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Design of novel geometries for microchannel heat sinks used for cooling diode lasers

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ABSTRACT

High power diode laser bars require thermal management packages with high cooling efficiencies and long-term stability. At a constant size, the power output of the diode laser is being increased rapidly; therefore, an efficient heat removal strategy has become even more important. High efficiency microchannel heat sinks are usually used to remove heat from the system. In this study, the fluid flow and heat transfer of an existing diode laser micro-channel heat sink is numerically simulated. To reduce the maximum temperature and obtain a uniform temperature distribution across the diode laser, which leads to extended lifetimes, the simulations are repeated for three different channel geometries. The hydrodynamic and thermal behavior of the heat sinks are then compared. The results show that among all geometries, the sinusoidal structure provides the best thermal performance. Although the system pressure drop increases by 18%, this configuration increases the diode lifetime by 44%.

1. Introduction

One of the most important issues in the electronic industries is thermal management of the electronic devices. High temperatures reduce the lifetime and the efficiency of the electronic systems such as diode lasers [1]; therefore, a good thermal management plan is required to reduce the maximum operating temperatures and distribute the temperature uniformly throughout the device. Microchannel heat sinks (MCHS) are high efficiency heat removal systems that are used in high power diode lasers.

Enhancing thermal efficiency of the systems always been of interest to researchers [2–8]. In the field of design and optimization of microchannels many studies have been done, such as [9–12]. However Application of microchannels for cooling the electronic devices was studied for the first time by Tuckerman and Pease in 1980 [13]. They designed and made a 1 cm × 1 cm compact rectangular silicon heat sink for cooling of an electronic circuit. They showed that the designed heat sink has a heat removal capability of 750 W/cm^2 with a pressure drop of 2.2 bar.

Kreutz et al. [14] in 2000, applied microchannels for heat removal of optoelectronic devices such as lasers. Their designed system reduced the thermal resistance of the laser which allowed them to increase the capacity of the device.

Hestroni et al. [15,16] conducted experimental and theoretical investigations on single-phase heat transfer in microchannels. They studied the fluid flow to learn about pressure drop and transition thresholds from laminar flow to turbulent flow in the channels. They also studied heat transfer in a continuum model with small Knudson numbers. They applied their study to a range of cross sectional geometries with different hydraulic diameters.

Wang et al. [17] in 2006, studied forced convection heat transfer for cooling of a slab of high-power solid-state laser. They numerically investigated the flow and temperature fields as well as stress distribution in the slab which was cooled by water. They applied a range of Reynolds numbers between 500 and 8000 for different channel geometries and proved that the maximum permissible thermal load could increase by increasing the Reynolds number and/or reducing the channel height. They also studied the thermal stresses in the heat sink and showed that the maximum thermal stress happens at the surface in contact with the coolant, and its location moves from the upstream end to the center of the surface with increasing the Reynolds number or reducing the channel height.

Optimization of microchannels in diode laser heat sinks was investigated by Jokar and Dix [18,19]. They applied computational and experimental methods to analyze the fluid flow and heat transfer performance of microchannel coolers for high-power

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diode laser applications. Four different heat sinks with different geometries of microchannels were placed at the heat input region of the heat sink. They observed that a symmetric flow distribution in zigzagged microchannels could increase the thermal and hydrodynamic efficiency of the microchannel heat sink. They also studied the flow and thermal fields in straight microchannels and showed the temperature distribution in the heat sinks with straight microchannels is more uniform as a result of optimal heat transfer surface utilization.

In this study the fluid flow and heat transfer of microchannel heat sinks used in the electronics laboratory are modeled. The heat removal capacity of the existing heat sinks is lower than electronic test requirements at the laboratory so the heat sinks usually experience temperatures higher than their allowed maximum temperatures. This causes significant reduction in the device lifetime. In order to better understand the problem and explore solutions, an existing heat sink was sectioned and accurately scanned to determine its internal dimensions. The extracted dimensions were applied to a numerical model to calculate the fluid flow field and heat transfer in the existing heat sinks. The internal geometry of the heat sink is generally similar to that studied in [19]; however, the number of microchannels and the hydraulic diameters are different.

In order to decrease the maximum temperature of the system, three different modifications were suggested utilizing the same external geometry constraints. The hydrodynamics and thermal behavior of the suggested models were numerically analyzed and the lifetime of the system was calculated for each model. The results show that the diode laser lifetime could be improved by 44% at the cost of 18% increase in the pressure drop if the straight microchannels were replaced by sinusoidal curved microchannels.

2. System structure

The microchannel heat sink (MCHS) studied in this research is used for cooling high power diode lasers. The heat sink includes several microchannels in which coolant fluid is circulating. The MCHS is usually made of copper or silicon. Because of the higher thermal conductivity of copper or silicon, the heat sinks made of copper generally have better thermal performances.

The manufacturing process of the MCHS consists of laser cutting thin copper or silicon plates, stacking the layers and soldering them [1]. Fig. 1 shows the schematic view of the diode laser heat sink used in this study. The diode laser is soldered to the front top of the heat sink. The heat sink area is painted in red[1] in Fig. 1. The cooling fluid enters the heat sink through the inlet and is then directed to the microchannels to absorb heat from the attached diode laser. The direction of the flow is shown by arrows in Fig. 1. High fluid velocity and large heat transfer surface area enable the microchannels to remove high heat fluxes.

3. Mathematical model

The fluid flow and heat transfer in the MCHS is analyzed in this study. The mathematical model was built based on the following simplifying assumptions:

- The diode laser ribbon has a constant heat flux.
- All external surfaces of the system other than the high heat flux region are insulated.
- There is no heat generation in the system.

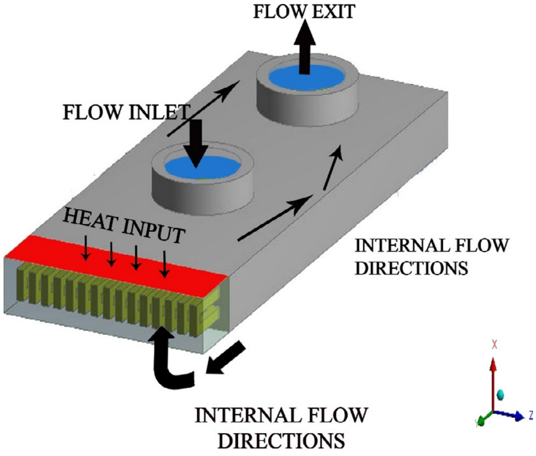

Fig. 1. Schematic view of the fluid flow in the micro-channel heat sink.

Table 1
Thermo-physical properties of the materials.

Material	Density (kg/m^3)	Specific heat (J/kg K)	Thermal conductivity (W/m K)	Viscosity (kg/m s)
Water	998.2	4182	0.643	0.001003
Copper	8987	381	398	–

Table 2
Model boundary conditions.

	Flow field boundary conditions	Temperature field boundary conditions
Fluid inlet	$\dot{V}_i = 200\ \mathrm{mL/s}$	$T_i = 24\ ^\circ\mathrm{C}$
Fluid outlet	$P_o = P_{ref}$	$\frac{\partial T}{\partial n} = 0$
Channel walls	$\mathbf{u}_s = 0$	*No tempperature jumb* $-k_s \frac{\partial T_s}{\partial n} = -k_f \frac{\partial T_f}{\partial n}$
Below the diode laser	–	$-k_s \frac{\partial T_s}{\partial n} = 317.5\ \mathrm{W/cm^2}$
Other external walls	–	$-k_s \frac{\partial T_s}{\partial n} = 0$

Table 3
Analysis of mesh independency on maximum temperature at heat flux 3.55.5 W/m^2.

Case	1	2	**3**	4
Number of elements	618,000	1,215,890	**1,817,324**	2,453,500
$T_{\max}$ [K]	331.5	334.6	**338.6**	338.1
T_{ave} [K]	327.7	330.6	**334.5**	334.4

- The fluid flow in the system is incompressible, steady, laminar and single phase.
- There is no slip flow and no temperature jump conditions on the microchannel walls.

Based on these assumptions, classic fluid mechanics are used to model the flow field and pressure distribution in the flow channels of the system. These equations consist of the continuity equation;

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

and the momentum equation;

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \left[-p\mathbf{I} + \mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right) - \frac{2\mu}{3}(\nabla \cdot \mathbf{u})\mathbf{I}\right] \tag{2}$$

In these equations $\mathbf{u}$ and p are the velocity vector and the pressure and ρ and μ are the density and the viscosity of the fluid respectively.

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[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.