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On the hydrodynamic characterization of a passive Shape Memory Alloy valve

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HIGHLIGHTS

- A miniature normally closed passive SMA valve for micro-fluidic cooling of Photonics devices is demonstrated in this paper.
- The passive dynamic behaviour of the valve in response to temperature change is observed.
- The design is hydrodynamically characterized through pressure-flow measurements.
- A correlation for head loss across the valve as a function of *Re* and blockage ratio is presented.

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ABSTRACT

An attractive approach to the thermal management of next generation photonics devices (heat fluxes > 10^2 W/cm^2) is micro-channel cooling, and micro-valves will be required for refined flow control in the supporting micro-fluidic systems. In this paper, a NiTi Shape Memory Alloy (SMA) micro-valve design for passive flow control and thermal management was prototyped at the macro scale and hydrodynamically characterized. The dynamic behavior of the valve was observed and the loss coefficient (ζ_v) derived from pressure-flow measurements. The hydrodynamic characterization study is important because ζ_v is sensitive to *Re* and geometry in the flow regime of the micro-fluidic system. Static replicas of the SMA valve geometry were tested for low *Re* (110–220) and a range of opening ratios (β) in a ø1 mm miniature channel. The loss coefficients were found to be sensitive to flow rate and decreased rapidly with an increase in *Re*. A correlation was developed to interpolate ζ_v from a given *Re* and β. The valve loss coefficients obtained in this work are important parameters in the modeling and design of future micro-fluidic cooling systems.

1. Introduction

As power densities of electronic devices continue to scale with Moores law, thermal management is more important than ever before. By lowering the operating temperature of a device, the reliability and lifespan is increased [1]. The general objective in thermal management is therefore to cool a device as much as possible whilst staying within given constraints e.g. limited cost, power, and footprint. However, this approach is not suitable in the thermal management of Photonics Integrated Circuits (PICs) for next-generation telecommunications equipment. PICs generate high heat fluxes at the device level (>10^2 W/cm^2) and the internal laser-arrays must be maintained within a narrow operating-temperature range (±0.1 K) [2].

Currently, local thermo-electric modules (TEMs) are used to control the temperature of the laser-arrays inside PICs. A promising enhancement is the use of a chip embedded micro-channel cooling system [3] to convect the heat away, reducing the TEM hot side temperature, and consequently the power required by the TEM. This system is depicted in Fig. 1: flow enters through a single inlet (1), splits into individual branches under the laser-bars in an array and then re-combines at the outlet (2). The heat transfer coefficient in the micro-channel under an individual laser-bar (3) and TEM (4) is controlled using a micro-valve (5) located downstream. During a period of increased chip workload, the TEM hot side temperature would be greater, increasing the power required by the TEM to generate this differential temperature. Sensing an increase in the coolant bulk temperature, the micro-valve would open to allow a

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Nomenclature

A_b	bluff body projected area, m^2
A_f	austenite finish temperature, °C
A_v	valve projected area, m^2
D_h	hydraulic diameter, m
E	Young's Modulus, GPa
f	friction factor, –
L	distance between pressure ports, m
$\dot{M}$	mass flow rate, kg/s
ΔP	differential pressure, Pa
Q	volumetric flow rate, m^3/s
Re	Reynolds number, –
S_f	shape factor, –
t_f	flow temperature, °C
u	mean velocity, m/s
w	width of valve opening, m
W	width of channel, m
β	opening ratio, –
ρ	density, kg/m^3
ζ	overall loss coefficient, –
ζ_v	valve loss coefficient, –

higher flow-rate in the channel and cool the TEM hot side, thereby increasing system efficiency.

Ideally this micro-valve would be passive, actuating in response to the coolant bulk temperature change and not requiring external control. Passive micro-valves are commonly found as a component of some oscillator micro-pumps where they are used to control the flow direction. These passive valves fall into two categories: mechanical and non-mechanical. Mechanical passive micro-valves take input from the force imparted by the fluid, opening and closing as necessary to control flow direction. The designs are either based on a cantilever-flap [4], ball [5] or thin membrane [6] that is manipulated by the flow. Non-mechanical passive valves have no moving parts, fluid passes unimpeded in one direction but the return flow is disrupted by the geometry of the valve [7].

Existing mechanical and non-mechanical passive valves take flow direction as an input. A passive valve to regulate temperature would require a thermal stimulus as an input. A Shape Memory Polymer (SMP) passive valve design was recently proposed for use in miniature-channel cooling [8]. The millimeter size SMP structures controlled the flow-rates in parallel mini-channels as a response to local temperature changes through numerical simulation. The open valve reduced the head loss in the individual mini-channel, leading to increased flow rate and greater heat transfer. Due to poor thermal conductivity (~0.2 W/mK) however, the SMP structures are slow to react to a temperature change [9].

Another way to achieve a thermally controlled passive valve would be to use a Shape Memory Alloy (SMA) as an actuator. With the use of this material, sensing and output are both managed by the Shape Memory Effect (SME). The SME occurs when the temperature of the SMA is raised to induce a phase transformation, and this occurs at relatively low temperatures (between −20 °C and 110 °C) [10]. When above the phase transition temperature, SMAs are Austenitic in micro-structure, and Martensitic when below. The phase transformation temperature is defined as the Austenite finish temperature (A_f), the temperature at which the micro-structure will be fully Austenitic. The SME results in deformation of the SMA to some pre-set shape [11]. As the SME is a thermally driven phenomenon, it could be used in a mechanical passive valve where actuation is induced by a temperature change in the localized valve region.

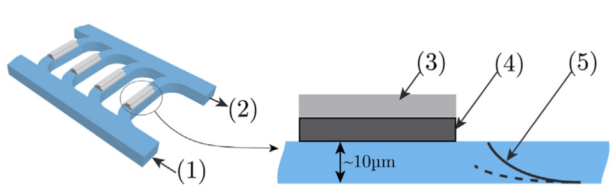

Fig. 1. Laser-array with integrated micro-fluidic cooling system. (1) Flow in; (2) flow out; (3) individual laser bar; (4) local TEM; and (5) passive SMA.

SMAs have in the past been used as actuators in micro-valves, and numerous examples can be found in the literature. Table 1 presents a diverse selection of existing NiTi based micro-valves. Information on the micro-valves' application, actuator material and length scale, maximum operating pressure and the permissible flow-rate is listed where available.

The micro-valves in Table 1 are all active mechanical micro-valves in classification. Joule heating of the SMA element is used to induce actuation in every case and external sensing and control systems are required to use these micro-valves in a thermal management application. The footprint of a passive SMA valve would be minimal as external control systems are not required. The objective of this work is to investigate a passive SMA micro-valve design, building on the previous work of Waddell et al [20].

2. Experimentation

In this section of the actuation and hydrodynamic characterization experiments carried out in this work are detailed. Shown first is the actuation experiment on the miniature prototype valve, and this is followed by the pressure-flow experiment on scaled down replica geometries of the prototype.

2.1. Actuation experiment

A miniature scale passive valve was developed from the NiTi SMA and the actuation of this prototype was observed in a ø9.3 mm miniature channel. The goal of the experiment was to observe the dynamic behavior of the valve in response to a temperature change in the channel flow.

2.1.1. Prototype SMA valve

The valve prototype was developed from equiatomic NiTi as it is the most widely studied and understood of the SMAs [21]. Fig. 2 shows the prototype valve developed in this work. The valve sits on an Acetal base (1) that slots into the miniature-channel test-rig. The main body of the valve and source of obstruction when closed is a 127 μm thick curved stainless steel shim (2). Inserted into the steel shim is a 0.4 mm NiTi actuator wire with an A_f temperature of 40 °C.

Table 1
SMA micro-valves.

Application	Actuator	Pressure (kPa)	Flow rate (mL/min)
Drug delivery [12]	ø0.12 mm NiTi wire	–	–
Pinch valve [13]	ø0.152 mm NiTi wire	206.84	16.8
Gas micro-valve [14]	TiNiPd foil	300	360
Flow dispensing [15]	ø76.2 μm NiTi wire	68.9	0.055
Pinch valve [16]	ø76.2 μm NiTi wire	103.4	–
Pinch valve [17]	ø381 μm NiTi wire	–	0.004
Bistable micro-valve [18]	20 μm NiTi foil	300	2200
Gas micro-valve [19]	NiTi foil	70	3100