15 Analyzing Nanofluids Suspension Using the Porous Media Interface Heat Transfer Model

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CONTENTS

15.1 INTRODUCTION

The impressive heat transfer enhancement revealed experimentally in nanofluid suspensions by Eastman et al. (2001), Lee et al. (1999), and Choi et al. (2001) conflicts apparently with Maxwell's (1891) classical theory of estimating the effective thermal conductivity of suspensions, including higher-order corrections and other spherical particle geometries developed by Hamilton and Crosser (1962), Jeffrey (1973), Davis (1986), Lu and Lin (1996), and Bonnecaze and Brady (1990, 1991). Further attempts for independent confirmation of the experimental results showed conflicting outcomes with some experiments such as Das et al. (2003) and Li and Peterson (2006) confirming at least partially the results presented by Eastman et al. (2001), Lee et al. (1999), and Choi et al. (2001), while others such as Buongiorno and Venerus (2010) and Buongiorno et al. (2009) show in contrast results that are in agreement with Maxwell's (1891) effective medium theory. All these experiments were performed by using the transient hot wire (THW) experimental method. On the other hand, most experimental results that used optical methods, such as the *optical beam deflection* (Putnam et al., 2006), *all-optical thermal-lensing method* (Rusconi et al., 2006), and *forced Rayleigh scattering* (Venerus et al., 2006), did not reveal any thermal conductivity enhancement beyond what is predicted by the effective medium theory. A variety of possible reasons for the excessive values of the effective thermal conductivity obtained in some experiments have been investigated, but only few succeeded to show a viable explanation. Jang and Choi (2004) and Prasher et al. (2005) show that convection due to Brownian motion may explain the enhancement of the effective thermal conductivity. However, if indeed this is the case, it is difficult to explain why this enhancement of the effective thermal conductivity is selective and is not obtained in all nanofluid experiments. Alternatively, Vadasz et al. (2005) showed that hyperbolic heat conduction also provides a viable explanation for the latter, although their further research and comparison to later published experimental data presented by Vadasz and Govender (2010) lead them to discard this possibility.

Vadasz (2006) derived theoretically a model for the heat conduction mechanisms of nanofluid suspensions including the effect of the surface area-to-volume ratio of the suspended nanoparticles/nanotubes on the heat transfer. The theoretical model was shown to provide a viable explanation for the excessive values of the effective thermal conductivity obtained experimentally by Eastman et al. (2001), Lee et al. (1999), and Choi et al. (2001). The explanation is based on the fact that the THW experimental method used in all nanofluid suspensions experiments listed in the previous text needs a major correction factor when applied to nonhomogeneous systems. This time-dependent correction factor is of the same order of magnitude as the claimed enhancement of the effective thermal conductivity. However, no direct comparison to experiments was possible because the authors Eastman et al. (2001), Lee et al. (1999), and Choi et al. (2001) did not report so far their temperature readings as a function of time, which is the base upon which the effective thermal conductivity is being evaluated. Nevertheless, in a paper by Liu et al. (2006), the authors reveal three important new results that allow the comparison of Vadasz's (2006) theoretical model with experiments. The first important new result presented by Liu et al. (2006) is reflected in the fact that the value of *effective thermal conductivity* revealed experimentally by using the THW method is time dependent. The second new result is that the authors present graphically their time-dependent *effective thermal conductivity* for three specimens and therefore allow the comparison of their results with theoretical predictions of Vadasz (2011) showing a very good fit. The third new result is that their time-dependent *effective thermal conductivity* converges at steady state to values that according to our calculations confirm the validity of the classical Maxwell's theory (1891) and its extensions Hamilton and Crosser (1962), Jeffrey (1973), Davis (1986), Lu and Lin (1996), and Bonnecaze and Brady (1990, 1991).

The objective of this chapter is to review the controversial results and provide an explanation that settles the conflict between the apparent enhancement of the effective thermal conductivity in some experiments and the lack of enhancement in other experiments. Vadasz (2011) demonstrated that the transient heat conduction process in nanofluid suspensions produces results that fit well the experimental data (Liu et al., 2006) and validates Maxwell's (1891) method of estimating the effective thermal conductivity of suspensions. The theoretical results presented by Vadasz (2011) are combined with experimental data (Liu et al., 2006) to conclude that, while there is no improvement in the effective thermal conductivity of nanofluids beyond the Maxwell's (1891) effective medium theory, there is nevertheless substantial heat transfer augmentation via nanofins. The latter are formed as attachments on the hot wire surface by a mechanism that could be related to electrophoresis and/or thermophoresis, and therefore such attachments depend on the electrical current passing through the wire and varies therefore between different experiments. Also, since the effective thermal conductivity does not increase beyond the Maxwell's (1891) effective medium theory, the experiments using optical methods such as Putnam et al. (2006), Rusconi et al. (2006), and Venerus et al. (2006) are also consistent with this conclusion.

In the present chapter, a *contextual notation* is introduced to distinguish between dimensional and dimensionless variables and parameters. The *contextual notation* implies that an asterisk subscript is used to identify dimensional variables and parameters only when ambiguity may arise when the asterisk subscript is not used. For example, t_* is the dimensional time, while t is its corresponding dimensionless counterpart. However, k_f is the effective fluid phase thermal conductivity, a dimensional parameter that appears without an asterisk subscript without causing ambiguity.

15.2 PROBLEM FORMULATION

The theoretical model derived by Vadasz (2006) to investigate the transient heat conduction in a fluid containing suspended solid particles by considering phase-averaged equations will be presented only briefly without including the details. The phased-averaged equations are

$$\gamma_s \frac{\partial T_s}{\partial t_*} = h\left(T_f - T_s\right) \tag{15.1}$$