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Optimized multi-floor throughflow micro heat exchangers

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A B S T R A C T

Multi-floor networks of straight-through counterflow liquid cooled microchannels have been investigated by performing conjugate heat transfer in a silicon substrate of size 15 × 15 × 1 mm. Two-floor and three-floor cooling configurations were analyzed with different numbers of microchannels on each floor, different diameters of the channels, and different clustering among the floors. Direction of microchannels on each floor changes by 90° from the previous floor. Direction of flow in each microchannel is opposite of the flow direction in its neighbor channels. Conjugate heat transfer analysis was performed by developing a software package which uses quasi-1D thermo-fluid analysis and a fully 3D steady heat conduction analysis. These two solvers are coupled through their common boundaries representing surfaces of the cooling microchannels. Using quasi-1D solver significantly decreases overall computing time and its results are in good agreement with 3D Navier–Stokes equations solver for these types of application. Multi-objective optimization with modeFRONTIER software was performed using response surface approximations and genetic algorithm. Maximizing total amount of heat removed, minimizing coolant pressure drop, minimizing maximum temperature on the hot surface, and minimizing non-uniformity of temperature on the hot surface were four simultaneous objectives of the optimization. Maximum number of cooling microchannels on each floor, diameter ranges of the microchannels on each floor, and vertical clustering range of the floors were the specified constraints. Pareto-optimal solutions demonstrate that thermal loads of 800 W cm^{-2} can be effectively managed with such multi-floor microchannel cooling networks. Two-floor microchannel configuration was also simulated with 1000 W cm^{-2} uniform thermal load and shown to be feasible.

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1. Introduction

Cooling systems for new generation portable, telecommunications and military electronic devices with higher capacity of heat removal, higher efficiency and smaller size is one of the challenges in the heat transfer field. One of the cooling system technologies is the cooling microchannel based compact heat sink. Significantly smaller sizes of the microchannels offer major advantage of this method which allows multichip integration. The main challenges of this method are high pressure drop which require higher pumping power, surface temperature non-uniformity, liquid maldistribution, and coolant leaks [1,2]. Microchannel heat sinks have been investigated both experimentally and numerically [3,4]. Colgan et al. [5] investigated practical implementation of a single phase microchannel flow in silicon substrates to enhance removal of heat load up to 300 W cm^{-2} using water as coolant. Walchli et al. [6] applied oscillating flow method on water cooling system for thin form factor high performance electronics with 180 W cm^{-2} heat flux load.

One of the first vestiges of the application of optimization methods to improve channel geometries was in the design of gas turbine blades. Intensive work was performed to maximize cooling efficiency of channel-based networks by means of optimizing their arrangement. Martin and Dulikravich [7,8] presented a fully automated program for inverse design and optimization of internally cooled turbine blades, which was validated against experimental results from Pratt & Whitney. A few years later, Jelisavcic et al. [9] applied hybrid evolutionary optimization to the same concept of channel network optimization for turbo-machinery applications. Hong et al. [10] presented a great effort to enhance the cooling uniformity of microchannel heat exchangers through the design of fractal tree-like networks, attempting to reduce coolant pumping pressure drop. Subsequently, Gonzales et al. [11] executed relevant work comprising 2D microchannel networks optimization. Genetic algorithms have been used by Wei and Joshi [12] to perform single objective optimization in order to minimize overall thermal resistance. Husain and Kim [13] performed single objective optimization

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Nomenclature

A	cross-sectional area of a microchannel
C_f	coefficient of wall friction
C	specific heat per unit mass
CV	coefficient of variation
D_h	hydraulic diameter
f	Darcy friction factor
h	convection heat transfer coefficient
k	thermal conductivity of the fluid
$K = K_{in} + K_{out}$	coefficient of inlet + exit losses
L	microchannel length
$\dot{m}$	mass flow rate
N_u	Nusselt number
P_{er}	perimeter of the microchannel
p	static pressure
P_r	Prandtl number
Q	total heat transferred into fluid
R_e	Reynolds number
S	surface area of the microchannel
T	absolute temperature
T_{ave}	average temperature
V	velocity vector magnitude

Greek symbols

η	efficiency of microchannel cooling
ε	channel inner wall surface roughness
τ_w	wall shear stress
ρ	coolant fluid density
σ	standard deviation

Subscripts

IN	microchannel inlet
OUT	microchannel exit/outlet
W	microchannel wall

using response surface approximation in order to find optimal microchannel width, depth, and fin width. Abdoli and Dulikravich [14] performed multiobjective optimization for 4-floor branching microchannel configurations with 67 design variables in order to improve heat removal and decrease temperature non-uniformity and coolant pumping pressure drop. There is still a need for more research on single-phase flow microchannels in order to increase heat transfer efficiency and decrease temperature non-uniformity and pressure drop [15].

In this paper, a cooling configuration involving multiple floors of microchannels is introduced. The main advantages of using straight through-flow cooling channels rather than branching cooling channels are: a) lower pumping power requirements, b) lower manufacturing cost, c) better uniformity of hot surface temperature; and higher reliability in case of plugs in any of the microchannels.

This work represents a significant improvement over the effort [14,16] to develop high efficiency compact heat exchangers based on optimally branched networks of microchannels.

2. Mathematical model description

An automatic 3D conjugate heat transfer analysis software package (CHETSOLP) was developed to model conjugate heat transfer phenomena and calculate flow-field and temperature field simultaneously in order to assess any microchannel heat sink topology. The most relevant mathematical formulations comprising the CHETSOLP package [16] are described in this section. The working logic of the package is to guess temperature distributions on the walls of the microchannels, solve for the coolant flow-field inside the microchannels, transfer the resulting heat fluxes on the walls of the microchannels to the 3D heat conduction analysis code, solve for temperature field in the solid part of the heat exchanger, update temperature on the walls of the microchannels, and iteratively repeat this procedure until the wall temperatures of the microchannels (initially guessed) converge. Data transfer at the solid/fluid interfaces is performed by a developed boundary condition transfer module that links the fluid and solid domain solvers. CHETSOLP consist of two parts; random geometry generator and analysis solvers.

In this research, microchannels have been arranged in four floors inside the silicon substrate with dimension of 15 × 15 mm (length and width), as shown in Fig. 1. Thickness of substrate was calculated based on number of floors, diameter of floors and vertical clustering values.

Fig. 1b shows one microchannel floor which has several separate straight microchannels. As this figure shows flow direction in each channel is in opposite direction of flow in its neighbor channels.

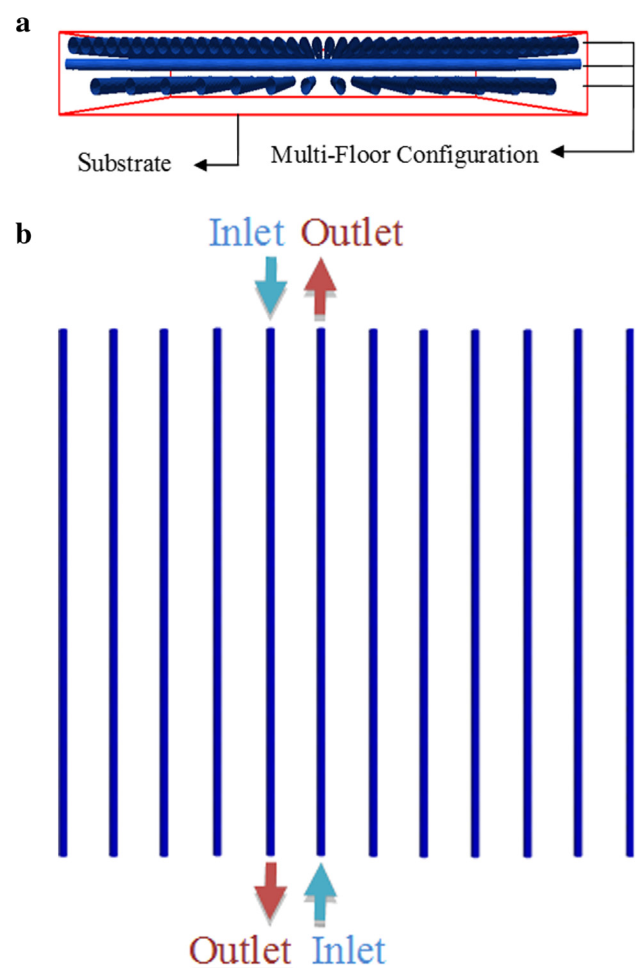

Fig. 1. a) 3D multi-floor microchannels, and b) flow direction in microchannels.

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