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A non-intrusive technique to determine the spatially varying heat transfer coefficients in a flat plate with flush mounted heat sources

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ABSTRACT

In this work, a novel experimental technique is developed to estimate spatially varying heat transfer coefficients from a flat plate with flush mounted discrete heat sources, using Bayesian inference with temperature measurements from liquid crystal thermography (LCT) at an adiabatic surface of the plate without disturbing the fluid flow. Steady state, laminar forced convection experiments have been done on a flat Bakelite plate with three identical embedded discrete aluminium heat sources of dimensions 0.16 × 0.06 × 0.015 (l × w × t all in m). The variation of local convective heat transfer coefficient is obtained in the form of a Nusselt number correlation $Nu = aRe^b(x/l)^c$. This correlation is first developed by limited numerical simulations for two dimensional conjugate convection. With this correlation, a computationally less complex problem of conjugate conduction in the flat plate also known as the forward model is repeatedly solved for various values of *'a'*, *'b'* and *'c'* to obtain the temperature distributions at select points on the adiabatic surface using COMSOL. A surrogate model obtained by Artificial Neural Networks (ANN) built upon the data from these simulations then replaces the forward model. This surrogate model is used to drive a Markov Chain Monte Carlo based Metropolis Hastings algorithm to generate the samples to the forward model to solve the inverse problem of getting *'a'*, *'b'* and *'c'* from temperature measurements at the adiabatic surface. Bayesian framework is then adopted to compare the experimental and the simulated temperatures to generate posteriors and the mean, maximum a posteriori and standard deviation of the parameters *'a'*, *'b'* and *'c'* are estimated. The effect of number of samples and the temperature points on the performance of the estimation process has been reported. Finally, with the retrieved values of *'a'*, *'b'* and *'c'* temperature distributions are obtained by solving the conduction problem and these are compared with those actually measured with TLC.

1. Introduction

Convective heat transfer plays a very important role in air-cooled systems, where in forced convection is often encountered, as for example in electronic devices and heat exchangers. A typical printed circuit board may contain several discrete components each of which may have a different power rating. Thermal management of such devices is complex and challenging. Convective heat transfer coefficient is the key quantity to be known a priori for efficient design of thermal management solutions. In literature, various techniques have been reported for the estimation of spatially varying local convective heat transfer coefficients. Ramadhyani et al. [1] solved the problem of conjugate heat transfer from discrete heat sources mounted on one wall of a channel and exposed to fully-developed laminar flow. For selected parameters, the governing equations with assigned boundary conditions were solved by the finite-difference method to obtain the solutions. Both single heat source and two adjoining heat sources were considered in this work. Mayinger [2] reviewed optical measuring techniques to determine the local heat transfer coefficients with computer aided data processing. They also claimed that optical techniques provide local data without disturbing the process with a high temporal resolution. According to this study, the results obtained from optical measuring techniques could be used to improve computer programs which describe physical processes. Goldstein and Cho [3] reviewed the naphthalene sublimation method used to study mass and heat transfer with confidence for various applications with limited constraints. They concluded that this method was particularly useful in complex flows for various geometries. Based on this study, the authors observed that the heat transfer coefficient, which is often desired, can be readily determined from the measured mass transfer results with good confidence

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Nomenclature

a	constant in the Nusselt number correlation
b	exponent of Reynolds number in the Nusselt number correlation
B	blue
c	exponent of dimensionless length
G	green
h	height
h_x	local heat transfer coefficient (W/m^2K)
H	hue
I	intensity
k	thermal conductivity (W/mK)
l	length (m)
Nu	Nusselt number
$P(x)$	prior density function
$P(x\|y)$	posterior probability density function
$P(y)$	normalizing constant
$P(y\|x)$	likelihood density function
q_v	volumetric heat generation (W/m^3)
q_s	heat flux(W/m^2)
Q	heat input (W)
r	correlation coefficient
R	red
Re	Reynolds number
S	saturation
t	thickness (m)
T	temperature (K)
w	width (m)
x/l	dimensionless distance along the plate

Greek letters

μ_p	mean of the prior density function
Ω	unit of resistance
σ	uncertainty in the temperature measurement (K)
σ_p	standard deviation of the prior
χ^2	chi squared

Subscripts

meas	measured
sim	simulated
∞	ambient

Abbreviations

ANN	artificial neural network
LCT	liquid crystal thermography
MAP	maximum *a posteriori*
MCMC	Markov Chain Monte Carlo
MH	Metropolis Hastings
MRE	mean relative error
PPDF	posterior probability density function
RMSE	root mean square error
SD	standard deviation
TLC	thermochromic liquid crystal

via the heat and mass transfer analogy. Sugavanam and Ortega [4] conducted a numerical investigation on the heat transfer from a uniformly powered strip heat source placed on a two-dimensional conducting substrate surface. The upper and lower surfaces of the substrate were cooled by forced laminar flow that is two-dimensional, steady and with constant properties. The problem is a “paradigm” for the investigation of the competing effects of substrate conduction and fluid convection in the cooling of electronic components on substrates that are cooled by air flowing parallel to the surface. The results obtained were used as a baseline for successively more complex situations of air-cooling of on-board components. Chyu et al. [5] employed a transient technique to determine the local heat transfer coefficient from transient heat conduction model penetrating the wall substrate with a reference temperature based on the inlet temperature of the test rig. Thermochromic liquid crystal (TLC) thermography was used to measure the temperature. The heat transfer coefficient based on the inlet temperature presented difficulty in data interpretation in the designs of heat exchangers, particularly for flow channels with large length-to diameter ratios. Different approaches were applied for the test model and were validated with experimental results. Naylor [6] presented a brief introduction of the working principle of classical and holographic interferometers, These techniques were then used for the measurement of convective heat transfer rates. Optical issues as well as the limitations of this experimental technique were highlighted. Recent developments in laser interferometry for measuring local convective heat flux rates on two and three dimensional temperature fields were also discussed. Ortega and Ramanathan [7] solved the conjugate problem of uniform parallel flow over the surface of a rectangular source of heat on a conducting plate using analytic Green's functions. Green's function provide a relationship between the local heat flux and surface temperature on the plate, effectively serving the same role as the heat transfer coefficient. The pointwise Green's function was coupled to a finite element discretization of the thin plate. The surface temperature and convective heat flux distributions on the heat source and its substrate were found by a non-iterative procedure. New correlations for the source Nusselt number as a function of flow Peclet number and board conductivity were presented. Das et al. [8] estimated the local Nusselt number distribution for a flat and a ribbed surface from transient liquid crystal images. Initially, a heated surface was subjected to forced flow for cooling and the time-varying surface temperature field was obtained by liquid crystal thermography (LCT). The inverse technique compared the numerical solution with the TLC transient temperature distribution for predicting the globally correct Nusselt number distribution. The conjugate gradient method with a stabilization scheme along with the measured temperatures and finite difference was used for solving the inverse problem. The local Nusselt number obtained from the inverse technique was compared with the full numerical solution based on unsteady incompressible laminar flow, as well as the one-dimensional semi-infinite solid approximation applied to experimental data. Taler [9] presented two techniques, to solve the inverse heat conduction problem of accurately estimating spatially varying heat transfer coefficient with the Levenberg-Marquardt method (method I) or the singular value decomposition (method II) and measured temperatures at interior points in the body. The methods were formulated as linear and non-linear least-squares problems. A good agreement between the results was obtained. The uncertainties in the estimated heat transfer coefficients were computed using the error propagation formula. The author claimed that the presented methods do not require any complex simulation of flow and temperature field in the fluid for the estimation of local heat transfer coefficient. Taler and Taler [10] analyzed the problem of determining heat flux and heat transfer coefficient with steady state and transient inverse methods. Ludowski et al. [11].