FORCED CONVECTION ANALYSIS IN MINI- AND MICRO-TUBES VIA INFRARED THERMOGRAPHY WITH MICROSCOPIC LENS

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Abstract. *Convective heat transfer in laminar flow within micro-tubes due to an electrically heated metallic wall is modeled accounting for the heat losses due to both natural convection and radiation at the exposed tube wall and for a fully developed flow condition. The partial differential formulation for the thermal entrance region is obtained by either neglecting or accounting for heat losses from the channel external wall. The Generalized Integral Transform Technique (GITT) as implemented within the Mathematica 7.0 platform is adopted as the solution methodology for the proposed models. In addition, an experimental setup has been modified to study forced convection of deionized water inside micro-tubes, by electrically heating the micro-channel wall, while measuring the external wall temperature through infrared thermography with the FLIR SC645 camera with microscopic lenses. A comparison of theoretical and experimental results demonstrates a reasonable agreement of the measurements with the fairly simple model of convective heat transfer with heat losses. Nevertheless, the experimental results reveal that conjugated conduction-convection effects may be significant in this physical situation depending on the mass flow rate and geometry*.

Keywords*: Micro-channel, Infrared thermography, Micro-tubes, Integral transforms, Laminar flow, Forced convection*

1. INTRODUCTION

The present work finds motivation on the trend of thermal systems miniaturization aimed at improving efficiency within various application fields, Sobhan & Peterson (2008). Devices with characteristic dimensions of a few hundreds of microns have been developed for electronics cooling, micro-reactors and micro-sensors, to name just a few applications (Kandlikar & Grande, 2003). However, along the development of such thermal micro-systems, various authors have identified discrepancies among experimental and theoretical results in predicting both friction factors and heat transfer coefficients, when the macro-scale models and correlations were employed in predicting the micro-scale behavior (Morini, 2004). Since then, efforts have been directed towards improving the modeling of convective heat transfer in micro-channels, so as to incorporate effects that are in general negligible at the macro-scale but cannot be always disregarded when the characteristic dimensions become micrometric. One such effect that appears to become more relevant at the micro-scale is the conduction-convection conjugation due to the participation of the channel walls in the heat transfer process, which has been first discussed by (Maranzana et al., 2004) and later demonstrated both theoretically and experimentally by (Nunes et al., 2010). More recently, both the the wall conjugation effects and axial diffusion within the fluid itself have been accounted for (Knupp et al., 2012), based on the proposition of a single domain formulation of the wall-fluid conjugated problem.

In this sense, this work addresses the problem of laminar forced convection within micro-tubes of metallic walls, obtained from anesthesia needles, generating heat by Joule effect at the wall. First, a mini-channel is considered, when it is not expected that the classical forced convection modeling based on the extended Graetz problem would involve appreciable deviations from the experimental results. An infrared thermography system based on the FLIR camera SC645 is utilized to provide non-intrusive external wall temperature measurements along the needle length, employing a microscopic lens. Then, two additional needles at the micro-range are prepared, characterized and measured in terms of their thermal behavior under electric wall heating, including heat losses to the external environment. The aim is to verify whether classical forced convection modeling can still reproduce such micro-scale heat transfer problems. Otherwise additional effects need to be incorporated into the modeling so as to more closely match the experimental findings, such as conjugated heat transfer with the channel wall, axial diffusion along the fluid, viscous dissipation and eventually irregular geometry effects.

The solution methodology here adopted for handling the proposed partial differential models is based on the Generalized Integral Transform Technique (GITT), (Cotta, 1993), through utilization of the multi-purpose open source code known as UNIT (UNified Integral Transforms) (Cotta et al., 2010).

2. EXPERIMENTAL APPARATUS AND METHODOLOGY

In the proposed experiment, the micro-channels correspond to commercial micro-needles of Rachidian anesthesia made of stainless steel by BD Medical, namely the 18G, 22G and 27G, of external diameters, approximately of 1.2mm, 0.7mm and 0.41mm, respectively. More accurate geometric characterization was obtained with a profilometer at INMETRO, providing for the 18G needle, for example, the length of 152 mm, external diameter of 1.22 mm and internal diameter of 0.966 mm.

The overall view of the experimental setup is shown in Fig.1 below, where the following components can be identified: (1)Deionized water reservoir; (2) Pump Shurflo 2088; (3) Digital multimeter ICEL MD-6110; (4) Pressure transducers WIKA S10; (5) Needle BD MEDICAL; (6) Infrared camera FLIR SC645; (7) Voltage regulator for the electrical resistance; (8) Precision scale MARTE AS2200 for mass flow rates measurement; (9) Voltage regulator MIT MEASTECH INSTRUMENTOS MS3053 for pressure transducers; (10) computers for data acquisition (infrared camera, mass flow rate and Agilent 34970-A for the thermocouples and pressure transducers).

Mass flow rate was estimated by measuring mass versus time using the computer clock along the automatic acquisition. The data then undergoes a linear fit to provide the volumetric flow rate estimate. A precision scale MARTE model AS 2200, with range 0-2000g and resolution of $\pm$0.0001g was employed. For the inlet and outlet fluid temperatures, as well as for the external environment temperature, type K thermocouples have been installed. The infrared thermography was obtained with the FLIR SC-645 research type camera, and with the aid of the ThermaCam Research acquisition and data handling proprietary software. A microscopic lens is employed, as required for measuring the thinner needles, by partitioning the full length of the needle in segments successively recorded. The needle is painted with a graphite ink of known emissivity of 0.97 so as to minimize the background effect.

The experimental procedure starts with the adjustment of the mass flow rate at room temperature. Then, the electrical heating is turned on, and the thermocouples are monitored until steady state has been reached. The mass flow rate is then measured again for the hot fluid. The thermocouple readings, the voltages at the resistance and pump, as well as the thermographic images are recorded all along the transient. The current through the resistance as well as at the pressure transducers are determined from the digital multimeters at steady state.

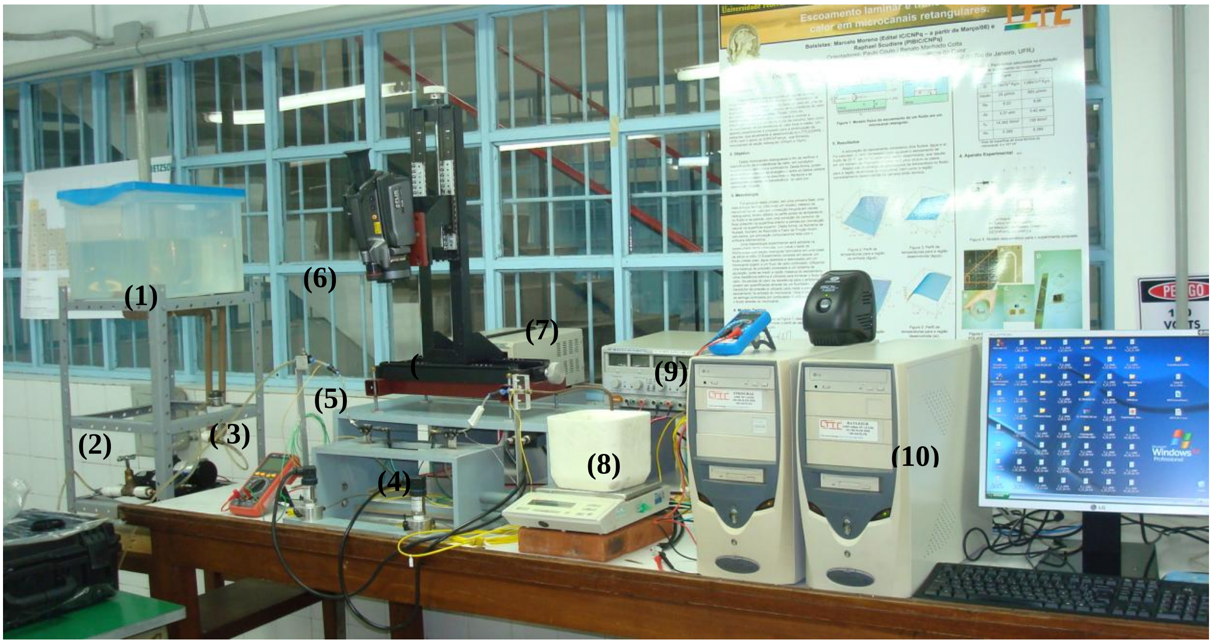


Figure 1. Overall view of the experimental setup for forced convection analysis in micro-needles.

3. MATHEMATICAL MODELS

The present work is aimed at verifying the adequacy of the classical forced convection modeling in predicting the heat transfer behavior of the metallic micro-needles here analyzed. The flow is considered to be fully developed when reaching the heated section of the needle, and for this reason the heating is not initiated at the very beginning of the needle, which in fact has a part of its length inserted into the plastic adaptor cap. Therefore, the proposed model involves an extended Graetz problem which includes the heat generation at the wall, the thermal resistance of the wall in the radial direction, and the heat losses by natural convection and radiation to the external ambient, here denoted Model II. Longitudinal heat conduction along the wall is however not considered in the present analysis. In order to allow for critical comparisons, the simpler Graetz problem with prescribed heat flux and negligible heat losses is also considered, here denoted Model I, which completely neglects the wall participation. The two models can be summarized as follows:

Model I - Classical Graetz problem with prescribe heat flux

$$(\rho cp)_f\, u(r)\frac{\partial T_f(r,z)}{\partial z}=\frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_f(r,z)}{\partial r}\right),\ 0<r<r_i \qquad T_f(r,0)=T_0,\ 0<r<r_i \tag{1a,b}$$

$$\left.\frac{\partial T_f}{\partial r}\right|_{r=0}=0,\ z>0 \qquad k_f\left.\frac{\partial T_f}{\partial r}\right|_{r=ri}=q_w \tag{1c,d}$$

Model II - Extended Graetz problem with wall participation and heat losses

$$(\rho cp)_f\, u(r)\frac{\partial T(r,z)}{\partial z}=\frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T(r,z)}{\partial r}\right),\ 0<r<r_i,\ z>0 \tag{2a}$$

$$T(r,0)=T_0,\ 0<r<r_i,\ z=0 \qquad \left.\frac{\partial T(r,z)}{\partial r}\right|_{r=0}=0,\ z>0 \tag{2b,c}$$

$$-k_f\frac{\partial T(r,z)}{\partial r}=g\left[\frac{r_i}{2}-\frac{\frac{k_S}{r_i}\left(\frac{h_{eff}}{4k_S}(r_e^2-r_i^2)+\frac{r_e}{2}\right)}{\frac{k_S}{re}+h_{eff}\ln\frac{r_e}{r_i}}\right]-\frac{k_S h_{eff}}{r_i\left(\frac{k_S}{re}+h_{eff}\ln\frac{r_e}{r_i}\right)}(T_\infty-T(r_i,z)),\qquad r=r_i,\ z>0 \tag{2d}$$

Both models have been solved by integral transforms, employing the UNIT code (Cotta et al., 2010), yielding temperature fields, bulk temperatures and Nusselt numbers along the thermal entrance region of the micro-tube.

4. RESULTS AND DISCUSSION

A few representative results for the 18G micro-needle are here presented for illustration of the proposed approaches, including both the external wall temperature distributions as obtained from the infrared thermography at steady state, and the theoretical results as obtained from the classical and extended Graetz problems, for different mass flow rates, 7g/min and 15g/min. Figures 2.a,b illustrate the infrared thermography images of the needle a few seconds after heating is initiated, Fig.2.a, and after the steady state is reached, Fig.2.b. Figures 3.a, b thus illustrate the experimentally determined wall temperatures (dots) at steady state and along the needle length, compared to the theoretical simulation for the classical and extended Graetz problems (red and pink dashed lines, respectively). Also shown for the sake of completeness are the simulated bulk temperatures (intermediate blue dashed and solid lines) and the channel´s center temperatures (lower blue dashed lines). It can be noticed that the two models provide essentially the same predictions, with a slight deviation at the end of the channel length, when the heat losses are observed to lower the temperature values of the extended problem with respect to the classical one. The experimental results are in reasonable agreement with the the two models, with some noticeable longitudinal heat conduction effects at the two ends of the needle, when the experimental gradients are slightly flatter than the predicted ones, with this effect being more noticeable for the lower mass flow rate. The wall conjugation effects may however be more significant for the thinner needles, requiring a more complete formulation such as the one recently proposed by (Knupp et al., 2012).

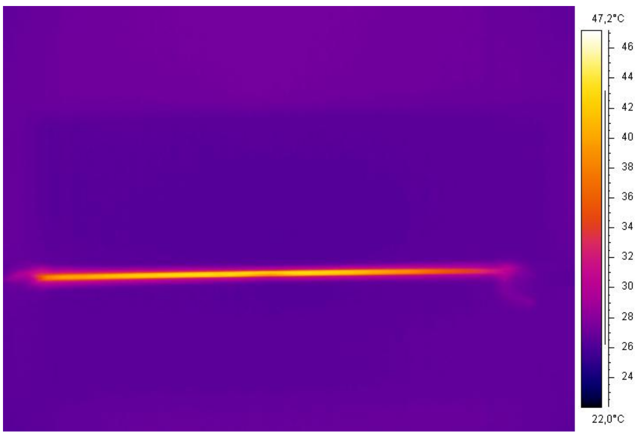


Fig.2.a - Infrared camera image after heating is turned on.

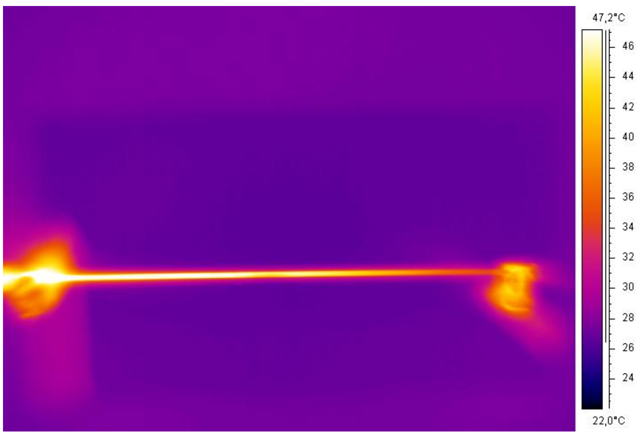
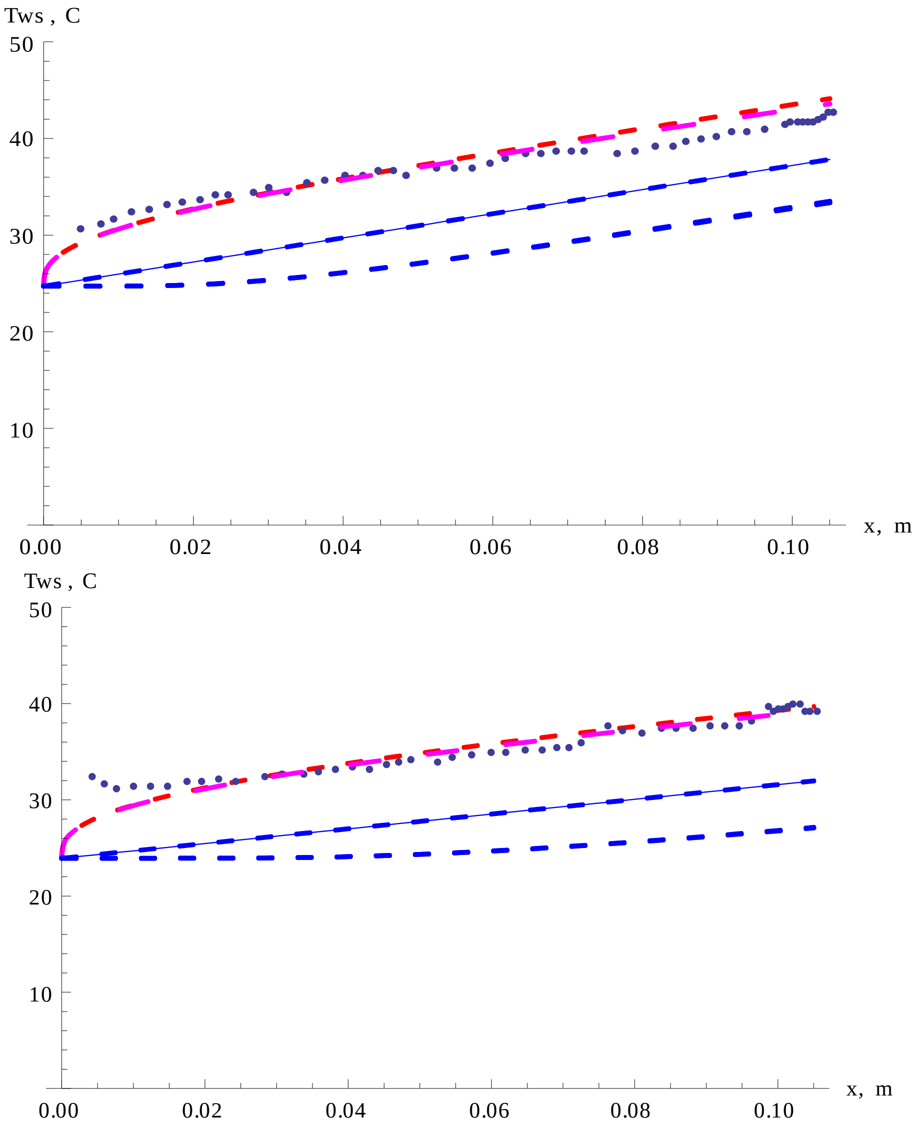


Fig.2.b - Infrared camera image of needle at steady-state



Figures 3.a,b - Experimental and theoretical wall temperatures for two mass flow rates: a)7g/min; b)15g/min.

5. ACKNOWLEDGEMENTS

The authos would like to acknowledge the financial support provided by CNPq, FAPERJ and CAPES.

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