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Theoretical–experimental analysis of conjugated heat transfer in nanocomposite heat spreaders with multiple microchannels

Diego C. Knupp [a], Carolina P. Naveira-Cotta [b], Renato M. Cotta [b,*]

[a] Laboratory of Experimentation and Numerical Simulation in Heat and Mass Transfer, LEMA, Dept. of Mechanical Engineering and Energy, Instituto Politécnico, IPRJ/UERJ, Rua Bonfim, 25, Nova Friburgo, RJ CEP 28624-570, Brazil

[b] Laboratory of Nano- and Microfluidics and Microsystems, LabMEMS, Laboratory of Transmission and Technology of Heat, LTTC, Mechanical Engineering Dept. & Nanoengineering Dept. – POLI&COPPE, UFRJ, Universidade Federal do Rio de Janeiro, Cidade Universitária, Cx. Postal 68503, Rio de Janeiro, RJ CEP 21945-970, Brazil

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ABSTRACT

The present work deals with conjugated heat transfer in heat spreaders made of a nanocomposite substrate with longitudinally molded multiple straight micro-channels. An experimental analysis is undertaken to validate a recently proposed methodology for the solution of conjugated conduction–convection heat transfer problems, which are often of relevance in thermal micro-systems analysis, based on a single domain formulation and solution of the resulting problem through integral transforms. The single domain formulation simultaneously models the heat transfer phenomena at both the fluid streams and the channels walls by making use of coefficients represented as space variable functions with abrupt transitions occurring at the fluid–wall interfaces. The Generalized Integral Transform Technique (GITT) is then employed in the hybrid numerical–analytical solution of the resulting convection–diffusion problem with variable coefficients. The experimental investigation involves the determination of the surface temperature distribution over the heat spreader with the molded microchannels that exchange heat with the base plate by flowing hot water at a prescribed mass flow rate. The infrared thermography technique is employed to investigate the response of the heat spreader surface temperature to a hot inlet fluid flow, aiming at the analysis of micro-systems that provide a thermal response from either their normal operation or due to a promoted stimulus for characterization purposes.

1. Introduction

Heat spreaders are continuously under development and improvement in order to meet the ever growing heat dissipation requirements in modern micro-electronics systems. Substrates and thermal interface materials have been more recently nanostructured, by selecting appropriate metalic or metalic oxide fillers with high thermal conductivity for each specific matrix material, towards improved thermal performance and minimal electrical conductivity [1,2]. On the other hand, a number of heat sink designs have been based on the micro-fabrication of channels and passages for augmentation of heat transfer coefficients and miniaturized configurations [3,4]. The combination of these heat transfer enhancement paths is here explored through a class of polymeric heat spreaders made of nanocomposite substrates with microchannels perfusion.

For the experimental characterization of such thermal microsystems via inverse problem analysis, it is of crucial importance to employ reliable temperature measurement techniques capable of capturing the essential thermal phenomena that take place throughout the domain. In this context it is of paramount importance to choose a technique that provides substantial amount of information on spatially distributed measurements, such as the non-intrusive technique of infrared thermography which is capable of providing measurements with high spatial resolution and high frequency [5]. One of the first works reporting the employment of infrared thermography in the analysis of heat transfer in microchannels is reasonably recent [6]. Other more recent works illustrate how this experimental technique can be very helpful in elucidating the thermal behavior in microsystems, even if the image resolution is of the same order of magnitude of the microchannels, as the example provided in reference [7] for the thermal characterization of a microchannel reactor. The main idea is that the macroscopic gradients within the microsystem chip contain the pertinent information related to the heat source term due to the microchannels. The infrared thermography method has been

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* Corresponding author. Tel.: +55 2125628567; fax: +55 2125628383.
E-mail addresses: cotta@mecanica.coppe.ufrj.br, renatocotta@hotmail.com (R.M. Cotta).

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Nomenclature

h_{eff}	effective heat transfer coefficient between the plate surface and surrounding environment
k	thermal conductivity
L_x, L_y, L_z	height, width, and thickness of the plate
M	truncation order of the eigenvalue problem solution via integral transforms
N	normalization integrals
S	contour of the region where the problem is defined
T	temperature field
u	flow velocity
V	region where the problem is defined
w	heat capacity
x	longitudinal coordinate
y	transversal coordinate (width)
z	transversal coordinate (thickness)

Greek letters

ψ	eigenfunction of the eigenvalue problem with space variable coefficients
μ	eigenvalues corresponding to ψ
Ω	eigenfunction of the auxiliary eigenvalue problem
λ	eigenvalues corresponding to Ω

Subscripts and superscripts

in	quantity corresponding to the entrance of the channel ($z = 0$)
i	order of eigenquantities
$*$	filtered temperature field
s	quantity corresponding to the solid region
f	quantity corresponding to the fluid flow region
$-$	integral transform
$\sim$	normalized eigenfunction

applied either with infrared transparent materials [8] or in mapping the surface temperatures of heated microchannels [7], as long as the conjugated heat transfer between the internally flowing fluid and the solid structure is sufficiently important to result in measurable temperature variations at the external face of the microsystem.

The thermal characterization of micro-systems is also quite dependent on an accurate and computationally efficient treatment of the associated direct problem, which in combination with the non-intrusive infrared thermography and robust inverse problem tools, may provide reliable properties and functional identifications, as recently achieved in the realm of heat conduction within heterogeneous materials [9–11] and forced convection within micro-channels [12]. However, conjugated heat transfer is often of major importance in thermal micro-systems [13], which may considerably complicate the direct problem formulation and require time consuming numerical approaches for a more refined computational simulation, in contrast to the analytically-based solution methodologies employed in [9–13] which are better suited for the intensive computational task associated with optimization and inverse problem analysis.

In this scenario, a theoretical approach has been recently advanced for dealing with conjugated convection–conduction problems, based on the reformulation of the coupled energy equations into a single domain model, which accounts for the heat transfer at both the fluid flow and the solid structure regions [14–16]. In such approach, by making use of coefficients represented as space variable functions with abrupt transitions occurring at the fluid–wall interface, the mathematical model is fed with the information concerning the two original domains of the problem. For the solution of the reformulated mathematical problem, the Generalized Integral Transform Technique (GITT), a hybrid numerical–analytical technique for the solution of convection–diffusion problems [17–22], is employed with the integral transformation being constructed based upon an eigenvalue problem with space variable coefficients, thus incorporating the information regarding the transition between the two original domains.

The present work is thus aimed at the theoretical and experimental analysis of conjugated heat transfer in nanocomposite heat spreaders with microchannels perfusion, with temperature measurements obtained through infrared thermography, seeking validation of the proposed model based on the single domain approach and its hybrid numerical–analytical solution methodology based on the Generalized Integral Transform Technique. This work is an essential step in developing a characterization approach for complex micro-systems, either through their normal operation thermal response or through stimulated thermal signals for this purpose, as recently accomplished in the inverse problem analysis of heat transfer in heterogeneous media [9–11] and of forced convection in microchannels [12].

2. Experimental setup and procedure

A fairly straightforward experiment has been prepared which consists basically in injecting a heated liquid inside the microchannels molded along the nanocomposite plate, which exchange heat with the surrounding environment by means of natural convection and radiation.

The experimental setup is presented in Fig. 1 and employs temperature measurements obtained from a high performance infrared camera FLIR645sc, with 640 × 480 pixel resolution. The main components of the setup are marked in Fig. 1 as: (a) infrared camera (FLIR645sc); (b) camera stand; (c) tweezers grabbing the (d) nanocomposite plate with microchannels; (e) thermocouples measuring the inlet fluid temperature and room temperature

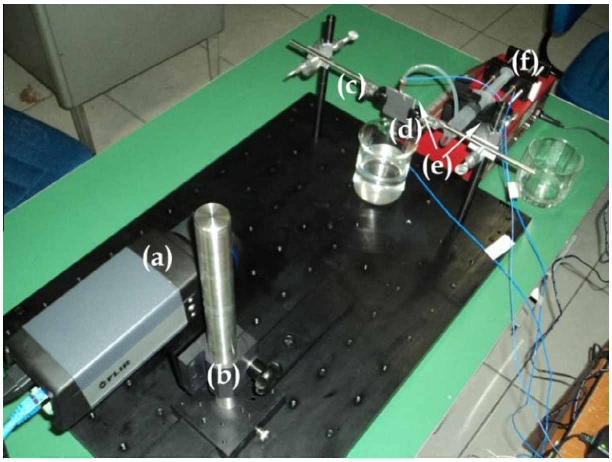

Fig. 1. Experimental setup: (a) infrared camera (FLIR645sc); (b) camera stand; (c) tweezers grabbing the (d) nanocomposite plate with microchannel; (e) thermocouples measuring the inlet fluid temperature and room temperature which are connected to the data acquisition system (Agilent 34970-A); and (f) syringe infusion pump.