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AN UPDATED OVERVIEW OF THE THERMOPHYSICAL CHARACTERISTICS OF NANOFLUIDS

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ABSTRACT

The current state of knowledge about thermophysical characteristics of nanofluids plays an essential role in the further development of decades to improve diverse heat transfer applications. This paper discusses about four thermophysical properties of nanofluids that varies accordingly by adding specified nanoparticles in the base fluid. These properties include density, specific heat, thermal conductivity, and viscosity. The main contribution of the overview paper different researchers has expressed different opinions about the effect of adding nanofluids on the values of these thermophysical properties. This study highlights the key findings concerning the enhancement of the thermophysical characteristics of nanofluids. There is a further development of nanofluids which makes suitable and knowing thermophysical properties more easily and reduces the complexity of characteristics of nanofluids to fulfill research of gaps of future research in this emerging field.

Keywords: Nanofluids, Density, Specific Heat, Thermal Conductivity, Viscosity.

I. INTRODUCTION

In the last several decades, technology has advanced significantly in a variety of industries. As a result, the necessity to enhance outcomes by maximizing advantages, minimizing thermal losses, and above all, improving method performance and adding new properties has led to a scenario in which nearly all research groups have identified the benefits of nanotechnology in their particular fields of study.

Heat transfer is no exception, since it is a critical factor that must be considered in the majority of modern industrial processes, such as application power generation, chemical, physical, and biological processes. On the other hand, refrigerated chambers, electronic cooling systems, datacenters, and power electronics all require it. However, heat transmission is required not just on an industrial scale, but also in the household, as well as in private and public structures. As a result, it is a problem that affects the entire society.

Traditional coolants, such as water, oils, and ethylene glycol, remain static due to their limits in terms of enhancing heat transfer capabilities. The thermo-physical characteristics of coolants in these liquids are constant. Then, nanotechnology appears as a viable alternative to investigate in order to assess the possibilities it provides for meeting heating and cooling transfer demands on an industrial scale.

In this case, there is a growing thought that considers this demand can be fulfilled through the usage of nanofluids. For this reason, at the moment, there are lots of research groups investigating this path, and some promising results are being observed although the physical background for nanofluids is still under research and development.

Development of nanofluids

Norio Taniguchi coined the term "nanotechnology" in 1974. He defined nanotechnology as the engineering of nanometer-sized materials. The researcher (1) coined the term “nanofluid” 1995 to describe this combination. Since then, the primary goal of nanofluids research has been to produce better heat transfer fluids. As evidenced by the fact that studies numbered just 10 in 2001, but climbed to 175 in 2006, 700 in 2011, and 2500 in 2018, nanofluids research has expanded throughout the years, leading to additional development for different decades of future technologies.

Modern nanotechnology has permitted the fabrication of metallic and nonmetallic nanoparticles of average sizes (less than 100 nm). Nanoparticles have superior mechanical, optical, electrical, magnetic, and thermal characteristics than conventional materials with coarse grain particles (2). Recognizing the possibility to employ nanotechnology in thermal engineering, Stephen Choi and his colleagues at the ANL (Argonne National Laboratory) introduced the idea of nanofluids in 1994 .

Recognizing the possibility to employ nanotechnology in thermal engineering, Stephen Choi and his colleagues at the ANL (Argonne National Laboratory) introduced the idea of nanofluids in 1994 and researched challenges connected to nanofluid foundations and applications. Researchers from Japan and Germany have also published papers describing fluids that are similar to the notion of nanofluids created at ANL. Japanese researchers(3).

Concept of Nanofluids

Nanofluids are a relatively new type of fluid that consists of a base fluid suspended in nano-sized particles (1–100 nm). These particles, which are usually made of metal or metal oxide, improve conduction and convection coefficients, allowing more heat to be transferred from the coolant(4).

In the past few decades, rapid advances in nanotechnology have lead to emerging of new generation of coolants called "nanofluids". Nanofluids are dilute suspensions of functionalized nanoparticles composite materials developed about a decade ago with the specific aim of increasing the properties of heat transfer fluids, which have now evolved into a promising nanotechnological area. Thermal nanofluids for heat transfer applications are distinct from ordinary colloids used in other applications. Compared to conventional solid–liquid suspensions for heat transfer intensifications, nanofluids possess the following advantages (4):

- More heat transfer surface between particles and fluids due to high specific surface area.
- Particle motion is dominated by Brownian motion, resulting in high dispersion stability.
- When compared to pure liquid, less pumping power is required to achieve equivalent heat transfer intensification.

II. METHODOLOGY

Method and analysis which is performed in your research work should be written in this section. A simple strategy to follow is to use keywords from your title in first few sentences.

Preparation of Nanofluids

The preparation of nanofluids is the first step in studying nanofluids experimentally. Two processes are used to make nanofluids: two-step preparation and one-step preparation.

Two step method

Nanoparticles, nanofibers, nanotubes, and other nanomaterials are used in the method, which are first made as dry powders using chemical or physical methods. By combining base fluids with commercially available nanopowders obtained through various mechanical, physical, and chemical routes, the method is widely used to synthesise nanofluids (e.g., milling, grinding, and sol-gel and vapour phase methods). To stir nanopowders with base fluids, ultrasonic vibrators or high shear mixing devices are commonly used.

Particle agglomeration is reduced when ultrasonication or stirring is used frequently(5). Agglomeration is a major issue in synthesizing nanofluids(6). The two-step method is the most economical method for large-scale production of nanofluids because nanopowder synthesis techniques have already been scaled up to industrial production levels(7). Because of their high surface area and activity, nanoparticles tend to agglomerate(8).

The two-step approach, According to researchers(9), is better at preparing nanofluids containing oxide nanoparticles than those with metallic nanoparticles. The powders combine quickly due to the high van der Waals interaction between nanoparticles, making stability a critical challenge for this approach.Despite its drawbacks, the approach is widely acknowledged as the most cost-effective method for generating nanofluids (10).

Although the process is cost-effective, it raises concerns about drying, storage, and transportation. Agglomeration and plugging issues reduce the thermal conductivity of nanofluids.

The benefit of this technology is that nanofluids may be produced on a huge scale. Nanoparticle aggregations, on the other hand, are difficult to break up using ultrasonication or stirring. As a result, the stability and thermal conductivity of nanofluids generated through dispersion are rarely optimal.

The two-step technique is depicted in shown below

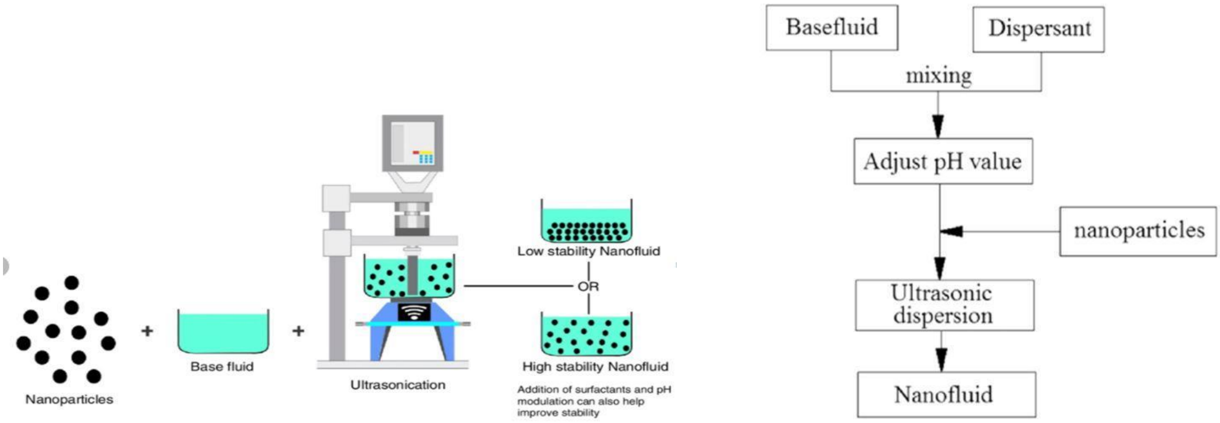


Figure 1: Two step method of nano-fluid preparation.

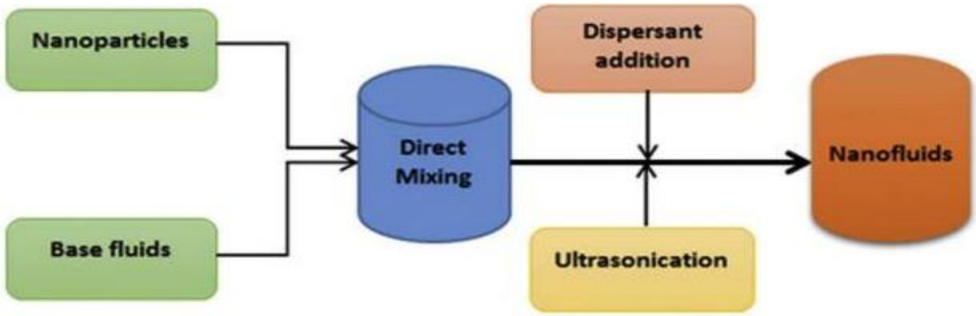


Figure 2: Two-step preparation process of nanofluids.

One step method

Due to the general difficulties in manufacturing stable nanofluids using the two-step procedure, advanced ways for producing nanofluids in a single step are being developed. The direct evaporation and condensation method, SANSS (submerged-arc nanoparticle synthesis system), and laser ablation methods(11) are examples of one-step processes in which metals are evaporated using physical technology and cooled into liquids to produce nanofluids.

These physical approaches produce stable nanofluids and have excellent control over particle sizes. The one-step process involves manufacturing and spreading particles in fluids at the same time(12). The approach incorporates both chemical liquid deposition and vapor deposition. Several researchers have employed this approach to create nanofluids. To reduce nanoparticle agglomeration and maximize fluid stability, by this approach avoids drying, storage, transportation, and nanoparticle dispersion(13).

The approach creates nanoparticles that are uniformly disseminated and stably suspended in base fluids. The method lowers manufacturing costs(14) Vacuum SANSS creates nanofluids from various dielectric liquids. The varying thermal conductivity qualities of dielectric liquids primarily impact and determine different morphologies. The nanoparticles created have needle-like, polygonal, square, and circular morphological forms. The approach does a good job of avoiding unwanted particle aggregation.

The method's principal disadvantage is that residual reactants remain in the nanofluids due to incomplete reaction or stabilization. It is difficult to explain the nanoparticle effect without addressing the impurity effect. Furthermore, a one-step CSM (chemical solution method) for designing nanofluids has recently been developed. CSM is capable of synthesizing nanofluids with a variety of microstructures and has successfully manufactured nine different types of nanofluids.

CSM-synthesised nanofluids show stronger conductivity enhancement and better stability than other approaches. Controllability is another feature that distinguishes CSM from other techniques. When using the one-step process, however, it is easy to synthesize nanofluids on a wide scale. The nanofluid microstructure can be altered and modified by modifying synthesis parameters [e.g., temperature, acidity (pH), ultrasonic and microwave irradiation, reactant and additive types and concentrations], as well as the order in which the additives are added to the solution(15).

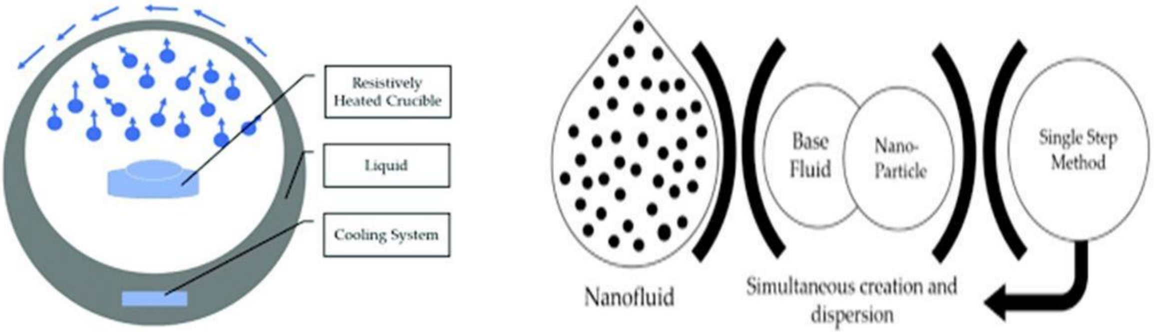
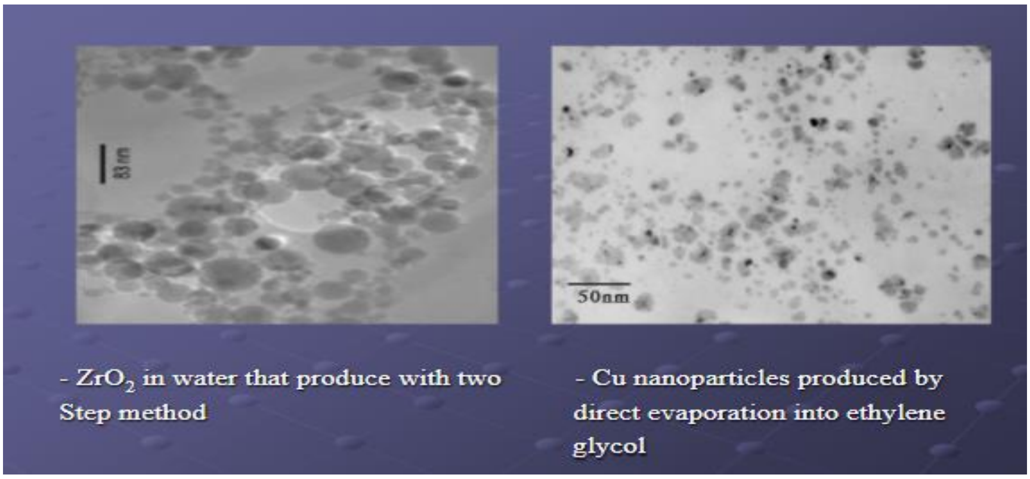


Figure 3: Vapor deposition method.



- ZrO_2 in water that produce with two Step method

- Cu nanoparticles produced by direct evaporation into ethylene glycol

Figure 4: Two step method nanofluids observed under scanning electron microscope.

Stability of Nanofluids

The fundamental difficulty in preparing nanofluids is their low stability, which is caused by the formation of agglomerates, which is caused by high surface areas and strong van der Waals forces between nanoparticles. Because the thermo-physical properties of unstable fluids alter over time, the stability of nanofluids is critical in practical applications. Although several methods for preparing nanofluids have been devised, all of them have instability issues due to particle agglomeration in base fluids.

The presence of uniformly diffused nanoparticles in the base fluid is required for stability. When nanofluids are stable, their thermal and electrical properties improve (16). The agglomeration of nanoparticles not only settles and blocks micro channels, but it also reduces the thermal conductivity of nanofluids (17).

Thus, the stability of nanofluids should be explored because it has a substantial impact on the properties of nanofluids for application; the factors influencing nanofluid dispersion stability should also be studied and assessed (18).

Surfactants improve the stability of nanoparticles in fluids. Surfactant functionality at high temperatures, on the other hand, is a serious challenge, particularly for high-temperature applications.

The sedimentation method, commonly known as the settling bed, is the most important and widely used approach for determining the stability of a nanofluid. Light absorbance is measured or the bed height is visually monitored over time using this method.

The main disadvantage of utilising this method on relatively slow settling suspensions is the long observation period; a faster alternative incorporates time-resolved determination of the sample's zeta potential. Another downside of this approach is that it limits sample viscosity and particle concentration.

The definition of stable nanofluids is unclear. Nonetheless, nanofluids are widely accepted to be stable when they remain as a single entity for an extended period of time (often three consecutive months or more from the date of preparation).

The below figure depicts two nanofluid samples, one of which is visually stable and the other in which particles are visibly separated from the liquid.

Figure 5: Stable (left) and unstable(right) nanofluids.

Thermophysical properties nanofluids:-

Nanofluids have four thermophysical properties that change when nanoparticles are added to the base fluid. Density, viscosity, thermal conductivity, and specific heat are some of these properties.

Different researchers have expressed differing opinions on the effect of nanoparticles on the values of these properties, but adding nanoparticles changes these thermophysical properties in general.

The addition of nanoparticles increases thermal conductivity, according to the majority of researchers. Three other properties, on the other hand, yielded different results. These properties have been reported to improve as well as decrease. The percentage of these changes is determined by a number of factors, including the volume percentage of nanoparticles, nanoparticle properties, temperature, and, most importantly, the base fluid.

The addition of nanoparticles, for example, increases the heat capacity of the base fluid, according to reference (19), while some researchers (20). reported different expressions. The addition of nanoparticles to the base fluid improves the nanofluid's heat capacity, according to the researchers. To determine these properties, either experimental or theoretical methods are employed. Although numerous experimental and theoretical studies have been conducted to investigate the thermophysical properties of various nanofluids, no suitable theories for predicting the thermal conductivity and viscosity of nanofluids based on the properties of nanoparticles and base fluids exist.

Although experimental methods are more reliable than theoretical methods, they are often difficult to implement due to the requirement of specialised equipment. Artificial neural networks have recently piqued the interest of scientists. Human brain function in identifying phenomena has inspired one of artificial intelligence's subjects. Artificial neural networks can be used to predict and model the phenomena. Predicting and modelling the thermophysical properties of nanofluids is one of its application.

Density (ρ): Density is defined as the mass per unit volume, and its units are kilogrammes per cubic metre (kg/m3). The fact that density varies with temperature and pressure is an important consideration when studying the temperature effect. This property is also important when making dispersions, because it's difficult to get a homogeneous mixture of materials with different densities.

Density: - mass /volume

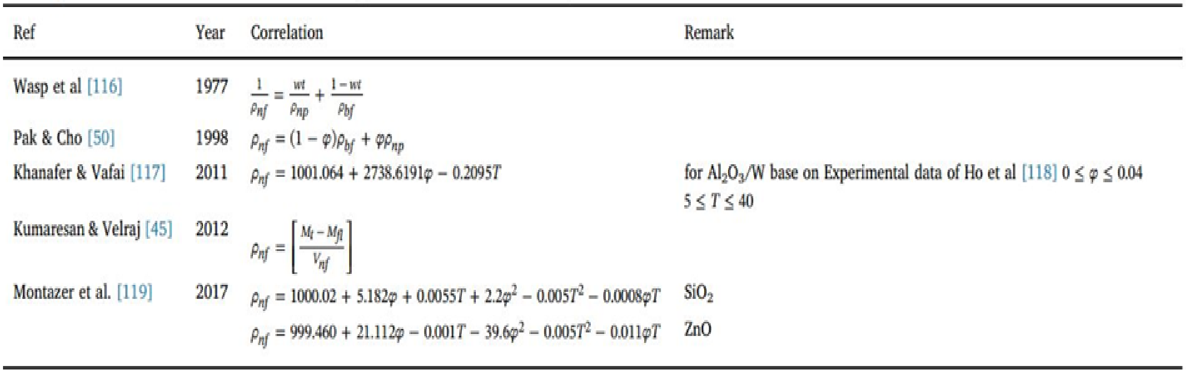
Emprical formula density :-

The effective density of nanofluid can be calculated easily .The density of a two-phase fluid is typically considered to be the product of the nanoparticle's density and the base fluid's volume concentration. The standard formula for calculating nanofluid density is as follows:

$$\rho nf=(1-\varphi)\rho bf + \varphi np \qquad (1)$$

“ρnp”, “ρnf”, “φ” and ρbf represent the nanofluid particle, the nanoparticle fluid, & volume concentration, and the base fluid density.

Density of empirical relations of various researchers listed out shown below :-



Ref	Year	Correlation	Remark
Wasp et al [116]	1977	$\frac{1}{\rho_{nf}}=\frac{wt}{\rho_{np}}+\frac{1-wt}{\rho_{bf}}$	
Pak & Cho [50]	1998	$\rho_{nf}=(1-\varphi)\rho_{bf}+\varphi\rho_{np}$	
Khanafer & Vafai [117]	2011	$\rho_{nf}=1001.064+2738.6191\varphi-0.2095T$	for Al_2O_3/W base on Experimental data of Ho et al [118] $0\leq\varphi\leq0.04$ $5\leq T\leq40$
Kumaresan & Velraj [45]	2012	$\rho_{nf}=\left[\frac{M_t-M_{fl}}{V_{nf}}\right]$	
Montazer et al. [119]	2017	$\rho_{nf}=1000.02+5.182\varphi+0.0055T+2.2\varphi^2-0.005T^2-0.0008\varphi T$	SiO_2
		$\rho_{nf}=999.460+21.112\varphi-0.001T-39.6\varphi^2-0.005T^2-0.011\varphi T$	ZnO

Figure 6: Empirical relations for density nanofluids values

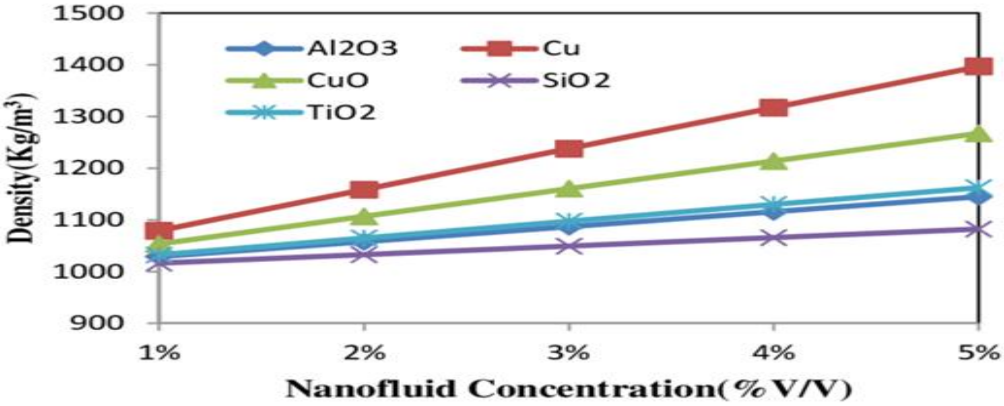


Figure 7: Density vs Nanofluid Concentration

Specific Heat

The ratio of the amount of energy that must be transferred to or from one unit of mass or amount of substance in order to change the system temperature by one degree is defined. J/kgK is the most common unit of measurement. As a result, it is preferable to use dilutions with high specific heats because this will aid in achieving high heat coefficient transfer in processes

$$Q=m*cp*\Delta t \qquad (2)$$

The heat recovery property of the fluid is directly influenced by the specific heat capacity of the nanofluids. Predicting the specific heat performance of nanofluids with accuracy expands their application possibilities. As a result, a variety of models for determining the specific heat capacity of nanofluids have been proposed. Using mixture theory, the specific heat of a water-based conventional nanofluid was calculated.

$$C_{nf}=C_{np}\varphi+C_{bf}(1-\varphi) \qquad (3)$$

Another method for predicting the specific heat of nanofluids is the thermal equilibrium model. The thermal equilibrium model, as shown in Eq (4), includes nanoparticle and base-fluid densities as variables that affect nanofluid-specific heat. Even though there are still significant differences between the model and experimental results, the thermal equilibrium model performed better than the mixture theory model.

$$\rho_{nf}C_{nf}=\rho_{np}C_{np}\varphi+c_{bf}\rho_{bf}(1-\varphi) \qquad (4)$$

where “Cbf” is the specific heat of the base fluid (21)

Other models for predicting the specific heat of nanofluids have been proposed in the last decade. Using thermal equilibrium models, (Zhou, 2010) proposed Eq. 5, (Shin, 2011) proposed Eq.6, and proposed (Kumaresan, 2012) Eq. 7 for predicting specificheat :

$$C_{nf}=[\rho_{np}C_{np}\varphi+C_{bf}\rho_{bf}(1-\varphi)]/[\varphi_{bf}\rho_{bf}+(1-\varphi)\rho_{np}] \qquad (5)$$

$$C_{pt}=(\varphi\varphi_{np}C_{np}+\varphi_{bf\rho np}\rho_{bf}C_{bf})/(\varphi_{np}+\rho_{np}+\varphi_{nf}\rho_{nf}) \qquad (6)$$

$$C_{nf}=[\rho_{np}C_{np}\varphi+C_{bf}\rho_{bf}(1-\varphi)]/[\varphi_{np}+(1-\varphi\rho_{bf})] \qquad (7)$$

Where,

φ = volume concentration

Over a wide range of volume concentrations, none of the proposed numerical equations accurately and consistently predicts the specific heat of nanofluids. For specific heat prediction, regression correlation equations have been found to be more accurate than classical models.

While the exact model for accurate specific heat prediction is still being developed, some outlines can be derived from existing experimental data. The volume concentration of nanoparticles, the nature of the base fluid, and the temperature of the fluid all influence the specific heat of nanofluids. The specific heat of water-based nanofluids tends to decrease as the volume concentration of nanoparticles increases.

The below graph shows specific heat vs volume concentration of varies for different nanofluids.

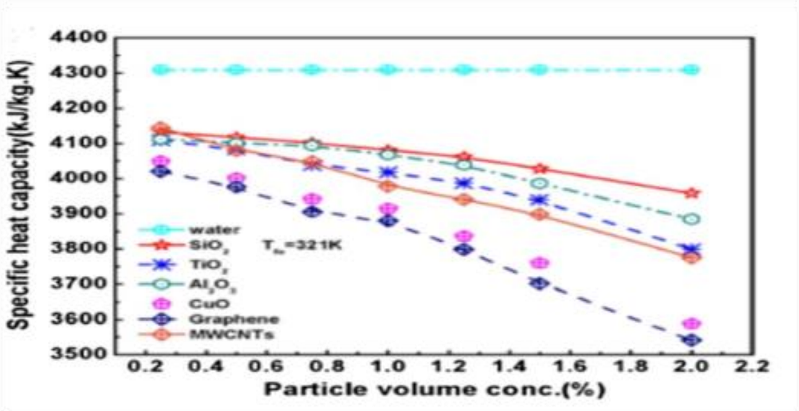
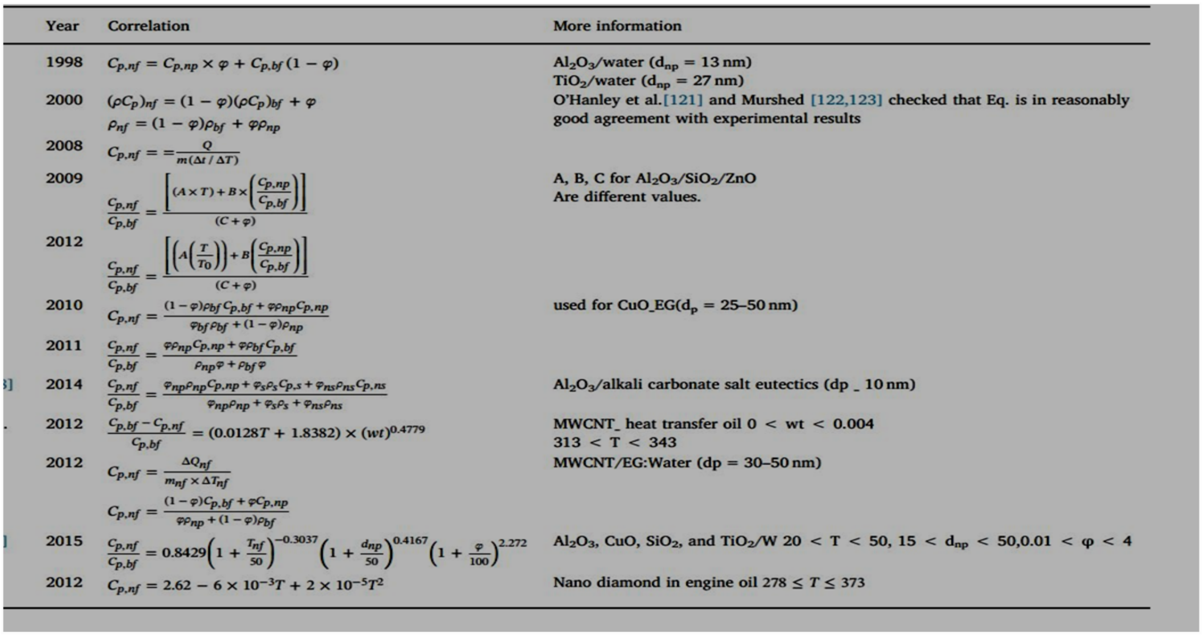


Figure 8: Specific heat vs volume concentration

Specific heat theoretical and empirical relations of various nanofluids:-



Year	Correlation	More information
1998	$C_{p,nf} = C_{p,np} \times \varphi + C_{p,bf}(1-\varphi)$	Al$_2$O$_3$/water (d_{np} = 13 nm) TiO$_2$/water (d_{np} = 27 nm)
2000	$(\rho C_p)_{nf} = (1-\varphi)(\rho C_p)_{bf} + \varphi$ $\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_{np}$	O'Hanley et al.[121] and Murshed [122,123] checked that Eq. is in reasonably good agreement with experimental results
2008	$C_{p,nf} = = \frac{Q}{m(\Delta t / \Delta T)}$	
2009	$\frac{C_{p,nf}}{C_{p,bf}} = \frac{\left[(A \times T) + B \times \left(\frac{C_{p,np}}{C_{p,bf}}\right)\right]}{(C+\varphi)}$	A, B, C for Al$_2$O$_3$/SiO$_2$/ZnO Are different values.
2012	$\frac{C_{p,nf}}{C_{p,bf}} = \frac{\left[\left(A\left(\frac{T}{T0}\right)\right) + B\left(\frac{C_{p,np}}{C_{p,bf}}\right)\right]}{(C+\varphi)}$	
2010	$C_{p,nf} = \frac{(1-\varphi)\rho_{bf} C_{p,bf} + \varphi\rho_{np} C_{p,np}}{\varphi_{bf}\rho_{bf} + (1-\varphi)\rho_{np}}$	used for CuO_EG(d_p = 25–50 nm)
2011	$\frac{C_{p,nf}}{C_{p,bf}} = \frac{\varphi\rho_{np} C_{p,np} + \varphi\rho_{bf} C_{p,bf}}{\rho_{np}\varphi + \rho_{bf}\varphi}$	
2014	$\frac{C_{p,nf}}{C_{p,bf}} = \frac{\varphi_{np}\rho_{np} C_{p,np} + \varphi_s\rho_s C_{p,s} + \varphi_{ns}\rho_{ns} C_{p,ns}}{\varphi_{np}\rho_{np} + \varphi_s\rho_s + \varphi_{ns}\rho_{ns}}$	Al$_2$O$_3$/alkali carbonate salt eutectics (dp _ 10 nm)
2012	$\frac{C_{p,bf} - C_{p,nf}}{C_{p,bf}} = (0.0128T + 1.8382) \times (wt)^{0.4779}$	MWCNT_ heat transfer oil 0 < wt < 0.004 313 < T < 343
2012	$C_{p,nf} = \frac{\Delta Q_{nf}}{m_{nf} \times \Delta T_{nf}}$ $C_{p,nf} = \frac{(1-\varphi)C_{p,bf} + \varphi C_{p,np}}{\varphi\rho_{np} + (1-\varphi)\rho_{bf}}$	MWCNT/EG:Water (dp = 30–50 nm)
2015	$\frac{C_{p,nf}}{C_{p,bf}} = 0.8429\left(1 + \frac{T_{nf}}{50}\right)^{-0.3037}\left(1 + \frac{d_{np}}{50}\right)^{0.4167}\left(1 + \frac{\varphi}{100}\right)^{2.272}$	Al$_2$O$_3$, CuO, SiO$_2$, and TiO$_2$/W 20 < T < 50, 15 < d_{np} < 50,0.01 < φ < 4
2012	$C_{p,nf} = 2.62 - 6 \times 10^{-3}T + 2 \times 10^{-5}T^2$	Nano diamond in engine oil 278 ≤ T ≤ 373

Figure 9: A synopsis of the research on theoretical and experimental models for the specific heat of nanofluids.

Thermal conductivity

The ability of a substance to conduct heat is determined by its thermal conductivity. It is calculated by dividing the rate of heat flow through an area in a substance by the area and subtracting the component of the temperature gradient in the flow direction, yielding W/mK. When high thermal conductivity nanoparticles are added to a fluid, the thermal conductivity of the dispersion is expected to increase.

$$K=\Delta Q/\Delta T*1/A*x/\Delta T \qquad (8)$$

In various engineering and industrial devices, the cooling process is one of the most difficult challenges. Motion, ignition, chemical reactions, and other factors all contribute to the generation of heat in various devices. A variety of fluids are used to keep these devices cool. These fluids' low thermal conductivity slows the cooling of these devices. Choi (Choi S. U., 1995) is discovered in 1995 that adding a nanoparticle to a base fluid increased the fluid's thermal conductivity for the first time.

Solids have a higher thermal conductivity than the fluids used to cool various devices, such as most metals, nonmetals, metal and nonmetal oxides, some composites, and others. The thermal conductivity of fluids can be improved by incorporating these nanoscale solids into the base fluid.

Nanofluids are classified according to the type of nanoparticles and the base fluid used. Adding metal nanoparticles to a basic fluid like water, ethyleneglycol, or a variety of oils (Pankaj Sharma, 2011) was one way to investigate thermal conductivity. Metal oxides are also one of the most commonly used nanoparticles in nanofluids, and many researchers have studied them (Haoran Li, 2015).

Other types of nanoparticles used to make nanofluids include nonmetals and nonmetal oxides (Gaweł Żyła, 2017,). Carbon nanotubes have also become commonplace in recent years (Liu Yang, 2017).

Hybrid nanofluids, on the other hand, are a relatively new type of nanofluid that has recently attracted the attention of many researchers. There are several different types of nanofluids used in this type of nanosilate. Many researchers (Ahmet Selim Dalkılıç, 2017)are interested in these nanofluids because they have better properties than mono nanofluids.

Thermal conductivity of different nanoparticles :-

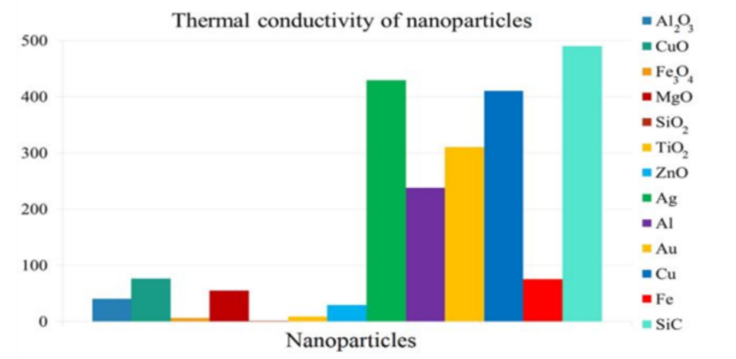


Figure 10: Thermal conductivity of various nanoparticles

Thermal conductivity of different basefluids :-

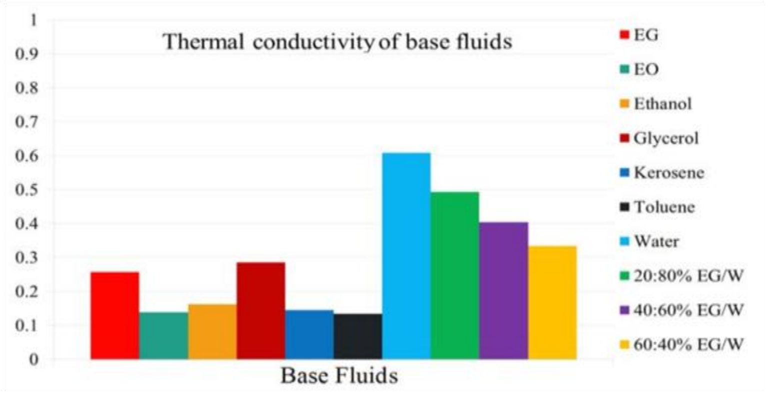
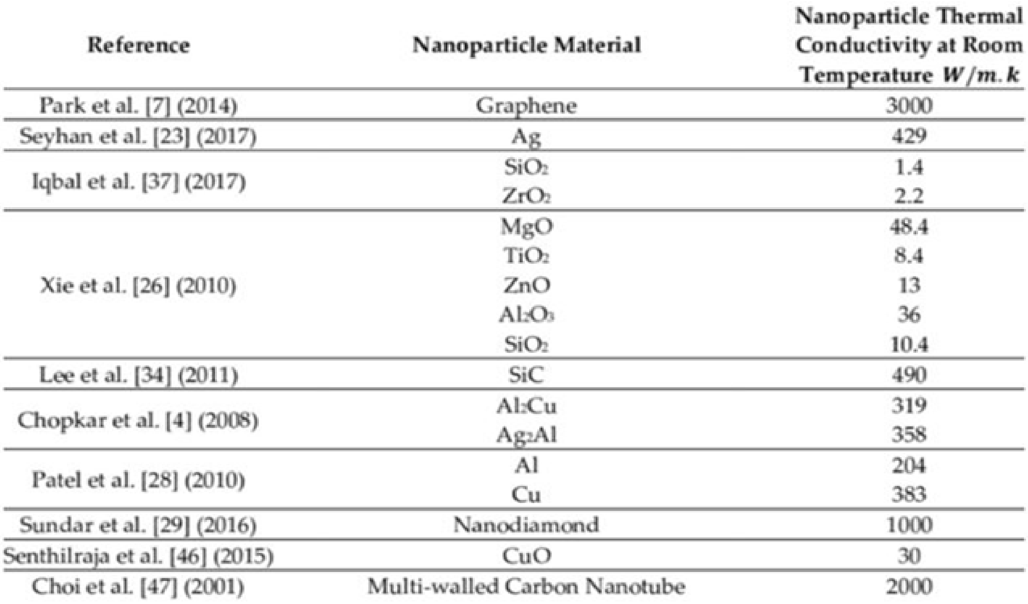


Figure 11: Thermal conductivity of various base fluids.

Thermal conductivity of different nanoparticles researchers provide the values shown below:-



Reference	Nanoparticle Material	Nanoparticle Thermal Conductivity at Room Temperature $W/m.k$
Park et al. [7] (2014)	Graphene	3000
Seyhan et al. [23] (2017)	Ag	429
Iqbal et al. [37] (2017)	SiO_2	1.4
	ZrO_2	2.2
Xie et al. [26] (2010)	MgO	48.4
	TiO_2	8.4
	ZnO	13
	Al_2O_3	36
	SiO_2	10.4
Lee et al. [34] (2011)	SiC	490
Chopkar et al. [4] (2008)	Al_2Cu	319
	Ag_2Al	358
Patel et al. [28] (2010)	Al	204
	Cu	383
Sundar et al. [29] (2016)	Nanodiamond	1000
Senthilraja et al. [46] (2015)	CuO	30
Choi et al. [47] (2001)	Multi-walled Carbon Nanotube	2000

Figure 12: Thermal conductivity of different values at room temperature

Parameters effect of thermal conductivity (experimental):-

- Particle volume concentration
- Particle materials
- Particle size
- Particle shape
- Base fluid material
- Temperature
- Additive
- Acidity

Particle volume:-

Effect of particle volume concentration:

From experimental results the general trend is clear.

Thermal conductivity improves as particle volume concentration rises, where different researchers given different values of thermal conductivity.

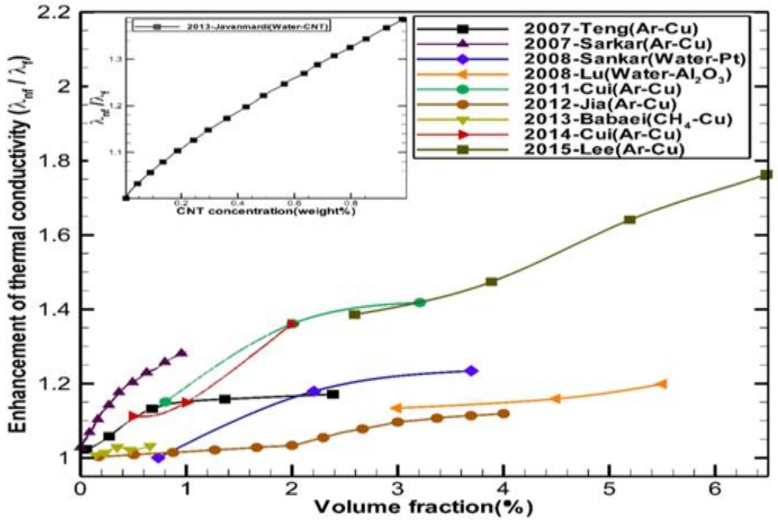


Figure 13: Thermal conductivity vs volume fraction different researchers given different values from the graph.

Effect of particle material:-

The thermal conductivity ratio is seen to increase faster metals than oxide particles.

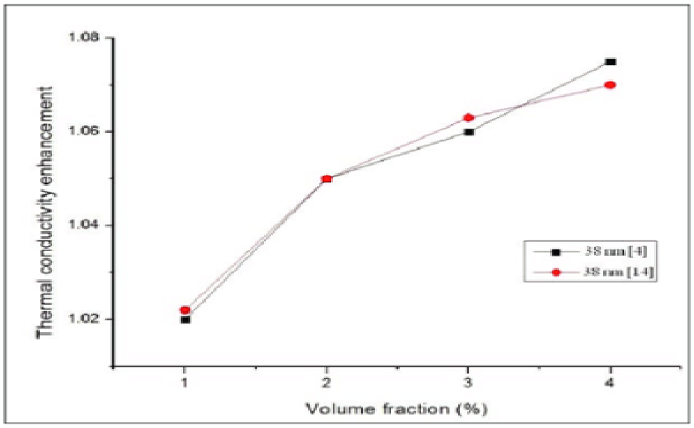


Figure 14: Thermal conductivity vs volume fraction% of nanofluids.

Effect of particle size:-

Larger particle diameters produce larger enhancement in thermal conductivity the trend appears .But in some cases the experiments show indicate the opposite.

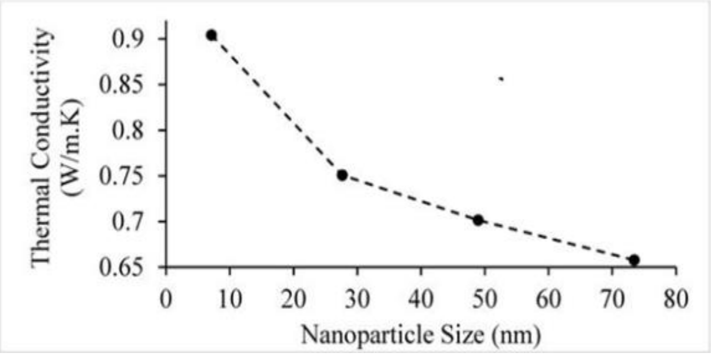


Figure 15: ThermalconductivityvsNanoparticlesize

Effect of particle shape:-

- All of the results indicate the elongated particles are superior to spherical sized particles for thermal conductivity enhancement.

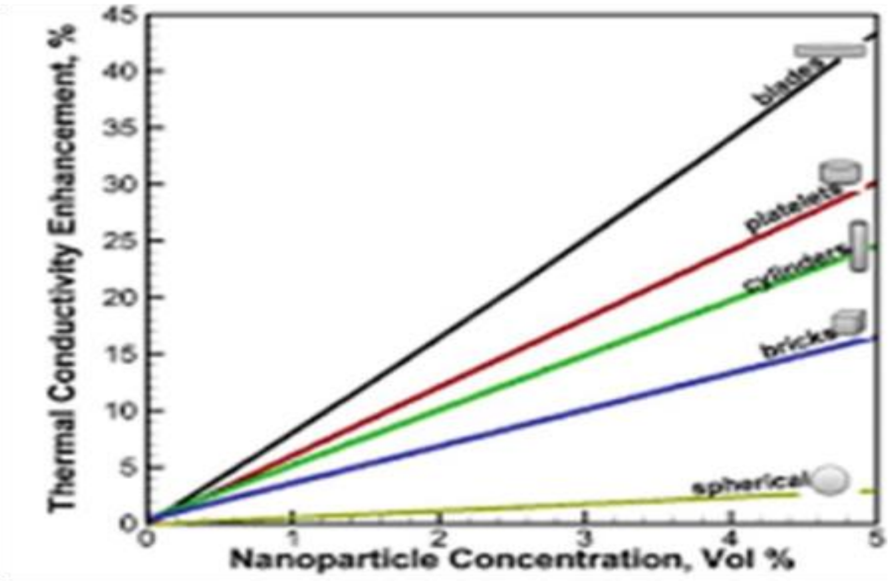


Figure 16: Thermal conductivity vs particle shape

Effect of base fluid material:-

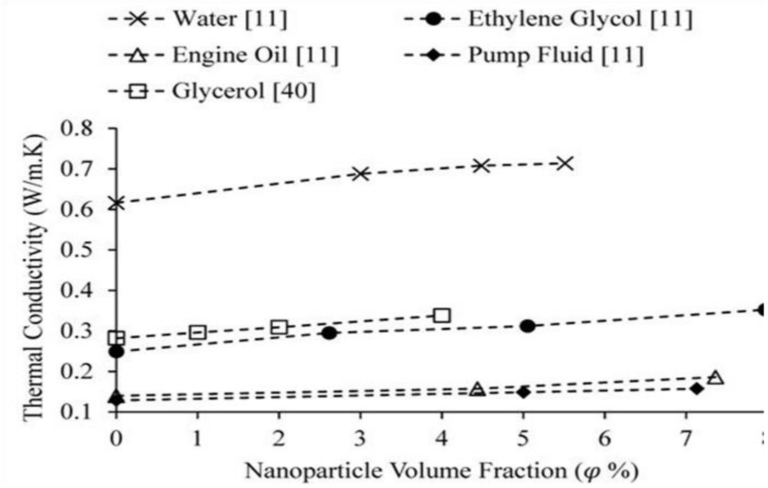
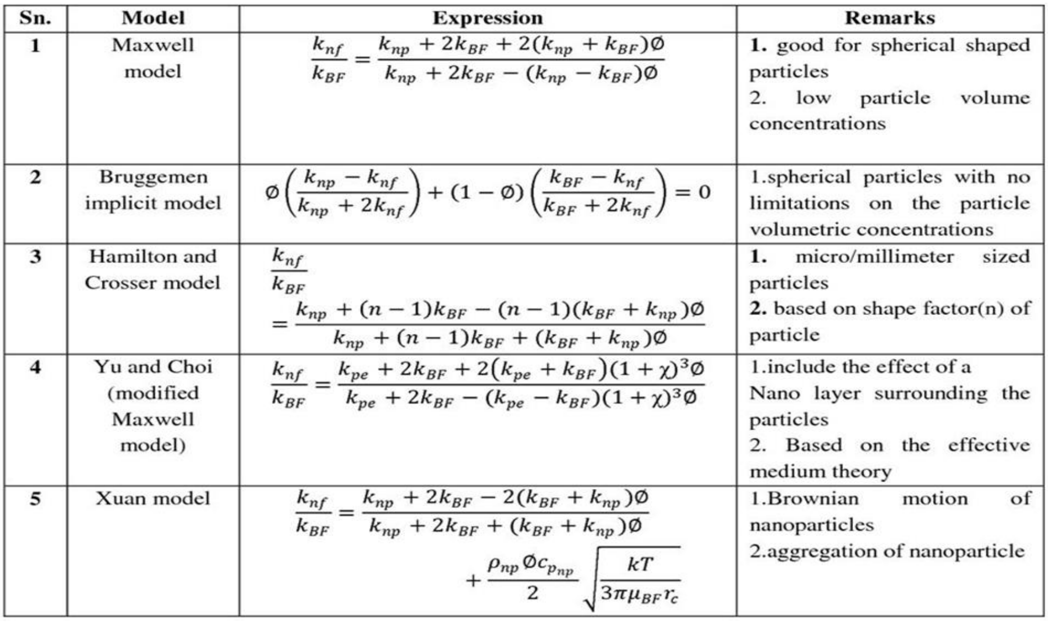


Figure 17: Thermal conductivity vs Nano particle volume concentration.

The results suggest that poorer (lower thermal conductivity) heat transfer fluids benefit from enhanced thermal conductivity augmentation. Water is the best heat transmission base fluid.

Thermal conductivity different models:-

Various researchers proposed different models of thermal conductivity based on nanofluids some of important formulas shown below:-

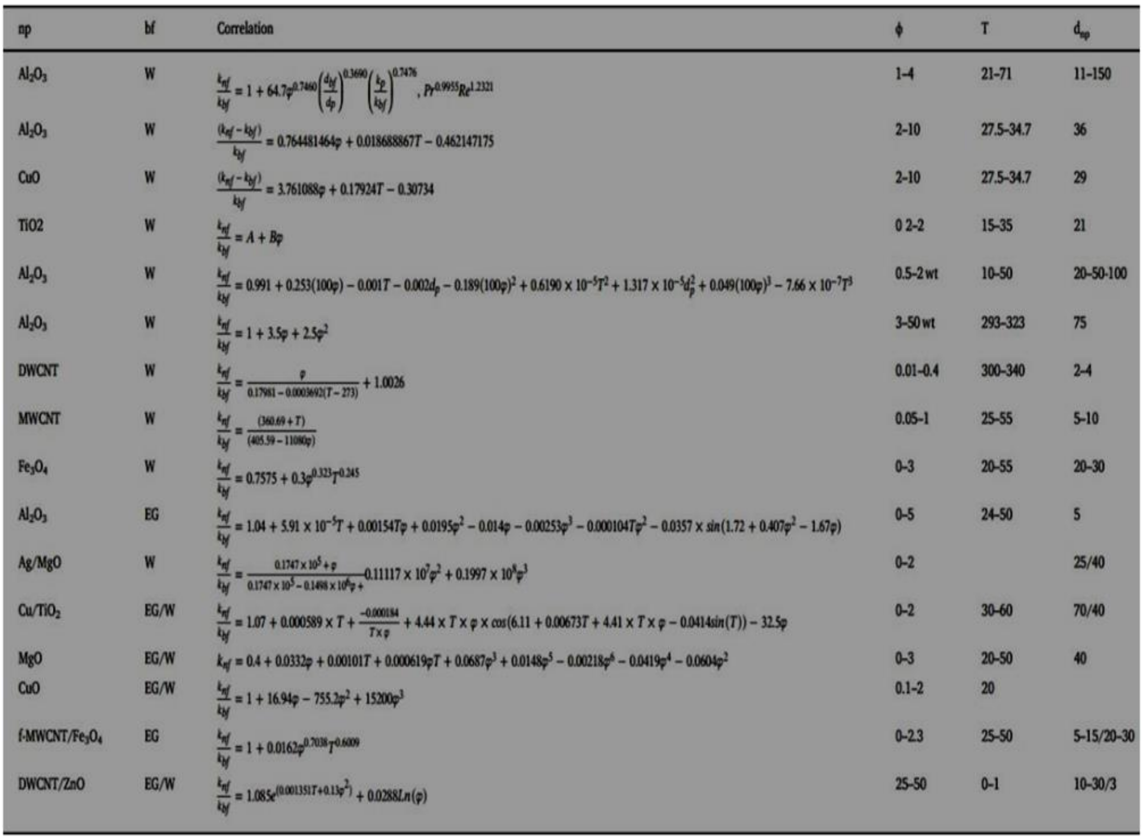


Sn.	Model	Expression	Remarks
1	Maxwell model	$\frac{k_{nf}}{k_{BF}} = \frac{k_{np} + 2k_{BF} + 2(k_{np} + k_{BF})\emptyset}{k_{np} + 2k_{BF} - (k_{np} - k_{BF})\emptyset}$	**1.** good for spherical shaped particles 2. low particle volume concentrations
2	Bruggemen implicit model	$\emptyset\left(\frac{k_{np} - k_{nf}}{k_{np} + 2k_{nf}}\right) + (1-\emptyset)\left(\frac{k_{BF} - k_{nf}}{k_{BF} + 2k_{nf}}\right) = 0$	1.spherical particles with no limitations on the particle volumetric concentrations
3	Hamilton and Crosser model	$\frac{k_{nf}}{k_{BF}} = \frac{k_{np} + (n-1)k_{BF} - (n-1)(k_{BF} + k_{np})\emptyset}{k_{np} + (n-1)k_{BF} + (k_{BF} + k_{np})\emptyset}$	**1.** micro/millimeter sized particles **2.** based on shape factor(n) of particle
4	Yu and Choi (modified Maxwell model)	$\frac{k_{nf}}{k_{BF}} = \frac{k_{pe} + 2k_{BF} + 2\left(k_{pe} + k_{BF}\right)(1+\chi)^3\emptyset}{k_{pe} + 2k_{BF} - (k_{pe} - k_{BF})(1+\chi)^3\emptyset}$	1.include the effect of a Nano layer surrounding the particles 2. Based on the effective medium theory
5	Xuan model	$\frac{k_{nf}}{k_{BF}} = \frac{k_{np} + 2k_{BF} - 2(k_{BF} + k_{np})\emptyset}{k_{np} + 2k_{BF} + (k_{BF} + k_{np})\emptyset} + \frac{\rho_{np}\emptyset c_{p_{np}}}{2}\sqrt{\frac{kT}{3\pi\mu_{BF}r_c}}$	1.Brownian motion of nanoparticles 2.aggregation of nanoparticle

Figure 18: Thermal conductivity of various models.

Thermal conductivity empirical formulas various nanofluids:-

Different researchers obtain different correlations for exhibit nanofluid from given figure:-



np	bf	Correlation	ϕ	T	d_{np}
Al_2O_3	W	$\frac{k_{nf}}{k_{bf}} = 1 + 64.7\varphi^{0.7460}\left(\frac{d_{bf}}{d_p}\right)^{0.3690}\left(\frac{k_p}{k_{bf}}\right)^{0.7476}, Pr^{0.9955}Re^{1.2321}$	1-4	21-71	11-150
Al_2O_3	W	$\frac{(k_{nf}-k_{bf})}{k_{bf}} = 0.764481464\varphi + 0.018688867T - 0.462147175$	2-10	27.5-34.7	36
CuO	W	$\frac{(k_{nf}-k_{bf})}{k_{bf}} = 3.761088\varphi + 0.17924T - 0.30734$	2-10	27.5-34.7	29
TiO2	W	$\frac{k_{nf}}{k_{bf}} = A + B\varphi$	0 2-2	15-35	21
Al_2O_3	W	$\frac{k_{nf}}{k_{bf}} = 0.991 + 0.253(100\varphi) - 0.001T - 0.002d_p - 0.189(100\varphi)^2 + 0.6190 \times 10^{-5}T^2 + 1.317 \times 10^{-5}d_p^2 + 0.049(100\varphi)^3 - 7.66 \times 10^{-7}T^3$	0.5-2 wt	10-50	20-50-100
Al_2O_3	W	$\frac{k_{nf}}{k_{bf}} = 1 + 3.5\varphi + 2.5\varphi^2$	3-50 wt	293-323	75
DWCNT	W	$\frac{k_{nf}}{k_{bf}} = \frac{\varphi}{0.17981 - 0.0003692(T-273)} + 1.0026$	0.01-0.4	300-340	2-4
MWCNT	W	$\frac{k_{nf}}{k_{bf}} = \frac{(360.69+T)}{(405.59-11080\varphi)}$	0.05-1	25-55	5-10
Fe_3O_4	W	$\frac{k_{nf}}{k_{bf}} = 0.7575 + 0.3\varphi^{0.323}T^{0.245}$	0-3	20-55	20-30
Al_2O_3	EG	$\frac{k_{nf}}{k_{bf}} = 1.04 + 5.91 \times 10^{-5}T + 0.00154T\varphi + 0.0195\varphi^2 - 0.014\varphi - 0.00253\varphi^3 - 0.000104T\varphi^2 - 0.0357 \times sin(1.72 + 0.407\varphi^2 - 1.67\varphi)$	0-5	24-50	5
Ag/MgO	W	$\frac{k_{nf}}{k_{bf}} = \frac{0.1747 \times 10^5 + \varphi}{0.1747 \times 10^5 - 0.1498 \times 10^6\varphi + }0.11117 \times 10^7\varphi^2 + 0.1997 \times 10^8\varphi^3$	0-2		25/40
Cu/TiO_2	EG/W	$\frac{k_{nf}}{k_{bf}} = 1.07 + 0.000589 \times T + \frac{-0.000184}{T \times \varphi} + 4.44 \times T \times \varphi \times cos(6.11 + 0.00673T + 4.41 \times T \times \varphi - 0.0414sin(T)) - 32.5\varphi$	0-2	30-60	70/40
MgO	EG/W	$k_{nf} = 0.4 + 0.0332\varphi + 0.00101T + 0.000619\varphi T + 0.0687\varphi^3 + 0.0148\varphi^5 - 0.00218\varphi^6 - 0.0419\varphi^4 - 0.0604\varphi^2$	0-3	20-50	40
CuO	EG/W	$\frac{k_{nf}}{k_{bf}} = 1 + 16.94\varphi - 755.2\varphi^2 + 15200\varphi^3$	0.1-2	20	
f-MWCNT/Fe_3O_4	EG	$\frac{k_{nf}}{k_{bf}} = 1 + 0.0162\varphi^{0.7038}T^{0.6009}$	0-2.3	25-50	5-15/20-30
DWCNT/ZnO	EG/W	$\frac{k_{nf}}{k_{bf}} = 1.085e^{(0.001351T+0.13\varphi^2)} + 0.0288Ln(\varphi)$	25-50	0-1	10-30/3

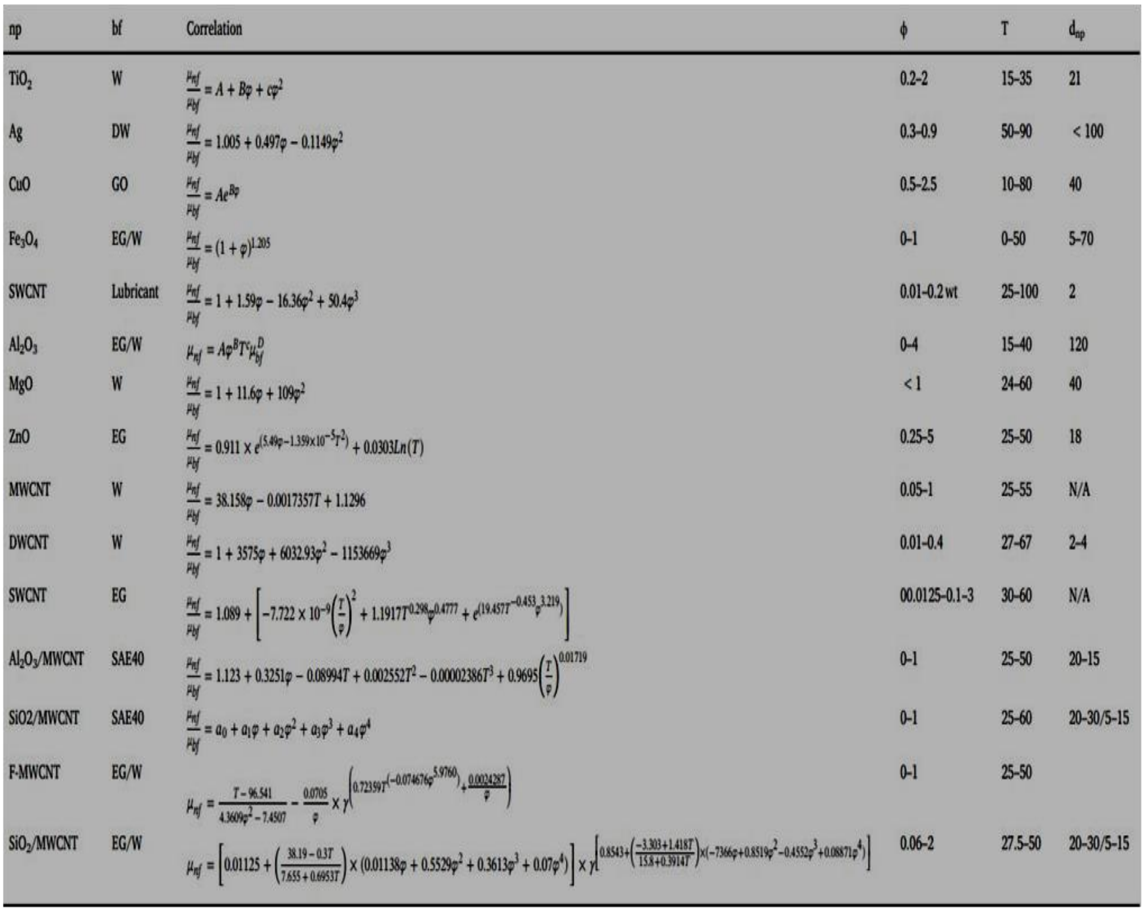
Figure 19: summary of the studies on the theoretical and experimental models for effective thermal conductivity of nanofluids.

Dynamic viscosity

It first and foremost, viscosity should be defined as a general concept. This is a measurement of a fluid's resistance to being deformed by shear or tensile stress; additionally, viscosity describes a fluid's internal resistance to flow and can be thought of as a measure of fluid friction; finally, viscosity is the fluid's thinness or thickness in common terms. It's calculated by dividing the tangential tension on a liquid in streamlined flow by the velocity gradient.

$$\mu = F.y/A.\upsilon$$

The quantity of pumping force can be influenced by changes in viscosity. The power required for pumping, and hence the pump's energy consumption, rises as the viscosity raises. Many of these investigations resulted in the formulation of numerical values for the viscosity of nanofluids under diverse situations. However, utilising experimental data, several researchers have developed a number of techniques to express the viscosity correlations. The viscosity of nanoparticles under various conditions is determined using these relationships. The crucial point is that each of these relationships holds true for a specific nanofluid under a specific set of circumstances. it shows the experimental relationships for the viscosity of nanofluids determined by various researchers. The values also determines the criteria under which these relation ships are valid. Viscosity of various nanofluids and correleation fluids shown below:-



np	bf	Correlation	ϕ	T	d_{np}
TiO_2	W	$\frac{\mu_{nf}}{\mu_{bf}} = A + B\varphi + c\varphi^2$	0.2-2	15-35	21
Ag	DW	$\frac{\mu_{nf}}{\mu_{bf}} = 1.005 + 0.497\varphi - 0.1149\varphi^2$	0.3-0.9	50-90	< 100
CuO	GO	$\frac{\mu_{nf}}{\mu_{bf}} = Ae^{B\varphi}$	0.5-2.5	10-80	40
Fe_3O_4	EG/W	$\frac{\mu_{nf}}{\mu_{bf}} = (1+\varphi)^{1.205}$	0-1	0-50	5-70
SWCNT	Lubricant	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 1.59\varphi - 16.36\varphi^2 + 50.4\varphi^3$	0.01-0.2 wt	25-100	2
Al_2O_3	EG/W	$\mu_{nf} = A\varphi^B T^c \mu_{bf}^D$	0-4	15-40	120
MgO	W	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 11.6\varphi + 109\varphi^2$	< 1	24-60	40
ZnO	EG	$\frac{\mu_{nf}}{\mu_{bf}} = 0.911 \times e^{(5.49\varphi - 1.359\times10^{-5}T^2)} + 0.0303Ln(T)$	0.25-5	25-50	18
MWCNT	W	$\frac{\mu_{nf}}{\mu_{bf}} = 38.158\varphi - 0.0017357T + 1.1296$	0.05-1	25-55	N/A
DWCNT	W	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 3575\varphi + 6032.93\varphi^2 - 1153669\varphi^3$	0.01-0.4	27-67	2-4
SWCNT	EG	$\frac{\mu_{nf}}{\mu_{bf}} = 1.089 + \left[-7.722\times10^{-9}\left(\frac{T}{\varphi}\right)^2 + 1.1917T^{0.298}\varphi^{0.4777} + e^{(19.457T^{-0.453}\varphi^{3.219})}\right]$	00.0125-0.1-3	30-60	N/A
Al_2O_3/MWCNT	SAE40	$\frac{\mu_{nf}}{\mu_{bf}} = 1.123 + 0.3251\varphi - 0.08994T + 0.002552T^2 - 0.00002386T^3 + 0.9695\left(\frac{T}{\varphi}\right)^{0.01719}$	0-1	25-50	20-15
SiO2/MWCNT	SAE40	$\frac{\mu_{nf}}{\mu_{bf}} = a_0 + a_1\varphi + a_2\varphi^2 + a_3\varphi^3 + a_4\varphi^4$	0-1	25-60	20-30/5-15
F-MWCNT	EG/W	$\mu_{nf} = \frac{T - 96.541}{4.3609\varphi^2 - 7.4507} - \frac{0.0705}{\varphi} \times \gamma^{\left(0.723597^{(-0.074676\varphi^{5.9760})} + \frac{0.0024287}{\varphi}\right)}$	0-1	25-50	
SiO_2/MWCNT	EG/W	$\mu_{nf} = \left[0.01125 + \left(\frac{38.19 - 0.37}{7.655 + 0.6953T}\right) \times (0.01138\varphi + 0.5529\varphi^2 + 0.3613\varphi^3 + 0.07\varphi^4)\right] \times \gamma^{\left[0.8543 + \left(\frac{-3.303 + 1.418T}{15.8 + 0.3914T}\right) \times (-7366\varphi + 0.8519\varphi^2 - 0.4552\varphi^3 + 0.08871\varphi^4)\right]}$	0.06-2	27.5-50	20-30/5-15

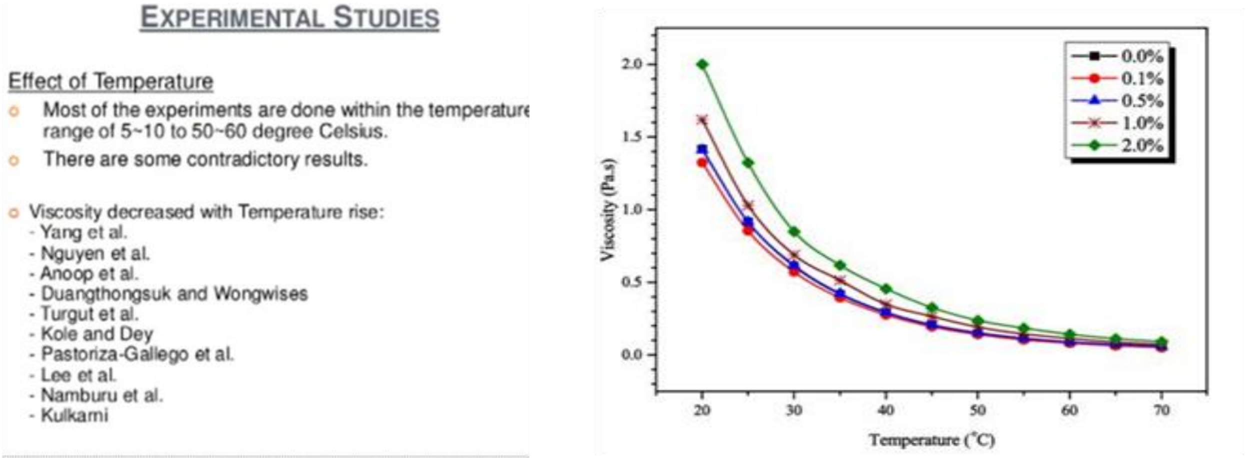
Figure 20: Empirical values of different nanofluids.

Main factors related viscosity:-

- Temperature
- Particle size
- Particle shape
- Volume concentration

Viscosity effect on temperature:-

Viscosity decreased with temperature raise in experimental studies of Nano-fluidparticles studied . It is exponential in nature.



EXPERIMENTAL STUDIES

Effect of Temperature

- Most of the experiments are done within the temperature range of 5~10 to 50~60 degree Celsius.
- There are some contradictory results.

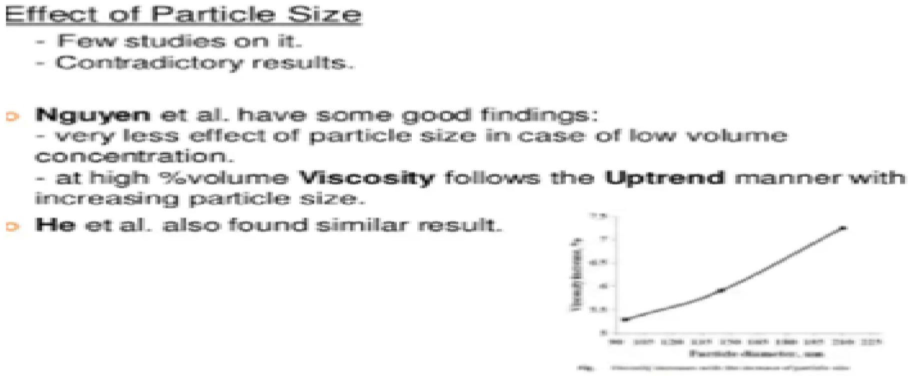
- Viscosity decreased with Temperature rise:
  - Yang et al.
  - Nguyen et al.
  - Anoop et al.
  - Duangthongsuk and Wongwises
  - Turgut et al.
  - Kole and Dey
  - Pastoriza-Gallego et al.
  - Lee et al.
  - Namburu et al.
  - Kulkarni

Figure 21: Viscosity effects vs varies temperature with different nanofluids.

$$\mu nf = \mu f/(1-\varphi)^{2.5}$$

Particle size:-

Low effect of particle size in low volume concentration.



Effect of Particle Size

- Few studies on it.
- Contradictory results.

- **Nguyen** et al. have some good findings:
  - very less effect of particle size in case of low volume concentration.
  - at high %volume **Viscosity** follows the **Uptrend** manner with increasing particle size.
- **He** et al. also found similar result.

Figure 22: viscosity vs particle size varies with temperature.

Particle shape:-

The viscosity of nanoparticles varies depending on particle form. The researchers look into how it varies depending on particle form and temperature of different shapes.

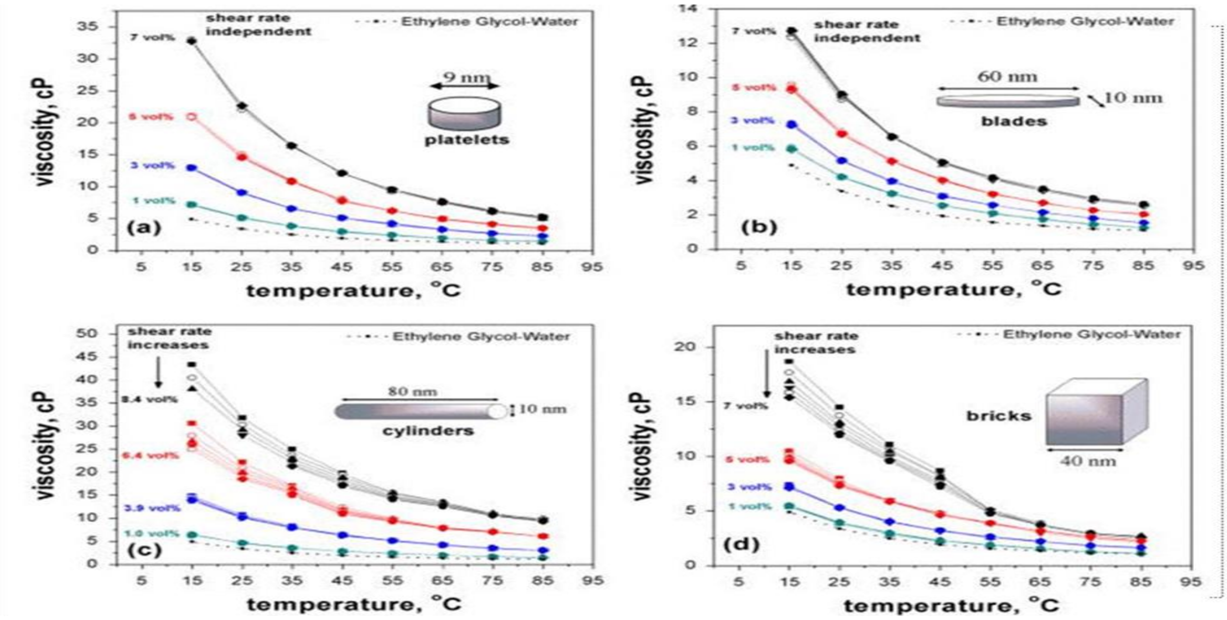


Figure 23: viscosity vs particle shape varies with different temperature.

Shear rate:-

Shear rate depend upon of fluid viscosity and alter for different fluids of volume concentration.

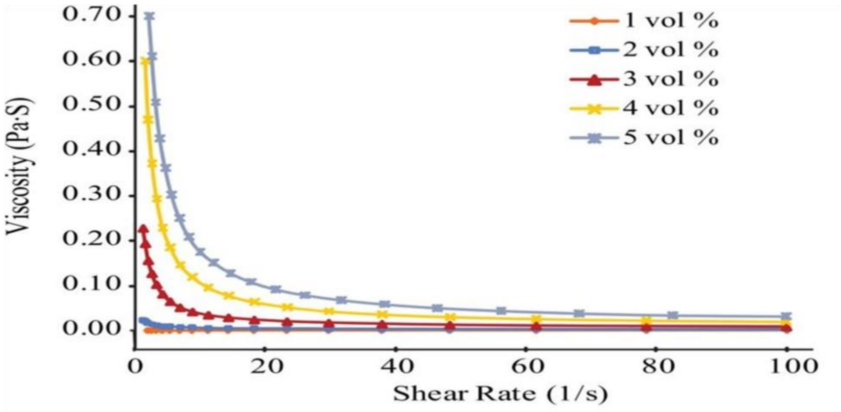


Figure 24: Viscosity vs shear rate per volume concentration.

Viscosity models:

Nanofluid consists various model shown in below:-

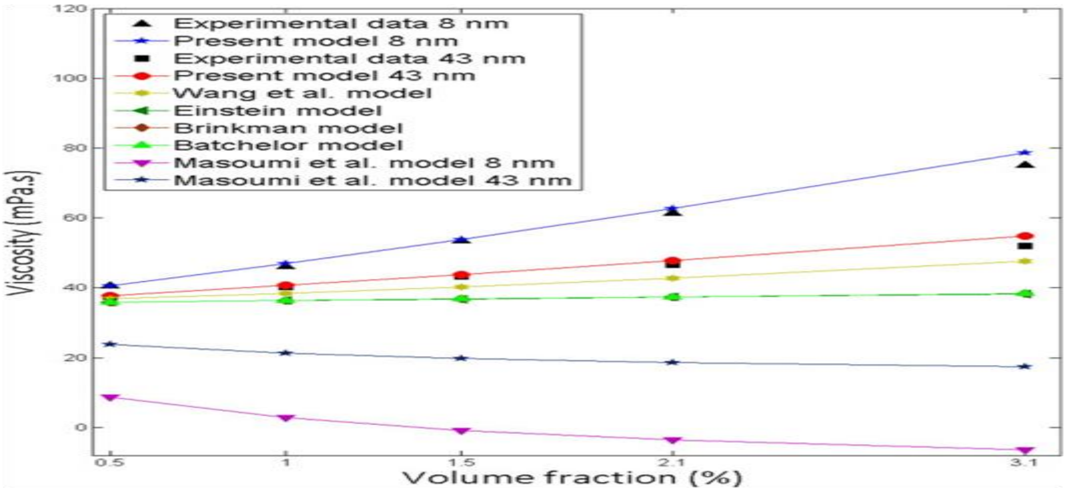


Figure 25: Viscosity vs volume fraction.

By above model researchers provides different models regarding viscosity with respect to volume fraction the nanofluids used experimental and present model with 8nm and 43nm

Advantages of Nanofluids

- More heat transfer surface between particles and fluids due to higher specific surface area.
- Lower pumping power required to achieve equivalent heat transfer intensification when compared to pure liquid.
- When compared to traditional slurries, particle clogging is reduced, allowing for system miniaturisation.
- Thermal conductivity and surface ability can be adjusted by varying particle concentration to suit different applications.

Limitations of Nanofluids

- Nanofluids have a lower specific heat than base fluids in most cases.
- The ideal coolant should have a higher specific heat value, but Nano fluids are superior coolant particles.
- Nano fluids can be made in a one-step or two-step process, both of which necessitate the use of advanced and sophisticated equipment.

Applications of Nanofluids

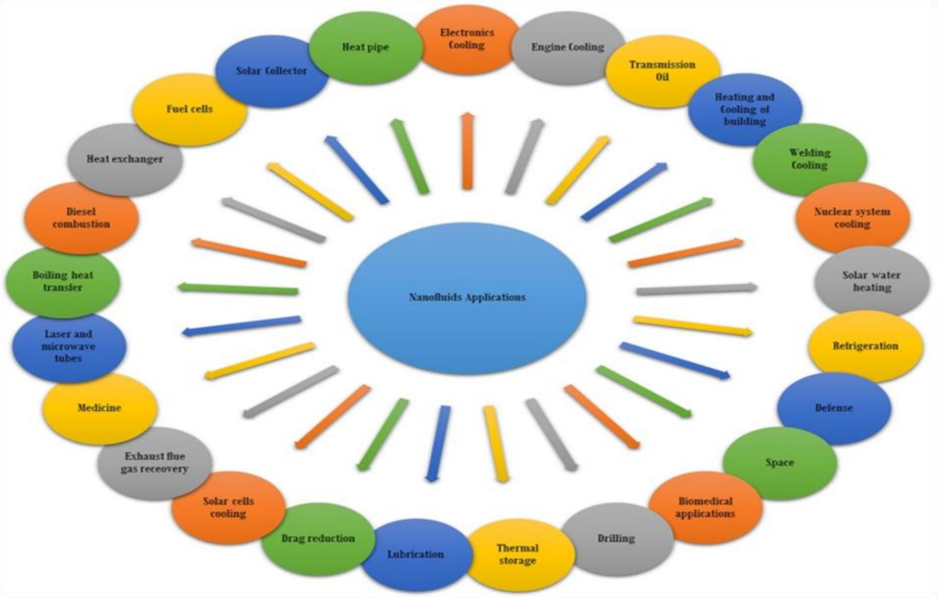


Figure 26: Applications of nanofluids in various applications.

Challenges of Nanofluids

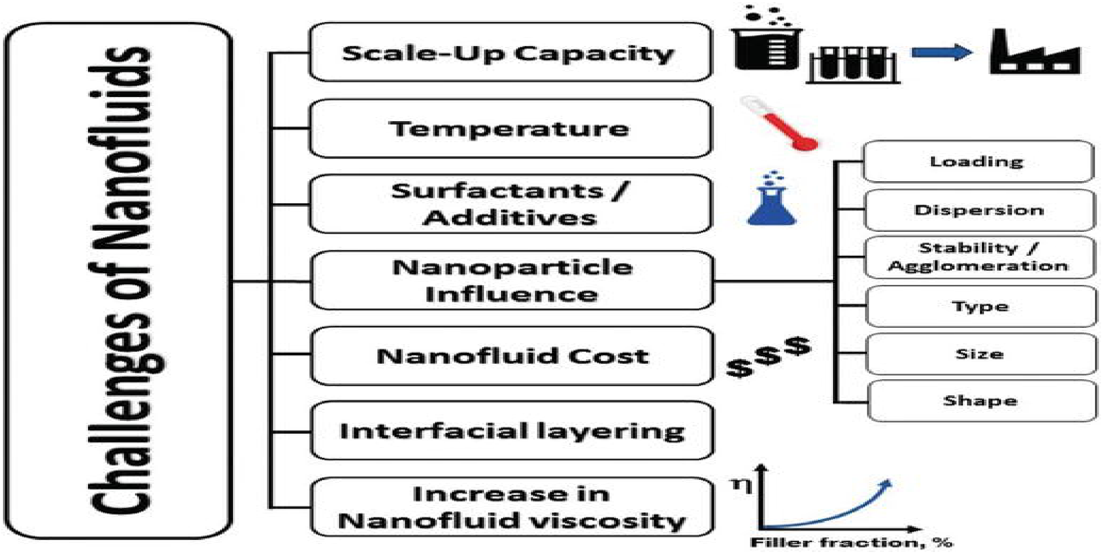


Figure 27: Challenges of Nanofluids.

III. RESULTS AND DISCUSSION

The thermophysical properties of nanofluids have been examined, as well as the factors that influence them. Particle size, temperature, material, size distribution, stability, and form of nanofluids employed in studies should all be tuned. Although these aspects of nanofluid technology are still in the early stages of development, the results thus far have been sufficient to establish trends in nanofluid heat transfer enhancement

- More research is needed to build new models and correlations that can more accurately predict thermal conductivity and the effect of different parameters. More broad correlations for heat transfer enhancement of nanofluids for practical applications should be developed.
- More study is needed to establish more precise correlations that can anticipate changes in nanofluid values induced by temperature, particle concentration, base fluid type, and so on, because these variables have an impact on nanofluid stability and thermophysical properties.

IV. CONCLUSION

- Some challenges of nanofluids must to be overcome while preparations of nanofluids and improve properties of nanofluids.
- Since nanofluids are expensive and difficult to produce, efforts should be made to develop cost-effective and efficient nanofluids.
- To serve the needs of heat transfer applications, new types of nanofluids with high thermal conductivity and low viscosity should be developed.
- There are few research using solid, liquid & hybrid nanofluids; this topic could be explored more for emerging nanotechnology in upcoming decades.

These are some of the potential options in which researchers can work on nanofluids in the future in order to disseminate their use in various applications.

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