ISSN: 0975-766X
CODEN: IJPTFI
Available Online through
Review Article
www.ijptonline.com

A REVIEW ON SOME THEORETICAL AND EXPERIMENTAL INVESTIGATIONS ON NANOFLUIDS

N.Sandeep[1*], B. Rushi Kumar[2*], R.Vijayaragavan[3*]
[1,2] Department of Mathematics, VIT University, Vellore-632014, Tamil Nadu, India.
[3]Department of Mathematics, Thiruvalluvar University, Vellore-632 115, India.
Email: dr.nsrh@gmail.com

Received on 23-03-2016 *Accepted on: 10-05-2016*

Abstract:

Past few decades, nanotechnology plays an important role to overcome the usage of traditional materials by improving the multifunctional material complex models. In the last two decades, the researchers have shown a keen interest on developing the complex models on nanofluids by considering the different particles or shapes or sizes with different designs. This review summarizes the theoretical and experimental investigations and developments in nanofluids

Keywords: Convection, Nanofluids, Nano particles, Heat transfer, MHD.

Introduction:

Nanofluid is not only the mixture of liquid-solid alloys. It is also having some special characteristics like stable suspension, durability and collection of particles. Nanofluids are the suspensions of the nano meter sized metallic or nonmetallic powders into base fluids. Fig.1 shows the pictorial presentation of the preparation of a nanofluid and cross section of nanofluid structure consisting of nano particles.

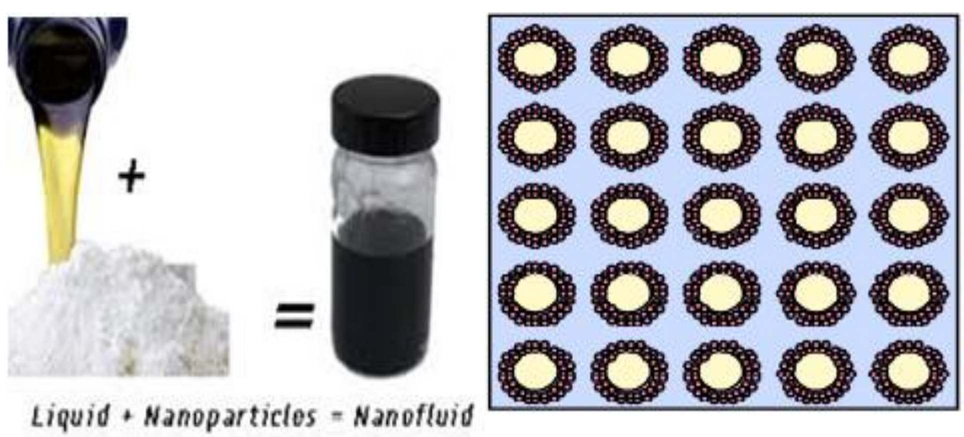

Fig.1 Preparation of nanofluid and its structure.

Convectional base fluids contain mm or micro meter sized particles. Due to this reason, the thermal conductivity of the convectional base fluids has inherently poor while compared with the solids. The suspension of nano powders into convectional base fluids helps to enhance the heat transfer rate. Table 1 depicts the materials for base fluids and nano particles.

Table.1: Materials for base fluids and nano particles.

Base Fluids	Nanoparticles material
Water	Oxide Ceramics - CuO, Al_2O_3,ZrO_2,TiO_2
Ethylene or try-ethylene glycols	Metals – A*l*, Cu, Zn, Ag
Polymer solutions	Nitrides – A*l*N, SiN
Bio fluids	Metal Carbides – SiC
Oil and other lubricants	Non-metals – Graphite , carbon nanotubes
Other common fluids	Phase change materials and Functionalized nano particles

Around 120 years ago, Maxwell [1] was the first person who discussed about the suspension of the particles into the liquids. He suspended the large size and high density particles into base fluids. Due to the stability variations in the suspension, there exists an erosion and additional flow resistance. This fails to prevent the solid particles from the suspension. Further in 1915, Ostwald [2] was the first person who discussed about the properties of nano particles including its shape, size and colour. The next generation of heat transfer in fluids suspended by particles was started with Choi [3] in Argonne National Laboratory, U.S.A. He suspended nano meter sized particles into convectional base fluids and named it as “Nanofluid”. He observed a significant enhancement in the heat transfer performance due to the suspension of the nano particles into base fluid. He also observed the increase in the stability of suspensions. Due to the fascinating thermal characteristics of nanofluids, this research has attracted a vast interest from the researchers worldwide. Lu and Lin [4] extended the basic model of Maxwell [1] by considering the spheroidal suspensions into the convectional flows and observed a rise in the heat transfer performance of the combined fluid. By using Boltzmann model Chen [5] observed depreciation in conductivity of nanofluid for nonlocal conduction and concluded that Boltzmann model fails to observe the enhancement in nanofluid conduction. In continuation of this Artus [6] studied the measurement of heat conduction by considering the prophoritic paste with heat sink.

Eastman et al. [7] investigated the heat transfer characteristics of nanofluids and found that the heat transfer enhancement in nanofluid is due to the larger surface area of nano particles. They also proved that there is 60% enhancement in thermal conductivity of water based nanofluid with the suspension of 5% volume of CuO nano particles. In continuation of this study Wagener et al. [8] developed a direct condensation process. Pak and Cho [9] investigated the heat transfer characteristics of magnetohydrodynamic flows immersed with spherical shaped metallic oxide Al_2O_3 and TiO_2 nano particles and found 30% heat transfer enhancement in nanofluid while compared with the base fluid. The basic principles of gas-solid interaction flows were discussed by Fan and Zhu [10]. Lee et al. [11] proposed a new concept for measuring the thermal conductivity of the convectional base fluids embedded with the oxide nano particles and found a significant increase in the heat transfer rate of the mixed fluid. With the extension of the above work, Wang et al. [12] investigated the thermal conductivity of the nanofluid by considering the ethylene glycol based copper oxide nano particles and found a noticeable enhancement in the heat transfer rate of a nanofluid. Whitaker [13] proposed a new method for investigating the volume averaging of the nanofluids. Fig.2 displays the power density of the nanofluids and water. It is clear that the nano fluids have high power density while compared with the water.

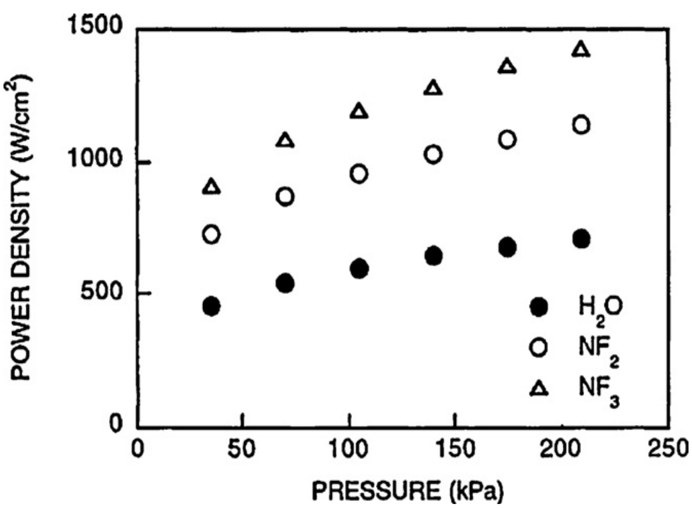

Fig.2 Power density with pressure for water and nanofluids [39]

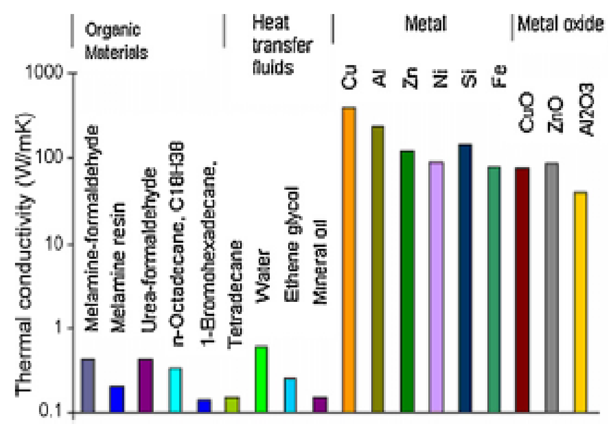

Fig.3 Thermal conductivity of some typical materials and base fluids [40]

For filling the gap between the results of theoretical and experimental data Eastman et al. [14] presented the thermal properties of the nano structured materials. Rise in the heat transfer coefficient also enhances the heat transfer rate. To enhance the heat transfer coefficient there is a need of adding the solid particles to the liquid coolants. The enhancement in the heat transfer rate due to the addition of nano meter sized particles was clearly described by Xuan and Roetzel [15]. With this inspiration Xuan and Li [16] analyzed the heat transfer characteristics of nanofluids and found a good enhancement in the heat transfer rate of nanofluid. High thermal conductivity of the nano tubes by considering the carbon and copper nano tubes were experimentally investigated by Berber et al. [17]. Eastman et al. [18] studied the heat transfer characteristics of the copper nano particles embedded ethylene glycol based nano fluid and found a gradual enhancement in the heat transfer rate of the mixed fluid. In continuation of the above work Choi et al. [19] analyzed the heat transfer characteristics of the nanofluid by considering the different types of nano fluids and found a large improvement in effective thermal conductivity of the fluids containing metallic nano particles. Fig.3 displays the thermal conductivity of some typical materials and base fluids.

The researchers [20-23] analyzed the heat transfer characteristics of nanofluid embedded with the alumina, silicon and copper oxide nano particles and found that copper oxide mixed nanofluid is effectively enhances the heat transfer rate while compared with the other two nanofluids. The pool boiling and colloidal suspensions of various nanofluids by considering the different nano particles were discussed by the researchers [24-27]. Faulkner et al. [28] studied the forced convection flow of a nanofluid and concluded that the heat transfer enhancement in the forced convection flow of a nanofluid is comparatively better than the heat transfer enhancement in the free convection flow of a nanofluid. The researchers [29-30] experimentally investigated the heat transfer in nanofluids at the entrance region and inside the hydraulic diameter flat tube. To enhance the heat transfer rate of nanofluids, the researchers [31-32] analyzed the heat transfer rate of nanofluid by considering the flow through carbon nano tubes and flow through the rotary blade coupling. In addition with this, the researchers [33-34] proved that the shape of the nano particle and Brownian motion effect also plays major role while improving the heat transfer rate of the nano fluid. The enhanced heat transfer in TiO_2-water, Fe-water and Al_2O_3-water nanofluids was discussed by the researchers [35-40]. Fig.4 depicts the rate of heat transfer against the Reynolds number for laminar and turbulent flows. It is evident that the heat transfer rate in Al_2O_3-water nanofluid is highly significant in laminar flows. But Cu-water nanofluids are effectively enhances the heat transfer rate for turbulent flows.

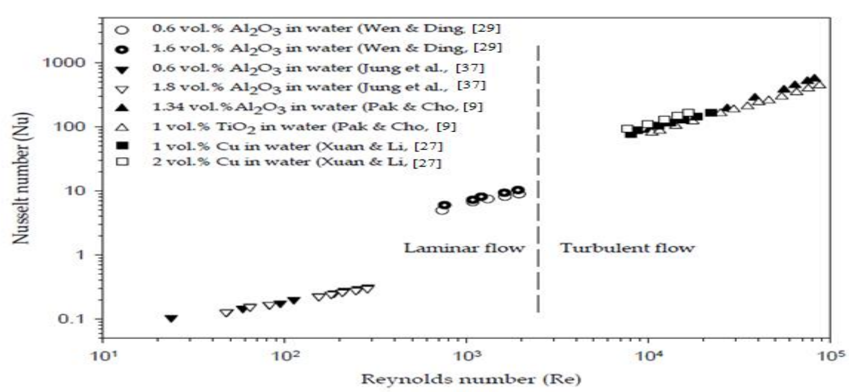

Fig.4 Convective heat transfer in nanofluids from various groups.

Applications:

Now a days the development in technology found in many areas like microelectronics, manufacturing and transportation, and has created a lot of ideas that have wide ranging influence on many problems facing today's scientific world. However, there are many factors involves in further development in these areas, one of the big challenge is the rapidly cool the devices being used. Cooling is very important for the reliability of new products. The demand for efficient cooling devices has increasing dramatically in the last few decades. Consequently, more companies are started to invest the more capital into the research for finding the efficient heat transfer processes.

In 1996, for cooling the microchannel heat exchangers Lee and Choi [41] used the nanofluid as coolant. They found a gradual enhancement in the cooling rates while compared with the general base fluids like water, ethylene, oil etc. Finally, they concluded that the increase in cooling rate is due to the suppression or mixing of the nano particles. Nanofluids are also plays a key role in biological applications such as X-ray, DNA, RNA and fluids contained in nano pores etc. A clear description on biological applications of nanofluids was presented by [42, 43]

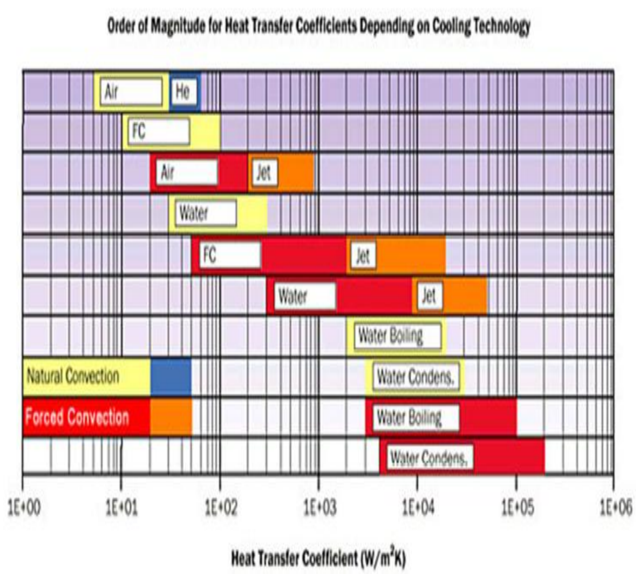

Fig.5 Heat transfer coefficients with different cooling technologies and fluids [44]

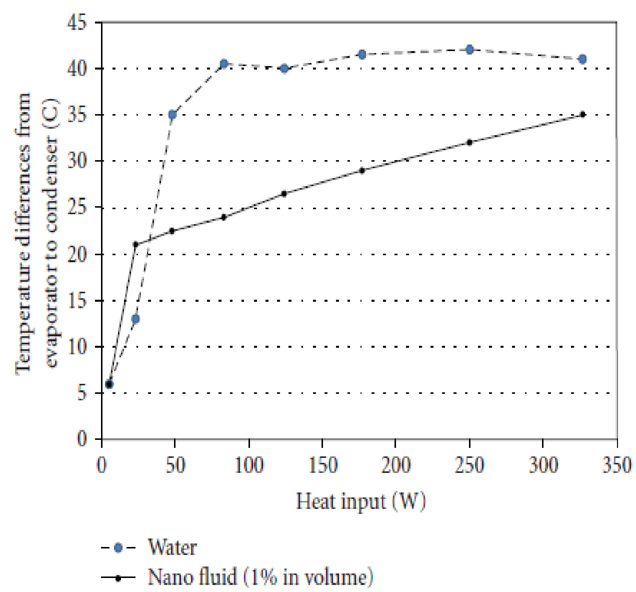

Fig.6 Nanofluid heat transfer capability [45]

Fig.5 illustrates the heat transfer coefficients with different cooling technologies and fluids. Sometimes heat source demands higher coefficients of heat transfer to fulfill the required cooling levels. In such situations free or forced convections plays a major role in cooling the devices. To enhance the heat transfer coefficient, different fluids have the different heat transfer properties. Based on the heat transfer coefficient levels of the base fluids, suitable nano mixtures helps to further enhancement of the heat transfer coefficient levels and it can be applicable in many engineering and industrial sectors. Fig.6 shows the heat transfer capacity of nanofluid at different temperatures. It is clear that nanofluid have a good thermal conductivity at lower temperatures also. It is also noticed a huge temperature difference of the water from nanofluid. It is evident to mention that with an increase of 1% volume fraction we have noticed a significant enhancement in heat transfer. So, increasing in the volume fraction of nano particles boost up the temperature profiles of the nanofluid. This is very useful for the manufacturing industries and engineering.

Variable viscosity and thermal conductivity of alumina-water nanofluid on heat transfer in free convective nanofluid was studied by Abu-nada [58]. The researchers [59-63] studied the convective heat transfer in free and forced convective nanofluid flows by considering laminar and turbulent models. Enhanced convective heat transfer using graphene dispersed nanofluids was illustrated by [64]. Numerical investigation of single phase forced convection heat transfer characteristics of nanofluid in a double-tube counter flow heat exchanger was numerically studied by [65]. Numerical investigation of convective heat transfer of nanofluids under a laminar flow regime was presented by [66]. The researchers [67, 68] presented a review on the convective heat transfer in nanofluids. A review of boiling and convective heat transfer with nanofluids was studied by [69]. , Numerical study of heat transfer enhancement in mixed convection flow along a vertical plate with heat source / sink utilizing nanofluid was studied by [70]. Experimental investigation of forced convective heat transfer coefficient in nanofluids was numerically investigated by the authors [71, 72].

Table.2: Summary of the experimental studies on thermal conductivity of nanofluids.

Authors	Size of the particles(nm)	Nanoparticles & Base Fluid	Observations/Findings
Lee et al. [11]	24.4, 38.4/ 18.6, 23.6	Al_2O_3/CuO+ Water/EG	4% volume of CuO+EG mixture 20% enhancement
Das et al. [38]	38.4/28.6	Al_2O_3/CuO+ Water	At 21^0C to 52^0C the conductivity is increased 2-4 times
Eastman et al. [7]	33/36/18	Al_2O_3/CuO/Cu+ Water/HE-200oil	5% volume of CuO in water 60% enhancement
Wang et al. [12]	28/23	Al_2O_3/CuO+Water/EG/PO/EO	3% volume of Al_2O_3+water mixture 12% enhancement
Xuan & Li [16]	100	Cu+water/Oil	successful suspension of relatively big metallic nanoparticles

Murshed et al.[35]	∅10□40,∅15	TiO_2/DW	33% & 30% enhancement at 5 vol % for ∅10□40 & ∅15
Xie et al. [20]	∅26,600	SiC+water/EG	15.8% enhancement at 4.2% vol for ∅26 SiC-Water & 22.9% at 4% vol for ∅600 SiC-Water
Hong et al. [36]	10	Fe+EG	18% enhancement for 0.55% vol Fe+EG mixture nanofluid
Liu et al. [31]	∅20-30	CNTs+EG/EO	12.4% for EG at 1% vol, 30% for EO at 2% vol

Table.3: Summary of the theoretical studies on thermal conductivity of nanofluids.

Authors	Mathematical Formula for thermal conductivity $\left(\frac{k_{nf}}{k_f}\right)$
Maxwell[17]	$\frac{k_p+2k_f-2\phi(k_f-k_p)}{k_p+2k_f+\phi(k_f-k_p)}$
Hamilton and Crosser[18]	$\frac{k_p+(n-1)k_f-(n-1)\phi(k_f-k_p)}{k_p+(n-1)k_f+\phi(k_f-k_p)}$
Bruggemen[19]	$\frac{1}{4}\left[(3\phi-1)\frac{k_p}{k_f}+(2-3\phi)+\frac{1}{4}\sqrt{\Delta}\right]$
Wasp [20]	$\frac{k_p+2k_f-2\phi(k_f-k_p)}{k_p+2k_f+\phi(k_f-k_p)}$
Jeffrey [51]	$1+3\left(\frac{k_p/k_f-1}{k_p/k_f+1}\right)\phi+\left(3\left(\frac{k_p/k_f-1}{k_p/k_f+1}\right)^2+\frac{3}{4}\left(\frac{k_p/k_f-1}{k_p/k_f+1}\right)^2+....\right)\phi^2$
Davis[52]	$1+\left(\frac{3\left(k_p/k_f-1\right)\phi}{(k_p/k_f+2)-(k_p/k_f-1)\phi}\right)(\phi+f(k_p/k_f)\phi^2)$
Lu and Lin [53]	$\frac{k_{nf}}{k_f}=1+(k_p/k_f)\phi+b\phi^2$
Yu and Choi [54]	$\frac{k_{nf}}{k_f}=\frac{k_p+2k_f-2\phi(k_f-k_p)(1+\beta)^3}{k_p+2k_f+\phi(k_f-k_p)(1+\beta)^3}$ s
Patel [55]	$\frac{k_{nf}}{k_f}=1+\frac{k_p d_f \phi}{k_f d_p(1-\phi)}\left[1+c\frac{2k_B T d_p}{\pi\alpha_f\mu_f d^2{}_p}\right]$

Koo and Kleinstreuer [56]	$\frac{k_{nf}}{k_f}=\frac{k_p+2k_f-2\phi(k_f-k_p)}{k_p+2k_f+\phi(k_f-k_p)}+5\times10^4\beta\phi\rho_f(C_p)_f\sqrt{\frac{k_BT}{d_p\rho_p}}f(T,\phi)$

Augmentation of free convective heat transfer nanofluids in the presence of magnetic field and uniform heat generation / absorption was discussed by [73]. Effect of thermophoresis and Brownian motion on magnetohydrodynamic flow of nanofluid was studied by [74]. The researchers [75-80] studied the heat transfer characteristics of MHD nanofluid flows by considering various geometries. Numerical investigation of MHD effects on alumina water nano nanofluid flow and heat transfer in a semi-annulus enclosure using LBM was studied by [81]. Heat and mass transfer of unsteady natural convection flow of some nanofluids past a vertical infinite flat plate with radiation effect was illustrated by [82]. Pressure drop and convective heat transfer of water and nanofluids in a double-pipe helical heat exchanger a double-pipe helical heat exchanger was studied by [83]. Heat transfer enhancement in MHD nanofluid flows was studied by the researchers [84-90]. The effect of radiation, chemical reaction, viscous dissipation, MHD, thermophoresis, Brownian motion and cross diffusion on nanofluid flows by considering the various geometries was numerically investigated by the researchers [91-110]. Very recently, the researchers [111-123] analyzed the heat and mass transfer characteristics of magnetohydrodynamic nanofluid flows.

Future scope:

Nanofluids, i.e., well-dispersed metallic nanoparticles at low volume fractions in liquids, enhance the thermal conductivity of the mixture’s over the convectional base-fluid values. Thus, they are potentially useful for advanced cooling of micro-systems. Still, key questions linger concerning the best nanoparticle-and-liquid pairing and conditioning, reliable measurements of achievable knf values, and easy-to-use, physically sound computer models which fully describe the particle dynamics and heat transfer of nanofluids. Keeping this into view authors may study the enhanced heat transfer of nanofluids by embedding the conducting dust particles of micrometer size.

References:

1. J.C. Maxwell, A Treatise on Electricity and Magnetism, second ed., Clarendon Press, Oxford, UK, 1881.
2. https://en.wikipedia.org/wiki/Wilhelm_Ostwald
3. S.U.S. Choi, Enhancing thermal conductivity of fluids with nano particles, Developments and Applications of Non-Newtonian Flows, FED-vol.231/MD-vol. 66,(1995), pp. 99–105.

4. S. Lu, H. Lin, Effective Conductivity of Composites Containing Aligned Spheroidal Inclusions of Finite Conductivity, Journal of Applied Physics, 79 (1996) 6761–6769.
5. G. Chen, Nonlocal and Non Equilibrium Heat Conduction in the Vicinity of Nano particles, Transactions of ASME, Journal of Heat Transfer, 118(3) (1996) 539–545.
6. R.G.C. Artus, Measurements of the Novel Thermal Conduction of a Prophoritic Heat Sink Paste, IEEE Transactions on Components, Packaging and Manufacturing—Part II, 19(3) (1996) 601-604.
7. J.A. Eastman, S.U.S. Choi, S. Li, L.J. Thompson, S. Lee, Enhanced thermal conductivity through the development of nanofluids, Materials Research Society Symposium Proceedings,457 (1997) 3–11.
8. M. Wagener, B.S. Murty, B. Gunther, in Nanocrystalline and Nanocomposite Materials II, edited by S. Komarnenl, J. C. Parker, and H. J. Wollenberger , Materials Research Society, 457 (1997) 149–154.
9. B. Pak, Y. Cho, Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles, Experimental Heat Transfer, 11(2) (1998) 151–170.
10. L.S.Fan and C.Zhu, Principle of Gas-Solid Flows, Cambridge University Press, Cambridge, UK, 1998.
11. S. Lee, S.U.S. Choi, S. Li, and J.A. Eastman, Measuring thermal conductivity of fluids containing oxide nano particles, Journal of Heat Transfer, 121(2) (1999)280–288.
12. X. Wang, X. Xu, and S. Choi, Thermal conductivity of nano particle-fluid mixture, Journal of Thermophysics and Heat Transfer, 13(4) (1999) 474–480.
13. S. Whitaker, The Method of Volume Averaging, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1999.
14. J.A. Eastman, S.U.S. Choi, S. Li, G. Soyez, L. J. Thompson, R.J. DiMelfi, Novel thermal properties of nanostructured materials, Materials Science Forum, 312–314 (1999) 629–634,.
15. Y.M. Xuan, W. Roetzel, Conceptions for heat transfer correlation of nanofluids. Int J Heat Mass Transfer, 43 (2000) 3701–7.
16. Y. Xuan, Q. Li, Heat transfer enhancement of nanofluids, International Journal Heat Fluid Flow 21 (2000) 58–64.
17. S. Berber, Y.K. Kwon, D. Tomanek, Unusually high thermal conductivity of carbon nanotubes, Physical Review Letters, 84, (2000) 4613-4616.

18. J.A.Eastman, S.U.S Choi, S .Li, W. Yu, L.J. Thompson. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticle. Appl. Phys. Lett. 78 (2001) 718–20.
19. S.U.S Choi, Z.G. Zhang, W. Yu, F.E. Lockwood, E.A.Grulke,Anomalous thermal conductivity enhancement in nanotube suspensions, Appl Phys Lett,79(14) (2001) 2252–4.
20. H. Xie, J. Wang, T. Xi, Y. Liu, F. Ai, Q. Wu, Thermal conductivity enhancement of suspensions containing nanosized alumina particles, Journal of Applied Physics, 91(7) (2002) 4568–4572.
21. H. Xie, J. Wang, T. Xi, Y. Liu, Thermal conductivity of suspensions containing nanosized SiC particles, International Journal of Thermophysics,23 (2) (2002) 571–580.
22. J.M. Li, Z.L. Li, B.X. Wang, Experimental viscosity measurements for copper oxide nanoparticle suspensions, Tsinghua Sci. Tech. 7 (2) (2002) 198–201.
23. P. Keblinski, S.R. Phillpot, S.U.S. Choi, J.A. Eastman, Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids), International Journal of Heat and Mass Transfer, 45 (2002) 855–863.
24. S. K. Das, N. Putra, W. Roetzel, Pool boiling characteristics of nano-fluids, International Journal of Heat and Mass Transfer, 46 (2003a) 851–862.
25. S. K. Das, N. Putra, W. Roetzel, Pool boiling of nano-fluids on horizontal narrow tubes. International Journal of Multiphase Flow, 29 (2003b) 1237–1247.
26. W. J. Tseng, K. C. Lin, Rheology and colloidal structure of aqueous TiO2 nano particle suspensions, Materials Science and Engineering A, 355 (2003) 186–192.
27. Y. Xuan, Q. Li, Investigation on convective heat transfer and flow features of nanofluids, Journal of Heat Transfer, 125(1) (2003) 151-155.
28. D. Faulkner, D.R. Rector, J.J. Davison, She, Enhanced Heat Transfer through the Use of Nanofluids in Forced Convection, in Proceedings of ASME, Heat Transfer Division, (2004) 219 - 224.
29. D. Wen and Y. Ding, Experimental Investigation into Convective Heat Transfer of Nanofluids at the Entrance Region under Laminar Flow Conditions, International Journal Heat Mass Transfer, 47 (2004) 5181–5188.
30. Y. Xuan and Q. Li, Flow and Heat Transfer Performances of Nanofluids inside Small Hydraulic Diameter Flat Tube, Journal of Engineering Thermophysics, 25(2) (2004) 305-307.

31. M.S. Liu, M. C.C. Lin, I.T. Huang, C.C. Wang, Enhancement of thermal conductivity with carbon nanotube for nanofluids, International Communications in Heat and Mass Transfer, 32(9) (2005) 1202–1210.
32. S.C. Tzeng, C.W. Lin, K. D. Huang, Heat transfer enhancement of nanofluids in rotary blade coupling of four wheel-drive vehicles, Acta Mechanica, 179(1-2) (2005) 11–23.
33. C. H. Chon and K. D. Kihm, Thermal conductivity enhancement of nanofluids by Brownian motion, Journal of Heat Transfer, 127(8) (2005) 810.
34. C. H. Chon, K. D. Kihm, S. P. Lee, and S. Choi, Empirical correlation finding the role of temperature and particle size for nanofluid (Al2O3) thermal conductivity enhancement, Applied Physics Letters, 87(15) (2005) ID 153107, 3 pages.
35. S. M. S. Murshed, K. C. Leong, C. Yang, Enhanced thermal conductivity of TiO_2-water based nanofluids, Int. J. Thermal Sciences, 44 (4) (2005) 367-373.
36. T. K. Hong, H. S. Yang, C. J. Choi, Study of the enhanced thermal conductivity of Fe nanofluids, Journal of Applied Physics ,97(6) (2005) 1-4.
37. J. Y. Jung, H. S. Oh, H.Y. Kwak, Forced convective heat transfer of nanofluids in microchannels, Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Chicago.(2006).
38. S.K. Das, N. Putta, P. Thiesen,W. Roetzel, Temperature dependence of thermal conductivity enhancement for nanofluids, ASME J. Heat transfer 125(2003) 567-574.
39. S. Lee, S.U.S Choi, Application of metallic nano particle suspensions. ANL, 1997.
40. D.Wen, G.Lin, S.Vafaei, K.Zhang, Review of nanofluids for heat transfer applications, Particuology 7 (2009) 141–150.
41. S. Lee, S. Choi, Application of Metallic Nano particle Suspensions in Advanced Cooling Systems, Recent Advances in Solids/Structures and Application of Metallic Materials, L. Shinpyo, eds., PVP-Vol. 342/MDvol. 72, ASME, New York, (1996) 227–234.
42. L.A. Pozhar, Structure and Dynamics of Nanofluids, Theory and Simulations to Calculate Viscosity, Physical Review E, 61(2) (2000) 1432–1446.

43. C. J. Yu, A. G. Richter, A. Datta, , M. K. Durbin, P. Dutta, Molecular Layering in a Liquid on a Solid Substrate, An X-Ray Reflectivity Study, Physica B, 283 (2000) 27–31.
44. C. J. M. Lasance and R.E. Simons, Advances in high performance cooling for electronics, Electronics cooling, November 2005.
45. H. B. Ma, C.Wilson, B. Borgmeyer, et al., Effect of nanofluid on the heat transport capability in an oscillating heat pipe," Applied Physics Letters, vol. 88, no. 14, Article ID 143116, 3pages, 2006.
46. H. B. Ma, C. Wilson, Q. Yu, K. Park, U. S. Choi, and M.Tirumala, An experimental investigation of heat transport capability in a nanofluid oscillating heat pipe, Journal of Heat Transfer, vol. 128 (2006) 1213–1216.
47. J. C. Maxwell, A treatise on Electricity and magnetism, Secon ed., Clarendon press, Oxford, UK, 1881.
48. R. L. Hamilton, O. K. Crosser, Thermal conductivity of heterogeneous two component systems, I& EC Fundam 1(1962) 182-191.
49. D. A. G. Bruggeman, Berchnung , B. V. P. K. V. Heterogen Substanzen, I. Dielektrizitskonstanten and leitfahigkeitender Mischkorper aus isotropen Subsanzen, Annalender, Physik, Leipzig, 24 (1935) 636-679.
50. E. J. Wasp, J. P. Kenny, R. L. Gandhi, Solid-liquid slury pipeline Transportation, BulkMaterial Handling, Trans Tech Publications, Germany, 1999.
51. D. J. Jeffrey, Proceedings of Royal Society A 335, 355 (1973).
52. R. H. Davis, International Journal of Thermo Physics 7, 609 (1986).
53. S. Lu and H. Lin, J. Appl. Phys. 79, 6761 (1996).
54. W. Yu and S. U. S. Choi, J. Nanoparticle Res. 5, 167 (2003).
55. H. E. Patel, T. Sundarrajan, T. Pradeep, A. Dasgupta, N. Dasgupta, and S. K. Das, Pramana Journal of Physics 65, 863 (2005).
56. J. Koo and C. Kleinstreuer, Journal of Nanoparticle Research 6, 577, (2004).
57. E. Abu-nada, Effects of variable viscosity and thermal conductivity of Al 2 O 3 – water nanofluid on heat transfer enhancement in natural convection, International Journal of Heat and Fluid Flow. 30 (2009) 679–690.
58. A. Fairbanks, Numerical study of turbulent flow and heat transfer characteristics of nanofluids considering variable properties, I. Journal, T. Sciences, (2009).doi:10.1016/j.ijthermalsci.2008.01.001.

59. S. Kaka, Review of convective heat transfer enhancement with nanofluids, I. Journal, M. Transfer, (2009). doi:10.1016/j.ijheatmasstransfer.2009.02.006.

60. J.J. Kriso, Forced Convective Heat Transfer of Nanofluids in Microchannels, I. Journal, M. Transfer, (2009). doi:10.1016/j.ijheatmasstransfer.2008.03.033.

61. D. Kim, L. Chengguo, Convective heat transfer characteristics of nanofluids under laminar and turbulent flow conditions, (2009). doi:10.1016/j.cap.2008.12.047.

62. S.K. Das, Entropy generation due to flow and heat transfer in Nanofluids, (2010). doi:10.1016/j.ijheatmasstransfer.2010.06.016.

63. T.T. Baby, S. Ramaprabhu, Enhanced convective heat transfer using graphene dispersed nanofluids, (2011) 1–9.

64. H. Demir, A.S. Dalkilic, N.A. Kürekci, W. Duangthongsuk, S. Wongwises, Numerical investigation on the single phase forced convection heat transfer characteristics of TiO 2 nano fluids in a double-tube counter flow heat exchanger, International Communications in Heat and Mass Transfer. 38 (2011) 218–228. doi:10.1016/j.icheatmasstransfer.2010.12.009.

65. E. Ebrahimnia-bajestan, H. Niazmand, W. Duangthongsuk, S. Wongwises, Numerical investigation of effective parameters in convective heat transfer of nanofluids flowing under a laminar flow regime, International Journal of Heat and Mass Transfer. 54 (2011) 4376–4388. doi:10.1016/j.ijheatmasstransfer.2011.05.006.

66. H.A. Mohammed, Convective heat transfer and fluid flow study over a step using nanofluids : A review, (2011). doi:10.1016/j.rser.2011.02.019.

67. H.A. Mohammed, Heat transfer and fluid flow characteristics in microchannels heat exchanger using nanofluids : A review, (2011). doi:10.1016/j.rser.2010.11.031.

68. S.M.S. Murshed, C.A.N. De Castro, M.J. V Lourenc, M.L.M. Lopes, F.J. V Santos, A review of boiling and convective heat transfer with nanofluids, 15 (2011) 2342–2354. doi:10.1016/j.rser.2011.02.016.

69. R. Bhargava, Numerical study of heat transfer enhancement in mixed convection flow along a vertical plate with heat source / sink utilizing nanofluids, (2011). doi:10.1016/j.cnsns.2011.03.014.

70. A. Zamzamian, S. Nasseri, A. Doosthoseini, A. Joneidi, Experimental investigation of forced convective heat transfer coefficient in nanofluids of Al 2 O 3 / EG and CuO / EG in a double pipe and plate heat exchangers under turbulent flow, Experimental Thermal and Fluid Science. 35 (2011) 495–502. doi:10.1016/j.expthermflusci.2010.11.013.

71. K. Anoop, R. Sadr, J. Yu, S. Kang, S. Jeon, D. Banerjee, Experimental study of forced convective heat transfer of nano fl uids in a microchannel ☆, International Communications in Heat and Mass Transfer. 39 (2012) 1325–1330. doi:10.1016/j.icheatmasstransfer.2012.07.023.

72. W.M. El-maghlany, Augmentation of natural convective heat transfer in square cavity by utilizing nanofluids in the presence of magnetic field and uniform heat generation / absorption, (2012). doi:10.1016/j.ijthermalsci.2012.02.029.

73. Z. Haddad, E. Abu-nada, H.F. Oztop, A. Mataoui, Natural convection in nanofluids : Are the thermophoresis and Brownian motion effects signi fi cant in nano fluid heat transfer enhancement ?, 57 (2012) 152–162. doi:10.1016/j.ijthermalsci.2012.01.016.

74. S.E. Reviews, S. Technology, T. Houa, A review on natural convective heat transfer of nanofluids, (2012). doi:10.1016/j.rser.2012.04.003.

75. S. Sarkar, S. Ganguly, G. Biswas, Mixed convective heat transfer of nanofluids past a circular cylinder in cross flow in unsteady regime, International Journal of Heat and Mass Transfer. 55 (2012) 4783–4799. doi:10.1016/j.ijheatmasstransfer.2012.04.046.

76. S. Sarkar, S. Ganguly, A. Dalal, Analysis of Entropy Generation During Mixed Convective Heat Transfer of Nanofluids Past a Square Cylinder in Vertically Upward Flow, 134 (2012) 1–8. doi:10.1115/1.4007411.

77. S. Abelman, Entropy Generation in Steady MHD Flow Due to a Rotating Porous Disk in a Nanofluid, (2013). doi:10.1016/j.ijheatmasstransfer.2013.03.004.

78. S.J. Kim, I.C. Bang, J. Buongiorno, L.W. Hu, S.J. Kim, I.C. Bang, J. Buongiorno, L.W. Hu, Effects of nanoparticle deposition on surface wettability influencing boiling heat transfer in nanofluids Effects of nanoparticle deposition on surface wettability influencing boiling heat transfer in nanofluids, 153107 (2013). doi:10.1063/1.2360892.

79. O.D. Makinde, W.A. Khan, Z.H. Khan, Buoyancy effects on MHD stagnation point flow and heat transfer of a nanofluid past a convectively heated stretching / shrinking sheet, International Journal of Heat and Mass Transfer. 62 (2013) 526–533. doi:10.1016/j.ijheatmasstransfer.2013.03.049.

80. M. Sheikholeslami, D.D. Ganji, Numerical investigation of MHD effects on Al 2 O 3 e water nano fl uid fl ow and heat transfer in a semi-annulus enclosure using LBM, Energy. 60 (2013) 501–510. doi:10.1016/j.energy.2013.07.070.

81. M. Turkyilmazoglu, I. Pop, Heat and mass transfer of unsteady natural convection flow of some nanofluids past a vertical infinite flat plate with radiation effect, International Journal of Heat and Mass Transfer. 59 (2013) 167–171. doi:10.1016/j.ijheatmasstransfer.2012.12.009.

83. L. Wang, Pressure drop and convective heat transfer of water and nanofluids in a double-pipe helical heat exchanger a double-pipe helical heat exchanger, (2013). doi:10.1016/j.applthermaleng.2013.06.051.

84. C. Yang, W. Li, A. Nakayama, Convective heat transfer of nano fluids in a concentric annulus, 71 (2013) 249–257. doi:10.1016/j.ijthermalsci.2013.04.007.

85. C. Yang, W. Li, Y. Sano, M. Mochizuki, On the Anomalous Convective Heat Transfer Enhancement in Nanofluids : A Theoretical Answer to the Nanofluids Controversy, 135 (2013) 1–9. doi:10.1115/1.4023539.

86. W.H. Azmi, K. V Sharma, P.K. Sarma, R. Mamat, S. Anuar, Comparison of convective heat transfer coef fi cient and friction factor of TiO 2 nano fl uid fl ow in a tube with twisted tape inserts, 81 (2014) 84–93. doi:10.1016/j.ijthermalsci.2014.03.002.

87. M.S. Kandelousi, KKL correlation for simulation of nanofluid flow and heat transfer in a permeable channel, Physics Letters A. 378 (2014) 3331–3339. doi:10.1016/j.physleta.2014.09.046.

88. M.M. Rashidi, Free convective heat and mass transfer for MHD fluid flow over a permeable vertical stretching sheet in the presence of the radiation and buoyancy effects, Ain Shams Engineering Journal. 5 (2014) 901–912. doi:10.1016/j.asej.2014.02.007.

89. M. Sheikholeslami, A study of natural convection heat transfer in a nanofluid filled enclosure with elliptic inner cylinder, 24 (2014) 1906–1927. doi:10.1108/HFF-07-2013-0225.

90. M. Sheikholeslami, M.G. Bandpy, R. Ellahi, M. Hassan, S. Soleimani, Journal of Magnetism and Magnetic Materials Effects of MHD on Cu – water nano fl uid fl ow and heat transfer by means of CVFEM, 349 (2014) 188–200. doi:10.1016/j.jmmm.2013.08.040.

91. V. Daikin, A. Fairbanks, A review and analysis on influence of temperature and concentration of nanofluids, (2015).

92. V.R.R. Janke, S. Naramgari, S. Vangala, MHD Flow of a Nanofluid Embedded with Dust Particles Due to Cone with Volume Fraction of Dust and Nano Particles, Procedia Engineering. 127 (2015) 1026–1033. doi:http://dx.doi.org/10.1016/j.proeng.2015.11.452.

93. M. Materials, Effect of thermal radiation on magnetohydrodynamics nanofluid flow and heat transfer by means of two phase model, (2015). doi:10.1016/j.jmmm.2014.08.021.

94. S. Naramgari, C. Sulochana, Mhd flow of dusty nanofluid over a stretching surface with volume fraction of dust particles, Ain Shams Engineering Journal. (2015). doi:10.1016/j.asej.2015.05.015.

95. S. Naramgari, C. Sulochana, Dual solutions for MHD stagnation-point flow of a nanofluid over a stretching surface with induced magnetic field, 9 (2015) 1–8.

96. J.V.R. Reddy, V. Sugunamma, N. Sandeep, C.S.K. Raju, M.J. Babu, Induced Magneticfield Effect on Stagnation-Point Flow of Magneto-Nanofluids Towards a Stretching Sheet, 7 (2015) 1–7. doi:10.1166/asem.2015.1791.

97. N. Sandeep, C. Sulochana, V. Sugunamma, Stagnation-point flow and heat transfer of a nanofluid towards stretching/shrinking cylinders, 6 (2015) 43–49.

98. M. Sheikholeslami, M.M. Rashidi, D.D. Ganji, Numerical investigation of magnetic nano fluid forced convective heat transfer in existence of variable magnetic field using two phase model, Journal of Molecular Liquids. 212 (2015) 117–126. doi:10.1016/j.molliq.2015.07.077.

99. V. Sugunamma, C. Sulochana, N. Sandeep, J.V.R. Reddy, MHD nanofluid flow over an exponentially stretching surface with suction/injection, 6 (2015) 50–56.

100. C. Sulochana, Radiation and Chemical Reaction Effects on MHD Thermosolutal Nanofluid Flow over a Vertical Plate in Porous Medium, 34 (2015) 28–38.

101. I.L. Animasaun, N. Sandeep, Buoyancy induced model for the fl ow of 36 nm alumina-water nano fl uid along upper horizontal surface of a paraboloid of revolution with variable thermal conductivity and viscosity, Powder Technology. 301 (2016) 858–867. doi:10.1016/j.powtec.2016.07.023.

102. M.J. Babu, N. Sandeep, 3D MHD slip flow of a nano fluid over a slendering stretching sheet with thermophoresis and Brownian motion effects, Journal of Molecular Liquids. 222 (2016) 1003–1009. doi:10.1016/j.molliq.2016.08.005.

103. M.J. Babu, N. Sandeep, Effect of nonlinear thermal radiation on non-aligned bio-convective stagnation point flow of a magnetic-nanofluid over a stretching sheet, Alexandria Engineering Journal. (2016). doi:10.1016/j.aej.2016.08.001.

104. M.J. Babu, N. Sandeep, Effect of variable heat source / sink on chemically reacting 3D slip flow caused by a slendering stretching sheet, 25 (2016) 58–69. doi:10.4028/www.scientific.net/JERA.25.58.

105. M.J. Babu, N. Sandeep, MHD non-Newtonian fluid flow over a slendering stretching sheet in the presence of cross-diffusion effects, Alexandria Engineering Journal. (2016). doi:10.1016/j.aej.2016.06.009.

106. S.K. Das, S.U.S. Choi, H.E. Patel, Heat Transfer in Nanofluids — A Review Heat Transfer in Nanofluids —, 7632 (2016). doi:10.1080/01457630600904593.

107. I. Journal, F. Flow, S. Technology, Application of nanofluids for heat transfer enhancement of separated flow encountered in a backward facing step separated flows encountered in a backward facing step, (2016). doi:10.1016/j.ijheatfluidflow.2007.07.001.

108. I. Journal, M. Flow, Boiling heat transfer characteristics of nanofluids in a flat heat pipe evaporator with micro-grooved heating surface, (2016). doi:10.1016/j.ijmultiphaseflow.2007.06.009.

109. S. Naramgari, C. Sulochana, MHD flow of dusty nanofluid over a stretching surface with volume fraction of dust particles, Ain Shams Engineering Journal. 7 (2016) 709–716. doi:10.1016/j.asej.2015.05.015.

110. A. Published, C. Link, D. Terms, Convective Heat Transfer Enhancement in Nanofluids : Real Anomaly or Analysis Artifact ? Citation Accessed Citable Link Detailed Terms, (2016).

111. K. Pushpalatha, V. Sugunamma, J.V.R. Reddy, N. Sandeep, Heat and Mass Transfer in Unsteady MHD Casson Fluid Flow with Convective Boundary Conditions, 91 (2016) 19–38.

112. C.S.K. Raju, N. Sandeep, Heat and mass transfer in MHD non-Newtonian bio-convection flow over a rotating cone/plate with cross diffusion, Journal of Molecular Liquids. 215 (2016) 115–126. doi:10.1016/j.molliq.2015.12.058.

113. C.S.K. Raju, N. Sandeep, A. Malvandi, Sc, Journal of Molecular Liquids. 221 (2016) 108–115. doi:10.1016/j.molliq.2016.05.078.

114. C.S.K. Raju, N. Sandeep, V. Sugunamma, Unsteady magneto-nano fluid flow caused by a rotating cone with temperature dependent viscosity : A surgical implant application, Journal of Molecular Liquids. 222 (2016) 1183–1191. doi:10.1016/j.molliq.2016.07.143.

115. A.M. Ramireddy, V. Sugunamma, J.V.R. Reddy, N. Sandeep, A. Pradesh, Influence of Non-linear Radiation on MHD 3D Casson Fluid Flow Past a Non-linearly Stretching Sheet with Non-uniform Heat Source / Sink, 3 (2016) 131–137.

116. M.M. Rashidi, C.S.K. Raju, N. Sandeep, S. Saleem, A Numerical Comparative Study on 3D Nanofluid Flows, 13 (2016) 1–8. doi:10.1166/jctn.2016.5353.

117. A.M.R. Reddy, J.V.R. Reddy, N. Sandeep, V. Sugunamma, Unsteady Flow of Nonlinear Radiative Powell-Eyring Fluid Past an Inclined Stretching Sheet with First Order Chemical Reaction, 24 (2016) 2366–2374. doi:10.5829/idosi.mejsr.2016.24.07.23795.

118. G. Reddy, S. Naramgari, Heat and mass transfer in radiative MHD Carreau fluid with cross diffusion, Ain Shams Engineering Journal. (2016). doi:10.1016/j.asej.2016.06.012.

119. J.V.R. Reddy, V. Sugunamma, N. Sandeep, C. Sulochana, ScienceDirect Influence of chemical reaction , radiation and rotation on MHD nanofluid flow past a permeable flat plate in porous medium, Journal of the Nigerian Mathematical Society. 35 (2016) 48–65. doi:10.1016/j.jnnms.2015.08.004.

120. N. Sandeep, EPJ Plus, (2016). doi:10.1140/epjp/i2016-16267-3.

121. N. Sandeep, M.S.J. Kumar, Heat and Mass Transfer in Nanofluid Flow over an Inclined Stretching Sheet with Volume Fraction of Dust and Nanoparticles, 9 (2016) 2205–2215.

122. N. Sandeep, O. Kolade, I. Lare, Modi fi ed kinematic viscosity model for 3D-Casson fl uid fl ow within boundary layer formed on a surface at absolute zero, Journal of Molecular Liquids. 221 (2016) 1197–1206. doi:10.1016/j.molliq.2016.06.049.

123. X. Wang, A.S. Mujumdar, Critical review of heat transfer characteristics nanofluids Heat transfer characteristics of nanofluids : a review, (2016). doi:10.1016/j.rser.2005.01.010.