CHAPTER-1

INTRODUCTION

Continuous technological developments in automobile industry focused on improving the fuel efficiency of internal combustion engines. Fuel efficiency is enhanced by maintaining the engine temperature at an optimum value which requires the engine heat to be extracted by circulating fluids like water, ethylene glycol etc., around the engine. However, the application of conventional fluids as coolants is limited by their low thermal conductivity which has to be improved. Thermal conductivity of these fluids can be improved by the addition of solid particles as these particles possess higher thermal conductivity than those of conventional liquids. The feasibility of usage of such suspensions with sizes in the order of millimeters (or) micrometers was investigated earlier and significant drawbacks were observed. These drawbacks include sedimentation of particles, clogging erosion of channel wells and increasing pressure drop which prevent their usage in practical application. These drawbacks can be overcome by reducing the particle size to nanoscale. The particle sedimentation speed (Stokes law) is expressed by equation (1.1), which indicates that the particle sedimentation speed depends on particle size, base fluid viscosity and density difference between particle and base fluid. The easiest way to be free from sedimentation is to minimize particle size as the sedimentation speed goes to zero with nanometer-size particle.

\[ U_s = \frac{2d_p^2}{\mu_f} \left( \rho_p - \rho_f \right) g \]

Where

- \( U_s \) - particle sedimentation speed, m/s
- \( d_p \) - diameter of particle, m
- \( \mu_f \) - viscosity of fluid, centistokes
- \( \rho_p \) - density of particle, kg/m³
- \( \rho_f \) - density of fluid, kg/m³
- \( g \) - acceleration due to gravity, m/s²
1.1. NANOFLUID

Nanofluids (Nanoparticle fluid suspensions) is the term coined by Choi (1995) to describe this new class of nanotechnology based fluids that exhibit thermal properties superior to those of their base fluids. Due to their small size usually less than 100 nm, nanoparticles fluidize easily inside the base fluid and as a consequence, clogging and erosion in channels are no longer a problem. These particles contain only a few thousand atoms and possess properties that are substantially different from their parent materials. The goal of nanofluids is to achieve the highest possible thermal properties at the smallest possible concentration by uniform dispersion and stable suspension of nanoparticles in base fluids. Recently there have been several advancements which have made the nanofluids more stable and ready for use.

Nanofluids find potential applications in electronic devices as they have higher denser chips with compact design which makes heat dissipation difficult, heat pipes in the computer devices to improve heat dissipation, industrial cooling applications resulting in great energy savings and emission reduction, for cooling nuclear systems, space and defense due to the restriction of space and heat exchangers to improve heat transfer rates, in fuel cell, Solar water heaters, chillers, domestic refrigerators and as lubricants in machining. However, some challenges posed with the nanofluids, are

- lack of agreement of results obtained by different researchers
- lack of theoretical understanding of the mechanisms responsible for changes in properties
- poor characterization of suspensions
- stability of nanoparticles dispersion
- increased pressure drop and pumping power
- nanofluid thermal performance in turbulent flow and fully developed region
- higher viscosity, lower specific heat
- high cost of nanofluids
- difficulties in production process
1.2. PREPARATION OF NANOFLUIDS

Nanofluids are not simply liquid-solid mixtures but are produced by dispersing nanometer-scale solid particles into base liquids such as water, ethylene glycol (EG), oils, etc without agglomeration. The two methods used for the preparation of nanofluids are (i) one-step and (ii) two-step methods.

One-step method combines the production and dispersion of nanoparticles in the base fluid in a single step as shown in fig 1.1. The limitations of this method are the low production capacities and residual reactants left in the nanofluid due to incomplete chemical reaction.

In two step method, nanoparticles are synthesized and then dispersed in the base fluids. Two-step method is advantageous when mass production of nanofluids is considered. The disadvantage of the two-step technique is that the nanoparticles form clusters without proper dispersion during the preparation of the nanofluid. Generally, ultrasonic equipment is used to intensively disperse the particles and reduce clustering. Besides the application of ultrasonic waves, other techniques such as control of pH of base fluid or addition of surface active agents (surfactants) are used.

1.3. PARTICLE MATERIAL AND BASE FLUID

Particle materials in general used are metals, metal- oxides, carbides and nitrides. Metal nanoparticles oxidize during preparation and their higher density leads to easy sedimentation. Oxide nanoparticles are found chemically stable and are easy to produce and disperse during preparation. Among the oxides Al₂O₃ nanoparticles find in major applications and exhibit less wear and friction properties compared to others apart from
high thermal conductivity and low density. Hence, Al₂O₃ nanoparticles are selected for the present study.

Base fluids mostly used in the preparation of nanofluids are the common working fluids in heat transfer applications; such as water, ethylene glycol and engine oil. Therefore, Al₂O₃- water nanofluids are suitable for cooling applications in the automotive industry. In the present work Al₂O₃ nanoparticles are dispersed in de-ionized water (here after referred to as water) in volume fractions of 0.2 %, 0.4 %, 0.6 %, 0.8 % and 1.0 %.

1.4. CALCULATION OF VOLUME FRACTION OF NANOPARTICLES

Unknown weight of Al₂O₃ nanopowder is estimated by the known percentage of the volume fraction. The quantity of Al₂O₃ required for different volume fractions is estimated from equation (1.2)

\[
\text{% of Volume fraction} = \frac{\text{Volume of Nanopowder}}{\text{Volume of Nanofluid}}
\]

\[
\text{% of Volume fraction} = \frac{\text{Volume of Al}_2\text{O}_3}{\text{Volume of Al}_2\text{O}_3 + \text{Volume of water}}
\]

\[
\text{% of Volume fraction} = \frac{W_a}{W_a + W_w} \cdot \frac{\rho_a}{\rho_a + \rho_w}
\]

Where \( w_a, \rho_a \) are weight and density of nanoparticles, \( w_w, \rho_w \) are weight and density of water. The density of alumina (\( \rho_a \)) is 3970 Kg/m³. The density of water (\( \rho_w \)) is 1000Kg/m³ at room temperature. The equivalent weights for assumed volume fractions are tabulated in table-1.1.

<table>
<thead>
<tr>
<th>Volume Fraction %</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
</table>

4
Weight of \( \text{Al}_2\text{O}_3 \) gms | 3.974 | 7.955 | 11.945 | 15.943 | 19.94 | 23.963 | 27.985 | 32.01 | 36.05 | 40.01

1.5. STABILITY OF NANOFLOUIDS

Stability of the suspensions is important as it influences the properties of nanofluids. Particle agglomeration and the formation of extended structures of linked nanoparticles affects stability and may be responsible for much of the disagreement between experimental results and the theoretical predictions.

Particles during dispersion may adhere together and form clusters of increasing size which may settle down due to gravity. Stability refers to the rate at which the particles settle to form agglomerates. The rate of agglomeration is determined by the frequency of collisions and the probability of cohesion during collision. Derjaguin, Verway, Landau and Overbeek (DVLO) developed a theory which dealt with colloidal stability [2, 3]. DVLO theory suggests that the stability of a particle in solution is determined by the sum of Vander Waals attractive and electrical double layer repulsive forces that exist between particles as they approach each other due to the Brownian motion, they undergo. If the attractive force is larger than the repulsive force, the two particles will collide and the suspension is not stable. If the particles have a sufficiently high repulsion, the suspensions would exist in stable state. For stable nanofluids or colloids, the repulsive forces between particles must be dominant. According to the types of repulsion, the fundamental mechanisms that affect colloidal stability are divided into two, namely (i) steric repulsion and (ii) electrostatic (charge) repulsion (fig 1.2).

(a) Steric stabilization
For steric stabilization (fig.1.2.a), polymers are always involved into the suspension system and they would adsorb onto the particle’s surface, producing an additional steric repulsive force.

For electrostatic stabilization (1.2.b), surface charge will be developed through one or more of the following mechanisms: (i) preferential adsorption of ions, (ii) dissociation of surface charged species, (iii) isomorphic substitution of ions, (iv) accumulation or depletion of electrons at the surface and (v) physical adsorption of charged species onto the surface.

The stability of nanofluid is enhanced by modifying the surface of nanoparticles through a film of surfactant using micro emulsion technique which involves usage of various surfactants during the preparation process. The other method includes changing the pH value of base fluid leading to variation in zeta potential which influences dispersion stability. When the oxide nanoparticles come in contact with water, a hydroxyl radical (-OH) is formed at the surface of the metallic oxide particle. The behavior of the particle and water interactions depend on whether the water is acidic or alkalic. Hence, a change in pH value may affect dispersion stability of nanofluids. The third method comprises of applying supersonic waves which generate cavitation oscillation and thus lead to effective dispersion. When nanoparticles are vibrated by the supersonic waves, high intensity ultrasound was developed into the liquid particles matrix mixture, where cavitation bubbles could develop and grow during several cycles until they attain a critical diameter, which induces their implosion. This collapse causes locally extreme conditions such as very high pressures and very high temperatures and this zone is referred as hot-spot. Due to these hot-spots splitting up of particles agglomerations could occur. The shock waves from implosive bubble collapse along with micro-streaming generated cavitation oscillations lead to dispersion effects. The supersonic waves travel longitudinally within the liquid and cause alternate positive and negative waves in the liquid, which result in homogeneous distribution of nanoparticles in the base fluid.

In the present work, dispersion of particles is done with magnetic stirring along with ultrasonication for a period of 30 minutes each. The stability of nanofluid is
enhanced with the addition of surfactant and changing pH values of base fluid. The optimum quantities of surfactant and pH for 30 days of nanofluid stability are obtained by conducting experiments with Design of Experiments (DOE) and analyzing through Response Surface Methodology (RSM).

The stability of nanofluid can be investigated using methods like centrifugation method, zeta potential analysis, spectral absorbency analysis and turbidity analysis. In the present work turbidity analysis is used to test the stability of nanofluids.

1.6. PROPERTIES OF NANOFLUIDS

Any fluid in heat transfer applications needs the following properties to be defined, namely thermal conductivity, viscosity, specific heat and density. The enhancement in thermal conductivity of nanofluid is due to the random movement of nanoparticles called as Brownian motion. The enhancement in heat transfer is because of the increase in thermal conductivity of nanofluids. The viscosity of nanofluids is the influencing factor in heat transfer as it suffers pressure drop during the flow. Specific heat of a nanofluid is important to estimate fluidic temperature changes at a particular rate of heat transfer and fluid flow. Density of nanofluids influences the flow behavior and hence has to be found out. The enhancement in thermal conductivity of nanofluid resulted in the increase of convective heat transfer coefficients. In the present work thermal conductivity and specific heat of nanofluids are measured by Guarded hot plate method, viscosity is estimated using Redwood viscometer-I and density is obtained with specific gravity bottle method. Mathematical correlations are developed based on the experimental data obtained to predict these properties under different situations.

1.7. AUTOMOTIVE COOLING SYSTEMS

In an automobile, combustion of fuel in the presence of air produces power. Most of the energy in the fuel (around 75%) is converted into heat, but only 25% of total energy produced is converted into effective work. If this unutilised heat is not removed from the engine, it results in overheating of components and thus leading to their damage. By using a liquid cooling system, heat is carried away by a coolant circulated around the engine. After heat extraction the coolant is pumped into a set of tubes in the radiator where air is forced over these tubes. As the air flows through the radiator, the heat is
transferred from the coolant to the air. The purpose of the air is to remove heat from the coolant, which causes the coolant to exit the radiator at a lower temperature than at which it enters. An automobile cooling system is shown in Fig (1.3). For current radiator designs, a common configuration is to use parallel tubes which have fins attached to them. Current radiator designs are limited by the air side resistance requiring a large frontal area to meet the cooling needs. The development of advanced nanofluids, which have better conduction and convection thermal properties, has presented a new opportunity to design a high energy efficient, light-weight automobile radiator.

1.8. APPLICATION OF NANOFLUIDS FOR ENGINE COOLING

Nanofluids are proven to be efficient heat transfer media in heat pipes and heat exchangers. It has been found that the size of heat exchangers reduce with the usage of nanofluids, as these fluids have higher heat transfer coefficients and thus requiring lesser volume. This has led to size reduction in the heat exchangers such as an automobile radiator. Since in the radiator as the fluid is flowing through finer tubes it needs low viscosities and higher heat extractions capability. The enhanced properties of nanofluids make them ideal for engine cooling systems due to their ability to respond quickly to

Fig.1.3 Automobile cooling system and components [6]
temperature changes allowing for the dissipation of more heat, using less coolant, in a shorter period of time.

1.9. PERFORMANCE EVALUATION OF NANOFLOIDS IN RADIATOR

In general Effectiveness -Number of Transfer Unit (ε-NTU) method, Performance- NTU (P-NTU) method and Mean Temperature Difference (MTD) methods are available for analysis of heat exchanger performance. The ε-NTU method is suitable for compact heat exchangers such as automobile radiator, hence it is used in the present study. Selection of the most appropriate ε- NTU relationship has a direct impact on the accuracy with which the characterization of a radiator can be performed.

The performance of nanofluids in radiators using ε-NTU method is evaluated by estimating the parameters such as effectiveness, heat capacity ratio and NTU of a radiator on which it reflects and defined as follows.

Effectiveness (ε) of the heat exchanger indicates its performance at the specific fluid flow rates and is expressed as equation 1.3.

\[
\varepsilon = \frac{Q_{\text{dissp}}}{Q_{\text{max}}} \tag{1.3}
\]

Heat capacity ratio (Rc) is defined as the ratio of the flow stream heat capacity rates i.e.

\[
R_c = \frac{C_{\text{min}}}{C_{\text{max}}} \tag{1.4}
\]

Number of Transfer Units (NTU) is defined as the overall heat transfer rate per degree Kelvin for the heat exchanger as a function of the mass flow rate and specific heat of the fluid having the lowest flow stream heat capacity,

\[
\text{NTU} = \frac{UA}{C_{\text{min}}} \tag{1.5}
\]

The basic equation from which the dependency of UA on fluid flow rates in the heat exchanger is based on the thermal resistance equation as shown in equation 1.6.
To solve the above equation (1.6) convective heat transfer coefficients of fluids are required. Modified Wilson plot method is used for predicting the convective heat transfer coefficients of fluids in the radiator based on experimental data obtained.

Equation 1.6 can be rearranged as

\[
\frac{1}{UA} = \left[ \frac{C_4}{D_{h,w}} \right] \left[ \frac{Re_w^{0.4} Pr_w^{0.4} A_w K_w}{\mu_{w,0.14}} \right] + \frac{R_w}{UA} + \left[ \frac{C_5}{D_{h,w}} \right] \left[ \frac{Re_w^{0.4} Pr_w^{0.4} A_w K_w}{\mu_{w,0.14}} \right] (1.7)
\]

Since, heat transfer coefficient, \( h = \frac{Nu k}{D} \)

Where \( Nu \)- Nusselt number (\( Nu = f (Re, Pr) \)), \( k \)- thermal conductivity of fluid and \( D \)-diameter

**1.10. OBJECTIVE OF THE PRESENT WORK**

The prime objective of the present work is to prepare \( Al_2O_3 \)-water nanofluids which are stable for a period of 30 days with optimum process parameters, characterize its thermo physical properties and study the performance as a coolant in an automobile radiator. Development of high performance heat transfer fluids can support designers and engineers in developing efficient automobile engines.

Nanofluids in different volume fractions are prepared using Design of Experiments (DOE). Response Surface Methodology (RSM) is used to find optimum process parameters (surfactant and pH values) to attain 30 days stability for various volume fractions of nanofluids. A mathematical model is developed using MINITAB 14 statistical software to predict optimum parameters. Analysis of Variance (ANOVA) is to be conducted to check adequacy of the developed model. Optimum process parameters such as surfactant quantity and pH value for each volume fraction of nanofluids to attain longer stability are to be identified. Stability testing is to be done for the fluids prepared with the obtained optimum values. \( Al_2O_3 \)-deionized water nanofluids in different volume fractions (0.2%, 0.4%, 0.6%, 0.8% and 1.0%) are to be prepared.

Experiments are to be done for predicting thermo physical properties of prepared nanofluids with the optimum process and study their response with temperature.
Empirical correlations are to be developed based on the experimental data and as these correlations can be used for further analysis.

Evaluation of the nanofluids performance in an automobile radiator as a coolant is to be done. The prepared nanofluids in different volume fractions are tested in an automobile radiator for evaluating the performance. The tests are to be conducted at different nanofluid rates by controlling engine speeds and at various air flow rates. Convective coefficients are to be predicted and characteristic equation should be developed.

1.11. THESIS ORGANISATION

The complete work is organized into seven chapters as described below.

The chapter-1 deals with introduction, preparation, nanoparticle materials and base fluids, calculation of volume fractions, stability of nanofluids, properties of nanofluids, automotive cooling systems and applications of nanofluids. It also summarizes the objective of the present work and layout of thesis.

A comprehensive study of the literature available on nanofluid preparation methods, stability enhancements, properties and applications of nanofluids, performance evaluation and characterization methods for fluids in heat exchangers is reported as in Chapter-2.

The details of preparation of nanofluids using various equipments and presents the stability analysis of nanofluids using Design of Experiments (DOE) based Response Surface Methodology (RSM) to predict optimum process parameters for enhancing stability are discussed in Chapter-3.

Evaluation of properties such as thermal conductivity, viscosity, specific heat and density for the prepared nanofluids using various equipments are described in Chapter-4 and discussions for variation in nanofluid properties are presented.
Chapter-5 presents the application of nanofluids as coolant in an automobile radiator, experimentation, prediction of convective heat transfer coefficients using modified Wilson plot method and development of mathematical model for heat dissipation using ε-NTU method.

Results obtained from the experiments and developed models are presented and discussed are discussed in Chapter-6.

In chapter-7, the conclusions drawn from the present work and scope for further work are mentioned.