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Direct nanofluids configuration optimization based on the evolutionary topology optimization method

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ABSTRACT

Nanofluids performance counts on nanoparticle configuration. The evolutionary topology optimization algorithm is applied in this work for direct nanoparticle configuration optimization. The initial random distribution of nanoparticles inside base fluid is found to well simulate practical nanofluids. The optimized nanofluids configuration proves to be continuous strips assembled by nanoparticles with width comparable to size of nanoparticles and length comparable to size of heat-transferring system. System overall thermal resistance is significantly reduced by the optimized nanoparticle configuration. Future nanofluids should be fabricated with strip-shaped nanoparticles in order to perform better.

1. Introduction

The process of heat transfer appears in every situation involving energy exchange. Heat transfer enhancement has been always a vital issue for researchers. Many techniques including fluid vibration, fluid stirring, inner finned tubes, corrugated tubes and so on have been coined to try to fulfill this goal. Development of nanofluids is also one of these efforts continuing to draw attentions. Being a mixture of nano-sized particles and conventional heat-transferring fluid, nanofluids are manifested by many researches as having anomalously good thermal properties [1–6]. Also there are researches stating that there is no such anomalous enhancement of the effective thermal conductivity for nanofluids [7].

In our previous work efforts have been taken to improve the nanofluids configuration to achieve better system heat-transferring performance. Under the dispersed configuration of nanofluids (fine nanoparticles dispersed in base fluids), constructal nanoparticle volume fraction distributions can be obtained based on the variational method [8]. Thus system performance can be improved through designing nanoparticle volume fraction distributions inside nanofluids. As constructal theory says, flow possessing at least two regimes with different resistances develops visible structure from global objective [9]. We thus further investigate assembling nanoparticles together to form continuous high-conductivity structures to enhance system performance, which is termed as the blade configuration of nanofluids. Preconceived high-conductivity structures are tested for different systems and it is proved that even with rather simple high-conductivity structures the system performance can be significantly improved [10,11]. Results from many other researchers also verify that chain-shaped agglomerates of nanoparticles enhance performance of nanofluids [12,13]. To maximize the system performance, however, we should find a method which can lead us directly to the optimized nanoparticle structures.

The evolutionary topology optimization algorithm developed by Xie and Steven in 1993 has been generally utilized in many areas including material strength, heat conduction, elastic torsion, incompressible fluid flow, and so on [14–17]. It is based on the criterion controlled self-morphing of the system to achieve the final optimal configuration. In this work this method is employed to optimize the nanoparticle configuration directly. The criterion is taken to be the system thermal resistance which is the best indicator of nanofluids' heat-transferring ability. And reposition of nanoparticles is performed constantly until the system thermal resistance does not decrease any more.

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Nomenclature

A	area, m^2
k	thermal conductivity, $W/(m \cdot K)$
$\tilde{k}$	thermal conductivity ratio
L	nanoparticle size, nm
l	mean free path
n	normal vector
q'''	volumetric heat generation rate, W/m^3
R_o	radius, m
T	temperature, K
r, *varphi*	Cylindrical coordinates, m and rad
x, y	Cartesian coordinates, m

Greek symbols

ϕ	volume fraction

Subscripts

e	effective
f	base fluid material
lower	lower limit
max	maximum
p	nanoparticle material
upper	upper limit
0	heat sink index/conventional scale index

Superscripts

$\sim$	nondimensional variable index

2. Nanoparticle configuration optimization based on the evolutionary topology optimization algorithm

2.1. Problem description

To illustrate the specific procedures for optimizing nanoparticle configuration, two typical heat-conduction systems utilizing nanofluids as heat-transferring medium are considered. System (a) is a square domain with homogeneous and fixed volumetric heat generation q''' inside base fluid. The domain center serves as heat sink with a temperature of T_0 and all the domain peripheries are adiabatic. System (b) is a circular domain with central heat sink T_0 and adiabatic peripheries. Also there is homogeneous and fixed volumetric heat generation inside base fluid. Due to symmetry, one quarter of the domain is analyzed for both of the two systems, as shown in Fig. 1. During calculation, the central heat sinks for systems (a) and (b) are both approximated as two short peripheries (bold lines in Fig. 1) at center of the domain, with lengths of one twenty-fifth of their attaching lines. The total amount of nanoparticle material is fixed by the volume fraction ϕ which is defined as

$$\phi = \frac{volume\ of\ nanoparticle\ material}{system\ total\ volume} \tag{1}$$

Heat conduction in nanoscale is believed to be no longer Fourier-type as the memory effect and size effect become significant [18,19]. For our steady-state problems, the memory effect is not present. The size effect is accounted for by the effective thermal conductivity defined as a function of the ratio between the mean free path of heat carries and particle's nanoscale size:

$$k_p(L) = \frac{k_{p0}L^2}{2\pi^2 l^2}\left[\sqrt{1+4\left(\frac{\pi l}{L}\right)^2}-1\right] \tag{2}$$

where k_p represents thermal conductivity of nanoparticles, L is size of the nanoparticles, k_{p0} is the conventional-scale thermal conductivity of the nanoparticle material, and l is the mean free path of heat carries inside nanoparticle material. For system (a), the heat-conduction governing equations for nanoparticles and base fluid are

$$\frac{\partial}{\partial\tilde{x}}\left(\tilde{k}\frac{\partial\tilde{T}}{\partial\tilde{x}}\right)+\frac{\partial}{\partial\tilde{y}}\left(\tilde{k}\frac{\partial\tilde{T}}{\partial\tilde{y}}\right)=0 \tag{3}$$

and

$$\frac{\partial}{\partial\tilde{x}}\left(\frac{\partial\tilde{T}}{\partial\tilde{x}}\right)+\frac{\partial}{\partial\tilde{y}}\left(\frac{\partial\tilde{T}}{\partial\tilde{y}}\right)+1=0 \tag{4}$$

respectively, where the nondimensional variables are defined as

$$\tilde{T} = \frac{T-T_0}{q'''A/k_f} \tag{5}$$

$$(\tilde{x},\tilde{y},\tilde{n}) = \frac{(x,y,n)}{\sqrt{A}} \tag{6}$$

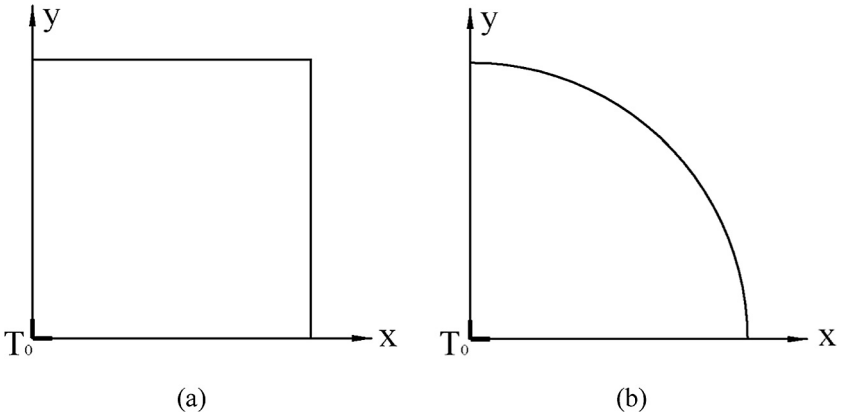

Fig. 1. The two heat-conduction systems considered for nanoparticle configuration optimization.