures, 2014; Flynn & Stachurski, 2006; Firefly Diapers, 2014; Crystal Mark Inc, 2014). If the image is not available this is taken using a Field Emission Scanning Electron Microscope (FESEM). The images are then subjected to a fractal analysis for the determination of the fractal dimensions using the HarFa software. Images are selected and pre-processed by “thresholding”.

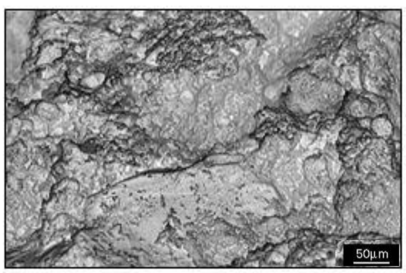
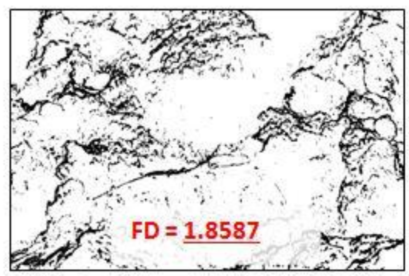
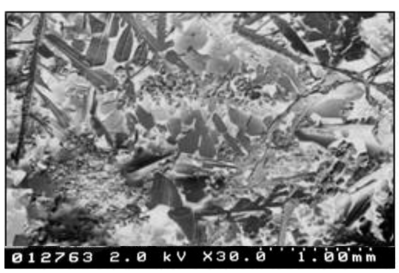
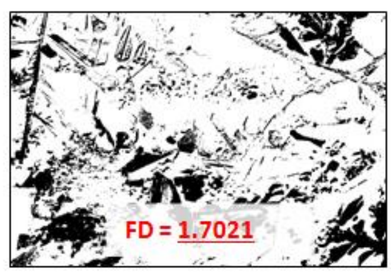
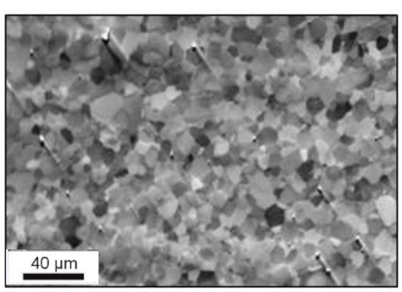
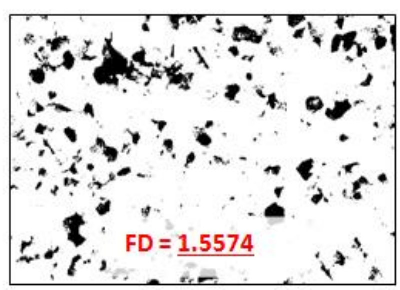
Fractal image analysis is a high-level image processing technique that identifies image features such as texture, roughness, smoothness, area and solidity. Fractal dimensions may be viewed as a measure of irregularity or heterogeneity of spatial arrangements in many areas of studies or physical processes (Shanmugavadivu & Sivakumar, 2012). The dimension of dark colors of an object's surface is used to quantify the emissive ability of the material (Cengel, et al., 2008; Zmeskal et al., 2013).

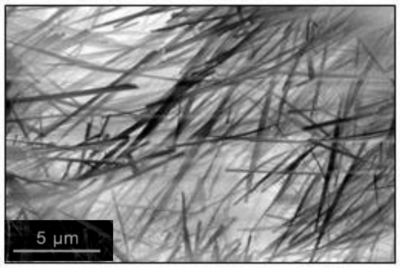
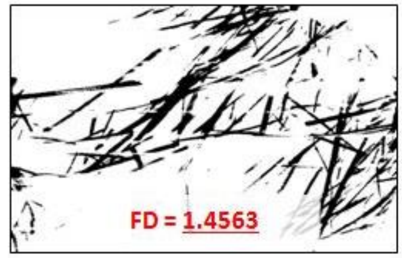
Important image information for surface roughness fractal analysis must focus on the surface structure, characteristics, features that affect surface emissivity. For oxidized surface it must be the oxidized surface structure, for polished surface it must be the microstructure of the surface.

"Thresholding" isolates an intensity range. The threshold range is 0 - 85 captures only the darker portions of the surface, 0 being black, 255 is the value for white and 85 is on a darker grey range. The dimension of dark colors of the object's surface is used to quantify the surface emissivity of the material (Cengel, et al., 2008; Zmeskal et al. 2013). Theoretically these dark portions should create significant effect on emissivity. Table 1 shows sample images and the "thresholding" effect with corresponding fractal dimension. Except for the FESEM images, downloaded images are images of material specimens that are prepared following imaging standards, that is, polished and cleaned.

Emissivity, surface fractal dimension, ***FD***, and other material properties must be taken from same material conditions or the same sample. The surface fractal dimensions and material properties are tabulated, Table 2. These are subjected to a regression analysis.

Table 1. HarFA Thresholding, the range of 0 to 85

Material	Sample Image	HarFA Thresholding and FD (range of intensity 0 to 85)
Concrete		
Snow		
Quartz		

Asbestos Fabric		

3.0 Results and Discussions

Table 2 shows the sample materials with the corresponding values of emissivity, thermal conductivity, specific heat, density and surface fractal dimension (***FD***) (EN12524, 2000; Engineering Toolbox, n.d; Fluke Corporation, 2007; Minkina & Dudzik, 2009; National Paloposki & Liedquist, 2005; Omega Engineering, n.d.; Physical Laboratory, 2008; Powell, Ho, & Liley, 1966; Wen & Mudawar, 2005). The values are published and scientifically accepted data and surface ***FD***'s are measured values.

Table 2. Emissivity, Thermal Conductivity, Specific Heat, Density and FD of Sample Materials

Material	Emissivity	Conductivity in $Wm^{-1}K^{-1}$	Specific Heat in $kJkg^{-1}K^{-1}$	Density 10^3 kgm^{-3}	surface FD (HarFa, range of 0-85)
Concrete	0.63 - 0.94	1.50	0.96	1.20	1.8587
Asbestos Fabric	0.78 - 0.96	0.125	0.84	2.50	1.4563
Snow	0.82 - 0.89	0.12	2.00	1.18	1.7021
Quartz	0.68 - 0.93	1.40	0.75	2.30	1.5574
Charcoal	0.80 - 0.95	0.20	1.00	1.55	1.507
Fired Clay	0.85 - .95	1.00	1.00	2.15	1.7814
Asphalt	0.90 - 0.95	0.70	1.00	8.40	1.7846
Common Brick	0.75 - 0.93	1.00	1.00	7.50	1.6696
Wood	0.9 - 0.95	0.13	1.60	8.90	1.5775
Paper	0.55 - 0.90	0.05	1.40	7.80	1.7548
Glass	0.47- 0.98	1.00	0.75	7.80	1.5498
Tar Paper	0.92	0.50	1.47	11.30	1.8865
Porcelain	0.92	1.30	1.07	8.70	1.9521
Cotton Cloth	0.77	0.04	1.34	7.50	1.7120
Carbon	0.80 - 0.98	1.70	0.71	8.03	1.9529
Brass*	0.03 - 0.40	120.00	0.38	7.50	1.6242
Cast Iron	0.21 - 0.81	50.00	0.45	19.25	1.9169
Copper*	0.01 - 0.20	380.00	0.38	7.31	1.3785
Galvanized Steel*	0.23- 0.88	50.00	0.40	2.70	1.9315
Mild Steel	0.20 - 0.90	50.00	0.45	1.20	1.7428

Lead	0.057 - 0.65	35.00	0.13	2.50	1.9279
Bronze*	0.10 - 0.55	65.00	0.38	1.18	1.9171
Wrought Iron	0.14 - 0.95	50.00	0.45	2.30	1.8856
Stainless Steel*	0.075 - 0.85	16.00	0.50	1.55	1.3632
Iron	0.14 - 0.95	50.00	0.45	2.15	1.7785
Tungsten	0.032 - 0.35	174.00	0.13	8.40	1.8625
Tin	0.04 - 0.30	66.80	0.21	7.50	1.5409
Aluminum*	0.04 - 0.25	205.00	0.91	8.90	1.6605

* (asterisk) indicates an FESEM taken image.

The tabulated values of emissivity are given in ranges. Theoretically emissivity is temperature and surface feature dependent. In like manner, thermal conductivity and specific heat of the material are also dependent on temperature. The subsequent scatter plot diagrams are generated to display relationships between data and regression results in Figures 2, 3, 4, 5, 6, 7, 8 and 9.

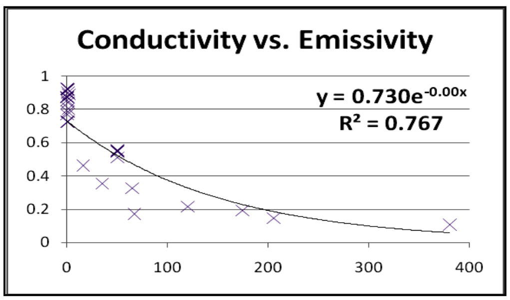


Figure 2. Regression Analysis of Conductivity and Emissivity

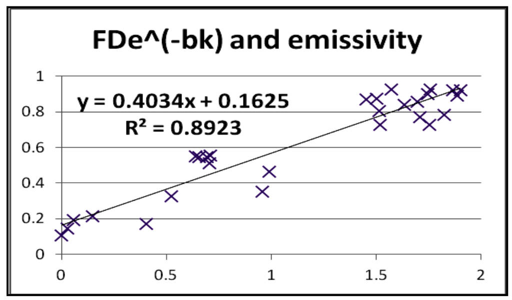


Figure 3. Regression of $FDe^{-0.02k(T)}$ and Average Emissivity Values ($x = FDe^{-0.02k(T)}$)

The regression analysis of conductivity and emissivity, Figure 2, shows an exponential decrease of the emissivity as thermal conductivity (***k***) increases in value.

The surface roughness dimension of the material, ***FD,*** when regressed does not show any relationship with emissivity. However, when combined with the exponential function of the conductivity, $FD*e^{-bk}$, the linear regression shows a strong correlation and is maximum when ***b = 0.02***, shown in Figure 3 where $x = FD\, e^{-bk}$. The inclusion of surface ***FD*** of the material to the equation improves the correlation of the exponential function of the conductivity of 76.7% to 89.22%.

Initial regression forms the equation 1:

$$\varepsilon = 0.4034\, FD\, e^{-0.02\, k(T)} + 0.1625 \quad \text{equation 1}$$

$$\text{or } \varepsilon = a\, FD\, e^{-b\, k(T)} + c$$

Where the following are:
$\varepsilon(FD, k)$ – emissivity
k(T) - thermal conductivity (temperature)
FD - fractal dimension, surface roughness measure
based on sensitivity tests with optimum correlation:
a **= 0.4034**
b **= 0.02**
c **= 0.1625**

The values of equation 1 showed a strong correlation with the published values, Figure 4. However, further analysis shows that when the material surfaces are highly polished, that is ***FD = 0*** (theoretical value), the emissivity values will be equal to ***c = 0.1625***, for all materials. This value is inaccurate. Materials differ in composition and thermodynamic properties and have different base values for emissivity.

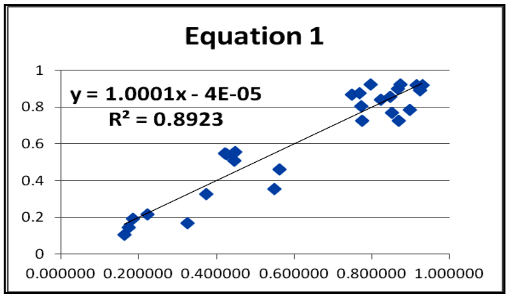


Figure 4. Regression of the result of equation 1

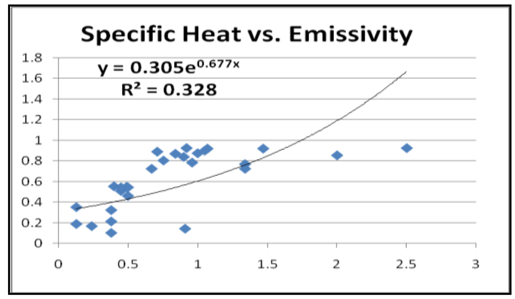


Figure 5. Regression Analysis of Specific Heat and Emissivity

The specific heat (C_P), when regressed, has no correlation with emissivity, Figure 5. However, the function, $\boldsymbol{1 - e^{-Cp}}$, Figures 6 and 7, determines a better correlation. The correlation is relatively stronger with the lower emissivity values, Figures 7. This function tends to agree with the base emissivity values of the different materials.

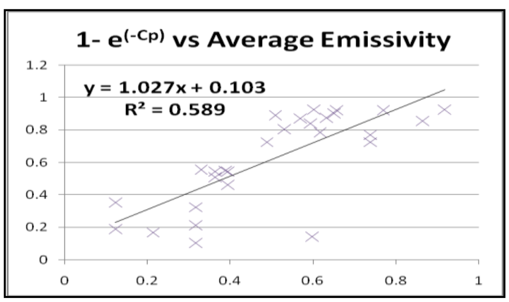


Figure 6. Regression Analysis of Unit Complement of $1/e^{Cp}$ and Average Emissivity Values

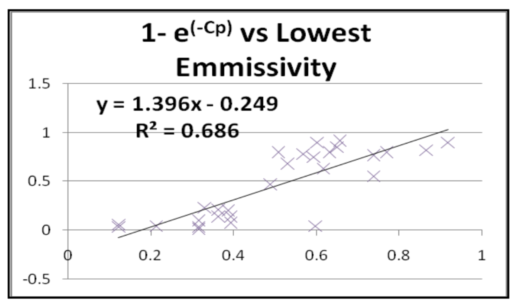


Figure 7. Regression Analysis of Unit Complement of $1/e^{Cp}$ and Lowest Emissivity Values

The specific heat function modifies the equation 1:

$$\varepsilon = 0.4034\, FD\, e^{-0.02\, k(T)} + 0.1625[1-e^{-Cp(T)}] \quad \text{equation 2}$$

$$\text{or } \varepsilon = a\, FD\, e^{-b\, k(T)} + c[1-e^{-Cp(T)}]$$

where: ε ***(FD,k,Cp)*** – emissivity

FD - fractal dimension, surface roughness measure

k(T) – thermal conductivity

Cp(T) – specific heat capacity

$c\,[1-e^{-Cp(T)}]$ – revised base emissivity value

constants base on sensitivity test:

a **= 0.4034**

b **= 0.02**

c **= 0.1625**

Regression analysis of equation 2 in Figures 8 and 9 reveals a strong correlation between the published emissivity values and those obtained using the equation. Hence, the fractal dimension of the surface roughness, along with the conductivity and the specific heat, can be highly associated to the material's surface emissivity. Between the computed values of equation 2, and the average values of emissivity the correlation is 90.10% and with emissivity base values of 87.12%. The inclusion of the function, $\boldsymbol{1 - e^{-Cp}}$, is a positive increase in the correlation of equation 1.

Table 3 shows the comparative data of the computed emissivity values obtained from the equation 2 and the published values. The selection and use of material images for fractal analysis in the emissivity calculation is critical. ***FD*** could vary in dimension from polished to highly oxidized material. The ***FD = 0*** is a value that can only be attained by a highly polished and perfectly white surface. Materials have microscopic grain structures, and not all materials can be polished similar to polished silver. A good example is carbon in its many material variations.

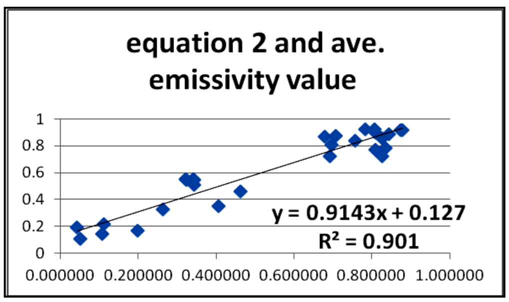


Figure 8. Regression Analysis of Emissivity using the Empirical Equation and Average Known Emissivity

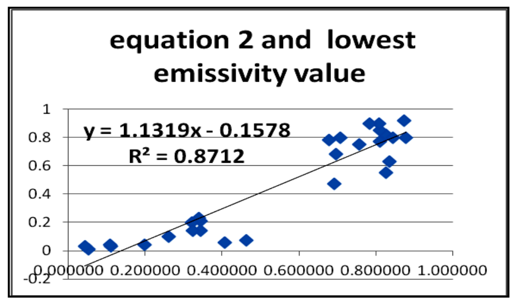


Figure 9. Regression Analysis of Emissivity using the Empirical Equation and Lowest Known Emissivity

The surface roughness dimension, ***FD***, should be taken from images that correspond to the exact condition of the material that is, either polished, oxidized, roughed, smooth and so on. FESEM images were taken from actual material samples and unpolished. On-line sourced images are treated as well-prepared material specimen that is, polished and cleaned.

Table 3. Computed Emissivity Values using Equation 2

Material	Published collated range Emissivity (ε)	Average Emissivity (ε)	Commonly used Emissivity (ε)	Equation 2 Emissivity (ε)
Concrete	0.63 - 0.94	0.785	0.85	**0.835821**
Asbestos Fabric	0.78 - 0.96	0.870	0.78	**0.678352**
Snow	0.82 - 0.89	0.855	0.80	**0.825489**
Quartz	0.68 - 0.93	0.805	0.93	**0.697031**
Charcoal	0.80 - 0.95	0.875	0.80	**0.708217**
Fired Clay	0.85 - .95	0.900	0.91	**0.810022**
Asphalt	0.90 - 0.95	0.925	0.93	**0.807640**
Common Brick	0.75 - 0.93	0.840	0.80	**0.756613**
Wood	0.80 - 0.95	0.875	0.88	**0.783872**
Paper	0.55 - 0.9	0.725	0.90	**0.827129**
Glass	0.47- 0.98	0.725	0.92	**0.692157**

Tar Paper	0.92	0.920	0.92	**0.878579**
Porcelain	0.92	0.920	0.92	**0.874028**
Cotton Cloth	0.77	0.770	0.77	**0.810019**
Carbon	0.80 - 0.98	0.890	0.80	**0.844073**
Brass*	0.03 - 0.40	0.215	0.22	**0.110811**
Cast Iron	0.21 - 0.81	0.510	0.21	**0.343358**
Copper*	0.01 - 0.20	0.105	0.07	**0.051651**
Galvanized Steel*	0.23- 0.88	0.555	0.28	**0.340213**
Mild Steel	0.20 - 0.90	0.550	0.24	**0.321584**
Lead	0.057 - 0.65	0.354	0.28	**0.406011**
Bronze*	0.10 - 0.55	0.325	0.10	**0.262137**
Wrought Iron	0.14 - 0.95	0.545	0.28	**0.343767**
Stainless Steel*	0.075 - 0.85	0.463	0.54	**0.463259**
Iron	0.14 - 0.95	0.545	0.31	**0.322819**
Tungsten	0.032 - 0.35	0.191	0.05	**0.042956**
Tin	0.04 - 0.30	0.170	0.05	**0.198088**
Aluminum*	0.04 - 0.25	0.145	0.07	**0.108191**

* (asterisk) indicates an FESEM image.

4.0 Findings

The formulated equation 2 is a result of a series of regression analyses and sensitivity tests. The results determine emissivity with a strong correlation to the summation of the product of the surface roughness and the exponential function of the thermal conductivity, $FD{*}e^{-bCp}$, and the unit complement of $1/e^{Cp}$ of specific heat. Conductivity and specific heat are a function of the temperature. Indirectly equation 2 is also a function of temperature.

This paper looks into the published emissivity values, ε, of the different materials and explores its relationship to its thermodynamic properties like; a) conductivity (***k***), b) specific heat (***Cp***), and c) density (ρ), and d) the surface microstructure roughness of the material, ***FD***. Key findings from the study are as follows:

1. Emissivity is exponentially decreased with the increase in thermal conductivity, ***k (T)***, Figure 2.
2. The product of the surface roughness and the exponential function of conductivity, ($FD{*}e^{-bk\,(T)}$) has a strong correlation with the average emissivity, Figure 3.
3. The inclusion of ***FD*** imparts a positive increase in the correlation of the exponential function of conductivity.
4. The correct selection and use of material images for fractal dimension (***FD***) analysis are essential for the correct emissivity calculation.
5. The unit complement of the exponential function of specific heat ($1 - e^{-Cp\,(T)}$), correlates closely and tends to agree with the base emissivity values of the different materials, Figure 7.

6. The inclusion of the function, $\boldsymbol{1 - e^{-Cp\,(T)}}$, in the equation brings about a positive increase in the correlation, Figures 8 and 9.

7. The equation, $\boldsymbol{\varepsilon = aFDe^{-bk(T)} + c[1-e^{-Cp(T)}]}$, with the empirical constants ***a = 0.4034, b = 0.02,*** and ***c = 0.1625*** has a strong correlation with the published emissivity values of the sample materials. This relationship forms the equation 2: $\boldsymbol{\varepsilon = 0.4034\, FD\, e^{-0.02\, k(T)} + 0.1625[1-e^{-Cp(T)}]}$

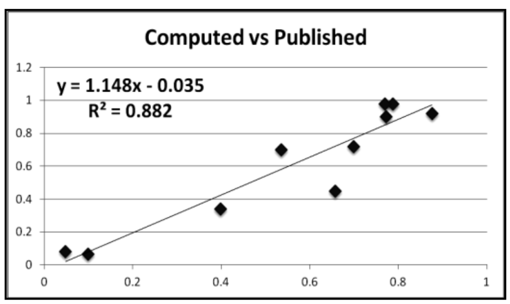
8. The silicon carbide emissivity value does not correlate with this equation and requires further study.

9. Table 4 shows additional sets of materials with the emissivity calculation showing a strong correlation of 88.20% with the average emissivity.

Table 4. New Sets of Data

	Material	Surface FD (HarFa, range of 0-85)	Conductivity in $Wm^{-1}K^{-1}$	Specific Heat Capacity in $kJkg^{-1}K^{-1}$	Emissivity (Published)	Computed Emissivity (Equation 2)
1	**Aluminum Foil**	1.3543	235.00	0.87	0.04 - 0.09	0.099389347
2	**Basalt**	1.6151	3.50	0.84	0.72	0.699830835
3	**Granite Rock**	1.5141	3.50	0.79	0.45	0.658245121
4	**Graphite**	1.8531	25.00	0.71	0.70 - 0.80	0.536014075
5	**Human Skin**	1.5759	0.32	3.15	0.985	0.787198986
6	**Limestone**	1.7180	1.26	0.91	0.90 - 0.93	0.772884593
7	**Plaster**	1.6590	0.20	1.00	0.98	0.769288575
8	**Platinum**	0.2855	70.00	0.13	0.054 - 0.104	0.048210237
9	**Salt Crystal**	1.5159	35.10	0.88	0.34	0.398159941
10	**Teflon Tape (Polytetrafluoroethylene)**	1.8772	0.25	1.40	0.92	0.875913611

Figure 10. Regression Analysis of Computed and Published Emissivity from the New Set of Data



5.0 Conclusions

Emissivity is a cantankerous variable. It varies by surface condition and other determined factors (Clausing, 2014). Theoretically, emissivity values of the different materials differ from one to the other due to its inherent material properties. On a specific material the value of emissivity vary to some degree due to the different material surface conditions and temperature variance (Berry, 2014; Cengel, et al., 2008; Musilová, 2010; Zmeskal et al., 2013). The study explores the relationship between emissivity, selected thermodynamic properties and surfaces roughness (***FD***) of the different materials.

Different concepts governing these relationships were reviewed. From the study, the following ideas and observations are accordingly presented and affirmed:

1. **The material's emissivity is a function of its surface roughness dimension, thermal conductivity, and specific heat capacity.**

   The equation, $\varepsilon = aFD\ e^{-bk(T)} + c[1 - e^{-Cp(T)}]$, with the empirical constants $a = 0.4034$, $b = 0.02$, and $c = 0.1625$, reveals a strong correlation with the published emissivity values.

2. **Emissivity is exponentially decreased with the increase of thermal conductivity.**

   Equation 1, $\varepsilon = 0.4034\ FD\ e^{-bk(T)} + 0.1625$, shows a strong correlation with the emissivity. Heat flows through the least resistance and at higher rate through conduction and convection. For a definite amount of internal energy and a thermally conductive material, heat is quickly distributed throughout the body. Heat flux per unit surface area is relatively less, and consequently surface temperature decreased. Radiative emission, therefore, is relatively less for highly conductive material than those materials with low conductivity.

3. **Fractal image analysis is an effective method for characterizing material surface roughness for the emissivity calculation.**

   The inclusion of the surface roughness dimension to the exponential function of conductivity, $FD\ e^{-bk\,(T)}$, increases the strength of the correlation. Energy released by radiation or absorbed by solids from a radiated source is regulated by its surface features (Fuji & Co., 2009; Cengel, et al., 2008). The influence of surface roughness on heat transfer is a fact; the rougher the surface, the more heat transfer. Dark colors on surfaces introduced issues related to radiant heat transfer (Cengel, et al., 2008; Zmeskal et al., 2013, Musilová, et al., 2010).

   Material surface images must be carefully selected accordingly to the state of the material studied. The lack of specific data for the different material surface conditions and time constraint prevented this study from progressing in that direction.

4. **The unit complement of the exponential function of specific heat, ($1 - e^{-Cp(T)}$), correlates closely with the base emissivity values of the different materials**.

   Solids cannot release energy that it has not absorbed. Kirchhoff's Law explained that absorbance coefficient relatively varies with the emissive coefficient. On the other hand, the specific heat of a material is also the amount of heat required by the body to change its temperature by a given quantity (Batchelor, 2000; Halliday & Resnick, 2013). Sensible heat is, therefore, attained when the specific heat is satisfied. Heat transfer occurs when surface temperature is relatively higher than the ambient temperature.

In quantifying emissivity, there are several procedures that can be adopted. Oftentimes, emissivity is measured by instruments or by experiment and often not all surface conditions are measured. This paper presents an analytical solution to solving emissivity. However, this may still require further specific studies and verification on specific materials and specific surface conditions. The use of the equation will require knowledge and understanding of fractal dimension and fractal image analysis. Overall, the results of the calculated emissivity values have shown strong correlations with the average published values.

Further, the derived relationships can be used on large composite surfaces that may not be easily mounted in a laboratory. Some examples are geographic features like land surfaces, cities, and the environment.

References:

Amonette, J. E., & Joseph, S. (2009). Characteristics of biochar: Microchemical properties. *Biochar for environmental management: Science and technology. Earthscan, London*, 33-52.

Astarita, T., & Carlomagno, G. M. (2013). Infrared Thermography for Thermo-Fluid-Dynamics.

Attalah, S. (1966). A relationship between emissivity and thermal conductivity of metals. *British journal of applied physics*, 17(573), 0508-3443.

Batchelor, G. K. (2000). *An introduction to fluid dynamics*. Cambridge university press.

Berry, B. (2014, November 14). *General Posts: Does emissivity change with temperature?* Retrieved June 23, 2015, from Thermal Vision: http://www.thermalvision.ie

Bloise, A., Fornero, E., Belluso, E., Barrese, E., & Rinaudo, C. (2008). Synthesis and characterization of tremolite asbestos fibres. *European Journal of Mineralogy*, *20*(6), 1027-1033.

Brewster, M. Q. (1992). *Thermal radiative transfer and properties.* John Wiley & Sons.

Cengel, Y. A., Klein, S., & Beckman, W. (1998). *Heat transfer: a practical approach.*

Chen, L., Yang, B. T., & Hu, X. (1990). Design principle for simultaneous emissivity and temperature measurements. *Optical Engineering*, 29(12), 1445-1448.

Crystal Mark Inc. (2014). Retrieved November 24, 2014, from Crystal Mark Inc: http://www.crystalmarkinc.com/wp-content/uploads

D'Annunzio, J. (2010). Reflectivity, emissivity important factors when selecting a cool roof. (Retrieve December 20 2014, from: http://www.facilitiesnet.com/roofing/article/Reflectivity-Emissivity-Important-Factors-When-Selecting-A-Cool-Roof--11641#)

Dozier, J., & Warren, S. G. (1982). Effect of viewing angle on the infrared brightness temperature of snow. *Water Resources Research*, 18(5), 1424-1434.

EN12524, B. S. (2000). Building materials and products–Hygrothermal properties–Tabulated design values. *British Standards Institution, London. ISBN 0*, *580*(34797), 4.

Engineering Toolbox. (n.d,). *Material Properties:*. Retrieved November 20, 2014, from The engineering Toolbox: http://www.engineeringtoolbox.com/material-properties-t_24.html

Especel, D., & Mattei, S. (1996). Total emissivity measurements without use of an absolute reference. *Infrared physics & technology*, 37(7), 777-784.

Flynn, A. J., & Stachurski, Z. H. (2006, Spetember). Microstructure and properties of stoneware clay bodies. *Clay Minerals, 41*, 775-789. Retrieved November 24, 2014, from Clay Minerals: http://claymin.geoscienceworld.org/content

Firefly Diapers. (2014). Retrieved November 24, 2014, from Firefly Diapers: http://www.fireflydiapers.com

Fluke Corporation. (2007, September 1). Emissivity of Common Materials. Everett, Washington, USA. Retrieved November 20, 2013, from www.frigidn.com/resources/EmissivityTable.pdf

Fuji & Co. (2009). Thermopile, (Retrieved December 20 2014 from: http://www.fuji-piezo.com/)

Grey Cast Iron Technical Data. (n.d.). Retrieved November 14, 2014, from Durham Foundry: http://www.castironcastings.com/images/high-tensile-strength-hardness.jpg)

Jalaal, M., Ghasemi, E., Ganji, D. D., Bararnia, H., Soleimani, S., Nejad, G. M., & Esmaeilpour, M. (2011). Effect of temperature-dependency of surface emissivity on heat transfer using the parameterized perturbation method. *Thermal Science*, *15*(suppl. 1), 123-125.

Johnson, R. B., Feng, C., & Fehribach, J. D. (1988, January). On the validity and techniques of temperature and emissivity measurements. In *1988 Orlando Technical Symposium* (pp. 202-206). International Society for Optics and Photonics.

Mandelbrot, B. B. (1983). *The fractal geometry of nature* (Vol. 173). Macmillan.

Merckx, B., Dudoignon, P., Garnier, J. P., & Marchand, D. (2012). Simplified Transient Hot-Wire Method for Effective Thermal Conductivity Measurement in Geo Materials: Microstructure and Saturation Effect. *Advances in Civil Engineering*, *2012*.

Micrographs : Microstructures. (2014). Retrieved November 24, 2014, from Internet Microscope for Schools: http://pwatlas.mt.umist.ac.uk/internetmicroscope/

Minkina, W., & Dudzik, S. (2009). *Infrared thermography: errors and uncertainties*. John Wiley & Sons.

Musilová, V. (2010). Factors that influence emissivity values, (Retrieved December 20, 2014, from: http://www.evitherm.org/default.asp?ID=216)

National Physical Laboratory. (2008,). *Kaye and Laby Table of Physical & Chemical Constants*. Retrieved November 20, 2013, from National Physical Laboratory: http://www.kayelaby.npl.co.uk/general_physics/2_3/2_3_7.html

Omega Engineering. (n.d.). *Temperature: Table of Total Emissivity*. Retrieved November 20, 2014, from Omega: www.omega.com/temperature/z/pdf/z088-089.pdf

Paloposki, T., & Liedquist, L. (2005). Steel emissivity at high temperatures. *Technical Research Centre of Finland. Research Notes*, (2299), 81.

Powell, R. W., Ho, C. Y., & Liley, P. E. (1966). *Thermal conductivity of selected materials* (No. NSRDS-NBS-8). NATIONAL STANDARD REFERENCE DATA SYSTEM.

Thompson, P. (2010, March 25). *FAQs: What is emissivity and why is it important?* Retrieved June 23, 2015, from NPL: http://www.npl.co.uk/

Shanmugavadivu, P., & Sivakumar, V. (2012). Fractal dimension based texture analysis of digital images. *Procedia Engineering*, 38, 2981-2986.

Siegel, R., & Howell, J. R. (1992). Thermal radiation heat transfer. *NASA STI/Recon Technical Report A*, 93, 17522.

Siegel, R. (2001). *Thermal radiation heat transfer* (Vol. 1). CRC press.

Siroux, M., Tang-Kwor, E., & Matteï, S. (1998). A periodic technique for emissivity measurements of insulating materials at moderate temperature. *Measurement Science and Technology*, 9(12), 1956.

Touloukian, Y. S., & DeWitt, D. P. (1989). *Themal radiative properties: Metallic elements and alloys. UMI.*

Voort, G. V. (n.d.). *Resources: Miecrostructure of Ferrous Alloy.* Retrieved November 24, 2014, from Vac Aero International Inc: http://vacaero.com/information-resources/metallography-with-george-vander-voort/894-microstructure-of-ferrous-alloys.html

Wen, C. D., & Mudawar, I. (2005). Emissivity characteristics of polished aluminum alloy surfaces and assessment of multispectral radiation thermometry (MRT) emissivity models. *International journal of heat and mass transfer*, 48(7), 1316-1329.

Wen, C. D., & Mudawar, I. (2006). Modeling the effects of surface roughness on the emissivity of aluminum alloys. *International journal of heat and mass transfer*, 49(23), 4279-4289.

Weng, Q. (2003). Fractal analysis of satellite-detected urban heat island effect. *Photogrammetric engineering & remote sensing*, 69(5), 555-566.

You, Z., & Butlar, W. (2010, January 31). *Imaging Technology Group*. Retrieved November 24, 2014, from Beckman Institute: https://itg.beckman.illinois.edu/communications/iotw/2003-12-23/

Zalba, B., Marín, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied thermal engineering*, *23*(3), 251-283.

Zmeskal, O. Bzatec, T., Nezadal, M. & Buchnicek, M. (2013). Image Fundamentals: HarFA Basics, (Retrieved December 20 2014, from: http://www.fch.vutbr.cz/lectures/imagesci.)