Convection Heat Transfer in Nanofluids

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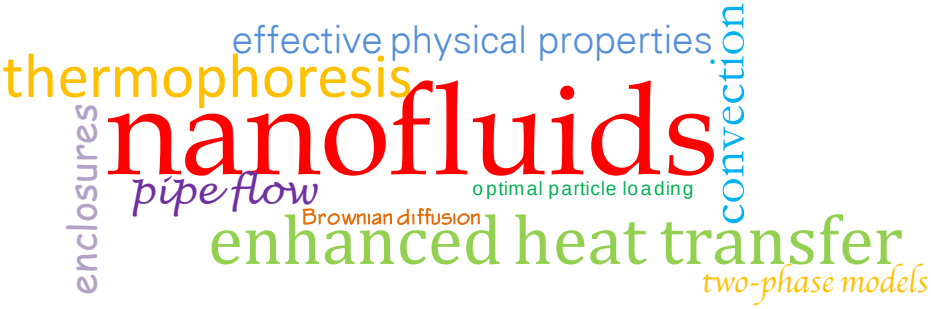

Effective cooling is one of the top challenges that high-tech manufacturing companies are continuously called to face in order to assure the reliability of their products, which justifies the considerable research effort dedicated to the development of advanced methods for heat transfer enhancement.

An important contribution to the cooling issue may derive by the replacement of traditional heat transfer fluids with colloidal nanoparticle suspensions, called nanofluids, whose thermal conductivity has been shown to be higher than that of the corresponding pure base liquid. This is the reason why, since their introduction, nanofluids have attracted the attention of the heat transfer community.

However, it must be pointed out that the thermal conductivity increase consequent to the dispersion of a given amount of nanoparticles into a base liquid is accompanied by a contemporary growth of the dynamic viscosity, which may represent a serious limitation to the energetic performance of nanofluids, either in terms of a drastic fluid motion decrease in natural convection situations, or in terms of an exaggerated pressure drop increase in forced convection applications.

Accordingly, the possibility of accurately evaluating the thermal conductivity and dynamic viscosity of nanoparticle suspensions seems crucial to establish if their use is beneficial with respect to the pure liquid. Unfortunately, the equations originally developed for composites and mixtures with micro- and milli-sized inclusions tend to underpredict such physical properties of nanofluids, mainly because they account only for the nanoparticle concentration effect, as is for example the case of the Maxwell and Brinkmann equations. Indeed, new theoretical and empirical models have been recently introduced, yet a wide number of them either fail in predicting the nanofluid thermo-mechanical properties or have very restricted ranges of applicability, which limits the reliability of most published numerical data.

Moreover, not always nanofluids can be studied using the so-called homogeneous or single-phase approach assuming that the solid and liquid phases are in local thermal and hydrodynamic equilibrium. In fact, such an approach cannot take into account the effects of the slip motion occurring between nanoparticles and base liquid, whose consequent non-uniform distribution of the solid phase throughout the liquid, mainly owing to Brownian diffusion and thermophoresis, can non-negligibly affect the heat and momentum transfer. Hence, the correct evaluation of the coefficients

of Brownian and thermophoretic diffusion is fundamental to decide about the advantage of using a nanofluid instead of the pure base liquid. On the other hand, the relationships available in the specialized literature for the calculation of the coefficient of thermophoretic diffusion seem to give underestimated values when applied to nanofluids.

Framed in this general background, we have performed and are currently carrying out researches on the main topics illustrated below.

- We have developed correlating equations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids, as well as the coefficient of thermophoretic diffusion of the suspended nanoparticles, that, satisfactorily matching a wide number of experimental data readily available in the literature, can be usefully employed for thermal engineering tasks. The good degree of agreement of these equations with a number of relations from other authors and experimental data different from those used in generating them gives further strength to their applicability.

- We have studied and are currently studying laminar and turbulent pipe flow of nanofluids. In this connection, it is worth emphasizing that almost all the experimental and numerical studies performed in this field by other research teams have reached the common conclusion that nanofluids offer better thermal performance than the corresponding base liquid at same Reynolds number, and that the heat transfer rate increases with increasing the concentration of the suspended nanoparticles. Actually, since the cited increase of the effective dynamic viscosity may imply an excessive increase in pressure drop, which may result in an exaggerated pumping power requirement, the merits of nanofluids in pipe flow applications are investigated in terms of global energetic performance, rather than simply in terms of the heat transfer enhancement. Indeed, this overall point of view seems to be of absolute relevance when the availability of electric energy for pumping purposes is reduced or in case of battery-operated pumps. Interestingly, if such an approach is followed, an optimal particle loading can be determined. Two different options are possible. The first option aims at determining how much the heat transfer rate changes as the concentration of the suspended nanoparticles is increased, keeping constant the pumping power. The second option has the scope to evaluate in what measure the pumping power changes with increasing the nanoparticle concentration, for an assigned heat transfer rate. Obviously, the addition of nanoparticles to the base liquid has to be considered as advantageous in all those cases in which either a heat transfer enhancement occurs at a fixed cost of operation or a lower amount of power is dissipated in friction at same thermal performance.

- We have devoted and are still devoting a great deal of attention to the study of natural convection, especially in enclosed spaces. In fact, although buoyancy-driven convection is the heat removal strategy often preferred by thermal engineers when a small power consumption, a negligible operating noise and a high reliability of the system are fundamental concerns, the number of papers available in the open literature on natural convection of nanofluids in enclosed spaces is not so high. Moreover, the main achievement of the relatively few experimental works dealing with the performance of differentially-heated enclosures is that the the addition of nanoparticles to a pure liquid is basically detrimental. Conversely, most of the numerical studies show contradictory results, which, as said, other than to an erroneous evaluation of the nanofluid physical properties, can be ascribed to the use of the single-phase approach or a two-phase approach in which the role of thermophoresis is underestimated. Therefore, we recently developed and validated a two-phase mixture model accounting for the effects of Brownian diffusion and thermophoresis as primary slip mechanisms between the solid and liquid phases, which incorporates the three mentioned empirical equations proposed for the evaluation of the effective thermal conductivity, the effective dynamic viscosity, and the coefficient of thermophoretic diffusion, in order to investigate the main features of the behavior of nanofluids in natural convection enclosed flows, and determine, for any analyzed configuration, the possible existence of an optimal particle loading as well as the rise of periodic heat transfer consequent to the overal motion of the suspended solid phase in the direction from hot to cold.

The main results of our studies are thoroughly discussed in the following scientific works:

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3) M. Corcione, Empirical correlating equations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids, Energy Conv. Manag. 52 (2011) 789-793.
4) M. Corcione, Optimal formulation of nanofluids for maximum free convection heat transfer from horizontal isothermal cylinders, Fluid Dynam. Mater. Process. 7 (2011) 175-199.
5) M. Cianfrini, M. Corcione, A. Quintino, Natural convection heat transfer of nanofluids in annular spaces between horizontal concentric cylinders, Appl. Therm. Eng. 31 (2011) 4055-4063.
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