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Myth about nano-fluid heat transfer enhancement

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ABSTRACT

The paper examines a few claims about the merit of using nano-particles to enhance the rate of heat transfer. In the literature, a few mechanisms were put forward to explain the magic of enhancing the rate of heat transfer by many folds compared with a clear fluid by adding a few percentages of nano-particles to the working fluid. In this work, a few introduced mechanisms is examined in the light of classical physics of the thermal diffusion and the fluid mechanics. Yet, no one able to break those simple physics; therefore, they should be valid for particles floating in a fluid. The paper for the first time reports the effect of particle alignment with the direction of heat flow (temperature gradient) effects on the effective thermal conductivity, which is significant. Furthermore, forced and natural convections are examined based on the classical theory of heat transport. We demonstrated the reason of why the rate of heat transfer decreases by adding nano-particles for a fluid experiencing natural convection.

1. Introduction

Fluid diluted with nano-particles called nano-fluid. Extensive researches have been done on the topic of the rate of heat transfer enhancement with non-fluids [1,2]. Extensive efforts have been put to study all aspects of nanofluids, even nano-fluid flow in porous media (as nano particles smoothly pass through the tortuous paths without adsorbing by the surfaces of the solid!). Over 21,700 titles of nano-fluid results of Google's scholar search. However, the main conclusion of 110 papers reviews by Wang and Mujumdar [1] was the lack of agreement between experimental results published by different authors (in other words, no conclusion). Similar conclusion was drawn by a group of eleven authors from different schools (MIT, Boston, China and Korea) [3]. Yu et al. [4] compared published data of over 100 papers, by considering different aspects of nanofluids. The main conclusions were more data or research need to be done. However, the results reveal that there is a tendency on enhancement of the effective thermal conductivity. On the other hand, using nanofluid has many problems, such as agglomeration, settling and erosion. Another review published in 2010 by Godson et al. [5]. The authors remarked that nano-fluid has potential applications and rate of heat transfer enhancement is substantially higher that of pure fluid. However, more experimental data and theoretical analysis are needed. They also mentioned that many researchers indicated that nonfluid behave like pure fluid, i.e., no heat transfer enhancement. The conclusion of another review paper [6] is that the level of understanding and knowledge is still at the early stage and much research is necessary. Also, the mechanisms involved in the heat transport phenomena are still not fully understood. Another review paper by Sarkar [7] states almost the same conclusion as before. Extensive review of natural convection published by Haddad et al. [8]. They stated that natural convection heat transfer enhancement using the nanofluid is still controversial. Also, they stated that the most of the numerical results showed that nanofluids significantly improve the rate of heat transfer while experimental data showed that the presence of nano-particles deteriorates the heat transfer.

Controversial results were published on the topic, a few researchers claim that using a nanofluid enhances the rate of heat transfer drastically. On the other hand, a few authors stated that the effect of a nanofluid on the rate of heat transfer is not noticeable or even decreases. In physics, there is no magic and Aladdin magic lamp only in One Thousand and One Nights fairy tale story. In the history of science, there are cases that the people claim that can generate work or power without energy input (perpetual machines). Also, it is not far from us, scientists claimed that they could carry nuclear fusion at room temperature ((1989, Pons and Fleischmann's experiment)). Hundreds of papers piled in many reputable journals' editorial offices claiming that the authors achieved cold fusion in their labs. On the bright side, Nicolas Leonard Sadi Carnot in 1824 came with simple physics, which established the maximum theoretical efficiency of an engine. A simple equation that efficiency of any thermal engine cycle, regardless kind of the working fluid, should be less than 1 – Tc/Th, where Th and Tc are the heat source and sink temperatures,

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Nomenclature

A	area
c	specific heat
h	heat transfer coefficient
K	thermal conductivity
L	length
Nu	Nusselt number
Pr	Prandtl number
R	thermal resistance
Ra	Rayleigh number
T	temperature
t	time
r	particle radius
V	volume

Greek letters

α	thermal diffusivity
β	coefficient
ϕ	volumetric ratio
ρ	density
μ	viscosity

Subscript

ef	effective
f	fluid
n	nano-fluid
r	ratio of nano to fluid
s	surface

respectively. Till now, no one able to reach this solid ceiling regardless how complicated the system is. Then what is the relation of Carnot efficiency with nano-fluid? The fact comes soon. The researchers which claim that adding nanoparticles to a fluid enhances the rate of heat transfer by many folds attributes to a few reasons, enhance the effective thermal conductivity, Brownian motion, micro-convection, near field theory, etc. Except using radiation theory is not explored for nano-gases problem. Let us discuss a few claims based on simple physics.

2. Nano-fluid enhances the effective thermal conductivity

The highest theoretical thermal conductivity (Carnot problem) can be achieved by nano-particles if those particles form a continuous chain between heat source and sink, without any contact resistance. Assuming one-dimensional (1-D) heat conduction, the effective thermal resistance equal to,

$$\frac{1}{R_{ef}} = \frac{1}{R_f} + \frac{1}{R_n} \tag{1}$$

where $R_{ef} = \frac{L}{AK_{ef}}$, $R_f = \frac{L}{A_f K_f}$ and $R_n = \frac{L}{A_n K_n}$

Hence,

$$K_{ef} = \frac{A_n}{A} K_n + \frac{A_f}{A} K_f \tag{2}$$

Volume ratio of nano fluid is $\text{Ø} = \frac{V_n}{V} = \frac{A_n L}{AL} = \frac{A_n}{A}$ and $\frac{A_f}{A} = 1 - \text{Ø}$

Therefore the effective thermal conductivity of nano fluid is,

$$K_{ef} = \text{Ø} K_n + (1 - \text{Ø}) K_f \tag{3}$$

The above equation is the maximum theoretical limit for the effective thermal conductivity, where contact resistances between nano-particles themselves and between the chain and the heat source and sink boundaries are neglected. For instance, water thermal conductivity is about 0.6 W/m K, if 5% of copper nano particles of thermal conductivity of 400 W/m K is added to the water the maximum theoretical effective thermal conductivity will be 20.57 W/m K. This value is not reachable, because it is impossible to align all particles together and make a short chain between the heat and sink sources in a continuum medium. Besides, if the particles by some method align together the point contact resistance between them drastically increases the total thermal resistance. Moreover, the particle within a time oxides and degrades the effective thermal conductivity.

If the nano-particles chain does not reach the boundaries of the system, then there will be a fluid (continuum medium) layer thermal resistance, Fig. 1. Let us say that nano-particles made a chain of length βL, where β is less than one (degree of alignment). The thermal resistance analysis yields,

$$\frac{K_{ef}}{K_f} = 1 + \frac{\text{Ø}(K_r - 1)}{\beta - (\beta - 1)K_r} \tag{4}$$

where K_r is the ratio of the thermal conductivity of the nano-particles to the thermal conductivity of the fluid, $K_r = K_n/K_f$. Eq. (4) is similar to Maxwell equation (Eq. (7)). In the limit of $\beta = 1$, Eq. (3) is recovered. Also, in the limit that K_r becomes large (greater than say 100), the above equation will be insensitive to the K_r (see Fig. 1), and Eq. (4) can be reduced to,

$$\frac{K_{ef}}{K_f} = 1 + \frac{\text{Ø}}{(1 - \beta)} \tag{5}$$

For $\beta = 0.95$, i.e., 95% of the distance between boundaries is chained by nano-particles, and for 5% (by volume) of copper nano-particles dispersed in water, the effective thermal conductivity will be 1.9708 W/m K, which is about 3.28 times higher than the base fluid's thermal conductivity. If $\beta = 90\%$, then the effective thermal conductivity will be 1.4926 W/m K, which is about 2.487 times the base fluid thermal conductivity.

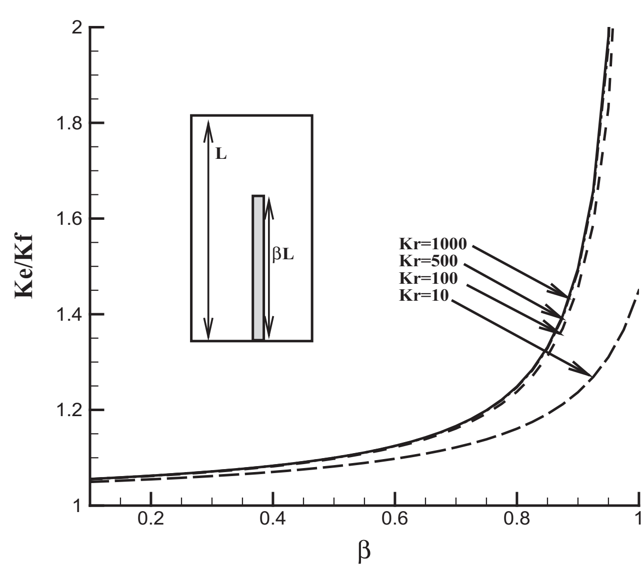

Fig. 1. The effect of alignment coefficient, *b*, on the ratio of effective thermal conductivity to base fluid conductivity for a range of thermal conductivity ratio (nano-particle to fluid thermal conductivity).