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IMAGE PROCESSING OF TEMPERATURE FIELDS FROM INFRARED TERMOGRAPHY OF MICRO-MIXERS WITH POLYMERIC SUBSTRATES

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Abstract. *The present work deals with the image processing and thermal analysis of micro-mixers from the data provided by an infrared camera thermographic system. The micro-mixers are prepared by photolitography on a polymeric substrate and the camera employed is the FLIR SC645 with the proprietary software ThermaCam Researcher Pro v2.10. The thermal analysis is aimed at understanding the direct contact heat transfer between two fluid streams at different inlet temperatures and mass flow rates, within mixers of various geometric configuration. Infrared thermography is thus employed to measure the external wall temperatures along the mixer length. Water at different inlet temperatures has been used as the working fluid in all cases and the mass flow rates of the two streams have been imposed through independent syringe pumps. The image processing and analysis of the experimental results show the basic qualitative features of the heat transfer phenomena and indicates that a conjugated heat transfer formulation of the micro-mixer structure should be pursued for accurate quantitative analysis in future theoretical predictions.*

***Keywords**: micro-mixers, infrared thermography, image processing, micro-channel, photolitography, conjugated problem.*

1. INTRODUCTION

Micro-mixers are one of the essential components required in the assembly of various types of MEMS (Micro-Electro-Mechanical Systems) due to the need of enhancing mixing effects in light of the laminar nature and predominant diffusive mixing of the more usual flows in microfluidic devices. The micro-mixers, by presenting small dimensions, become appropriate in controlling the mixture of reagents under very low Reynolds number and laminar flows. Besides using small amounts of reagents, they also allow to easily, safely and quickly test a great number of reaction configurations (Tabeling, 2003). Thus, micro-mixers are essential components in microfluidic systems, of great interest to both industry and academy within numerous applications, such as chemical and biochemical analysis, monitoring and control of processes, automation of operations in petroleum reservoirs, among others.

The studies about the theoretical principles and applications of these devices are fairly recent and have attracted the interest of many researchers, mainly in relation to the fluid flow and heat/mass transfer of mixing streams in micro-channels. For instance, Engler *et al.* (2004) demonstrated by numerical simulations and experiments the effects of vorticity in a static micro-mixer of rectangular section and concluded that the increase of the effect of vorticity can improve the quality of mixing and that the development of vortices does not depend only on the Reynolds number, but also highly on the channel geometry. Pradere *et al.* (2004) performed an analysis of the temperature fields in micro-reactors using infrared thermography and image processing methods, with the aim of proposing a new estimation method in order to access the source term distribution inside the channel, that consisted in inverting the pseudo-temperature fields inside and outside the channel using simplified models. Pohar and Plazl (2009) reported the benefits and the significant advances in the use of micro-reactors in existing manufacturing processes or in the complete substitution , since with micro-systems there is a better control of the temperature due to the resulting high rates of heat and/or mass transfer and achievement of high reaction rates and consequent reduction of the reaction time. Xu *et.al.* (2010) experimentally and numerically investigated the flow and mixing features of two miscible fluid streams in a T-shaped micro-channel.

The study of the thermal behavior of mixtures is also of fundamental importance once the information of the temperature within the devices serves as a tracer to the monitoring of the process. Then, it is necessary to use reliable measurement techniques, capable of precisely providing the variations of temperature along the micro-mixers. In this context, the use of the infrared thermography technique provides non- intrusive temperature measurements with high temporal resolution and nowadays progressively improving spatial resolution.

The main objective of the present work is the qualitative thermal analysis of a Y-shaped micro-mixer, which works with direct contact heat transfer between two fluid streams at different inlet temperatures, using infrared thermography to compare various cases with different temperatures and mass flow rates of the two streams. We also present an estimation of the flow Peclet number through the pseudo-temperature field outside the channel, processing the infrared images in a micro-mixer made of polymeric substrate.

The fabrication technique of the micro-devices based on photolitography used in this work was developed by Fernandes and Ferreira (2006). It uses a photoresist based in the urethane and acrylate oligomers (UA) and was described in detail in a previous work by Costa Junior *et al.* (2012).

2. EXPERIMENTAL SETUP

The experimental setup presented in Fig. (1) employs temperature measurements obtained from the infrared camera FLIR SC645, a high performance infrared system with 640x480 pixels. During the experiments the working distance between object and lens was 28cm and, in this configuration, we have an estimated pixel size of 190 µm.

The main components of the setup are marked on Fig. (1) as a) the micro-system consisting in this case of a Y-shaped mixer; b) the dual syringe pumps for controlled and independent flow rates; c) the data acquisition system (Agilent 34970-A); d) the microcomputer for data acquisition from the thermocouples and from the precision scale, to obtain the total mass flow rate at the outlet of the micro-mixer; f) infrared camera FLIR SC645. Three thermocouples were used to measure the bulk temperatures in the fluid, two of them located at each entry of the micro-mixer and one located at the outlet of the mixing micro-channel. A fourth one was used to measure the ambient temperature.

All experiments conducted during this study were performed in a Y-shaped micro-mixer manufactured by the photolithography process with average width of 450 µm and a mixing length of 6 cm, worked on a 8 x 4 cm polymer chip and positioned horizontally, as described in detail in Costa Junior *et.al.* (2012). Fig. (2) shows the micro-mixer with the access needles and microscopic images obtained by an optical microscope to provide the dimensions.

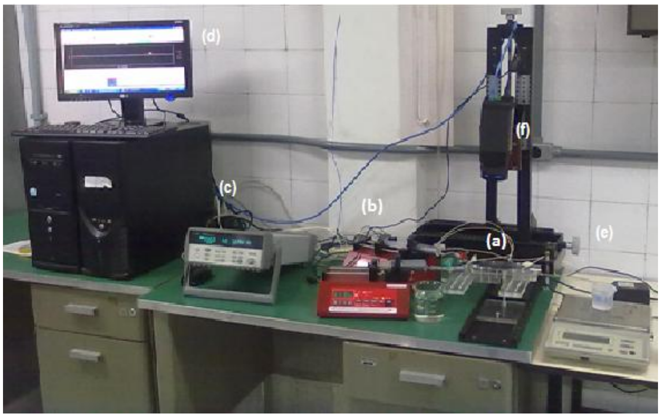


Figure 1. Experimental setup

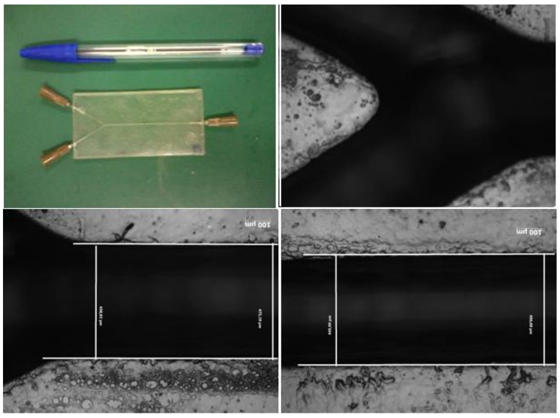


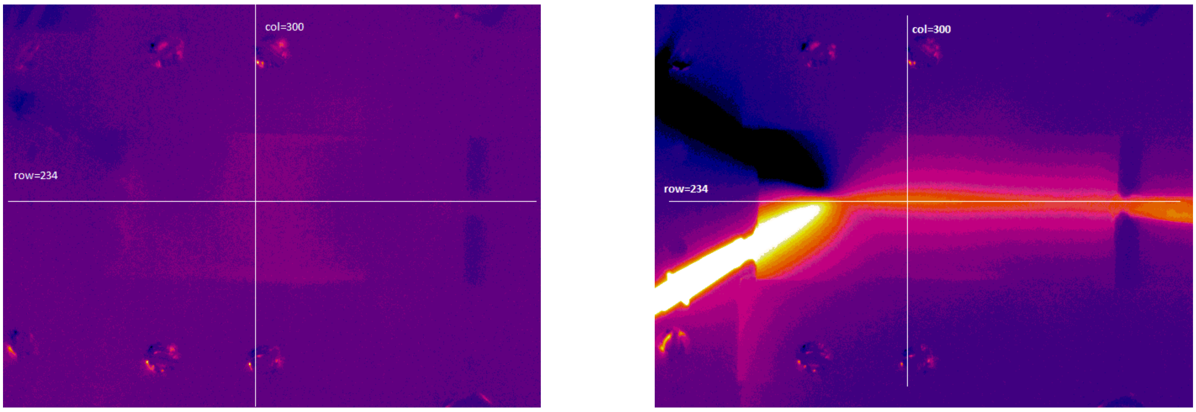
Figure 2. Tested micro-mixer and microscopy images;

The present analysis deals with a process of thermal mixing via direct contact heat transfer between water at different inlet temperatures, one below and the other above room temperature, and equal or different mass flow rates, imposed through the two independent syringe pumps. The experimental procedure is initiated by prescribing the flow rates at the syringe pumps and setting the parameter values relative to the infrared camera, such as the emissivity of the object, the distance between the object and the camera, relative humidity and ambient temperature. The data acquisition system is started and after a certain number of preliminary measurements to allow for averaging the initial conditions, the pumps switches are turned on to start the two fluid streams. The temperatures variation may be followed through the computer monitoring of both the infrared camera and the thermocouples acquisitions.

3. RESULTS AND DISCUSSION

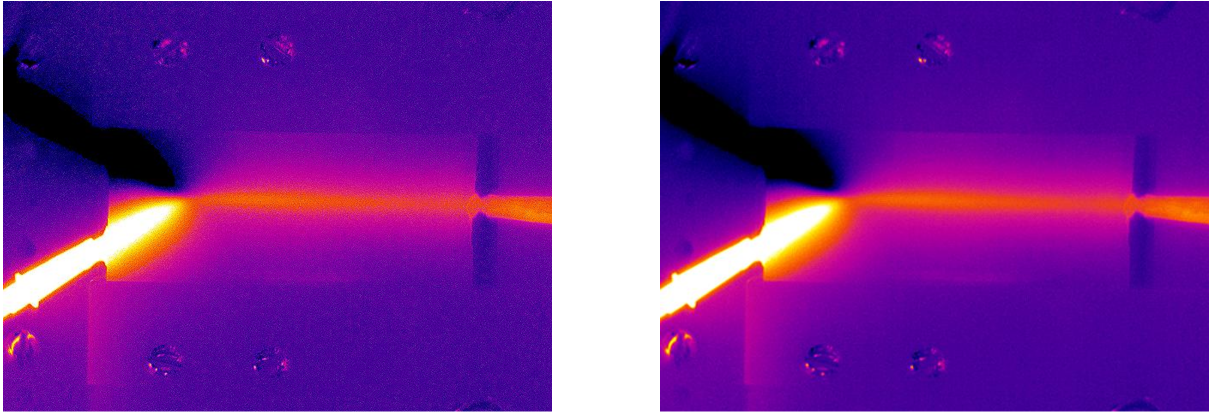
Figures 3.a,b present the infrared image for the initial condition and at steady state for the case of mass flow rates of 1ml/min of water in both inlet channels. In both figures it can been seen two lines drawn, respectively, in column number 300 and another one approximately in the middle of the channel in row 234. These correspond to the pixel lines that will be analyzed in what follows. Fig.3.a for the initial condition shows that the emissivity is fairly uniform, as assumed, since the micro-mixer is supposed to be in thermal equilibrium with the external environment. Fig.3.b is taken at t=500sec, and represents the steady state of this particular experimental run. One can observe the mixing along the micro-channel length, but also the lateral heat diffusion to the substrate, increasing along the channel length as well. Figure 4.a presents the subtraction of the Laplacian filter from the original image presented in Fig3.b, as obtained from the Mathematica v7.0 image processing routines, to emphasize the details. In Figure 4.b we then compute the mean value in a 3X3 block centered on each pixel, which represents the mean filter of the image presented in Figure 4.a, so as to denoise the image. Both of them show in much more detail the edges of the plate and especially the contour of the source term, here represented by the double stream in direct contact heat transfer and diffusing heat to the substrate.

Figures 5.a,b present the temperature profile along the pixel column 300, for different times from 60s to 100s with a step of 10s and from 200s to 500s with a step of 100s. Fig.5.b is just a close up view in the vicinity of the micro-channel, but shows that the temperature peak occurs at around the pixel line 234. One can clearly observe the temperature peaks within the hot stream region along the channel, as well as the broadening of the temperature distribution, due to the lateral diffusion to the substrate as time progresses. Figure 6 shows the longitudinal temperature distribution along the micro-mixer length, at pixel row 234. The linear portion of Fig. 6 (red line), which allows for estimation of the Peclet number, has angular coefficient -0.1101, yielding an estimate of Pe=600.4, against a pre-calculated value of Pe=639.8 as obtained from approximating the mean velocity by u_m=0.209 m/s.



(a) (b)

Figure 3. Infrared images of micro-mixer for the (a) initial and (b) steady state conditions;



(a) Filtered Image with Laplacian filter of Fig.3.b (b) Filtered Image with mean filter of Fig.4.a

Figure 4. Filtered Infrared images of micro-mixer for the steady state condition

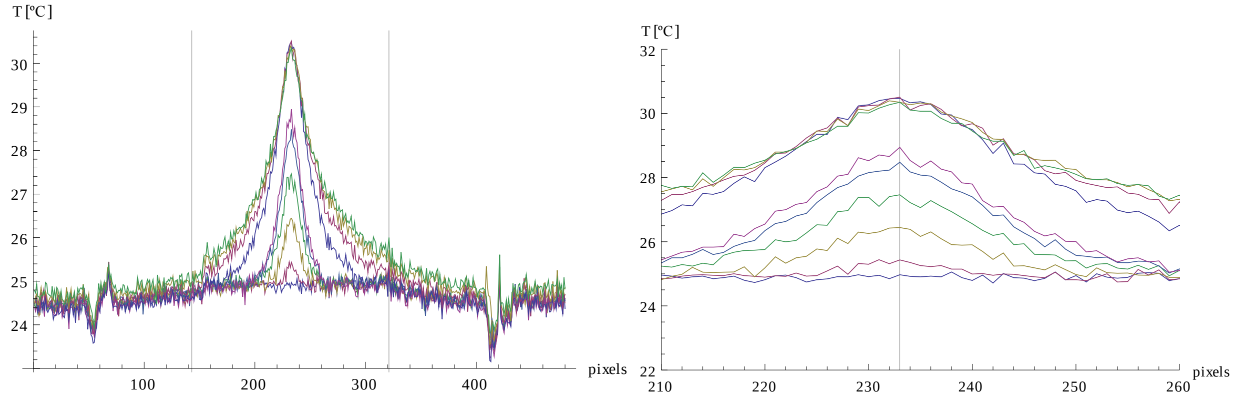


Figure 5. Micro-mixer and microscopic images;

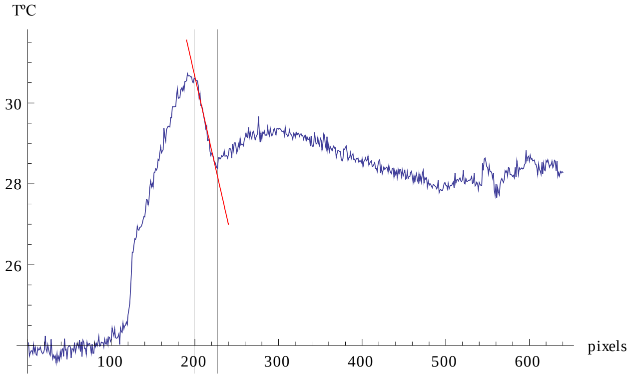
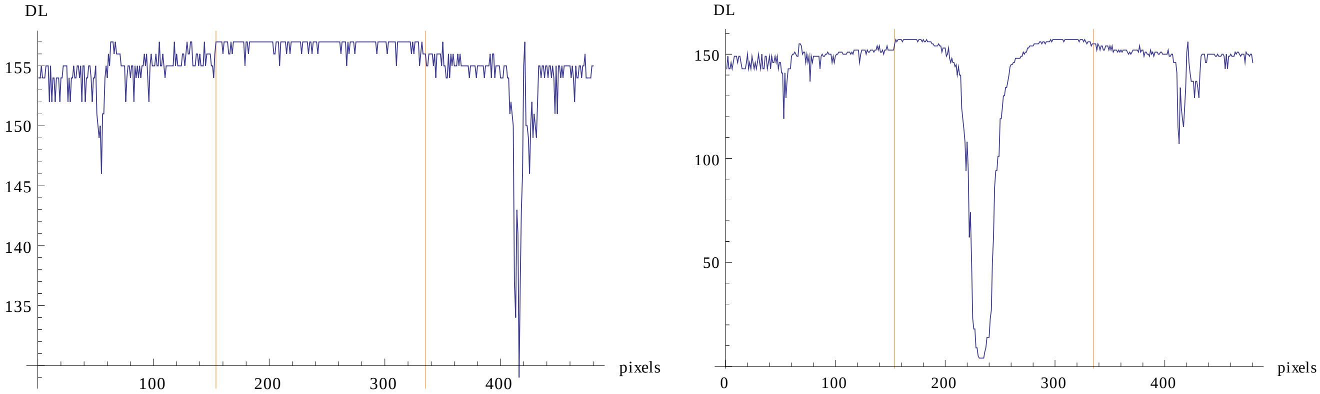


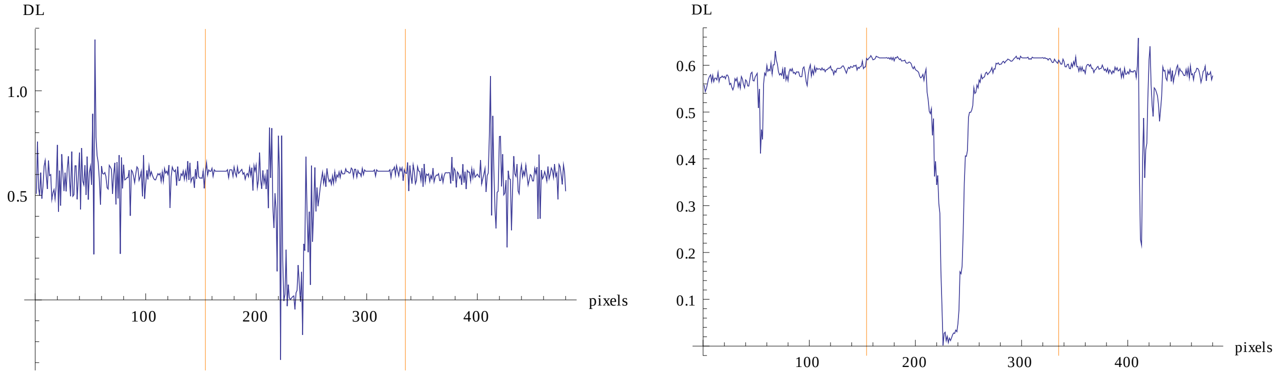
Figure 6. Longitudinal temperature profile along pixel row 234 for the image presented in Fig.3.b

Figures 7.a-b and 8.a-b present the graphs of the digital level from images 3.a-b and 4.a-b, respectively, at the pixel column 300 in all cases. In red vertical lines we show the limits of the micro-mixer polymeric chip. From Fig.7.a one can observe the practically uniform digital level that corresponds to the uniform initial temperature condition. Fig.7.b shows the marked variation of the digital level at the micro-channel region, within a few pixels, but also the lateral influence due to diffusion to the substrate. Fig.8.a shows the significant noise level that is is present after application of the Laplacian filter and subtracting from the original image, while Fig.8.b confirms that the mean filter applied to the previous case, offers a marked denoising effect.



(a) Digital Level for image presented in Fig. 3.a (b) Digital Level for image presented in Fig. 3.b

Figure 7. Digital Level along column 300 for the (a) initial and (b) steady state conditions for images presented in Fig.3



(a) Digital Level for image presented in Fig.4.a (b) Digital Level for image presented in Fig.4.b

Figure 8. Digital Level along column 300 for the images presented in Fig.4

4. ACKNOWLEDGEMENTS

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