International Journal of Heat and Mass Transfer 115 (2017) 471–478

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Heat transfer modeling using analytical solutions for infrared thermography applications in multilayered buildings systems

C. Serra [a,*], A. Tadeu [a,b], N. Simões [a,b]

[a] ITeCons – Institute for Research and Technological Development in Construction, Energy, Environment and Sustainability, Rua Pedro Hispano s/ n., 3030-289 Coimbra, Portugal
[b] ADAI – LAETA, Department of Civil Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

ARTICLE INFO

*Article history:*
Received 6 April 2017
Received in revised form 11 August 2017
Accepted 16 August 2017

*Keywords:*
Active infrared thermography
Analytical solutions
Phase contrast
Multilayered
Building elements

ABSTRACT

There is growing interest in implementing predictive maintenance techniques to buildings and structures and consequently there is a pressing need for research in effective non-destructive testing (NDT) tools. Infrared thermography (IRT) is a popular NDT tool that has been used in various areas. However, since most known IRT testing techniques have been developed for evaluating materials such as metals, its use in buildings has been limited. In this study, we seek to further IRT applications in buildings by conducting experimental active IRT tests and comparing the results with heat transfer simulations. A simulation model based on analytical expressions is used to compute heat transfer by diffusion in multilayered media and active IRT tests are carried out in a controlled environment using a test specimen that imitates a defective building element. The test duration and frequency of acquisition are varied, as are the specimen characteristics (defect depth, thickness and thermal properties). A phase contrast approach is used to access features which could be useful in evaluating and characterizing defect depth, thickness and thermal properties. Additionally, the influence of noise on phase contrast results is analyzed by introducing random temperature variations in the time domain results that are generated by the simulation model.



## 1. Introduction

An infrared thermography (IRT) camera is a device which is able to record the energy radiated by any object whose temperature is other than absolute zero by generating thermal images of the object's surface. When defects are present beneath the surface of any material the propagation of heat within the material is affected, resulting in changes to the thermal patterns of the images captured by the IRT camera, which are known as thermal or thermographic images. Thanks to its effectiveness at detecting and characterizing hidden defects in materials or products in a non-invasive manner, IRT has become a prominent non-destructive testing (NDT) tool that is used in a great number of applications in many sectors [1]. In buildings, IRT is most commonly used in energy efficiency studies to detect concentrated heat loss caused by missing or damaged insulation, thermal bridges and air leakages, and areas of excessive moisture [2]. Studies focused on evaluating historic building materials pathologies [3] for assessing the integrity of structures and buildings [4,5] have also been carried out. IRT has been used successfully to quantitatively assess heat flow through building components with thermal bridges [6,7]. Quasi-quantitative and quantitative approaches have been proposed to assess moisture variation [8], leakage points [9] and to study buildings dynamic thermal behavior [10]. However, most IRT applications in buildings are meant to give a qualitative assessment of the state of a building envelope. They are performed assuming a steady state and use passive thermography whereby materials are analyzed at their natural temperature. However, it is known that thermal images obtained successively during a certain period can further characterize defects and materials. However, this requires the use of advanced thermal data processing techniques combined with active IRT tests [11].

Active IRT is the term used when an artificial heat source is used to produce a greater temperature difference between defective and sound areas of thermal images, thus making the detection of defects possible. If a known stimulus is used, it is possible to characterize the defects found and perform a quantitative IRT analysis [12]. A range of active IRT techniques have been used for some time in industrial NDT, mostly in the fields of aeronautics, electronics and mechanics [1]. Different techniques can be categorized based on the thermal stimulation and data processing method employed. Pulse thermography (PT) is one of the most popular techniques. In PT, a test specimen is heated briefly (flash heating)

* Corresponding author.
*E-mail address:* cserra@itecons.uc.pt (C. Serra).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.08.042
0017-9310/

**Nomenclature**

| | | | |
|---|---|---|---|
| x,y,z | cartesian coordinate system | $T_{0b}$ | prescribed temperature |
| $T$ | temperature | $K$ | thermal diffusivity |
| $t$ | time | $\phi$ | thermal wave phase |
| $f$ | frequency | $\Delta\phi$ | phase contrast |
| $f_{ch}$ | characteristic frequency | $\Delta\phi_{\max}$ | maximum phase contrast |
| $f_b$ | blind frequency | $\varepsilon$ | emissivity |
| $d$ | defect depth | $\lambda$ | thermal conductivity |
| $h$ | layer thickness | $\rho$ | density |
| $c$ | specific heat | $\omega$ | angular frequency |

using laser, light beams or lamps, the temperature decay is recorded and analyzed simply using thermal contrast [13]. Another widely used technique is lock-in thermography (LT), in which a specimen is subjected to a sinusoidal stimulus using lamps, thermal emitters, microwave, ultrasound or eddy current, and thermal wave phase results are obtained via Fourier transform [14]. Phase images offer some benefits over thermal images since they are less affected by external factors such as reflections, surface emissivity changes and non-uniform surface heating, which are some of the weaknesses of PT. Nonetheless, LT requires previous knowledge of the optimal modulation frequency, which depends on the properties of the specimen.

Over the years, both LT and PT techniques have been successfully used to inspect defects in thin specimens made of highly conductive materials. However, because most construction materials generally exhibit lower conductivity values and require a greater depth of inspection than metals, the use of active IRT in buildings has for some time been very limited. Adding to that the size and immobility of buildings and structures, then there are many difficulties inherent to applying conventional IRT techniques to surfaces on such a large scale. Nonetheless, various approaches have been attempted to use active thermography to evaluate concrete and masonry structures [15–17], as well as to characterize the hygrothermal behavior of building elements [18]. More recently, Arndt suggested using pulsed phase thermography (PPT) for IRT applications in civil engineering [19]. PPT is a technique that combines the advantages of both LT and PT [20,21]. PPT results come in the form of phase images that are able to provide a better resolution of the defect's geometry and enable probing at greater depths. Nonetheless, this type of technique uses processing methods that involve complex algorithms.

Since most known active IRT techniques were developed for defect evaluation in materials such as metals they are generally inadequate for common building materials. Furthermore, the increasing interest in improving energy efficiency and taking predictive maintenance action in ageing buildings and structures to cut the cost of repairs points to a clear need for further research into IRT applications in buildings.

Looking to contribute to the understanding of results of experimental IRT applications in buildings, this study describes a series of active thermography experiments and presents a heat transfer model. Maldague [20] states that, while the comparison between heat transfer modeling and IRT test results may not always be direct, it can be useful to define test procedures and assess the limitations of applying this technique. Additionally, modeling heat transfer helps improve our understanding of the thermal behavior of the materials in question and sets the foundation for solving inverse heat transfer problems for defect characterization [22]. The development and application of heat transfer modeling tools helps to define active IRT experimental setup parameters, such as recording time or type of stimulation, and to establish the limits of its effectiveness. Models such as the one presented here can be used to determine defect detectability and to quickly estimate the observation time required for best visibility of defects with different characteristics or located at different depths. The model presented here may be particularly useful for simulating results of active IRT tests performed on defective or layered building elements, contributing to the interpretation of experimental IRT performed in buildings and structures and to the definition of test parameters, since without such simulations, establishing effective test parameters would require numerous experimental tests and consequently the wastage of a great number of test specimens.

In this study, a phase contrast approach was used to benefit from the advantages shown by phase images. Section 2 deals with the methodology used in this study, in particular the analysis of the phase contrast curves.

Active IRT tests were performed under laboratory conditions on a test specimen which simulates a building element containing a defect. The tests were performed under varying conditions to study the influence that changing experimental setup parameters and defect characteristics (thermal and geometric) has on phase contrast curves. Both the experimental setup and the case study test specimen are thoroughly described in Section 3.

Thermal and phase results in the frequency domain were computed using analytical solutions for modeling heat transfer in multilayered systems. In Section 4, the problem is formulated and a multilayered simulation model of the experimental case study is presented.

The experimental and analytical results are compared. Results are shown in Section 5 of this paper. The influence of noise on the recorded data is also analyzed. The main conclusions are drawn with focus on the effects of varying certain crucial test parameters such as acquisition rate and depth of the defect, as well as the thickness and thermal characteristics of the materials.

## 2. Methodology

An active infrared thermography analysis was performed using a phase contrast approach. The term "phase contrast" refers to the difference between the thermal wave phase recorded in a defective area and in a sound area. A phase contrast curve can be extracted for any pixel within the field of view, *i.e.* the image captured by an infrared camera in IRT tests, and contains useful information about the soundness of the particular zone being inspected for defects. In fact, interpreting and comparing phase contrast curves makes it possible to characterize defects.

The graph in Fig. 1 shows a phase contrast curve obtained from an IRT test for a specific pixel. To start with, the fact that any phase contrast is recorded at this specific area means that a defect is present, since in sound areas phase contrast is null in any frequency.

In the lower frequencies, the phase contrast reaches a maximum absolute value ($|\Delta\phi_{\max}|$) at a frequency known as the characteristic frequency ($f_{ch}$). This is the frequency at which the defect is most visible in terms of phase contrast images. The frequency at