EVALUATION OF INFRARED THERMOGRAPHY EXPERIMENTAL ANALYSIS OF A SINGLE MICRO-CHANNEL HEAT SPREADER

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Abstract. *The present work analyzes the temperature distribution over a heat spreader made of a polymeric thin plate with a longitudinally molded single micro-channel that removes heat by flowing water at an adjustable mass flow rate. The use of infrared thermography to analyze the response of the heat spreader with such small scale channels is critically evaluated, 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. A single micro-channel heat spreader configuration was here initially considered to facilitate the analysis, and its thermal behavior is characterized by observing the thermal images that result from water flow through the circular micro-tube at different mass flow rates, injected by a syringe pump. The Flir SC660 infrared camera provides the measurements of the temperature field at the surface of the plate, and a simplified two-dimensional improed lumped heat conduction model is employed for predicting the temperature distribution at the plate surface, together with a lumped-differential model for the energy equation in the fluid stream, offering a theoretical basis for comparison against the temperature measurements. Finally, the overall thermal behavior of the heat spreader is evaluated.*

Keywords*: Heat spreader, Infrared thermography, Conjugated heat transfer, Inverse problem, Microchannel*

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. In parallel, thermal interface materials have been more recently nanostructured, by selecting the appropriate high thermal conductivity fillers for each specific matrix material, towards improved thermal performance and minimal electrical conductivity. 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 (Kandlikar & Grande, 2003; Yarin et al., 2009). The combination of these heat transfer enhancement paths is here advanced towards the development of a class of heat spreaders made of nano-composite substrates with micro-channels cooling by liquid flow.

For the characterization and design optimization of such thermal micro-systems, it is of crucial importance to employ reliable temperature measurement techniques capable of describing the physical phenomena that take place in these heat spreaders with micro-channels. One must also seek a technique that provides the maximum information of spatially distributed measurements, for a successful solution of the appropriate inverse problem. In this context, the use of the non-intrusive technique of infrared thermography becomes of major interest, for being capable of providing measurements with high spatial resolution and high frequency (Fudym, 2006). One of the first works employing infrared thermography in the analysis of heat transfer in micro-channels is reasonably recent, presented in (Hetsroni et al., 2002).

Although heat transfer in micro-channels have been analyzed in various previous works, recent contributions have shown significant discrepancies between experimental results and macro-scale correlations and simulations (Morini, 2004; Yener et al., 2005) which may be the result of neglecting terms that are usually not important at the macro-scale, but whose effects may have significant importance in micro-scale heat transfer (Hetsroni et al., 2005). In order to achieve simulated results with better agreement against experimental data, a lot of effort is being dispended for the proposition of models and solution methodologies to deal with fluid flow and heat transfer in microchannels, but improvement should also be sought on the experimental techniques, especially for temperature measurements. Besides, inverse problem analysis with a reasonable amount of data is crucial in verifying proposed models and/or identifying boundary conditions, physical properties and source terms that might be required for a closer match between theory and experiments. In a recent work, (Naveira-Cotta et al., 2010a) have shown that boundary conditions and interface parameters in convection within micro-channels for gas flow could be accurately identified employing a combination of integral transforms for the direct problem solution and Bayesian inference as a MCMC algorithm for the inverse analysis, from the availability of an infrared thermography measurement system.

Therefore, an adequate experimental technique can be very helpful in elucidating the thermal behavior in micro-systems, even though the image resolution is of the same order of magnitude of the micro-channels. For instance, (Pradère et al., 2006) provide an example of thermal characterization of a microchannel reactor, where the microchannel width has the same order of magnitude than the pixel size. The main idea is that the macroscopic gradients within the microreactor plate contain the pertinent information related to the heat source term within the microchannel. The infrared thermography method has been applied either with infrared transparent materials (Patil & Narayanan, 2005) or for mapping of surface temperatures of heated micro-channels (Pradère et al., 2006; Hetsroni et al., 2011), as long as the conjugated heat transfer between the internally flowing fluid and the microchannel walls is sufficiently important to result in measurable temperature variations at the external walls of the micro-system. Nunes et al. (2010), motivated by the theoretical conclusions reached by Maranzana et al. (2004), presented some experimental and theoretical results showing the importance of taking into account the heat conduction within the microchannel wall, leading to a conjugated problem whose solution yields results in much better agreement with the available experimental data. The theoretical approach then employed was an extension of the work of (Guedes et al., 1991), based on the Generalized Integral Transform Technique (GITT), a hybrid numerical-analytical technique for the solution of convection-diffusion problems (Cotta, 1993; Cotta & Mikhailov, 1997; Cotta & Mikhailov, 2006), and accounting for the longitudinal heat conduction along the asymmetric walls.

The present work is thus aimed at progressing into the analysis of conjugated heat transfer in heat spreaders with microchannels, evaluating the experimental methodology for temperature measurements through infrared thermography. Thus, inspired by the well succeeded approach developed by (Naveira-Cotta et al., 2010; Naveira-Cotta et al., 2011) and (Knupp et al., 2010; Knupp et al., 2011) for the experimental-theoretical analysis of heat conduction problems in heterogeneous media, we evaluate in this paper the use of infrared thermography in analyzing heat transfer in a polymeric (polyester) thin plate with a central micro-channel, heated by an electrical resistance at one face and exposed to the IR camera on the other one. In order to illustrate the usefulness of the approach, critical comparisons are performed against an improved lumped-differential two-dimensional model for heat conduction within the plate, and a lumped model for the bulk temperature evolution within the micro-channel. An inverse problem analysis is performed to extract the major parameters related to the experiment, such as thermophysical properties and the external heat transfer coefficient, based on the simpler configuration without water flow, which provide the necessary data for estimating the surface temperature distribution from the simplified two-dimensional model.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental setup presented in Figures 1 employs temperature measurements obtained from a high performance infrared camera FLIR SC660, with 640x480 pixel resolution. The main components of the setup are marked on Fig. 1a as (a) IR camera (FLIR SC660); (b) camera stand; (c) frame with the heated plate with the microchannel; (d) sample support; (e) data acquisition system (Agilent 34970-A); (f) microcomputer for data acquisition; (g) syringe infusion pump (Cole Parmer 74900-20). Fig. 1b shows the plate, which is made of polyester resin, with thickness (2.8 mm) and lateral and vertical dimensions (4x4cm), and manufactured in such a way that the microchannel, with 450 μm diameter, passes through the center of the plate along its height. Figure 2 presents an schematic drawing of the front and upper views of the plate and the single microchannel.

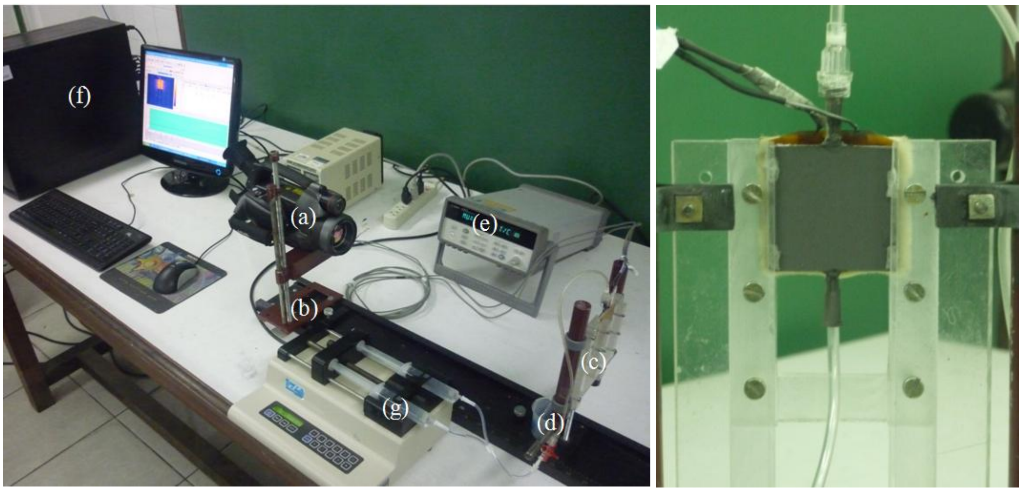


Figure 1 – (a) General view of the experimental setup and (b) Detailed view of the plate with the microchannel.

Injection needles are placed into the microchannel's entrance (top of the plate) and exit (bottom), so that a small plastic tubing that comes from the syringe infusion pump can be connected to the microchannel entrance and another similar tubing can be connected to the exit in order to collect the water for temperature measurement. A kapton electrical resistance (38.2 Ω) with the same lateral dimensions (4x4 cm) is attached to the plate with the aid of a thermal compound paste, being the opposite face insulated and kept in place by the frame, with insulated corners. In order to reduce uncertainty in the IR camera readings, the plate surface that faces the infrared camera was painted with a graphite ink, which brought its emissivity to a constant value of $\varepsilon = 0.97$, as stated by the ink manufacturer.

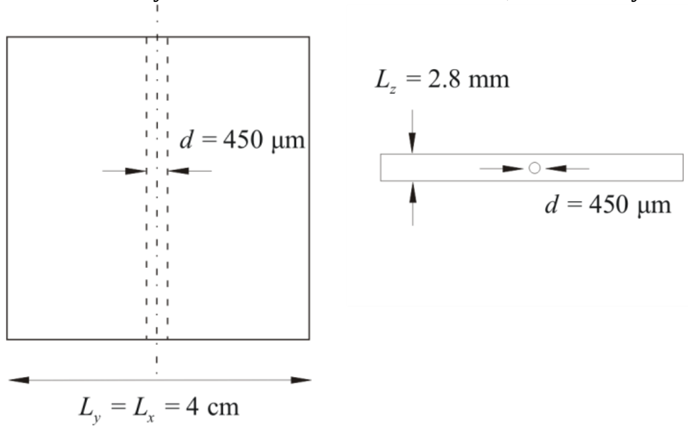


Figure 2: Front and upper views of the single microchannel heat spreader

The experimental procedure is initiated by prescribing a voltage difference to be imposed on the electrical resistance, with a DC voltage regulator. The data acquisition is started and after a certain number of preliminary measurements, the DC source switch is turned on to heat the plate (a nominal voltage of 6.8V has been applied through the DC source). The temperature increase may be followed through the computer monitoring. Figure 3 illustrates the image produced by the FLIR SC660 camera of the heated plate, after steady-state has been achieved in the case without water flow through the microchannel. Next, the syringe infusion pump is turned on with a prescribed volumetric flow rate and the experiment is carried on until the steady-state is again achieved. Figures 4a,b illustrate, respectively, the thermographic images at some elapsed time after the pump is turned on and as steady-state is achieved. One may clearly observe the marked temperature drop throughout the plate, especially at the region near the microchannel (note that Fig. 4b is much less brighter than Fig. 4a).

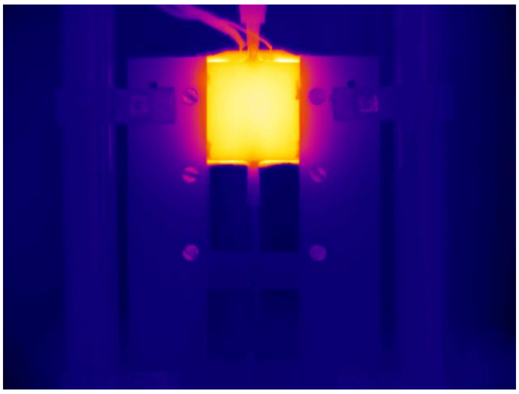
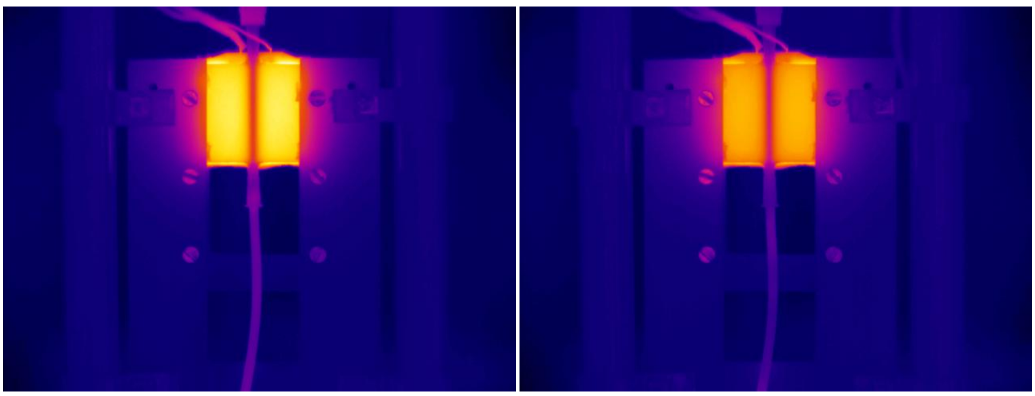


Figure 3 – Infrared camera image of the heated plated (without water flow through the microchannel)



(a) (b)

Figure 4 – Infrared camera image at: (a) some elapsed time after the syringe pump is turned on; (b) steady-state

3. PROBLEM FORMULATION

The physical problem under analysis is graphically represented by Figure 5. A vertical plate with thickness *Lz* and lateral dimensions *Lx* and *Ly* is assumed to be uniformly heated by an electrical resistance which provides a time dependent heat flux., installed at the back of the plate, while the unheated surface looses heat by convection and radiation to its surroundings, and on this front face the experimental surface temperatures are taken with the infrared camera. The lateral surfaces were considered to be insulated.

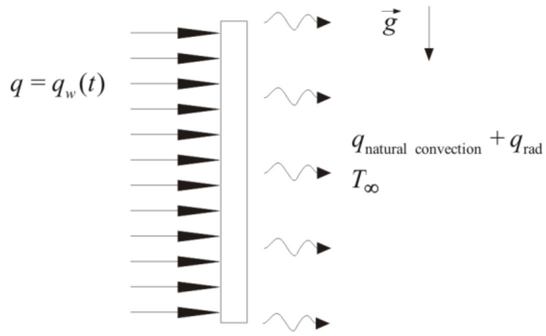


Figure5: Schematic representation of the heated plate and boundary conditions

We now seek to model the conjugated heat transfer problem involving conduction in the polymeric plate and convection in the water flow within the microchannel. Although the plate is fairly thin (Lz < 3mm), a plain lumping of the temperature distribution in this direction can introduce substantial error, in light of the low thermal conductivity of the employed material. Therefore, an improved lumped-differential model is proposed, based on the so called Coupled Integral Equations Aproach (CIEA) (Cotta & Mikhailov, 1997). Following the formalism in the Coupled Integral Equations Approach (CIEA) we can define the z-averaged temperature and temperature derivative as:

$$T_{m,s}(x,y,t) = \frac{1}{L_z}\int_0^{Lz} T_s(x,y,z,t)dz \simeq \frac{1}{2}\left[T_s(x,y,0,t) + T_s(x,y,L_z,t)\right] + \frac{L_z}{12}\left[\left.\frac{\partial T_s}{\partial z}\right|_{z=0} - \left.\frac{\partial T_s}{\partial z}\right|_{z=Lz}\right] \tag{1a}$$

$$\int_0^{Lz} \frac{\partial T_s}{\partial z}dz = T_s(x,y,L_z,t) - T_s(x,y,0,t) \simeq \frac{L_z}{2}\left[\left.\frac{\partial T_s}{\partial z}\right|_{z=0} + \left.\frac{\partial T_s}{\partial z}\right|_{z=Lz}\right] \tag{1b}$$

where the corrected trapezoidal and trapezoidal rules were used to approximate the two integrals. Eliminating the center temperature from these two expressions, and employing the boundary conditions at z=0 and z=L_z, the surface temperature can be directly related to the averaged temperature as:

$$T_s(x,y,L_z,t) = \frac{T_{m,s}(x,y,t) - \frac{L_z q_w(t)}{6k} + \frac{L_z h_e(x)}{3k}T_\infty}{1 + \frac{L_z he}{3k}} \tag{1c}$$

The two dimensional improved lumped formulation, the mathematical model which describes the z-averaged temperature distribution at the solid wall is obtained by integrating the three dimensional heat conduction equation in the z direction, and employing the boundary conditions at z=0 and L_z:, without substituting the surface temperature by the average temperature, as in the classical lumped system analysis, and using eq.(1c) instead, yielding:

$$\rho Cp\frac{\partial T_{m,s}(x,y,t)}{\partial t} = k\left(\frac{\partial^2 T_{m,s}(x,y,t)}{\partial x^2} + \frac{\partial^2 T_{m,s}(x,y,t)}{\partial y^2}\right) + \frac{q_w(t)}{L_z} - \frac{h_e(x)}{L_z}\left(T_s(x,y,L_{z,}t) - T_\infty\right), \tag{2a}$$

$$t > 0;\ 0 < x < L_x; 0 < y < L_y$$

$$T_{m,s}(x,y,0) = T_0(x,y) \tag{2b}$$

$$\left.\frac{\partial T_{m,s}(x,y,t)}{\partial x}\right|_{x=0} = \left.\frac{\partial T_{m,s}(x,y,t)}{\partial x}\right|_{x=Lx} = 0 \tag{2c,d}$$

$$k_s \left.\frac{\partial T_{m,s}(x,y,t)}{\partial y}\right|_{y=0} = h_i\left(T_{m,s}(x,0,t) - T_{f,b}(x,t)\right) \tag{2e}$$

$$\left.\frac{\partial T_{m,s}(x,y,t)}{\partial y}\right|_{y=Ly/2} = 0 \tag{2f}$$

The full transient two-dimensional mathematical model that describes the temperature distribution in the laminar fluid flow within the micro-channel is given by:

$$\rho Cp_f\left(\frac{\partial T_f(x,r,t)}{\partial t} + u(r)\frac{\partial T_f(x,r,t)}{\partial x}\right) = k_f\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_f(x,r,t)}{\partial r}\right) \quad t>0;\ 0<x<L_x;0<r<R_i \tag{3a}$$

$$T_f(x,r,0) = T_0(x,0) \tag{3b}$$

$$T_f(0,r,t) = T_{in} \tag{3c}$$

$$\left.\frac{\partial T_f(x,r,t)}{\partial r}\right|_{r=0} = 0 \tag{3d}$$

$$T_f(x,R_i,t) = T_{m,s}(x,0,t) \tag{3e}$$

where $u(r)$ is the parabolic fully developed velocity profile. A simplified lumped model is also here proposed for the bulk temperature evolution within the microchannel, starting from its definition:

$$T_{f,b}(x,t) = \frac{2\pi\int_0^{Ri} ru(r)T_f(x,r,t)dr}{2\pi\int_0^{Ri} ru(r)dr} = \frac{2}{\overline{u}R_i^2}\int_0^{Ri} ru(r)T_f(x,r,t)dr \tag{4}$$

Since transients are very short at the micro scale, the first term related to the thermal capacitance of the fluid is neglected, and operating Eqs. (3) with $\frac{2}{\overline{u}R_i^2}\int_0^{Ri} ru(r)\_\_\_\_\_\_ dr$ we obtain a lumped formulation for the convective heat transfer problem as:

$$\frac{\partial T_{f,b}(x,t)}{\partial x} = -\frac{2h_i}{\rho Cp_f\overline{u}R_i}\left(T_{m,s}(x,0,t) - T_{f,b}(x,t)\right) \quad t>0;\ 0<x<L_x \tag{5a}$$

$$T_{f,b}(0,t) = T_{in} \tag{5b}$$

The above equation has an exact solution given by:

$$T_{f,b}(x;t) = T_{in}e^{-\gamma x} + \gamma\int_0^x e^{-\gamma(x-x')}T_s(x',0,t)dx' \qquad \text{where} \quad \gamma = \frac{2h_i}{\rho Cp_f\overline{u}R_i} \tag{6}$$

Eqs.(1.c), (2.a-f) and (6) provide a simplified improved lumped-differential formulation to this conjugated heat transfer problem, providing estimates for the average and surface temperatures at the plate, and for the bulk temperature of the fluid. The numerical solution of the direct problem is then based on the Method of Lines implemented in the subroutine *NDSolve* available in the software *Matemathica* 7.0 (Wolfram, 2005).

4. INVERSE PROBLEM SOLUTION

In this work we also make use of Bayesian inference (Kaipio & Somersalo, 2004; Gamermann & Lopes, 2006) for the estimation of the thermophysical properties of the polyester plate, the effective heat transfer coefficient at the plate´s exposed surface, and the heat flux partition with the insulation. The inverse problem analysis is based on recent developments for the identification of space variable thermophysical properties in heterogeneous media (Naveira-Cotta et al., 2010; Naveira-Cotta et al., 2011), which introduce two novel aspects which are the eigenfunction expansion of the functions to be estimated themselves and the integral transformation of the experimental data, thus promoting a significant data volume reduction, operating the inverse problem computations in the transformed domain. In the present phase of verification of the proposed lumped-differential model for the conjugated problem, we have tested the possibility of feeding the model with parameters and functions identified through the experiment without flow within the microchannel. Then, the inverse analysis can be handled through a one-dimensional model for the heat conduction within the fluid, varying essentially with the longitudinal coordinate, in the form (Knupp et al., 2010; Knupp et al., 2011):

$$\rho Cp_s \frac{\partial T_{m,s}(x,t)}{\partial t} = k_s \frac{\partial^2 T_{m,s}(x,y,t)}{\partial x^2} + \frac{q_w(t)}{L_z} - \frac{h_e(x)}{L_z}\left(T_{m,s}(x,t) - T_\infty\right), \qquad t > 0;\ 0 < x < L_x; \tag{7a}$$

$$T_{m,s}(x,0) = T_\infty \tag{7b}$$

$$\left.\frac{\partial T_{m,s}(x,t)}{\partial x}\right|_{x=0} = \left.\frac{\partial T_{m,s}(x,t)}{\partial x}\right|_{x=Lx} = 0 \tag{7c,d}$$

In the inverse analysis we thus attempt to identify the thermophysical properties ρCp_s and k_s, the effective heat transfer coefficient, $h_e(x)$, and the applied heat flux, $q_w(t)$, employing the Markov Chain Monte Carlo (MCMC) method implemented with the Metropolis-Hastings algorithm (Naveira-Cotta et al., 2010; Naveira-Cotta et al., 2011). With this methodology, the sampling procedure used to recover the *posterior* distribution is in general the most expensive computational task, since the direct problem is calculated for each state of the Markov Chain. In this context, the use of a fast, accurate and robust computational implementation of the direct solution is extremely important. Thus, the integral transformation approach (Cotta, 1993; Cotta & Mikhailov, 1997; Cotta & Mikhailov, 2006) becomes very attractive for the combined use with the MCMC method. Such is the case because analytical expressions can be obtained for different quantities required in the implementation, thus avoiding repetitive numerical tasks.

A major aspect in the methodology advanced in (Naveira-Cotta et al., 2010; Naveira-Cotta et al., 2011) was the solution of the inverse problem in the transformed field, from the integral transformation of the experimental temperature data, thus collapsing the experimental measurements in the space variables into a few transformed temperature fields. Once the experimental temperature readings have been obtained, one proceeds to the integral transformation of the temperature field at each time through the integral transform pair below:

Transform:
$$\overline{T_{\exp,i}}(t) = \int_0^{Lx} w(x)\tilde{\psi}_i(x)[T_{\exp}(x,t) - T_\infty]dx \tag{8a}$$

Inverse:
$$T_{\exp}(x,t) = T_\infty + \sum_{i=0}^{Ni} \tilde{\psi}_i(x)\overline{T_{\exp,i}}(t) \tag{8b}$$

The eigenfunctions $\tilde{\psi}_i(x)$, are obtained from the chosen eigenvalue problem below:

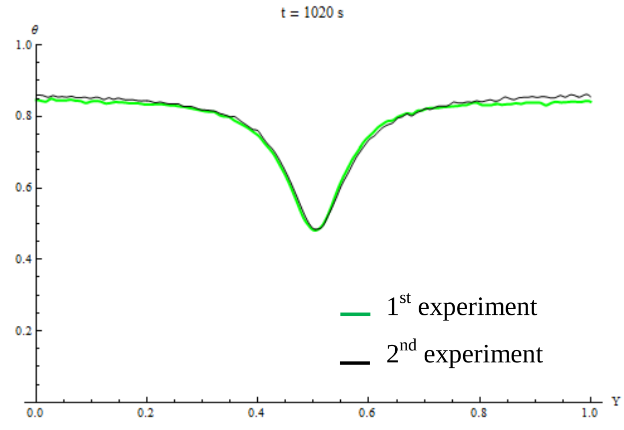
$$\frac{d}{dx}\left[k(x)\frac{d\tilde{\psi}_i(x)}{dx}\right] + [\mu_i^2 w(x) - d(x)]\tilde{\psi}_i(x) = 0, \quad x \in [0, L_x] \tag{9a}$$

$$\frac{d\tilde{\psi}_i(x)}{dx} = 0, \quad x = 0 \qquad\qquad \frac{d\tilde{\psi}_i(x)}{dx} = 0, \quad x = L_x \tag{9b,c}$$

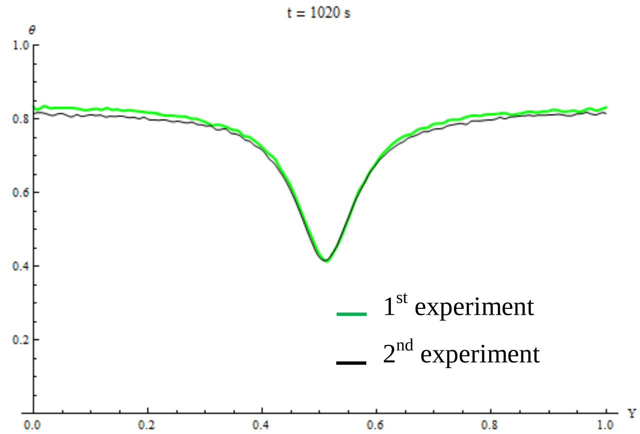
where the coefficients k, w and d, are respectively k_s, ρCp_s, $\frac{h_e(x)}{L_z}$, which is solved by constructing an auxiliary eigenvalue problem of known analytical solution to offer the basis for the eigenfunction expansion (Naveira-Cotta et al., 2011).

5. RESULTS AND DISCUSSION

Results were here analyzed more closely for two different volumetric flow rates, 0.5ml/min and 1ml/min, and we start by illustrating the repeatability of the experimental procedure, in Figures 6 and 7, respectively, for each mass flow rate. Figures 6a,b show the dimensionless temperature distributions along the y variable for a steady-state situation (t=1020s), for x=L_x/2 and for the two flow rates, while Figures 7a,b show the time evolution of the dimensionless temperature at the center of the plate, x=L_x/2 and y=0. These results confirm the excellent agreement between two independent experiments, and also demonstrate the expected symmetry of the temperature distribution along the transversal coordinate. It is also observed that the transient state occurs roughly within the first five minutes.

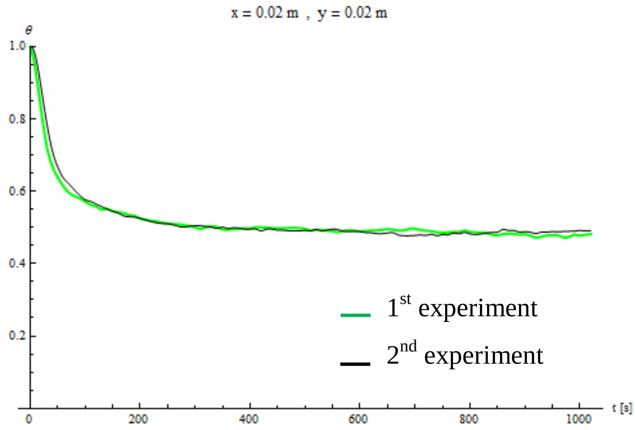


(a) 0.5ml/min

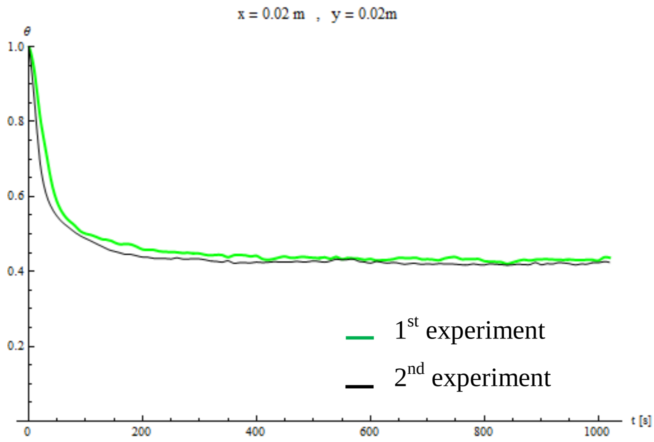


(b) 1ml/min

Figures 6 – Dimensionless temperature along the dimensionless transversal coordinate Y= $(y+L_y/2)/L_y$, for x=0.02m and t=1020s (steady-state).



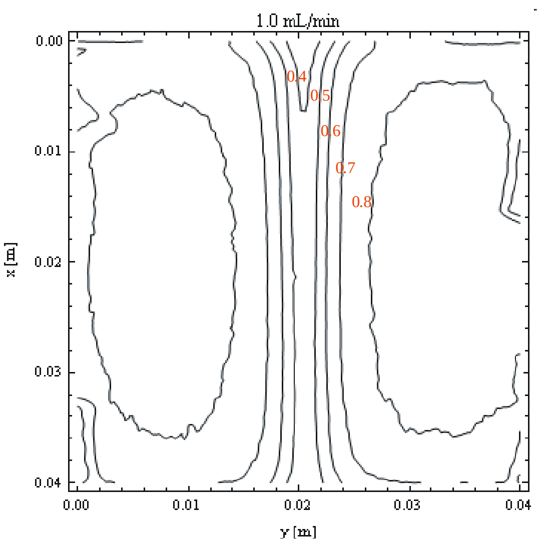
(a) 0.5ml/min



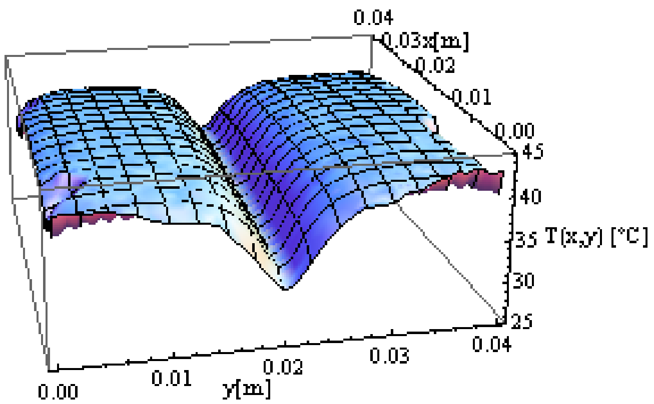
(b) 1ml/min

Figures 7 – Dimensionless temperature time evolution at the plate center (x=0.02m e y=0.m).

Figures 8a,b illustrate the behavior of the surface plate temperatures for the volumetric flow rate of 1 ml/min, both as a contour plot of the dimensionless temperature for steady-state and as a three-dimensional plot of the dimensional temperature. It is now more evident the marked depression of the plate´s surface temperature as the convection is established, due to the high heat transfer coefficients that are achievable at the micro-scale. Some boarder effects are also observable, in light of the difficulty in fully insulating the plate from the frame and surrounding air.



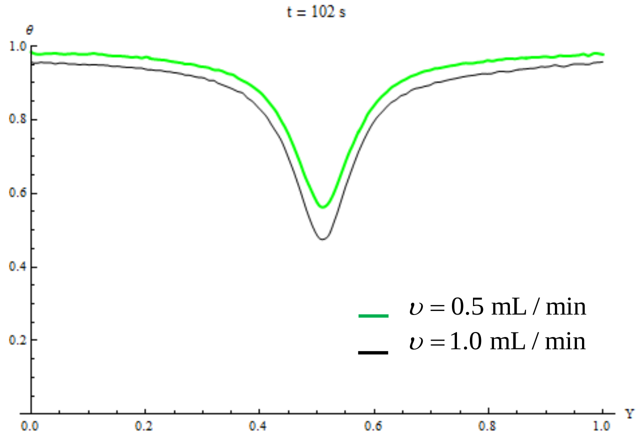
(a)



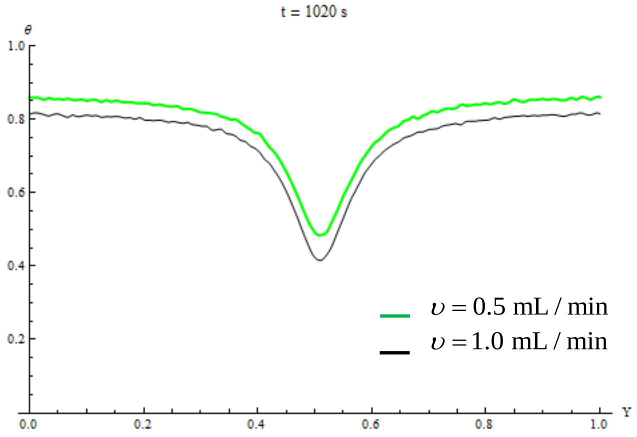
(b)

Figures 8 – Experimental surface temperature distributions at steady-state for volumetric flow rate of 1.0 ml/min.

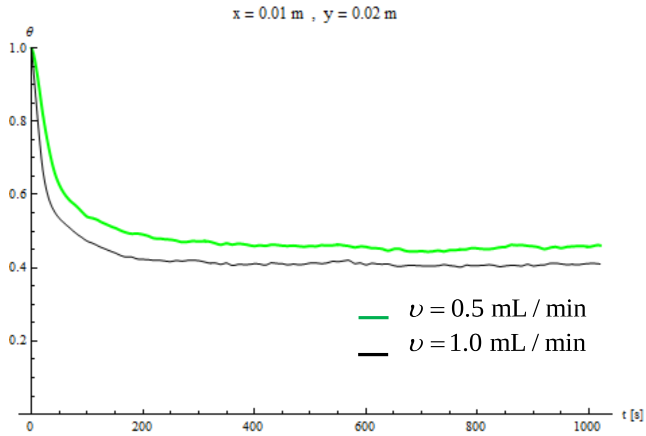
Figures 9a,b show a comparison of the dimensionless experimental temperatures along the transversal coordinate for the two volumetric flow rates, 0.5 and 1.0 ml/min, at two different stages, within the transient (t=102 s) and at steady-state (t=1020s). One can observe the more pronounced temperature depression in the microchannel region, as well as the overall reduction throughout the plate´s surface, due to the higher flow rate, but a marked difference between the two temporal states is not registered. Similarly, Figures 9c,d illustrate the time evolution of the dimensionless temperature at two different positions along the longitudinal centerline (y=0) at x=0.01m and 0.03m. The same trends are here observable, but in addition one may observe the more pronounced difference between the temperatures from the two experiments with different flow rates for regions closer to the microchannel exit.



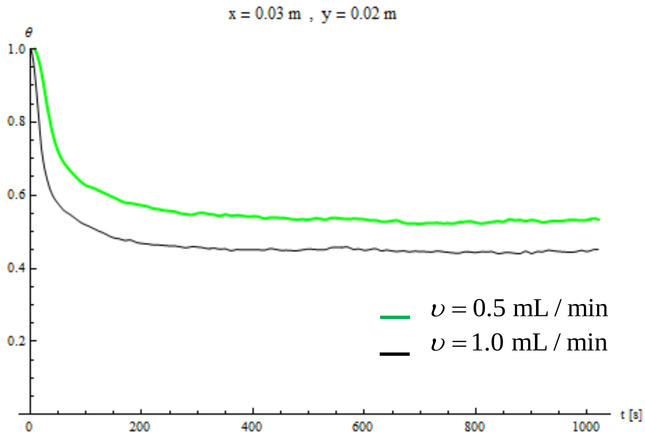
(a) t = 102 seconds



(b) t=1020 seconds



(c) x=0.01m and y=0.02m



(b) x=0.03m and y=0.02m

Figures 9 – Comparison of dimensionless experimental temperatures for different flow rates, 0.5ml/min and 1ml/min

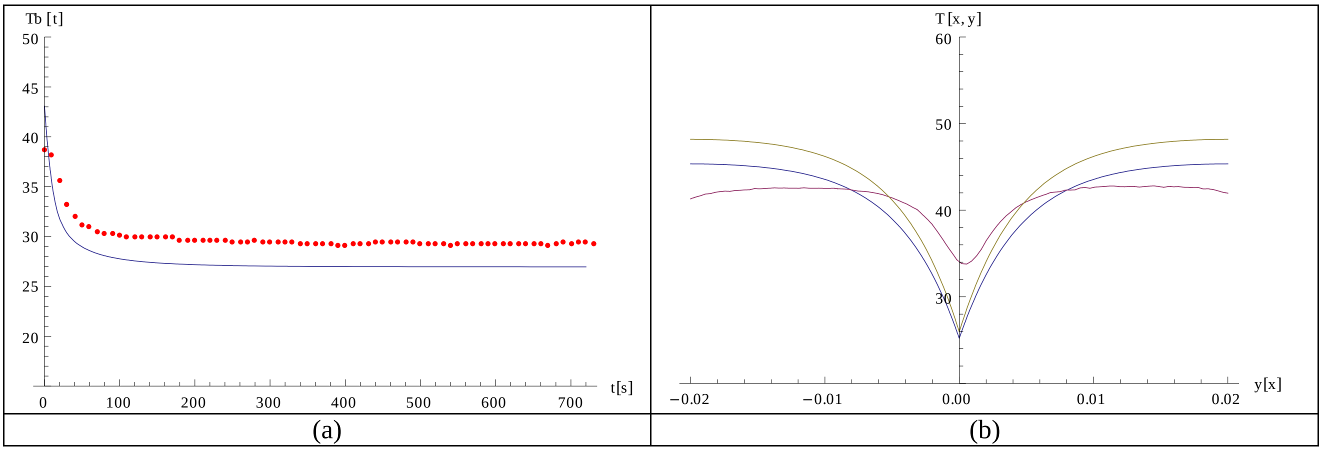
The inverse problem analysis provides estimates for the thermophysical properties of the polyester plate, for the effective heat transfer coefficient and for the heat flux partition with the insulation, as summarized in Table 1 below.

Table 1 – Estimates of the thermophysical properties, heat flux partition, and effective heat transfer coefficient.

Parameters	$k_s[W/m^oC]$	$\rho Cp_s[J/m^{3\,o}C]$	f	$h_e(x)[W/m^{2\,o}C]$
Estimated values	0.158	$1.565 \quad 10^6$	0.5472	1.23165 (23.6189 - 11.6638 Sin[78.5398 x] - - 0.138166 Sin[157.08 x] - 3.65355 Sin[235.619 x] - - 0.149853 Sin[314.159 x] - 1.82654 Sin[392.699 x])

The heat flux partition is employed to estimate the actual prescribed heat flux, as a fraction of the power provided to the electrical resistance, $q_w(t) = f\ (q_{\inf})$, where $q_{\inf} = V.I/A$.

The estimated parameters are then fed into the improved lumped-differential model, Eqs. (1c, 2a-f, 6), to allow for calculation of the simulated surface temperatures along the transient. The comparison of the simulated and experimental temperatures are provided in Figures 10, allowing for a critical evaluation of the proposed simplified model. Figure 10a shows the exiting bulk temperatures time evolution ($x=L_x$), in solid line for the simulated values and in red dots for the experimental values. Figure 10b compares the temperature distributions at steady-state as a function of the transversal coordinate, at the mid-plane of the plate ($x=L_x/2$), showing the experimental values in purple, the simulated surface temperatures in blue, and simulated z-averaged temperatures in green. From such comparisons it is clear that the overall characteristics of the phenomena are captured by the model, such as the transient duration and the spatial behavior of the temperature depression due to the cooling of the microchannel water flow. However, it appears that the estimated parameters are not the most adequate to simulate this more involved conjugated problem, including the internal heat transfer coefficient, which was here estimated from the asymptotic Nusselt number for a prescribed wall heat flux (Nu=4.364), the effective heat transfer coefficient, which may experience some spatial changes in behavior due to the surface temperatures variation in the transversal coordinate, and most certainly the heat flux partition, which should now favor even further the polyester plate, due to decrease in thermal resistance provided by the presence of the microchannel convection, but should experience some spatial variation.



Figures 10 – Comparisons of simulated and measured temperatures: a)Bulk temperature at the microchannel exit; b) Simulated surface (blue) and z-averaged (green) temperatures and experimental surface temperature (purple).

4. CONCLUSIONS

In this work we have constructed and employed an experimental apparatus, based on infrared thermography, to analyzed polymeric heat spreaders internally cooled with microchannels. A single microchannel configuration on a polyester matrix was first tested, for two different volumetric flow rates, to demonstrate the experimental technique and provide a set of experimental results for model verification. Repeatability and physical results of the experimental campaign are then illustrated. An improved lumped-differential model was proposed, which distinguishes between the surface and thickness averaged temperatures, and is as simple as the classical lumping procedure that neglects the temperature variations across the plate thickness. An inverse problem analysis was also implemented to estimate parameters and functions to feed the model, based on the experiment without cooling by the microchannel. Although the proposed model recovers the main features of the conjugated heat transfer problem, it has been concluded that the inverse analysis of the one-dimensional model was useful mainly in identifying the thermophysical properties of the polyester resin, and a dedicated inverse analysis should be implemented, accounting for the two-dimensional effects introduced by the water cooling.

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6. REFERENCES

Cotta, R.M. (1993), “Integral Transforms in Computational Heat and Fluid Flow”, CRC Press, Boca Raton.
Cotta, R.M. and Mikhailov, M.D. (1997), “Heat Conduction: Lumped Analysis, Integral Transforms, Symbolic Computation”, Wiley-Interscience, Chichester, UK.
Cotta, R.M. e Mikhailov, M.D. (2006), “Hybrid Methods and Symbolic Computations”, in: Handbook of Numerical Heat Transfer, 2nd edition, Chapter 16, Eds. W.J. Minkowycz, E.M. Sparrow, and J.Y. Murthy, John Wiley, New York.

Fudym, O. (2006), "Velocity and Heat Transfer Parameters Mapping: Thermal Quadrupoles and Infrared Image Processing", 11th Brazilian Congress of Thermal Sciences and Engineering – ENCIT, Curitiba – Brazil, Dec. 5-8.

Gamerman, D. and Lopes, H.F., 2006, "Markov Chain Monte Carlo: Stochastic Simulation for Bayesian Inferenc", Chapman & Hall/CRC, 2nd ed., Boca Raton.

Guedes, R.O.C., Cotta, R.M., and Brum, N.C.L. (1991) "Heat Transfer in Laminar Tube Flow with Wall Axial Conduction Effects", J. Thermophysics & Heat Transfer, vol. 5, no. 4, pp.508-513.

Hetsroni, G., Mosyak, A., Segal, Z., Ziskind, G., 2002, "A Uniform Temperature Heat Sink for Cooling of Electronic Devices", Int. J. Heat Mass Transf., v. 45, no.2, pp. 3275-3286.

Hetsroni, G., Mosyak, A., Pogrebnyak, E., Yarin, L.P., 2005, "Heat transfer in Micro-channels: Comparison of Experiments with Theory and Numerical Results", Int. Journal of Heat and Mass Transfer, v. 48, pp. 5580–5601.

Kaipio, J. and Somersalo, E., 2004, Statistical and Computational Inverse Problems, Springer-Verlag.

Kandlikar, S. G., Grande, W. J., 2003, "Evolution of Microchannel Flow Passages – Thermohydraulic Performance and Fabrication Technology", Heat Transfer Engineering, v.24, pp.3-17.

Knupp, D.C., C.P. Naveira-Cotta, J.V.C. Ayres, H.R.B. Orlande, and R.M. Cotta, "Experimental-Theoretical Analysis in a Transient Heat Conduction Setup via Infrared Thermography and Unified Integral Transforms", Int. Review Chemical Eng., IRECHE, V.2, no.6, pp.736-747, 2010.

Knupp, D.C., C.P. Naveira-Cotta, J.V.C. Ayres, R.M. Cotta, and H.R.B. Orlande, "Identification of Thermophysical Properties of Heterogeneous Nanocomposites via Integral Transforms, Bayesian Inference and Infrared Thermography", 7th International Conference on Inverse Problems in Engineering, ICIPE, Orlando, Florida, USA, May 4-6, 2011.

Maranzana, G., Perry, I. Maillet, D. "Mini and Microchannels: Influence of Axial Conduction in the Walls", Int. J. Heat Mass Transfer, vol. 47, pp. 3993-4004.

Morini, G. L. (2004), "Single-Phase Convective Heat Transfer in Microchannels: a Review of Experimental Results, Int. J. of Thermal Sciences, vol. 43, pp. 631-651.

Naveira-Cotta, C.P., H.R.B. Orlande, and R.M. Cotta, 2010a, "Inverse Analysis of Forced Convection in Microchannels with Slip Flow via Integral Transforms and Bayesian Inference", Int. J. Thermal Sciences, V.49, pp.879-888.

Naveira-Cotta, C.P., H.R.B. Orlande, R.M. Cotta, and J.S. Nunes, 2010b, "Integral Transforms, Bayesian Inference, and Infrared Thermography in the Simultaneous Identification of Variable Thermal Conductivity and Diffusivity in Heterogeneous Media", 14th Int. Heat Transfer Conf., Washington, DC, USA, August 2010.

Naveira-Cotta, C.P., R.M. Cotta, and H.R.B. Orlande, 2011, "Inverse Analysis with Integral Transformed Temperature Fields for Identification of Thermophysical Properties Functions in Heterogeneous Media", Int. J. Heat & Mass Transfer, V.54, no.7-8, pp.1506-1519.

Nunes, J. S., Cotta, R. M., Avelino, M., Kakaç, S. (2010), "Conjugated Heat Transfer in Microchannels", In: Kakaç, S.; Kosoy, B.; Pramuanjaroenkij, A. (Eds.). (Org.). Microfluidics Based Microsystems: Fundamentals and Applications. : NATO Science for Peace and Security Series A: Chemistry and Biology, v.1, pp. 61-82.

Patil, V.A. and Narayanan, V., 2005, "Measurement of Near-Wall Liquid Temperatures in Single Phase Flows Through Silicon Microchannels", Proceedings of the 3rd International Conference on Microchannels and Minichannels (ICMM 2005) Toronto, Canada, ICMM2005–75212.

Pradère C., Joanicot M., Batsale J-C., Toutain J., Gourdon C, 2006, "Processing of Temperature Field in Chemical Microreactors with Iinfrared Thermography", QIRT Journal, v. 3, pp.117-135.

Wolfram, S., 2005, "The *Mathematica* Book", version 5.2, Cambridge-Wolfram Media, 2005.

Yarin, L.P., Mosyak, A., Hetsroni, G., 2009, "Fluid Flow, Heat Transfer and Boiling in Micro-Channels", Heat and Mass Transfer, Springer.

Yener, Y., Kakaç, S., Avelino, M., Okutucu, T. (2005), "Single-Phase Forced Convection in Microchannels – a State-of-the-art Review", in: S. Kakaç, L.L. Vasiliev, Y. Bayazitoglu, Y. Yener (Eds.), Microscale Heat Transfer – Fundamentals and Applications, NATO ASI Series, Kluwer Academic Publishers, The Netherlands, pp. 1-24.

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