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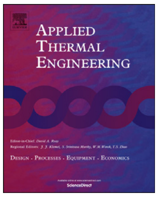

Fast approach of Pareto-optimal solution recommendation to multi-objective optimal design of serpentine-channel heat sink

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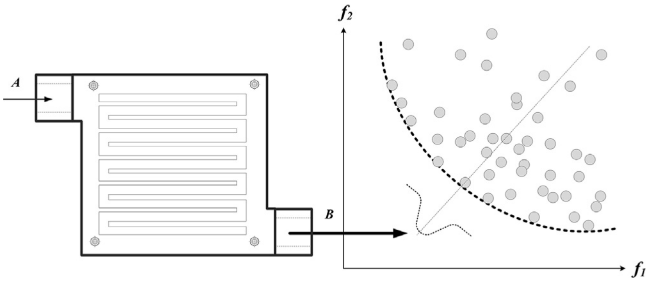
HIGHLIGHTS

- The structural modelling of serpentine channel heat sink and experimental validation.
- Multi-objective artificial fish swarm algorithm using non-dominated sorting method.
- The approach of fast Pareto-optimal solution recommendation (FPR).
- Pareto risk index (PRI).
- Trend indices of mean average precision (mAP) and mean standard deviation (mSTD).

GRAPHICAL ABSTRACT



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ABSTRACT

A multi-objective structural design of a serpentine channel heat sink is presented in this paper. In the structural modelling of the heat sink, channel width, fin width, channel height and inlet velocity are defined as the design variables, 'total thermal resistance' and the 'pressure drop' as the two objectives, subject to constraints of fixed length and width of the heat sink. In this study, a multi-objective artificial swarm fish algorithm with a variable population size using a non-dominated sorting method (MOAFNS) has been developed to handle the optimisation, in which fast approach of Pareto-optimal solution recommendation using the Pareto risk index is proposed to handle the optimal trade-offs between the two conflicting thermal objectives. Then, the optimal solutions have been validated by performing related experiments. The Pareto-front indicates a trade-off between 'total thermal resistance' and 'pressure drop'. Numerical results and experimental data have reached an agreement that reduction in both thermal resistance and pressure drop can be achieved via determination of channel configuration and inlet velocity using MOAFNS, which results in desired thermal performance of the heat sink.

1. Introduction

Heat sinks have widely been used to enhance heat dissipation and to remove from various devices, such as from a hot surface to a cooler ambient. With the growing demand for dissipation of high heat fluxes, the use of liquid-cooled heat sinks has increased widely. The structural design and optimisation of a heat sink should be such that it can dissipate as much heat as possible, e.g. a heat flux of 750 W/cm^2 [1] and 270 W/cm^2 [2], under given conditions of pumping power, volume, or weight limit. In recent years, researchers have worked on the structural design and optimisation of thermal performance of heat sinks for their various applications.

In 1981, Tuckerman and Pease [3] designed a micro-channel heat sink. In 1992, Knight et al. [4] presented a dimensionless

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form of the governing equations of fluid dynamics and heat transfer for both laminar and turbulent flow and used it to determine the geometry of a micro-channel heat sink. In 2000, Perret et al. [5] presented a cooling device which embed the heat sink's micro-channels into the silicon wafer. In 2006, Hilbert et al. [6] performed multi-objective design optimisation concerning the blade shape of a heat exchanger, considering the coupled solution of the heat transfer processes. Wang et al. [7] studied a membrane-electrode assembly model of the serpentine cooling channels for polymer electrolyte membrane fuel cells. In 2008 and 2010, Husain et al. [8,9] carried out multi-objective performance optimisation of a micro-channel heat sink using surrogate analysis, in which the design variables were micro-channel width, depth, and fin width and the two objective functions, were thermal resistance and pumping power. In 2009, Biswal et al. [10] employed an analytic model to optimise the single-phase liquid-cooled micro-channel heat sink. Copiello and Fabbri [11] investigated optimisation of heat transfer from wavy fins cooled by a laminar flow. In 2012, Turkakar et al. [12] reported their work on dimensional optimisation of silicon micro-channel heat sinks by minimising the total thermal resistance. Hung et al. [13] used an optimisation procedure consisting of a simplified conjugate-gradient method and a three-dimensional fluid flow and heat transfer model to investigate the optimal geometric parameters of a double-layered micro-channel heat sink. In 2014, Xie et al. [14,15] carried out numerical investigation on microchannel heat sink to study the laminar fluid flow and thermal performance based on constructal theory.

In designing a heat sink, both thermal resistance and pressure drop should be low. In many previous works, pressure drop was considered as a constraint, and parallel heat sinks were modelled. In this research, a multi-objective optimal design of a serpentine channel heat sink has been proposed, which is targeting to reduce the overall thermal resistance and pressure drop, with four design variables: the number of channels, channel width, channel height and inlet velocity.

There are some widely used algorithms to solve multi-objective formulations, such as the non-dominated sorting genetic algorithm II (NSGA-II) [16], etc. In this paper, a multi-objective artificial swarm fish algorithm with the variable of population size using the non-dominated sorting method (MOAFNS) is proposed to handle the optimisations of a serpentine channel heat with two design objectives. By borrowing the intelligence of swarm fish's social behaviours in searching, swarming, following, the artificial swarm fish algorithm [17] is parallel and independent to the initial values and able to achieve a global optimum. An artificial swarm fish algorithm with a variable population size was developed for a spatial analysis [18] and the prediction of lithium-ion battery capacity [19].

Generally, a multi-objective optimisation problem can be written as shown in Equation (1), subject to equality constraints $G_i(\mathbf{x})$, as given in Equation (2), and inequality constraints $H_i(\mathbf{x})$, as given in Equation (3). Here, J is the number of objective functions, given by F_i: $\Re^n \rightarrow \Re$; M is the number of the equality constraints; I is the number of the inequality constraints; $\mathbf{x} = [x_1, x_2, \ldots, x_K]$ is the decision variables vector, and K is the number of the variables.

$$\text{minimise}: F_i(\mathbf{x}) = \left[f_1(\mathbf{x}), f_2(\mathbf{x}), \cdots, f_J(\mathbf{x})\right], i = 1, 2, \cdots, J \tag{1}$$

$$G_i(x) = 0, i = 1, 2, \cdots, M \tag{2}$$

$$H_i(\mathbf{x}) \leq 0, i = 1, 2, \cdots, I \tag{3}$$

All vectors satisfying Equations (2) and (3) are named as the solution set $\mathcal{F}$, in which the decision variables set of $\mathbf{x}^* = [x_1^*, x_2^*, \ldots, x_K^*]$ yields the optimum values of all the objectives. The vector of decision variables $\mathbf{x}^* \in \mathcal{F}$ is Pareto optimal if there is no feasible vector of decision variables $\mathbf{x} \in \mathcal{F}$, which will increase some criteria without causing a simultaneous decrease in any other criteria. The vectors $\mathbf{x}^*$ corresponding to the solutions included in the Pareto-optimal set are called non-dominated vectors. The image of the Pareto-optimal set under the objective functions is called Pareto front [20–22].

Real-world applications, such as optimisation of fluid flow and geometric structure [23], structural optimisations of space systems [24], parameters determination for financial market quantitative modelling [25], urban study [26], automotive engineering [27], Terahertz spectroscopic analysis of drug or explosive mixtures [28], and analysis and management of 'Big Data', usually involve multiple objectives. Thus, people need to search for 'trade-offs', rather than a single solution, which leads to the different solution of 'optimality' under the multi-objective situations. The most widely used concept is the Pareto optimality, an engineer can make trade-offs within this set under practical requirements by focussing on the set of Pareto-front choices, which provides a visualised demonstration of the Pareto-optimal solution, but with an unclear indication of optimal diversities for decision-making.

In this paper, we propose a fast approach of Pareto-optimal solution recommendation (FPR) using the Pareto risk index (PRI), which provides users with a recommendation list of optimal ranking and optimal trend indications with different risk tolerance. This paper is organised as follow: Section 1 introduces the background of this research work; Section 2 discusses the structural modelling of a serpentine channel heat sink; Section 3 discusses the experimental setup for heat sink validation; Section 4 introduces the framework of MOAFNS; Section 5 describes the FPR; Section 6 defines the two fitness functions for the structural design of the heat sink; Section 7 gives the empirical results and verifications of the optimal design; and Section 8 concludes this paper.

2. Structural modelling of a heat sink

Compared with parallel channels, serpentine channels have perfect flow distribution uniformity. In a serpentine channel, the flow is interrupted periodically at the bends of the channels which results in periodic interruptions at the thermal boundary layers. The impingement, recirculation and flow separation at these sharp bends lead to flow distortion, and consequently enhances the heat transfer performance in serpentine channels.

The structural modelling of a serpentine channel heat sink with one 'inlet' and one 'outlet' is shown in Fig. 1(a), which has n channels with width W_c and $(n-1)$ fins with width W_b. Fig. 1(b) is the 3D model of this heat sink. The heat sink's dimension is $W \times L \times H$, which consists of a uniform heat flux from the base plate. The insulated 'top plate' is used solely for containing the coolant flow, and the heat is taken away by the coolant.

In this modelling, the two factors are considered to represent the performance of the heat sink, which are: 1, total thermal resistance R_t and 2, pressure drop of the serpentine channel P_d.

2.1. Total thermal resistance

A serpentine channel heat ink has several sharp bends, the total thermal resistance of a serpentine channel heat ink can be written as given in Equation (4), which ignores the spreading thermal resistance caused by the temperature difference between the outlet and the inlet or the thermal resistance across the interface between the device and the heat sink.