Application of Infrared Thermography in Chemical Engineering

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N. Bolf

University of Zagreb, Faculty of Chemical Engineering and Technology
Savska c.16/5a, 10 000 Zagreb, Croatia
Phone: + 385 1 4597 151; Fax: + 385 1 4843 556
E-mail: bolf@fkit.hr

The infrared (IR) thermography has become a powerful tool for basic and applied research in various scientific fields, varying from heat transfer to non-destructive testing, fluids and solids mechanics, biomedical application, environmental protection, etc.

This paper has the intention to familiarize researchers and industrial staff with possibilities of applying IR thermography in the field of chemical engineering and process industry aiming in safe operating, saving of energy and environmental protection.

A brief history of the IR thermography development, basic function principles of a modern system for thermographic measurements, and application overview have been shown. Following applications have been highlighted: nondestructive testing, preventive maintenance, and condition monitoring of process equipment. A special attention has been paid to industrial application regarding quality control and process control.

Keywords: *Infrared thermography, process diagnostic, non-destructive testing, process control, quality control*

Introduction

All the objects are characterized by a variety of physical quantities such as dimensions, shape, and mass. However, the most frequently measured physical property is temperature. Heat from electrical, mechanical or chemical activity is a byproduct of all processes. Unexpected temperature variation my indicate design flaws, poor workmanship, or damaged components. Excessive temperatures often exhibit just before failure.

Temperatures may be measured with either a contact or non-contact devices. Contact device includes the common liquid-in-glass thermometer, resistance thermometer, thermistor and thermocouple. Non-contact devices may be either non-imaging or imaging systems. A non-imaging system (such as a radiometer) simply measures the radiation. The system's calibration converts the output voltage to a temperature. Imaging systems create a two-dimensional electronic image of an object. As with the radiometer, the imaging system measures the power radiation that appears to emanate from the object, where calibration provides a two-dimensional representation of the surface temperature.

The major advantage of thermography is the large number of possible industrial applications. Temperature and thermal behavior of plant machinery, power generation and distribution equipment, materials and fabricated parts in process, are the most critical factors in the manufacturing process and maintenance of safe and cost-effective plant operation. Also, it is mostly non-hazardous to personnel and workplace, immune to electromagnetic noise, applicable to explosive environments and reliable.[1] The industrial application of IR thermal imaging as a diagnostic monitoring tool has increased as a result of technological advancements associated with imaging and software, resulting in extremely reliable and portable measurement instruments.

Brief history of IR thermography

In 1800, *William Herschel* discovered infrared rays. Later, *John Herschel* in 1840 produced the first infrared image. In 1929 *Czerny* provided an improvement to image creation. In 1946, when the military developed the first infrared line scanner by putting many lines together, a two-dimensional image was created. By adding a scanner (1954), the system could directly create a two-dimensional image. 1966 could be considered the year that thermal imaging systems, as we them know today, were created. Rapid advances in technology, stimulated by expanding applications, occurred in '60s, '70s, and '90s.

The greatest advances in system design occurred in the '90s: the introduction of high-resolution focal plane arrays (FPAs) and uncooled microbolometers 320 x 240 pixels. Solid-state electronics and no moving parts allow focal-plane arrays to provide real-time images with more details and better resolution of a relatively large area than is possible with the more mechanically complex optomechanical technology.

Today, thermal imaging technology has advanced to a level that makes it portable, affordable and easy to use, Fig. 1.

Fig. 1 — *The state of the art - non-cooled thermal imaging portable camera*

Slika 1 — *Najsuvremenija prijenosna nehlađena infracrvena kamera*

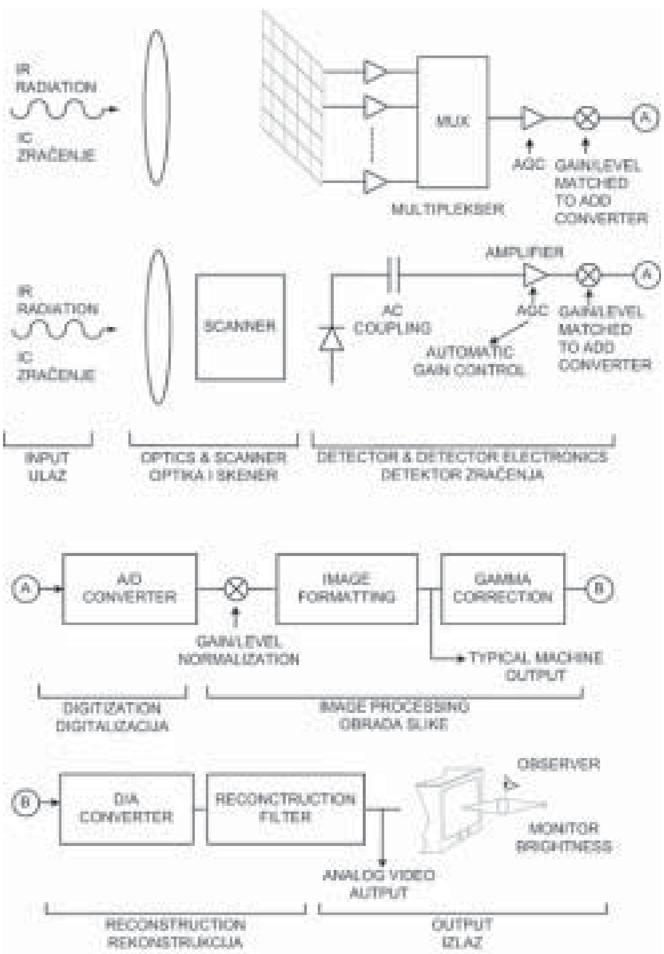

Fig. 2 — *The functional electro-optical block diagram of thermographic system*

Slika 2 — *Funkcijski elektro-optički prikaz termografskog sustava*

Imaging systems can now produce hundreds of images per second and high-speed electronics provide real-time image processing. An added benefit is the ability to store digitized images in computers for more extensive analyses. There are five major subsystems of IR camera: optics & scanner, detector, digitalization, image processing, and image reconstruction, Figure 2.[2]

Due to the fact that there is the number of many commercial applications, various terminologies appeared. Nondestructive testing (NDT), nondestructive inspection, (NDI) and nondestructive evaluation (NDE), are names for describing methods of testing without causing damage to object being tested. *Vavilov*[3] offered the following definitions:

Thermography - method of determining the spatial distribution of heat in objects.

Thermal nondestructive testing - material inspection by monitoring heat flux disturbances caused by defects.

Thermal wave nondestructive testing - nondestructive testing where heat is applied in a periodic fashion.

Measurements can be either qualitative or quantitative:

a) *Qualitative thermography measurements* rely on analysis of thermal patterns to reveal the existence and locate the position of anomalies and evaluate them.

b) *Quantitative thermography measurements* use temperature measurements as a criteria to determine the seriousness of an anomaly, in order to establish repair priorities.

Interpretation of the results of infrared inspection depends upon decisions made by the observer. To obtain any degree of consistency, it is assumed that the observers are qualified. Both qualitative and quantitative infrared techniques require a high level of training and knowledge. Training occurs in many venues, including formal short courses, attendance at conferences, and interaction with other industry professionals and ITC.

Application overview

A change in temperature may indicate a change in an object's operating condition. By monitoring an object's temperature, we can assess its "health". Any thermal anomaly, whether the presence of heat or the absence of heat, may suggest that a problem exists.

Condition monitoring and predictive maintenance activities have many well-defined application. Others include medical, biological, geological, and remote sensing applications. Many research and development endeavors have employed or at least cosider the possibility that a thermal imaging system can provide answers that cannot be elicited by other means.

Predictive maintenance is the periodic testing and monitoring of equipment. It is generally used to plan activities for maintaining equipment to assure longer life of equipment. The results of the predictive maintenance determine when preventive maintenance should take place.[4]

Nondestructive testing

Nondestructive testing (NDT) combines thermal imaging and controlled heat injection. Although called "heat injection", it is actually flooding the surface for a brief amount of time with radiation. The heat may be injected as impulse (flash pulse), wide pulse, or a series of periodic pulses. The radiation (heat) may be applied by high intensity xenon flash lamps, lasers, incandescent lamps, or heat guns. If the surface reflectivity is low (high emissivity), the surface will heat up and then the heat will propagate (via conduction) through the material.

However, NDT methods are also implemented if there is a controllable method to reduce surface temperature. This could be done by flooding the surface with cold water, liquid nitrogen, or any other liquid that evaporates quickly.

Applications of NDT

A sampling of the rather extensive literature indicates the widespread application of this technique, including the detection of debonding in adhesive joints and honeycomb structures, voids in ceramics, hot spots in printed circuit boards, and delimitations or cracking in composites. Emerging techniques will improve defect detection capability.

In general, a good structural bond is a good thermal bond. Therefore, any deviation from structural integrity tends to modify heat flow. Voids, disbands, delaminations, foreign matter (inclusions), badly cured areas, and surface cracks can be detected. Since thermal diffusion can completely obliterate the signal from a defect, the NDT method tends to be limited to thin materials. One major advantage is that the item under test does not have to be disassembled.

Identifying the existence of voids in material is useful for evaluating the reliability, the useful life, or determining the safe loading limits of materials that require structural strength. Examples of material where this technique would prove useful include pipe line welds, turbine wheels, and ceramic components.

The information that would be useful for an NDT test system to provide would be:

1) to identify whether voids exist in the material;

2) to locate the void position, and

3) to characterize the type of defect, size, and depth.

The depth is important because it has been shown that defects that are structurally significant are usually located near the surface of the material.[5]

Much work has been performed on the newer composites. These composites are lighter, stronger, and more corrosion resistant compared to existing materials. Composites are used in automobiles, aircraft, boats, and many other components such as printed circuit boards. These materials include carbon fiber reinforced plastics (CFRP), continuous fiber ceramic matrix composites (CFCC) and glass, reinforced plastics (RP).[2]

Industrial application in the process/quality control

Within any industry that consumes energy, the importance given to energy conservation is great. The need to reduce energy consumption in the world is increasing. At the same time demand for energy seems also to be increasing.

There are many documented industrial applications of IR monitoring, particularly in the steel production, power generation, building services, automotive, paper, cement, offshore, glass and electronic industries, Table 1.[6]

Table 1 — *The industrial application of IR monitoring in Process Control / Quality Control (Source: the Academy of Infrared Thermography)*

Tablica 1 — *Industrijska primjena IR termografije na području vođenje procesa i osiguranja kvalitete (Izvor: the Academy of Infrared Thermography)*

Industry Industrija	Process control/quality control Vođenje procesa / osiguranje kvalitete
Automotive	Metal casting, refractory materials, molds, conveyors, bearings, plastics and composite testing, bumpers, tires, spot welding, forming equipment, paint process, paint curing, window defrosters, electronic parts, tires, brakes, lighting balance.
Automobilska	Lijevanje metala, vatrostalni materijali, kalupi, transporteri, ležajevi, ispitivanje plastika i kompozita, odbojnici, gume, točkasto zavarivanje, oprema za oblikovanje, procesi bojanja, sušenje boje, odmrzivači stakla, elektronički dijelovi, gume, kočnice, balansiranje svjetala.
Cement / Lime	Burning zone, kiln shell, hot clinkers, control of electrostatic filter for exhaust smoke purification.
Cementna / Proizvodnja vapna	Zona izgaranja, oplata peći, vrući klinker, provjera elektrostatskih filtara za pročišćavanje ispušnih plinova.
Chemical / Petrochemical	Pipe thinning, deposits, corrosion, furnace tube coking, refractory, insulation, steam systems, sludge levels, liquid level on storage tanks, exchanger fouling, and heat loss quantification.
Kemijska / Petrokemijska	Stanjivanje cijevi, stvaranje naslaga, korozija, stvaranje naslaga koksa na cijevima peći, vatrostalna izolacija, izolacija, parni sustavi, razina taloga/muljeva, razina kapljevina u spremnicima, naslage u izmjenjivačima i kvantificiranje toplinskih gubitaka.
Die casting and molding	Thermal distribution of mold surfaces, cooling channel blockages, prototype evaluations.
Lijevanje i kalupljenje	Toplinska raspodjela na površini kalupa, začepljenje rashladnih kanala, provjera valjanosti prototipa.

Industry Industrija	Process control/quality control Vođenje procesa / osiguranje kvalitete
Electronics	Malfunction of components on printed circuit boards, poor solder joints, shorts, and improper heat sinking.
Elektronička	Neispravnost komponenata na tiskanim pločicama, loše zalemljeni spojevi, kratki spojevi, neprikladno odvođenje topline.
Food	Energy loss, seals, insulation of freezers, baking ovens, candy/chocolate mixing, deep fat fryers, coffee roasters, drying processors, conveyors, bearings, and packaging/sealing.
Prehrambena	Gubici energije, hermetičko zatvaranje, izolacija rashladnih uređaja, pećnice, miješanje konditorskih proizvoda/čokolade, posude za prženje, pržionice kave, sušare, transporteri, ležajevi, pakiranje/hermetičko zatvaranje.
Glass	Refractory material, glass, molds, annealing, thermal monitoring of reinforced glass.
Staklarska	Vatrostalni materijali, staklo, kalupi, kaljenje, toplinsko motrenje armiranog stakla.
Metal	Temperature monitoring during melting, pouring and rolling of metals.
Metalna	Nadziranje temperature pri taljenju, lijevanju i valjanju metala.
Paper	Coating and printing of wallpaper and photographic paper, moisture profile irregularities, drying, misaligned press rolls, irregular steam distribution, bearing condition, heat ducts, defective press roll covers.
Papirna	Prevlačenje i tiskanje tapeta i fotografskog papira, neravnomjerna raspodjela mokrine, sušenje, neugođeni tlačni valjci, nejednoliko isparavanje, stanje ležajeva, parovodi, oštećenja na površini valjaka za miješanje.
Plastics	Thermoforming, bottle forming, vacuum forming, coating laminating, calendaring, fiber optic cable extrusion.
Plastična	Toplinsko oblikovanje, oblikovanje boca, vakuumsko oblikovanje, lameliranje prevlaka, kalendriranje, ekstruzija optičkih vlakana.
Rubber	Milling, mixing, molding, calendering, extruding, quality evaluation, vulcanizing, tire testing, cooling and rolling of hot rubber sheets.
Gumarska	Mljevenje, miješanje, kalupljenje, kalendriranje, ekstrudiranje, procjena kvalitete, vulkaniziranje, ispitivanje guma, hlađenje i valjanje toplih gumenih površina.
Thin films	Web monitoring, coating lamination, printing, packaging, thermal consistencies.
Tanki filmovi	Motrenje mrežaste strukture, lameliranje prevlaka, tiskanje, pakiranje, toplinska konzistentnost.

Thermal imaging is frequently used to inspect pressure vessels, heat exchangers, chillers, tanks, and piping systems. Inspection of finished products for flaws and quality control is expanding into many industries with the ability to perform image processing in real time. Applications differ from facility to facility depending upon the process equipment and the material being manufactured.

Petrochemical

Crude oil flows through process heater tubes inside a furnace. If the oil gets too hot, it cracks: hydrogen is separated from the carbon. The carbon remains in the form of coke. The coke insulates the tube wall from the cooling effect of the crude oil and that causes the tube temperature to increase further. Heater tubes fail more frequently than any other component at a refinery, Fig. 3.

Infrared radiation from the furnace flame provides significant path radiance that obscures the tubes. Fortunately, gas flames have spectral features in the infrared. A flame filter centered at 3.9 μm allows seeing though the flame and measuring the temperature of the tubes. Since oil is flowing through the tubes, they will be cooler than walls of the furnace. If coke is present, the tube temperature will increase since the coke prevents the oil from cooling the tubes.[7]

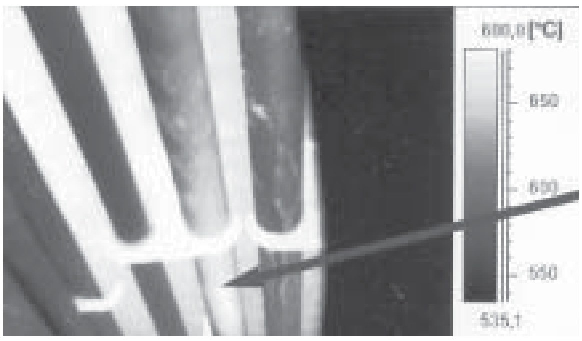

Fig. 3 — *Cracks in refinery tubes and coke build-up*

Slika 3 — *Pukotine na cijevima i naslage koksa*

Refractory

Refractory generally refers to any material with very low thermal conductivity. Refractory materials are used to line the inside of furnaces to keep the heat inside. It lowers heating costs and protects the exterior shell. In a well-designed furnace, the exterior temperature will be fairly uniform. A low temperature could mean that there is a buildup of scale. High temperatures suggest defects in the refractory, Fig. 4. The lining can crack and separate from the exterior shell. In both cases, the hot gases will affect the integrity of the exterior shell.

The temperature range requirement of refractory structures, such as kilns and furnaces can be between 0 and 1500 °C, and thermal patterns can reveal internal problems. Inspection can be carried out while the plant is operating to predict the condition and to plan any remedial maintenance.[2]

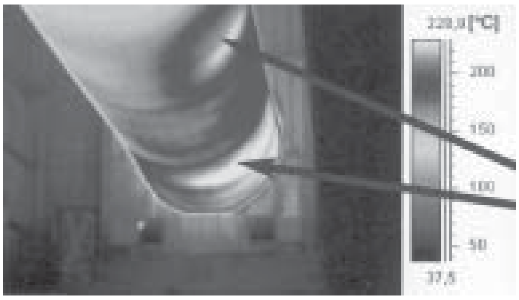

Fig. 4 — *Breakdown of refractory on a rotary cement kiln*

Slika 4 — *Propuštanje izolacije rotacijske peći pri proizvodnji cementa*

Die castings and molding

With injection molding and blow molding of plastics, quality depends upon effective heat transfer from the part to the mold. Dimensional precision and surface finish are maintained when there is a minimal temperature gradient in the part. Large complex parts can vary in thickness by a factor of 10 over a few centimeters of distance. Thermal gradients and hot spots on the part and mold create residual stresses in the part that lead to wrapage.[8]

Metals

Most metals have a low emissivity when manufactured. The emissivity increases when the surface is stained, oxidized, or scratched. The difference in emissivity creates a difference in detected radiation. As a qualitative measurement the precise value of the emissivity is not necessary. This is actually an advantage. The emissivity of the manufactured material is often not known precisely and can vary slowly. The detected radiations from the "normal" material also change slowly. This slow change can be ignored. However, a flaw or defect creates an abrupt change in emissivity with a corresponding abrupt change in detected radiation, which is a condition that is easily recorded.

For hot metals, emissivity is strongly dependent upon surface conditions. Any scratch on the material will more strongly radiate than the smooth regions due to multiple reflections between the sides of the indentation. Any void or inclusion within the metal may results in conduction properties different from metal of homogeneous composition. If these flaws are near enough to the surface, they will alter the radiance in localized regions.[9]

Steel industry

Within the manufacturing and process industry such as steel, large amounts of steam are consumed and condition monitoring plays an extremely important role, Table 2.

Many steel processing operations, such as continuous casting, hot rolling and continuous annealing, require the use of non-contact temperature measurement devices because the product moves and cannot be measured by contact means. There are requirements for non-contact temperature measurement in several common steel industry processing operations, and examples of the benefits derived from temperature sensors are presented.[10]

The temperature distributions from furnaces and sometimes the product itself can indicate the furnace and product condition. In the steel industry, location of steel strip within a furnace can be monitored by fixed thermal cameras and insulation of the furnace walls with portable thermal imaging cameras. Other examples include monitoring condition of torpedo card and basic oxygen steel-making vessels, operation of water-cooled elements and even measuring the actual product temperature.[1]

Table 2 — *Industrial applications of IR thermography within the steel industry*

Tablica 2 — *Primjena IR termografije u proizvodnji čelika*

Type of plant Postrojenje	Monitored condition Motreno stanje
Blast furnace stack and stove, hot blast main, hot metal transfer ladles and converters	Lining condition
Dimnjak visoke peći i kaupera, dovod vrućeg zraka, kutlače za prijenos sirovine i konverteri	Stanje oplate
Dirty gas mains, valve blockages, effluent gas ducting	Deposits
Nečisti plinski vodovi, začepljenje ventila, odvođenje otpadnog plina	Nataloženi slojevi
Boilers, steam distribution pipelines	Heat losses and thermal efficiency
Kotlovi, cjevovodi za distribuciju pare.	Gubici topline i toplinska djelotvornost
Boiler tubes, reheat furnaces	Thermal efficiency
Kotlovske cijevi, peći za dogrijavanje	Toplinska djelotvornost
Sinter plants, thermal profile of steel strip	Thermal efficiency
Postrojenja za sinteriranje, toplinska raspodjela u čeličnim trakama	Toplinska djelotvornost

The condition of the refractory lining of a converter is usually monitored by periodically measuring the wear of the wall with a laser measuring device during shutdowns or between heats. A breakout of the lining is very costly due to resulting interruptions of the manufacturing process. Thermal scanning has the significant advantage over other thickness measuring methods, since the process need not to be interrupted for measuring.[11]

Faulty insulation and fluid leaks are readily visible as local increases in temperature, whereas blocked pipes are detected as differential temperatures across a pipe. Other examples include: identifying defective valve in steam traps, fluid leaks, blocked pipes and radiators, damaged refrigerator sections of a heat exchanger.

Process Control

Usually, it is necessary to monitor the temperature in order to perform an efficient process control. In this case the emissivity must be known. Low emissivity materials reflect significant radiation. Since manufacturing facilities have numerous furnaces it is desirable to shield these sources in order to make accurate measurements. Oxidation and scale can further change temperature measurements.

Valves

The leakage in valves, in general, could mean high economic loses and also can cause many trouble to any industrial installation or power facilities. Especially steam valves and traps must be carefully checked because a wrong close may cause loss of energy. Avoiding the leakage is the challenge in any maintenance organization. The test just how closed a valve is with infrared thermography, offers the users one quite approximate idea of what is the real situation in a inspected valve.[12]

Ventilation systems

Ventilation systems supply air to and remove air from working spaces, and control environmental conditions for a number of purposes. Removal of hazardous vapors or gases, positive pressure atmosphere, or negative pressure atmosphere are a few examples. Compressor equipment has normally high operating temperatures, relative to other rotating equipment. The compression of gases is exothermic, and as a result, most compressors rely on an integral cooling process to function properly. Uniformity of temperature distribution on equipment surfaces, function of cooling systems, and verification of proper operation of loading and relief of valves, proved an overall illustration of equipment health.[13]

Cooling towers

IR can be used to provide thermal performance information for other key plant systems, including assessment of cooling towers.

Cooling tower performance directly affects availability and heat rate in fossil and nuclear power plants. Optimal tower performance contributes to efficient turbine operation and maximum power output. It is estimated that up to half of the installed cooling towers have failed to meet their design performance specifications. As a result, any additional degradation of tower performance resulting form fouling, valve degradation, unbalanced flow, or a poor maintenance practice has a direct effect on generation output.[14]

Glass industry

Much is unknown about the variable involved is producing a bottle. This lack of familiarity leaves room for defects which result in a loss of funds and production. Thermal imaging is used to analyze the cooling effect due to different variable changes. The goal is to achieve uniformity in the iron temperature and glass flow, which improves the quality of the bottle and also allows for reduction in the total amount of glass necessary to form a bottle.[15]

Plastics

Infrared thermal analysis is used to characterize and optimize injection molding and blow molding of plastic parts colored with 2—4 % carbon black. Thermographic and ultrasonic data show that during injection molding shrinkage of the plastic in the mould creates a gap between the part and mould, which produces a thermal contact resistance thereby reducing the cooling efficiency of the mould. Thermal analysis of blow molding provides evidence of a "skin" on the surface which affects the wetting of the part and the mould.[8]

Other examples of use of IR thermography in predictive maintenance are: condenser air-in leakage; condenser tube leaks; and boiler casing leaks. These areas have plagued the utility industry badly, causing unscheduled downtime, increasing maintenance costs, and creating performance difficulties.[16]

Conclusion

Modern IR technologies enable fast time acquisition and processing of data with high accuracy, which keep widening application of thermography. Thermal imaging is a growing technology that has many uses. IR thermography is used to make practical temperature measurements and solve problems in a wide range of industrial disciplines. Recent advances in infrared technology, specifically development of high-density imaging sensors, have opened a new level of applications unreachable prior to the availability of this technology. Real-time infrared image acquisition and processing allows implementation of advanced thermographic test methods. The detailed infrared analysis in the most cases can quickly determine the origin of the process-related problem causing.

Those are reasons indicating the need for increased usage of the IR thermography to ensure safe and economical production.

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SAŽETAK

Primjena infracrvene termografije u kemijskom inženjerstvu

N. Bolf

Infracrvena (IC) termografija postala je djelotvorno tehničko sredstvo za fundamentalna i primijenjena istraživanja na širokom spektru znanstvenih polja od prijenosa topline, nerazarajućih ispitivanja, mehanike fluida i krutina, biomedicinskih primjena, zaštite okoliša itd.

U članku je dan sažeti pregled primjene termografije na polju kemijskog inženjerstva i procesne industrije, kako bi se znanstvenike i procesne inženjere uputilo na mogućnosti primjene infracrvene termografije radi sigurnog i štedljivog rada te zaštite okoliša.

Prikazana je kratka povijest razvoja IR termografije, osnovna načela rada suvremenog sustava za termografska mjerenja i pregled primjene. Istaknute su primjene nerazarajućih ispitivanja, preventivnog održavanja i motrenja stanja procesne opreme. Poseban naglasak dan je na industrijsku primjenu radi osiguranja kvalitete i automatskog vođenja procesa.

Sveučilište u Zagrebu,
Fakultet kemijskog inženjerstva i tehnologije,
Zavod za mjerenja i automatsko vođenje procesa
Savska c. 16/5a, 10 000 Zagreb, Hrvatska
e-mail: bolf@fkit.hr

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