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A topology optimization method for a coupled thermal–fluid problem using level set boundary expressions

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ABSTRACT

This paper presents a topology optimization method for a coupled thermal–fluid problem based on the two- and three-dimensional steady-state Navier–Stokes and energy equations. In this research, the optimization problem is formulated as a heat exchange maximization problem to obtain structures that function as high-performance cooling devices. Such devices, for example, liquid-cooled heat sinks, have recently attracted considerable attention as an engineering application for thermal cooling devices. The proposed optimization method employs level set boundary expressions and a Tikhonov-based regularization scheme enables qualitative control of the geometric complexity of the optimal configurations. Using the developed methodology, we provide two- and three-dimensional numerical examples that confirm the applicability, from an engineering standpoint, of the optimization method for the design of cooling devices.

1. Introduction

Multiphysics optimization problems that combine fluid behavior formulations with those of other physical phenomena are especially challenging, and the development of particularly useful optimal configurations based on designer intuition is extremely difficult.

One example of a typical multiphysics optimization problem for an engineering application is a thermal device used for cooling mechanical or electronic systems, i.e., a heat sink. Since the physical phenomena active in a heat sink are mainly governed by thermal and fluid dynamic interactions, optimal cooling performance can be obtained by maximizing the exchange of heat. Among various heat sink designs, the liquid-cooled type [1,2] has recently attracted much attention as a high-performance cooling device. A schematic design of a liquid-cooled heat sink is shown in Fig. 1. This basic design has been implemented in a variety of sizes, including compact designs for micro-scale thermal devices used in microelectromechanical system (MEMS) applications. Many researchers have investigated the relationship between the performance of heat sinks and the geometrical configuration of their channels, using experimental [3], analytical [4], and numerical [5,6] approaches. However, as mentioned above, the intuition of designers is usually ineffective when the goal is to develop optimal configurations for such devices, since their performance must satisfy multiple demands, such as maximal heat exchange with minimal pressure drop or pumping power. Thus, given the utility of mathematical optimization approaches for the design of these devices, several optimization methods for the design of high-performance devices have been proposed [1,7,8]. However, most previous research has been based on size optimization that only allows changes in sizes, such as length, height, and depth, with respect to the geometry of the device. Therefore, the initial channel configuration setting for the optimization is crucially important to the realization of a high-performance device, and the optimal solution strongly depends on this initial setting. Although size optimization methods are useful at the detailed design stage of a heat sink design problem, the low degree of design freedom is an obstacle to achieving dramatic improvements in heat sink performance during the conceptual design stage.

As a conceptual design optimization method, topology optimization [9] is a particularly useful approach for obtaining optimal configurations based on mathematical and physical laws. It is based on the replacement of a structural optimization problem by a material distribution problem, which enables flexible derivation of optimal configurations for a variety of physical problems. Topology optimization uses a characteristic function that expresses the existence of a material domain in a fixed design domain as a design variable, and derives optimal configurations via a mathematical approach.

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Borravall and Petersson [10] developed a topology optimization method for fluid mechanics problems in which the fixed design domain was defined as consisting of both fluid and solid domains, with the fluid domain governed by the Stokes equation. The solid domain was assumed to have the properties of a porous medium, based on Darcy's law [11], hence a fictitious force could be applied to the solid domain and the velocity of the porous regions would be retarded depending on the magnitude of this fictitious force, which is controlled by the design variable. Consequently, this approach can derive optimal configurations using an expanded governing equation that contains a fictitious force term defined only in the solid domain. Several researchers [12–15] expanded this methodology to the Navier–Stokes equation, applied it in minimization of fluid dissipation energy problems, and succeeded in deriving appropriate optimal configurations for different Reynolds numbers. However, since almost all methodologies for fluid problems are constructed under an assumption of isothermal conditions, they cannot be used for heat sink design problems.

Li et al. [16,17] constructed a topology optimization method based on a heuristic approach, the so-called evolutionary structural optimization method for heat conduction problems. Based on the density approach, Bruns [18] proposed a topology optimization method for heat transfer problems. While these two methods use the finite element method (FEM) for calculating the thermal field, Anflor and Marczak [19] treated thermal diffusion problems based on the boundary element method, using the topological derivative [20]. Although these previous efforts aimed to construct a design method for cooling devices, the heat exchange caused by the interaction of fluid moving over a heated solid was not considered.

As previously mentioned, coupled thermal–fluid problems are especially attractive research topics, since they focus on a range of engineering applications such as cooling devices for MEMS devices, semiconductors, and other thermal devices. Several researchers [21–23] have proposed methodologies for thermal–fluid problems using conventional topology optimization method, such as the density approach [24], and have successfully obtained optimal configurations for various objectives. Unfortunately, when such approaches are applied to heat transfer or diffusive problems, the resulting optimal configurations often have excessive geometric complexity, and may include grayscale regions that are not meaningful in an engineering sense. When the aim is to develop high-performance products that can be easily engineered, optimal configurations that have clear boundaries and an appropriately simple structure are desirable.

On the other hand, a level set-based structural optimization method is a particularly useful approach for obtaining meaningful optimal structures for engineering applications [25,26], because such methods are immune to the problem of grayscales. In such methods, the value of the level set scalar function represents the material domain, the void domain, and the boundary between them, with positive values representing material domains, negative values void domains, and the zero iso-surface the structural boundaries. Thus, the structural boundaries of the obtained configuration are clear, that is, they do not include any grayscale regions [27,28]. Zhuang et al. [29] pioneered a level set-based methodology for heat conduction problems, and constructed a topology optimization method for deriving the effective transport path of heat dissipation under a given volume constraint.

Yamada et al. [30] proposed a level set-based methodology based on the concept of the phase field method, and obtained clear optimal configurations. This method has been applied to many problems, such as structural mechanics problems [30], thermal diffusive problems [31], electromagnetic problems [32], and fluid dynamics problems [33]. Furthermore, using the Tikhonov regularization method, this approach enables qualitative control of the geometric complexity of the optimal configurations, by setting appropriate values of a regularization parameter, which allows the design of high-performance structures that have a desired degree of structural complexity for ease of fabrication. In addition, this approach can easily implement a uniform cross-section surface constraint by using anisotropic variation of the regularization parameter, hence a three-dimensional optimal configuration with a uniform cross-sectional surface can be obtained.

In this paper, we present a level set-based topology optimization method for a thermal–fluid engineering application, to derive a highly efficient cooling device, and we control the geometric complexity of the optimal configuration to obtain an appropriately simple structure. The remainder of this paper is organized as follows. First, the governing equations in the coupled thermal–fluid problem are described and then we introduce the methodology for incorporating level set boundary expressions that enable the fluid and solid domains to be distinguished. Using this method, we formulate an optimization problem to maximize the heat exchange between a flow channel and a heated structure, using the governing equations for the thermal–fluid. Next, we construct an algorithm for the topology optimization method using the FEM. Last, we provide two- and three-dimensional numerical examples, to confirm the applicability of the optimization method for the design flow channel devices that provide high-performance cooling.

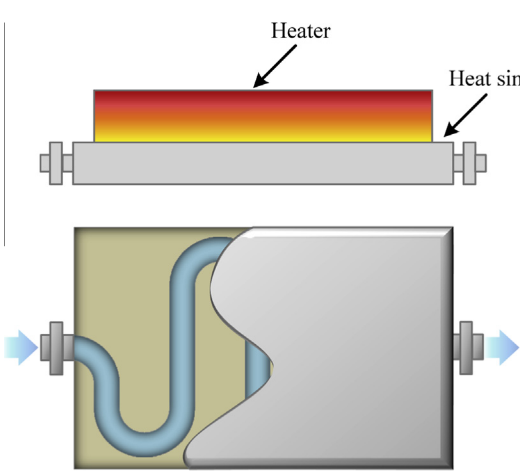

Fig. 1. Schematic of liquid-cooled type heat sink.

2. Formulations

2.1. Governing equations

In this study, we discuss internal flow channel problems that deal with an incompressible thermal–fluid in a steady-state. The formulation of the governing equations must therefore take into account the conservation of mass, momentum, and energy. The non-dimensional continuity, Navier–Stokes, and energy equations that govern the flow are given as follows:

Continuity equation :

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

Navier—Stokes equation :

$$(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2 \mathbf{u}, \tag{2}$$

Energy equation :

$$\mathrm{Re}\,\mathrm{Pr}(\mathbf{u} \cdot \nabla)T = \nabla^2 T, \tag{3}$$

where the Reynolds number Re, Prandtl number Pr, non-dimensional gradient operator ∇, and non-dimensional variables $\mathbf{u}$, $\mathbf{p}$, and T are defined as follows: