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# Spatial temperature resolution in single-phase micro slot jet impingement cooling

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ABSTRACT

Local temperature measurements were made in a microchannel jet impingement cooling system with a single slot jet ($D_h$ = 68 μm and standoff distance of 210 μm). A 40%/60% solution of propylene glycol in deionized water was used as the working fluid. Resistance temperature detectors (*RTDs*) were fabricated over a rectangular heater of size 1500 μm × 400 μm allowing local temperature measurements. Nominal heat fluxes ranged between 50 W/cm$^2$ and 150 W/cm$^2$, and jet Reynolds numbers were in the range of 122–435. A three-dimensional conduction/convection conjugated numerical model with laminar and turbulent variants was developed to predict the jet hydrodynamics and heat transfer process. Good agreement was achieved between the model and the experimental data in terms of flow coefficients and local wall temperatures. Furthermore, a generalized Nusselt number dependence on Reynolds number was formulated, taking into account the temperature-dependent viscosity of the working fluid. The results provide valuable information about local and surface-averaged heat transfer due to a flow field generated by an impinging micro slot jet.



## 1. Introduction

Micro jet impingement cooling using liquids offers very high heat transfer coefficients, particularly in the stagnation region, making it a practical method for the electronics cooling industry [1–4]. Extensive research efforts on micro jet impingement have been undertaken over the years, with varying length and time scales, nozzle configurations, standoff distances and working fluids [5–9]. Variables of interest are the temperature distribution, the heat transfer coefficient or Nusselt number, the pressure drop, and flow coefficient across the jet orifice. Numerous correlations can be found in the literature for these variables, which have been obtained from experiments and numerical studies. Initially, jet impingement cooling was explored at conventional scales with nozzles spanning several millimeters and more [10–14]. Local temperatures at such scales have been measured using thermocouples [15], liquid crystal thermography [16], and infrared thermal imaging [17]. Depending on the nature of fluids involved, both micro scale and macro scale jets are usually classified as free-surface or submerged jets and, in each of these categories, they are further separated into confined or unconfined jets, based on flow conduit configuration. Descriptions of the various types of jet impingement can be found in Robinson and Schnitzler [18]. Active work in the field involves such innovations as the use of nanofluids with jet impingement [19]. Other researchers have introduced geometrical modifications – a comparative study of confined jets with different slot shapes can be found in the work by Rau et al. [20]. Two recent papers [21,22] address heat transfer and pressure drop characteristics of microchannels proper, but specifically mention jet impingement as one of the main enhancement mechanisms for single-phase flow in micro domains. A very recent paper by Robinson et al. [23] explored a hybrid microjet-microchannel cooling system.

Both macroscale and microscale jet impingement result in high heat transfer coefficients in the stagnation region [17], [24–30], which decrease with increasing distance from the stagnation point or line. Additionally, secondary peaks in the heat transfer coefficient have often been observed away from the stagnation region. This phenomenon has been attributed to the transition to

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turbulence of the wall jet [14,17,28,31]. The surface-averaged Nusselt number has been reported to scale with the jet Reynolds number as $Nu \sim Re^{\alpha}$, where $\alpha$ is in the range 0.5–0.8 [6,14,28,32–35]. Extensive literature can also be found on the unique flow and thermal characteristics of multiple jets or jet arrays at both the macro and the micro scales [5,10,15,33,36–38]. In the case of multiple jets, jet-to-jet spacing and jet-to-heater area ratios influence the heat transfer characteristics.

Reduced dimensions of flow conduits have posed new challenges in understanding flow and heat transfer effects and in obtaining local measurements of different variables of interest. Micro jet impingement typically results in submerged jet and confined flow of spent fluid, which can have significantly different thermal and hydrodynamic phenomena, compared to macro scale flow. Studies reporting local temperature measurements in micro-scale jet impingement are sparse. Shen and Gau [39] designed and fabricated a 40 μm thick thermal chip, with a heater and twenty-three sensors, all made of polysilicon and doped with different concentrations of Boron. The sensors provided a spatial resolution of 100 μm × 2 μm. Air was used as the working fluid to produce a submerged jet and visualization was done using a thin smoke wire. A micro nozzle with a rectangular slot of 2000 μm × 100 μm formed the jet orifice. Local Nusselt numbers were found to decrease with distance from the stagnation region, in accordance with established findings. Patil and Narayanan [29] studied a compressed air jet impinging on a 25.4-μm-thick heated Inconel foil and made local temperature measurements using infrared thermography. The effect of the jet was reported to be insensitive to the standoff distance. The obtained values of Nusselt number differed from those predicted by the widely used macroscale correlation proposed by Martin [10]. Elison and Webb [28] experimentally investigated liquid jet impingement on a heated metallic foil, using water as the working fluid. Jet diameters of 250 μm, 320 μm and 580 μm were tested for $300 \le Re \le 7000$ in free-surface and submerged configurations. Local temperature measurements were made by embedding a thermocouple in thermal grease at the back of the foil. A decrease in Nusselt number with radial location was observed for all conditions along with secondary maxima at $r/D = 2$. For both types of jets, the Nusselt number varied as $Nu \sim Re^{0.5}$ in the turbulent regime and $Nu \sim Re^{0.8}$ in the laminar regime; a number of considerations were proposed to explain the different results.

While the above studies offer valuable insight into the temperature distribution and heat transfer characteristics as a function of the flow field, the flow between the nozzle and the heated surface was unconfined and so the flow structures do not include confinement effects of microchannel flows. In addition, techniques like infrared thermal measurements are hindered by the lack of transparency of several substrate materials to the infrared wavelength.

In this study, we present local heat transfer measurements for confined liquid jets issuing into a microchannel and impinging on a micro heater. The jet dimensions and standoff distance were selected relative to the heater dimensions and are representative of a typical high power laser diode, as it is obvious that micro-scale cooling of power electronics is one of the possible applications of micro-jet cooling systems [35,40]. Local surface temperatures were experimentally measured at seven different Reynolds numbers and for three different nominal heat fluxes. A three-dimensional numerical model was used to predict the flow field and to infer the local and spatially-averaged heat transfer coefficients.

## 2. Experimental study

### 2.1. Micro device fabrication

The micro device used to obtain local temperature measurements comprised of three layers made of silicon, vinyl tape, and Pyrex (Figs. 1 and 2). The heater and resistance temperature detectors (*RTDs*) were fabricated on the Pyrex substrate using sputter deposition and standard photolithography. A 100 nm layer of titanium was first deposited on the Pyrex wafer. This layer was coated with photoresist and then patterned and wet-etched to form the heater. A 1 μm layer of aluminum was then deposited by sputtering over the titanium layer to form the heater vias. To electrically

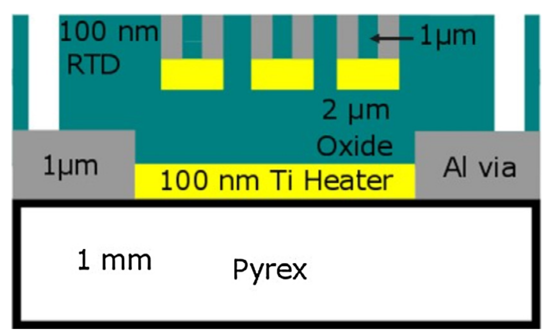


**Fig. 2.** Cross-sectional schematic (not to scale) of the heater and sensor layout as deposited on the Pyrex component of the micro device. Heater and sensor layer thicknesses were approximately 100 nm each.

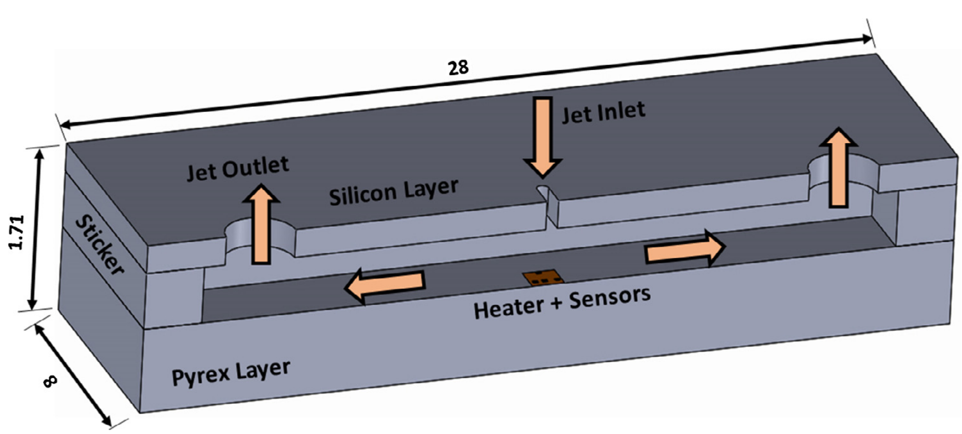


**Fig. 1.** Cross-sectional schematic (not to scale) of micro device layout as viewed through the plane of symmetry of the device. The device was formed by bonding three layers – silicon, vinyl tape (sticker), and Pyrex. Device thickness is exaggerated to illustrate channel configuration. Actual device width was twice the width shown in the figure. All dimensions in mm.