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Measurement of the Temperature Non-Uniformity in a Microchannel Heatsink using Microscale Laser-Induced Fluorescence

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ABSTRACT

Ratiometric Laser Induced Fluorescence (LIF) Thermometry is developed as a tool for temperature measurements using microscale visualization methods. Rhodamine B (RhB) and Rhodamine 110 (Rh110) are used as the temperature-dependent and temperature-independent dyes, respectively. The temperature responses of the two dyes are carefully measured as a function of concentration. The traditional two-dye LIF technique is compared to the single-dye LIF technique for microfluidic temperature measurement. The capabilities of these methods are demonstrated by visualizing the mixing plane between a hot and a cold fluid stream near a 'T' junction. The method is then applied to study the non-uniform temperature profiles generated due to flow maldistribution in a silicon microchannel heat sink. The experimental results illustrate the importance of proper design of inlet and outlet manifolds to maximize the performance of a microchannel heat sink. The technique is demonstrated to have a maximum uncertainty of ± 1.25 °C for single-pixel measurements and a minimum uncertainty of ± 0.6 °C for measurements averaged over a large area in a temperature range of 20 °C to 50 °C.

Keywords: Laser Induced Fluorescence Thermometry, microfluidics, non-intrusive temperature measurement, temperature-dependent dyes

NOMENCLATURE

I_0	- Irradiation intensity
I_f	- Fluorescence intensity of the die
β_C	- Collection efficiency
Φ	- Quantum efficiency
ε	- Molar absorptivity
b	- Absorption path length
C	- Die concentration
$I_{NR-LIFT}$	- Intensity obtained by the normalized ratiometric laser induced fluorescence technique
I_{0-RhB}	- Intensity of Rhodamine B dye at reference temperature
$I_{0-Rh110}$	- Intensity of Rhodamine 110 dye at reference temperature
I_{RhB}	- Intensity of Rhodamine B dye at measurement temperature
I_{Rh110}	- Intensity of Rhodamine 110 dye at measurement temperature
I_{CO}	- Intensity ratio of I_{0-RhB} and $I_{0-Rh110}$
$\dot{m}$	- Mass flow rate of coolant
C_p	- Specific heat of coolant
ΔT	- Temperature rise in the coolant
e_T	- Total error in the measurement
e_C	- Error involved due to calibration
e_N	- Error due to thermal noise

INTRODUCTION

Thermal micro-devices such as μ TAS, PCR and thermal inkjet printer heads are gaining popularity due to the speed, efficiency and portability that they offer. Lab-on-a-chip devices, which miniaturize and integrate various chemical processes such as mixing, reaction, separation and detection, have revolutionized many aspects of analytical chemistry and biochemistry. It has been demonstrated that the control of fluid temperatures in such devices is essential for enzyme-activated reactions as well as polymerase chain reaction (PCR) amplification of DNA.

In the electronics industry there is a continual demand for faster and smaller chips for laptops, cell phones and other portable devices. As a result, the number of transistors per chip has increased by five orders of magnitude [1] since the invention of the first microprocessor. The heat generated by these chips has correspondingly increased and has already reached or exceeded 100 W/cm^2 in some of the high-performance chips currently available in the market [2]. It is essential that the temperature of the circuits not exceed a temperature of 125°C to ensure reliable operation of these chips. As a result, considerable effort is being made to develop innovative cooling technologies to keep up with the heat dissipation requirements [3].

Tuckerman and Pease [4] introduced the use of microchannel heat sinks as a potential technique to achieve high cooling rates. The liquid coolant is generally used in either a single-phase laminar flow regime or two-phase flow regime with flow boiling occurring in the channels. Recently, a significant amount of research has been directed at understanding heat transfer in microchannel heat sinks for both the single-phase and two-phase flow regimes [5, 6]. The restrictions imposed by the small length scales involved have posed challenges in obtaining accurate, microscale measurements.

To facilitate study of the wide range of applications in which microscale convective heat transfer is encountered, it is necessary to develop techniques which can measure fluid temperatures at small length scales. Commonly used temperature measurement techniques often prove inadequate for microscale applications. Thermocouples are the most widely used temperature sensors and are often embedded along the microchannel base [7-8]; or fabricated along the inside walls of the channel [9-12]. Resistance temperature detectors (RTDs) have also been applied to microscale flows [13-15] by fabricating the resistor element onto the channel surface, the geometry and material of which is decided based on the required accuracy and the temperature measurement range of interest. Thermochromic liquid crystals (TLCs) have also been used to measure temperature [16-17] due to their unique optical properties which are

dependent on temperature. TLC slurries and paints used to make surface measurements can achieve a maximum spatial resolution of $\sim 1\text{ }\mu\text{m}$, while encapsulated TLCs range from 10 to 150 μm in size. Infrared thermography has been applied for surface temperature measurements in microchannel heat sinks [18-20] as well as for localized temperature measurements near the triple line of an evaporating meniscus [21-22]. The inherent limitation of IR thermography is that it can only be used to measure surface temperatures. Also an accurate value of the emissivity of the medium is essential to obtaining meaningful measurements. Molecular Tagging Velocimetry (MTV) has been used to measure the velocity [23] as well as the temperature of the fluid [24-25] at the microscale. Among the various methods available, laser-induced fluorescence shows great promise as a method capable of making non-intrusive, whole-field measurements inside a volume of liquid. Laser Induced Fluorescence (LIF) Thermometry exploits the temperature-dependent fluorescence intensity of dyes to measure temperature. LIF has been used to measure the temperature of reacting species or dyes in flames for combustion studies [26-28] and the temperature of dyes suspended in liquids [29-31]. The two-color LIF method [32-34] can be used to overcome the uncertainty introduced due to non-uniformity in the illumination. Lavieille et al. [35] reported a new technique where the necessity of two dyes can be circumvented by using the ratio of fluorescence from the same dye at different spectral frequencies. Coppeta and Rogers [36] analyzed the temperature dependence of the fluorescence characteristics of various dyes. Rhodamine B (RhB) was recommended as the temperature-sensitive dye while Rhodamine 110 (Rh110) was chosen as the temperature-insensitive dye.

Studies of this technique to date have been conducted in macroscale environments using laser light to illuminate the dye. Kim et al. [37-38] demonstrated microscale resolution for the method using a laser light sheet. In typical microfluidic experiments, the entire volume of the channel is illuminated as it is not possible to achieve such a thin sheet of light. Ross et al. [39] applied the LIF method with a single dye to measure the temperature in a microfluidic system with an uncertainty ranging from 2.4 – 3.5°C.

In the present work, the ratiometric LIF method is applied to measure the temperature in a volume-illuminated microfluidic setup. RhB and Rh110 are used as the temperature-sensitive dye and the temperature-insensitive dyes, respectively. The single-dye method proposed by Ross et al. [39] is compared to the traditional two-dye technique for microfluidic temperature measurement. The method is then applied to study the non-uniform temperature profiles generated due to flow maldistribution in a silicon microchannel heat sink. The experimental

results illustrate the importance of proper design of inlet and outlet manifolds to maximize the performance of a microchannel heat sink.

EXPERIMENTAL SETUP

The experiments were conducted in a standard μ PIV setup, shown in Figure 1, which consists of an upright Nikon Eclipse (ME600) microscope and an interline transfer Charge Coupled Device (CCD) camera (Roper Scientific Photometrics, CoolSNAP HQ). A Nikon mercury-arc lamp was used as the illumination source. Metamorph imaging software was used to acquire images. Laser-grade Rhodamine B and Rhodamine 110 (Acros Organics) dissolved in deionized (DI) water were used for all the experiments. The dyes were mixed in 1 ml of methanol before making the solution to increase their solubility in DI water. For the ratiometric LIF thermometry technique, the image of the Rh110 dye is used to normalize the image of the RhB dye. The two images were acquired with the help of a filter wheel attached in front of the mercury arc lamp. The imaging software controlled the filter wheel and was capable of acquiring multiple images alternating between the two filters. An excitation filter of $\lambda \sim 542$ nm was used for the RhB dye while an excitation filter of $\lambda \sim 488$ nm was used for the Rh110 dye.

LIF THERMOMETRY MEASUREMENTS

Laser Induced Fluorescence is a well-known phenomenon and has been used in analytical chemistry for many years. At low concentrations, the dependence of fluorescence irradiation, I_f , on the concentration of the dye, C , can be expressed using the simple equation [40]

$$I_f = \beta_C \Phi I_0 \epsilon b C \quad (1)$$

where, β_C , Φ , I_0 , ϵ , and b are the collection efficiency, quantum efficiency, incident irradiation, molar absorptivity and absorption path length, respectively.

Since LIF uses fluorescence intensity to calculate temperature, factors such as non-uniform illumination, fluctuation of light, non-uniform dye concentration and photo-bleaching can all affect the measurements. Uncertainty caused due to illumination can be eliminated using the two-color LIF method, where the fluorescence intensity of a temperature-insensitive dye is used to normalize intensity of the temperature-sensitive dye.

The ratio of the fluorescence intensities of the dyes is given as

$$\frac{I_{RhB}}{I_{Rh110}} = \frac{\beta_{CRhB} \epsilon_{RhB} C_{RhB} \phi_{RhB}}{\beta_{CRh110} \epsilon_{Rh110} C_{Rh110} \phi_{Rh110}} \quad (2)$$

It can be seen that Equation (2) is independent of incident irradiation, I_0 , as well as the absorption path length, b .

Calibration experiments were first conducted in a 400 μm square glass microchannel (Vitrocom, Inc.) submerged in a well machined into an aluminum block. The glass channel was filled with the dye solution, sealed on both ends, and placed in the well. The well was then filled with DI water and sealed on top with an acrylic plate, such that the glass channel was surrounded by water on all sides. The aluminum block was heated using a thermofoil resistance heater (Minco Products, Inc.) and was enclosed in an insulating material. The temperature of the water bath was measured using a thermocouple and used as the reference temperature. Measurements were obtained in the temperature range of 20°C to 70°C, in intervals of 2°C. At each temperature setting, the setup reached equilibrium in approximately 10 to 15 minutes, at which time the thermocouple showed a steady temperature reading.

Figure 2 shows the fluorescence intensity of the dyes for three different concentrations. It can be seen that the temperature dependence of Rhodamine B (Figure 2(b)) is much stronger than that of Rhodamine 110 (Figure 2(a)). Rhodamine B and Rhodamine 110 show a 2% and a 0.2% decrease in intensity per degree increase in temperature, respectively. The temperature response of Rhodamine B is thus an order of magnitude greater than that of Rhodamine 110. Figure 3 shows the intensity ratio (RhB/Rh110) of the two dyes, which is typically used as the calibration curve for temperature measurements. It can be seen that the slope of the calibration curve increases as the concentration of the dyes is increased. This slope also depends on the illumination intensity as well as the exposure time of the image. Since the entire depth of the channel is illuminated in the volume illumination approach employed in this work, in contrast to the light sheet approach, changing the depth of the channel also affects the slope. Hence, a new calibration curve needs to be obtained if the channel geometry, dye concentration or the illumination source is changed. This can be avoided by normalizing the calibration curve by the intensity ratio value at some particular temperature. The fluorescence intensity at room temperature, 24°C, is arbitrarily chosen to normalize the intensity values for all the concentrations. Figure 3(b) shows the normalized fluorescence intensity ratio, which is used as the calibration curve for the visualization experiments. It can be seen that the normalized intensity-ratio curves are independent of dye concentration. This calibration curve is used for the temperature measurements discussed below.

Normalizing the intensity ratios makes the technique system-independent and avoids an extra calibration step for each different experimental setup. However, it requires knowledge of the intensity ratio at some particular temperature for the experimental setup being used. If the temperature of the fluid at some location is known, then the intensity ratio at that point can be used for normalization. If the measurement region consists of spatially varying geometric features, like a step, the intensity ratio for the reference temperature at each location of the image must be known to conduct the normalization. In such a case, a set of images can be taken at a known temperature without any heat sources present and that image can be used for normalization.

MIXING PLANE VISUALIZATION AT A T-JUNCTION

The procedure for calculating the normalized image $I_{NR-LIFT}$ for the ratiometric LIFT technique (NR-LIFT) can be expressed as

$$I_{NR-LIFT} = \frac{I_{RhB}/I_{Rh110}}{I_{0-RhB}/I_{0-Rh110}} \quad (3)$$

where I_{0-RhB} and $I_{0-Rh110}$ denote the images for the temperature-dependent and temperature-independent dyes at the reference temperature and I_{RhB} and I_{Rh110} denote the images for the temperature-dependent and temperature-independent dyes at the measurement temperature. The calibration curve shown in Figure 3 can be used to convert the intensities in the normalized image to temperature values. This procedure is cumbersome, as it requires four images to obtain a single temperature measurement. If the ratio of the intensities of the two dyes at room temperature is known, the normalization step in the NR-LIFT method can be obtained using the following expression,

$$\frac{I_{RhB}/I_{Rh110}}{C_0} \quad (4)$$

where, C_0 is the ratio of I_{0-RhB} and $I_{0-Rh110}$.

Since Rh110 is temperature-independent, the image at the reference temperature $I_{0-Rh110}$ will be identical to the image at the measurement temperature I_{Rh110} . Hence, Equation (4) can be simplified as

$$I_{N-LIFT} = \frac{I_{RhB}}{I_{0-RhB}} \quad (5)$$

where a single image of the temperature-dependent dye at a reference temperature can be used to

account for the non-uniform illumination effect as well as the normalization process. This normalization process will be called the N-LIFT method to differentiate it from the ratiometric NR-LIFT method. Since only a single reference image is sufficient for all the measurements, this method can be used to make instantaneous measurements with a single camera. Care should be taken to ensure that the measurement region in the reference image is identical to that in the measurement image. Also, if the optical path length changes locally during the experiment such as in phase change flows, this method cannot be used.

The three methods described above are compared through simple visualization experiments in a ‘T’ junction. For the experiments, a microchannel (Figure 4) was cut into double-sided adhesive tape (Adhesives Research Inc.) and sandwiched between two glass slides. The width of the channel is 500 μm and the depth is 200 μm . Holes were drilled into the top glass slide for the inlet and outlet ports. The tubing for the hot liquid is passed through a hot water bath to heat the liquid to different temperatures. The temperature in the hot liquid bath is measured using thermocouples and used as the reference temperature. A small amount of heat loss is expected to occur through the length of the tubing (~ 2 cm) from the hot water bath till the inlet port. Hence the temperature of the liquid at the ‘T’ junction is expected to be a few degrees cooler than the temperature of the water bath. The objective of this experiment was not to make quantitative measurements but to test the normalization procedures, hence the absolute temperature drop was not considered important.

The raw experimental images of flow in the T junction are shown in Figure 5. In Figure 5 and Figure 6, cold liquid at room temperature is flowing from left to right in the image and hot liquid is being added through the branch at the top and flows to the right. The images for RhB and Rh110 at room temperature are shown in Figure 5(a) and Figure 5(b). The images at a higher temperature for RhB and Rh110 are shown in Figure 5(d) and Figure 5(e). Arbitrary units of intensity are used to color all the images. The non-uniformity present in the illumination source is visible in Figure 5(a), where the center of the image is bright and it trails off towards the edges. In Figure 5(d), it can be seen that the hot fluid coming from the top branch has a lower intensity than the fluid in the left branch, as expected. Also the images for Rh110 at room temperature and at the higher temperature are identical as expected. The ratios of RhB and Rh110 at room temperature and the higher temperature are shown in Figure 5(c) and Figure 5(f). Since the rough edges reflect the incident light, they appear as bright outlines in the images.

Once the intensity ratios are obtained and normalized, the calibration profile is used to convert these values into temperature measurements. The normalization procedure ensures that the same calibration profile can be used in different experimental setups.

Figure 6 shows a comparison of three different normalization procedures. Since the temperature of the cold liquid is known, the intensity ratio of the cold liquid can be used to normalize the images, as shown in Figure 6(a) (2-image NR-LIFT method as described in Equation (5)). The effect of non-uniform illumination is apparent towards the edges of the image. Hence, only the measurements near the central region of the image can be used with this method. The temperatures obtained using the 4-image NR-LIFT method (described in Equation (4)) are shown in Figure 6(b). It can be seen that the image is uniform, even at the edges. The temperatures obtained using the N-LIFT method are shown in Figure 6(c) and again show no non-uniformity. Since, the NR-LIFT method involves four images, the noise present in the measurement is twice that of the N-LIFT method. This random noise for single-pixel measurements across the mixing plane is shown in Figure 7. The noise for the 2-image NR-LIFT method (Figure 6(a)) is the same as that of the N-LIFT method. This noise can be reduced by averaging the measurements over a larger number of pixels.

TEMPERATURE NON-UNIFORMITY IN A MICROCHANNEL HEAT SINK

Jones and Garimella [41] studied the flow non-uniformity introduced in a microchannel heat sink due to the manifold design. The velocities along different channels were measured for $Re = 10.2$ and $Re = 102$. The Reynolds number is calculated based on the hydraulic diameter and the average velocity through each microchannel. It was observed that for low Reynolds numbers the flow is distributed uniformly across the channels, but at $Re = 102$, the flow rate through the center of the chip was 33% greater than that near the edges. Lee [42] and Jones et al. [43] used the same channel geometry to numerically study the effect of manifold design on the flow field and the temperature field across the microchannel array. The numerical model was able to predict the non-uniform distribution of flow rates and showed good agreement with the experimental data in [41]. The model was then used to predict the temperature profile across the chip with a uniform heat flux applied on the underside of the heat sink. It was observed that hot spots were formed at the edges near the outlet region (Figure 8) due to the flow maldistribution. The same microchannel heat sink is used here to experimentally study the temperature field in the liquid at various heat flux inputs.

The silicon microchannel heat sink used in these experiments, shown in Figure 9(a), was fabricated by Sandia National Laboratories. It consists of a series of 76 parallel microchannels, each 110 μm wide and 9 mm in length. The average depth of the channels was 371 μm . The channels are separated by 22 μm thick fins. The inlet and outlet sections are 2 mm long with a semicircular recessed region for tubing ports. A double-sided clear adhesive tape (Adhesives Research Inc.) is used to seal the microchannel against an acrylic sheet. A thin film heater (Minco Products, Inc.) is attached to the bottom surface of the chip. The size of the heater (12.7 mm x 12.7 mm) is slightly larger than the footprint covered by the microchannels (10 mm x 9 mm). The underside of the heater is insulated to minimize heat loss. Experiments were performed at flow rates of 10 ml/min, 20 ml/min and 40 ml/min ($\text{Re} = 10.2, 20.4$ and 40.8 based on the hydraulic diameter of the individual channel). The temperature of the fluid at the inlet and exit is measured using thermocouples in order to measure the heat absorbed by the fluid. Measurements were made at 5 different input powers. The power input to the heater in comparison to the heat input to the liquid ($\dot{m}C_p\Delta T$) is shown in Figure 10. The difference between the electrical power input to the heater and the heat input to the fluid is attributed to the heat loss through the top surface of the heat sink. The heat input to the fluid ($\dot{m}C_p\Delta T$) will be referenced in the remaining part of the discussion.

Measurements were made at eight different power inputs spanning three different flow rates. Temperature visualization at $\text{Re} = 40.8$ and power inputs of 30.5 W, 39.4 W and 49.7 W are shown in Figure 11, Figure 12 and Figure 13 respectively; only a sub-set of the all the results obtained is shown for the sake of brevity. Measurements were made at the four locations as shown by the dotted squares in Figure 9(b). The mean temperature (T_M) averaged over the region denoted by the white box is shown in each image. The inlet temperature T_i of the fluid is 24 $^{\circ}\text{C}$ for all the measurements. It can be seen that there is a rise in the temperature between the inlet and outlet region. The temperature at the ‘inlet center’ region is same as that in the ‘inlet bottom’ region while the temperature at the ‘outlet bottom’ region is greater than the temperature at the ‘outlet center’ region. The temperature non-uniformity at the outlet is seen to increase with the input power in these images. The difference in temperature between the ‘outlet center’ and the ‘outlet bottom’ as a function of the heat input is plotted in Figure 14. For the highest power input, there is a 4.3 $^{\circ}\text{C}$ difference between the temperatures at the ‘outlet bottom’ region and the ‘outlet center’ region. It should be noted that the temperatures measured using this technique are

averaged over the entire depth of the channel, and the fluid temperature near the bottom surface of the channel may be higher than the measured average temperatures.

Jones and Garimella [41] observed that the average flow rate through a channel at the center of the chip was about 6% greater than the flow rate through a channel near the edge of the chip, for $Re = 10.2$. The $4.4\text{ }^{\circ}\text{C}$ temperature difference between the center and the edge of the chip is attributed to this flow maldistribution. At higher flow rates this flow maldistribution is expected to increase and as a result, the temperature non-uniformity is also expected to increase. Such temperature non-uniformities are even more important if the microchannel heat sink is operated in the two-phase flow regime as early dry-out can occur in the channels with higher temperature leading to failure of the chip. Hence, care should be taken in designing the inlet and outlet manifolds to minimize flow maldistribution.

UNCERTAINTY ANALYSIS

The thermal noise present in the camera and the uncertainty involved in the calibration curve are the two main sources of error in this technique. The temperature of a stationary pool of water was measured using the N-LIFT method over a span of 15 minutes and it was observed that the temperature increase caused due to the light source was negligible. The uncertainty involved in the calibration curve represents the accuracy of the method while the thermal noise represents the variation in the measurements. The error involved in the measurement of temperature e_T can be expressed as,

$$e_T = \pm \left\{ (e_C)^2 + (e_N)^2 \right\}^{1/2} \quad (6)$$

where e_C is the error involved in the calibration curve and e_N is error due to thermal noise. The error due to the thermal noise e_N , defined as the standard deviation of the single pixel measurement, was $\pm 1.1\text{ }^{\circ}\text{C}$ for the N-LIFT method and $\pm 2.6\text{ }^{\circ}\text{C}$ for the NR-LIFT method. The thermal noise in each image contributes to the total temperature measurement uncertainty. Since the NR-LIFT method requires 4 images, the uncertainty for this method will be greater than the N-LIFT method, which requires only 2 images. The uncertainty involved in the calibration curve depends on the difference between the normalization temperature and the measured temperature increases. The mean uncertainty involved in the calibration curve e_C was measured to be $\pm 0.6\text{ }^{\circ}\text{C}$ for the N-LIFT method and $\pm 0.64\text{ }^{\circ}\text{C}$ for the NR-LIFT method. The total error in the

measurement of temperature was estimated to be ± 1.25 °C for the N-LIFT method and ± 2.68 °C for the NR-LIFT method.

The uncertainties listed above are for single-pixel measurements. The error due to the thermal noise can be reduced by averaging over larger areas. For the mean temperatures T_M reported in the previous section, e_N can be effectively neglected as it was averaged over a large number of pixels. Hence, the uncertainty involved in the measurements will be e_C , ± 0.6 °C.

CONCLUSIONS

The ratiometric LIFT method was applied to measure the temperature in a volume-illuminated microfluidic device. The traditional two-dye LIF technique (NR-LIFT) is compared to the single-dye method (N-LIFT). The N-LIFT method was shown to have a lower uncertainty (± 1.25 °C) than the NR-LIFT method (± 2.68 °C) for single-pixel measurement. This uncertainty can be further reduced by averaging the measurements over a larger area.

The N-LIFT method was applied to measure the non-uniform temperature profiles generated due to flow maldistribution in a silicon microchannel heat sink. It was observed that a temperature difference of over 4 °C can exist between the center and the edges of the microchannel heat sink for a Reynolds number of 40.8 and a heat input of 49.7 W. These values show qualitative agreement with the numerical results obtained by Jones et al.[43]. This temperature non-uniformity is expected to increase with increases in flow rate and heat input rate. Measurements of this nature can help in improving the design of the inlet and outlet manifolds to avoid flow maldistribution.

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Figure 1. μ LIF thermometry experimental setup.

(a)

(b)

Figure 2. Fluorescence intensities of the dyes for different concentrations: (a) Rhodamine 110, and (b) Rhodamine B.

(a)

(b)

Figure 3. (a) Fluorescence intensity ratio of (RhB/Rh110) for different concentrations of the dyes. (b) Normalized fluorescence intensity ratio (RhB/Rh110).

Figure 4. Experimental setup for mixing plane visualization. The width and depth of the microchannel is 500 μm and 200 μm respectively.

Figure 5. Raw experimental images obtained for mixing plane visualization: (a) RhB at room temperature, (b) Rh110 at room temperature, (c) ratio of RhB and Rh110, (d) RhB at a higher temperature, (e) Rh110 at a higher temperature, and (f) ratio of RhB and Rh110 at the higher temperature.

Figure 6. Experimental temperature visualizations after the normalization process for the 4X objective: (a) Temperature measured using NR-LIFT method (using the 2 image method described in Equation (4)) (b) temperatures measured using NR-LIFT method, (using the 4 image method described in Equation (3)) and (c) temperature measured using N-LIFT method (using the 2 image method described in Equation (5)).

Figure 7. The temperature profile measured across the mixing plane using both the N-LIFT method and the 4-image NR-LIFT method.

Figure 8. The temperature contour at the bottom surface of the microchannel heat sink for a uniform heat flux of 100 W/cm^2 at $\text{Re} = 102$ [42]. The flow is towards the top in the image.

(a)

(b)

Figure 9. (a) A photograph of the microchannel heat sink. (b) An illustration of the microchannel heat sink showing the measurement regions. The dark grey region represents the footprint covered by the microchannels.

Figure 10. Electrical power input to the thin-film heater compared to the measured heat input to the liquid.

Figure 11. Temperature visualization at the four measurement locations for $Re = 40.8$ and a heat input of 30.2 W . T_M is the mean temperature measured over the region shown in the white box.

Figure 12. Temperature visualization at the four measurement locations for $Re = 40.8$ and a heat input of 39.4 W . T_M is the mean temperature measured over the region shown in the white box.

Figure 13. Temperature visualization at the four measurement locations for $Re = 40.8$ and a heat input of 49.7 W . T_M is the mean temperature measured over the region shown in the white box.

Figure 14. Temperature non-uniformity as a function of heat input at different flow rates.