Experimental Studies on Entrainment Characteristics of Alumina-Water Nanofluids

A thesis submitted
in partial fulfilment of the requirements
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DECLERATION

I hereby declare that the work being presented in the thesis report entitled **"Experimental Studies on Entrainment Characteristics of Alumina-Water Nanofluids"** in the partial fulfilment of the requirements for the award of degree of Masters of Technology in Chemical Engineering, from Department of Chemical Engineering, Thapar University, Patiala, is an authentic record of my own work carried under the supervision of **Dr. D. Gangacharyulu**, Professor, and **Dr. Vijaya Kumar Bulasara**, Assistant Professor, Department of Chemical Engineering, Thapar University, Patiala. The matter presented in this report has not been submitted in any other University/Institute for the award of Masters of Technology or any other degree.

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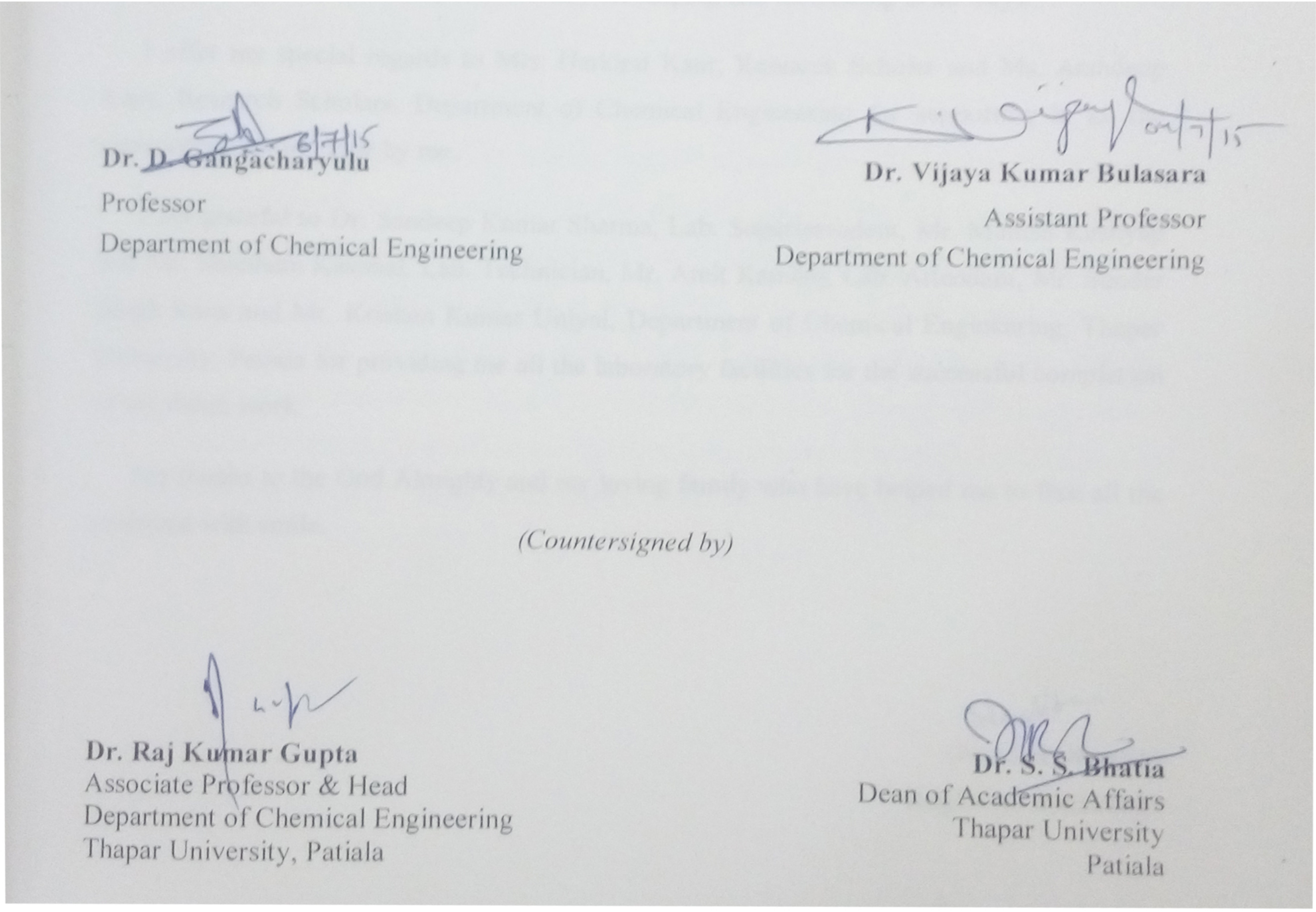
CERTIFICATE

This is to certify that the thesis report entitled **“Studies on Entrainment Characteristics of Alumina-Water Nanofluids”** being submitted by **Ms. Nandita Dhawan** in partial fulfilment for the requirement of degree of **Master of Technology** in **Chemical Engineering** in the **Department of Chemical Engineering**, **Thapar University**, **Patiala** is a record of candidate’s own work carried out by her under our supervision. To the best of our knowledge, the content of this thesis does not form a basis for the award of any other degree.



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ABSTRACT

This thesis presents experimental investigation on the preparation and thermo-physical properties of Al_2O_3-water nanofluid. In addition, the entrainment characteristics of Al_2O_3-water nanofluids in a vertical tube have been studied experimentally. Applications of Al_2O_3-water nanofluid along with its advantages and disadvantages are also discussed. Entrainment in two-phase passive heat transfer devices is also discussed along with their application using nanofluid as working fluid.

Nanofluids are solid-liquid composite materials consisting of solid nanoparticles with sizes typically of 1 to 100 nm suspended in a liquid (base fluid). In this work, alumina nanoparticles of 40-50 nm diameters were suspended in distilled water by two step method to prepare a stable Al_2O_3-water nanofluid. The volume concentration of Al_2O_3 nanoparticles has been varied between 0.01%, 0.05% and 0.1% vol. to study its thermo-physical properties.

The prepared Al_2O_3-water nanofluids were stable over a period of three weeks without using any surfactant. Results showed that the density and viscosity of nanofluids decrease on increasing the temperature and increase on increasing the particle concentration. The thermal conductivity of nanofluids was found to increase with increasing the particle concentration as well as temperature. Entrainment of nanoparticles into the vapour phase has been experimentally studied in a vertical pipe using Al_2O_3-water nanofluids of different concentrations at different temperatures. In comparison with pure water, nanofluid resulted in severe entrainment due to the foaming action of the nanoparticles. The degree of entrainment increased with increasing the particle concentration as well as temperature.

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ABBREVIATIONS

Abbreviation	**Description**
CTAB	Cetyltrimethylammonium bromide
CTAC	Cetyltrimethylammonium chloride
DI	Deionised water
DLS	Dynamic light scattering
EG	Ethylene glycol
PAA-co-PAA	Polyacrylamide-co-poly acrylic acid
PID	Proportional-integral-derivative
PVP	Polyvinylpyrrolidone
SDS	Sodium dodecyl sulfate
SEM	Scanning electron microscope
TEM	Transmission electron microscopy
UV/VIS spectrometer	Ultraviolet visible spectrometer
XRD	X-ray diffraction

SYMBOLS

Symbol	Description	Units
ΔP	Pressure head	m
wt%	Weight percentage	-
vol.%	Volume percentage	-
ρ	Density	g/cm^3
m	Mass	g
V	Volume	ml
T	Temperature	˚C
t	Time	Seconds
k	Thermal conductivity	W/mK
q	Heat transfer rate	W/m^2K
nm	Nanometer	
Al_2O_3	Alumina	-
H_2O	Water	-
Au	Silver	-
Ag	Gold	-
Cu	Copper	-
˚C	Degree Celsius	-
SiO_2	Silicon oxide	-
CuO	Copper oxide	-

CHAPTER 1

INTRODUCTION

Two-phase passive heat transferdevices like heat pipes and thermosyphon have played an importantrole in a variety of engineering heat transfer systems,ranging from electronics thermal management to heat exchangersand reboilers.These devices transfer latent heat of a working fluid present inside from one point to another. The present scenario of highthermal loading coupled with high flux levels demands explorationof new heat transfer augmentation mechanisms besidesthe conventional techniques.'Nanofluids' are fast emerging asalternatives to conventional heat transfer fluids (Choi, 1995).

Nanofluid is a high thermal conductance fluid. Its most important application is transportation of heat. The thermal conductance of nanofluid as compared to conventional heat transfer fluid is very high.At 0.5vol% Al_2O_3 nanoparticles, 11.2% enhancement in thermal conductivity has been achieved (Zhu *et al.*, 2011).

1.1 Entrainment

Entrainment is the entrapment of one substance by another substance (Perry and Green, 1984), for example:

- The entrapment of liquid droplets or solid particulates in a flowing gas, as with smoke.
- The entrapment of gas bubbles or solid particulates in a flowing liquid, as with aeration.
- Given two mutually insoluble liquids, the emulsion of droplets of one liquid into the other liquid, as with margarine.
- Given two gases, the entrapment of one gas into the other gas.

Entrainment for thermosyphon and heat pipe having nanofluids as working fluid can be defined as suspension of nanoparticles due to counter flow at interface between the two phases i.e. vapour and liquid. Vapour rising from evaporator exerts shear force on liquid coming back to the evaporator from condenser entraining nanoparticlein vapour flow. The magnitude of shear force applied by vapour on liquid depends on vapour properties and velocity of vapour (Faghri, 1995).

Entrainment of nanoparticles in vapour leads to dry out of evaporator and flooding in condenser. Liquid surface tension opposes entrainment of liquid droplets in vapour phase. Entrainment limit in heat pipe is given by Weber Number (Dunn and Ready, 1978).

Weber Number is a dimensionless number which is defined as the ratio of vapour inertial force to liquid surface tension forces.

$$\text{Weber Number} = \frac{\text{Vapour inertial forces}}{\text{Liquid surface tension forces}} \tag{1.1}$$

1.2 Thermosyphon

Thermosyphon is a wickless, gravity assisted heat transfer pipe. In thermosyphon, heat is transferred from one end to another end with the help of a working fluid. A thermosyphon can be divided into three sections, which are an evaporator section, an adiabatic section and a condenser section (Dunn and Ready, 1978).

Thermosyphon is used for transporting heat from one end to another with quite extraordinary properties. Heat transport in thermosyphon occurs via evaporation and condensation of the working fluid and the working fluid is re-circulated by gravitational force. The thermosyphon hascapability to transport heat at high rates over appreciable distances, virtually isothermally and does not require any external pumping devices (Sabharwall *et al*., 2007).

1.3Heat pipe

Heat pipe is a high thermal conductance device. The concept of heat pipe was first suggested by R. S. Gaugler in 1942 (Dunn and Reay, 1978). In early 1960, the remarkable properties of heat pipe were acutely studied and developed.

Heat pipe is very similar to thermosyphon. It is also two phase passive heat transfer device. Like thermosyphon, it also transfers energy from one end to another with the help of latent energy of the working fluid. The working fluid used is evaporated in evaporator section and the vapours carry heat from the adiabatic section to the condenser where it is cooled. Condensate returns to evaporator section.

Heat pipe has three evaporator section, condenser section and adiabatic section. The inner surface of pipe is covered with a wick; wick helps the condensate to return from condenser to evaporator. The shape and size of heat pipe as well as wick has been developed over time.

1.4 Properties of working fluid for thermosyphon and heat pipes

The working fluid used in thermosyphon should fulfil the following criteria (Dunn and Reay, 1978).

a) Operating temperature: The evaporation temperature of working fluid should be in the range required for operation.
b) Thermal stability: Working fluid should be thermally stable. Certain organic fluid requires operating temperature to be lower than low a specified value to prevent it from breaking into its components.
c) Vapour pressure: Vapour pressure of the working fluid should not be too high or low in the operating temperature range to avoid high vapour velocity.
d) Latent heat: Working fluid should have high latent heat; more the latent heat more heat will be transferred.
e) Thermal conductivity: High thermal conductivity working fluid is used as heat transfer rate is directly proportional to the thermal conductivity of the fluid.
f) Viscosity: Viscosity of working fluid and its vapour should be low. Viscosity is resistance to the flow and for better operation of thermosyphon, resistance should be very small.

1.5 Properties of container of thermosyphon and heat pipes

The container is used to isolate the system from environment and to protect it from contamination. It should be properly sealed (i.e. leak-proof) to maintain the pressure inside the tube.

The choice of material for container of heat pipes and thermosyphon depends on following factors:

a) Compatibility with working fluid and in case of heat pipe also with wick. Material used should be also well-suited with outside environment.
b) Strength of material used should be high for use in space craft.
c) Thermal conductivity of material should be such that the heat loss to the surrounding is minimum.
d) The material used should be ductile, malleable, weldable, etc for easy fabrication of pipe.
e) The material used should be non-porous to prohibit entrance and exit of gases and liquid.

1.6 Operating parameters of thermosyphon and heat pipe

For satisfactory operation of heat transfer devices, maximum pumping head$(\Delta P_p)_{max}$ must be greater than the total pressure drop in the pipe (Dunn and Reay,1978). The total pressure drop comprises of following components:

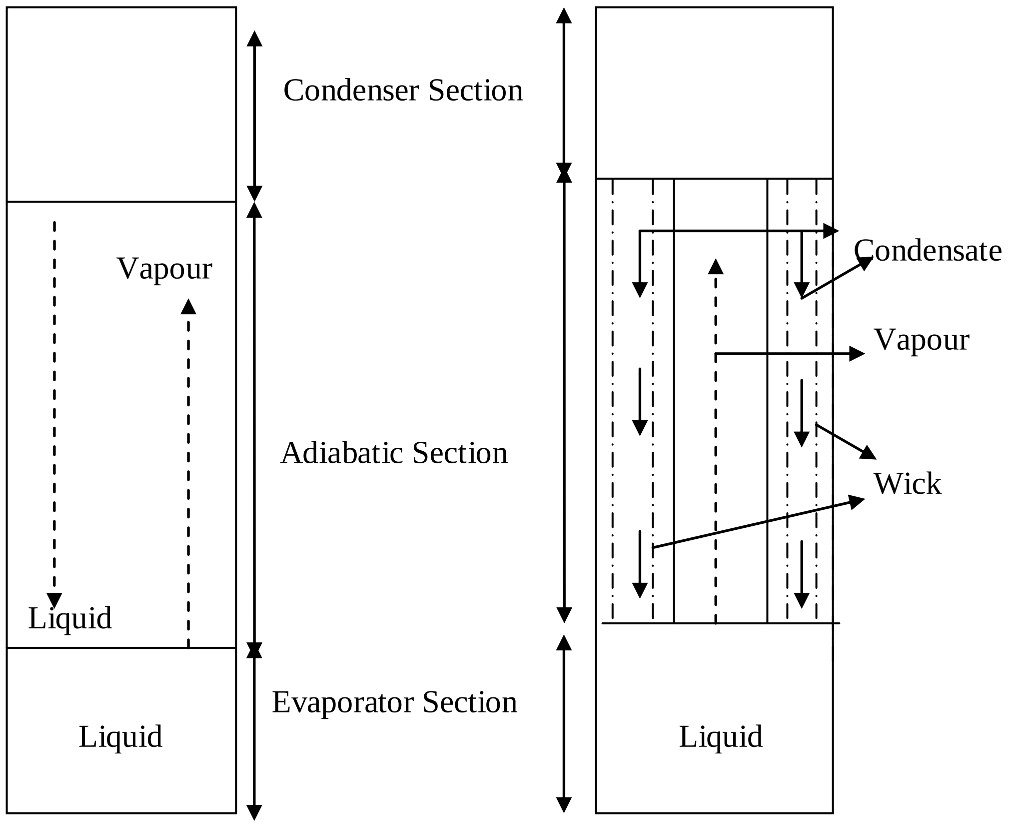
a) Pressure drop needed by liquid to return from condenser to evaporator (Δp_l).
b) Pressure drop needed by vapour to move from evaporator to condenser (ΔP_v).
c) Gravitational head, which can be positive, negative or zero depending upon the heat transfer device used (ΔP_g).

If these conditions are not met the heat transfer device will not work properly.

$$(\Delta p_{p\ max}) \geq (\Delta p_l + \Delta p_v + \Delta p_g) \tag{1.2}$$

1.7Comparative study of thermosyphon and heat pipe

Thermosyphon and heat pipe are used for transport of heat from one point to another.



(a) Thermosyphon (b) Heat pipe

Figure 1.1: The thermosyphon and heat pipe.

Difference between these two is heat pipe are used for zero gravity application and thermosyphon cannot be used in zero gravity. Heat pipe has wicked structure but thermosyphon does not has wick present.The difference between thermosyphon and heat pipe construction is represented in Figure 1.1.

Heat pipe and thermosyphon are very similar in design as well as construction. Comparative study of both heat transfer devices is presented in Table 1.1.

Table 1.1: Comparative study of thermosyphon and heat pipe.

S. No.	Parameters	Thermosyphon	Heat pipe
1.	Construction	Wick structure is absent.	Few layers of gauze or metallic wick are present.
2.	Position of condenser	Condenser is present above the evaporator for condensate to return to the evaporator section.	Position of condenser is not restricted in heat pipe. It is designed for zero gravity application.
3.	Method of condensate return	Gravity force.	Capillary force.
4.	Operational limits	(a) Flooding limit, (b) Sonic limit, (c) Entrainment limit.	(a)Viscous limit, (b) Sonic limit, (c) Capillary limit, (d) Entrainment limit, (e) Boiling limit.
5.	Heat transfer efficiency	Heat transfer efficiency is better.	Heat transfer efficiency is lower in presence of gravity.
6.	Temperature distribution	Temperature distribution is good for heat transfer over large distance.	Temperature distribution is good for heat transfer over limited distance.
7.	Nanofluid as working fluid	Nanofluid is used as working fluid.	Nanofluid is used as working fluid but over a period of time nanoparticles tend to block wick structure.

1.8 Nanofluids

Nanofluid is a kind of new engineering material consisting of nanometer-sized solid particles or fibres in base fluids, has superior thermal properties and many potential applications.

Recent experiments on nanofluids have indicated significant increases in thermal conductivity compared with liquids without nanoparticles or with larger particles, strong temperature dependence of thermal conductivity and significant increases in critical heat flux in boiling heat transfer (Keblinski *et al.*, 2005).

Nanoparticles are used in variety of products ranging from hydrogen storage devices, through food, drugs, and cosmetics to coating, paints and high performance materials (Schmid and Rediker, 2008). During manufacture of such products, nanoparticles are practically always suspended in liquids forming solid–liquid suspension (two-phase system) which frequently undergoes thermal treatment. Choi *et al.* (1995) and Das *et al.*(2009)reported that very dilute suspensions of nanoparticles in liquids show unusual dramatic improvements in thermal properties and coined the term ‘nanofluid’.

Nanofluids represent improved stability compared with conventional fluids added with micrometer or millimeter-sized solid particles because of size effect and Brownian motion of the nanoparticles in liquids. With such ultrafine nanoparticles, nanofluids can flow smoothly in a microchannel without clogging and the size of the heat transfer system can be reduced for the use of nanofluids with high heat transfer efficiency (Haddad *et al.*, 2014).

Nanofluids are solid-liquid composite materials consisting of solid nanoparticles or nanofibers with sizes typically of 1-100 nm suspended in base fluid.

1.9 Summary

Two-phase passive heat transfer devices such as heat pipe and thermosyphon are discussed in this section. The heat is transfer in heat pipe and thermosyphon from one end to another by latent heat of working fluid. In presence of gravity the efficiency of thermosyphon is more than that of heat pipe (Ahmad and Yousif, 2012).

The working fluid used in present study is nanofluid. Nanofluid is heat transfer fluid. The thermal conductivity of nanofluid is more than conventional heat transfer fluid.

The main focus of this study is entrainment limit of nanofluid in a vertical pipe. This setup is similar to thermosyphon. Thermosyphon has been chosen because of its simplicity and flexibility for collecting samples at different locations and time interval.

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CHAPTER 2

LITERATURE REVIEW

In this chapter, entrainment studies on heat pipe and thermosyphon, heat pipe,thermosyphon, preparation methods of nanofluids, properties of nanofluids and applications of nanofluid in thermosyphon arereviewed.

2.1 Entrainment

Entrainment in two phase heat transfer devicesis caused by shear force that exists at the counter current flowing liquid-vapour interface. At high relative velocities, drops of liquid are suspended in vapour phase or entrained in the vapour flowing toward the condenser section. If the entrainment is more, the evaporator dries out. The heat transfer rate at which this occurs is called the entrainment limit. Entrainment can be detected by the sounds made by droplets striking the condenser end of the heat pipe. The entrainment limit is often associated with low or moderate temperature heat pipes or thermosyphon with small diameters, or high temperature heat pipes or thermosyphon when the heat input at the evaporator is high (Dunn and Reay, 1978).

Sabharwall(2007) studied entrainment for thermosyphon as well as heat pipe, entrainment in a heat pipe may be modelled by the Weber number which is the ratio of the inertial forces in the vapour to the tension forces in the liquid surface. At the interface between the wick surface and the vapour, the vapour exerts shear force on the liquid in the wick and its action will be to entrain liquid droplets, this action is resisted by the surface tension in the liquid. Therefore, Weber number 1 or more than 1 indicates entrainment. The phenomenon of entrainment reduces the amount of liquid pumped back to the evaporator by returning it to the condenser and limits the amount of heat flow through the heat pipe.

Gibson(2013) analysed the flooding limit in thermosyphon for reduced gravity.The flooding limit occurs when the shear forces due the counter current flow between the vapour and liquid overpowers the gravity forces required to maintain the level of working fluid in the evaporator. This will occur near the top of the evaporator, where the liquid layer is at its thickest point and the vapour is travelling through the local minimized cross sectional area at high velocity.

2.2 Thermosyphon

Thermosyphon is a two-phase gravity assisted heat transfer device. Heat is transfer in thermosyphon by the latent heat of evaporation of working fluid. In a thermosyphon no wick is present so capillary force is absent in thermosyphon. Condensate returns to evaporator from condenser by gravitational force. Evaporator must be present below the condenser for condensate to properly return to the evaporator. The performance of thermosyphon is better than that of heat pipe working with gravity. The loss in heat transferred by thermosyphon over large distance is very less (Dunn and Reay, 1978).

2.2.1Parameters effecting working of thermosyphon

Khazaee(2014) observed that the working of thermosyphon is affected by the type of working fluid, filling ratio, inclination angle, operating pressure (or corresponding saturation temperature), and length of various sections of the pipe. During operation various heat transfer limits occur as a result of the dryout of liquid film in the evaporator. When the heat input tothe evaporator is relatively high, intensive liquid film evaporation causes the vapour flow to moveupwards, quickly, exceeding the flooding limit. The drying out of the liquid film may result from liquid droplet entrainment from the liquid film by the interfacial shearing effect of high speed vapour flow, resulting in the entrainment limit.

2.2.2Applications of thermosyphon

Applications of thermosyphon are very far and wide. Thermosyphon is basically used for transfer of heat from source to sink without loss of energy. Thermosyphons are used as: heat pipe, heat exchanger, solar energy system, cooling of electric components, snow melting, etc. (Khazaee, 2014).

To improve the adsorption cycle for refrigeration: Heating and cooling in an adsorption cycle can be dramatically improved by using two separate thermosyphon for both the purpose. As thermosyphon is a simple device it can be easily installed and designed according to application (Critoph, 2000).

In thermal diodes and switches: Thermosyphon is the simplest type of thermal diode available where the heat transport is only in one direction and when the position is reversed no heat is transferred due to the restriction of gravity (Dunn and Reay, 1978).

In temperature control: It is used for cooling and heating purposes such as two phase thermosyphon is used for cooling of aircraft using dielectric fluid as working fluid. Passive cooling in aircraft using thermosyphon is highly effective (Lohse and Schmitz, 2010).

For removing heat from nuclear plants: Transfer of heat between nuclear plant and chemical plant was more effectively attained by using thermosyphon having alkali metal as working fluid (Sabharwall *et al*., 2007).

In improving the performance of photovoltaic cells: Thermosyphon with water as working fluid is used to improve the performance of photovoltaic cells. The results found can promote the use of photovoltaic cells in domestic sector (Chow *et al*., 2006).

Other industrial cooling applications of two phase thermosyphon include: gas turbine blade cooling, electrical machine rotor cooling, transformer cooling, steam tube for bakers oven, internal combustion engine cooling, electronics cooling, etc.

2.2.3 Advantages of thermosyphon

Advantages of using thermosyphon are described below. Thermosyphon is very economic and easy to install. Its heat transfer efficiency is high. It operates under the gravitational effect.

a) High thermal conductance: Thermosyphon transports heat in the form of latent energy of vaporization which is very high. So, the heat transferred from one end to other is also very high with small loss of heat.

b) No external pump: Thermosyphon does not require pump for pumping working fluid as it is a gravity assisted device. The condensate returns for condenser to evaporator due to gravitational force acting on it.

c) Passive heat transfer device: It is a passive two phase heat transfer device. It does not require any external power for operation. It does not produce or consume heat it transfers the heat in form of latent energy of vapours from one place to another place.

d) Design: It is space efficient and does not require large space for installation. The size of condenser and evaporator of thermosyphon can be changed according to the application. It is designed is according to the requirement.

e) The system is isolated so working fluid does not get contaminated. Thermosyphon is sealed from top and bottom so no working fluid is lost or contaminated during the operation.

f) Isothermal: Operating condition of thermosyphon is virtually isothermal. The heat is not lost during transfer from one point to another.

2.2.4 Disadvantages of thermosyphon

Thermosyphon working requires condenser to be placed above evaporator for condensate to return to evaporator by gravity. The tube should be properly sealed so that the working fluid is not lost. Significant difference in temperature is required to start operation of thermosyphon.

2.3 Heat Pipe

Heat pipe is a two-phase passive heat transfer device. Latent heat of vaporization of working fluid is the medium of transfer of heat in heat pipe. The orientation of evaporator in a heat pipe may or may not be below condenser. As in heat pipe wick structure is present which helps condensate to return form condenser to evaporator. Capillary force acts as driving action for return of condensate to the evaporator. Heat pipe is used for zero gravity application as it does not require gravity for return of condensate.

There are different methods of liquid condensate to return to evaporator section (Dunn and Reay, 1978). In thermosyphon condensate returns to evaporator section only by gravity, heat pipes are designed to operate at zero gravity. The various modes of condensate to return to evaporator are mentioned in Table 2.1. Optimum wick thickness is very important. Increase in thickness of wick increases radial thermal resistance and less thickness of wick leads to lower heat transfer capability. Wick can be made of glass fibre, felt metal, nickel powder, nickel fibre, copper powder, titanium, bronze, etc. The shape of wick varies from screen wick, open channels, channels covered with screen, annulus behind screen, artery, corrugated screen, etc.

Table 2.1: Modes of condensate return.

Heat transport device	Method of condensate return
Gravity	Thermosyphon
Capillary force	Heat pipe
Centripetal force	Rotating heat pipe
Osmotic force	Osmotic heat pipe

2.3.1Working of heat pipe

Heat is applied to one end of the heat pipe (evaporator), the local temperature is raised leading to evaporation of the working fluid. Because of the saturation conditions this temperature difference results in a difference in vapour pressure which in turn causes vapour to flow from the heated section to the cold section of the pipe (condenser). The rate of vaporization is equal with heat absorbed in the form of latent heat of evaporation. The resulting condensate is returned to the heated end (evaporator) of the container by the action of capillary forces in the liquid layer which is contained in a wick lining the inside of the cavity (Sabharwall, 2007).

2.3.2 Applications of heat pipe

Similar to thermosyphon the heat pipe's major application is for heat transfer. Heat pipe is used as heat transfer device where gravity is absent and when the condenser is placed above the evaporator. Major areas of applications of heat pipe are discussed below:

a) Heat transfer in space: Heat transfer in space is difficult due to vacuum. Thermosyphon cannot be used due to absence of gravity. Due to the presence of capillary force heat pipe is ideal for transfer of heat in space (Thieme and Schreiber, 2003).
b) Cooling of electronic gadgets: Heat pipe is successfully used for cooling of electronic gadgets such as cell phones, computers, etc.
c) Use in solar energy collector: Solar energy is absorbed and transported into the living space by convection to the interior air or stored in a water tank with the help of heat pipe. Application of heat pipe is preferable such area than thermosyphon. It is also used in photovoltaic cells and for heating of space with the help of ocean as well as geothermal energy (Singh *et al.*, 2011).
d) Use in fuel cell: Fuel cell system produces electrical energy at high efficiencies based on the lower heating value (LHV) of the fuel. Heat pipes can be utilized in fuel cell systems for thermal management purposes which allow for effective use of the fuel cell by product, heat, leading to a substantial increase in heat transfer and overall system efficiency.
e) Heat exchangers: Heat pipe has high heat transfer capabilities with no external power requirements so it is used in heat exchangers for various applications. In the power industry, heat pipe heat exchangers are used as primary air heaters on boilers (Faghri, 1994).
f) Heat pipe is also used in heat pumps, gas turbine engines and automotive industry, production tool, machine and human body temperature control, ovens and furnace, permafrost stabilization, manufacturing, transport system and deicing.

g) Vasiliev (2005) studied the use of heat pipe in heat exchanger. It was concluded that the heat pipes are very capable heat transfer devices, they can be easily used as thermal links and heat exchangers in various systems for the energy saving and environmental protection.

h) Chiang *et al*. (2014) used heat pipe in air conditioning and observed high performance of heat pipe. Nanofluid was used as working fluid.

i) High temperature heat pipes are proposed to use in the manufacturing of glass bottles (Brost *et al.*, 1973).

j) Heat pipes are used in energy systems. Singh *et al*. (2011) presented the design and characteristics of different energy conservation systems and renewable energy systems utilizing heat pipes as the thermal control mechanism. A wide range of energy systems including data centre cooling, agricultural products cold storage, bakery waste heat recovery and automotive dashboard cooling were discussed. It was argued that zero emission and economical advantages can be achieved by using thermosyphon and capillary pumped loop.

2.3.3 Advantages of heat pipe

Heat pipe is used in variety of applications due to its adaptability according to the requirement. It has high thermal conductance. Advantages of heat pipe are discussed below:

a) High heat flux: Heat flux generated in heat pipe is quiet high hence it is used for transfer of heat with minimum loss of heat.

b) High thermal conductivity: The thermal conductivity of a heat pipe having water as working is even higher than thermal conductivity of metals.

c) Passive energy device: Heat pipe is a passive energy device. It does not generate or consume heat; it only transfers it from one place to other.

d) Isothermal operation: The temperature change in heat pipe is very small. It operates at nearly isothermal state.

e) No moving parts: No moving parts present in heat pipe. It can be easily installed and has a long life.

f) Limited space, low maintenance/high reliability applications: Heat pipe require less working depending on space according to the application and is highly reliable.

g) No noise pollution: Noise-sensitive environments, where heat can be dissipated to a larger, remote heat sink from a large source without making any noise.

h) No external power: No external power such as pump is required for operation of heat pipe.
i) Zero gravity: Unlike thermosyphon, heat pipes can be used in zero gravity environments for transfer of heat.

2.3.4 Disadvantages of heat pipe

Heat pipe has many limitations which effects its operation. Optimum thickness of wick structure is essential for proper utilization of heat pipe. The working fluid used in heat pipe should be compatible with container as well as wick structure, else or it leads to erosion of both over time. The pipe should be sealed properly so that system is not contaminated.

2.4Operating limits of thermosyphon and heat pipe

There are various parameters that limit and constraint the steady and transient operations of heat pipe and thermosyphon. Phenomena that limit heat transport in heat pipe and thermosyphon are capillary, sonic, entrainment, boiling and vapour pressure. The heat transfer limitation can be due to any of the above limitations depending on the size and shape of the pipe, working fluid, wick structure, and operating temperature.

a) Capillary limit: Capillary limit is only for heat pipe as it is observed due to presence of wick structure. The capillary structure is provided for the circulation of a given working fluid. This limit is also known as capillary limitation or hydrodynamic limitation. The capillary limit is the most commonly encountered limitation in the operation of low-temperature heat pipes. It is observed when the pumping of liquid is not sufficient to provide enough liquid to the evaporator section. This occurs when some liquid and vapour pressure drops exceed the maximum capillary pumping pressure that the wick can uphold. The maximum capillary pumping pressure for a given wick structure depends on the physical properties of the wick as well as working fluid. Any attempt to increase the heat transfer above the capillary limit will cause dry out in the evaporator section (Faghri, 1995).
b) Sonic limit: This limit is observed in both heat pipe as well as thermosyphon. Sonic limit is the only operational limit that is observed at high temperature. The vapour velocity increases as it moves from the evaporator and reaches a maximum when it reaches condenser section. The vapour velocity at that point is equivalent to the local speed of sound. This condition is known as sonic limitation. The sonic limit occurs either during start-up or during steady state operation when the heat transfer

coefficient at the condenser is high. The sonic limit is due to high vapour velocities and low densities. When sonic limit is exceeded, it does not do serious failure. Increasing the evaporator temperature will increase sonic limit. Once sonic limit is reached, increase in the heat transfer rate can be obtained only when the evaporator temperature is also increased.

c) Boiling limit: When the radial heat flux in evaporator becomes high, the liquid in the evaporator boils and the wall temperature also increases. The vapour bubbles prevent the liquid from wetting the pipe wall, which causes hot spots. If this boiling is severe, it dries out the wick in the evaporator, which is defined as the boiling limit. However, under a low or moderate radial heat flux, low intensity stable boiling is possible without causing dryout. The boiling limit is often associated with heat pipes of non-metallic working fluids. For liquid-metal pipes, the boiling limit is rarely seen.

d) Entrainment limit: Entrainment limit is observed in two phase flow. During counter-current flow of liquid and vapour, shear force exists at the interface. At high vapour velocities, droplets of liquid are entrained into the vapour flowing toward the condenser section. If the entrainment is high, the evaporator dries out. The heat transfer rate at which this occurs is called the entrainment limit. Entrainment can be detected by the sounds made by droplets striking the condenser end of the heat pipe. The entrainment limit is often associated with low or moderate temperature pipes with small diameters, or high temperature pipes when the heat input at the evaporator is high.

e) Viscous limit: At low temperature, viscous forces act as dominant for the vapour moving down the pipe. For a long liquid-metal pipe, the vapour pressure in the condenser reduces to zero. The heat transport of the heat pipe is limited under this condition. The viscous limit is encountered when operation occurs at temperatures below normal operating temperature. As the vapour pressure is very small with the condenser pressure nearly zero.

f) Flooding limit: The flooding limit is most common in long thermosyphon with large liquid fill ratios, large axial heat fluxes, and small radial heat fluxes. This limit occurs because of the instability of liquid film generated by high value of interfacial shear, which is due to the large vapour velocities induced by high axial heat fluxes. The vapour shear prevents the condensate from returning to the evaporator from condenser and leads to a flooding in the condenser section. This causes a partial dry out of the evaporator, which leads to increase in wall temperature and limiting the operation of the system (Faghri *et al.*, 1989).

2.5Nanofluids

Choi coined the term ‘nanofluid’ in 1995. Nanofluid is a new engineered heat transfer fluid. Nanofluid has enhanced thermal properties. The concept of nanofluid was first introduced by Choi in 1993. The size, shape and interface area of nanoparticles used in preparation of nanofluid effect the thermo-physical properties of nanofluid. Review of few papers on preparation of nanofluids, its properties and applications is given below. In these papers preparation of alumina-water nanofluid is described without using any surfactant.

2.5.1 Need of nanofluids

Nanofluids are desirable due to following reasons:

a) Suspending nanofluids in a base fluid gives a colloidal suspension of high thermal conductivity (Kim *et al.*, 2007).
b) Nanofluids have higher heat transfer coefficient than the conventional heat transfer fluids (Utomo *et al.*, 2012).
c) Low concentration nanofluids behave as Newtonian fluids (Longo and Zilio, 2011).
d) Small particle size has low pressure drop.

2.5.2Preparation of nanofluids

Nanofluids are prepared by adding variety of metallic and non metallic nanoparticles such as silver, copper, aluminium, gold, silicon, alumina, carbon nanotubes, etc to conventional base fluids such as water, ethylene glycol, engine oil, etc.

Non-metallic nanofluids such as oxide nanofluids, ceramic nanofluids, etc are prepared by two-step method. Two-step method is synthesis method in which nanofluid is prepared in two steps. Nanoparticles are prepared in first step by physical process or chemical process. Physical process includes inert-gas condensation and mechanical grinding. Chemical methods for preparation of nanoparticles are chemical precipittion, thermal spray, chemical vapour deposition, spray pyrolysis and micro emulsion (Das *et al.*, 2009).

It is followed by second step in which nanoparticles are dispersed in a base fluid. Nanoparticles are dispersed in base fluid by mechanical agitation, ultrasonic probe or ultrasonic bath. The duration of agitation or ultrasonication depends upon the type of nanoparticles used. Uniform and stable nanofluid show improved thermo-physical properties.

Stable nanofluids are prepared by adding surfactant, controlling pH of nanofluids, ultrasonic agitation and altering surface properties. Agglomeration of nanoparticles while preparing nanofluid by two-step method is a challenge. Two-step method cannot be used to prepare metallic nanofluids.

2.5.2.1Two-step method:Nanofluids are synthesized in a two-step process which is the most classic synthesis method of nanofluids.

In the first step, nanoparticles are prepared by mechanical comminuting, chemical reaction, vapour condensation or decomposition of organic complex. Then it is followed by the second step in which the produced nanoparticles are dispersed into base heat transfer fluids with mechanical agitation (stirring).Despite the large degree of nanoparticle agglomeration that typically occurs with the gas-condensation process, it works well in some cases, for example, with oxide nanoparticles dispersed in deionised water.

The main advantage of this two-step synthesis method is that it produces nanoparticles under clean conditions, without undesirable contaminants.

The major problem is that agglomeration of nanoparticles may occur.When finely divided solid nanoparticles are immersed in liquids, they often do not form a stable dispersion. Non-metallic nanofluids require high volume concentration of nanoparticles (approximately 10 times of metallic nanoparticles) (Das *et al.*, 2009). Two-step method cannot be used to produce metallic nanofluids.

Outline of nanofluids prepared by this method are shown in Table 2.2.

Table 2.2: Nanofluids prepared by two-step method.

Authors	**Particle material**	**Base fluid**	**Parameter**	**Surfactant/ pH control**	**Ultra sonication duration (Hours)**	**Nanofluid stability**
Kim *et al.* (2007)	Al_2O_3	H_2O	D = 38 nm	SDS	1.0	No change observed for 5 hours.
Longo and Zilio. (2011)	Al_2O_3	DI- H_2O	D=30-50nm, Φ= 1%,2% and 4 vol.%	-	48.0	Stable for over a month.
Tajik *et al.* (2012)	Al_2O_3	DI- H_2O	D= 30-40 nm Φ= 0.15% and 0.2 vol.%	-	0.5	-
Qu and Wu (2011)	Al_2O_3	H_2O	D= 56 nm Φ= 0.1%, 1.2 vol.%	pH = 4.9	4.0	Alumina particles were better dispersed.
Suresh *et al.* (2012)	Al_2O_3	DI- H_2O	D= 40.3 nm Φ= 0.3%, 0.4 and 0.5 vol.%	-		Nanofluid was stable for several weeks.
Heyhat *et al.* (2013)	Al_2O_3	DI- H_2O	D= 40 nm Φ= 0.1%-2 vol.%	-	1.0	Nanofluid was physically stable.
Pandey and Nema (2012)	Al_2O_3	DI- H_2O	D= 40-50 nm Φ= 2%, 3% and 4 vol.%	-	8.0-16.0	Nanofluid produced was stable after 24 hours.
Lee *et al.* (2008)	Al_2O_3	DI- H_2O	D= 40-50 nm Φ= 2%, 3% and 4 vol.%	-	5.0	Good dispersion with little aggregation
Jacob *et al.* (2012)	Al_2O_3	DI- H_2O	D= 40-50 nm Φ= 2%, 3% and 4 vol.%	-	5.0-6.0	-

2.5.2.2 One-step method:In one step method the direct-evaporation technique has been used with success to produce nanofluids containing dispersed metal nanoparticles. This technique synthesizes nanoparticles and disperses them into a fluid in a single step. In this case, condensation of the vapour to form nanoparticles occurs via contact between the vapour and a liquid. Nanoparticle agglomeration is minimized by continuous flow of liquid.

One step method is further divided into two as:

i. One step physical process

ii. One step chemical process

Nanoparticle of metals can be formed by one-step method. The nanofluids prepared by one-step chemical method are well dispersed nanofluids. Another advantage of one-step synthesis method is that nanoparticle agglomeration is minimized. But one-step physical method can be used only for low vapour pressure host liquid. This methodis not very economical for large scale industrial applications.

Zhu *et al.*(2004) used one-step chemical method for preparation of metallic nanofluid by using a reducing agent. One-step chemical method is cheaper and faster than one-step physical method. Some metallic nanofluids prepared by this method as given in Table 2.3.

Table 2.3: Nanofluids prepared by one-step method.

Authors	**Particle material**	**Base fluid**	**Parameter**	**Surfactant/ pH control**	**Nanofluid stability**
Patel *et al.* (2003)	Au Ag	H_2O Toluene	D = 10-20 nm D = 3-4 nm Φ= 0.0005 vol%	Thiolate	Nanofluid was stable for several weeks.
Parametthanuwat *et al.*(2010)	Ag	DI-H_2O	D < 100 nm Φ = 0.5 vol%	-	-
Sharma *et al.* (2011)	Ag	EG	Φ = 1000-10,000 wt.%	PAA-co-AA	-
Hari *et al.*(2013)	Ag	DI-H_2O	-	CTAB	Nanofluid was stable for a week.
Paul *et al.*(2012)	Au	H_2O	D < 100 nm Φ=0.6 X 10 $^{-4}$ to 2.6 X 10 $^{-4}$ vol%	-	-
Yang *et al.* (2012)	Cu	CTAC/NaSI	D = 50 nm Φ = 0.05-2.5 vol.%	-	-
Peng *et al.* (2011)	Cu	R113	D = 20 nm Φ = 0.1, 0.5 and 1.0 wt%	SDS, CTAB and Span-80.	Nanofluid was stable after 24 hours.
Kole and Dey (2013)	Cu	DI- H_2O	D = 40 nm Φ = 0.0005-0.5 vol%	-	No visible trace of sedimentation for > 15 days.
Robertis *et al.* (2012)	Cu	EG	D = 50 nm	PVP	Few particles sedimentation

2.5.3 Characterization of nanofluids

Characterization of nanofluids comprise of analysis of size of nanoparticles used for preparation of nanofluids, the shape of nanoparticles, mobility of nanoparticles in the base fluid and stability of nanofluids. Characterisation of nanofluids is done by Transmission Electron Microscopy (TEM), Scanning Electron Microscope (SEM), X-Ray Diffraction (XRD), UV/VIS Spectrometer, Zeta Potential Analyzer, Dynamic Light Scattering (DLS), etc.

In transmission electron microscopy (TEM) a beam of electrons is transmitted through an ultra-thin sample. A magnified image of the sample is captured. TEM has very high resolution and it is preferred over SEM for characterization of nanofluids.

Kim *et al*. (2007) used this method for characterization of alumina-EG nanofluid and found that no change was observed upto 5 hours. Qu and Wu (2011) found that alumina-water nanofluid is well dispersed and stable for several days. Lee *et al*,(2008) concluded that the low concentration alumina-water nanofluid was well dispersed with little aggregatesand remained stable after 5 hours of preparation.

Scanning electron microscope (SEM) produces the image of specimen by scanning it with a focused beam of electrons. SEM is used to study the surface of the specimen and its composition.

Tajik *et al*.(2012) used SEM for characterization of alumina-water nanofluid. Heyat *et al*.(2013) found that alumina-water nanofluid was physically stable for several days.

2.5.4 Properties of nanofluids

Review of properties of nanofluids is discussed in this section.

2.5.4.1 Density

Heyat *et al*.(2013) found that the density of alumina-water nanofluid increases with increase in the particle concentration. Pandey and Neam(2012)also observed that the density of alumina-water nanofluid at room temperature (27˚C) increases with increase in the concentration of nanoparticles.

2.5.4.2 Viscosity

Longo and Zilio(2011) observed that the relative viscosity of oxide-water nanofluid depends on particle concentration and its size but it is independent of temperature. Dynamic viscosity increases with increase in concentration of nanoparticles.Heyat *et al*.(2013) analyzed that the dynamic viscosity of alumina-water nanofluid changes with change in temperature using Ubbelohde viscometer. Pandey and Neam(2012) observed that viscosity of alumina-water nanofluid at room temperature (27˚C) increases with increase in the concentration of nanoparticles. Lee *et al.* (2008) concluded for that the low concentration alumina-water nanofluid viscosity significantly decreases with increase in temperature. The viscosity of nanofluid as well as base fluid increases with increase in the pressure (Anoop *et al.*, 2013).

2.5.4.3 Thermal conductivity

Thermal conductivity is an essential parameter for heat transfer fluid. Due to the presence of nanoparticles it is observed that nanofluids have higher thermal conductivity than conventional heat transfer fluid.Tajik *et al.*(2012) observed that the thermal conductivity decreases with increase in the agglomeration of nanoparticles in nanofluid. There are two methods for measurement of thermal conductivity of nanofluid,namely transient hot- wire method and temperature oscillation method.

Kim *et al.*(2007) determine the thermal conductivity of alumina-EG nanofluid. In this study it was found that the thermal conductivity of alumina-EG nanofluid was linearly proportional to the particle size in given range. Longo and Zilio(2011) found that the thermal conductivity of oxide-water nanofluid varies with nanoparticle volume fraction, temperature and stability of nanofluid. Heyat *et al.*(2013) concluded that the thermal conductivity of a well dispersed nanofluid higher than the base fluid. Pandey and Neam(2012)found that thermal conductivity of alumina-water nanofluid at room temperature (27˚C) increases with increase in the concentration of nanoparticles. Lee *et al.*(2008) concluded for that the low concentration alumina-water nanofluid the thermal conductivity linearly increases with increase in the concentration.

2.5.5 Applications of alumina-water nanofluid

With high desired thermal properties and potential benefits, nanofluids can be seen to have a wide range of industrial and medical applications, which are elaborated here.

Longo and Zilio(2011) suggested that nanofluid can be used for cooling of electronic equipment, medical diagnostics and electricalgears, cooling and heating of heat exchangers in process industries, cooling of power plants, nuclear reactors, internal combustionengines and fuel cells, thermal transport in chillers and heat pumps condensersand evaporators.

Pandey and Nema(2012) used alumina-water nanofluid for experimental analysis of heat transfer and friction factor of nanofluidas a coolant in a corrugated plate heat exchanger and found that the heat transfer characteristics are improvedwith decrease in the concentration of nanofluid and increase inReynolds and Peclet number.

Qu and Wu(2011) used alumina-water nanofluid for thermal performance comparison of oscillating heat pipes with SiO_2-water and Al_2O_3-water nanofluids and concluded that for the alumina nanofluids in oscillating heat pipe(OHP), there existed an optimal concentration of 0.9 wt%, at which the overall thermal resistance is minimum.

Youselfi *et al.*(2012) analyzed the effect of alumina-water nanofluid on the efficiency of flat plate solar collectors. The results show that using the 0.2 wt% Al_2O_3 nanofluid increases the efficiency of solar collector in comparison with water as working fluid by 28.3%.

2.5.6 Advantages of nanofluids

Advantages of nanofluids are as follows:

a) Improved heat transfer and stability: Nanoparticles have high specific surface area because heat transfer takes place at the surface of the particles; it is desirable to use particles with larger surface area (Murshed *et al.*, 2008). The nanoparticles have relatively larger surface areas compared to microparticles and provide improved heat transfer capabilities. With such ultra-fine particles, nanofluids can flow smoothly in micro channels. Because the nanoparticles are small, gravity becomes less important and thus chances of sedimentation are also less, making nanofluids more stable.

b) Micro channel cooling without clogging: Nanofluids will not only be a better medium for heat transfer in general, but they will also be ideal for micro channel applications where high heat loads are encountered. The combination of micro channels and nanofluids will provide both highly conducting fluids and a large heat transfer area.

c) Miniaturized systems: Nanofluids technology will support the current industrial trend toward component and system miniaturization by enabling the design of smaller and lighter heat exchanger systems. Miniaturized systems will reduce the inventory of heat transfer fluid and will result in cost savings.

d) Reduction in pumping power: It was shown that by multiplying the thermal conductivity by a factor of three, the heat transfer in the same apparatus was doubled (Siginer and Wang, 1995). The required increase in the pumping power will be very moderate unless there is a sharp increase in fluid viscosity. Thus, very large savings in pumping power can be achieved if a large thermal conductivity increase can be achieved with a small volume fraction of nanoparticles.

2.5.7 Challenges of nanofluids

Following challenges are faced during preparation and applications of nanofluids:

a) Long term stability of nanoparticle dispersion: Nanoparticles tend to agglomerate when kept for long periods of time. In case of Al_2O_3 it was found that nanofluids kept for 30 days exhibit some settlement and concentration gradient compared to fresh nanofluids (Lee and Mudawar, 2007). It indicates that long term degradation in the thermal performance of nanofluids could happen. Particles settling must be examined carefully since it may lead to clogging of coolant passages.

b) Thermal conductivity: Thermal conductivity is an important factor for enhancing the heat transfer performance of a heat transfer fluid. Many researchers have reported experimental studies on the thermal conductivity of nanofluids. In the past few years, many experimental investigations on the factors influencing thermal conductivity of nanofluids such as theinfluence of nanoparticles, influence of base fluids and influence of the liquid–solid interface have been reported (Namburu *et al.*, 2009).

c) Lower specific heat: The specific heat of nanofluid is lower than that of base fluid. It was observed that CuO-ethylene glycol nanofluids, SiO_2-ethylene glycol nanofluids and Al_2O_3-ethylene glycol nanofluids exhibit lower specific heat compared to base fluids (Lee and Mudawar, 2007). An ideal coolant should possess a higher value of specific heat which enables the coolant to remove more heat.

d) Higher viscosity: The viscosity of nanofluid is generally higher than that of the base fluid and depends both on the type of particles and on their concentration. In the case of Al_2O_3–H_2O nanofluid, the values obtained in the present work also show increase in viscosity as the concentration increases.

e) Increased pressure drop: The pressure drop developed during the flow through heat exchanger is an important parameter in the application of nanofluids in heat exchanger. The results show significant increase in the pressure drop and consequently increase in the pumping power when the nanofluid is applied. From the experimental data it is calculated that the pumping power could be increased by about 40% compared to water for a given flow rate (Kanaris et al., 2009).

f) High cost of nanofluids: High production cost of nanofluids also limits the application of nanofluids in industry. Nanofluids can be produced by either one step or two steps methods. Both methods involve advanced and sophisticated equipments.

g) Difficulties in production process: The manufacture of nanofluids has employed either a single step that simultaneously makes and disperses the nanoparticles into base fluids, or a two-step approach that involves generating nanoparticles and subsequently dispersing them into a base fluid. Using either of these two approaches, nanoparticles are inherently produced from processes that involve reduction reactions or ion exchange (Das, 2006).

2.6 Applications of nanofluid in thermosyphon and heat pipe

Nanofluid is a high conductance heat transfer fluid. Heat pipe and thermosyphon are high performance heat transfer passive two-phase devices. The use of nanofluid in heat transfer devices such as heat pipe and thermosyphon increases the efficiency of the system. Few research papers in which nanofluid is used as working fluid in heat pipe and thermosyphon are mentioned below:

a) Khandekar *et al.*(2008) analysed the thermal performance of two-phase closed thermosyphon using nanofluid as working fluid. In this analysis three types of nanofluids are used i.e. Al_2O_3, CuO, and laponite clay in water. It was found that thermal performance deteriorates when nanofluids are used as working fluids. Maximum deterioration was observed with laponite, while minimum deterioration was for aluminium oxide particles based nanofluids.

b) Noie *et al.*(2009) used alumina and copper nanofluid in two phase thermosyphon. It was concluded that nanofluids showed better thermal performance than pure water. Temperature distributions were better using nanofluid compared to pure water. Temperature differences between the evaporator and condenser sections with nanofluids were less than pure water, i.e. thermal resistance of the nanofluids was less.

c) Sarafraz and Hormozi (2014) experimentally studied the efficiency of a copper thermosyphon using alumina-glycol nanofluid. They observed that the efficiency of thermosyphon increases on using nanofluid. As the concentration of nanofluid increases the thermal conductivity of nanofluid also increases.

d) Chen *et al.* (2013) studied the heat transfer characteristics of flat heat pipe using nanofluid. They found that the performance was better for water heat pipe than for ethanol heat pipe. Efficiency was more for smaller nanoparticles of Cu.

e) Putra *et al.*(2014) concluded that the application of nanofluid in biomaterial wick loop heat pipe lowers the total heat resistance and the performance of nanofluid is better than distilled water. Alumina nanoparticles blocked the pores of wick which was analysed using TEM.

f) Alawi *et al.*(2014) concluded that the thin porous layer of nanoparticles are formed at wick structures and in the evaporator which enhances the thermal performance for the heat pipe as it increases wettability and capillary wicking performance. The heat transfer is increased and heat resistance is decreased using nanofluid in heat pipe.

2.7Summary

Thermosyphon and heat pipe both are two-phase passive heat transfer devices. Wick structure is present in heat pipe and absent in thermosyphon. Thermosyphon is gravity assisted and heat pipe may or may not be gravity assisted. Condensate returns to evaporator in heat pipe because of capillary action. Wick structure present in heat pipe enables it to be used for zero-gravity application. There are various limits that hinder the operation of these heat transfer devices. Entrainment is an important consideration in case of heat pipe and thermosyphon.

Nanofluid is high thermal conductivity fluid used for transport of heat energy. Two-step method is widely for large scale production of preparation non-metallic nanofluid. One-step method is used for production of metallic nanofluids. TEM is the most appropriate method for characterization of nanofluid. Hot-wire transient method is used to determine the thermal conductivity of nanofluid.

The applications of heat transfer devices using nanofluid as working fluid is widely used in various fields.

2.8Gaps in literature

Production of stable nanofluid on large scale is a challenge. The properties of nanofluids change over time as the nanoparticles agglomerates. A solution to this problem of nanofluid is required for its use in industry. Regeneration and disposal of unstable nanofluid is also a challenge that requires attention.

Over time various equations are given to explain and calculate the increased thermal properties of nanofluid. But none of them can completely predict thermal conductivity of nanofluids. A single correlation is required to explain the behaviour of nanofluids. The behaviour of nanofluid at high temperature and pressure is to be studied thoroughly.

Entrainment in small diameter thermosyphon and heat pipe using nanofluid as working fluid needs a detailed attention along with operation of heat transfer devices and different limits affecting it.

With nanofluid as working fluid in heat transfer devices, various new fields of interest are coming up. The combined thermal properties of compact heat transfer devices and nanofluids are very high and hence the efficiency of various existing applications can also be improved.

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CHAPTER 3

OBJECTIVES

The overall objective of this work is to study the entrainment characteristics of nanofluid experimentally. The specific objectives of this thesis work are as follows:

a) Preparation of stable alumina-water nanofluid by two-step method of nanofluid preparation.
b) Experimental study on entrainment of alumina-water nanofluidin a vertical pipe for different concentration of alumina-water nanofluid and size of pipe.
c) Comparisonof entrainment characteristicsof water and nanofluid.

CHAPTER 4

EXPERIMENTAL METHODOLOGY

In this chapter, methodology of preparation of alumina-water nanofluid by two-step method is discussed. Determination of thermo-physical properties of alumina-water nanofluid such as density, viscosity and thermal conductivity with the help of pycnometer, Brookfield DV-II+ Pro Programmable viscometer and KD2 pro thermal properties analyzer respectivity is done. Description of experimental setup for measurement of entrainment characterstics of alumina-water nanofluid with its schematic diagram, experimental procedure and equations used for calculation are also discussed.

4.1Preparation of nanofluids

For the present work alumina (Al_2O_3) nanoparticles are used for the preparation of the nanofluid and distilled water is used as base fluid. Alumina-water nanofluid of volume fractions 0.01%, 0.05% and 0.1 vol.% are prepared. Alumina-water nanofluid is prepared without use of any surfactant.

Alumina particles used in this study are bought from Alfa Aesar, Ward Hill. The properties of alumina are described in the Table 4.1given below.

Table 4.1:Properties of alumina nanoparticles.

S. No.	Characteristic	Unit	Values
1.	Structure	-	Crystalline
2.	Colour	-	Milky white
3.	Form	-	Powder
4.	Molecular weight	g/mol	101.96
5.	Formula	-	Al_2O_3
6.	Particle density	g/cm^3	3.95
7.	Boiling point	˚C	2980
8.	Melting point	˚C	2045
9.	Average nanoparticle size	nm	40-50
10.	Surface area	m^2/g	32-40
11.	Purity	Percentage	99.5%
12.	Shape	Spherical	

Alumina nanoparticles are in added in distilled water with constant mixing. Magnetic stirrer is used for constant mixing of alumina nanoparticles in distilled water. This suspension is then placed in ultrasonic bath for 70 minutes.Alumina-water nanofluid 0.01 vol.% is shown in Figure 4.1.

Figure 4.1: Alumina-water nanofluid (0.01%).

Note: All the data in Table 4.1 is taken from Alfa AesarWard Hill, Massachusetts.

Ultraconic bath used for preparartion of nanofluid Branson 3800 ultrasonic bath. In ultrasonic bath, ultrasonic sound (sonics) is used for cleaning materials and parts, and for dissolving, homogenizing and degassing liquids. Figure 4.2 shows ultrasonicator.

Figure 4.2: Ultra sonicator.

Note: All the above data and Figure. 4.2 is taken from Ultrasonic BathModels 3800 Operator's Manual (version 3), supplied by Branson Ultrasonics, Danbury USA.

4.2 Density

Measurement of density of base fluid and nanofluid in present study is done by pycnometer. Pycnometer is shown in Figure 4.3.

Figure 4.3: Pycnometer

Density for a homogeneous object it is defined as the ratio of its mass m to its volume V.

$$\rho = \frac{m}{V} \tag{4.1}$$

Numerically it represents the mass per unit volume of matter. The SI unit of density is kg/m^3.

4.3Viscosity

Viscosity is a measure of a fluid’s resistance to flow. The SI unit of viscosity is mPa.s.Viscosity measurement of base fluid and nanofluid is done with the help of Brookfield DV-II+ Pro Programmable viscometer bought from Brookfield Engineering Laboratories, INC. Middleboro, MA, USA. Brookfield DV-II+ Pro Programmable viscometer is shown in Figure 4.4.

Figure 4.4: Brookfield DV-II+ Pro Programmable viscometer

Brookfield DV-II+ Pro Programmable viscometer gives viscosity in cp C.G.S. unit of viscosity.

1 cp = 1 mPa.s

Specifications of Brookfield DV-II + Pro Programmable viscometer are given in Table 4.2.

Table 4.2: Specifications of Brookfield DV-II+ Pro Programmable viscometer

Parameters	Values
Net weight	9 kg
Temperature Sensing Range	100˚C to 300˚C
Viscosity Accuracy	±1.0% of full scale range
Viscosity Repeatability	±0.2%
Temperature Accuracy	±1°C -100°C to +149°C ±2°C +150°C to +300°C
Input Voltage	115 VAC or 230 VAC
Power Consumption	30 VA

Note: All the above data and Figure 3.3 is taken from Brookfield DV-II+ Pro Programmable viscometer,Operator's Manual, supplied by Brookfield Engineering Laboratories, INC. Middleboro, MA, USA.

4.4 Thermal conductivity

In present study thermal conductivity of Al_2O_3-H_2O nanofluid is measured using KD2-Pro from Decagon devices. The KD2-Pro thermal properties analyzer is a portable field and lab thermal properties analyser. It uses the transient line heat source method to measure thermal conductivity. KD2-Pro thermal properties analyzer Figure 4.5.

Figure4.5: KD2 pro thermal properties analyzer.

The specifications of KD2-Pro thermal analyzer are mentioned below in Table 4.3

Table 4.3: Specifications of KD2- Pro thermal properties analyzer.

Parameters	**Values**
Accuracy	±5%
Operating environment of the sensor	-50 to 150˚C
Measurement speed	1 to 5 minutes
Data storage	4,095 readings, flash memory
Battery source	4AA
Display	Liquid Crystal Display (LCD) 7.5 x 4cm
Case Dimension	15.5 x 9.5 x 3.5 cm

Note: All the above data, Figure4.5 and Figure4.6 is taken from KD2 pro thermal properties analyzer,Operator’s Manual (Version 10), supplied by Decagon Devices, Inc., WA 99163 USA.

4.5 Experimental setup

The experimental set up used to study the entrainment of alumina-water nanofluid is shown in Figure4.6. It consists of a heating mantle, a round bottom flask, a condenser, a thermometer, two sensors with digital display, pipe, burette and power supply. The set up is similar to a thermosyphon as it has three sections as present in a thermosyphon.Heating mantle and evaporator are evaporator section; pipe (ID 10mm and 20mm) is isothermal section and condenser is condenser section.

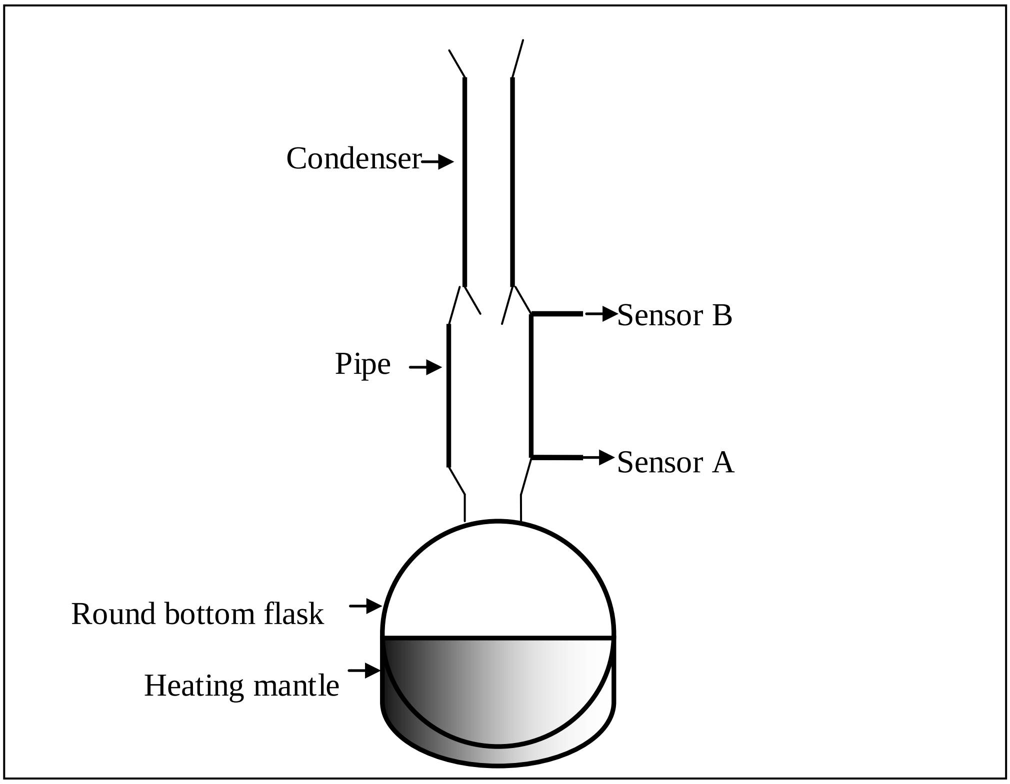

Figure4.6: Line diagram of experimental setup.

4.5.1 Description

A photographic view of the experimental setup used to investigate the entrainment of nanofluid is shown in Figure4.7. It consists of a round bottom flask having a capacity of 250 ml which is placed on a heating mantle of power 150 W, a thermometer is attached to the round bottom flask to monitor the temperature of the content of the flask. Aborosilicate pipe of length 13 cm is fitted to it. For experiment two pipes are used,the internal diameters of these pipes are 10 mm and 20 mm. Two RTD-Pt 100 sensors are fixed in the pipe to monitor the temperature of pipe during experiment. A condenser is mounted on the pipe which converts the vapours into liquid. This liquid returns to evaporator from the condenser due to gravitational force. A burette of 50 ml capacity is placed on top of condenser to refill the level of working fluid in the evaporator.

The round bottom flask is covered with insulation to minimize the loss of heat to the environment. The setup is vertical so that the gravitational force is acting in only one direction.

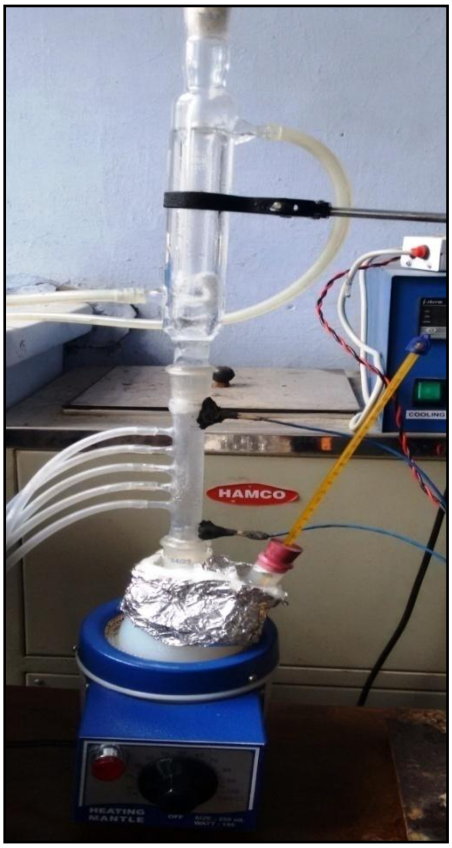

Figure 4.7: Photographic view of experimental setup.

Sensor A and sensor B is two RTD-Pt 100 temperature sensors which are used to observe the temperature of the pipe during experiment.

The borosilicate pipe used has 5 openings. Each opening is 0.8 cm and is 1 cm apart from each other. The openings are connected to silicon tube through which the sample is collected in test tube. Till adiabatic stage is achieved, the silicon tubes are closed with the help of pinch clips. Photographic view of both the pipes is shown in Figure 4.8 and line diagram of pipe is shown in Figure 4.9.

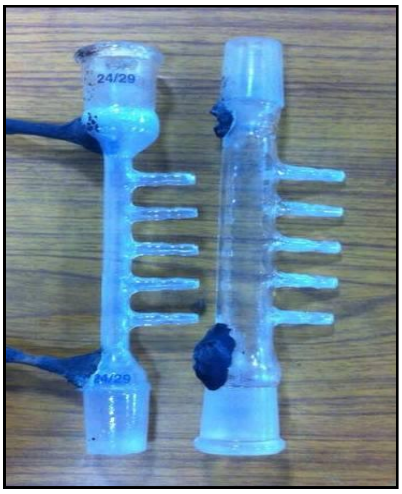

Figure 4.8: Photographic view of pipes; (ID = 10 mm and 20mm).

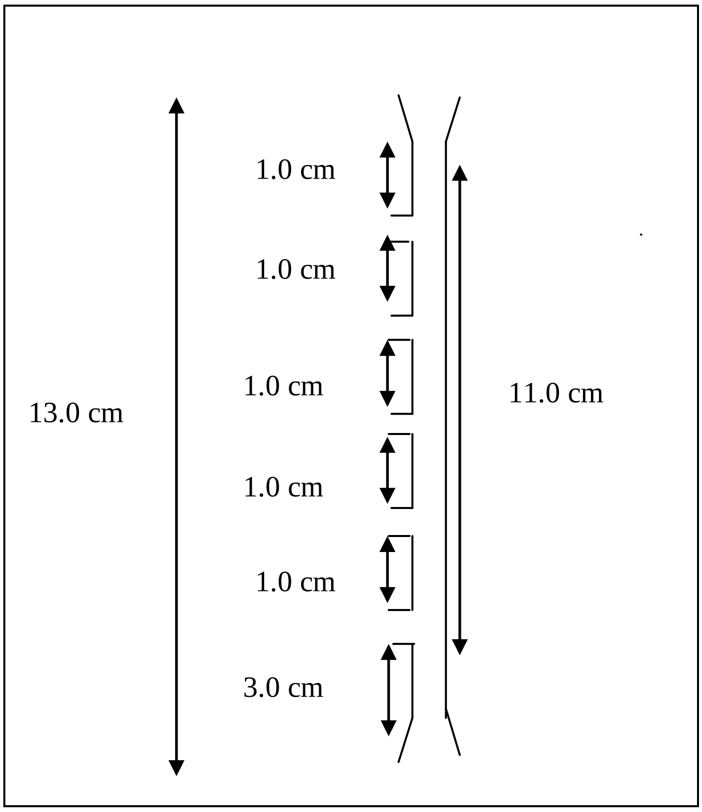

Figure 4.9: Line diagram of pipe.

4.5.2 Experimental Procedure

The round bottom flask is filled with alumina–water nanofluid. The heating mantle is switched on. The temperature of alumina–water nanofluid increases gradually which is observed with the help of thermometer attached to the round bottom flask. As the alumina-water nanofluid reaches near the boiling point the heat supply is reduced. Condenser converts the vapours to liquid. The condensate returns to evaporator from the condenser. When drop in level of working fluid is observed distilled water is supplied with the help of burette. The temperature of vapour and liquid in pipe is monitored with the help of the two RTD-Pt 100 sensors attached to the pipe. When steady state is achieved the samples are collected from each opening. Sample is first collected for top most opening and then from the bottom ones.

4.6 Equations used for study of entrainment

The data obtained from the experiment were used to calculate the entrainment characteristic of alumina-water nanofluid. The thermal conductivity, density and viscosity of nanofluids for various concentrations were measured. The nanoparticle lost during experiment and the change in concentration of the working fluid is calculated using following method:

Weight of nanoparticles lost (m_L) is calculated by subtracting the weight of nanoparticles left in round bottom flask (m_f) after experiments and weight of nanoparticles present in the samples (m_k) from the initial weight of nanoparticles in nanofluid (m_i).

$$m_L = m_i - [m_f + m_k] \tag{4.2}$$

where,

m_L is mass of nanoparticles lost during experiment,

m_i is initial mass of nanoparticles used for synthesis of nanofluid,

m_f is final mass of nanoparticles remaining in round bottom flask after experiment,

m_k is mass of nanoparticles in samples, k = [1,5].

The concentration of nanofluid remaining in round bottom flask after experiment is calculated with the help of following equation:

$$\text{Vol.\%} = \frac{\text{Volume of nanoparticles}}{\text{Volume of nanofluid}} \times 100 \tag{4.3}$$

Volume of nanofluid left in round bottom flask is measured with the help of a measuring cylinder. Weight of nanoparticles is determined by drying the water of nanofluid with the help of an electric oven in a beaker. The difference of weight of empty beaker (m_e) and weight of beaker with dried nanoparticles (m_d) give the weight of nanoparticles (m_{np}).

$$m_{np} = m_d - m_e \tag{4.4}$$

In next chapter, all the results obtained by these measurements are discussed thoroughly.

Reference

Brookfield DV-II+ Pro Programmable viscometer, *Operator's Manual*, supplied by Brookfield Engineering Laboratories, INC. Middleboro, MA, USA.

KD2 Pro Thermal Properties Analyzer, *Operator's Manual (Version 10),* supplied by Decagon Devices, Inc., WA, USA.

Ultrasonic Bath Models 1800, 2800, 3800, 5800, 8800, *Operator's Manual (version 3)*, supplied by Branson Ultrasonics, Danbury USA.

CHAPTER5

RESULTS AND DISCUSSION

In this chapter, all the results from the experiments conducted on the experimental setup and all observations found during the preparation of nanofluids, calculation are discussed. The thermo-physical properties of nanofluids are evaluated at different temperatures by using KD2 pro thermal properties analyzer, Brookfield DV-II+ Pro Programmable viscometer and Pycnometer for thermal conductivity, viscosity and density, respectively, as mentioned in previous chapter.

5.1 Observations of prepared alumina-water nanofluid

i. Alumina nanoparticles are dispersed in distilled water by sonicating it for 1.5 hours continuously, without adding any surfactant.

ii. The prepared nanofluids (0.01%, 0.05% and 0.1 vol.%)remained stable for 3 weeks, after which nanoparticle started to settle down. A sample alumina-water nanofluid is shown in Figure 5.1.

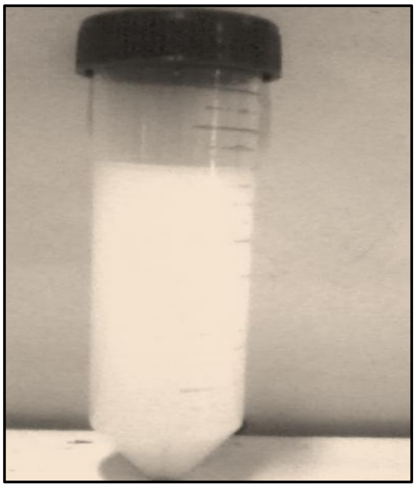

Figure 5.1: Alumina-water nanofluid sample.

5.2 Measurement of density

The density of nanofluids and distilled water is measured by using Pycnometer in present work. The density is measured in the temperature range of 25°C (i.e. room temperature) to 100 °C for base fluids i.e. distilled water, as shown in Table 5.1.

Table 5.1: Density of distilled water at different temperature.

S. No.	Temperature (˚C) (Error ± 1˚C)	Theoretical Density (kg/m^3)	Density (kg/m^3)
1.	25	997.08	996.95
2.	30	995.74	995.57
3.	35	994.14	993.95
4.	40	992.29	992.2
5.	45	990.27	990.15
6.	50	988.17	988.1
7.	55	985.77	985.65
8.	60	983.38	983.2
9.	65	980.64	980.5
10.	70	977.89	977.8
11.	75	974.93	974.8
12.	80	971.89	971.8
13.	85	968.74	968.55

Density of 0.01%, 0.05% and 0.1% volume fractions of alumina-water nanofluids at different temperatures is given in Table 5.2. The variation of thermal conductivity with temperature is shown in Figure 5.2.

Table 5.2: Variation in density of 0.01%, 0.05% and 0.1 vol.% alumina-water nanofluids with change in temperature

S. No.	Temperature (˚C)	Density (kg/m^3)		
		0.01 vol. %	0.05 vol. %	0.1 vol. %
1.	25	1000.99	1001.39	1001.89
2.	30	999.75	1000.15	1000.64
3.	35	997.99	998.39	998.89
4.	40	996.25	995.65	997.14
5.	45	994.2	994.59	995.09
6.	50	992.15	992.59	993.04
7.	55	989.7	990.09	990.59
8.	60	987.25	987.64	988.13
9.	65	984.55	984.94	985.43
10.	70	981.85	982.24	982.73
11.	75	978.85	979.24	979.72
12.	80	975.85	976.24	976.72
13.	85	972.6	972.98	973.47

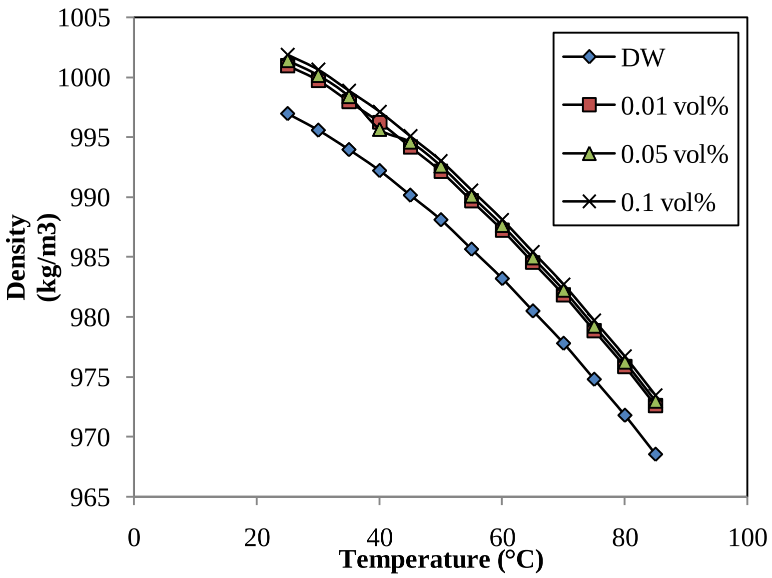

Figure 5.2: Variation in densitiesof distilled water and nanofluid with change in temperature.

The density of nanofluid is higher than that of distilled water. It has been observed that the density decreases with increase in temperature. In case of distilled water, density decreased by 4% (from 996.95 to 958.4 kg/m^3) when the temperature is increased from 25 to 100°C. Density increases with increase in concentration of nanofluid.

5.3 Measurement of viscosity

The viscosity is measured in the temperature range of 25°C (i.e. room temperature) to 100°C for base fluids i.e. distilled water, as shown in Table 5.3.

Table 5.3: Viscosity of distilled water with change in temperature.

S. No.	Temperature (˚C)	Viscosity (cP)
1.	25	0.9
2.	30	0.798
3.	35	0.725
4.	40	0.653
5.	45	0.6
6.	50	0.547
7.	55	0.507
8.	60	0.467
9.	65	0.435
10.	70	0.404
11.	75	0.379
12.	80	0.355
13.	85	0.335

The viscosity of 0.01%, 0.05% and 0.1% volume fractions of alumina-water nanofluids at different temperatures is given in Table 5.4. The variation of viscosity with temperature is shown in Figure 5.3.

Table 5.4: Variation in viscosity of 0.01%, 0.05% and 0.1 vol.% alumina-water nanofluid with change in temperature

S. No.	Temperature (˚C)	Viscosity (cP)		
		0.01 vol. %	**0.05 vol. %**	**0.1 vol. %**
1.	25	0.90605	0.92789	0.95591
2.	30	0.80339	0.82276	0.84761
3.	35	0.73043	0.74804	0.77063
4.	40	0.65745	0.67330	0.69364
5.	45	0.60411	0.61867	0.63736
6.	50	0.55076	0.56404	0.58107
7.	55	0.51049	0.52280	0.53859
8.	60	0.47023	0.48157	0.49611
9.	65	0.43852	0.44909	0.46265
10.	70	0.40681	0.41662	0.42919
11.	75	0.38215	0.39135	0.40317
12.	80	0.35748	0.36609	0.37715
13.	85	0.33748	0.34547	0.35591

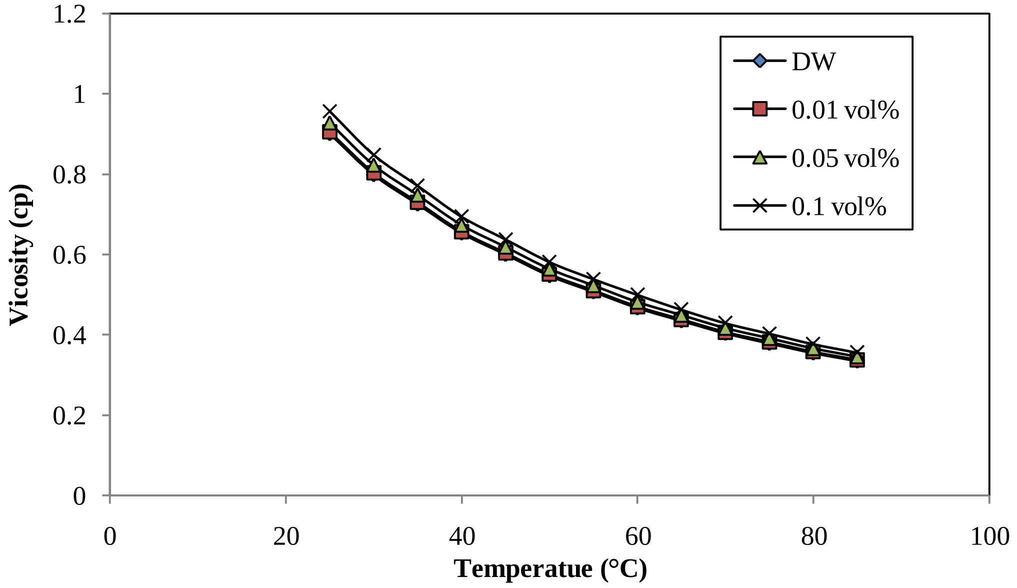

Figure 5.3: Variation in viscosities of distilled water and nanofluid with change in temperature.

The viscosity of nanofluid is higher than that of distilled water. Viscosity decreases with increasing temperature. Viscosity of distilled water decreased from 0.9 to 0.282 cP when temperature was increased from 25 to 100˚C corresponding to 67% decrease. Viscosityincreases with increase in concentration of nanofluid.

5.4Measurement of thermal conductivity

Thermal conductivity of nanofluids is measured by using KD2 pro thermal property analyzer and KD’s KS-1 sensor needle is used in present work. The thermal conductivity is measured in the temperature range of 25°C (i.e. room temperature) to 100 °C for base fluids i.e. distilled water, as shown in Table 5.5.

Table 5.5: Thermal conductivity of distilled water at different temperature.

S. No.	**Temperature (˚C)**	**Thermal conductivity (W/m-K)**
1.	25	0.60922
2.	30	0.61232
3.	35	0.61865
4.	40	0.62559
5.	45	0.63453
6.	50	0.64751
7.	55	0.65518
8.	60	0.66441
9.	65	0.68025
10.	70	0.69497
11.	75	0.71656
12.	80	0.73199
13.	85	0.75190

The thermal conductivity of 0.01%, 0.05% and 0.1% volume fractions of alumina-water nanofluids at different temperatures is given in Table 5.6. The variation of thermal conductivity with temperature is shown in Figure 5.4.

Table 5.6: Variation in thermal conductivity of 0.01%, 0.05% and 0.1 vol.% alumina-water nanofluid with change in temperature.

S. No.	**Temperature (˚C)**	**Thermal conductivity (W/ m-K)**		
		0.01 vol. %	**0.05 vol. %**	**0.1 vol. %**
1.	25	0.61118	0.61424	0.61809
2.	30	0.61485	0.61792	0.62177
3.	35	0.62051	0.62357	0.62742
4.	40	0.62802	0.63108	0.63493
5.	45	0.63729	0.64035	0.64420
6.	50	0.64828	0.65134	0.65519
7.	55	0.66092	0.66398	0.66783
8.	60	0.67257	0.67823	0.68208
9.	65	0.68801	0.69407	0.69792
10.	70	0.70841	0.71147	0.71532
11.	75	0.72433	0.73042	0.73524
12.	80	0.73975	0.75081	0.75699
13.	85	0.76166	0.77272	0.77965

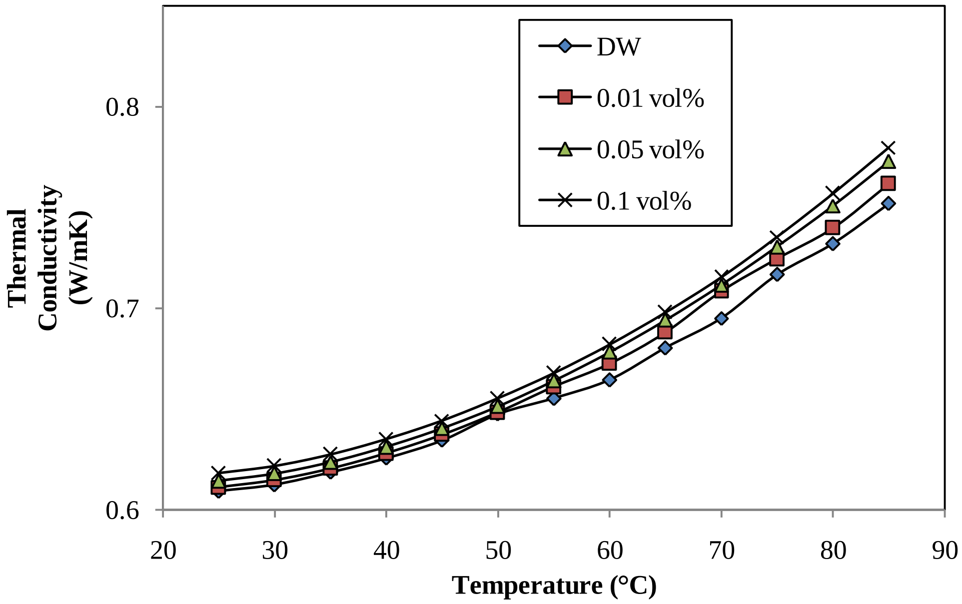

Figure 5.4: Variation thermal conductivities of distilled water and nanofluid with change in temperature.

The thermal conductivity of nanofluid is higher than that of distilled water. Thermal conductivity increases with increase in temperature as well as increase in concentration of nanofluid.

5.5 Entrainment

Entrainment analysis of alumina-water nanofluid at different concentration and for different pipe diameter is given below.

5.5.1 Entrainment for pipe diameter 20mm

The entrainment observed for 0.01%, 0.05% and 0.1 vol.% alumina-water nanofluid and distilled water for pipe diameter 20mm is given in Table 5.7 below.

Table 5.7: Results of entrainment study for 20 mm pipe.

Weight of nanoparticles (g)		**Volume of nanofluid/ distilled water (ml)**		**Volume%**		**Volume of samples (ml)**	**Volume% of samples**
Initial	Final	Initial	Final	Initial	Final		
(a) Distilled water							
0.0	0.0	350	330	-	-	1st=3.0	-
						2nd=10.0	-
						3rd=14.0	-
						4th=6.0	-
						5th=9.5	-
(b) For 0.01 vol.%							
0.1382	0.0275	350	313	0.0100	0.0021	1st=9.0	1st=0.0330
						2nd=4.0	2nd=0.1530
						3rd=10	3rd=0.0130
						4th=8.0	4th=0.0097
						5th=30.0	5th=0.0182
Nanoparticles lost = 0.0158 g							
(c) For 0.05 vol.%							
0.6420	0.5227	350	300	0.0466	0.0441	1st=3.0	1st=0.0451
						2nd=6.0	2nd=0.0506
						3rd=10.0	3rd=0.0388
						4th=11.0	4th=0.0330
						5th=20.0	5th=0.0300
Nanoparticles lost = 0.0485 g							
(d) For 0.1 vol.%							
1.3825	1.1352	350	313	0.1	0.0918	1st=5.8	1st=0.1033
						2nd=7.3	2nd=0.1754
						3rd=10	3rd=0.3434
						4th=12	4th=0.0369
						5th=14	5th=0.0215
Nanoparticles lost = 0.0872g							

It is observed that for 20 mm pipe, maximum of concentration of nanoparticles was obtained from the first, second and third outlets for 0.01%, 0.05% and 0.1 vol.% alumina-water nanofluids respectively.

Foaming height was found to increase with increase in concentration and temperature.

5.5.2 Entrainment for pipe diameter 10 mm

The entrainment observed for 0.01%, 0.05% and 0.1 vol.% alumina-water nanofluid and distilled water for pipe diameter 10mm is given in Table 5.8 below.

Table 5.8: Results of entrainment study for 10 mm pipe.

Weight of nanoparticles (g)		**Volume of nanofluid/ distilled water (ml)**		**Volume%**		**Volume of samples (ml)**	**Volume% of samples**
Initial	Final	Initial	Final	Initial	Final		
(a) Distilled water							
0.0	0.0	330	300	-	-	1st=3.3	-
						2nd=12.0	-
						3rd=16.0	-
						4th=6.3	-
						5th=11	-
(b) For 0.01 vol.%							
0.1348	0.0359	330	275	0.0103	0.0033	1st=10.0	1st=0.0044
						2nd=4.0	2nd=0.0060
						3rd=11.0	3rd=0.0865
						4th=9.9	4th=0.0219
						5th=35.0	5th=0.0062
Nanoparticles lost = 0.0492 g							
(c) For 0.05 vol.%							
0.7900	0.5132	330	280	0.0606	0.0393	1st=5.1	1st=0.0349
						2nd=7.5	2nd=0.3507
						3rd=9.9	3rd=0.0300
						4th=10	4th=0.0510
						5th=50	5th=0.0316
Nanoparticles lost = 0.1341 g							
(d) For 0.1 vol.%							
1.3043	0.9788	330	280	0.1000	0.0884	1st=13.0	1st=0.4735
						2nd=10.0	2nd=0.4219
						3rd=6.4	3rd=0.5234
						4th=10.0	4th=0.9383
						5th=13.0	5th=0.1014
Nanoparticles lost = 0.2738 g							

It is observed that for 10 mm pipe, maximum of concentration of nanoparticles was obtained from the third, fourth and fifth outlets for 0.01%, 0.05% and 0.1 vol.% alumina-water nanofluids respectively.

Foaming height was found to increase with increase in concentration and temperature.

5.6 Comparison of entrainment in 10 mm and 20 mm diameter pipes

Entrainment increases on decreasing the pipe diameter and increasing the concentration of nanofluid. As shown in Figure 5.5, foaming height also increases on decreasing pipe diameter and increasing concentration of nanofluid. The volume of solution entrained is more for 10 mm pipe than 20 mm pipe. Total volume of entrained solution increases with increase in nanoparticles volume fraction.

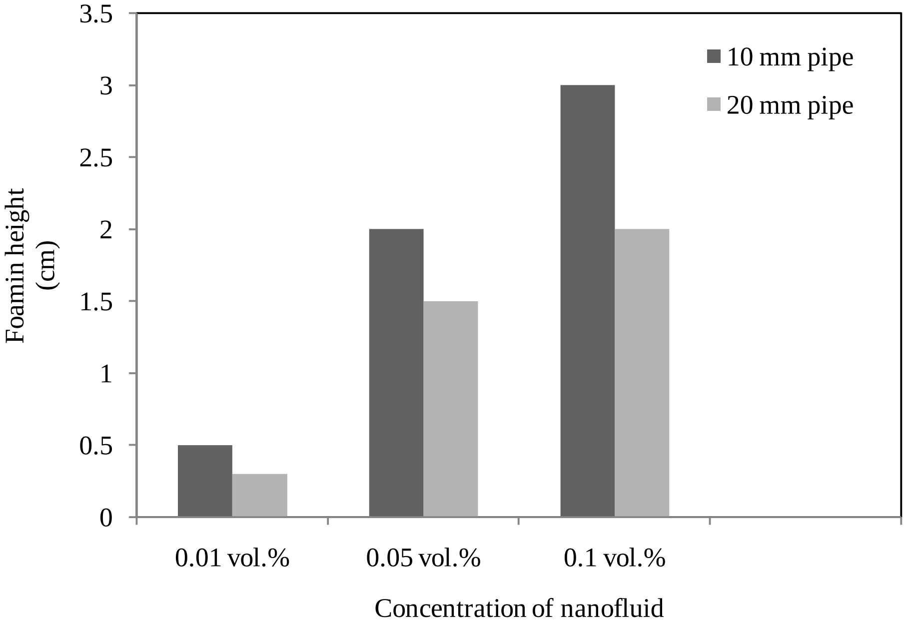

Figure 5.5: Effect of nanoparticle concentration and pipe diameter on foaming height.

5.7 Summary

Three different concentration i.e. 0.01%, 0.05% and 0.1 vol.% alumina-water nanofluid are prepared by two-step method. The density, viscosity and thermal conductivity of nanofluid is determined.

The thermo-physical properties of alumina-water nanofluid are effect by concentration of nanofluids as well as temperature. Where thermal conductivity increases with increase in concentration as well as temperature, density and viscosity increase with increase in concentration and decrease with increase in temperature.

Alumina-water nanofluid used for experiment is freshly prepared. As old nanofluid become unstable after experiment. The reduction in pipe diameter increases entrainment of nanoparticles. For low concentration alumina-water nanofluid the volume of samples collected is more. Foaming is observed during experiment. Foaming increases on increasing the temperature.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Based on the experiment following conclusions are drawn

i. Alumina-water nanofluids (0.01%, 0.05% and 0.1 vol.%) are prepared by two-step process without using surfactant. An ultrasonicator is used to disperse the particles properly and to minimize particle agglomeration to get a uniform stable suspension.
ii. Nanofluid remained stable for 3 weeks.
iii. Density of alumina-water nanofluid is higher than that of distilled water and it increases with increase in particle concentration at a particular temperature. But as temperature increases density decreases. 3.8% decrement is observed in density of 0.01 vol.% nanofluid whereas density of water decreases by 4% with increase in temperature from 25 to 100˚C.
iv. Viscosity of alumina-water nanofluid is more than that of distilled water. Viscosity increases with concentration and decreases with temperature. Viscosity of 0.01 vol.% nanofluid decreases by 67% and that of distilled water also decreases by 67% when the temperature is increased from 25 to 100˚C.
v. Thermal conductivity of nanofluid is higher than distilled water. It increases with temperature as well as concentration.
vi. Entrainment increases on increasing the concentration of nanoparticles and the temperature of evaporator. It increases on decreasing the pipe diameter from 20 mm to 10 mm.
vii. Foaming observed during the experiment increases with the concentration of nanoparticles from 0.01% to 0.1 vol.% and temperature from 25 to 80˚C. Foaming height decreases with increase in pipe diameter.
viii. During experiment, bubbly flow is observed prior to entrainment and it changes to slug flow as entrainment increases.

6.2 Scope for future work

There is a lot of scope for further research in this area since entrainment limit has not been thoroughly studied in literature.

i. The effect of nanoparticle size on entrainment characteristic of alumina-water nanofluid.
ii. Development of theoretical equations for optimizing entrainment characteristic of alumina-water nanofluids.
iii. Effect on entrainment of alumina-water nanofluids in an inclined pipe.
iv. Study of entrainment characteristics of alumina-water nanofluids at higher temperature.