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Heat transfer enhancement strategies in a swirl flow minichannel heat sink based on hydrodynamic receptivity

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ABSTRACT

The swirl flow minichannel heat sink has shown to be a promising alternative for thermal management of high heat flux applications, such as electronics and concentrated photovoltaics. Effective heat transfer enhancement strategies for this device are identified by studying the receptivity of temperature disturbances to a momentum forcing input. Steady state laminar flow is calculated numerically and experimental measurements are carried out to validate the results for subcritical Reynolds numbers. Using the framework of nonmodal stability theory, a harmonically driven linear perturbation problem is formulated, and the methodology to apply the local and parallel flow approximations based on order of magnitude arguments is detailed. The input-output response of temperature perturbations to forcing of the radial, azimuthal, and wall-normal momentum components is calculated for a range of wavenumbers, waveangles and temporal frequencies. The largest amplification is presented by streamwise vortices and streaks, followed by axisymmetric inward travelling waves, and then by streamwise propagating waves. Micromachining the channel walls with streamwise spiral grooves is proposed as a heat transfer enhancement technique. Excitation of streamwise independent structures in the wall-normal direction is expected, therefore maximum amplification should be obtained. Due to its simple implementation, we also propose using a pulsating flow rate as a heat transfer enhancement technique. Receptivity results for streamwise propagating waves of radial forcing show a response curve with moderate amplification for a wide range of actuation frequencies. Experimental work is conducted to measure the performance of the swirl flow channel heat sink using flow pulsations at the range of forcing frequencies suggested by the receptivity study. Compared to the unforced case, a lower wall temperature (up to 5 °C cooler) was observed with pulsations, at the same imposed heat flux and flow rate. To get the same wall temperature as in the unforced case, a pumping power reduction of up to 26.6% was observed, and using the same pumping power resulted in up to a 10.3% Nusselt enhancement. Hydrodynamic receptivity was successfully used to identify effective heat transfer enhancement strategies, resulting in a significant performance improvement for the swirl flow channel heat sink. This physics based approach can be extended to other techniques, for instance, to select the wavelength of a wavy surface, the periodicity of surface roughness elements, or the frequency of acoustic vibrations.

1. Introduction

High heat flux removal is required in numerous industrial applications, such as electronics cooling [1], laser diodes cooling [2], and concentrated photovoltaics [3]. Thermal management is important for the performance, safety, and lifetime of these devices [4,5], which is why high heat flux cooling technologies is one of the most active fields of heat transfer research today. Most promising solutions using single phase liquid cooled heat sinks include designs with jet impingement, flow through porous media, and microchannels [6–8]. During the last decade, several researchers have investigated single-phase heat transfer enhancement techniques for microchannels and minichannels with the goal of extending the applicability of single-phase cooling for critical applications, before more aggressive techniques, such as flow boiling, are considered [9–13]. Typical strategies include passive techniques, such as surface roughness, flow disruptions, channel curvature, out of plane

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mixing and fluid additives, as well as active techniques, such as vibration, electrostatic fields and flow pulsation [9]. In general, most advances on heat transfer augmentation are inspired by techniques that have proven to be successful in the past.

The swirl flow channel heat sink consists of an annular cavity closed at the top and bottom, where fluid is admitted through the outer radius, it spirals radially inward and exits through the inner radius, heat is removed from one of the cavity walls whereas the other one is insulated. This device was designed and first studied by Ruiz and Carey in 2012 [14,15]. In subsequent work in 2015, they built a prototype and compared experimental measurements using water to an analytical model for the heat and momentum transport in the heat sink. They found that the model underpredicted both, the pressure drop and total heat flux, due to not taking into account secondary flows and instabilities induced by rotation. The results from Ruiz and Carey also showed that the design is promising, a heat flux of 113 W/cm^2 was achieved while maintaining a surface temperature below 80 °C and a ratio of pumping power to heat rate of 0.03% [14,15]. Steady state flow in this heat sink was studied numerically using integral methods by Herrmann-Priesnitz et al. in 2016 [16], and different boundary layer structures were observed depending on the governing parameters. In subsequent work, a thermal design exploration of this device was carried out [17]. Rotation of the fluid induces a crossflow and entrainment, which was found to enhance convective heat transfer considerably due to motion of fluid towards the heat exchange surface. This effect depends on the structure of hydrodynamic boundary layers, and is intensified for small flow inlet angles and high Reynolds number. Device performance was compared to other single phase microchannel heat sinks for high heat cooling applications reviewed by Agostini et al. [6]. Although the swirl flow channel heat sink presented about 25% of the heat flux achieved with other devices, the total pressure drop was much lower, resulting in a ratio of pumping power to heat rate that of about 20% of the lowest value reported in Ref. [6]. It was concluded that the swirl flow channel heat sink is suitable for applications where low pumping cost is required. Furthermore, for high heat flux applications, there is a significant margin to use heat transfer enhancement techniques even if the pumping cost increases.

The velocity profiles found in this type of channel are similar to those observed in other rotating boundary layer flows, such as von Kármán, Ekman and Bödewadt flows. The first experimental observation of stationary crossflow vortices and the first theoretical stability analysis for the rotating disc flow were presented by Gregory et al. [18]. Work on the modal and spatial stability continued with Malik, who computed the neutral curves for stationary disturbances using the parallel flow approximation [19]. Lingwood followed by studying the absolute or convective nature of the instabilities [20]. More recently, Serre et al. and Lopez et al. used DNS and found that the Bödewadt layer is unstable to axisymmetric circular radial waves and three-dimensional multi-armed spiral waves [21,22]. In a follow up study, Do et al. showed that in the absence of any external forcing, the circular waves are transitory, but low amplitude forcing can sustain them indefinitely [23].

Over the past two decades, nonmodal stability theory has emerged to provide a more complete picture of the linear perturbation dynamics for fluid flows using an initial-value problem formulation [24–27]. This framework allows the incorporation of an external harmonic forcing term that may represent free-stream turbulence, wall roughness, acoustic perturbations or body forces among others. The response of the system to these external disturbances, i.e. receptivity of the flow, is determined by the particular solution to the harmonically driven problem. A componentwise receptivity analysis for plane channel flows was carried out by Jovanović and Bamieh in 2005 [28]. Their results showed how the roles of Tollmien-Schlichting (T-S) waves, oblique waves, and streamwise vortices and streaks can be explained as input-output resonances of the spatio-temporal frequency responses. Therefore, one can identify efficient mechanisms to favor the emergence of specific flow structures. In a similar manner, a receptivity analysis can be used to identify efficient mechanisms to enhance convective heat transfer. This approach, based on physics rather than experience has not been presented elsewhere.

In this work, we use the framework of nonmodal stability theory to study the response of temperature disturbances to a momentum forcing. The steady state flow is calulated using the integral method developed in Ref. [16] for the velocity field, and the spatial discretization presented in [17] followed by matrix inversion is used for the temperature field. A swirl flow channel heat sink is fabricated and experimental measurements of the pressure drop and wall temperature are used to validate the base flow in the laminar range of flow rates. A harmonically driven linear perturbation problem is formulated, and the methodology to apply the local and parallel flow approximations based on order of magnitude arguments is detailed. The amplification of temperature perturbations to forcing of the radial, azimuthal, and wall-normal momentum components is calculated for a range of wavenumbers and temporal frequencies. Characteristics of the most receptive types of forcing are used to identify effective heat transfer enhancement techniques, resulting in a significant performance improvement for the swirl flow channel heat sink.

2. Theoretical analysis

2.1. Steady state flow

The swirl flow minichannel heat sink consists of an annular cavity, which is open at the outer and inner radii, r_o and r_i, respectively. The top and bottom boundaries are solid walls with a separation of $2h$, and it has a very small aspect ratio $h/r_o \ll 1$. Incompressible fluid enters the channel at r_o with an inlet angle θ_o with respect to the tangent, it spirals radially inward, and exits through r_i, heat is removed from the top channel wall whereas the bottom one is insulated. A schematic of the heat sink design is shown in Fig. 1.

The steady state flow is axisymmetric, it presents a boundary layer nature, and viscous dissipation and buoyant effects are negligible, therefore the governing steady state equations are

$$\frac{1}{r}\frac{\partial(rU)}{\partial r} + \frac{\partial W}{\partial z} = 0, \tag{1a}$$

$$U\frac{\partial U}{\partial r} + W\frac{\partial U}{\partial z} - \frac{V^2}{r} = -\frac{1}{\rho}\frac{\partial P}{\partial r} + \nu\frac{\partial^2 U}{\partial z^2}, \tag{1b}$$

$$U\frac{\partial V}{\partial r} + W\frac{\partial V}{\partial z} + \frac{UV}{r} = \nu\frac{\partial^2 V}{\partial z^2}, \tag{1c}$$

$$0 = -\frac{1}{\rho}\frac{\partial P}{\partial z}, \tag{1d}$$

$$U\frac{\partial T}{\partial r} + W\frac{\partial T}{\partial z} = \alpha\frac{\partial^2 T}{\partial z^2}, \tag{1e}$$

$$\begin{aligned} z = h: &\quad \mathbf{U} = 0, \quad \kappa\frac{\partial T}{\partial z} = q''_w, \\ r = r_o: &\quad \mathbf{U} = U_o(1, \cot\theta_o, 0)^T, \quad T = T_o, \\ z = -h: &\quad \mathbf{U} = 0, \quad \frac{\partial T}{\partial z} = 0, \\ r = r_i: &\quad P = 0, \end{aligned} \tag{1f}$$