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Research Paper

Thermal contact theory for estimating the thermal conductivity of nanofluids and composite materials

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HIGHLIGHTS

- The popular models to predict the thermal conductivity of nanofluids and composite materials can be modeled using thermal resistance concept.
- The parallel and series thermal resistance models set the upper and lower limits of the effective thermal conductivity of the composite, respectively.
- The experimental data are within the range of predictions of the classical models.
- It is demonstrated that the shape (aspect ratio) and orientation of the discrete materials have a significant effect on the effective thermal conductivity.
- The results may explain the discrepancy in the published experimental data.

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ABSTRACT

Recently, extensive researches are going on the heat transfer enhancements of low thermal conductivity materials by adding a few percentage of high thermal conductivity materials, especially in the topic of the nanofluids and polymers. Also, metal meshes have been used in the thermal storage systems to enhancing the thermal conductivity of the systems. A few theories have been suggested on the heat transfer enhancement in nanofluids or composite materials. However, the discrepancies in the published experimental data are wide and results are not conclusive. In this work, the most popular models are discussed and critically analyzed. Also, a model is developed based on thermal resistance analysis and compared with those models. Furthermore, numerical analyses are performed to closely understand the effect of adding a few percentage of high thermal conductive material to a low thermal conductive material. The findings are very interesting, where more than 30% enhancements can be achieved if a small percentage of high thermal conductivity of material embedded in a low thermal conductivity materials, provided that the particles are long enough and align with the temperature gradient. However, if the particles align perpendicular to the temperature gradient, the heat transfer enhancement is insignificant. Hence, aspect ratio and orientation of the particles are the defining factors in heat transfer enhancement.

1. Introduction

Heat transfer enhancements have extensive applications in a wide spectrum of industries and application ranges from nano to macro scales. Especially, in electronic industry [1], where dense electronic devices extensively packed into a small volume and a major issue is how to dissipate the generated heat from those devices. Heat dissipation from smartphones needs a high thermal conductivity casing. Hence, the thermal conductivity of a polymer case can be enhanced by adding high thermal conductivity materials into the case. The thermal conductivity of the medium plays a major rule in conduction and convection mechanism, where the convection is a combined of conduction at the contact surface and advection mechanisms. In macro-scale, the thermal conductivity of a material is phenomenological property of the material. Extensive researches haven been done and going on in enhancing low thermal conductive materials (fluids and solids) by adding a few percentage of high thermal conductive materials into those of low thermal conductive materials. However, the experimental results of adding high thermal conductive materials (nano) into fluids are not conclusive. A group of researcher claims that adding a few percentage of highly conductive materials into a fluid enhances the effective thermal conductivity significantly, other's results do not show a significant enhancement and in some cases even the rate of heat transfer decreases. There are a few review papers on the topic of the nano-fluid [2–7]. The key conclusions of those review papers are that there is inconsistency in the published results and there is a need for more data and experimental

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Nomenclature

A	geometrical parameter
k	thermal conductivity
L	length
l	height
n	geometrical constant
T	temperature
S	geometrical parameter
Greek letters	
β	coefficient
ϕ	volumetric ratio
θ	angle defined after Eq. (14)
Subscript	
c	continuum medium
d	particle or discrete medium
ef	effective
f	fluid or the main medium
r	ratio of particle (discrete) to the continuum medium

works. However, the paper of a group of researchers from a few universities and from difference countries published a benchmark study on the thermal conductivity of nanofluids concluded that there is no anomalous enhancement of the thermal conductivity of nanofluids beyond the expectations [8].

The heat transfer enhancement is very important in a thermal storage system with charging and discharging processes. To enhance the rate of heat transfer and/or to shorten the charging and discharging process for phase change and/or sensible thermal storage tanks, it is suggested to use high thermal conductivity meshes or particles [9–12]. A few researchers used encapsulated phase change materials to enhance the thermal storage capacity. However, efficient utilizing meshes or particles on the heat transfer enhancement needs to understand the physics of the problem clearly. The present work shows that orientation of the meshes added to the thermal storage systems has significant effect on the efficiency of the systems.

Recently, the work of Mohamad [13] showed that the enhancing the thermal conductivity of a material by adding high thermal conductive materials is a strong function of the particle alignment with the temperature gradient direction. The finding may explain the discrepancy in the experimental results of nanofluid. However, it is difficult to align the particles in the desired direction, unless magnetic particles used with an external force. To further explore the topic extensive numerical analyses are carried out in this work and find that the aspect ratio (length/width) of the particles is also an important factor beside the particle orientation along the temperature gradient.

Historically, the work of Maxwell on the theory of the effective thermal conductivity of composite material was published in 1891 [14], which gives,

$$\frac{k_{ef}}{k_f} = 1 + \frac{3\varnothing(k_r - 1)}{\varnothing + 2 - (\varnothing - 1)k_r} \tag{1}$$

The Maxwell equation can be applied for spherical particles embedded in a medium. Later on, Hamilton and Crosser [15] modified Maxwell's equation by replacing factor 3 by a variable parameter, n, the sphericity, to account for the shape of the particle. For spherical particles n = 3 and for cylindrical particles n = 6. The Hamilton and Crosser's equation (HC) is,

$$\frac{k_{ef}}{k_f} = 1 + \frac{n\varnothing(k_r - 1)}{\varnothing + (n-1) - (\varnothing - 1)k_r} \tag{2}$$

In the limit, $k_r \gg 1$, the HC equation will be, $1 + n\phi/(\phi - 1)$, which is not a function of k_r. It should mention that the Maxwell and HC models are valid for a low concentration of nanoparticles.

However, the HC model does not account for the cylinder aspect ratio, length/diameter, nor to the cylinder orientation in the medium. There are a few other models to estimate the effective thermal conductivity developed by a few authors [16–20]. Recently, Khanafer and Vafai [21] develop a method for effective thermal conductivity as a function of volumetric ratio, particle diameter, temperature and viscosity. Moreover, Corcione [22] model included Reynolds and Prandtl numbers, which contradicts the definition of the thermal conductivity concept. To the author's understanding that the thermal conductivity is defined for stagnant media, which is different than the concept of the thermal dispersion. Interested readers may consult the mentioned review papers. Also, to the author's knowledge, none of the developed models account for the aspect ratio of the particles, except works of Nielsen [23,24]. However, no work mentioned on the effect of the particles orientation with respect to the temperature gradient in the media. The current work, shows the importance of these two parameters on the effective thermal conductivity of the composite media and/or nanofluids. Furthermore, all the mentioned models can be derived using the simple thermal resistance concept, as discussed in the following sections.

2. General discussion

We can identify two special cases for two-phase composite materials, series and parallel models. Those models define the lower and upper limits of adding high thermal conductivity materials (discrete) to a continuum media. Series model assumes that the two phases are separated and layered, where the one layer is on the top of the other year and oriented perpendicular to the temperature gradient. Hence, the thermal resistance analysis yields,

$$\frac{K_e}{K_c} = \frac{K_r}{\varnothing + (1 - \varnothing)K_r} \tag{3}$$

On the limit $K_r \gg 1$, the equation does not depend on the K_r, and ratio of the effective thermal conductivity to the continuum medium thermal conductivity becomes inversely proportional to $(1 - \phi)$, Fig. 1.

On the other hand, the parallel mode assumes that the two phases separated and layered, where the layers are parallel to each other and oriented along the temperature gradient. Hence, the thermal resistance analysis yields,

$$\frac{K_e}{K_c} = (1 - \varnothing) + \varnothing K_r \tag{4}$$

The effective thermal conductivity linearly increases with K_r, Fig. 1. Notice that the effect of the thermal contacts between the system and the heat source and the heat sink are neglected.