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FLUID FLOW AND HEAT TRANSFER PERFORMANCE TESTING ON MICROCHANNELS USING A NOVEL MODULAR TEST SYSTEM

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ABSTRACT

This paper demonstrates the feasibility of producing relatively large (Hydraulic Diameter 255 to 317µm) microchannels in silicon and plastic using three different methods. It also describes the experimental equipment and methods used to measure the pressure-flow and heat transfer characteristics of the manufactured channels.

Wet Etching, Deep Reactive Ion Etching (DRIE) and Precision Sawing have been used to create microchannels in silicon and thermoset plastic. Glass covers were anodically bonded over the DRIE and Wet Etched silicon channels. SU-8 photoresist was used as an adhesive to bond glass covers over the plastic channels. Mechanical sawing produced near rectangular channels in two types of thermoset plastic. Channel dimensions were measured individually using a scanning electron microscope.

A modular type test system was designed and built in order to test each sample using the same inlet and outlet manifolds, pressure tappings, pumping system, temperature sensors and instrumentation. The pressure drop across the channels was measured using an inductive pressure transducer. The mass flow rate through the system was measured by directly weighing fluid collected from the system over a timed interval. System temperatures were measured using calibrated K type thermocouples.

The measured pressure flow and heat transfer behaviour were compared with theoretical values as calculated from macro scale theory. Error analysis was then carried out in order to determine the overall accuracy of the experimental work and determine whether any deviation from theoretical values is of experimental significance. Predicted pressure drops were found to correlate well with experimental values with no deviation from theory outside a 95% confidence interval being observed. Heat transfer data from the channels correlates well with literature.

1. INTRODUCTION

The manufacture and testing of microchannel heat sinks was first described paper by Tuckerman and Pease (1981)[19], using wet etched silicon channels. Since then many other manufacturing methods have been used including DRIE (Perret et al, 2000)[15], Electroplating (Joo et al 1995)[8], Precision Sawing (Kishimoto and Sasaki 1987)[10], Electro-discharge Machining (Adams et al 1999)[1], CNC Milling (Yuan et al 2000) [21] and LASER ablation (Hahn et al 1997)[6].

A considerable body of research has been performed on fluid flow in microchannels with inconclusive results. Variation in measured friction factors from 0.5 to 2.5 times predicted theoretical values have been reported by 6 separate experimenters (Paputski, 1999)[14], Judy, (2002)[9] references papers measuring friction factors above and below theoretical values, but finds no experimentally significant deviation from expected values at all. Wu (2003)[20] and Gao (2002)[5] also report experimental values close to theoretical predictions.

The same is true for heat transfer measurements from microchannels. Owhaib and Palm (2003)[12] measured heat transfer coefficients from the surface of channels of diameters from 1.7 to 0.8mm for laminar flow, concluding that the heat transfer coefficient did not vary significantly with channel diameter and that the Nusselt number increased as the Reynolds number increased. The same behaviour was noticed by Rahman (2000)[16]. Experiments by Harms et al [7] found no significant deviation from developing flow theory in 25mm long microchannels. Björn Palm, in a review paper in 2001 [13], concluded that there is no general agreement as to whether flow friction and heat transfer in microchannels should deviate from macro scale correlations. There is also little agreement as to whether values greater or less than macroscale theory should be expected from this deviation.

This paper describes the production of a variety of comparable microchannels using diverse methods. The channels were tested using the same inlet and outlet manifolds and occupy a 16×30mm area. This allows the same inlet and outlet manifolds and thermocouples to be used for all measurements. Since the area cooled by each microchannel sample is the same, and the same inlet and outlet manifolds and pressure transducer are used, pressure drop and heat transfer results can be compared without the complications introduced by the more common arrangement where the manifolds are changed with each channel tested.

2. MANUFACTURING PROCESSES

The processes used to manufacture the channels were wet etching, deep reactive ion etching (DRIE) and precision sawing. Wet etching a (100) silicon wafer using a KOH solution produced trapezoidal channels of width 577µm and height 413µm.

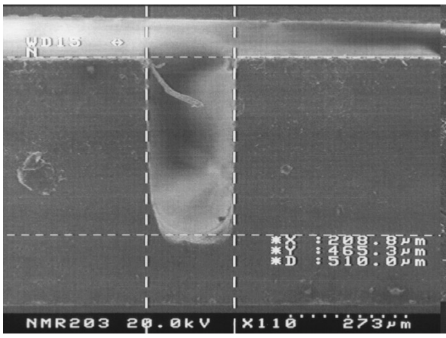

Figure 1: Plascon plastic channel. This is cut with the same blade as the Nitto channel, giving channels the same width but slightly different depths.

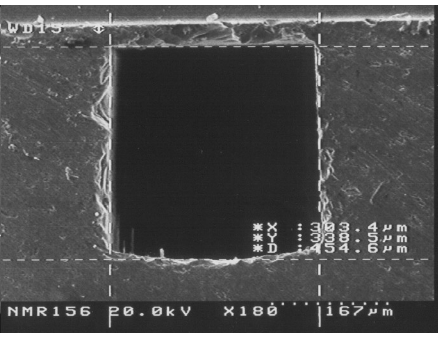

Figure 2: DRIE channel. Damage visible around the channel and the step in the glass over the channel are due to the process in which the wafer was diced into 16×30mm samples.

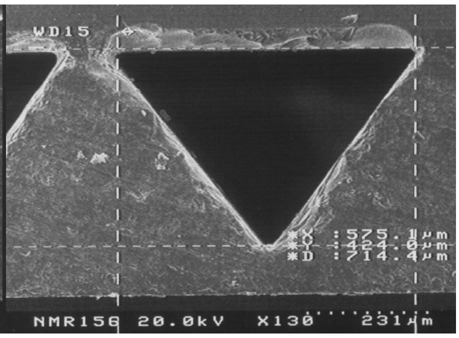

Figure 3: Wet etched trapezoidal channel with anodically bonded pyrex cover. The etch was stopped when the channel was just short of being triangular.

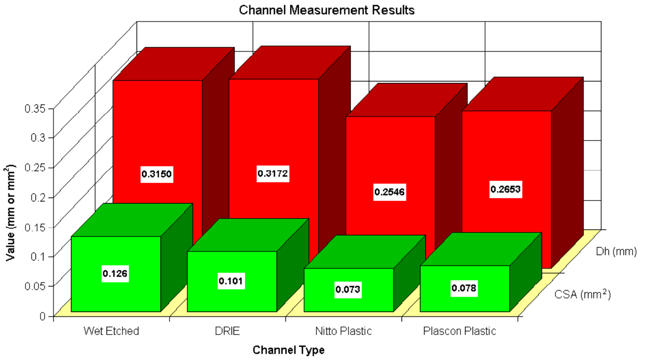

Figure 4: Averaged hydraulic diameters and cross-sectional areas for the 4 channels tested.

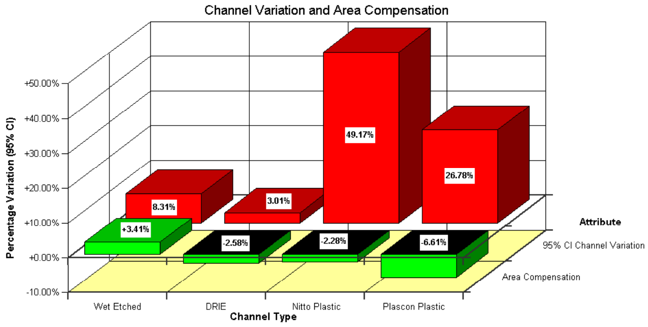

Figure 5: Percent variation between channels on each sample based on 95% confidence interval and percent difference between ideal and CAD modeled channels.

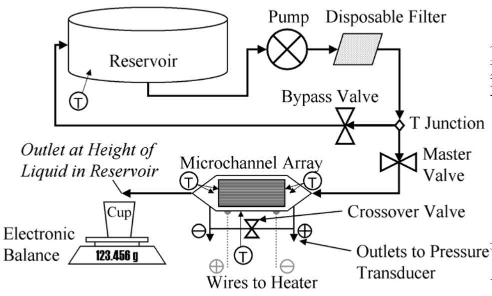

Figure 6: Schematic of the microchannel characterisation equipment. The encircled 'T's show where thermocouples are fitted to the system.

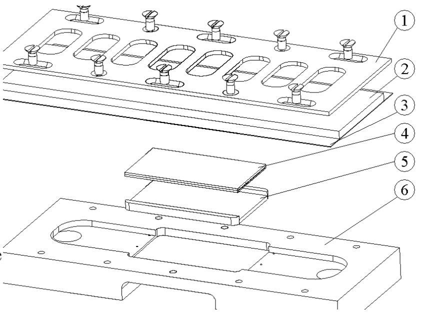

Figure 7: Manifold detail. Sample (4) and Shim (5) fill cavity in manifold block (6). Sealing is provided by gasket paper (3) clamped between the glass slide (2), and manifold block (6) by a cover plate (1).

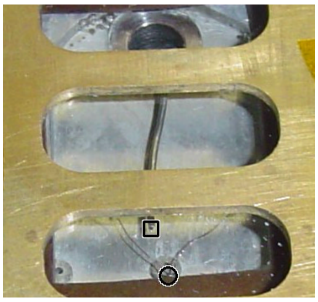

Figure 8: A 76µm diameter bare wire thermocouple is glued to surface of the test sample (Circled). The pressure tapping is just above this circle. The square marks the tip of the fluid temperature probe.

Deep Reactive Ion Etching (DRIE) using the Bosch process produced rectangular channels in (100) silicon of width 304µm and height 332µm. These channels also had a glass cover anodically bonded over them. Mechanical sawing was used to cut near rectangular samples of thermoset plastic, trade named Nitto and Plascon. The plastic channels are 203µm wide by 344 (Nitto) or 382µm (Plascon) deep. Glass covers were bonded over these channels using a thin spun on layer of SU-8 photoresist, cured under UV light to complete the bond. More details of the manufacture process can be found in Eason et al (2004)[3]. Figure 1, Figure 2 and Figure 3 show scanning electron microscope (SEM) photographs of the channels.

3. CHANNEL MEASUREMENTS

In order to make an accurate theoretical prediction of the performance of a microchannel, the exact size of the channel needs to be known. In fact, for a constant mass flow rate, the pressure drop along a channel is inversely proportional to the diameter of the channel to the power of four. This makes it critically important to have a high level of confidence in the channel diameter. To gather this information for the channels tested in this paper, channel samples were examined in a scanning electron microscope (SEM), calibrated monthly to ±0.3µm on a 10µm measurement. Individual measurements were made for each of the 22 channels in each sample in order to calculate the average channel size and the sample standard deviation in the channel dimensions.

The channels were also photographed in the SEM, in order that their exact shape can be measured. A computer aided drawing (CAD) program was used to calculate the actual cross section of several channels in each sample. This was compared to the cross sectional area calculated from the width and height measurements for the same channel. The difference between these areas, expressed as a percentage, is shown in Figure 5, along with the 95% confidence interval for the channel size.

4. EXPERIMENTAL EQUIPMENT

A schematic of the test system is shown in Figure 6. The test fluid, in this case distilled, deionised water, is stored in a large diameter reservoir, from which it flows downwards to a Tuthill DDS.19 gear pump, driven by a speed controlled motor. The water is filtered using a disposable glass fibre filter and then passes through a junction where micrometer adjustable valves control how the flow is split between test channels and the bypass loop. This bypass loop allows flow rates lower than the pump can supply directly to be generated.

K-Type thermocouple probes are fitted as marked by the 'T's in Figure 6. These are used to measure the temperature of the fluid in the reservoir, the inlet and outlet fluid temperatures, the inlet and outlet sample surface temperature and the temperature of the power resistors used to heat the channels.

The pressure drop across the channels is measured using a Validyne DP15 differential pressure transducer. For the experiments described here a diaphragm with pressure range from 0 to 14kPa, calibrated to ±35Pa was used. Mass flow was measured by directly weighing the flow from the system over a timed interval. Detail on the calculation of these uncertainties can be found in Eason (2004)[4]. The 95% confidence interval for mass flow and pressure measurement uncertainty is given for each channel in the results section.

As can be seen from Figure 7, the sample (4) fits into the shim (5), which then fits into the manifold block (6). Because the samples are available in a variety of thicknesses, several shims have been made with different depth grooves. The result of this is that all the channel samples, when fitted in their corresponding shims, occupy the same volume. Since the only change in the flow system from sample to sample is the size of the channels being tested, the effects of different manifolds, pressure tapping locations and thermocouple locations are eliminated as sources of variation between the different channels being tested.

Figure 8 shows the locations of the thermocouples inside the inlet manifold. This arrangement is mirrored in the outlet manifold. A 76.2µm (0.003") diameter bare wire thermocouple is glued to the surface of the test sample at inlet and outlet to give surface temperatures for the sample. A 0.5mm diameter thermocouple probe is used to measure the fluid temperature at the inlet and outlet. Note that while experiments are running these thermocouples sit between 3 and 4mm from the entrance of the channels. It is assumed that the fluid temperature at this location will be reasonably close to the actual average temperature of the fluid in the same cross section. The effects of heat transfer from the inlet and outlet manifold surfaces to the fluid have been calculated to be negligible in most cases compared to the heat transferred from the microchannels. The average of the inlet and outlet temperatures is used to calculate the properties of the water for theoretical calculations.

5. RESULTS

The following pressure flow characteristics were recorded for the channels during the heat transfer experiments. The results do not fall on a straight line because the temperature in the system varies with the power supplied to heat the channels. The effect of this temperature variation on the theoretical pressure flow behaviour of the channels is accounted for on a point-by-point basis.

6. DISCUSSION

The data presented in Figure 5 and Figure 6, shows a high level of similarity between the dimensions of the two different plastic channels manufactured.

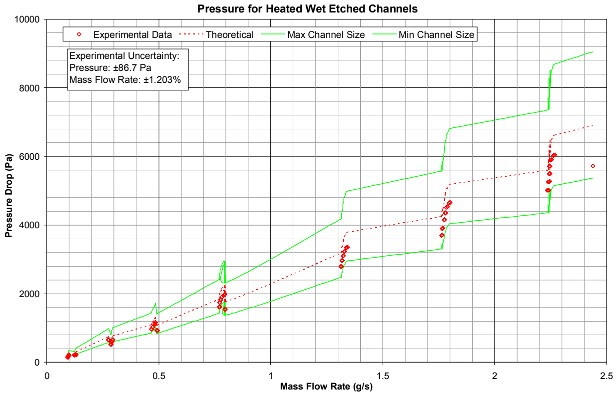

Figure 9: Pressure Flow Characteristic for Wet Etched Channels. D_h=315µm.

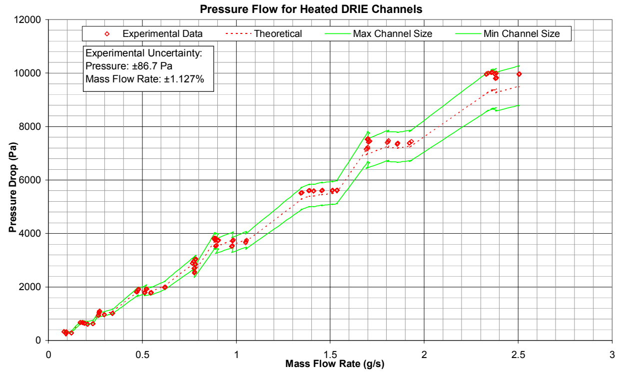

Figure 10: Pressure Flow Characteristic for DRIE Channels. D_h=317.2µm.

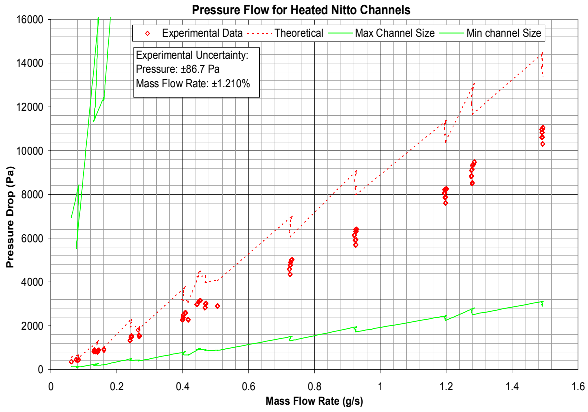

Figure 11: Pressure Flow Characteristic for Nitto Channels. D_h=254.6µm.

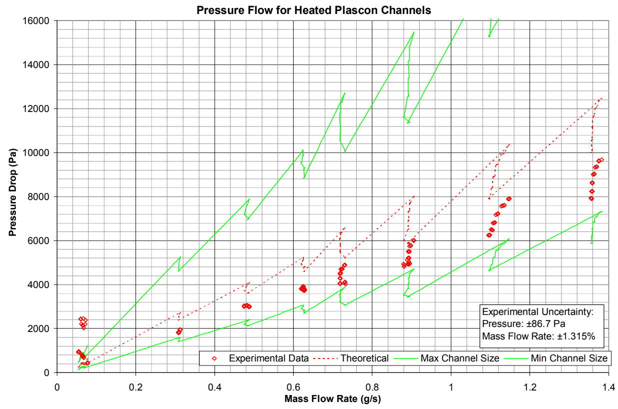

Figure 12: Pressure Flow Characteristic for Plascon Channels. D_h=265.3µm.

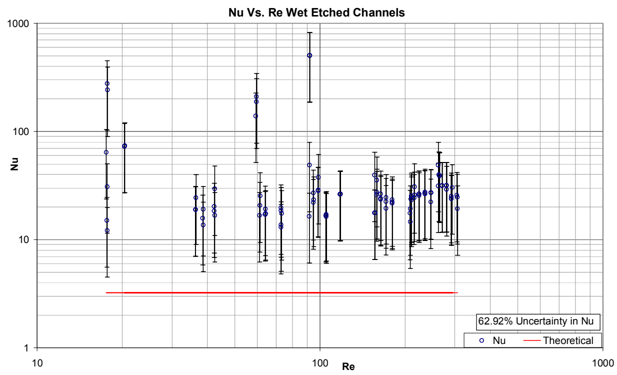

Figure 13: Nusselt Data for Wet Etched Channels.

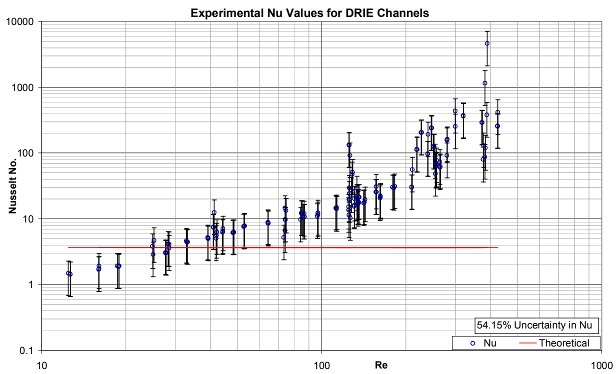

Figure 14: Nusselt Number Data for DRIE Channels.

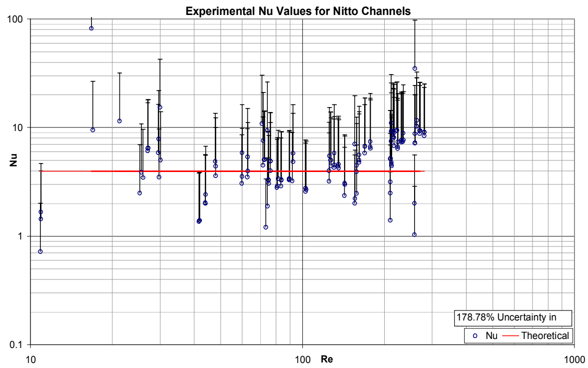

Figure 15: Nusselt Number Results for Nitto Channels.

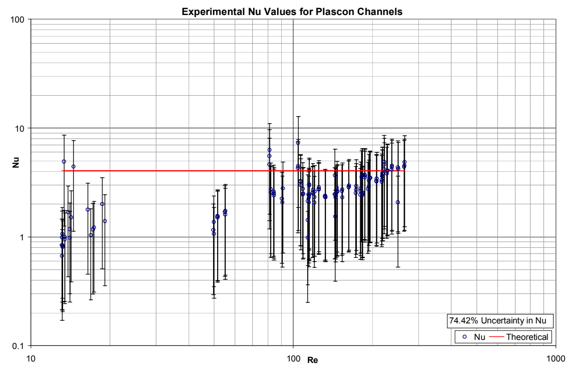

Figure 16: Nusselt Number Results for Plascon Channels.

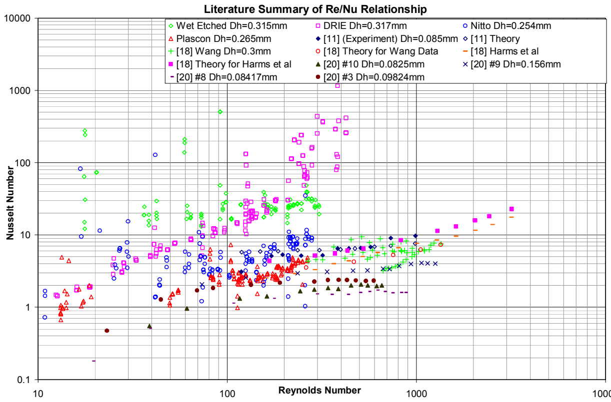

Figure 17: Comparison of Nu results with Literature

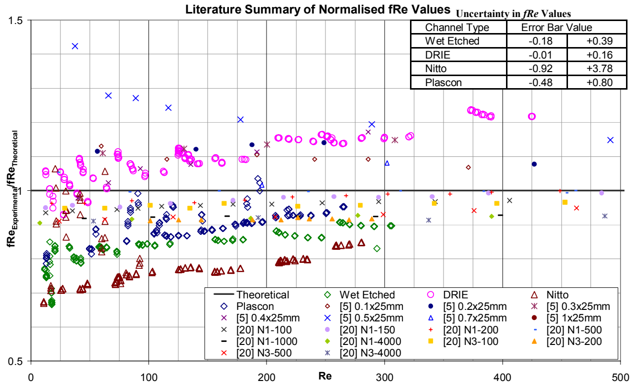

Figure 18: Comparison of *fRe* Results with Literature.

The DRIE and Wet Etched silicon have very similar hydraulic diameters, but different cross sectional areas due to the channels being different shapes. It can be seen from Figure 5 that the Nitto channel is the least reliable in terms of its shape. A 95% confidence interval (Average ±2×Sample Standard Deviations) on the dimensions of this channel gives an uncertainty envelope of ±49% about the average channel size. The DRIE channels are the most consistent from channel to channel in the same sample with there being a 95% chance that all channels will be within ±3% of the average size.

The area compensation term is a measure of the difference between cross section of each channel calculated from direct width and height measurements, assuming the channel is perfectly rectangular or perfectly trapezoidal and the actual cross section of the channel as measured from a CAD model of the channel built based on SEM photographs of the channels. More details on how the compensation is applied are available in [4]. It is interesting to note that the Nitto channels analysed were the closest in shape to being perfectly rectangular, but had the least consistent channel-to-channel sizes.

The experimental results presented here for the pressure drop along the channels include the inlet and outlet losses due to the change in flow area as the fluid moves from the manifolds to the channel and back again. The theoretical values also account for these losses and the area compensation term. Upper and lower limits for the results are calculated by running the theoretical calculation for each mass flow rate based on channels with dimensions set to the upper and lower limits of the 95% confidence interval for the channel size.

To compare the results measured in these experiments with results from other researchers, the friction factor times Re, as measured from the test system, was divided by the theoretical *fRe* values for each channel shape using correlations from Çengel (1998)[2] and Rohsenow (1985)[17]. Figure 18 is a plot of the normalized *fRe* measured from the experiments described here, as well as results from papers by Gao et al (2002)[5] and Wu and Cheng (2003)[20]. The closer each y-value is to 1, the better it correlates with accepted macro scale flow theory.

The experimentally measured Nusselt Numbers from each channel are plotted against the Reynolds Number. The error bars on each point indicate the limits of the 95% confidence interval for these measurements. The lower error bars are omitted from the Nitto plot, as they cannot be displayed due to the logarithmic plot axes. The horizontal line on each plot marks the theoretical fully developed constant wall heat flux Nusselt number calculated for the channel based on data in Çengel [2] for the rectangular channels and Rohsenow [17] for the trapezoidal channels. It should be noted that the theoretical calculations do not account for developing flow effects. This may explain the deviation in the channels from the theoretical values.

When the data measured in this work is compared with that of other researchers in Figure 17, it can be seen that values measured here are on the whole slightly higher than those of other researchers. This is more than likely due to heat being transferred from the walls of the inlet and outlet manifolds to the cooling fluid affecting the measured temperature of the fluid at the inlet and outlet from the channels. Preliminary calculations indicate that this effect may contribute from 2 to 7% of the heat transferred to the cooling fluid.

7. CONCLUSIONS

For the experiments described in this paper, the flow behaviour correlates very well with standard macro scale laminar flow theory. The 95% confidence interval for the results encompasses virtually all the 559 independent data points measured.

The *fRe* values calculated from the system correlate well with theory and the work of other researchers. The 95% confidence interval for these measurements is given on the plot in Figure 18. For the range of Reynolds numbers used, the microchannels tested here do not seem to show experimentally significant differences in behaviour compared to larger channels.

The heat transfer performance of the channels is generally greater than the theoretical values calculated for channels of the same geometry, though the influence of convection from the manifolds must be eliminated before a definite conclusion can be drawn. An increase in Nu with Re has been measured as in previous literature.

In conclusion, for the microchannels tested, the experimental measurements show no evidence of an experimentally significant deviation from the macro scale theoretical behaviour of channels in terms of their pressure-flow behaviour. The heat transfer behaviour of the channels however, is higher than expected theoretical values for each channel. This is most likely due to a combination of developing flow in the channel and convective heating of the fluid in the manifolds affecting the inlet and outlet temperature measurements.

8. ACKNOWLEDGEMENTS

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