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Methods and techniques of improving experimental testing for microfluidic heat sinks

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ABSTRACT

There exist numerous methods of experimentally testing designs for heat sinks in the laboratory, especially for microscale fluidic devices, which can lead to a problem for comparison between new studies and those in the literature. To explore this issue, laboratory-based experiments on the heat transfer and flow impedance properties of a sample microchannel heat sink were repeated over a varying range of equipment. Three types of heat source (hot plate, film heater and copper block with cartridge heaters), two types of piping (polymer and metal), and the presence or absence of manifolds were investigated and the differences in heat sink performance were noted.

Overall, especially in terms of achieving consistent, repeatable results, it was found that the arrangement of copper block heater, metal piping and the inclusion of manifolds was superior for this particular microchannel device. Hence, it is suggested that future testing of heat sinks and heat exchanger devices employ a similar arrangement of equipment for greater accuracy and comparability. In particular, the plastic tubing and hot plate configurations were found to have relatively poor consistency when testing the heat sink, and the film heater produced non-uniform heating, even over a small surface area.

1. Introduction

Experimental testing remains the most important means of evaluating the actual performance of a thermal transfer device, whether the objective is cooling [1], waste heat recovery [2], or even desalination [3]. However, it has been observed that large discrepancies exist within reported experimental results for microscale heat sinks and heat exchangers, leading to difficulty in comparison between studies, or with existing devices in industry [4]. One possible cause for this inconsistency is the sheer number of potential methodologies without an objective evaluation standard. For example, experimental heat sources can be either hot plates [5–7], film heaters [8–10], cartridge heaters [11–13] or various other less-common sources. Similarly, testing rig connectors can be either polymer or metal, and may also have manifolds to attach sensors [14,15]. These studies all require reliable measurements to permit confidence in their findings, and thus it is therefore important to know how much contribution the equipment employed has on the results gathered. A previous attempt has been made to investigate this issue through examination of variations between measurement techniques, wall roughness and between open and closed fluidic loops [16].

To expand such investigations, the work reported in this paper studies the effect of altering the heat source and connection technique of a heat sink under study. The three most common types of heat source discussed above, as well as both metal and polymer connectors, were employed as the variable equipment to be tested. Preliminary testing suggested that metal piping would produce

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Nomenclature

A	Heat transfer area - m
C_p	Specific heat capacity of the fluid – J/kg·K
D_h	Hydraulic diameter (characteristic length) - m
L	Total channel length - m
ΔP	Pressure drop across the channel - Pa
T	Temperature - K
k	Thermal conductivity of the fluid – W/m·K
$\dot{m}$	Mass flow rate of the fluid – kg/s
v	Flow velocity – m/s

Greek symbols

ρ	Density of the fluid – kg/m^3
σ	Standard derivation

Subscripts

f	Bulk fluid flow parameter
in	Parameter at channel inlet
out	Parameter at channel outlet
w	Parameter at channel wall

superior results to polymer tubing, so customised manifolds were added to the former for an additional configuration option. The heat sink used was a spiral microchannel, chosen to provide a more interesting and complex heat transfer relationship against flow rate than a conventional one (e.g. a straight channel).

The majority of the experimental arrangement, including the heat sink, was kept identical between experiments, allowing demonstration of the amount of variation caused by using different equipment, and comparison of this equipment in terms of heat transport (via Nusselt Number) and flow impedance (via friction factor), examining both consistency over repeated readings and agreement with other studies. In this way it can be determined which equipment produces the most reliable results.

The large amount of variation due to experimental differences discovered in this paper demonstrates the necessity for uniformity in equipment for future research. Currently, it is difficult to compare (on a consistent basis) studies that employ dissimilar equipment, such as those mentioned above. Hence, future experimental research should employ only the heat sources and connection techniques shown herein to achieve higher levels of reliability.

2. Experimental methods and description

In order to compare the different experimental arrangements, the performance of each setup was analysed via the average Nusselt Number for heat transfer efficiency, and the Darcy friction factor (hereafter friction factor) for flow impedance. For microchannel experiments, the former was derived in [17] as:

$$\overline{Nu} = \frac{D_h \dot{m} C_p (T_{f,in} - T_{f,out})}{kA} \frac{\ln\left(\frac{T_w - T_{f,in}}{T_w - T_{f,out}}\right)}{(T_w - T_{f,in}) - (T_w - T_{f,out})}. \tag{1}$$

Similarly, the friction factor can be derived via rearranging the Darcy–Weisbach equation as:

$$f = \frac{2D_h \Delta P}{L\rho v^2}. \tag{2}$$

The arrangement of the general experimental testing rig is shown in Fig. 1. A New Era NE-4000 Programmable 2 Channel Syringe Pump using two linked 60 ml syringes was employed to generate a steady, adjustable flow of deionized water. To study the temperature change and pressure drop within the system, two sets of OMEGA Ultra Precise RTD Sensors and Pressure Transducers were connected to a LabVIEW control and data-acquisition system. The heat sink for all experiments was a spiral microchannel with a square 600 × 600 µm cross-section, an 88 mm length and a glass bottom contact area of 20 × 20 mm.

The microchannel was placed in contact with a range of heat sources, illustrated in Fig. 2. As shown in (a), the Hot Plate used was a Hebei Peltier TEC1-12706 Hot Plate, monitored by a k-type thermocouple attached to the heated surface and controlled by an adjustable power supply (maximum: 30 V, 3 A). Insulation was positioned around the Hot Plate to reduce heat loss. The Film Heater in (b) is a WATLOW Etched Foil Element Heater with an in-built k-type thermocouple, connected to a WATLOW EZ-Zone PID Controller. A Teflon housing was fabricated, as in (d), enveloping the Film Heater to reduce heat loss and create a flat contact surface. In (c), a 175 W Watlow Cartridge Heater is shown - this was attached to the same power supply as the Hot Plate. To create the Copper Block Heater, both the copper block itself and a Teflon housing to reduce heat loss were constructed, as in (e) and (f). Four cartridge heaters were inserted into the copper block, as well as an RTD for measurement of the heater's temperature. All heaters were set to 325 K surface temperature (with calibrations conducted to factor in heat loss), with the fluid in the syringes kept at a constant 295 K. Thermal grease was applied throughout all contact areas.

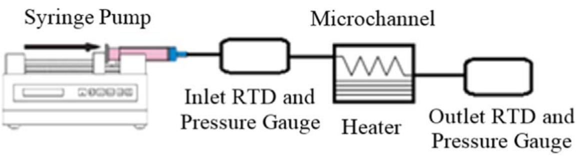

Fig. 1. Equipment arrangement for all experiments, adapted from [18]