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Infrared Imaging Analysis as Non-Destructive Maintenance of Food Processing Equipment

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A B S T R A C T

The use of infrared imaging is a recently developed non-destructive tool to assess the safety, quality and efficiency of the food industry. This article explores the application areas and benefits of using infrared imaging in the maintenance of machinery used in the food industry. Applications covered include food quality control, packaging inspection, temperature monitoring and control, hygiene and sanitation control, foreign object detection, energy saving through optimization, baking, as well as cooking process monitoring and research. By using infrared cameras to their full potential, it is possible to reveal defects, check the level of cleanliness, optimize the maintenance of machines, and examine the thermal attributes of food. This article also provides an in-depth analysis of the historical development of infrared imaging technology. We also explore the basic ideas behind infrared image analysis. This includes the Stefan-Boltzmann Law, Planck's Law, and Wien's displacement law. Infrared image analysis has many advantages and some disadvantages. Despite these drawbacks, infrared imaging analysis has continued benefits. It saves costs, ensures equipment longevity and increases productivity. This makes it very important for the safety of food industry machinery.

1. INTRODUCTION

Food processing equipment is often subjected to infrared imaging analysis. It helps detect temperature changes and potential hot spots without damaging the machines.

Infrared imaging analysis for the study of heat patterns in machines began in 1914 [1]. It was then that the first infrared detector was patented. Going back to 1929, a Hungarian physicist named Kalman Tihanyi invented an infrared sensitive electronic camera - night vision technology for British air defense [1]. Since then, infrared detectors have become more sophisticated and sensitive. Now even small temperature changes can be easily detected using this amazing technology.

Noticing hot spots is key for food factories. Cameras see heat, spotting issues. Machines get extra warm if struggling. Infrared imaging helps catch odd temperatures. Lasers identify problems for examination. Hot areas may mean part failure soon. Figure 1 shows an infrared camera setup. Visual cameras pair with thermal detecting ones. Timely repairs prevent breakdowns and losses.

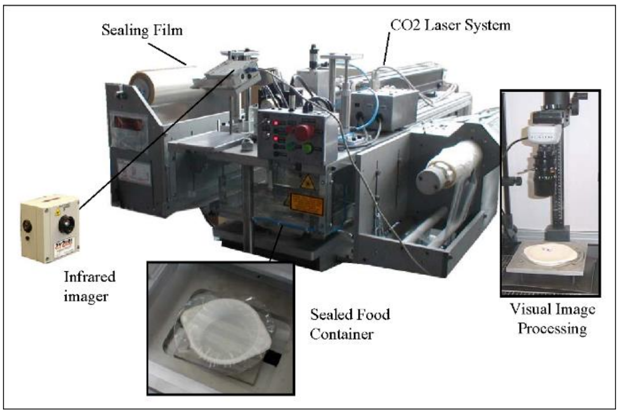

Fig. 1. The setup for experiments had an infrared camera, a visual camera, and a laser device [2].

The Stefan-Boltzmann Law links infrared imaging and thermal analysis. It explains how black bodies emit radiation totally. A black body absorbs all incoming radiation perfectly. The Law uses formula (1) to describe the radiant emittance, which is the total radiation emitted:

$$Q=\varepsilon\cdot\sigma\cdot A\cdot T^4 \quad (1)$$

The complete radiant energy given off is Q. ε shows how easily an object radiates heat, from 0 to 1. σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), A represents the surface area. T is the object's absolute temperature in Kelvin [3].

A key law when talking about food processing machinery is Planck's law. It describes how much infrared radiation emitted from a blackbody at a specific temperature and wavelength [4]. This law is really important to understand the relationship between temperature and how intense infrared radiation is emitted. The formula for Planck's law is shown in equation (2):

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1} \quad (2)$$

The intensity (I (λ, T)) is decided by lots of things. These are h, c, K, B, λ, and T. h is the Planck constant, c is the speed of light in a vacuum, K is the Boltzmann constant, B is the wavelength, and T is the absolute temperature [5]. The observed spectrum aligns closely with Planck's law, indicating a well-fitted relationship.

Emissivity is another essential factor in infrared imaging and thermography. Emissivity has determined good sized application in infrared thermography, enabling the non-contact temperature evaluation of objects. In this method, infrared cameras capture the emitted infrared radiation from an item, and the emissivity value is employed to compute its temperature [5].

Emissivity is a dimensionless value ranging from 0 to at least one, where zero indicates an excellent reflector (no emission) and 1 a great emitter [5]. The relationship among the emitted radiation and the radiation of a black body is given by using equation (3):

$$E_{object} = \varepsilon \times E_{black\ body} \quad (3)$$

Where E_{object} is the emitted radiation from the object, ε is the emissivity of the material, and $E_{black\ body}$ is the radiation emitted through a black body. This relationship underscores how the emissivity element (ε) affects the quantity of radiation emitted by using an object in comparison to the radiation emitted via an idealized black frame. An emissivity factor, which refers to the efficiency of a substance in emitting infrared radiation, with higher values indicating a better resemblance to a large emitter.

Wien's Displacement Law is an essential equation in thermal radiation that relates the height wavelength of the spectral radiance of a black body to its temperature. The regulation states that the wavelength of maximum emission (λ_{max}) is inversely proportional to the temperature of the black frame (T) [6]. The equation for Wien's Displacement Law is given by using equation (4):

$$\lambda_{max} = \frac{b}{T} \quad (4)$$

Here, λ_{max} is the wavelength of maximum emission, T is the temperature of the black body in Kelvin, and b is Wien's displacement constant, that's equal to $2.897771955 \times 10^{-3}$ m K.

2. MATERIALS AND METHODS

2.1 Principles of infrared imaging in maintenance

The Imaging Principle of Infrared Thermal Camera is a generation that makes use of an infrared thermal digicam to come across the infrared radiation emitted by items in a non-contact way. At the same time, after detecting the radiation strength of rotating machinery, the surface temperature of the object may be calculated in actual time in keeping with the Stefan–Boltzmann law. Because the temperature distribution at the surface of rotating machinery is one of a kind in the course of operation, the radiation intensity at the surface is special. The thermal photos amassed via the infrared thermal digicam use unique colors and brightness to represent different radiation intensities, so exceptional radiation intensities correspond to one-of-a-kind surface temperatures.

As proven in Figure 2, the infrared thermal photo of a reducer test bench may be used to reveal the surface temperature of the whole reducer. If the reducer is about to fail or has failed, its fitness states may be judged consistent with the shade distribution of the infrared thermal image or the abnormal temperature of a pixel.

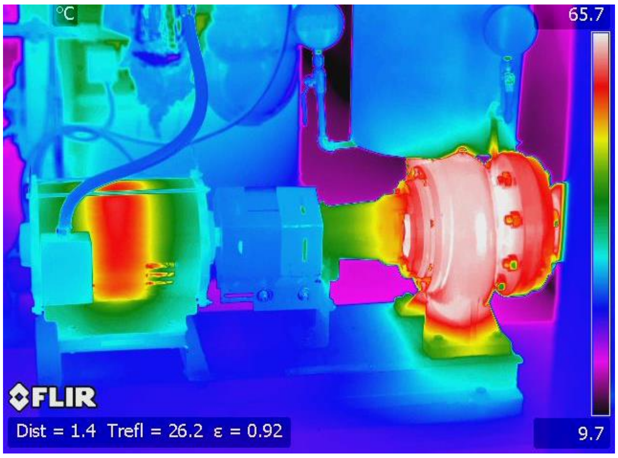

Fig. 2. Picture of a reducer taken with infrared thermograph [7].

As demonstrated in Figure 2, the infrared thermal picture naturally displays the temperature field distribution on the equipment surface using a range of color schemes and provides comprehensive health information about the equipment. The key component of Infrared Thermal Camera systems are infrared thermal cameras.

The structure and capabilities of the infrared thermal camera have grown increasingly sophisticated and intelligent with the quick advancement of current science and technology, and they have been progressively implemented into a wide range of industrial and human endeavors [8]. Typically, an optical device, infrared detector, video amplifier, and display make up an infrared thermal camera. Object characteristic information is carried by infrared radiation, and this information can be used objectively to discriminate between different measured object temperatures and thermal distributions using infrared remote sensing technology.

Table 1. Structure and principle of infrared thermal camera.

Component	Description
Optical Device	The optical tool of an infrared thermal digicam includes lenses and other optical elements that cognizance incoming infrared radiation onto the camera's detector array. It determines the field of view (FOV) and spatial decision of the digital camera.
Infrared Detector	The infrared detector array is the center detail of the thermal digicam, comprising thousands of individual detector factors (pixels). Each pixel is sensitive to infrared radiation and converts it into an electrical sign.
Video Amplifier	The video amplifier processes the electrical signals generated by the detector array. It amplifies, digitizes, and analyzes the signals to extract temperature information from the detected infrared radiation.
Display	The display system of the infrared thermal camera visually represents the processed thermal data. It presents the thermal image of the observed scene, where different colors or shades represent different temperature levels, allowing users to visualize temperature variations.

Because of this feature, the video amplifier can simulate the spatial distribution of the temperature on the object's surface after the optical device and the infrared detector convert the power signals emitted by the object's heating component into electrical signals. Eventually, the system processing creates the thermal image video signal, which is then sent to the display to produce the infrared thermal image - the thermal picture that corresponds to the temperature distribution on the object's surface. Table 1 summarizes the structure and imaging principle of an infrared thermal camera, highlighting the roles of its key components in capturing and visualizing thermal radiation emitted by objects.

2.2 Advantages of infrared imaging analysis

Here are several key advantages of using infrared imaging analysis in the food machines and equipment. Firstly, thermal image analysis can help detect any defects early on before they become more serious by providing insight into the distribution and patterns of temperature in machine components. Several studies have shown that thermal imaging is a useful tool for identifying a wide range of problems, including gear, bearing, and motor failures.

The primary benefit of Infrared thermal camera-based fault detection and condition monitoring technologies is their reduced instrumentation requirements. An infrared thermal camera, a tripod, and a video output unit for displaying the captured infrared thermal pictures are the three main pieces of hardware needed for this application. A typical Infrared thermal camera experimental device is schematically shown in Figure 3, together with the infrared thermal camera, display, and original photos of the gear reducer taken during the process.

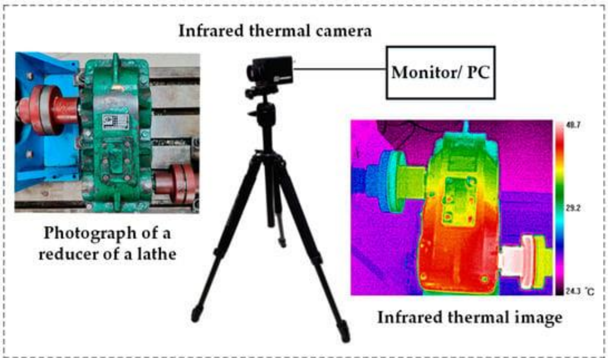

Fig. 3. A schematic illustration of the experimental setup for Infrared thermal imaging [9].

In the area of motor diagnostics, infrared imaging analysis demonstrates promise in identifying various types of failures such as misalignments, cooling issues, bearing damage, and connection defects [10]. Its application extends to the detection of faults encompassing electrical, mechanical, thermal, and environmental factors in field induction motors.

Infrared imaging is an emerging, non-invasive method suitable for the food industry [11]. Recent advances and ability packages of infrared imaging for food protection and excellent assessment, including temperature inspection and foreign frame detection, and food quality evaluation, are reviewed [12].

According to Jonathan Trout, Noria Corporation, infrared imaging analysis can provide valuable insights into the efficiency of food processing operations [13]. By monitoring equipment temperature profiles, operators can pick out regions of overheating, underutilization, or inefficiencies in warmth switch. This statistics may be used to streamline tactics, boom throughput, lessen processing time, and improve average productiveness.

According to Fluke Corporation's web article named as Thermal Imaging, Fundamentals, infrared imaging analysis can prevent costly damage to food machines and equipment. By detecting abnormal temperature gradients or excessive heat build-up, operators can intervene to prevent equipment overheating, component failure or fires. Timely preventive measures can extend the service life of equipment and reduce the need for costly repairs or replacements [14].

Infrared image analysis can help food manufacturers meet regulatory compliance requirements [15]. By controlling the temperature of the equipment, it ensures that the food machines and equipment meet the specified temperature ranges for the different processing stages. This helps maintain optimal conditions for food safety and meet regulatory standards.

2.3 Disadvantages of infrared imaging analysis

Infrared imaging analysis has won considerable attention inside the food industry as a non-destructive and non-touch approach for assessing the first-class and safety of food merchandise. However, like every other generation, it additionally has its obstacles and downsides. In this section, we can explore some of the important hazards of using infrared imaging evaluation in food production machines and equipment.

Infrared imaging is in the main designed for surface analysis, limiting its potential to discover troubles which are positioned deeper inside equipment. For example, when examining apple tissues, the penetration depth of light was observed to be approximately 1.8 to 2.3 mm [16]. Consequently, defects or damages occurring beyond this range may escape detection using this technique.

The accuracy of infrared imaging analysis can be affected by the surrounding environment, such as ambient temperature, humidity, and other factors. According to RF Wireless World, interpreting infrared images becomes challenging when dealing with objects exhibiting erratic temperatures [17]. This implies that variations in the surrounding temperature can potentially impact the accuracy of the infrared imaging analysis.

According to RS Components LTD, UK, materials such as metal, glass, or liquids have the capacity to reflect radiation from external sources, leading to distortions in thermal images [18]. These reflections may generate hot spots or inaccurate readings.

According to Teledyne FLIR LLC, implementing infrared imaging analysis in food machines and equipment requires investment in specialized hardware and software, which can be costly [19]. This initial investment may pose a financial barrier for small or medium-sized food businesses, limiting their ability to adopt this technology.

To ensure accurate and reliable results, infrared imaging analysis requires proper calibration [20]. This calibration process can be time-consuming and requires skilled technicians to set up and maintain the system.

Additionally, according to Quantum Food Solutions, regular recalibration may be needed to ensure continued accuracy, adding to the operational costs [21].

Infrared imaging may not be applicable to all food products or every stage of the food supply chain. For instance, it may be less proficient in identifying specific contaminants or evaluating certain quality attributes [22]. This limited applicability can restrict the overall usefulness of this technology in certain food processing and manufacturing settings.

3. RESULTS AND DISCUSSION

In the food enterprise, infrared imaging plays a crucial function throughout diverse machines and strategies, making sure product first-rate, safety, and efficiency. Some of the main areas where infrared image analysis is commonly applied are as follows:

Quality control of food products: Infrared imaging analysis is used to evaluate the first-rate of food products by way of detecting defects together with bruising, discoloration, and irregularities in shape or size. For instance, infrared cameras can pick out internal defects in end result without the want for physical contact or invasive methods [23].

Packaging Inspection: Infrared imaging is employed to look into packaging substances for defects, leaks, or seal integrity problems. This ensures that packaged meals merchandise stay protected from contamination and keep their freshness [24].

Temperature Monitoring and Control: According to GAO Tek organization, infrared thermography is applied for tracking and controlling temperature for the duration of meals processing and storage [25]. It facilitates in identifying hotspots or temperature versions in equipment like ovens, fridges, and freezers, ensuring that food is cooked or stored at the appropriate temperatures to prevent spoilage and ensure food safety.

Sanitation and Hygienic Monitoring: Infrared imaging is used to discover microbial infection and determine cleanliness in food processing equipment and centers. It can pick out areas with residual organic depend or microbial growth, allowing for targeted sanitation efforts to keep hygienic situations [26].

Detection of Foreign Objects: Infrared cameras are employed to come across foreign items along with metallic, glass, or plastic contaminants in food merchandise [27]. By analyzing differences in material composition and density, infrared imaging can become aware of foreign objects even within complex meals matrices.

Energy Efficiency in Food Processing: Infrared imaging is applied to optimize electricity usage in food processing system by way of identifying regions of warmth loss or inefficient warmness distribution [28]. This facilitates in improving strength efficiency and decreasing operational costs.

Baking and Cooking Process Monitoring: Infrared cameras are used to reveal the baking and cooking techniques in industrial ovens and fryers [29]. They offer real-time temperature profiles of food products, ensuring uniform cooking and satisfactory consistency.

Research and Development: Infrared imaging evaluation is utilized in food research and development to observe thermal residences, moisture content material, and texture of food merchandise. It aids in developing new products, optimizing processing strategies, and enhancing overall product quality [30].

These application areas spotlight the flexibility and importance of infrared imaging analysis in ensuring the high-quality, protection, and performance of food enterprise machinery and process.

4. CONCLUSION

To conclude, infrared imaging evaluation is an effective tool in the food industry. It gives a non-touchable and non-destructive manner to assess the first-class, protection, and efficiency of food processing tools and operations. By the use of infrared cameras, food producers and processors can remedy many problems and enhance special elements of their paintings.

Firstly, Imaging analysis enables pick out defects in food merchandise without destructive them.
Secondly, it is able to additionally be used to check if food packaging is properly sealed. Infrared cameras can decide the temperature of the food before and after cooking or garage.

Additionally, they also can be used to pick out any debris or impurities on a surface, which allows to ensure hygienic popular situations are properly stored.

Lastly, infrared imaging evaluation is beneficial for research and improvement in the food industry. It allows scientists to take a look at the residences of food like heat distribution, moisture levels, and texture. This know-how can cause new product ideas, better approaches of making food, and universal improvements.

While there are some obstacles to the use of infrared imaging evaluation (like the ability to examine surfaces), its lengthy-term advantages outweigh the demanding situations. These advantages include saving costs on maintenance, increasing productivity, and making sure that food is safe to eat.

Overall, infrared imaging analysis is an essential technology for the food industry, driving advancements in excellent assurance, procedure optimization, and product innovation. As technology advances, we will see even more ways that infrared imaging analysis can help a food business grow and succeed.

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