A Review of Recent Advances in the Use of Thermography in Pulp And Paper Industry

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ABSTRACT

The aim of the present paper is to shortly overview existing work and to describe the most relevant work and experiences devoted to the use of infrared thermography in paper industry. All objects at a temperature above absolute zero (-273° C) emits electromagnetic radiation, which fall in the infrared part of electromagnetic spectrum i.e. 1 to 1000 μm. This radiation is invisible to naked human eyes and termed as infrared. However, with the help of modern and proper instrument we can convert this invisible radiation to visible representation of the temperatures on the surface of the object. This representation of invisible to visible is termed as "Infrared Image" or a "Thermogram"and it becomes a versatile tool for surface temperature mapping. This feature represents a great potentiality to be exploited in many parts of paper industry, but this technique is still not adequately exploited in industrial instrumentation because of lack of adequate knowledge. At first sight, it seems too expensive and difficult to use. The present paper highlights the two applications, either as validating infrared thermography as a full measurement instrument, or as presenting infrared thermography as a novel technique enable to deal with several requirements, which are difficult to perform with other techniques. This review study is also an attempt to give indications for a synergic use of the different thermographic methods in various fields of paper industry.

Introduction

Infrared (IR) thermography is a technique to determine the temperature of an object from the measurement of the energy radiated by the body. The technique is capable of detecting even small changes in temperature with very good resolution without contacting the object being measured. Measurements of this type are not possible with typical thermometers or thermocouples [1]. IR thermography was first developed and used by the American military in World War II. Today, the technique has been developed as a powerful tool in a number of applications in heat transfer [2-5], fluid dynamics [6], and corrosion [7].

The IR thermography technique basically includes a camera that contains an infrared detector. The detector converts the IR energy emitted from the surface under measurement into an electric voltage or current.

For the purpose of IR thermography, the electromagnetic radiation over the wavelength ranging from 0.75 m to 1000 m is used[8]. Five subdivisions of the entire IR spectrum along with common detector materials and application areas are given in Table-1.

*Si :Silicon ;In :Indium ;Ga :Gallium ;As:Arsenic ;Pb :Lead ;S :Sulfur ;Sb :Antimony ;Se :Slenium ;Pt :Platinum ;Hg:Mercury ;Cd :Cadmium ;Te :Tellurium.

The emittance at each wavelength of a surface depends on its temperature and spectral emissivity. For a blackbody (an "ideal" emitter with the emissivity identically equal to one), the spectral emittance is given by the well-known Planck equation [9].

$$E_b(\ ,T)\quad \frac{2hc_0^2}{{}^5[\exp(hc_0/\ \ kT)\ \ 1]} \tag{1}$$

Where

$E_b(\lambda, T)$ = power irradiated by a black body per unit of solid angle at wavelength (W/m^2 m)

h=6.6256x10^{-34} Js (Planck's constant)

k=1.380x10^{-23} JK^{-1} (Boltzmann constant)

c_0 = 2.998x_{10}^{8}m/s (speed of light)

T= Temperature (K)

When Equation (1) is plotted for E_b as a function of wave length, λ at a given temperature for certain selected temperature range[10], some important features evolved out are as follows.

1. The emitted radiation varies continuously with wavelength.
2. At any wavelength the magnitude of the emitted radiation increases with increasing temperature
3. The spectral region in which the radiation is concentrated depends on temperature, with comparatively more radiation appearing at shorter wavelengths as the temperature increases.
4. A significant fraction of the radiation emitted by the sun, which may be approximated as a blackbody at 5800K, is in the visible region of the spectrum. In contrast, for T800 K, emission is predominantly in the infrared region of the spectrum and is not visible to eye.

Table 1: Infrared spectral range with its sensors and applications

Spectral bands	Range (m)	Common detector materials*	Application
Near infrared region (NIR)	0.74-1	Si	Telecommunication
Short wave infrared region (SWIR)	1-3	InGaAs, PbS	Remote sensing
Middle wave infrared region (MWIR)	3-5	InSb, PbSe, PtSi, HgCdTe	High temperature inspection (indoors, Scientific researches)
Long wave infrared region (LWIR)	8-14	HgCdTe	Ambient temperature (outdoor, industrial inspection)
Very long wave infrared region (VLWIR)	14-1000	----------	Spectrometry, Astronomy

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Although Eq(1) deals with the energy emitted by a radiating body, the energy is not emitted continuously. The energy is emitted as photons, which are small bursts of energy. The energy associated with a single photon varies only with wavelength and is given by hc/λ. Therefore, the expressions can be altered to account for the number of photons released by dividing by the energy of a photon.

A photon detector uses semiconductor technology to determine the number of photons from the amount of energy collected by the detector [11]. The number of photons emitted ($N_{\lambda b}$) is given by Planck's equation divided by the photon's energy.

From the above facts, one can see that the black body spectral distribution has a maximum value and that the corresponding wavelength λ_{max} depends on temperature. The nature of this dependence may be obtained by differentiating equation (2) with respect to λ and setting the result equal to zero. Hence one can obtain

$$\lambda_{max}T=C \qquad [3]$$

Where C_3=Third radiation constant= 2897.8 μ m.K

The ratio of the maximum wavelengths for two temperatures, T and T', is

$$\frac{_{max}}{'_{max}} \quad \frac{T'}{T} \qquad [4]$$

Equation (3) is known as Wein's displacement law, and the locus of the point described by the law is available elsewhere [10]. Accordingly,the maximum spectral emissive power is displaced to shorter wavelengths with increasing temperature. This emission is in middle of the visible spectrum (0.50m) for solar radiation, since the sun emits approximately as a blackbody at 5800 K. For blackbody at 1000K, peak emission occurs at 2.90 , with some of the emitted radiation appearing visible as red light. With increasing temperature, shorter wavelengths become more prominent, until eventually significant emission occurs over the entire visible spectrum. Integrating equation (2), one can get the total emissive power of a blackbody Emay be expressed as

$$E_b= {}_0 \frac{C_1}{{}^5 \exp(C_2 / \ T) \ \ 1} d \qquad [5]$$

Performing the integration, the following equation is obtained.

$$E_b= \quad T^4 \qquad [6]$$

Where the Stefan-Boltzmann constant, which depends on C_1 and C_2, has the numerical value σ = 5.670 x10^{-8} W/m^2.K^4.This is wellknown as Stefan-boltzmann law. It enables calculation of the amount of radiation emitted in all directions and over all wavelengths simply from knowledge of the temperature of the blackbody.

Most objects do not operate as perfect blackbodies over the entire electromagnetic spectrum, but instead the emission is altered by any or all of the following three factors: light may be absorbed, reflected, or transmitted. When an object falls between a blackbody and a perfect reflector, it is known as a Gray body. For most objects, the deviation from a blackbody is wavelength dependent, meaning that an object may act as a blackbody, gray body, and perfect reflector at different wavelengths. White paint, for example is white in the visible, grey around 2 μm, and it becomes black past 3 μm. To mathematically account for the differences created by the deviations from blackbody radiation, the material property of emissivity (ε) is used. The emissivity is the ratio of the emission of an object(Eλ, T) to that of a blackbody (Eλ, b) at a particular wavelength and is mathematically represented as follows

$$\varepsilon= \frac{E_{\ ,T}}{E_{\ ,b}} \qquad [7]$$

The emissivity ranges in value from 1 for a true blackbody to 0 for a perfect mirror. By knowing the emissivity at the wavelengths that are measured, the Stefan-Boltzmann equation can be adjusted to accurately calculate the temperature from the measured emittance. The property is purely experimental with no theoretical basis, requiring the values to be measured[12]. Additionally, changes due to temperature and geometry will alter the emissivity values of materials. It is also important to note that emissivity values are reported in several different forms. Spectral data is a function of wavelength and is commonly used for temperature measurements. Total emissivity is measured at a specific temperature and is typical of heat transfer data. Monochromatic data is specified for a very narrow range of wavelengths[13].Table 2 shows the emissivity of some common material including paper.[14]

Types of Thermography:

IR thermography can be divided into two types, the passive and the active type. In passive thermography, the temperature gradients are present in the materials and structures under tests naturally. In active thermography, the relevant thermal contrasts are induced by an external stimulus [15].

The passive method has been widely applied in diverse areas such as production, predictive maintenance, medicine, detection of forest fire, thermal efficiency survey of buildings,

Table 2

Material	Emittance
Glass	0.86
Wood	0.90
Vinyl tape	0.90
Paper	0.90
Gold	0.02
Shiny aluminium	0.04
Common paint	0.09

Table- Advantages and limitations of IR thermogrphy.

Advantages	Limitations
1) It is non-destructive test method. 2) It is capable of catching moving targets in real time. 3) Able to find deteriorating components prior to failure. 4) Make easier to find defects in shafts and other metal parts. 5) Measurement in areas inaccessible or hazardous for other methods.	1) Ability to only measure surface areas. 2) Images can be hard to interpret accurately even with experience. 3) Duality cameras are expensive and are easily damaged. 4) Most cameras have ±2% or worse accuracy (not as accurate as contact).

road traffic monitoring, agriculture and biology, detection of gas and in NDT. In all these applications, abnormal temperature profiles indicate a potential problem to take care of.

The use of active thermography is increasing in numerous applications in non destructive evaluations. Various models of active thermography are: pulsed thermography, vibrothermography and Lock-In thermography.

Pulsed thermography:

The most popular thermal simulation method in IR thermography is pulse thermography. One reason for its popularity is the quickness of the inspection relying on a thermal stimulation pulse, with duration going from a few ms(milliseconds)for high thermal conductivity material inspection (such as metal parts) to a few seconds for low thermal conductivity specimens (such as plastics, graphite-epoxy components)[16]. The presence of defect reduces the diffusion rate so that when observing the surface temperature defects, appear as different areas with respect to surrounding sound areas. Observation time 't' is a function of the squared of the depth 'Z' and the loss of thermal contrast c is proportional to the cube of the depth. Where is the thermal diffusivity of material.

$$C \sim 1/Z^3 \text{ and } t \sim Z^2/\alpha \qquad [8]$$

Vibrothermography:

Vibrothermography is a technique where under the effect of mechanical vibrations induced externally to the structure direct conversion from mechanical to thermal energy occurs and the heat is released by friction precisely at locations where defects such as cracks and desalinations are located. The advantage and disadvantage of vibrotherography includes, detection of flaws is better than any other infra red thermography schemes, ability to inspect large structural areas, whereas mechanical loading might be sometimes difficult.

Lock-In thermography:

Lock-in thermography (or LT) is based on thermal waves generated inside the specimen under study in the permanent regime. Here, at a frequency , the specimen is submitted to a sine-modulation heating ,which introduces highly attenuated and dispersive thermal waves of frequency inside the material (in a close to the surface region).These waves are known as “thermal waves”. The resulting oscillating temperature field in the stationary regime is remotely recorded through its thermal infrared emission with the infrared camera. The lock-in terminology refer to the necessity to monitor the exact time dependence between the recorded temperature signal and the reference signal (i.e. the sine-modulation heating).This can be done with a lock-in amplifier in a point by point laser heating or with a computer in full-field deployment. In LT, phase and magnitude images become available through simple manipulations of thermograms recorded in the permanent regime. A thermogram is a mapping of the emitted thermal infrared power while a phase image is related to the propagation time and a modulation image is related to the thermal diffusivity. A strong point of LT for NDE is the phase image which is relatively independent of local optical surface features (such as non-uniform heating).

The depth range of magnitude image is roughly given by the thermal diffusion length μ expressed by

$$\mu = \frac{2K}{c}^{\frac{1}{2}} \qquad [9]$$

With thermal conductivity K, P density, specific heat c and modulation frequency. In the case of phase images the depth range is about twice larger . Equation (9) indicates that higher modulation frequencies will restrict the analysis in a near surface region while lower frequencies will allow to probe deeper under the surface.

Applications in Paper Industry

The use of IR thermal imaging has increased in the paper industry in recent years(17-28). Most of the applications in areas of general maintenance are discussed with respect to electrical, mechanical, and infrastructure in paper industry. A few of the many other uses for IR thermography in the paper industry are given below.

1) **CD moisture profiling in paper reel:** The variations in the sheet moisture at the reel are usually found to correlate with the temperature difference. Paper with lower moisture content is warmer as compared to that at higher moisture content.

2) **Monitoring of the refractory lining of lime kilns:** Any fault in lining will result in abnormal temperature profile in the kiln.

3) **Identification of defective stream traps:** Improper temperature differential between inlet and outlet of the trap would indicate malfunction of the trap and wastage of energy.

4) **Monitoring of condition of thermal insulation of process equipment:** Areas of a boiler, digester or other equipments where the insulation is inadequate can be located.

5) **Monitoring of motors:** Conditions such as inadequate air flow, partial discharge, unbalanced voltage, bearing failure, insulation failure and degradation in the rotor or stator can be identified. Abnormal thermal patterns can also identify misalignment in couplings when these devices are used in conjunction with motors.

6) **Monitoring of performance of Yankee dryers:** Problems such as excessive edge wear, repetitive surface wear, out-of-round dryer, skipped crepes, excessive doctor blade loading, sheet plugging, uneven dryer coating, steam leaks and many more, can be detected.

7) **Detection of stickies:** Due to different thermal conductivity, it is easy to identify based on the relative cooling that each achieves following a period of heating [25]. This method showed promising results for pure stickies, but mill stickies are nearly always a mixture of several adhesives, reducing the accuracy of the method.

8) **Evaluation of thermal properties of paper:** A study of temperature gradients induced by local heating of a paper specimen will enable accurate determination of such thermal properties of the paper as thermal conductivity, and specific heat.

9) **Evaluation of loadability of fiber:** IR thermography can be used to monitor the temperature of a fiber as it is placed under stress. This provides information about the deformation in the fiber and its load-carrying ability [27].

10) **Paper quality:** Common product quality issues such as cockle and curl can be quantified using IR thermography with controlled heating or cooling of a sheet of paper in contact with a flat surface. The areas where the paper does not touch the surface because of cockle or curl will show different temperatures [28].

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