Significance of Thermophoresis (Soret Effect) in Heat Transfer Augmentation using Nanofluids

M. Eslamian*, M. Z. Saghir**

* Texas A&M University-Corpus Christi, TX, USA 78412, morteza.eslamian@tamucc.edu
**Ryerson University, Toronto, ON, Canada, zsaghir@ryerson.ca

ABSTRACT

This paper discusses the significance of thermophoresis or Soret effect in heat transfer augmentation in nanofluids. Heat transfer in natural convection and forced convection in large and small chnnels is critcally reviewed. It is concluded that the presence of thermophoresis as well as Brownian diffusion makes the flow heterogeneous. This causes slip between particles and the flow, and therefore heat transfer is augmented in almost all flow condtions and particle shapes.

Keywords: nanofluids, thermophoresis, Soret effect, Heat transfer augmentation, natural and forced convection

1 INTRODUCTION

Nanofluid is a term which is used for a fluid that contains suspended nanoparticles so as to alter the properties of the base fluid. Nanofluids have attracted tremendous research interest owing to the anomalous increase in their thermal conductivity compared to the base fluid. An increase in thermal conductivity of fluids with inclusion of nanoparticles is accompanied with an increase in the fluid viscosity as well, which is undesirable in heat transfer applications. An immediate question here is that whether nanofluids can be used to enhance heat transfer rate in various applications from miniature electronic chips and micro-channels, to large industrial heat exchangers? Also, whether an increase in the nanofluid pumping power compared to the base fluid can be compensated by heat transfer augmentation or not.

There is a difference in the response of nanofluids to a temperature gradient in the natural convection in a cavity compared to the forced convection in a laminar or turbulent flow. In natural convection, thermal forces induced by a temperature gradient and Brownian motion affect the composition and heterogeneity of the mixture and the heat transfer coefficient; in forced convection, these small scale effects are less significant in the flow core and large scale effects such as eddies and fluid flow are more important. The force applied on nanoparticles because of a temperature gradient in the fluid is called the thermophoretic force and the phenomenon is called thermophoresis. Due to neglecting or inadequate inclusion of thermophoresis effect, experimental and theoretical studies in heat transfer augmentation in nanofluids are confusing and contradicting in several areas. In experimental studies, particularly in natural convection, lack of control on the size and uniformity of the suspended particles as well as particle agglomeration may lead to misleading results and conclusions. In forced convection, agglomeration is reduced due to the flow momentum. The overall observation is that heat transfer coefficient in forced convection of laminar and turbulent flow increases significantly compared to the base fluid, whereas in natural convection, the data are contradicting and the results are inconclusive. While the earlier measurements in natural convection showed a decrease in heat transfer rate in nanofluids, recent experimental and theoretical studies confirm minor increase in the heat transfer coefficient.

There are numerous papers on various aspects of nanofluids including their heat transfer characteristics. Below, we review the key papers as well as some recent works. A review of experimental methods and investigations is found in Ref. [1], and a short review of correlations for forced, natural, convection in microchannels, as well as pressure drop is found in Ref. [2]. While many researchers have studied the heat transfer characteristics of nanofluids in various flow arrangements, there are few papers that address the fundamental science behind it. Lack of theoretical explanations have resulted in contradicting, or redundant studies with misleading conclusions. The increase in heat transfer coefficient in nanofluids (to be discussed further) is only partially due to an increase in thermal conductivity, supported by the fact that the heat transfer correlations developed for base fluids such as the Dittus-Boelter's equation used with the properties of nanofluids, underestimate the heat transfer coefficient in nanofluids [3]. This is because the base fluid is homogenous, whereas the presence of nanoparticles in a nanofluid makes it heterogeneous for the entire flow field in natural convection in cavities, and in the boundary layers closed to the walls in forced convection in channels and tubes. Buongiorno [3] studied the relative effect of seven phenomena that cause a slip motion between the main fluid and nanoparticles. These effects include inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage, and gravity. These effects may potentially cause nanoparticle dispersion and slip with respect to the main flow. Based on a time scale analysis, it was concluded that only thermophoresis and Brownian diffusion can cause slip. Despite their importance both of these

effects have been neglected in many studies in nanofluids resulting in contracting and erroneous results and conclusions.

In another study, and in an attempt to explain discrepancies in the experimental data, Thajudeen and Johan Jr. [4] using Monte-Carlo simulation studied the effect of nanoparticle aggregation on heat transfer enhancement or deterioration in nanofluids. They generated four types of particle aggregates, two with linear/chain morphology and two with compact spherical shapes. Also, two metal-oxide and metal nanoparticle types were employed in their simulation. It was shown that depending on the aggregation and material type, heat transfer rate can be enhanced or deteriorated. In forced convection, while all experimental data predict an increase in the heat transfer coefficient, simulations predict a decrease in metal oxide nanoparticles if they are aggregated and have formed a chain. One explanation is that, in actual experiments, particles tend to coalesce and form ball- like aggregates, and it is unlikely that chain-like nanoparticle aggregate exist in a forced convection flow field. Momentum of the flow may result in the break down of such aggregates owing to their weak bonding. In natural convection, there is no agreement among various experimental studies (to be discussed later). While earlier studies predict a decrease in heat transfer coefficient, theoretical studies and some experimental data predict an increase. Thajudeen and Johan Jr. [4] simulations predict an increase in heat transfer coefficient for compact aggregates of metal oxides and a decrease in heat transfer coefficient for chain-like aggregates. Therefore, the discrepancy in experimental data may be due to insufficient or lack of control on particle aggregation. Their data also shows that if metal nanoparticles are used, heat transfer coefficient increases almost always and regardless of the aggregate type.

2 FORCED CONVECTION

Investigations in forced convections are either in laminar or turbulent flows. Most experimental and numerical results in forced convection indicate a significant increase in heat transfer rate, e.g. [5-7]. This enhancement effect increases with an increase in the particle volume fraction. On the other hand, compared to the base fluid, the viscosity of nanofluid increases, as well. He et al. [5] state that *at fixed Re number*, the pumping power only increases slightly. However, given that Re is proportional to the mass flow rate and inversely proportional to the fluid viscosity, an increase in viscosity of nanofluids has to be compensated by an increase in the mass flow rate to keep the flow Re number constant. An increase in mass flow rate would result in an increase in the pressure drop. Therefore, it seems that the results concerning the extent of a change in the pressure drop and pumping power in nanofluids are not conclusive yet.

Numerical and theoretical works on forced convection in conventional and micro-channels are abundant, e.g. [8-16]. The heat transfer characteristics in the entrance region defers from the fully-developed region. Thermophoresis effect, which is suggested to be responsible for heat transfer augmentation beyond the enhancement in thermal conductivity, has been considered only in some of these works. For instance, Tahir and Mital [11] used the correlation developed by McNub and Meisen [17] to account for thermophoresis, and the Stokes-Einstein formula for the Brownian diffusion. We have recently shown that the MacNub and Meisen formula [17] overestimates the thermophoresis effect [18]. Using the regression analysis on their numerical calculations, Tahir and Mital [11] developed a correlation for heat transfer coefficient augmentation of nanofluids with respect to water as a function of nanoparticle size, volume fraction, and Re number. Duangthongsuk and Wongwises [10] developed an analytical expression for the estimation of heat transfer coefficient in a forced convection laminar flow. In their model, Brownian diffusion is considered but thermophoresis is neglected. Their results overestimate the experimental data. In an experimental and numerical work, He et al. [5], studied forced convection of titania nanofluids in laminar flow in a mili-channel. In their numerical analysis, several effects such as thermophoresis was considered; however, the Talbot et al. [19] expression for thermophoretic force, which is applicable to gases only, was used to model thermophoresis of liquid nanofluids. A discrete phase modeling approach was used in their simulation. Both their experimental data and modeling results show an increase in the heat transfer coefficient in nanofluids, particularly in the entrance region.

Due to importance of heat transfer augmentation in electronic circuits, studies have been performed on the application of nanofluids in microchannels as well. In an experimental study [16], forced convection laminar flow of alumina nanoparticles in water-ethylene base fluid was studied. A significant increase in heat transfer coefficient and a minor increase in friction loss in rectangular microchannels was observed. In a similar study, Raisi et al. [8] performed a numerical analysis on forced convection in a laminar flow within microchannels, assuming a single fluid model combined with effective physical properties of nanofluids. In their analysis, slip and no-slip velocity boundary conditions were considered, as well as Brownian diffusion of nanoparticles. It was concluded that at high Re numbers in microchannels, the heat transfer rate increases as the slip velocity coefficient increases. Their results also shows an increase in heat transfer rate in nanofluids with respect to the base fluids for Re numbers of about 50 and higher for all particle volume fractions, but no augmentation for Re = 10. In another study, Mital [15] performed an analysis of heat transfer and pumping power in laminar flow of nanofluids in microchannels. That work started with a correlation for Nu number in channels using pure fluids and then was extended to nanofluids. Singh et

al. [14] studied the effect of thermophoresis on particle trajectory and sedimentation of nanoparticles in the flow passing through a microchannel, using a discrete phase model in the Fluent software. They showed that applying a temperature gradient across the walls of a channel can balance the effect of the gravitational force on nanoparticles, thus preventing particle sedimentation and trap within the channel. In their analysis, however, the Talbot et al. [19] expression was used, which is only valid for thermophoresis in gases and overestimates thermophoresis effect in liquids. In a similar study, flow and migration of alumina-water nanofluids in a channel was studied, considering all forces including thermophoresis; however, the Talbot expression was used again, which introduces errors to the calculations [13].

3 NATURAL CONVECTION

Natural convection in an enclosure can be also altered by adding nanoparticles to the base fluid. In natural convection, a temperature gradient is usually applied on two walls, either top-bottom horizontal walls or two side vertical walls. The walls may be inclined as well. The most widely studied configurations are enclosures heated from below (Rayleigh-Benard convection), and heated from one vertical side. There are many studies in natural convection in contradiction with one another. For instance, Glassl et al. [20], Elhajjar et al. [21], and Hwang et al. [22] conclude that the stability of the flow increases in the Rayleigh-Benard configuration, assuming that the Soret coefficient is positive, meaning that nanoparticles move toward the colder wall, whereas Kim et al. [23] and Tzou [24] conclude the opposite! The critical Ra number for a pure fluid is 1708, above which the destabilizing buoyancy forces due to the temperature gradient dominate the viscous forces and flow circulations and convection emerge in the enclosure. Experimental results of Wen and Ding [25] on titania/water nanofluid in a Rayleigh-Benard configuration indicate a reduction in heat transfer coefficient. While they tried to minimize particle aggregation in their experiments, the large particle sizes in the fluid indicated the presence of aggregates. Alumina and copper oxide/water nanofluids were used by Putra et al. [26] in natural convection in an enclosure heated from one side. Their experimental results also showed deterioration of heat transfer when nanofluids are used.

In theoretical analysis of natural convection in nanofluids, thermophoresis and Brownian diffusion play a key role in determining the level of heat transfer augmentation or deterioration. This is because these two effects make a nanofluid heterogeneous. Neglecting these effects, i.e. assuming that the nanofluid is homogenous introduces error in the simulation; then simulation may either predict an increase or decrease in heat transfer rate depending on what formula is used for the thermal conductivity and more importantly for the viscosity of the nanofluid [22]. Haddad et al. [27] numerically investigated natural convection of nanofluids in the Rayleigh-Benard problem with and without the effect of Brownian motion and thermophoresis. Without considering these two effects, the presence of nanoparticles makes the nanofluid more viscous, which results in predicting heat transfer deterioration, which is erroneous. When these two effects are considered, the fluid becomes heterogeneous, and heat transfer rate increases as a result of a slip velocity between the base fluid and the nanoparticles. Oueslati et al. [28, 29] numerically and analytically studied natural convection in an enclosure heated and cooled from vertical side walls, while the top and bottom walls were kept adiabatic. In their study, they found that if thermophoresis effect is considered, the flow becomes heterogeneous resulting in a heat transfer enhancement, while without the thermophoresis, the flow was homogeneous and even a decrease in heat transfer coefficient was observed in nanofluids compared to the base fluid. Abu-Nada and Oztop [30] numerically studied natural convection in an inclined enclosure heated from two opposing sides and although thermophoresis was neglected and flow was assumed homogenous, an increase in heat transfer coefficient of nanofluids was predicted compared to the base fluid. This might be due to the effect of inclination that modifies the nanofluid flow and circulation patterns compared to the base fluid. Using a single-phase homogenous model, Corcione [31] investigated heat transfer in a Rayleigh-Benard configuration. Although thermophoresis was neglected, a slight heat transfer enhancement was observed, perhaps due to the choice of correlations used for the thermal conductivity and viscosity of nanofluids. The extent of heat transfer enhancement compared to those investigations that considered the thermophoresis is much smaller in this case. Abu-Nada and Chamkha [32] numerically investigated natural convection in an enclosure heated and cooled from vertical sides using a single phase homogenous approach, i.e., neglecting thermophoresis. They obtained both heat transfer enhancement and deterioration, depending on the choice of the correlations.

Recently, Abouali and Ahmadi [33] performed a numerical analysis on natural convection in several enclosure configurations and compared their numerical results with results obtained from correlations prescribed for pure fluids. They concluded that there is no need for a separate numerical analysis for each configuration and pure-fluid correlation linked with nanofluid properties may be used to estimate the heat transfer coefficient. However, we note that in base fluid correlations flow is single phase and homogenous and the thermophoresis effect is irrelevant, whereas nanofluids are heterogeneous. Therefore, Abouali and Ahmadi results, which predict a decrease in heat transfer coefficient in natural convection, are erroneous. In another controversial study, Pakravan and Yaghoubi [34] performed an analysis on heat transfer in natural convection considering Soret and Brownian motion. Under the impression of experimental data of Putra et al.

[26] and Wen and Ding [25], which predict a decrease in heat transfer coefficient, in their analysis it was assumed that the Soret effect has a deteriorating effect in heat transfer; therefore they subtracted a term they derived for thermophoresis contribution from the general term for the Nu number of the base fluid. As a result, their model, predicts a decrease in heat transfer coefficient in nanofluids, which is against the recent findings.

4 CONCLUSION

The forgoing literature review reveals that heat transfer rate increases both in natural and forced convection, although the degree of enhancement and pressure drop depends on the type, shape, physical and surface properties and volume fraction of the added nanoparticles. It is also concluded that thermophoresis and Brownian diffusion play a key role for heat transfer enhancement in nanofluids, particularly in natural convection. In forced convection, thermophoresis is present in the boundary layers (adjacent to the wall surfaces) resulting in boundary layer destabilization and therefore heat transfer augmentation. In natural convection, thermodiffusion is present within the entire domain resulting in uneven and heterogeneous distribution of particles in the mixture. In other words, a change in the physical properties of nanofluids such as an increase in thermal conductivity is not the sole effect responsible for an increase in heat transfer coefficient; thermodiffusion (thermophoresis or Soret effect) and Brownian diffusion are important as well. Soret effect has been taken into account in only few nanofluids studies, such as [14, 27, 35], although its effect has been considered qualitatively assuming approximate values for the Soret or thermodiffusion coefficients. This is partly because of the lack of theoretical work on nanofluids as well as lack of experimental data or a reliable theory that can be used to estimate thermophoresis coefficient (mobility) in nanofluids. Using wrong or inaccurate values for thermophoresis coefficient may obscure, overestimate or underestimate its effect on heat transfer rate in nanofluids.

REFERENCES

1. S. Thomas, C. B. P. Sobhan, Nanoscale Research Letters, 6 (2011) 377.
2. J. Sarkar, Renewable and Sustainable Energy Reviews, 15 (2011) 3271-3277.
3. J. Buongiorno, J. of Heat Transfer, 128 (2006) 240-250.
4. T. Thajudeen, C. J. Hogan Jr., Journal of Nanoparticle Research, 13 (2011) 7099-7113.
5. Y. He, Y. Men, Y. Zhao, H. Lu, Y. Ding, Applied Thermal Engineering 29 (2009) 1965-1972.
6. Y. He, Y. Jin, H. Chen, Y. Ding, D. Cang, H. Lu, Int. J. of Heat and Mass Transfer 50 (2007) 2272–2281.
7. D. Kim, Y. Kwon, Y. Cho, C. Li, S. Cheong a, Y. Hwang, J. Lee, D. Hong, S. Moon, Current Applied Physics, 9 (2009) e119-e123.
8. A. Raisi, B. Ghasemi, S. M. Aminossadati, Numerical Heat Transfer, Part A 59 (2011) 114-129.
9. J. Bayat, A. H. Nikseresht, International Journal of Thermal Sciences, 60 (2012) 236-243.
10. W. Duangthongsuk, S. Wongwises, Int. J. of Heat and Mass Transfer, 55 (2012) 3138-3146.
11. S. Tahir, M. Mital, Applied Thermal Engineering, 39 (2012) 8-14.
12. J. P. Coleman, A.G. A. Nnanna, ASME 2011 Int. Congress & Exposition, IMECE2011-62957.
13. D. Wen, L. Zhang, Y. He, Heat and Mass Transfer, 45 (2009) 1061-1067.
14. S. Singh, A. Kumar, N. Sharma, Int. J. of Research in Eng. and Applied Sciences, 2 (2012) 1707-1718.
15. M. Mital, Ap. Thermal Eng., 50 (2013) 429-436.
16. J-Y. Jung, H-S Oh, H-Y. Kwak, Int. Journal of Heat and Mass Transfer, 52 (2009) 466-472.
17. G. S. MacNab, A. Meisen, Journal of Colloids and Interface Science 44 (1973) 339-346.
18. M. Eslamian, M. Z. Saghir, Under Review.
19. L. Talbot, R. K. Cheng, R. W. Schefer, D. R. Willis, Journal of Fluid Mechanics, 101 (1980) 737-758.
20. M. Glassl, M. Hilt, W. Zimmermann, Physical Review E 83 (2011) 046315.
21. B. Elhajjar, G. Bachir, et al., Comptes Rendus Mecanique, 338 (2010) 350-354.
22. K. S. Hwang, J-H Lee, S. P. Jang, In. Journal of Heat and Mass Transfer, 50 (2007) 4003-4010.
23. J. Kim, Y. T. Kang, C. K. Choi, International Journal of Refrigeration, 30 (2007) 323-328.
24. D. Y. Tzou, International Journal of Heat and Mass Transfer, 51 (2008) 2967-2979.
25. D. Wen, Y. Ding, IEEE Transactions on Nanotechnology, 5 (2006) 220-227.
26. N. Putra, W. Roetzel, S. K. Das, Heat and Mass Transfer, 39 (2003) 775-784.
27. Z. Haddad, E. Abu-Nada, H. F. Oztop, A. Mataoui, Int. J. of Thermal Sciences, 57 (2012) 152-162.
28. F. S. Oueslati, R. Bennacer, Nanoscale Research Letters, 6 (2011) 222.
29. F. S. Oueslati, R. Bennacer, H. Sammouda, Prog. in Computational Fluid Dynamics, 12 (2012) 260-269.
30. E. Abu-Nada, H. F. Oztop, International Journal of Heat and Fluid Flow, 30 (2009) 669-678.
31. M. Corcione, International Journal of Heat and Fluid Flow, 32 (2011) 65-77.
32. E. Abu-Nada, A. J. Chamkha, International Journal of Thermal Sciences, 49 (2010) 2339-2352.
33. O. Abouali, G. Ahmadi, Applied Thermal Engineering, 36 (2012) 1-13.
34. H. A. Pakravan, M. Yaghoubi, International Journal of Thermal Sciences, 50 (2011) 394-402.
35. R. Savino, D. Paterna, Physics of Fluids 20 (2008) 017101.