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Review

Infrared thermography for condition monitoring – A review

S. Bagavathiappan, B.B. Lahiri, T. Saravanan, John Philip *, T. Jayakumar

Radiography & Thermography Section (RTS), Non-Destructive Evaluation Division, Metallurgy and Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, Tamil Nadu, India

HIGHLIGHTS

- Infrared thermography (IRT) is a non-contact condition monitoring (CM) tool.
- We review the advances of IRT for CM of machineries, equipment and processes.
- Applications in various industries are covered in this critical review.
- Basics of IRT, experimental procedures and data analysis techniques are reviewed.
- Sufficient background information for the beginners and non-experts are provided.

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ABSTRACT

Temperature is one of the most common indicators of the structural health of equipment and components. Faulty machineries, corroded electrical connections, damaged material components, etc., can cause abnormal temperature distribution. By now, infrared thermography (IRT) has become a matured and widely accepted condition monitoring tool where the temperature is measured in real time in a non-contact manner. IRT enables early detection of equipment flaws and faulty industrial processes under operating condition thereby, reducing system down time, catastrophic breakdown and maintenance cost. Last three decades witnessed a steady growth in the use of IRT as a condition monitoring technique in civil structures, electrical installations, machineries and equipment, material deformation under various loading conditions, corrosion damages and welding processes. IRT has also found its application in nuclear, aerospace, food, paper, wood and plastic industries. With the advent of newer generations of infrared camera, IRT is becoming a more accurate, reliable and cost effective technique. This review focuses on the advances of IRT as a non-contact and non-invasive condition monitoring tool for machineries, equipment and processes. Various conditions monitoring applications are discussed in details, along with some basics of IRT, experimental procedures and data analysis techniques. Sufficient background information is also provided for the beginners and non-experts for easy understanding of the subject.

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* Corresponding author. Address: Head, Smart Materials Section, Radiography & Thermography Section, Non-Destructive Evaluation Division, Metallurgy and Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamil Nadu, India. Tel.: +91 044 27480500x26447; fax: +91 044 27480356.
E-mail address: philip@igcar.gov.in (J. Philip).

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1. Introduction

The process of monitoring the condition of machineries and processes is called condition monitoring. Condition monitoring aims to prevent unplanned breakdowns, maximize the plant availability and reduce associated hazards. It enables detection of problems before a major malfunction of a machine or component. E.g. The wear and tear of oil and gas pipelines, internal leakages in valves and pressure vessels, etc. can be catastrophic as they can lead to explosions and fire [1]. For aerospace, civil and mechanical engineering infrastructure industries, the process of implementing a damage identification strategy for condition monitoring is known as structural health monitoring (SHM) where damages are defined as changes to the material and geometric properties [2]. Unpredicted failure of machineries and components in industries may result in major accidents and huge economic losses, which warrant regular maintenance of those machineries and components. In large scale industries, the maintenance cost can be as high as 40% of the total budget [3]. Apart from financial losses, poor maintenance of machineries also leads to major accidents which may cause environmental pollution and damage to human lives. Table 1 shows the principal causes behind major accidents [4]. It is evident from the table that mechanical failure causes 38% of all major accidents, which stress the importance of efficient condition monitoring practices. Bragatto et al. observed that, risk based inspection is an essential requirement for sustained operation of critical industrial components [5]. The principal objective of an efficient condition monitoring system is to detect process, component and machine faults, thereby, enhancing the quality of manufactured products and reducing the down time and maintenance cost [6]. Several NDT techniques such as radiography, eddy-current testing, ultrasonic testing, acoustic emission and vibration analysis are routinely used for condition monitoring. It is well known that temperature is one of the most useful parameter that indicates the structural health of an object [7]. Therefore, monitoring the temperature of machineries or a process is undoubtedly one of the best predictive maintenance methodologies. Various temperature measurement systems like thermocouples and resistance temperature detectors (RTD) are in general contact type and does not provide a visual image of the object under investigation. Infrared thermography (IRT) is a novel NDT method that measures the temperature of a body remotely and provides the thermal image of the entire component or machinery. In general, faults associated with abnormal temperature distribution can be easily detected by IRT in advance that allows preventive maintenance before failure.

IRT has been successfully utilized for several condition monitoring applications such as civil structures [8–10], inspection of electrical equipment [11–13], monitoring of plastic deformations [14], inspection of tensile deformation [15–17], evaluation of fatigue damages in materials [18–20], inspection of machineries [21–23], weld inspection [24–27], monitoring of electronic printed circuit boards (PCBs) [28–30] and evaluation of chemical vapor deposition process [31]. IRT has also been utilized in nuclear [32–34], aerospace [35,36], food [37], wood [38], high-level current density identification over planar microwave circuit sectors [39] and paper industries [40,41]. Basics of IRT methodology, operating principle of infrared camera and applications of IRT in building envelope inspection, roof inspection, electrical and mechanical inspection, detection of buried objects, surveillance, process control and condition monitoring of power distribution systems have been discussed in detail by Holst [42]. Applications of IRT for condition monitoring purposes in various fields like nuclear, electrical, PCBs, aerospace, civil, etc. are also described by Reeves [43] and Maldague [44]. Origin of IRT, development of infrared detectors, perspective of IRT applied to building science, application of IRT to thermo–fluid dynamics and combustion systems are well described in a recent book edited by Meola [45]. In this article, we review the applications of IRT in the field of condition monitoring with typical case studies. We also describe the basics of IRT with theoretical background, developments of infrared camera over the last few decades, experimental methodologies and data analysis techniques.

2. Background of IRT and infrared cameras

The origin and theory of IRT has been described in detail elsewhere [46]. For completeness, the basic theory and the fundamental equations are described here. All objects with temperature above 0 K (i.e. −273 °C) emits electromagnetic radiation in the infrared region of electromagnetic spectrum. Infrared radiation (wavelength in the range of 0.75–1000 μm) is positioned in-between microwave and visible part of the electromagnetic spectrum. This vast range can be further subdivided into near infrared or NIR (0.76–1.5 μm), medium infrared or MIR (1.5–5.6 μm) and far infrared or FIR (5.6–1000 μm). In 1800, Sir William Herschel discovered infrared radiation and the recording of the first thermal image was done by his son John Herschel which added new dimension to the temperature measurement. It took almost two centuries to adopt IRT in civilian domain mainly because of non-availability of quality equipment and technical knowhow.

In thermal radiation theory, blackbody is considered as a hypothetical object which absorbs all incident radiations and radiates a continuous spectrum according to Planck's law as follows.

$$L_\lambda = \frac{c_1}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T}\right) - 1\right]} \tag{1}$$

where λ is the wavelength of the radiation (μm), L_λ is the power radiated by the blackbody per unit surface and per unit solid angle for a particular wavelength (W m^{-2} μm^{-1} sr^{-1}), T is the temperature in absolute scale (K), c_1 and c_2 are the first and second radiations constants respectively. On integrating Planck's law over all

Table 1
Principal causes behind major accidents [4].

Causes	Frequency
Mechanical failure	38
Operational errors	26
Unknown/miscellaneous	12
Process upset	10
Natural hazards	7
Design errors	4
Arson/sabotage	3