***Effects of Dispersants on Thermal Conductivity of Nanofluids for Industrial Applications***

Pavithra K S\* and Vinay Parol\*

*1Department of Chemistry, Bapuji Institute of Engineering and Technology, An Autonomous Institute Affiliated to VTU, Belagavi, Davanagere-577004, Karnataka, India.*

*2Department of Physics, Bapuji Institute of Engineering and Technology, An Autonomous Institute Affiliated to VTU, Belagavi, Davanagere-577004, Karnataka, India.*

*Corresponding author email:* *pavithraks073@gmail.com*

*vinayparol@gmail.com*

**Abstract:**

Nanofluids, colloidal suspensions of nanoparticles in a base fluid, have garnered significant attention in recent years due to their enhanced thermal properties and potential applications in various heat transfer systems. Among the key factors influencing the thermal conductivity of nanofluids, the role of dispersants or surfactants remains paramount. This chapter provides a comprehensive review of the effects of dispersants on the thermal conductivity of nanofluids, elucidating the underlying mechanisms and exploring strategies for optimizing thermal performance. The dispersants or surfactants in nanofluids serve crucial functions in stabilizing nanoparticles against agglomeration and controlling their dispersion within the base fluid. However, the choice of dispersant and its concentration can exert profound effects on the thermal conductivity of nanofluids.

Key words: Thermal conductivity, Dispersants, Stability, Mechanism, Heat transfer

**Chapter investigates the following aspects:**

1. Dispersant Chemistry: The chemical structure and functional groups of dispersants influence their affinity for nanoparticles and the base fluid, thereby impacting dispersion stability and thermal conductivity enhancement.
2. Surface Modification: Surface-modified dispersants can facilitate stronger interactions between nanoparticles and the base fluid, leading to improved dispersion stability and enhanced thermal conductivity.
3. Dispersant Concentration: The concentration of dispersants in nanofluids can significantly influence particle dispersion and interfacial interactions, thereby affecting thermal conductivity. Optimal dispersant concentrations must be determined to balance dispersion stability and thermal enhancement.
4. Agglomeration Prevention: Effective dispersants play a crucial role in preventing nanoparticle agglomeration, which can impede heat transfer and diminish thermal conductivity enhancement.
5. Synergistic Effects: The interplay between dispersants and other additives, such as stabilizers or functionalizing agents, can result in synergistic effects on thermal conductivity, offering opportunities for further enhancement.

Furthermore, this chapter discusses experimental techniques for characterizing the thermal conductivity of nanofluids with varying dispersant formulations and concentrations. Computational models are also explored to elucidate the underlying mechanisms governing dispersant-mediated thermal conductivity enhancement in nanofluids. A comprehensive understanding of the effects of dispersants on the thermal conductivity of nanofluids is crucial

1. **Introduction**

The development of high-efficiency heat transfer and cooling devices is progressively increasing with the advancement of technologies and industrial applications. Heat exchangers are the heat transfer devices which are used widely in food industry, power production, automobile radiators, chemical industry etc. Currently, about 90 % of the world’s energy budget is associated with the production, transmission, storage or heat dissipation 1. Successive efforts have been made to enhance the heat transfer to resolve extreme heat diffusion during operation and to ensure the capacity, thermal efficiency, and working life of heat pumps are of great significance in the industries.2,3

Even though numerous strategies have been implemented to improve the heat transfer, their efficiency is still restricted by the low heat capacity of the conventional working fluids, which restricts the efficiency and repeatability of the heating systems. With the ongoing advances in the field of science and technology, miniaturization of devices, there is a need to develop innovative kinds of heat exchangers that are far more effective in terms of improving heat transfer. Nanofluids are the colloidal suspension of nanoparticles (NPs) such as Cu, Ag, TiO2, CuO, Al2O3, and ZnO with sizes of 1–100 nm in conventional working fluids. It has been intensively studied as one of the newly emerging materials for advanced engineering applications.

The stable dispersion of nanofluids is a fundamental requirement for the achievement of their potential and realizing industrial applications. However, the added NPs exhibit a poor compatibility with the conventional fluids and have a strong tendency to form aggregation. Over a period of time, accumulated/aggregated NPs would be phase-separated and precipitated from fluids. Nanofluids would not only lose their economic benefits, such as heat transfer and potentiality that relies on dynamic Brownian motion of NPs within the conventional fluids, but also cause clogging and abrasion issues in particular for heat-transfer channels in microelectronic systems.

To date, dispersion stability has been considered to be one of most challenging issues that limit the practical conception and further development of nanofluids.4 Especially for nanofluids, they are subjected to high temperature operations for successive heating/cooling cycles, which enormously increase the chances of NPs collision and accumulation. Thus, making it even harder, to achieve a stable dispersion of nanofluids. In order to overcome these issues, significant efforts have been devoted to ameliorate the dispersion stability of the nanofluids using numerous approaches viz. vigorous stirring, ultrasonic treatment, addition of surface-active agents or dispersants.

The amphiphilic grafted copolymers are the new class of dispersants which have recently received more attention due to their diverse properties offered by the anchoring functional groups such as amides, anhydrides, sulphonyl, carboxylic etc. and soluble polymeric side chains. This creates an effective steric barrier that prevents the particles agglomeration and enhances the dispersion stability.5–7 These are used to optimize the dispersion behaviour and to be promising as colloidal stabilizers in high temperature operations. Based on the understanding that the functionalized copolymers create a steric/electrostatic barrier between the NPs mainly due to the specific functional groups.

1. **Techniques to stabilize the nanofluids**
	1. **Addition of surfactants/dispersants**

Based on the nature of hydrophilic functionality, surfactants are categorised into 4 types –(i) Anionic surfactants (ii) Cationic surfactants (iii) Non-ionic surfactants (iv) Zwitterionic surfactants. 8

##### Anionic Surfactant

##### Surfactants with negatively charged functional groups such as sulphates (ROSO3−), carboxylates (RCOO−), phosphates (RPO4−) and sulfonates (RSO3−) (Figure 1). In case of anionic surfactants, the hydrophilic part of dispersant acquires a ‘- ve’ charge when it is dissolved in H2O. The stability of the nanofluids may either increase or decrease. This is mainly due to the molecular weight and the hydrophobic chain length of the dispersant. The examples of the anionic dispersants for the preparation of nanofluids are given below in Table 1

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**Figure 1:** Graphical view of anionic surfactants

##### Table 1: Examples of anionic surfactants

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Dispersant | Nanofluids | Hydrophilic group | Conclusion | Ref. |
| Synthonics Sodium Dodecyl Sulfate Or Sodium Lauryl Sulfate, Rs ... | Graphene and carbon nanotube (CNT) | Sulfonic group | Potent to increase the stability and thermal conductivity | 9,10 |
| Sodium Dodecylbenzene Sulfonate (SDBS) | Cu-water and Alumina -water | Phenyl sulfonic group | Optimized value of SDBS concentration, increases the thermal conductivity and stability of nanofluids | 11, 12 |
| SODIUM LAURYL SULPHATE 20% SOLUTION , CH3(CH2)11OSO3Na | Loba ... | Cu-water | Sulfonic group | Potent to stabilize the nanofluids up to 3 weeks in the presence of SLS dispersant | 13 |
|  | Surface modification of SiO2 NPs | Carboxyl group | Super hydrophobicity with water contact angle of 151°. With an enhanced stability and UV protection | 14 |
| BiOBr-photocatalyzed cis – trans isomerization of 9-octadecenoic ...BiOBr-photocatalyzed cis – trans isomerization of 9-octadecenoic ... | TiO2 – lubricant engine oil | Carboxylic acid | Enhancement of suspension stability with the presence of oleic acid as dispersants as compared with the ionic dispersants. | 15 |

##### Cationic Surfactant

Cationic surfactants that have positively charged single or multiple head groups. This charge may be either permanent or only exists at certain pH range. They are less common than their anionic counterparts. Quaternary ammonium salts (QAS) $NR\_{4}^{+}$, R- alkyl /aryl functional groups are the common cationic surfactants studied in the petroleum industry **(Figure 2)**.16 As a result, cationic surfactants are frequently used as stabilizers in foaming processes.1 CTAB is the most widely known due to its high surface activity.14 The examples of the cationic dispersants for the preparation of nanofluids are given below in **Table 2.**



**Figure i2:** Graphical view of cationic surfactants

##### Table 2: Examples of cationic surfactants

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Dispersant** | **Nanofluids** | **Hydrophilic group** | **Conclusion** | **Ref.** |
| Electrochemical effect of cationic gemini surfactant and halide ... | Ag-waterAu-waterCNTs | Quaternary ammonium salt | Two hydrophilic head group linked to a spacer chain and hydrophobic tail creates an effective barrier between the NPs. | 17, 18 |
| Dielectric behaviour and conductivity of high-filled BaTiO 3 –PMMA ... | Fe2O3 -waterCNT-water | Trimethyl ammonium | Potential for improving the stability ofnanofluids at an optimum dispersant concentration | 19 |
| Figure 1 from Cationic lipids and surfactants as antifungal agents ... | Nanoencapsulation of phase change materials for thermal energy storage | Quaternary ammonium salt | Improving the thermal storage efficiency and system stability | 20 |

* + 1. **Non-ionic Surfactant**

[Non-ionic surfactants](https://www.sciencedirect.com/topics/engineering/nonionic-surfactant) do not have surface charges in the hydrophilic part, but are highly hydrophilic owing to the presence of polar functional groups such as alcohol [ethoxylates](https://www.sciencedirect.com/topics/engineering/ethoxylates), alkylphenol ethoxylates, polysorbates and polyoxyethylene (–CH2CH2O–)*n*–H, (*n -* no of [ethylene oxide](https://www.sciencedirect.com/topics/engineering/ethylene-oxide) units or [polyols](https://www.sciencedirect.com/topics/engineering/polyols)) **(Figure 3)**. Non-ionic [surfactants](https://www.sciencedirect.com/topics/materials-science/surface-active-agent) have significant advantages over [ionic surfactants](https://www.sciencedirect.com/topics/materials-science/ionic-surfactant) that by modifying [molecular structures](https://www.sciencedirect.com/topics/physics-and-astronomy/molecular-structure), especially in lipophilic moiety, surfactants with a wide range of hydrophilic-lipophilic balance (HLB).21 Examples of the non-ionic dispersants for the preparation of nanofluids are given below in **Table 3.**

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**Figure I 3: i** Graphical view of non-ionic surfactants

##### Table 3: Examples of non-ionic surfactants

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Dispersant** | **Nanofluids** | **Hydrophilic group** | **Conclusion** | **Ref.** |
| Scheme 1. Chemical structure of Triton X-100 | Download Scientific ... | Pd-NPsCNT-water | Polyethylene glycol | Enhances the stability and catalytic activity due to the presence of polar group | 22**,** 23 |
| Chemical structure of (a) PVP, (b) PVA, (c) CTAB, (d) TEA, and (e ... | Ag-waterCuO-water | Pyrrolidone moiety | Ag nanofluids, stability and thermal conductivity increased with the addition of PVP compared to SDS | 24**,** 25 |
|  | Au -NPs | Polyoxyethylene(Polyether) | Improve the stability of Au NPs in solution of biomolecules | 26 |

##### Zwitterionic Surfactant

##### Zwitterionic or amphoteric surfactants carrying either positive or negative charges or it can have both charges on the hydrophilic head groups depending on the pH of the suspension (Figure 4). These are seldom used as stabilizers. Some of the examples for amphoteric surfactants are lecithin, sodium lauroamphoacetate, hydroxysultaine, etc.



**Figure 4:** Graphical view of zwitter-ionic surfactants

**3. Surface modification of NPs**

The use of functionalized NPs is one of the potential tools to achieve long-term stability of nanofluids regardless of conventional working fluids as considered as surfactant free technique. Surface modification of NPs by means of organic or polymer molecules through multi-point noncovalent interactions, such as hydrogen bonding, dipole–dipole, zwitter- ionic and acid–base interaction.27,28 In order to improve the homogenous dispersion stability, polarity and bio-compatibility of NPs for various applications 29,30. Natalia Alzate-Carvajal et al. have attempted the surface functionalization of graphene oxide (GO) and nano-diamond (ND) using amine-based solvent free gas phase technique. Dispersion stability and thermal efficiency of the system is increased compared to non-functionalized GO.31,32

* 1. **Mechanism for stabilization of nanofluids**

Nanofluids stability is a challenging issue because the high surface area of the NPs tends to aggregate resulting in a reduced stability. The theory proposed by Derjaguin, Landau, Vervey, and Overbeek (DVLO), i33,34 implies that the stability of the particle in the suspension is determined by the sum of interactions between Van der Walls and the repulsive forces generated by the electrical layer between the particles. The stability of the nanofluids is related to that of the two opposing forces. If the electrostatic repulsion is greater than the attractive force, it is considered stable, or else the system would be unstable.35 Based on the repulsive interactions, the nanofluids are stabilized through three kinds of mechanisms viz. electrostatic, steric and electro-steric **(Figure 5).**

* + 1. **Electrostatic stabilization**

In the electrostatic stabilization process, the NPs in the conventional fluids acquires surface charges either by the ionization of functional groups or by the adsorption of molecules. The electrical double layer is created around the surface s of the NPs, the repulsive force produced by electrical double layer offsetting the attractive force between the NPs to ensure a uniform dispersion in the conventional fluids. Commonly ionic surfactants like SDS, CTAB, SDBS, etc. stabilize the nanofluids through electrostatic stabilization. It is effective only in the dispersion of NPs in the polar solvents like water and ethanol.36–38

* + 1. **Steric stabilization**

The steric stabilization is also called the “polymerisation stabilization technique” which involves non-ionic and amphiphilic functionalized polymers having hydrophilic head and hydrophobic tails. The hydrophilic head (sulphonyl, amides and carboxylic moieties) are strongly adsorbed on the particle surface and the hydrophobic tails extend into nanofluids to create a steric barrier between the NPs. The polymer chain length and the adsorption behaviour of polymers plays a key role in the stabilization of nanofluids. Steric stabilized nanofluids remain well dispersed and sustain for a longer period of time and are more effective than the electrostatic stabilization at higher particle concentration.39–42



**Figure. 5:** Stabilization of nanofluids a) Steric b) Electrostatic 21

* + 1. **Electro-steric stabilization**

Electro-steric stabilization is the combination of electrostatic and steric stabilizations techniques. In this approach, ionic copolymers get adsorbed on the charged surface of the NPs which creates a protective layer (steric hindrance effect) and the ionic head group creates an electric potential layer (electrostatic) between the NPs. This enhances the long-term stability of the nanofluids **(Figure 6)**. The polymers used as dispersants for this purpose are generally called polyelectrolyte, which are made up of repeating units of monomer having ionizable functional groups such as carboxylic, sulfonic acid group etc. Sodium styrene sulfonate, poly (acrylic acid) -b- poly (butyl acrylate), poly (methacrylic acid) etc., are some of the examples of electro-steric stabilizers.43–46



**Figure 6:** Electro-steric stabilization of nanofluids44

* 1. **Use of polymeric dispersants over the linear polyelectrolytes**

Generally, the dispersants /linear polyelectrolytes are widely used for the stabilization of nanofluids for various applications. Linear polyelectrolytes lose their properties during high temperature operations. It results in particle aggregation and causes the instability of the suspension. Considering these drawbacks, extensive attempts have been made to improve the development of materials which acts as supplements to the particle instability. Polymer dispersants are the new class of dispersants, which can be used as dispersing agents instead of linear polyelectrolytes due to their enhanced properties over the linear polyelectrolytes.47–49 As a result, synthesis of amphiphilic copolymers with controlled polymeric chain length have been given significant importance by the researcher to achieve the long-term stability and thermal conductivity of nanofluids even at lower dispersant concentrations. The polymeric dispersants enhance the effective dispersion property, leading to an increased stability of the nanofluids compared with the linear polyelectrolytes. The use of polymeric dispersants is found in many industries such as the oil , detergents, coatings, emulsifier industries , as well as in the textile industry.50–53

* 1. **Functionalized copolymers as dispersants**

Surface modification by non-covalent bonding is one of the most widely used methods for dispersing and stabilizing solid particles in base fluids, due to its convenience, wide applicability and processability, particularly in industrial applications. It is usually carried out by using surfactants or macromolecules to adsorb onto the surface of the particles, in order to minimize the specific surface energy and the physical attractiveness of the particles, and to prevent their agglomeration.54,55 Traditionally, these are small molecular surfactants, but recent advances in polymer chemistry have resulted in more effective polymer dispersants for various applications.56,57

Structurally well-defined anchoring chains of copolymers can be robustly adsorbed to the surface of the particles through multi-point noncovalent interactions such as dipole–dipole, hydrogen bonding, zwitter-ionic, acid–base interaction and others. At the same time, their stabilizing chains can form steric stabilizing barriers around the particles in solvent media, allowing for homogeneous dispersion and stabilization while preventing them from aggregating. As a result, copolymers with properly designed molecular structures and compositions can provide effective dispersion stability for solid particles. 55

* + 1. **Hydrophilicity and hydrophobicity**

The hydrophobic and hydrophilic balance of an amphiphilic copolymer / grafted copolymers significantly reflects how the macromolecules affect the thermal stability and thermal conductivity of the nanofluids for heat transfer applications. Macromolecules with highly functional head groups and alkyl chain create an effective barrier between the NPs, keeping the particles go away from each other and ensuring homogeneous dispersion.

In this view, research is focused on the use of copolymers and so used the grafted copolymers as the dispersing agents to prepare stable nanofluids. Copolymers and the grafted copolymers can either be synthesized by the free radical polymerisation technique or by the esterification process. These polymers were found to be most interesting dispersants, due to their ability to reduce the surface energy, which in turn enhances the stability of the system.

1. **Significance of the thermal nanofluids for heat transfer applications**

Polymer dispersants significantly influence the thermal conductivity of nanofluids by stabilizing nanoparticles in the fluid and improving their dispersion. Here’s a detailed look at how they affect the thermal conductivity:

* 1. **Stability and Reliability**
* **Dispersant Action**: Dispersants enhance the long-term stability of nanofluids by preventing the settling and agglomeration of nanoparticles, which is crucial for maintaining consistent heat transfer properties 58.
* **Reduced Maintenance**: Stable nanofluids require less maintenance and replacement, making them more reliable for industrial applications.
	1. **Interfacial Thermal Resistance**

The interfacial thermal resistance between nanoparticles and the base fluid can be reduced by using polymer dispersants. These dispersants create a bridge that enhances thermal transport across the interface, thus improving the overall thermal conductivity of the nanofluid 59.

* 1. **Viscosity and Pumping Power**
* **Optimized Viscosity**: Proper dispersion of nanoparticles can optimize the viscosity of the nanofluid, balancing the trade-off between enhanced heat transfer and increased pumping power requirements.
* **Energy Efficiency**: Stable nanofluids can lead to energy savings by reducing the power needed for pumping while still providing improved heat transfer performance.
	1. **Electrical Conductivity and Heat Transfer**

Some polymer dispersants can improve the electrical conductivity of nanofluids, which indirectly affects thermal conductivity through enhanced heat transfer mechanisms 21,60.

* 1. **Concentration of Nanoparticles:**

Effective dispersion achieved by polymer dispersants allows for higher concentrations of nanoparticles without causing agglomeration. Higher concentrations typically enhance thermal conductivity, provided the dispersion is stable 61.

* 1. **Thermal Conductivity Enhancement Mechanisms:**

Polymer dispersants can influence various mechanisms of thermal conductivity enhancement, such as:

* **Brownian Motion:** Enhanced nanoparticle dispersion promotes Brownian motion, contributing to heat transfer.
* **Phonon Transport:** Improved interface conditions facilitate phonon transport, boosting thermal conductivity 4.
1. **Applications in Various Industries**
* **Electronics Cooling**: Nanofluids are used in cooling high-power electronics and computer processors, where efficient heat removal is critical.
* **Automotive Industry**: They are employed in automotive cooling systems, including radiators and engine cooling, for better thermal management.
* **HVAC Systems**: Heating, ventilation, and air conditioning systems benefit from the improved heat transfer capabilities of nanofluids.
* **Industrial Processes**: Chemical processing, power generation, and other industrial processes use nanofluids for enhanced thermal management.
1. **Research and Development**
* **Ongoing Innovations**: Research continues to explore new nanoparticle materials and dispersants to further enhance the thermal properties and stability of nanofluids.
* **Customized Solutions**: Tailored nanofluid formulations are being developed to meet specific application requirements, improving overall system efficiency and performance.
1. **Summary**

This book chapter discusses the development and challenges of enhancing heat transfer and cooling devices, particularly heat exchangers, which are crucial in various industries. Despite efforts to improve heat transfer, conventional working fluids have low heat capacities, limiting their efficiency. Nanofluids, which are colloidal suspensions of nanoparticles (NPs) in conventional fluids, have emerged as potential solutions due to their superior heat transfer properties. However, the stability of nanofluids is a significant challenge due to the tendency of NPs to aggregate, reducing their effectiveness and causing operational issues.

To address this, various techniques have been explored to stabilize nanofluids, including the use of surfactants and dispersants. These can be categorized into anionic, cationic, non-ionic, and zwitterionic surfactants, each with specific properties that influence the stability and thermal conductivity of nanofluids. Recent attention has focused on amphiphilic grafted copolymers, which provide steric barriers preventing NP aggregation and enhancing dispersion stability, particularly under high-temperature operations.

Stabilization mechanisms such as electrostatic, steric, and electro-steric stabilization are crucial for maintaining nanofluid stability. Electrostatic stabilization relies on surface charges creating repulsive forces, while steric stabilization involves polymers creating physical barriers. Electro-steric stabilization combines both approaches for enhanced stability.

Polymeric dispersants, especially amphiphilic copolymers, are highlighted as superior to traditional linear polyelectrolytes, offering better thermal stability and conductivity even at lower concentrations. These advancements in polymer chemistry have led to more effective and stable nanofluids suitable for various industrial applications.

Polymer dispersants play a crucial role in enhancing the thermal conductivity of nanofluids by improving nanoparticle dispersion, reducing interfacial thermal resistance, and optimizing fluid properties. The choice and concentration of dispersants must be carefully tailored to achieve the desired thermal performance.

**Reference**

1. Turgut M. Gür. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. ***Energy Environ. Sci.* 2018, 11**, 2696-2767. <https://doi.org/10.1039/C8EE01419A>.
2. Song, W.; Ge, C.; Zhang, R.; Han, W.; Zhang, X.; Shen, Y. Multiwalled Carbon Nanotubes Encapsulated Polystyrene: A Facile One-Step Synthesis, Electrical and Thermal Properties. *J. Mater. Sci*. **2019**, 54, 6227–6237.

<https://doi.org/10.1007/s10853-018-03267-w>.

1. Fang, Y. K.; Osama, M.; Rashmi, W.; Shahbaz, K.; Khalid, M.; Mjalli, F. S.; Farid, M. M. Synthesis and Thermo-Physical Properties of Deep Eutectic Solvent-Based Graphene Nanofluids. *Nanotechnology*. **2016**, 27, 75702-75714. <https://doi.org/10.1088/0957-4484/27/7/075702>.
2. Babita; Sharma, S. K.; Gupta, S. M. Preparation and Evaluation of Stable Nanofluids for Heat Transfer Application: A Review. *Exp. Therm. Fluid Sci.* **2016,** 79, 202–212. <https://doi.org/10.1016/j.expthermflusci.2016.06.029>.
3. Koorengevel, M. C.; Killian, J. A.; Scheidelaar, S.; Dörr, J. M.; Dominguez, J. J.; van Walree, C. A.; Schäfer, M. The Styrene–Maleic Acid Copolymer: A Versatile Tool in Membrane Research. *Eur. Biophys. J.* **2015,** 45, 3–21.

<https://doi.org/10.1007/s00249-015-1093-y>.

1. Ajithkumar,; M. P. Yashoda M.P.; Prasannakumar S. Synthesis, Characterization, Microstructure Determination and Thermal Studies of Poly (N -Vinyl-2-Pyrrolidone – Maleic Anhydride – Styrene) Terpolymer. *Iran Polym J.* **2014,** 23, 93–101.

<https://doi.org/10.1007/s13726-013-0204-9>.

1. Zhang, W.; Du, Z.; Wang, W.; Wang, T. Synthesis and Aggregation Behavior of Grafted Maleic Acid Copolymers. *J. Colloid Interface Sci.* **2012,** 374, 187–196.

<https://doi.org/10.1016/j.jcis.2012.01.052>.

1. Borode, A. O.; Ahmed, N. A.; Olubambi, P. A. Surfactant-Aided Dispersion of Carbon Nanomaterials in Aqueous Solution. *Phys. Fluids.* **2019,** 31, 071301.

 <https://doi.org/10.1063/1.5105380>.

1. Kim, S.; Tserengombo, B.; Choi, S.; Noh, J.; Huh, S. Experimental Investigation of Dispersion Characteristics and Thermal Conductivity of Various Surfactants on Carbon Based Nanomaterial. *Int. Commun. Heat Mass Transf.* **2018,** 91, 95–102.

<https://doi.org/10.1016/j.icheatmasstransfer.2017.12.011>.

1. Wusiman, K.; Jeong, H.; Tulugan, K.; Afrianto, H.; Chung, H. Thermal Performance of Multi-Walled Carbon Nanotubes (MWCNTs) in Aqueous Suspensions with Surfactants SDBS and SDS. *Int. Commun. Heat Mass Transf.* **2013,** 41, 28–33.

<https://doi.org/10.1016/j.icheatmasstransfer.2012.12.002>.

1. Wang, X. ju; Zhu, D. sheng; yang, S. Investigation of PH and SDBS on Enhancement of Thermal Conductivity in Nanofluids. *Chem. Phys. Lett.* **2009,** 470, 107–111. <https://doi.org/10.1016/j.cplett.2009.01.035>.
2. Li, X. F.; Zhu, D. S.; Wang, X. J.; Wang, N.; Gao, J. W.; Li, H. Thermal Conductivity Enhancement Dependent PH and Chemical Surfactant for Cu-H2O Nanofluids. *Thermochim. Acta.* **2008,** 469, 98–103. <https://doi.org/10.1016/j.tca.2008.01.008>.
3. Shenoy, U. S.; Shetty, A. N. Simple Glucose Reduction Route for One-Step Synthesis of Copper Nanofluids. *Appl. Nanosci.* **2014,** 4, 47–54.

 <https://doi.org/10.1007/s13204-012-0169-6>.

1. Teli, M. D.; Annaldewar, B. N. Superhydrophobic and Ultraviolet Protective Nylon Fabrics by Modified Nano Silica Coating. *The Journal of The Textile Institute,* **2016,** 108 (3), 460-466. <https://doi.org/10.1080/00405000.2016.1171028>.
2. Ghasemi, R.; Fazlali, A.; Mohammadi, A. H. Effects of TiO2 Nanoparticles and Oleic Acid Surfactant on the Rheological Behavior of Engine Lubricant Oil. *J. Mol. Liq.* **2018,** 268, 925–930. https://doi.org/10.1016/j.molliq.2018.07.002.
3. Agble, D. [Mendes-Tatsis](https://www.sciencedirect.com/science/article/pii/S0017931099001842%22%20%5Cl%20%22%21), M.A. The effect of surfactants on interfacial mass transfer in binary liquid–liquid systems, Int. *J. Heat Mass Transf*. **2000,** 43, 1025–1034. [https://doi.org/10.1016/S0017-9310(99)00184-2](https://doi.org/10.1016/S0017-9310%2899%2900184-2).
4. Li, D.; Fang, W.; Feng, Y.; Geng, Q.; Song, M. Stability Properties of Water-Based Gold and Silver Nanofluids Stabilized by Cationic Gemini Surfactants. *J. Taiwan Inst. Chem. Eng.* **2019,** 97, 458–465. <https://doi.org/10.1016/j.jtice.2019.02.017>.
5. Chen, L.; Xie, H. Properties of Carbon Nanotube Nanofluids Stabilized by Cationic Gemini Surfactant. *Thermochim. Acta.* **2010,** 506, 62–66.

<https://doi.org/10.1016/j.tca.2010.04.016>.

1. Wang, J.; Li, G.; Li, T.; Zeng, M.; Sundén, B. Effect of Various Surfactants on Stability and Thermophysical Properties of Nanofluids. *J. Therm. Anal. Calorim.* **2020.** <https://doi.org/10.1007/s10973-020-09381-9>.
2. Shchukina, E. M.; Graham, M.; Zheng, Z.; Shchukin, D. G. Nanoencapsulation of Phase Change Materials for Advanced Thermal Energy Storage Systems. *Chem. Soc. Rev.* **2018,** 47, 4156–4175. <https://doi.org/10.1039/c8cs00099a>.
3. Kong, L.; Sun, J.; Bao, Y. Preparation, characterization and tribological mechanism of nanofluids. ***RSC Adv.*** **2017, 7,** 12599–12609. <https://doi.org/10.1039/c6ra28243a>.
4. Gaikwad, D. S.; Undale, K. A.; Patil, D. B.; Pore, D. M.; Kamble, A. A. Triton X-100 Stabilized Pd Nanoparticles and Their Catalytic Application in One-Pot Sequential Heck and Hiyama Coupling in Water. *Res. Chem. Intermed.* **2018,** 44, 265–275. <https://doi.org/10.1007/s11164-017-3102-5>.
5. Choi, T. J.; Jang, S. P.; Kedzierski, M. A. Effect of Surfactants on the Stability and Solar Thermal Absorption Characteristics of Water-Based Nanofluids with Multi-Walled Carbon Nanotubes. *Int. J. Heat Mass Transf.* **2018,** 122, 483–490.
6. Iyahraja, S., Rajadurai, J.S. Stability of Aqueous Nanofluids Containing PVP-Coated Silver Nanoparticles. *Arab J Sci Eng.* **2016,** 41,653–660.

<https://doi.org/10.1007/s13369-015-1707-9>.

1. Khamliche, T.; Khamlich, S.; Doyle, T. B.; Makinde, D.; Maaza, M. Thermal Conductivity Enhancement of Nano-Silver Particles Dispersed Ethylene Glycol Based Nanofluids. *Mater. Res. Express.* **2018,** 5, 035020. <https://doi.org/10.1088/2053-1591/aab27a>.
2. Zhao, Y.; Wang, Z.; Zhang, W.; Jiang, X. Adsorbed Tween 80 Is Unique in Its Ability to Improve the Stability of Gold Nanoparticles in Solutions of Biomolecules. *Nanoscale.* **2010,** 2, 2114–2119. <https://doi.org/10.1039/c0nr00309c>.
3. Hwang, Y.; Lee, J. K.; Lee, C. H.; Jung, Y. M.; Cheong, S. I.; Lee, C. G.; Ku, B. C.; Jang, S. P. Stability and Thermal Conductivity Characteristics of Nanofluids. *Thermochim. Acta.* **2007,** 455, 70–74. <https://doi.org/10.1016/j.tca.2006.11.036>.
4. Liu, X. Y. Z. A Kind of Nanofluid Consisting of Surface-Functionalized Nanoparticles. [*Nanoscale Research Letters*](https://www.researchgate.net/journal/1556-276X_Nanoscale_Research_Letters)*.* **2010,** 5, 1324–1328.

<https://doi.org/10.1007/s11671-010-9646-6>.

1. Chen, L.; Xie, H.; Li, Y.; Yu, W. Nanofluids Containing Carbon Nanotubes Treated by Mechanochemical Reaction. *Thermochimica Acta.* **2008,** 477, 21–24.

<https://doi.org/10.1016/j.tca.2008.08.001>.

1. Chen, L.; Xie, H. Surfactant-Free Nanofluids Containing Double- and Single-Walled Carbon Nanotubes Functionalized by a Wet-Mechanochemical Reaction. *Thermochimica Acta.* 2010, 497, 67–71. <https://doi.org/10.1016/j.tca.2009.08.009>.
2. Far, M. H.; Bogdanchikova, N.; Basiuk, V. A. Solvent-free one-step covalent functionalization of graphene oxide and nanodiamond with amines. ***RSC Adv.*** **2016,** **6**, 113596-113610. <https://doi.org/10.1039/C6RA22658B>.
3. Wang, R.; Liu, W. Cost effective surface functionalization of gold nanoparticles with a mixed DNA and PEG monolayer for nanotechnology applications. ***RSC Adv.*** **2017,** 7, 3676–3679. <https://doi.org/10.1039/C6RA26791B>.
4. Missana, T. On the Applicability of DLVO Theory to the Prediction of Clay Colloids Stability. *J. Colloid Interface Sci.* **2000,** 156, 150–156.

<https://doi.org/10.1006/jcis.2000.7003>.

1. Carstens, J. F.; Bachmann, J.; Neuweiler, I. A New Approach to Determine the Relative Importance of DLVO and Non- DLVO Colloid Retention Mechanisms in Porous Media. *Colloids Surf. A.* **2019,** 560, 330–335. <https://doi.org/10.1016/j.colsurfa.2018.10.013>.
2. Popa, I.; Gillies, G.; Papastavrou, G.; Borkovec, M. Attractive and Repulsive Electrostatic Forces between Positively Charged Latex Particles in the Presence of Anionic Linear Polyelectrolytes. *J. Phys. Chem. B.* **2010,** 114, 9, 3170–3177.

 <https://doi.org/10.1021/jp911482a>.

1. Choudhary, R.; Khurana, D.; Kumar, A.; Subudhi, S. Stability Analysis of Al2O3 / Water Nanofluids. *J of Exp. Nanoscience.* **2017,** 12, 140-151.

<https://doi.org/10.1080/17458080.2017.1285445>.

1. Ghadimi, A.; Metselaar, I. H. The Influence of Surfactant and Ultrasonic Processing on Improvement of Stability, Thermal Conductivity and Viscosity of Titania Nanofluid. *Exp. Therm. Fluid Sci.* **2013,** 51, 1–9. <https://doi.org/10.1016/j.expthermflusci.2013.06.001>.
2. Mo, S.; Chen, Y.; Jia, L.; Luo, X. Investigation on Crystallization of TiO2 – Water Nanofluids and Deionized Water. *Appl. Energy*. **2012,** 93, 65–70.

<https://doi.org/10.1016/j.apenergy.2011.07.014>.

1. Li, D.; Hong, B.; Fang, W.; Guo, Y.; Lin, R. Preparation of Well-Dispersed Silver Nanoparticles for Oil-Based Nanofluids. *Ind. Eng. Chem. Res.* **2010,** 49, 1697–1702. <https://doi.org/10.1021/ie901173h>.
2. Hwang, Y.; Lee, J.; Lee, J.; Jeong, Y.; Cheong, S.; Ahn, Y.; Kim, S. H. Production and Dispersion Stability of Nanoparticles in Nanofluids. *Powder Tech*, **2008,** 186, 145–153. <https://doi.org/10.1016/j.powtec.2007.11.020>.
3. Sahooli, M.; Sabbaghi, S. Preparation of CuO / Water Nanofluids Using Polyvinyl pyrolidone and a Survey on Its Stability and Thermal Conductivity. *Int. J. Nanosci. Nanotechnol.* **2012,** 8, 27-34.
4. Bandyopadhyaya, R.; Nativ-roth, E.; Regev, O.; Yerushalmi-rozen, R. Stabilization of Individual Carbon Nanotubes in Aqueous Solutions. *Nano Letters.* **2002,** 2, 25–28. <https://doi.org/10.1021/nl010065f>.
5. Asua, M.; Leiza, R. The Role of Methyl Methacrylate on Branching and Gel Formation in the Emulsion Copolymerization of BA / MMA*. Polymer.* **2007,** 48, 2542–2547. <https://doi.org/10.1016/j.polymer.2007.03.015>.
6. Piacenza, E.; Presentato, A.; Turner, R. J.; Piacenza, E.; Presentato, A.; Stability, R. J. T. Stabilization Theory of Chemical Nanostructures Stability of Biogenic Metal (Loid) Nanomaterials Related to the Colloidal Stabilization Theory of Chemical Nanostructures. *Crit. Rev. Biotechnol.* **2018,** 38, 1137–1156.

<https://doi.org/10.1080/07388551.2018.1440525>.

1. Yeap, S. P.; Ahmad, A. L.; Ooi, B. S.; Lim, J. Electrosteric Stabilization and Its Role in Cooperative Magnetophoresis of Colloidal Magnetic Nanoparticles. *Langmuir* **2012,** 28, 14878–14891. <https://doi.org/10.1021/la303169g>.
2. González, E.; Paulis, M.; Barandiaran, M. J. Effect of Controlled Length Acrylic Acid-Based Electrosteric Stabilizers on Latex Film Properties. [*European Polymer J*](https://www.sciencedirect.com/science/journal/00143057)*.* **2014,** 59, 122–128. <https://doi.org/10.1016/j.eurpolymj.2014.07.023>.
3. Samyn, P.; Deconinck, M.; Schoukens, G.; Stanssens, D. Synthesis and Characterization of Imidized Poly (Styrene-Maleic Anhydride) Nanoparticles in Stable Aqueous Dispersion. *Polym. Adv. Technol.* **2012,** 23, 311–325.

 <https://doi.org/10.1002/pat.1871>.

1. Huang, J.; Turner, S. R. Recent Advances in Alternating Copolymers: The Synthesis, Modification, and Applications of Precision Polymers. *Polymer.* **2017,** 116, 572–586. <https://doi.org/10.1016/j.polymer.2017.01.020>.
2. Bai, Y.; Ma, X.; Wang, W.; Yin, Q.; Du, Z.; Wang, G. Synthesis, Aggregation and Dispersity Properties of Novels Amphiphilic Comb-like Terpolymers. *Colloids Surfaces A Physicochem. Eng. Asp.* **2016,** 526, 40-47.

<https://doi.org/10.1016/j.colsurfa.2016.11.011>.

1. Amstad, E.; Reimhult, E. Nanoscale Stabilization and Functionalization of Iron Oxide Nanoparticles for Biomedical Applications. ***Nanoscale*,** **2011, 3**, 2819-2843.

<https://doi.org/10.1039/c1nr10173k>.

1. Reutz, S.; Jérôme, R.; Kaptijn, G.M.P. *et al.* Design of Polymeric Dispersants for Waterborne Coatings. *Journal of Coatings Technology,* **1998,** 70,41–46.

<https://doi.org/10.1007/BF02720518>.

1. Yossif, N. A.; Kandile, N. G.; Abdelaziz, M. A.; Negm, N. A. Preparation and Characterization of Polymeric Dispersants Based on Vegetable Oils for Printing Ink Application. *Prog. Org. Coatings*. **2017,** 111, 354–360.

<https://doi.org/10.1016/j.porgcoat.2017.06.005>.

1. Hasan, A. M. A.; Abdel-raouf, M. E. Applications of Guar Gum and Its Derivatives in Petroleum Industry: A Review. *Egypt. J. Pet.* **2018,** 27, 1043–1050.

<https://doi.org/10.1016/j.ejpe.2018.03.005>.

1. Wang, S.; Gao, M.; Liu, Y.; Sun, Y.; Zhao, M. The first study of surface modified silica nanoparticles in pressure-decreasing application. ***RSC Adv.*** **2015, 5**, 61838-61845.

<https://doi.org/10.1039/C5RA09883A>.

1. [Kharisov](https://pubs.rsc.org/en/results?searchtext=Author%3ABoris%20I.%20Kharisov), B. L.;   [Dias](https://pubs.rsc.org/en/results?searchtext=Author%3AH.%20V.%20Rasika%20Dias),H. V. R.;   [Kharissova](https://pubs.rsc.org/en/results?searchtext=Author%3AOxana%20V.%20Kharissova), O. V. Solubilization, dispersion and stabilization of magnetic nanoparticles in water and non-aqueous solvents: recent trends***. RSC Adv.*** **2014, 4**, 45354-45381. <https://doi.org/10.1039/C4RA06902A>.
2. Raj, S. I.; Jaiswal, A.; Uddin, I. Tunable porous silica nanoparticles as a universal dye adsorbent. [*RSC Adv.*](file:///D%3A%5CThesis%5CThesis%20final%5CCorrected%5CRSC%20Adv) **2019,** **9**, 11212-11219. <https://doi.org/10.1039/c8ra10428j>.
3. Peng, F.; [Ke](https://pubs.rsc.org/en/results?searchtext=Author%3AYangchuan%20Ke), Y.; [Lu](https://pubs.rsc.org/en/results?searchtext=Author%3AShichao%20Lu), S.; [Deng](https://pubs.rsc.org/en/results?searchtext=Author%3AQingchun%20Deng) Q. Anion Amphiphilic Random Copolymers and Their Performance as Stabilizers for O/W Nanoemulsions. *RSC Adv.* **2019,** 9, 14692-14700. <https://doi.org/10.1039/c9ra01383k>.
4. Jin, J. et al. An efficient and environmental-friendly dispersant based on the synergy of amphiphilic surfactants for oil spill remediation. *Chemosphere.* **2019,** 215, 241–247. https://doi.org/10.1016/j.chemosphere.2018.09.159.
5. Al-Sabagh,; A. M., Sabaa, M. W.; et al. Synthesis of polymeric additives based on itaconic acid and their evaluation as pour point depressants for lube oil in relation to rheological flow properties. *Egypt. J. Pet.* **2012**, 21, 19–30.

https://doi.org/10.1016/j.ejpe.2012.02.003.

1. Ponmani, S., Gupta, P., Jadhawar, P. & Nagarajan, R. Investigations on the thermal and electrical conductivity of polyethylene glycol-based CuO and ZnO nanofluids. *Indian Chem. Eng.* **2019,** 1–11. https://doi.org/10.1080/00194506.2019.1677513.
2. Liu, J., Ran, Q., Miao, C. & Zhou, D. Synthesis and characterization of comb-like copolymer dispersant with methoxy poly (ethylene oxide) side chains. *Polym. - Plast. Technol. Eng*. **2011,** 50, 59–66. https://doi.org/10.1080/03602559.2010.512351.