Chapter 2

Silver Nanofluids - Synthesis, Properties and Applications

This chapter describes the general introduction of nanofluids and the methods of preparation of silver nanofluids employed for the studies presented in the thesis. A brief idea of the properties and applications of silver nanoparticles are also presented.
2.1. Introduction

The field of nanoscience has blossomed over the last twenty years and the need for nanotechnology will increase as miniaturization becomes more and more essential in areas such as computing, sensors and biomedical applications. Advances in this field largely depend on the ability to synthesize nanoparticles of various materials, sizes and shapes as well as to efficiently assemble them into complex architectures. The synthesis of nanoparticles, however, is a fairly established field as particles of submicron or nanosized dimensions have been synthesized for centuries. The first example of considerable recognition is the Roman Lycurgus cup, a bronze cup lined with colored glass that dates to the fourth century AD. The glass scatters a dull green light and transmits red light. According to a study commissioned by the British Museum, who currently displays the cup, the glass contains 70 nm particles that are an alloy of silver (70%) and gold (30%) [1]. Silver nanoparticles of this size are known to scatter green light and transmit orange, and the addition of Au shifts the absorption band to longer wavelengths. Although this particular application of nanoparticles may have been unintentional, small nanoparticles were often used in last centuries to create stained glass with small, ruby red Au and lemon-yellow Ag particles.

Nanofluids are a new class of fluids engineered by adding nanoscale particles (nanoparticles, nanofibers, nanotubes, nanowires, nanorods, nanosheet, or droplets) in low volumetric fractions to a base fluid in order to enhance or improve their mechanical, optical and thermal properties. The word nanofluid is developed by Choi et al. [2] in 1995. The base fluid can be any liquid such as oil, water, ethylene glycol, or conventional fluid mixtures. In other words, nanofluids are nanoscale colloidal suspensions containing condensed
nanomaterials. They are two-phase systems with one phase (solid phase) in another (liquid phase). Nanoparticles stay suspended much longer than microparticles and, if below a threshold level and/or enhanced with surfactants/stabilizers, remain in suspension almost indefinitely. Furthermore, the surface area per unit volume of nanoparticles is much larger (a million times) than that of microparticles (the number of surface atoms per unit of interior atoms of nanoparticles is very large). Nanoparticles having high surface area to volume ratio provides a tremendous driving force for diffusion, especially at elevated temperatures. These properties can be utilized to develop stable suspensions with enhanced flow, heat transfer and other characteristics. The nanoparticles suspended in a base liquid are in random motion under the influence of several acting forces such as the Brownian force and London van der Waals force. Nanofluids offered significant thermophysical properties such as thermal conductivity, thermal diffusivity, viscosity and convective heat transfer coefficients relative to those of conventional heat transfer fluids with no or micro-sized particles. The enhanced thermal conductivity of fluids contributes to improve the efficiency of heat transfer fluids. Since nanosized particles in fluids provide advantages such as better dispersion behavior, less clogging and larger total surface area, nanofluids have great potential to improve the efficiency of heat transfer behavior of the conventional heat transfer fluids.

Nanofluids possess a unique combination of the two most essential features desired in the thermal engineering applications, namely, physical and chemical stability and high thermal conductivity. The attractive features which made nanoparticles probable candidates for suspension in fluids are the large specific surface area, less particle momentum and high mobility. Other features [3, 4] that led to the excitement of using nanofluids include (a)
enhancement in thermal conductivity far beyond the level any theory could predict, (b) dependence of thermal conductivity on particle size apart from concentration, (c) greater stability of suspension using a stabilizing agent, (d) strong temperature dependence and (e) increase in critical heat flux. It has demonstrated great potential applications in many fields. The main driving force for nanofluids research lies in a wide range of applications. Although some review articles involving the progress of nanofluid investigation were published in the past several years [5-10], most of the reviews are concerned of the experimental and theoretical studies of the thermophysical properties or the convective heat transfer of nanofluids. The purpose of this work focuses not only on thermal properties but also on optical properties like quantum yield, energy transfer efficiency which provides the new application trends for nanoparticles. More recently, there have been several studies related to resonant energy transfer (RET), in presence of metal nanoparticles, in biotechnology to develop assays based on molecular proximity. Researchers have measured the effects of metallic nanoparticles on RET from the intrinsic tryptophan of a protein to a bound probe as the acceptor. These experiments revealed a dramatic increase in the apparent Förster distance and the results suggest the use of metal nanoparticles for detecting long range proximity between biomolecules and for biotechnology applications based on RET [11].

Of the three metals (Ag,Au,Cu) that display plasmon resonances in the visible spectrum, Ag exhibits the highest efficiency of plasmon excitation [1]. More over optical excitation of plasmon resonances in nanosized Ag particles is the most efficient mechanism by which light interacts with matter. A single Ag nanoparticle interacts with light more efficiently than a particle of the same dimension composed of any known organic or inorganic
chromophore. The light interaction cross section (extinction cross section) for Ag can be about ten times that of the geometric cross section, which indicates that the particles capture much more light. This nontrivial fact, which indicates that a particle interacts with light both directly impinging on it and passing within close proximity, can be understood by assuming the following intuitive model [1]. Generally, collisions between two objects depend on their geometric cross-sections and, if one of the objects is much smaller than the other one, the interaction is dominated by the geometric cross-section of the larger object. The photon can be assumed to have a “geometric cross-section” related to its wavelength that is considerably larger than the particle size, thereby providing a possibility for the extinction cross section to be larger than the geometric cross-section of the particle. Whether or not this possibility is realized also depends on the rate at which a particle can dissipate energy from the field. In the case of Ag nanoparticles, efficient energy dissipation is achieved through the absorption and scattering of light via excitation of surface plasmon resonance. Silver is also the only material whose plasmon resonance can be tuned to any wavelength in the visible spectrum and does not damp out the plasmon mode as strongly as does gold.

### 2.2. Approaches for the synthesis of Nanoparticles

Most applications require a precisely defined, narrow range of particle sizes (monodispersity). Specific synthesis processes are employed to produce the various nanoparticles, coatings, dispersions or composites. Defined production and reaction conditions are crucial in obtaining such size dependent particle features. Particle size, chemical composition, crystallinity and shape can be controlled by temperature, pH-value, concentration, chemical composition, surface modifications and process control. Two basic approaches are used for the synthesis of nanoparticles: “top-down” and
“bottomup” [12-13]. The term “top-down” refers to the synthesis of nanostructures from bulk through physical process (the mechanical crushing of source material). The “bottom-up” approach refers to the formation of nanoparticles from constituent atoms, i.e., structures are built up by chemical processes (Figure. 1).

Figure 1. Schematic representation of top-down and bottom-up approach.

Current physical processes include mechanical grinding and the inert gas condensation technique [14] pioneered by Granqvist and Buhrman. Current chemical processes include chemical precipitation, chemical vapor deposition, micro emulsions, spray pyrolysis, thermal spraying etc [15]. Both
strategies play very important role in modern industry and most likely in nanotechnology as well. Attrition or Milling is a typical top down method in making nanoparticles, where as the colloidal dispersion is a very good example of bottom up approach in the synthesis of nanoparticles.

2.3. Preparation methods for nanofluids

Preparation of nanofluids is the first key step in experimental studies with nanofluids. Nanofluids are not just dispersion of solid particles in a fluid. The essential requirements that a nanofluid must fulfill are even and stable suspension, adequate durability, negligible agglomeration of particles, no chemical change of the particles or fluid, etc. In the synthesis of nanofluids, agglomeration is a major problem. There are mainly two techniques used to produce nanofluids: the one-step and the two-step method [4].

2.3.1. Two step method

Two-step method is the most widely used method for preparing nanofluids. Nanoparticles, nanofibers, nanotubes, or other nanomaterials synthesized in this method are first produced as dry powders by chemical or physical methods. Then, the nanosized powder will be dispersed into a fluid in the second processing step with the help of intensive magnetic force agitation, ultrasonic agitation, high-shear mixing, homogenizing and ball milling. Two-step method is the most economic method to produce nanofluids in large scale, because nanopowder synthesis techniques have already been scaled up to industrial production levels. Due to the high surface area and surface activity, nanoparticles have the tendency to aggregate. The two step method is extensively used in the synthesis of nanofluids considering the available commercial nanopowders supplied by several companies. As shown in figure 2, for the preparation of nanofluids, the nanoparticles are dispersed in
different fluids. For example researchers [16-18] have used this method to produce $Al_2O_3$ nanofluids. In another study [19] $TiO_2$ suspension in water is prepared using the two-step method. Other nanoparticles reported in the literature are gold (Au), silver (Ag), silica and carbon nanotubes. The two-step technique works well for oxide nanoparticles [20, 21], while it is less successful with metallic particles. The main problem of this technique is the nanoparticle agglomeration due to attractive van der Waals forces. Generally, ultrasonic equipment is used to intensively disperse the particles and reduce the agglomeration of particles. Due to the difficulty in preparing stable nanofluids by two-step method, several advanced techniques are developed to produce nanofluids, including one-step method.

*Figure.2. A number of liquids (heat transfer fluids) that can host nanoparticles for the production of nanofluids.*
2.3.2. One step method

One-step method is favorable for metallic nanoparticles—since the nanoparticles are dispersed in the base fluid as they are produced, this process helps prevent oxidation of the particles. An advantage of the one-step technique is that nanoparticle agglomeration is minimized. The one-step process consists of simultaneously making and dispersing the particles in the fluid [22]. In this method, the processes of drying, storage, transportation, and dispersion of nanoparticles are avoided, so the agglomeration of nanoparticles is minimized, and the stability of fluids is increased. The one-step processes can prepare uniformly dispersed nanoparticles and the particles can be stably suspended in the base fluid. One-step physical method cannot synthesize nanofluids in large scale and the cost is also high, so the one-step chemical method is developing rapidly. The vacuum-SANSS (submerged arc nanoparticle synthesis system) is another efficient method to prepare nanofluids using different dielectric liquids. The method avoids the undesired particle aggregation fairly well. Zhu et al. presented a novel one-step chemical method for preparing copper nanofluids by reducing $CuSO_4 \cdot 5H_2O$ with $NaH_2PO_2 \cdot H_2O$ in ethylene glycol under microwave irradiation. Well-dispersed and stably suspended copper nanofluids were obtained. Mineral oil-based nanofluids containing silver nanoparticles with a narrow-size distribution were also prepared by this method. The particles can be stabilized by Korantin, which coordinated to the silver particle surfaces via two oxygen atoms forming a dense layer around the particles. The silver nanoparticle suspensions were stable for about 1 month. Stable ethanol-based nanofluids containing silver nanoparticles could be prepared by microwave-assisted one-step method. In the method, polyvinylpyrrolidone (PVP) was employed as the stabilizer of colloidal silver and reducing agent for silver in solution.
2.3.3. Chemical reduction method

Chemical reduction method, the reduction of metal salts, is the simplest and most commonly used one step method for metal nanoparticles. The production of nanosized metal silver particles with different sizes and morphologies using chemical reduction of silver salts has been reported [23, 24]. This method involves reduction of an ionic salt in an appropriate medium in the presence of stabilizing and reducing agents [25]. Moreover chemical reduction method has been extensively used because of its advantages of yielding nanoparticles without agglomeration, high yield and low preparation cost [26-28]. In our research work, we have preferred one-step chemical reduction method to synthesize silver nanoparticle suspensions. The common chemical reduction method is the Lee-Meisel method [29] which produces broad distribution of particle sizes. Silver nanoparticles having different sizes were prepared based on various modifications of the Lee-Meisel method. Nanosized silver particles were synthesized by the reduction of silver nitrate with tri sodium citrate.

2.4. Synthesis of silver nanofluids

2.4.1. Method for size around 11nm

Silver nitrate (AgNO₃, sigma Aldrich, 99.99%), the metal precursor and the reducing agent, trisodium citrate (C₆H₅O₇Na₃, sigma Aldrich, 99.99%) are used as the starting materials to prepare the silver nanofluid in double distilled water. 50 ml of 2×10⁻³ M silver nitrate solution is heated at 80°C for several minutes. 50 ml of 2×10⁻² M trisodium citrate is added to this warm solution and is stirred vigorously. The solution is heated until color changes from pale yellow to golden yellow indicating the formation of Ag
NPs and stirred until cooled to room temperature. The prepared silver nanofluid is shown in figure 3. Silver nanoparticles having average particle size around 11 nm is obtained in this preparation method.

![Figure 3. Silver nanofluid having average particle size around 11nm.](image)

2.4.2. Method for size above 11 nm

250 ml of $1\times10^{-3} M$ silver nitrate solution is heated at 85°C for 15 minutes. Then 5 ml of 1% trisodium citrate solution was added drop by drop to this boiling silver nitrate solution, accompanied by vigorous stirring. The mixed solution was refluxed at 85°C to 90°C for another 20 minutes. Finally a greenish-yellow silver nanofluid was obtained. Then it was removed from the heating element and stirred until cooled to room temperature. Silver nanofluids consisting of different particle sizes were prepared by adding 10, 20 and 40 ml of citrate to the boiling silver nitrate solution. The color of the solution ranging from greenish yellow to reddish green with increase in size of the nanoparticle. Silver nanoparticles having particle size ranging from 12 nm to 31nm were obtained. The color change is slower for larger nanoparticles than for small nanoparticles. The amount of citrate
concentration highly influences the size of silver nanoparticle. The faster the capping of the nanoparticles by the citrate, the smaller are the resulting nanoparticles. According to Mie theory, Ag nanoparticles spectra increase in absorption with the increase of size of NPs.

The resultant silver nanofluids are found to be highly stable and there is no precipitation or change in color on standing for several weeks. To produce a stable nanofluid either the particle size should be small enough to be suspended or the particles must be protected against aggregation by electric charge or other protective coatings. Here tri sodium citrate first acts as reducing agent and later as stabilizing agent (capping agent). Due to the large positive reduction potential of Ag, nanoparticle oxidation is thermodynamically unfavorable resulting in quite stable aqueous suspensions without the aid of additional capping agents. Aggregation can be inhibited by the thick electric double layers of absorbed citrate and /or nitrate ions that form around metal nanoparticles.

2.5. Properties of Silver nanofluids

2.5.1. Physical properties

A bulk material has constant physical properties regardless of its size, but at the nano-scale size-dependent properties are often observed. Thus, the properties of materials change as their size approaches the nanoscale and as the percentage of atoms at the surface of a material becomes significant. For bulk materials larger than one micrometer (or micron), the percentage of atoms at the surface is insignificant in relation to the number of atoms in the bulk of the material. The interesting and sometimes unexpected properties of nanoparticles are therefore largely due to the large surface area of the material, which dominates the contributions made by the small bulk of the
material. A well known feature of nanometric particles is the lower melting temperature with respect to the bulk since solid-liquid transition begins at interfaces.

2.5.2. Thermal properties

Extensive studies have been conducted to investigate thermal properties of nanofluids in the past decade and improved thermal properties have been observed in many nanofluid systems. Many factors such as particle size, concentration, effect of surfactant, dispersion of particles and thermal property of dispersed particles have been expected to influence the thermal property of nanofluids. Nanofluids were found to exhibit enhancement in thermal properties such as thermal conductivity, thermal diffusivity, thermal effusivity etc.

Thermal diffusivity is an important thermophysical parameter, which essentially determines the diffusion of heat through a sample, i.e. the resulting signal depends on how heat diffuses through the sample. Physically, the inverse of thermal diffusivity is a measure of the time required to establish thermal equilibrium in a system for which transient temperature change has occurred. Thermal diffusivity of nanoparticles has become an important parameter determining the performance of many engineering systems. The application of nanoparticle includes increment in the efficiency of thermoelectric energy conversion enhanced heat conduction in heat transfer fluids. All of these applications depend on the thermal transport between the nanoparticles and the base fluid. The thermal diffusivity of a material is closely related to thermal conductivity, specific heat and thermal expansion as given by \( \alpha = k/\rho c \) where \( k \) is the thermal conductivity, \( \rho \) and \( c \) are the sample density and specific heat. Nanoparticles
having high light absorbance and the structural elements of a system that interacts with laser radiation, may significantly influence the thermal diffusivity of the system. Recently, measurement of thermal diffusivity and conductivity of silver nanofluids were reported using thermal lens technique and transient hot wire technique respectively [30-31].

The thermal effusivity, similar to thermal diffusivity, is also another important thermal property of nanofluid. The major difference between the two is that diffusivity is a bulk property of the sample whereas the effusivity is a surface property. Actually, the thermal effusivity is a measure of the sample's thermal impedance or it is a measure of the sample's ability to exchange heat with the environment. The thermal effusivity is defined by

\[ e_s = \sqrt{k \rho c} \]

with dimension \( W s^{1/2} cm^{-2} K^{-1} \), where \( k \) is the thermal conductivity, \( \rho \) is the density and \( c \) is the specific heat capacity. Though the thermal effusivity is an abstract thermal quantity and is a relevant thermophysical parameter for surface heating and cooling as well as in quenching processes, it is one of the least explored quantities in physics. Recently thermal effusivity measurement of metal oxide nanofluids in different solvents were reported using front pyroelectric configuration technique [32]. By knowing the values of thermal diffusivity and thermal effusivity, thermal conductivity can be evaluated using the relation given by

\[ e = \frac{k}{\sqrt{\alpha}}. \]
2.5.3. Optical properties

Nanoparticles often possess unexpected optical properties as they are small enough to confine their electrons and produce quantum effects. The interesting optical attributes of metal nanoparticles, as reflected in their bright intense colors, are due to their unique interaction with light. Surface Plasmon Resonance (SPR) is the most outstanding optical property of metallic nanostructures. In the case of metallic nanoparticles, where the electrons are confined in the three dimensions, the electron oscillations induce an electric field around the NP that can be much larger than the incident light one. Electric fields of incident light and that created by electron oscillations is given in figure 4.

![Figure 4. Illustration of electric fields of incident light and that created by the electron oscillations near the NP.](image)

SPR is defined as the collective oscillation of conduction electrons excited by the electromagnetic field of light. The factors that collectively lead to these oscillations are (1) acceleration of the conduction electrons by the electric field of incident radiation, (2) presence of restoring forces that result from the induced polarization in both the particle and surrounding medium, and (3) confinement of the electrons to dimensions smaller than the wavelength of light. The surface obviously plays a very important role for the observation of the surface plasmon resonance as it alters the boundary
conditions for the polarizibility of the metal and therefore shifts the resonance to optical frequencies. For spherical silver nanoparticles having diameter between 2 and 100 nm, the position of the surface plasmon absorption is around 400 nm.

When the size of a metallic particle is reduced to the few nanometre range, the optical properties are dramatically modified by the appearance of SPR and its behaviour results completely different from the bulk metal. SPR open the possibility to amplify, concentrate and manipulate light at the nanoscale, overcoming the diffraction limit of traditional optics and increasing resolution and sensitivity of optical probes. Consequently, the SPR can be used in a wide range of fields, including biomedical [33-36], energy [37], environment protection, sensing and information technology [38] applications. Nowadays, there are well established applications of SPR that increases rapidly with the development of our capabilities to fabricate and manipulate nanomaterials.

2.5.3.1. Physical concept of Surface Plasmon Resonance

Plasmonic behavior is a physical concept that describes the collective oscillation of conduction electrons in a metal (or a doped semiconductor) [39]. Many metals (e.g., alkali metals, Mg, Al, and to some extent noble metals such as Au and Ag) can be treated as free-electron systems whose electronic and optical properties are determined by the conduction electrons alone. In the Drude–Lorentz model, such a metal is denoted as plasma, because it contains equal numbers of positive ions (fixed in position) and conduction electrons (free and highly mobile). Under the irradiation of an electromagnetic wave, the free electrons are driven by the electric field to coherently oscillate at a plasma frequency of \( \omega_p \) relative to the lattice of
positive ions. For a bulk metal with infinite sizes in all three dimensions, $\omega_p$ can be expressed as

$$\omega_p = \left(\frac{N e^2}{\varepsilon_0 m_e}\right)^{1/2}$$

(1)

where $N$ is the number density of electrons, $\varepsilon_0$ is the dielectric constant of a vacuum, and $e$ and $m_e$ are the charge and effective mass of an electron, respectively. Quantized plasma oscillations are called *plasmons*. In reality, we have to deal with metallic structures of finite dimensions that are surrounded by materials with different dielectric properties. Since an electromagnetic wave impinging on a metal surface only has a certain penetration depth (<50 nm for Ag and Au), the electrons on the surface are the most significant [40].

### 2.5.3.2. Fundamentals of Surface Plasmon in Nanoparticles

The scientific study of SPR started when Gustav Mie published his pioneer work explaining the surprising optical properties of metallic colloids [41]. However, SPR in NPs have been empirically used for a long time, particularly for glass coloring. Glasses from the final bronze age (1000-1200 BC) found in Fratessina di Rovigo (Northern Italy) were colored by the presence of metallic Cu NPs [38]. The Lygurcus cup is probably the most famous example of the use of SPR in the ancient times [8], exhibiting different coloration when observed upon illumination inside or outside of the cup. Actually many Roman mosaics used metallic NPs to achieve red coloration. There is also evidence of the ancient use of metallic NPs in glass and pottery from Egyptian dynasties, Celtic enamels, Japanese and Chinese glasses [38]. In the Middle Ages, the development of glass manufacturing processes induced outstanding advances on stained glasses fabrication. The variety of metallic NPs for glass coloring increased substantially as we can
observe in many church windows from that period. The development of glass chemistry during Renaissance and modern age provided better tuning of coloration effects based on the SPR of metallic NPs [42-43]. All these developments were empirically achieved without knowing the real origin of the surprising optical effects appearing when metallic atoms were introduced in the glass. After Mie’s work, the origin of the optical properties of metallic NP was understood, but further exploitation was limited by the capabilities to synthesize and manipulate NPs in a controlled way. Michael Faraday was the first to show that metal particles many times smaller than the wavelength of light scatter and absorb light strongly, such that even dilute solutions exhibit bright colors. The surface plasmon resonance in metal particles enables scattering and absorption of light at a particular frequency, giving them color in the case of silver and gold.

When excited by light, the induced charges characteristic to surface plasmons can propagate as an electromagnetic wave along the surface of bulk gold or silver. The oscillating charges can also be confined and enhanced on the surface of a nanoparticle, in that case it is called localized surface plasmon resonance (LSPR). A typical picture of localized surface plasmon is given in figure. 5.

![Figure 5. A Localized surface plasmon](image-url)
The surface plasmon oscillation decays by radiating its energy resulting in light scattering or decays non radiatively as a result of conversion of absorbed light to heat [36]. The electric field intensity and the scattering and absorption cross-sections are all strongly enhanced at the LSPR frequency [35] which for gold, silver, and copper lies in the visible region [44]. Since copper is easily oxidized, gold and silver nanostructures are most attractive for optical applications.

SPR correspond to an interaction between matter and the electromagnetic field of the light. A simplified classical picture can be more useful to understand the physical meaning of SPR. A metallic NP can be described as a lattice of ionic cores with conduction electron moving almost freely inside the NP (the Fermi sea) as figure.5 and 6 illustrates.

*Figure. 6. Scheme of the light interaction with a metallic NP. The electric field of the light induces the movement of conduction electrons which accumulate at the NP surface creating an electric dipole. This charge accumulation creates an electric field opposite to that of the light.*

When the particle is illuminated, the electromagnetic field of the light exerts a force on these conduction electrons moving them toward the NP surface. As these electrons are confined inside the NP, negative charge will be accumulated in one side and positive charge in the opposite one, creating an electric dipole. This dipole generates an electric field inside the NP opposite
to that of the light, which will force the electrons to return to the equilibrium position. The larger the electron displacement, the larger the electric dipole and consequently the restoring force. The situation is similar to a linear oscillator with a restoring force proportional to the displacement from the equilibrium position. If the electrons are displaced from the equilibrium position and the field is later removed, they will oscillate with a certain frequency that is called the resonant frequency; in the case of surface plasmon it is named the \textit{plasmonic frequency}. Actually, the electron movement inside the NP exhibits some damping force. The ionic cores and the NP surface partially damp the electron oscillations. Thus, the system is similar to linear oscillator with some damping. When an alternating force is applied to a linear oscillator, the system oscillates with the same frequency that of the external force but the amplitude and phase will depend on both the force and the intrinsic parameters of the oscillator. In particular, the oscillating amplitude will be maxima for the resonant frequency. It is quite straightforward to understand that, if the frequency of the external force is the same as that of the plasmonic frequency of the NP, it will be easy to make the electrons oscillate, but as we move far way from this frequency the movement of electrons will be more difficult, i.e., with reduced amplitude. The electronic oscillation implies an increase of kinetic and electrostatic energies associated to the electric fields of the dipole. As energy must be conserved, this increase of energy must be provided by the illuminating light. Therefore, the light extinguishes partially when exciting surface plasmon inside the NP. The larger the electron oscillations, the larger the light extinction, so the optical absorption spectrum allows to detect the excitation of surface plasmon. The resonant frequency for these oscillations in metallic
NPs corresponds typically to UV-VIS light and consequently, the surface plasmon arise absorption bands in this region of the spectrum.

### 2.5.3.3. Mie Theory of surface plasmon resonance.

Dating back to 1908, Gustav Mie [41] was the first to explain the colour of nanoparticle solutions and began to investigate the behavior of colloidal particles in an aqueous solution in order to characterize these particles by their electrical and optical properties. During this time, Mie developed a theory that mathematically describes the scattering of incident light by spherical particles. He solved Maxwell’s equation for an electromagnetic light wave interacting with small spheres. An accurate calculation of the SP and the associated light absorption requires solving the Maxwell equations at the NP region using the proper boundary conditions. The Mie theory provides an exact solution for spherical NPs assuming that they are non-interacting (i.e., the distance between the NPs is large enough so we may assume that the electric field created by a NP does not affects to the rest of them). By series expansion of the involved fields into partial waves, one obtains the following expressions for the extinction cross-section $\sigma_{\text{ext}}$ and scattering cross-section $\sigma_{\text{sca}}$.

\[
\sigma_{\text{ext}} = \frac{2\pi}{|k|^2} \sum_{L=1}^{\infty} (2L + 1) \text{Re} \left( a_L + b_L \right) 
\]

\[
\sigma_{\text{sca}} = \frac{2\pi}{|k|^2} \sum_{L=1}^{\infty} (2L + 1) \left( |a_L|^2 + |b_L|^2 \right) 
\]

with $\sigma_{\text{abs}} = \sigma_{\text{ext}} - \sigma_{\text{sca}}$ and
where \( n \) is the complex refractive index of the particle and \( n_m \) the real refraction index of the surrounding medium, \( k \) is the light wave-vector in the dielectric medium and \( x = |k|r \) with \( r \) being the radius of a nanoparticle. \( \psi_L \) and \( \eta_L \) are the Ricatti - Bessel cylindrical functions. The prime indicates differentiation; \( L \) is the summation index of the partial waves. \( L=1 \) corresponds to the dipole oscillation while \( L=2 \) is associated with the quadrupole oscillation and so on. For nanoparticles much smaller than the wavelength of light \( \lambda \) or roughly \( r < \lambda_{\text{max}} / 10 \) only the dipole oscillation contributes significantly to the extinction cross-section. The Mie theory then reduces to the following relationship (dipole approximation):

\[
\sigma_{\text{ext}}(\omega) = 4 \pi \frac{\varepsilon_m^{3/2} V}{c} \frac{\varepsilon_2(\omega)}{[\varepsilon_1(\omega)+2\varepsilon_m]^2 + \varepsilon_2(\omega)^2} \]

where \( V \) is the particle volume, \( \omega \) is the angular frequency of the exciting light, \( c \) is the speed of light, and \( \varepsilon_m \) and \( \varepsilon(\omega) = \varepsilon_1(\omega) + i\varepsilon_2(\omega) \) are the dielectric functions of the surrounding medium and the material itself respectively. While the first is assumed to be frequency independent, the latter is complex and is a function of energy. The resonance condition is fulfilled when \( \varepsilon_1(\omega) = -2\varepsilon_m \) if \( \varepsilon_2 \) is small or weakly dependent on \( \omega \)[44]. The above equation has been used extensively to explain the absorption spectra of small metallic nanoparticles in a qualitative as well as quantitative
manner. However, for larger nanoparticles where the dipole approximation is no longer valid, the plasmon resonance depends explicitly on the particle size as \( x \) is a function of the particle radius \( r \). The larger the particles become, the more important are the higher-order modes as the light can no longer polarize the nanoparticles homogeneously. These higher-order modes peak at lower energies and therefore the plasmon band red shifts with increasing particle size. At the same time, the plasmon bandwidth increases with increasing particle size. As the optical absorption spectra depend directly on the size of the nanoparticles, this is regarded as an extrinsic size effect.

2.5.3.4. Factors influencing the surface plasmon resonance of nanoparticle.

The surface plasmon resonance is extremely sensitive to nanoparticle size, shape, surrounding medium etc.

(a) Size effects

NPs size has a dramatic effect on the SP resonance processes and consequently on the optical properties of the NPs. Actually, there are different mechanisms inducing size dependence of the surface plasmon properties. As a general approach, we may distinguish two regimes corresponding to small NPs (fairly smaller than the light wavelength) and large ones with size comparable to the wavelength.

For small NPs (up to ~50 nm), we may assume that the NP is properly described by a dielectric dipole. The size dependence of the surface plasmon affects mainly the width and the intensity of the resonance band while the effect on the resonance wavelength is quite reduced [38, 45]. The intrinsic size effects (small NPs) are related to the damping of the electron oscillations. When surface plasmons are excited, the electrons are damped in
their movement by the scattering with the ionic cores and with the surface. The damping constant for the electron oscillations is given by:

$$\gamma = \gamma_0 + A \frac{V_F}{R}$$  \hspace{1cm} (5)

The first term $\gamma_0$ describes the damping due the scattering of the oscillating electrons with the ionic cores. It is size independent and its value is given by

$$\gamma_0 = \frac{V_F}{I_\infty}$$  \hspace{1cm} (6)

being $V_F$ the velocity of the conduction electrons (Fermi velocity) and $I_\infty$ the electron mean free path in the metal. This term depends just on the nature of the metal and the crystal structure. The second term corresponds to the scattering of oscillating electrons with the particle surface. $A$ is a material dependent constant that takes into account the features of the surface scattering. It is commonly considered as a phenomenological parameter although it is well established that it depends on the surface features as crystal quality, facets, capping species, strain, etc. The electrons in a certain shell close to the NP surface will scatter when they oscillate. As the particle size increases, the fraction of electrons in the shell close to the surface decreases and therefore the total damping is reduced. Therefore, the surface damping is proportional to the Fermi velocity in the metal and inversely proportional to the particle radius $R$.

NPs with radius larger than 50 nm (extrinsic size effect) cannot be considered much smaller than the light wavelength inside the metal. Thus, the particle is no more described by a dipole and further multipolar terms are required. As a consequence, the resonance band splits into several peaks: two peaks for quadrupole, three peaks for a octopole, etc.
(b) Shape effects

The surface Plasmon (SP) resonance is strongly affected by the particle shape. Since the restoring force for SP is related to the charge accumulated at the particle surface, it will be influenced by the particle geometry. The most clear example of these shape effect are the nanorods [34, 35]. For a nanorod, the charge accumulation at the NP surface will be different for electron oscillations along the rod axis (longitudinal plasmons) and or along perpendicular direction (transversal plasmons). For nanorods, the resonant frequency of transversal plasmons falls at about the same position that for spherical NPs (actually, at wavelengths slightly smaller) while the resonance of longitudinal plasmons shifts toward larger wavelengths when the nanorod aspect ratio (length/width) increases. This behaviour provides a method to tune the resonance of the SP at the desired wavelength by controlling the aspect ratio, which is especially useful for biomedical purposes. Other geometries as triangular prisms, nanocubes or nanocages give rise to more complicated effects, but in general [34] deviation from sphericity shifts the resonance toward larger wavelengths.

(c) Surrounding media

The excitation of SP not only depend on the NPs features but also significantly modified by the surrounding medium [38]. It has two clear effects on the SP excitation process. The dielectric function of the surrounding medium determines the light wavelength at the vicinity of the NP hence altering the geometry of the electric field at the NPs surface. But the most important effect is related to the polarization of the medium. During SP excitation, the charge accumulation creates an electric field in the vicinity of the NPs (beside that of the incident light). This field induces the polarization of the dielectric medium, resulting in a charge accumulation at
the edges of the medium (i.e., at the interface between the dielectric and the metallic NPs) that will partially compensate the charge accumulation due to the conduction electrons movement. This reduction of charge will depend on the dielectric function of the media; the larger $\varepsilon_m$, the larger the polarization charge, and hence, the larger the effect on the SP. Reducing the net charge at the NP surface implies a reduction of the restoring force. For an oscillator, it is well known that reducing the restoring force leads to smaller resonant frequency. Thus, increasing the dielectric constant of the surrounding media will shift the SP resonant band toward larger wavelengths (i.e., smaller frequencies).

2.6. Applications

The high absorption coefficient associated with the excitation of SP opens a wide range of potential applications of metallic NPs in many fields. The possibility to concentrate, amplify and manipulate light at the nanoscale through SP, provides a method to improve optical effects or activate processes in a controlled way. The enhancement in the optical and photothermal properties of noble metal nanoparticles arises from localized surface plasmon resonance. The plasmon resonance can either radiate light (Mie scattering), a process that finds great utility in optical and imaging fields, or be rapidly converted to heat (absorption); the latter mechanism of dissipation has opened up applications in several new areas. Nanotechnology provides a platform to modify and develop the important properties of metal in the form of nanoparticles having promising applications in diagnostics, biomarkers, cell labeling, contrast agents for biological imaging, antimicrobial agents, drug delivery systems and nano-drugs for treatment of various diseases [46]. The researchers are moving towards nanoparticles especially silver nanoparticles (Ag NPs) to solve the problem of emerging
pathogens including multi-drug resistant bacteria [47]. Ag NPs are more effective because of the high surface area to volume ratio so that a large proportion of Ag NPs are in direct contact with their environment. Moreover, the ability to integrate Ag NPs into biological systems has greatest impact in biology and biomedicine. Other applications to illustrate capabilities of SP are in the fields of energy, environment protection and information technologies and some of these applications are highlighted below. Also development of nano-devices using biological materials and their use in wide array of applications on living organisms has recently attracted the attention of biologists towards nanobiotechnology [48].

2.6.1. Biomedicine

Biomedical applications are certainly the most developed SP potential uses. NPs have the biological size, comparable to entities as virus, DNA chains, cells or bacteria. Hence, it is possible the NPs to interact individually with these organisms increasing efficiency and specificity of medical treatments. Moreover, noble metal NPs are highly biocompatible and easy to functionalize (mainly through thiol chains that create strong bonds with NPs surface and may act as linkers with larger organic molecules). Thus, in vitro applications of metallic NP exploding SP are well established while in vivo ones (always slower to develop due to the requirements of long term effect essays) show certainly promising results. The recent emergence of nanotechnology has provided a new therapeutic modality in Ag NPs for use in medicine. The distinctive properties of Ag NPs extend its application in antibacterial, antifungal, anti-viral and anti-inflammatory therapy [49].
2.6.1.1. Anti bacterial effect of silver nanoparticle

In this modern era the priority areas of research are concerning the development or modification in antimicrobial compounds in order to improve bactericidal potential. Microorganisms (bacteria, yeast and fungi) play an important role in toxic metals remediation through reduction of metal ions. Ag NPs have been known to have inhibitory and bactericidal effects and thus extend its application as an antibacterial agent. Antibacterial activity of the silver-containing materials can be used, for example, in medicine to reduce infections as well as to prevent bacteria colonization on prostheses, catheters, vascular grafts, dental materials, stainless steel materials and human skin [50]. Because of their high reactivity due to the large surface to volume ratio, Ag NPs play a crucial role in inhibiting bacterial growth in aqueous and solid media. The combined effect of Ag NPs with antibiotics has proven to be fruitful. Such effects were first observed in Staphylococcus aureus and E. coli using disk diffusion method. The antibacterial activity of Ag NPs can be extended to the Textile Industry as well. The biologically synthesized Ag NPs could be of immense use in medical textiles for their efficient antimicrobial function. The sterile cloth and materials play an important role in hospitals, where often wounds are contaminated with microorganisms, in particular fungi and bacteria, like S. aureus. Thus, to reduce or prevent infections, various antibacterial disinfections techniques have been developed for all types of textiles. The Ag NPs were incorporated in cotton and silk cloths. Anti-bacterial activity was observed when Ag NPs were incorporated in cotton cloth [51]. Contrary to bactericide effects of ionic silver, the antimicrobial activity of colloidal silver particles are influenced by the dimensions of the particles, the smaller the particles, the greater antimicrobial effect.
2.6.1.2. Anti viral nanosilver and its HIV interaction.

Nanomaterials with such excellent properties have been extensively investigated in a wide range of biomedical applications, in particular regenerative medicine. Ag NPs have been used to exhibit the antimicrobial efficacy against viral particles. Ag NPs have been shown to exhibit promising cytoprotective activities towards HIV-infected T-cells; however, the effects of these nanoparticles towards other kinds of viruses remain largely unexplored.

2.6.1.3. Nanoparticles as Drug Delivery Systems

Drug delivery systems (DDSs) can improve several crucial properties of "free" drugs, such as solubility, in vivo stability, pharmacokinetics, and biodistribution, enhancing their efficacy [52]. In this aspect nanoparticles can be used as a potential DDS owing to their advantageous characteristics. Moreover, doping of Ag/Au nanoparticles serves as an antenna to absorb the energy from a laser beam of "biologically friendly" near-infrared (NIR) region, causing local heating and disruption of microcapsules.

2.6.1.4. Nanosilver in cancer therapy

Nanotechnology may be translated into nanomedicine thereby referring to treatment and curing of diseases at a molecular scale. Indeed, the use of nanoparticles for delivery and targeting of therapeutic and diagnostic agents is at the forefront of projects in cancer medicine. The targeting and accumulation of drugs to specific sites where the agent is released provides a means to reach high drug concentration at a designated area with far less systemic side effects [53]. Cancer remains one of the world's most devastating diseases and current cancer treatments include surgical intervention, radiation and chemotherapeutic drugs, which often also kill
healthy cells and cause toxicity to the patient. The emerging trend of using nanoparticles as drug carriers has exploited the potential of nanoparticles to revolutionize cancer therapy. Silver has been now recognized as a developing therapeutic molecule and will surely extend its use as a drug carrier. Ag NPs can be used for both active and passive targeting of drugs. Ag NPs have recently emerged as an attractive candidate for delivery of various payloads into their targets. The payloads could be small drug molecules or large biomolecules, like proteins, DNA or RNA. Efficient release of these therapeutic agents is a prerequisite for effective therapy.

2.6.1.5. Sensing

The sensing of biological agents, diseases, and toxic materials is an important goal for biomedical diagnosis, forensic analysis, and environmental monitoring. A sensor generally consists of two components: a recognition element for target binding and a transduction element for signaling the binding event. The unique physicochemical properties of NPs coupled with the inherent increase in signal-to-noise ratio provided by miniaturization [54] makes these systems promising candidates for sensing applications [55, 56].

Ag NPs have remarkable importance in the area of optical sensing due to its SP resonance. An interesting attribute of the surface plasmon oscillation is that its resonance frequency depends on the dielectric constant, that is, refractive index (RI), of the medium surrounding the nanoparticle [36, 57-58]. With increase in medium RI, the LSPR red-shifts. When this shift is followed using absorption spectroscopy (for colloidal NPs) or scattering spectroscopy (for nanoparticles deposited on a substrate), changes in the nanoparticle environment can be sensed. In order to sense
chemical/biological species, the nanoparticles are conjugated with recognition molecules, which specifically bind the target analyte, while appropriate surface capping is required to minimize nonspecific binding. The binding of the target molecule to the recognition molecules causes a plasmon band shift due to a local RI change, serving as an optical sensing tool. To achieve sensitivities down to few molecules bound per nanoparticle, the plasmon band shift is desired to be as high as possible in response to small RI changes. Nanostructure geometry can be readily tuned to enhance plasmonic sensitivity, defined as the plasmon shift per refractive index unit (RIU) change. When the particle volume is increased, sensitivity increases by a limited extent, possibly due to increase in radiative damping and retardation. However, more molecules would be required to effectively change the RI around a larger nanoparticle. In addition, the plasmon band broadens due to damping and retardation, reducing the sensitivity of determining band shifts. Nanoparticle shape offers a handle for tuning sensitivity without changing particle volume. Interestingly, nanostructure geometries that offer plasmon resonance tunability also offer high plasmon sensitivity. Silver nanoprisms due to their high sensitivity have been used to sense Alzheimer’s disease markers [59] and in single-particle assays [60].

Silver nanoparticles open exciting new ways to create efficient optical probes based on the strongly enhanced spectroscopic signals that can occur in their local optical fields. One of the most impressive effects associated with local optical fields is surface-enhanced Raman scattering [61-64]. This technique is a form of Raman spectroscopy (RS) based on the interaction of the incident light with a molecule adsorbed onto the roughened metal surface. Since strong enhancement in Raman signals is observed for molecules attached to rough metal surfaces, the effect was named surface-
enhanced Raman scattering (SERS). A useful capability of SERS in the field of biophysics comes from the potential of the method for providing information on molecules residing on surfaces and interfaces. SERS has also been considered as an attractive method for DNA detection because of its single molecule level sensitivity, molecular specificity and insensitivity to quenching. These distinct advantages have led to the development of a number of ingenious SERS sensing platforms. Derived from Raman spectroscopy, there are other interesting techniques employing AgNPs as substrate, such as Surface-Enhanced Resonance Raman Scattering (SERRS) [65] and Surface-Enhanced Raman Optical Activity (SEROA) [66].

2.6.1.6. Biological imaging

Due to the strongly enhanced LSPR, noble metal nanoparticles scatter light very strongly at the LSPR frequency, making them very promising for optical imaging and labeling of biological systems. Therefore, taking advantage of both the intense plasmon-resonant properties of Ag nanoparticles and the enhanced resolution obtainable with the high illumination system in physiological solutions, studies on the interactions between Ag nanoparticles and live cells have been made possible. However, the use of silver nanoparticles in the imaging of neural tissue and cells, in particular, raises concerns over the possibility of contributing to neurodegenerative diseases (e.g. Parkinson’s and Alzheimer’s) due to their ability to produce reactive oxygen species and oxidative stress [67]. Amanda et al. [68] demonstrated that low concentrations of Ag nanoparticles become bound to the plasma membranes of live cells, and intensely scattered light when imaged at submicron resolution with high illumination light microscopy, thereby opening the possibility for their potential use as biological labels. The tailor ability of the Ag nanoparticles through surface
engineering lends itself to a greater variety of in vivo applications such as imaging agents [69], products for wound healing [70] and the development of cancer therapies [71-72]. Therefore, taking advantage of the highly desirable properties of Ag nanoparticles while protecting the body from harmful side effects is a worthwhile long-term goal, and surface modification of nanoparticles seems to be one of the keys to achieving that goal.

2.6.2. Energy

The current energy problem impels to search for energy sources different to traditional ones based on fossil fuels. In this search, the sun appears as a clean source of energy with lifetime over 5000 million years releasing daily 4000 times the earth electric energy consumption. The use of solar energy can be addressed by different techniques including photovoltaic [73], photochemical or photothermal effect [74]. The main limitation of these technologies relays on the efficiency of the light absorption and conversion processes that make them hardly viable from an economical point of view. The capabilities to concentrate and locally amplify the light electric field by means of SP offer new methods to increase the efficiency of photoenergetic process, overcoming the efficiency limitation required for the massive implantation of these technologies.

Photovoltaic devices represent the most exploded way to harvest solar energy. While there are several generations of photovoltaic devices [75], all of them are based on junctions where electron-holes pairs created by light absorption are separated; leading to charge accumulation that produces electric voltage, i.e., electric energy. The main limitation in the development and implantation of photovoltaic devices is their efficiency. A key problem in improving efficiency of photovoltaic devices is that large thicknesses are
required to absorb most of the incoming light, especially for silicon based solar cells, due to the indirect gap nature of silicon. However, these larger thicknesses enhance the electron-hole recombination probability increasing loses and requires larger amount of material (i.e., larger production costs). This problem can be solved to some extent by the incorporation of nanoparticles. The incorporation of metallic NPs in solar cells can increase the efficiency of charge separation by several physical processes. As figure 7 illustrates, if we place metallic NPs at the device surface, upon light illumination, the large scattering cross section associated with SP can scatter the normal incident light beams.

![Figure 7. Nanoparticles at the surface and junction interface](image)

Hence, the effective path across the active absorption layer is increased. Moreover, with a proper architecture, this scattering may be used to promote total reflection inside the layer trapping the photons until they are finally absorbed. Another method to improve efficiency exploding SP, consists of placing the NPs at the junction interface as shown in figure 7. The light concentration and local amplification in the vicinity of the NP when SPs are excited increases the absorption efficiency. Stuart and Dennis [76] demonstrated an increase up to a factor 20 in the photocurrent of a silicon photodetector by placing silver NPs on the surface. Increases of photovoltaic
cells efficiency of the order of 10-15% have been achieved by incorporating Ag NPs on the cell surface [77].

Photothermal technology is an alternative to photovoltaics especially when the energy is used for heating. In typical photothermal devices, a fluid absorbing light increases its temperature and is submitted to a thermal cycle releasing energy. The efficiency of thermal cycles is limited by the temperature difference between the hot and cold focus. Thus, reducing the mass that absorbs the solar light will increase its temperature and consequently improve the efficiency of the device. The huge extinction cross section of SP provides a method to achieve intense light absorption by small masses. Moreover, the tunability of SP resonance band allows the design of selective absorbers that reduces energy losses due to blackbody radiation. Besides the pure physical methods, SP can also be used to catalyze reactions for energy harvesting using chemical paths.

In general, any photoenergetic process addresses the problem to explode the wide solar spectrum. As most of optical transitions in bulk materials exhibit well defined absorption bands, it is difficult to design materials capable to absorb efficiently over a large part of the solar spectrum. SP are not an exception, but, as described above, it is possible to tune the SP band in a wide range, something not straightforward with other absorbing materials as dyes or semiconductors. This tunability renders SP especially advantageous for wide spectrum photo-energetic processes.

2.6.3. Environment

The development of technological societies requires a progressive increase of the industrial activity. Many industrial processes result in hazardous products for humans and environment [78]. Reaction of these products to be
transformed in inert ones is mandatory in order to ensure a secure and sustainable development of our society. Catalysis provides a pathway to eliminate these hazardous products quickly, hence reducing their potential danger. Among the different catalytic processes, photocatalysis exhibits particular importance since it is a clean process that can use solar light [79]. Metallic NPs exhibit catalytic activity [80] that can be improved upon light illumination to excite SP [81]. However, the most exploded use of SP in photocatalysis is the enhancement of photocatalytic efficiency in transition metal oxides by incorporation of metallic NPs. Transition metal oxides (as TiO2) exhibit an energy gap in the UV-VIS part of the spectrum. Thus, upon illumination, electrons can be promoted to the conduction band. The excited electrons are available to participate in the oxidation of the products that are absorbed on the catalytic surface. Similarly, holes created in the valence band allow the donation of an electron from the absorbed products yielding their reduction. It is straightforward to understand that the efficiency of the catalytic surface (measured as the number of reaction that takes place per unit area and time) will depend critically on the light absorption process that governs the number of active electrons/holes in the material.

The incorporation of metallic NPs have been used in the past since they act as electron traps retarding electron-hole recombination and therefore increasing the process efficiency. However, the use of NPs exhibiting SP resonance by the photocatalytic surface generates additional increase of light absorption efficiency by the local electric field amplification and scattering processes as in the photovoltaic devices described. Awazu et al. [82] demonstrated the increase of photocatalytic efficiency of a TiO2 layer by embedding Ag NPs near the surface as shown in figure 8.
The mechanism of efficiency improvement is basically the same as for photovoltaic devices. The light scattering at the silver NPs increases the effective optical path of photons leading to a higher absorption rate, while the local electric field enhancement also assists the absorption processes. With this arrangement, they found an increase above one order of magnitude in the decomposition rate of methylene blue under near-UV irradiation. The incorporation of metallic NPs holding SP in photocatalytic materials may have additional advantages. A key problem in some photocatalyst as ZnO is the photo-instability in aqueous solution due to photocorrosion upon UV illumination [83]. It has been reported that incorporation of Ag NPs onto ZnO films leads to an increase of photocatalytic efficiency and higher stability of ZnO preventing the photocorrosion. The presence of Ag NPs avoid the photodegradation upon UV illumination.

2.6.4. Heat transfer intensification

Since the origin of the nanofluid concept about a decade ago, the potentials of nanofluids in heat transfer applications have attracted more and more attention. Due to higher density of chips, design of electronic components with more compact makes heat dissipation more difficult. Advanced electronic devices face thermal management challenges from the high level of heat generation and the reduction of available surface area for heat removal. So, the reliable
thermal management system is vital for the smooth operation of the advanced electronic devices [84]. In general, there are two approaches to improve the heat removal for electronic equipment. One is to find an optimum geometry of cooling devices; another is to increase the heat transfer capacity. Nanofluids with higher thermal conductivities have convective heat transfer coefficients compared to those of base fluids. Recent researches illustrated that nanofluids could increase the heat transfer coefficient by increasing the thermal conductivity of a coolant.

The thermal requirements on the personal computer is essential with the increase in thermal dissipation of CPU. One of the solutions is the use of heat pipes. Nanofluids, employed as working medium for conventional heat pipe, have shown higher thermal performances, having the potential as a substitute for conventional water in heat pipe. Chen et al. [85] studied the effect of a nanofluid on flat heat pipe (FHP) thermal performance, using silver nanofluid as the working fluid. The temperature difference and the thermal resistance of the FHP with the silver nanoparticle solution are lower than those with pure water. The plausible reasons for enhancement of the thermal performance of the FHP using the nanofluid can be explained by the critical heat flux enhancement by higher wettability and the reduction of the boiling limit. The thermal performance investigation of heat pipe indicated that nanofluids containing silver could be used as an efficient cooling fluid for devices with high energy density.

2.7. Conclusion

This chapter describes the general introduction of nanofluids, method of preparations of silver nanofluids, properties and applications in various fields. Due to the above mentioned wide range of applications, I have selected silver nanofluids for the study.
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