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Infrared Thermographic NDT
Research Committee

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The Experience of Using IR Inspection Techniques in Industrial Applications and Research

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Abstract
The thermal nondestructive testing (NDT) laboratory of Tomsk Polytechnic University, Institute of Introscopy, has gained the considerable experience of using stationary and transient infared (IR) thermography in technical diagnostics and materials inspection. The paper contains the short review of the state-of-the-art of IR thermographic NDT, as well as the description of some particular applications. A special attention is paid to the thermal NDT software developed by the authors.

1. Introduction

The ideas of infrared (IR) thermographic diagnostics and nondestructive testing (NDT) can be traced to the XIXth century when simple thermopile detectors were used to detect remotely animals and human beings (see the old but comprehensive book by R. Hudson [1]). In 1914, Parker patented the IR detector of icebergs. In 1934, Barker proposed to use IR technique to detect forest fires. The analysis of hot rolled metals was one of the first industrial IR applications (Nichols, 1935). The modern techniques for determining thermal properties of materials can be reduced to the Vernotte's work devoted to the analysis of thermal properties of human skin [2]. In the 60s, the Swedish company AGA (then-AGEMA Infrared Systems, now-FSI, U.S.A.) started using IR thermography in the inspection of electronic components. In 1965, Beller proposed the prototype of modern transient thermal NDT applied to the inspection of Polaris rocket motor cases [3]. In general, the 60s were characterized by an explosive growth of IR applications, in particular, in predictive maintenance and condition monitoring. However, the use of transient thermal NDT for detecting material defects was rather qualitative by that time. A new impact to thermal NDT was produced when the classical theory of heat conduction developed by Carslaw and Jaeger [4] was applied to the analysis of heat transfer mechanism that occurs in solids with subsurface defects. Such the 'thermophysical' approach was used by Balageas [5], Vavilov and Taylor [6], Maclaughlin and Mirchandani [7] who introduced one-two and three-dimensional thermal NDT models.

There are two main application areas for IR thermography: 1) technical diagnostics (predictive maintenance and condition monitoring), and 2) NDT of materials. The main features of these techniques are compared in Table 1.

Table 1

Comparing technical diagnostics and thermal NDT

Feature	Technical diagnostics	Nondestructive testing
The mechanism for creating temperature signals ΔT over defects	Due to object functioning	Due to external thermal stimulation
ΔT amplitude	1-100 °C	0.1-10 °C
Dependence of ΔT on time	$\Delta T \neq f(\tau)$	$\Delta T = f(\tau)$
The number of images to be analyzed	Single images	Image sequences
IR camera performance	Imaging or radiometric, portable	Radiometric, portable or stationary

This paper contains the short review of the state-of-the-art of IR thermographic diagnostics and NDT, as well as the description of some application areas where the authors have their personal experience. A special attention will be paid to the thermal NDT software developed by the authors. A more detailed information on the features and the applications of IR thermography can be found in the recent publications [8-11].

2. IR Cameras

An exhaustive description of IR cameras is beyond the scope of this paper. We shall limit ourselves with the following statements related to modern IR cameras.

- The systems using opto-mechanical scanning are becoming increasingly old-fashion being replaced with focal plane array (FPA) systems that can be regarded as full analogs of TV cameras but operating in an IR region.
- In thermal technical diagnostics, imaging portable FPA systems that require no cooling are typically used. Many such cameras include the detectors consisted of 320x240 sensitive elements.
- In thermal NDT, the requirements to both the temperature resolution and data stability of IR cameras are more rigid than in predictive maintenance. Therefore, computerized IR systems often include radiometric cameras allowing digital data recording in a real time. The best cameras use a snap-shot mode where all picture elements are stared at one time. In NDT, a typical temperature resolution can reach 30-50 mK.

The performance of some IR cameras is described in Table 2.

Table 2

IR cameras (examples)*

Performance parameters	**Model**		
	Imaging (predictive maintenance) **	**Radiometric (predictive maintenance & NDT)**	**Ultra-fast (NDT)**
	PalmIR™250 (Raytheon)	**ThermaCam ™ 595 (FSI)**	**Galileo (Raytheon)**
Detector type (Format)	Uncooled ferroelectric (320x240)	Uncooled ferroelectric (320x240)	InSb (256x256 to 64x64)
Spectral response	7 to 14 μm	7.5 to 13 μm	3 to 5 μm
Video update rate	30 Hz	60 Hz	120 Hz to 1400 Hz
Temperature resolution	-	0.1 °C at 30 °C	0.025 °C at 23 °C
Digitizing resolution	-	14 bit	12 bit
Field of view	12° x 9°	24° x 18° built in	1.8° to 17.5°
Weight without batteries	1.2 kg	1.9 kg	< 4.5 kg

* The information in this table is not provided for advertisement purposes and it should not be taken as an endorsement by the authors.

** Recommended application areas

3. Heaters

Heaters are necessary to stimulate thermally the objects that have an ambient temperature before a test. The nomenclature of heaters is vast but only few of them are used in practice. The most typical are flash tubes and quartz lamps. A single flash photographic tube is capable to deliver a 3 kJ pulse of optical energy for 5-10 ms. A set of 2-10 tubes allows flash heating of 10 cm^2 to 1 m^2 areas. Such heaters are optimal if the thermal processes in a solid to be inspected exist for very short times (from few milliseconds to few seconds). Tubular quartz lamps are of continuous operation delivering power of 0.5-2 kW per a lamp. They are used in the inspection of thick objects where observation times are from seconds to minutes.

Thermal stimulation can be done by applying hot (cold) air or liquids. Metals can be also stimulated by passing an electric current through the sample to be tested. A special case is the analysis of mechanical stresses caused by a cyclic sample deformation.

4. Thermal Technical Diagnostics

4.1. Summary of features

- Any object, that has a temperature different from ambient, exchanges energy with the environment and is characterized by a specific temperature distribution. The analysis of this distribution supplies the information on object parameters and operation.

- Objects of a complex geometry might have very complicated temperature patterns that can serve as references in evaluating the quality of the objects. Surface temperature distributions are typically static and their amplitude depends on the temperature difference between the object and the environment.
- In many practical cases, decision making should be done by a trained operator who deals with single IR images.
- In outdoor surveys, some external factors, such as solar radiation, rain, snow, the presence of neighbor hot objects, etc., might essentially affect inspection results.
- The main application areas are as follows: 1) evaluating building envelopes and building ventilation systems, 2) detecting moist areas in building roofs, 3) detecting forest fires, 4) evaluating thermal insulation of furnaces, chemical reactors, etc., 5) detecting gas and oils leakages from buried pipelines, 6) detecting water losses from city underground pipelines.

4.2. Applications

In Russia, a new federal law requires inspecting all industrial installations that might represent a potential danger to people and nature. This creates a new motivation to using IR thermography as a fast non-contact tool of monitoring the operation of such technical installations where surface temperature distributions are directly related to possible internal defects. The authors have fulfilled the inspection of several chemical reactors at Achinsk Petrochemical Plant that is one of major producers of gasoline in Russia. The IR thermogram in Fig. 1 shows that a lack of thermal insulation between the reactor case and the protective aluminum cover leads to temperature gradients above 100°C.

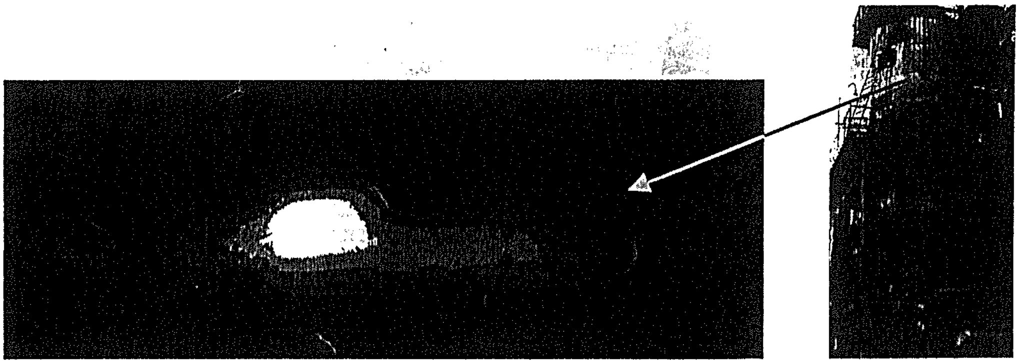

Fig. 1. Insulation deficiency in the thermal protection of the chemical reactor
(Achinsk Petrochemical Plant, Russia, the temperature gradient exceeds 100°C)

The IR thermographic inspection of buildings is another application area that provides significant economical benefits. This technique allows: 1) easy detection of air leaks and lacks of insulation, 2) evaluation of wall thermal resistance, and 3) monitoring heat losses. Following the authors' experience in using IR building thermography during the last decade, the Mayor of Seversk, that is a medium-size city in the Tomsk region, where one of famous Russian nuclear station is located, has issued the local law that requires IR inspecting of all new residential buildings (see Fig. 2). Recently, the Gosstandard, that is the federal institution responsible for standardization and certification in Russia, approved the building inspection guidelines developed by the authors [11].

Smokestacks that are plentiful at Russian power stations and industrial enterprises must be regularly checked for a lack of possible defects of which air in-leaks and lacks of internal thermal insulation are most typical. The existing inspection guidelines allow using IR thermography without stopping smokestack operation. A smokestack is surveyed from 5-6 observation points resulting in a panoramic IR thermogram. The greatest temperature gradients (up to 10°C) are observed over air in-leaks that look like cold ('dark') lines (Fig. 3). The computer analysis of experimental data allows producing a defect map that outlines significant surface and subsurface defects and can be used by a building company as a repair map (Fig. 3). The authors have developed the inspection guidelines that are being currently reviewed by the Gosstandard [13].

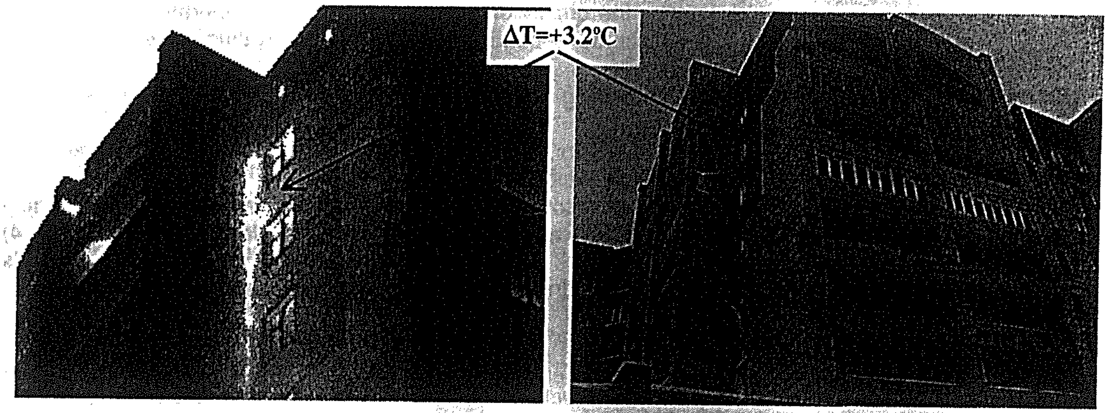

Fig. 2. A lack of mineral wool in the vertical envelope junction creates the vertical temperature gradient up to 3.2°C (multi-store residential building in the City of Seversk, Russia, ambient temperature −23°C)

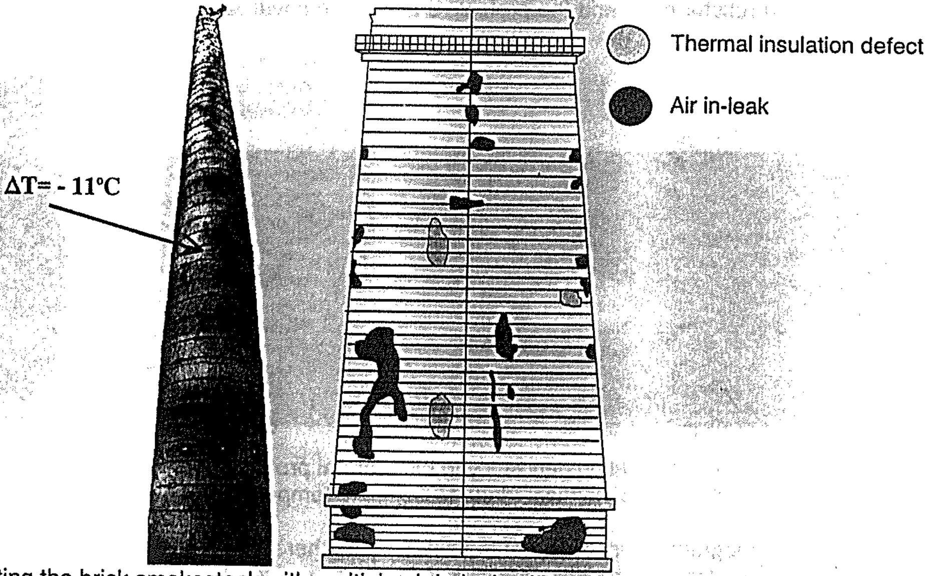

Fig. 3. Inspecting the brick smokestack with multiple air in-leaks: IR panoramic image and defect map (Samara Petrochemical Plant, Russia, ambient temperature +15°C)

5. Thermal NDT

5.1. Summary of features

- Philosophically, thermal NDT, like any other NDT technique, can be regarded as probing a 'black box', i.e. a sample, by applying some kinds of thermal stimulation. Therefore, thermal tests are essentially transient. A thermal stimulus can be modeled by a Dirac pulse, square pulse, step-function or periodical (harmonic) function.
- The pulsed technique involves heating a sample with a single heat pulse. Using short (Dirac) heat pulses leads to a 'true' pulsed method, while using long pulses might transit into continuous heating. Data treatment is performed in the time-domain. Synthetic images, conventionally called a *maxigram* and a *timegram*, are considered to be useful as a result of treating long image sequences.
- Thermal wave technique implies using periodical heating with data being treated in the frequency-domain. The most useful information is supplied by the analysis of phase images (*phasegrams*).

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- There is no principal difference between the above-mentioned techniques. A square pulse can be represented as a combination of thermal waves that are characterized by different frequencies and, thus, penetrate samples to different depths. A phasegram can be considered as a substitute for the corresponding timegram.
- There are the following techniques used within a pulsed procedure: 1) *pulsed thermal wave* method (defect signals are captured at their optimal observation time in the cooling stage), 2) *dynamic thermal tomography* (signal time delays are used to 'slice' a sample by depth), 3) *time-resolved IR radiometry* (is similar to a pulsed method but typically implements long heating; therefore, temperature signals are analyzed in the heating stage), 3) techniques that use some *integral transformations*, such as Fourier, Laplace or wavelet (*pulse phased thermography* is the most known technique).
- Thermal wave technique was originally developed as a *photothermal* method (a sample is scanned point-by-point). In thermal NDT, *lock-in thermography* has become known for the last decade (a surface temperature phase shift is analyzed in each pixel to obtain phasegrams at different frequencies).
- Each technique described above should be optimized by the parameters involved. The comparison between different techniques is done by applying them to particular reference samples. A signal-to-noise ratio can serve as a universal comparison criterion.
- Low-conductive and/or thick samples are to be inspected by applying a one-sided test, while high-conductive and/or thin samples can be tested by applying both a one- and two-sided test.
- Low-conductive materials create temperature signals that exist for longer times without significant lateral diffusion. Oppositely, in high-conductive materials, temperature signals survive for shorter times and experience strong heat diffusion. However, the use of powerful pulsed optical heaters in combination with high-speed FPA IR cameras allows capturing fast thermal events thus providing a quality of images comparable to those obtained with ultrasonics.
- In a one-sided procedure, temperature signals strongly decrease with growing depth thus allowing thermal NDT only for the detection of shallow defects. Since defect depth strongly influences on the observation time (or thermal wave phase), this fact is used for developing defect characterization algorithms, such as *dynamic thermal tomography*.
- A two-sided test is relatively more sensitive to defect thickness, while changing defect depth does not influence much on amplitude and time (frequency) features of temperature signals.
- Due to heat diffusion phenomena, thermal NDT requires to inject a probing heat flux perpendicularly to the main defect plane. Hence, uniform surface heating is more suitable for detecting laterally extended defects, such as delaminations, disbonds, etc. Detecting vertical cracks requires using point-like heating (photothermal procedure).
- Several defect characterization algorithms are available. The accuracy of depth profiling is about 5-30%, while determining defect thickness (thermal resistance) is characterized by a worse accuracy of about 30-60%. The defect lateral size can be evaluated directly by defect surface footprints, although some simple procedures, such as measuring a half-maximum width, are also proposed.

5.2.Thermal NDT software

Several commercial computer programs intended for numerical modeling of heat transfer processes, such as Abaqus, Ansys, Matlab, Samsef, etc., can be used to simulate thermal NDT problems. Such programs implement the ideas of Computer-Aided Design (CAD) and Computer-Aided Modeling (CAM); they are flexible and allow to model objects of complicated geometries. The disadvantages of commercial packages are as follows: 1) their accuracy, in particular, for short temporal steps, is not guaranteed; 2) these programs are expensive and require using of rather powerful computers.

There are some specialized programs used by world thermal NDT teams. These programs are not well formalized and cannot be easily shared with other users.

As a compromise between the above-mentioned programs, the Innovation, Inc. (Russia) has developed the commercial package of simple programs intended for modeling thermal NDT problems and processing experimental data. This package is shortly described in Table 3.

Table 3

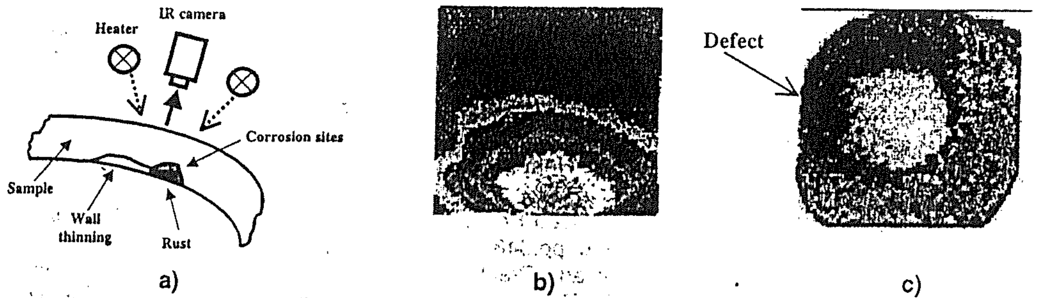
Thermal NDT software (Innovation, Inc. Russia)

Program	Description
	Modeling programs
Multilayer-3	Analytical solution for non-adiabatic square pulse heating of a three-layer plate
ThermoCalc-2D	Numerical solution for non-adiabatic heating of a disk-shaped body containing a disk-shaped defect (cylindrical two-dimensional geometry, square- and cosine-pulse heating) Thermal waves Convection and radiation heat exchange
ThermoCalc-3D	Numerical solution for non-adiabatic heating of a three-layer parallelepiped-like body containing up to nine parallelepiped-like defects (Cartesian three-dimensional geometry, square- and cosine-pulse heating and cooling) Arbitrary heating function All parameters can be modeled as arbitrary functions of time Heating by using both an experimental and artificial mask image Producing a synthetic image sequence
	Data processing programs
ThermidgePro	Analyzing image sequences recorded in a transient thermal NDT test Standard image processing Thermal characterization of defects Dynamic thermal tomography Corrosion evaluation
ThermoFourier	Analyzing image sequences recorded in a transient thermal NDT test Performing the Fourier transformation in time Producing images of phase
ThermoStat	Analyzing statistical features of single images Comparison between a defect and non-defect area Producing binary defect maps with a pre-described values of false alarm and correct detection

5.3.Applications

The theory and the basic experiments on corrosion detection by using pulsed IR thermography were presented in [14]. The most successful experimental results have been related to the inspection of thin aluminum panels widely used on aircraft [15]. Civil aircraft panels are shiny and require black painting, while aluminum parts of military airplanes are typically pre-painted, thus having a rather high emissivity. Flash tubes delivering the energy of about 10kJ for 5-10 ms are the best heaters for inspecting aluminum parts (see the test scheme in Fig. 4a). Observation times can be about 50-500 ms, therefore image recording must be done in real time. A minimum detectable material loss has been reported about 3-5%, but, to our opinion, a more realistic estimate should be within 15-20%.

The inspection of thick steel samples, such as above-ground tanks intended for storing gas and oil, is another topic under intensive discussion. The problem with thick metals is that the amount of energy needed to create reasonable temperature signals should be quite high, therefore heating should be rather long that might lead to smashing of temperature gradients. In such cases, sophisticated data processing can be useful. For example, due to uneven heating, the source image of a15 mm-thick steel sample shown in Fig. 4b reveals no clear indication of the corrosion site. However, after having applied the thermal tomography technique, the corrosion defect becomes clearly visible (Fig. 4c).

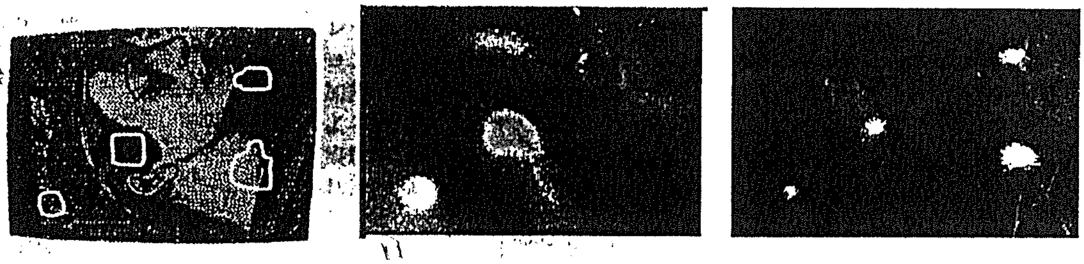


a) b) c)

Fig. 4. IR thermographic corrosion detection:

a-test scheme,
b-source image (35% material loss in a 15 mm-thick steel sample; 1 kW/m2 heating for 300 s),
c-thermal tomogram (computer processing of the source sequence shown in b)

The test scheme shown in Fig. 4a is applied to the inspection of composite structures widely used in aero space. In [16], we have discussed the potentials of cutting-edge numerical modeling and data processing in the inspection of graphite epoxy composites. For example, we have shown that thermal tomography can be helpful in presenting the sections of impact damages located at different depths. In this paper, we demonstrate advantages of thermal tomography in the inspection of wall frescos (see also [17]). Some recent results obtained in the cooperation with ITEF-CNR, Italy, are presented in Fig. 5. Frescos represent a difficult object for thermal NDT because of extremely uneven heating determined by paints of different colors (Fig. 5a). The special procedure called *normalization* is typically used to reduce uneven heating phenomena. Normalization is performed by dividing each image in a sequence by a chosen image where heating patterns are present but defect footprints are not seen (very often the image taken at the end of flash heating serves as normalizing). This technique is very useful in the inspection of composites but in the case of frescos its efficiency is low because of long observation times and strong lateral heat diffusion. For example, the normalized thermogram in Fig. 5b is characterized by the signal-to-noise ratio (SNR) equal only to 1.1. To improve normalization efficiency, we have recently proposed the method called *3D filtering* (or 3D normalization). The idea of this method is to create a replica synthetic sequence by using 3D numerical software, such as a ThermoCalc-3D program described in Table 3. The synthetic sequence is calculated for a non-defect sample but using an experimental image as a heating mask. As a result, the replica sequence contains all dynamic patterns of uneven heating but no defect indications. Therefore, by dividing the images from the experimental sequence by the corresponding images from the calculated sequence, it is possible to create the third normalized sequence where images are less subject to uneven heating phenomena. The example of such image is shown in Fig. 5c where the SNR value reaches 3.4.



a) b) c)

Fig. 5. IR thermographic inspection of the wall fresco:

a-fresco (four subsurface detachments are shown),
b-optimal source image after conventional normalization, SNR=1.1,
c-maxigram after 3D filtering, SNR=3.4

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