# CHAPTER I

# 1. INTRODUCTION TO NANOFLUIDS AND ITS HEAT TRANSFER APPLICATIONS

## 1.1 INTRODUCTION

Nanofluids are two phase mixtures engineered by dispersing nanometer sized particles with sizes ranging below 100 nm in base fluids (Sarit K. Das et al. 2008). The nanometer sized particles which are used for the dispersion in base fluids are nanoparticles, nanofibers, nanotubes, nanowires and nanorods. Materials generally used as nanoparticles include metal oxides (e.g., alumina, silica, zirconia, titania), oxide ceramics (e.g. $Al_2O_3$, CuO), chemically stable metals (e.g. gold, copper), carbon in various forms (e.g., diamond, graphite, carbon nanotubes, fullerene) metal carbides (e.g. SiC) and functionalized nanoparticles. The base fluid types include oils, water, organic liquids such as glycols, refrigerants, polymeric solutions, bio fluids, lubricants and other common liquids.

## 1.2 ADVANTAGES OF NANOFLUIDS

Particle size is the major physical parameter in nanofluids, since it can be used to attune the nanofluid thermal properties as well as the suspension stability of nanoparticles. Hence, nanofluids can able to flow freely through mini or micro channels with the dispersion of nanoparticles. The nano suspensions show high thermal conductivity which is mainly due to enhanced convection between the nanoparticles and base liquid surfaces. Another potential benefit is that the nanoparticles have lower dimensions so that the dispersed nanoparticles seems to be like a base fluid molecule in suspension.

The advantages of suspending nanoparticles in base fluids:

- ❖ The surface area and heat capacity of the fluid are increased.
- ❖ The effective thermal conductivity of the fluid is enhanced.
- ❖ The collision and interaction among particles, the surface of flow passage and base fluids are intensified.

- Reduction of particle clogging rather than conventional slurries.

The combination of these factors makes nanofluids highly preferable for designing heat transfer fluids.

## 1.3 PREPARATION METHODS FOR NANOFLUIDS

The initial key step in experimental studies with nanofluids and the optimization of nanofluid thermal properties requires successful preparation methods for producing stable suspensions of nanoparticles in liquids. Some special requirements are essential (i.e.) negligible agglomeration of particles, uniform, durable and stable suspension and no chemical change of the fluid, etc. There are two main techniques adopted for the preparation of nanofluids: single-step method and two-step method.

### 1.3.1 Single step method

Single step method simultaneously produces and disperses the nanoparticles directly into the base fluid medium which is suitable for metallic nanofluids. The aggregation problem can be much reduced with direct evaporation condensation method. This inert-gas technique involves the vaporization of source material in a vacuum. In this process of preparation, the condensation forms nanoparticles through direct contact between the base fluid and vapor.

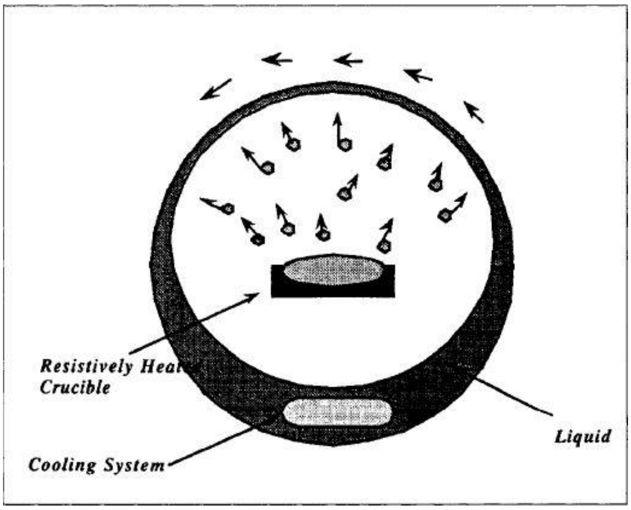


**Figure 1.1** *Schematic representation of one-step method of nanofluid preparation*

The continuous circulation of base fluids minimizes the agglomeration of nanoparticles. The schematic representation of direct evaporation condensation technique is shown in figure 1.1. The researchers from Argonne National Laboratory reported yet another interesting technique is laser ablation technique, in which the metal nanoparticles in deionized water are synthesized by using multi-beam laser ablation in liquids, where the laser parameters controls the size and distribution of nanoparticles.

### 1.3.2 Two step method

Two-step method is the most common method for the preparation of nanofluids and its schematic representation is shown in figure 1.2. Nanosized solid particles such as nanorods, nanotubes, nanofibers, or other functionalized nanomaterials are used in this method. Nanoparticles are initially synthesized in powder form by physical or chemical methods. Then, the nanosized powder particles are dispersed in base fluid in the successive processing step with the aid of intensive ultrasonication method or by using surfactants. This method is most widely used economic method for large scale production of nanofluids, since nanoparticle synthesis techniques were scaled up to industrial production levels.

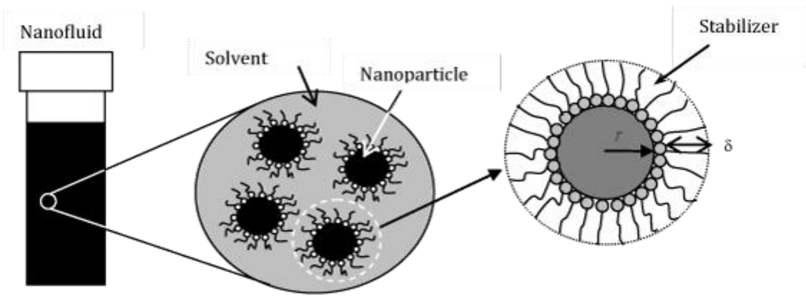


**Figure 1.2** *Schematic representation of two-step method of nanofluid preparation*

## 1.4 TYPES OF HEAT TRANSFER MECHANISMS

Heat transfer is the science that predicts energy transfer between material bodies as a consequence of temperature difference. The heat transfer depends not solely on the transfer of heat energy, but also to predict the heat exchange rate, that take place under certain specified conditions. Heat transfer supplements the principles of thermodynamics by providing additional experimental rules that are used to establish energy-transfer rates (Holman et al. 2010).

### 1.4.1 Conduction Heat transfer

When a temperature gradient exists in a body, there is an energy transfer from high temperature region to low temperature region. The energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient

$$\frac{q}{A} \sim \frac{\partial T}{\partial x} \qquad (1.1)$$

When the proportionality constant is inserted,

$$q = -kA\frac{\partial T}{\partial x} \qquad (1.2)$$

where $q_x$ is the heat-transfer rate, $\partial T/\partial x$ is the temperature gradient in the direction of the heat flow and k is the positive constant which is the thermal conductivity of the material. Here, the minus sign is inserted so that the second principle of thermodynamics will be satisfied; i.e., heat must flow downward on the temperature scale, as indicated in the coordinate system of figure 1.3. Equation (1.1) is called Fourier's law of heat conduction and Equation (1.2) is the defining factor for thermal conductivity.

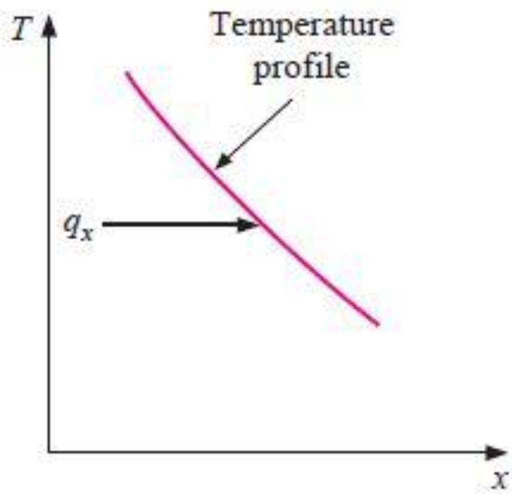


**Figure 1.3** *Sketch showing direction of heat flow*

Thermal conductivity, in general is strongly temperature-dependent and expressed in units of watts per meter per Kelvin per Celsius degree when the heat flow is expressed in watts. When a heat rate is involved, the thermal conductivity value indicates the rate of heat flow in a given material.

**Table 1.1:** *Thermal conductivity of various materials*

| **Elements** | **Material** | **Thermal conductivity (W/mK)** |
|---|---|---|
| Metallic solids | Silver<br>Copper<br>Aluminium | 429<br>401<br>237 |
| Non-metallic solids | Diamond<br>CNT<br>Silicon<br>Alumina | 3300<br>3000<br>148<br>40 |
| Metallic liquids | Sodium at 644K | 72.3 |
| Non-metallic liquids | Water<br>Ethylene Glycol<br>Engine Oil | 0.613<br>0.253<br>0.145 |

The physical mechanism of thermal energy conduction in liquids was explained as follows: Assume the kinetic energy of a molecule with its temperature. The molecules have greater velocities in high temperature region rather than in lower-temperature region. The molecules in continuous random motion, exchange their energy and momentum by colliding with one another. The molecule transports kinetic energy to the lower temperature part of the system when it moves from a high temperature region to a region of lower temperature and gives up this energy through collisions with lower energy molecules. Thermal conductivity of some typical liquids is shown in figure 1.4.  Thermal energy will be conducted in solids by two modes: transport by free electrons and lattice vibration.

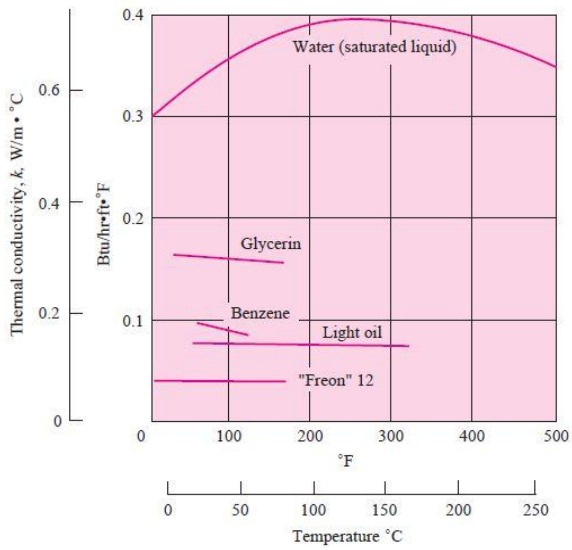


**Figure 1.4** *Thermal conductivity of some typical liquids*

In good electrical conductors, large number of free electrons move about in the lattice structure of the material and these electrons transport electric charge and carry thermal energy from a high temperature region to lower temperature region. Energy is also be transmitted in the form of vibrational energy in the lattice structure of the material. Thermal conductivity of some typical solids is shown in figure 1.5.

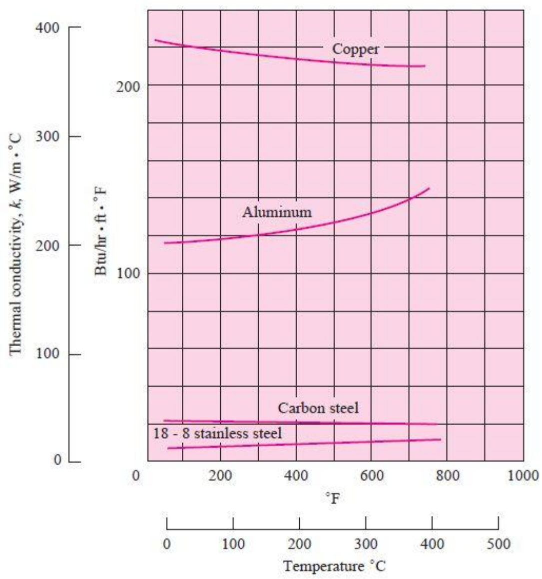


**Figure 1.5** *Thermal conductivity of some typical solids*

### 1.4.2 Convection heat transfer

It is well known, that a hot metal plate will cool faster while it was placed in front of a cooling fan rather than when exposed to still air. Convection heat transfer is the process in which the heat is convected out. The term convection provides with an intuitive notion concerning the heat transfer process. Consider the heated plate shown in figure 1.6 and the temperature of the plate is $T_w$, and the temperature of the fluid is $T_\infty$. The velocity of the flow appeared as shown, being reduced to zero at the plate as a result of viscous action. Since the velocity of the fluid layer at the wall is zero, the heat energy is transferred only by conduction at that point.

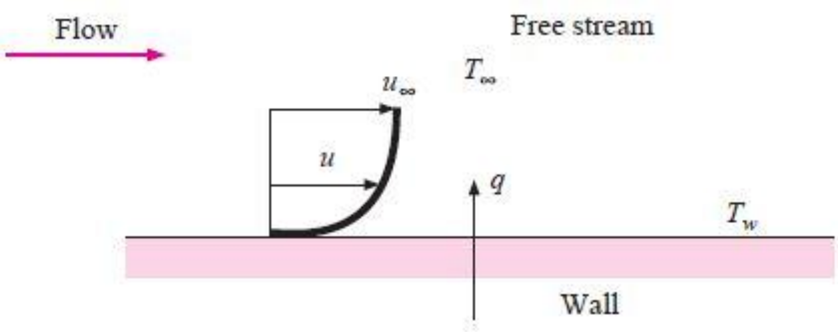


**Figure 1.6** *Convection heat transfer from a plate*

The heat transfer is computed, using Equation (1.3), with the thermal conductivity of the fluid and the fluid temperature gradient at the wall. Here, the temperature gradient is dependent on the rate at which the fluid carries the heat away and high velocity produces a large temperature gradient. Thus the temperature gradient at the wall depends on the flow field, and an expression relating the two quantities were developed to express the overall effect of convection:

$$q = hA\,(T_w - T_\infty) \qquad (1.3)$$

Here, the heat transfer rate is related to the overall temperature difference between the wall, fluid and the surface area A. The quantity ‘h’ is termed as convection heat transfer coefficient. Convection heat transfer have dependence on the viscosity of the fluid in addition to its dependence on the thermal properties of the fluid like specific heat capacity, thermal conductivity and density (Massoud

Kaviany et al. 2011). This is expected because viscosity influences the velocity profile and, correspondingly, the energy transfer rate in the region near the wall.

### 1.4.3 Radiation heat transfer

In contrast to the mechanisms of conduction and convection, where energy transfer through a material medium is involved, heat energy is also transferred through regions where a perfect vacuum exists. The mechanism in this case is electromagnetic radiation. Electromagnetic radiation that is propagated as a result of a temperature difference is known as thermal radiation. Thermodynamic considerations show that an ideal thermal radiator, or blackbody, will emit energy at a rate proportional to the fourth power of the absolute temperature of the body and directly proportional to its surface area. Thus

$$q_{emitted} = \sigma A T^4 \tag{1.4}$$

where σ is the proportionality constant and is called the Stefan-Boltzmann constant with the value of $5.669\times10^{-8}$ $W/m^2\cdot K^4$.

## 1.5 NANOFLUIDS AS HEAT TRANSFER FLUIDS

Less weight fractions of nanoparticles, when dispersed and suspended stably in base fluid medium, provide drastic enhancements in the thermal properties of base fluids. This nanofluid technology, is given primary importance where thermal engineering and nanotechnology meet together, has developed largely over the past decade. The vital role of nanofluids is to attain the highest possible thermal properties with low particle weight fractions by uniform dispersion and stable suspension of nanoparticles in base fluid medium. In order to achieve this goal, it is crucial to determine the enhancement of thermal energy transport in liquids. Several engineers and scientists, in the growing nanofluid era, have performed research breakthrough by investigating unexpected thermal properties of nanofluids and also proposed new mechanisms behind improved thermal properties of nanofluids.


**Figure 1.7** *Preparation of Nanofluid*

Nanofluid technology even offers a vital part for the development of compact and cost effective cooling systems. Figure 1.7 shows nanofluid preparation and schematic representation of this heat transfer fluid is shown in figure 1.8. Within the realm of thermal science, nanofluids are developed for their inexplicably enhanced thermal conductivities, which provides the concept of utilizing nanofluids as heat transfer fluids.

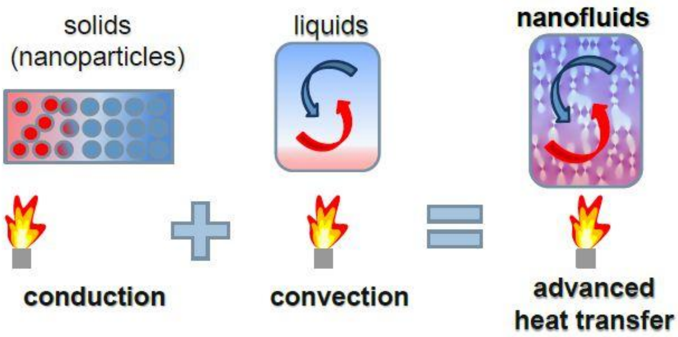


**Figure 1.8** *Schematic view of heat transfer fluid*

The improved thermal properties of nanofluids provide a better insight into an enormous innovation for heat transfer intensification, which is of major importance to industrial sectors including power generation, transportation, thermal therapy for cancer treatment, micro manufacturing, metallurgical and chemical sectors, as well as cooling, heating and air conditioning.

### 1.5.1 Liquid cooling

Cooling is the major technical challenge facing high tech industries such as microelectronics, metrology, manufacturing and transportation. It is highly desirable for the maintenance of various electronic products at desired operating temperatures for long life time and proper functioning. The cooling performance was significantly enhanced with the aid of nanofluids (Lee and Choi 1996). In the realm of electronics cooling, the industrialists started using nanofluids instead of conventional liquids. In addition, nanofluids could effectively remove hot spots and maintain components at uniform temperatures. Considering the range of efforts to extend liquid cooling technologies and the superior thermal properties, nanofluids would be utilized for hot spot cooling systems for computer, high heat flux, telecom, defence and power electronics uses.

### 1.5.2 Crystal Silicon Mirror Cooling

An advanced cooling technology was developed using nanofluids to cool crystal silicon mirrors (Lee and Choi 1996) in high intensity x-ray sources was one among the initial applications in the field of nanofluid research. Lee and Choi performed analysis for the estimation of better performance of microchannel heat exchangers with liquid nitrogen, conventional water and finally nanofluids as working fluids. Their research efforts showed that nanofluids could significantly increase power densities and reduce thermal resistances. Furthermore, the chance of flow-induced vibration and thermal distortion were much eliminated by passing nanofluids through microchannels within the silicon mirror. The researchers also investigated that power densities of around 3000 W/cm$^2$ for high aspect ratio microchannels were accomplished with nanofluids.

### 1.5.3 Electronics Cooling

Ice Dragon cooling nanofluid coolant -32oz is the most advanced cooling liquid available for electronic applications and is capable of improving heat transfer rates as much as 20%. Upon certain limitations on practical heat exchanger designs, this cooling fluid was produced for the electronics field by allowing increased heat removal with the smaller sized cooling hardware. This cooling fluid was exclusively designed for liquid cooled computer systems capable of allowing more thermal head room and pushing the thermal envelope of performance than any other cooling fluid. Solvent-free ionic molybdenum disulphide ($MoS_2$) nanofluids were synthesized by functionalizing nanoscale $MoS_2$ from hydrothermal synthesis with an ionic oligomeric canopy and charged corona. These synthesized nanofluids were homogeneous amber-like fluids with Newtonian flow feature. They are inevitable candidates for the lubrication of nano and micro electro mechanical systems.

Chien et al. (2003) investigated experimentally that the thermal resistance of the heat pipe was much reduced (40%) with water based gold nanofluids. Tsai et al. (2004) revealed experimentally that, there is significant reduction (37%) in the thermal resistance of heat pipe using gold nanofluids in conventional meshed circular heat pipe. Kang et al. (2006) experimentally measured temperature distribution of conventional grooved circular heat pipe and found that the thermal resistance of heat pipe was much reduced by 10 to 80% at an input power of 30 to 60 W with water-based silver nanofluids. Ma et al. (2006a, b) investigated experimentally that an oscillating heat pipe (OHP) with water-based $Al_2O_3$ nanofluids was capable in heat removal in excess of 1000 W/cm$^2$. Similarly, diamond nanofluids could reduce the temperature difference at an input power of 80.0 W from 40.9 in an OHP with water to 24.3°C in an OHP.

Chien and Huang (2005) numerically investigated silion microchannel heat sink (MCHS) performance using nanofluids and observed that the thermal performance got enhanced due to thermal dispersion of nanoparticles and increased thermal conductivity of nanofluids. Similarly, Koo and Kleinstreuer (2005) simulated steady laminar flow of nanofluids in microchannels and predicted that the copper nanofluids at low volume fractions (1 to 4%) to high-Prandtl-number base fluids significantly increased the thermal transfer performance of microchannel heat sink. Chein and Chuang (2007) experimentally investigated MCHS performance analytically using water based CuO nanofluids and shown that, for the less flow rate, the quantity of heat absorbed by CuO nanofluids was greater.

Palm et al. (2006) investigated heat transfer enhancement abilities of $Al_2O_3$-water nanofluids inside typical radial flow impingement jet cooling systems. Zhou (2004) experimentally investigated heat transfer characteristics of copper-acetone nanofluids and observed that, both pool boiling and single-phase natural convection were enhanced remarkably. These significant works will facilitate and improve the state of the art in nanofluid applications and hasten the development of highly efficient cooling device for ultrahigh-heat-flux systems.

### 1.5.4 Vehicle Cooling

Nanoparticles could not only be dispersed in engine oils and coolants, but also in gear oils, lubricants, transmission fluids and other fluids as well. These nanofluids provide better insight into thermal management system and better lubrication. Tzeng et al. (2005) were the pioneers by using nanofluid technology in automatic power transmission system. In their research work, $Al_2O_3$ and CuO nanoparticles were dispersed in transmission oil to investigate the optimum possible compositions of nanofluid for enhanced heat transfer performance. The temperature distribution of the RBC exterior were measured at four varying rotating speeds (400, 800, 1200, and 1600 rpm) and the conditions of real car at various rotating speeds were simulated. The investigations revealed that better heat transfer effect was achieved with CuO nanofluids and they have the efficiency of lowest temperature distribution at both low and high rotating speeds. This work is vital since it shows real world application of nanofluids representing a greater step forward for industrial applications of nanofluids.

### 1.5.5 Transformer Cooling

The power generation industry is greatly interested in transformer cooling application with the usage of nanofluids for reducing size and weight of the transformer. The ever increasing demand for greater electricity production, especially in our nation will require upgrades of most transformers at some point in the near future at a potential cost of millions of dollars in hardware retrofits. Yu et al. (2007) and Xuan and Li (2000) examined that the heat transfer properties of transformer oils could be significantly improved by using additives of nanoparticles. Specifically, nanofluid based transformer oil is likely to be the next-generation cooling fluid in transformers.

### 1.5.6 Space and Nuclear Systems Cooling

Vassallo et al. (2004) and You et al. (2003) explained the unprecedented phenomenon that nanofluids could able to increase the critical heat flux (CHF) by triple fold measure in pool boiling. Kim et al. (2006) found that the high surface wettability produced by nanoparticle addition could demonstrate remarkable thermal properties of nanofluids. Experimental investigation is required in developing realistic predictive models of CHF in nanofluids. The upper heat flux limit in nucleate boiling systems and the ability to increase the CHF, is of paramount practical importance to ultrahigh heat flux devices that use nucleate boiling, such as nuclear reactor components and high power lasers. Hence, nanofluids have raised up exciting possibilities for simplifying cooling requirements for space applications and increasing chip power in electronic devices. The Massachusetts Institute of Technology (MIT), United States has established an interdisciplinary centre for nanofluid technology for the nuclear energy industry. The researchers were evaluating the vital impact of the use of nanofluids on the safety, economic and neutronic performance of nuclear systems.

### 1.5.7 Defense Applications

Numerous military systems and devices, such as military vehicle components radars, high powered military electronics, lasers, require high heat flux cooling to the level more than 1000 W/cm$^2$. Cooling with conventional heat transfer fluids at this high level is much difficult. Nanofluid technology also provides advanced cooling systems for military combat vehicles, high-power laser diodes and submarines. It seems that nanofluid research in defense applications considers energy harvesting through chemical reactions or multifunctional nanofluids with added thermal energy storage.

### 1.5.8 Tribological Applications

Nanofluid technology was applied in developing better lubricants and oils. Li et al. (2004) reported performance on lubricant nanofluids containing $ZrO_2$ and $IrO_2$ nanoparticles. The experimental results showed that nanoparticles decreases friction on the surface of 100 C6 steel. Que et al. (1997) reported that surface modified nanoparticles stably dispersed in mineral oils are very effective in enhancing load-carrying capacity and reducing wear in lubrication application.

### 1.5.9 Biomedical Applications

Nanofluids were also developed for medical treatments, including cancer therapy. Iron-based nanofluids could be used to produce higher temperatures around the tumor cells, by killing cancerous cells without affecting the nearby healthy tissues (Jordan et al. 1999). Nanofluids could also be used for safer surgery by cooling around the surgical region, thereby enhancing a patient's chance of survival and reducing the risk of organ damage.

## 1.6 Recent applications

### 1.6.1 Nanofluids in CPU cooler

The Reserator 3 Max nanofluid cooler was developed by Zalman's company with the features of nanofluidic technology and created the first commercial CPU cooler which is shown in figure 1.9.

**Figure 1.9** *Zalman's Reserator 3 Max nanoliquid cooler*

This cooler system achieved cooling of loads up to 400W of heat through a single CPU water block by using a dual pure-copper radial radiator design. An integrated high-performance pump was provided and the liquid through the system can withstand 90 litres per hour flow rate. In this Reserator system, the added nanoparticles increase the thermal conductivity of the liquid coolant. This Zalman Reserator 3 Max is the world's first nanofluids applied cooler and it won an award at CES 2013.

### 1.6.2 Nanofluid application in microprocessor

To determine the beneficial effects of heat transfer enhancement, nanofluids were used in cooling of high heat output microprocessor which is shown in figure 1.10. The experimental set up consisted of developing laminar flow regime of nanofluids flowing inside the heat sink which was installed on top of the heat output microprocessor. On the heat sink external surfaces, the convective condition of heat loss towards the ambient air were imposed throughout, except for a 10 X 10 mm contact area where the total heat Q has been specified.

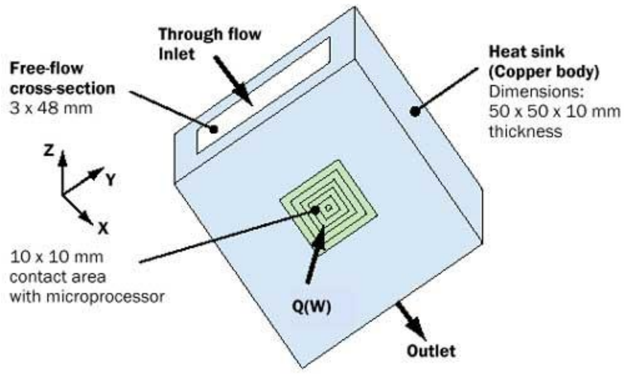


**Figure 1.10** *Heat transfer enhancement in microprocessor*

### 1.6.3 Nanofluid application in nuclear power plant

The analysis of functional requirements in nuclear power plants was focused for integrating the conventional ECCSs and nanofluid injection mechanism without loss of performance and reliability (Fig.1.11). The ECCS designs were decoupled with the installation of separate nanofluids injection tank adjacent to the safety injection tanks which is shown in figure 1.11. Low pH environment for nanofluids could be maintained at atmospheric pressure which is favorable for nanofluid injection in passive manner.

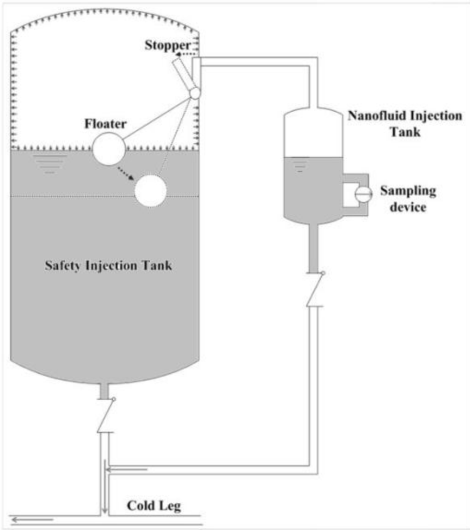


**Figure 1.11** *Design process of nanofluid injection mechanism in nuclear power plants*

### 1.6.4 $CO_2$ removal process using Nanofluids

Iranian researchers from Shiraz University increased the efficiency of adsorption and separation process of carbon dioxide in the designed system at laboratorial scale. The nanofluids were used in hollow fiber membranes as solution could be considered as an appropriate substitute for normal solutions in the removal of acidic gases, specially in gas- sweetening industries. In the gas removal process, nanofluids could adsorb carbon dioxide with unique characteristics such as high thermal stability, mechanical stability, easy reduction, high ability in storage and gas adsorption and other transfer properties. Therfore, nanofluids could be a good replacement instead of other solutions or additives to the usual solutions in order to increase the efficiency of $CO_2$ removal.

In this research, adsorption properties of nanofluids in the two-phase contactor hollow fiber membranes and its mass transfer properties were also investigated. The effects of various parameters such as the concentration and type of nanofluids, temperature, gas and liquid flow rates were also analyzed. The results showed that there was significant increase in the adsorption of carbon dioxide gas by using nanofluids. The efficiency of carbon dioxide removal for silica nanofluid, specially carbon nanotube, significantly increased in comparison with distilled water. When the concentration of nanoparticles was increased, the efficiency of $CO_2$ removal also increases. Moreover, the use of carbon nanotubes was more effective than with silica nanofluid.

### 1.6.5 Other Cooling Applications

Other possible areas for the application of nanofluid technology includes cooling in next generation computers and other electronic devices for use in defence, military systems, spacecrafts and airplanes, as well as for large-scale cooling. Nanofluids could also be utilized to maintain high temperature gradient in thermoelectrics which could convert waste heat energy to useful electrical energy in the near future. Nanofluids could be used in buildings by increasing the energy efficiency without the requirement of more powerful pump, by saving the energy in high vacuum system. In the renewable energy industry, nanofluids could be utilized to increase the energy density and to enhance thermal energy transfer from solar collectors to storage tanks. It could also be used in some more cooling appliances for major process industries, which include chemical, materials, oil, gas, food and drinking products, textiles, paper and printing process. Innovative projected applications of nanofluids include sensors and diagnostics that instantly detect chemical warfare agents in water, biomedical applications such as drug delivery, detecting unhealthy substances in the blood, cooling medical devices, and development of advanced technologies such as advanced vapor compression refrigeration systems. These are just a few of the almost endless variety of nanofluids applications. Therefore, nanofluids are highly important for high value added niche applications as well as for high volume applications.

## 1.7 OBJECTIVE OF THE WORK

This work presents systematic studies on the synthesis and characterization of ZnO, Cu doped ZnO and Al doped ZnO nanofluids for heat transfer applications.

The objective of the present work is achieved by the following systematic procedures.

- Synthesis and characterization of ZnO, Cu doped ZnO and Al doped ZnO nanoparticles.
- Preparation of ZnO, Cu doped ZnO and Al doped ZnO nanofluids with better stability.
- Ultrasonic characterization for the analysis of molecular interactions within the nanofluids with the influence of particle concentration and temperature.
- Analysis of optical properties for the nanofluids by refractive index measurements.
- Determination of flow characteristics of nanofluids by rheological studies.
- Analysis of heat transfer properties by observing thermal conductivity enhancement in nanofluids.
- To obtain better insights into the effect of dopant materials on thermo-physical properties of nanofluids.