

# **Study of Heat Transfer in Microchannels Using Aluminum Oxide Nanofluids**

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by

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July, 2016

*Dedicated to every  
engineer  
who  
strides  
at work  
towards the  
Nation development*


# CERTIFICATE

I hereby declare that the thesis entitled “**Study of Heat Transfer in Microchannels Using Aluminum Oxide Nanofluids**” is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering in Thermal Engineering** at **Thapar University, Patiala** under the supervision of **Dr. D. Gangacharyulu**, Professor, Chemical Engineering Department, Thapar University, Patiala and **Sumeet Sharma**, Associate Professor, Mechanical Engineering Department, Thapar University, Patiala during July, 2014 to July, 2016. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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# Abstract

High performance heat exchanger devices with higher thermal conductivity of coolants are the need for micro industry, domestic and automobile industry. Thermal conductivity of coolants plays an important role in designing, selection, fabrication of high surface to volume ratio devices to extract higher heats from small spaces. Lower thermal conductivity of conventional fluids like water, ethylene glycol and oils has put a question on their credibility in small spaces high heat extraction devices. Nanofluids, suspensions have nano sized particles (upto 100nm) is seems to be promising solution of this problem. Furthermore, higher surface to volume ratio devices extract more heat than convention heat exchanging devices, microchannels stands by these constraints and proved a valuable asset for heat exchanger category. In the present study investigation of thermophysical properties of nanofluids and performance of microchannels have been carried out at different particle volume concentration ( 0.1%, 0.25%, 0.5% (vol.)) and with different flow rates ranging from 0.5ml/min to 2ml/min. the relation of thermal conductivity, viscosity has been investigated with concentration and temperature. Thermal conductivity increases and viscosity decreases with increase in temperature. Thermal conductivity and viscosity increases with increase in concentration of nanofluids. Heat transfer coefficient, Prandtl number, Reynolds number also studied for different concentrations and flow rates. It is seen that heat transfer coefficient and Prandtl number increases with increase in concentration of particles whereas Reynolds number decreases with increase in concentration. The heat transfer coefficient increased by maximum of 27% for 0.5% (vol.) concentration and Prandtl number increased by 22% maximum. However Reynolds number had decreased by maximum of 28% for 0.5ml/min flow rate and least decrease by 18% for 2ml/min flow rate. However, microchannels give the high surface to volume ratio of  $8.05\text{mm}^{-1}$ . This encourages the use of microchannels in small spaces where high heat transfer coefficients are required.

**Key words:** Nanofluids; Preparation; Stability; Applications; Microchannels; Performance

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# Nomenclature

$D_h$  = Hydraulic diameter of microchannels, mm

$T_1, T_2, T_3, T_4, T_5$  = Temperature at different locations in microchannels, k

$W_{ch}$  = width of microchannels, mm

$D_{ch}$  = depth of microchannels, mm

$L_{ch}$  = length of microchannels, mm

$f$  = fanning friction factor, Pa-s

$Nu$  = Nusselt number, dimensionless

$Re$  = Reynolds number, dimensionless

$Pr$  = Prandtl number, dimensionless

$A_c$  = Area of cross section of microchannels,  $m^2$

$P$  = perimeter of microchannels, m

$v$  = velocity of flow inside microchannel, m/s

$\dot{m}$  = mass flow rate, kg/sec

$C_p$  = specific heat capacity, J/kgk

$T_o$  = outlet temperature, k

$T_i$  = inlet temperature, k

$T_m$  = mean temperature, k

$A_w$	= area of heat transfer, $m^2$
$U$	= overall heat transfer coefficient, $W/m^2k$
$H$	= convective heat transfer coefficient, $W/m^2k$
$h_1$	= heat transfer coefficient of left side of microchannels, $W/m^2k$
$h_2$	= heat transfer coefficient of right side of microchannels, $W/m^2k$
$A_1$	= area of heat transfer on left side of microchannels, $m^2$
$A_2$	= area of heat transfer on right side of microchannels, $m^2$
$q$	= the constant heat rate supplied, $W$
$\ln t_2$	= natural log of time at the end
$\ln t_1$	= natural log of time at the start

## Subscripts

nf	= Nanofluids
F	= base fluid
P	= nanoparticles
2	= Final state
1	= Initial state

## Greek Symbols

$\varphi$	= Particle volume concentration, % [vol.]
$\rho$	= Density, kg/m <sup>3</sup>
$\mu$	= Dynamic viscosity, N-s/m <sup>2</sup>
$\nu$	= kinematic viscosity, m <sup>2</sup> /s
$\Omega$	= ohm

## Acronyms

CNC	= computer numeric control
PWR	= pressurized water reactor
DVLO	= Derjaguin, Verway, Landau, and Overbeek
RIE	= Reactive ion etching
DRIE	= Deep reactive ion etching
CCD	= Charge-coupled device
MMC	= Manifold microchannels
LIPMM	= Laser induced plasma micromachining
CMHE	= Counterflow microchannel heat exchanger
NIIRT	= National Institute for Industrial Research and Training
SEM	= Spectral electron microscopy



# Chapter 1

## Introduction

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### 1.1 Introduction

With the advancement in microelectronics industry, high heat flux devices have been started manufactured, but their heat dissipation is critical issue for their prominent use in industry and day to day life, since electronic chips slows down their functioning or even may damage completely due to heat accumulation. Hence the heat dissipation from these electronic chips and circuitry is most important and challenging task. This heat dissipation can be achieved by employing two methods: increasing the surface to volume ratio of heat exchangers or by using better coolants or by both [1]. However, the conventional coolants (water, oils and ethylene glycols) were proved futile because of their low thermal conductivity which leads to poor heat dissipation and slower performance of electronics chips. Therefore in 1873, J.C Maxwell proposed to add very small solid particles in the fluids (base fluid) to increase their thermal conductivity which further can increase the heat dissipation. Small solid particles have higher thermal conductivity than base fluid hence an overall increase in heat dissipation capacity and thermal conductivity of base fluid [2]. It is known that micro and millimeter sized particles increases the thermal conductivity of base fluids, but when experiments were carried out it was found that in addition to increase in thermal conductivity some more problems like abrasive wear of pipeline, clogging of channels, sedimentation of particles and pressure drop, has been surfaced which restricted their use in micro industry. Later, to avoid these problem nano sized particles were introduced, with the development in nano scale industry and nanotechnology they gained the momentum for use in research area [3]. Nano particles are fine powdered particles which have size smaller than 100 nm. In 1993 Masuda et al[4] used the ultra-fine particles to enhance the thermal conductivity of liquid. Later in 1995, S.U.S Choi [5] proposed the use of nanoparticles in base fluids to increase the thermal conductivity. These particles may be metallic and non-metallic:  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ ,  $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{Cu}$ ,  $\text{Ni}$ ,  $\text{Al}$ ,  $\text{ZnO}$  [6]. The fluids made by dispersing nanoparticles in them are known as nanofluids.

Nano fluids are the class of fluids which formed by dispersing nano sized high conductivity materials (nanofibers, nanotubes, nanorods, nanowires, nanoparticles or nanosheets) into the base fluid. In other words nanofluids are dilute suspensions having condensed nanomaterial dispersed in them. The nanomaterials having size lesser than 100nm are dispersed in base fluid. The dilute suspensions of nanofluids are advantageous over colloidal solution for being having high heat transfer surface between fluid and particles. With these advantages nanofluids have applications in : transportation, heat transfer intensification, electronics applications, industrial cooling applications, heating buildings and reducing pollution, nuclear cooling, energy storage, solar absorption, friction reduction, magnetic sealing, biomedical application, nano drug delivery etc. [7]. However we are confining our study to the application in electronics industry use only. Microelectronics as the science of developing world; the heat dissipation from such small places is the major issue to be focused on. To tackle this challenge small scale heat exchangers are to be needed with high heat flux coolants. In achieving these objectives the idea small micro size heat exchanger: microchannels have been introduced. Hence the use of nanofluids in microchannels meets the demand of time.

Microchannels are the micro sized flow passages with hydraulic diameter ranging from 10 to 200 micrometers. Such small passages have high surface to volume ratio which enables higher heat transfer rates [8]. Microchannels are the small heat exchanging devices which fits in very small and compact spaces where heat dissipation is more and conventional methods fails to dissipate the accumulated heat. Many experiments have been carried out by many researchers to study the heat transfer behavior in microchannels using nanofluids [9][10][11]. These experiments show an increase in thermal conductivity of fluid using nanofluids and high heat dissipation capacity upto  $790 \text{ W/cm}^2$  with maximum temperature rise of  $71^{\circ}\text{C}$  above the water temperature [12]. Microchannels have been shown in Figure 1.1 we can see the small slots which have hydraulic diameter in range of 10 to 200 nm. Microchannels are made generally on silicon wafer due to ease in manufacturing and simple process of stereo lithography. This method has drawbacks of manufacturing accuracy which leads to deviation in experimental and theoretical results. Hence by avoiding this method a new idea to use CNC wire cutting on aluminium has been incorporated. The impulse for microchannels research has started after the revolutionary work of Tuckerman and Pease [13] in 1981. After the work of Tuckerman and Pease the research was focused on design implementation from 1986-1988. The design implementation followed by

understanding of fundamentals of fluid flow in microchannels in the period of 1992-2002, 2005-2006 focus was shifted on the practical implementation.

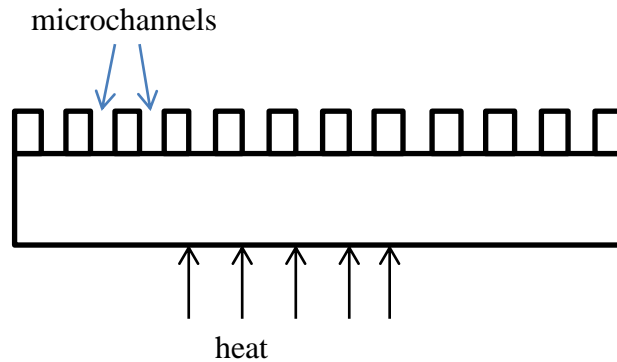


Figure 1.1: Microchannels

After 2006 the time was left to validate the research which has been done yet; from these findings of Sathish. G. Kandlikar [8] more study has to be done in microchannel field for practical use. Significant literature is available that uses silicon microchannels [10] [14] [15] [9] , but very less or no literature has been found yet which has used aluminium microchannels, also most of the studies are numerical investigation and optimizations, very less experimental work is available in literature. Only few researchers [9][16][6][12] has done the experimental work in the field of microchannels. They found that with increase in Reynolds number pressure drop increases and heat carrying capacity of microchannel also increases and moreover the agglomeration of nanoparticles were also examined in the studies available. Wu *et al* [9] examined the particle agglomeration in the microchannels, it was found that at no noticeable deposition was reported with temperatures inlet- 25-35° C, outlet 30-40°C, but at higher temperatures where boiling starts severe deposition of nanoparticles was observed. Hence the low temperature i.e. room temperature is taken for the experimental work to be carried. Gunnasegaran *et al* [12] has studied the friction factor impact on different shapes of microchannel. From this study of Gunnasegaran rectangular shape cross sectional geometry of microchannels have been selected.

Due to lack of available literature on aluminum microchannels; a direction has been seen to do an experimental work on heat dissipation characteristics of aluminum rectangular microchannels.

## **1.2 Objectives**

Measurement of thermal performance of nanofluids and microchannels is one of the main concerns now days because of applicability of duo in electronic industry. This research work concentrates on the following points

1. To study the heat transfer behavior of alumina nanofluids/water in single pass microchannel.
2. To compare the heat dissipation capacity of water and nanofluids at different flow rates and at different concentration of nanofluids.
3. To study the effects of concentration on certain parameters such as Reynolds number, Prandtl number.

# Chapter 2

## Literature review

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The first part of this chapter deals with the general information about nanofluids and microchannel. Later part consists of findings of researchers and scientists about the thermal characteristics of nanofluids and microchannels. Lastly the literature available related to experimental and theoretical work on nanofluids and microchannels has been discussed.

### 2.1 Nanofluids

Nanofluids are new class of materials which consist the dispersion of nano sized (less than 100 nm), high conducting material particle in base fluid. Due to dispersion of nanoparticles; surface to volume ratio of fluid increases and hence thermal conductivity increases. Moreover the Brownian motion among particles results in collisions of particles as consequence of which heat transfer rate of base fluid increases. The viscosity of nanofluids changes inversely with temperature, this is due to more Brownian motion at higher temperature and which further increases conductivity [17]. Some review articles on nanofluids had been published in recent years [7], [18], [19]. Many reviews are confined to theoretical and experimental studies.

### 2.2 Materials for nanofluids

Particle size smaller than 100 nm with higher thermal conductivity than the base fluid; made the material suitable to be used as nanoparticles. Nanofluids consist of two parts i.e. nanoparticles and base fluid. Dispersion of nanoparticles into base fluid is known as nanofluids.

Nanoparticles and base fluids which are commonly used are listed below:

1. Nanoparticles –
  - a. Metallic particles- Cu, Al, Fe, Au, Ag etc.
  - b. Metal oxides –  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{CuO}$ ,  $\text{TiO}_2$ .
  - c. Carbon nanotubes.

2. Base fluids –
  - a. Water, Oil, Ethylene Glycol.

## **2.3 Preparation of nanoparticles**

Nanoparticles are prepared by two methods which are: two-step method and one step method. Both the methods to manufacture nanofluids are discussed as follows.

### **2.3.1 Two-step method**

It is most widely used method to prepare nanofluids. In this method two-steps are followed; this is why it is called two-step method. Nanofibers, nanoparticles, nanotubes etc. produced by this method are first prepared as dry powders by different means of physical and chemical methods, this formation of nanoparticles ends the first step. Now the powdered form nanoparticles are dispersed into base fluid with the help of high shear mixing, ultrasonic agitation, force agitation and ball mixing. This is the most economical technique to make nanofluids due to cheaper method to synthesize nanoparticles in industry. However nanoparticles have the tendency to agglomerate. Due to lesser stability of nanofluids by this method new method has been developed: one-step method.

### **2.3.2 One-step method**

As the name suggests this method has one step completion process. Eastman *et al* [20] had developed physical vapor condensation method for preparation of Cu, ethylene glycol nanofluids. The method used by them is known as one-step method. In one-step method simultaneously making and dispersing the particles into fluid is carried out. Many processes like transportation, drying and dispersion has been avoided hence the problem of agglomeration has been minimized. One-step physical method is not so efficient and we cannot make nanofluids on large scale because of high cost of preparation. Chemical preparation method has been gaining momentum for high production rates. Moreover in one-step method residual particles of incomplete reaction are left behind in the nanofluids, due to which it is difficult to explain exact nanofluids behavior.

### **2.3.3 Other methods**

To synthesize Cu nanofluids Wei *et al* developed a new method called continuous-flow microfluidic microreactor, the properties and microstructure can be varied by adjusting the parameters such as flow rate, additive etc. Zhu *et al* [21] synthesized CuO nanofluids by precursor transformation novel method with microwave and ultrasonic irradiation.

## **2.4 Application of nanofluids**

### **2.4.1 Electronic applications**

Due to high heat generations in chips electronic circuitry components with compact designs and geometry suffering from thermal management. To extract such a high heat from these compact devices has become difficult. Heat can be removed by two methods: by optimizing the design of cooling system and other by using high heat dissipating capacity fluids. Here nanofluids play the role of higher heat carrying capacity fluids than conventional coolants. Nanofluids have higher thermal conductivity compared to those of base fluids, as proved by many researchers.

### **2.4.2 Transportation**

Nanofluids have the capacity to advance the cooling systems of heavy duty engines and heat generating parts of automobiles. Nanofluids increase the heat carrying rates and thus lower the weight and reducing the complexity of cooling jackets. This helps in creating compact designs for same horse power with lighter radiators. It is beneficial for high performance and high fuel economy.

### **2.4.3 Heating buildings and reducing pollution**

Kulkarni *et al* [22] evaluated heating of buildings in cold region with the help of nanofluids. In colder regions ethylene glycol mixed water in different proportions is used as heat transfer fluid. The analysis by Kulkarni *et al* showed that by using nanofluids in heat exchanger, could reduce the mass and volumetric flow rates, which results in overall saving in pumping power. Nanofluids call for smaller and compact heating systems, which are capable of delivering the same amount of energy as larger systems.

#### **2.4.4 Nuclear cooling systems**

Researchers at Massachusetts Institute of Technology are exploring the applications of nanofluids in nuclear science. They are mainly focused in three areas: 1) Main reactor pressurized water reactors (PWRs). 2) As a coolant for emergency condition for core cooling. 3) Coolant for invessel retention of the molten core during severe accidents in high-power-density light water reactors.

#### **2.4.5 Space and Defense**

The restriction of space, energy and weight at space stations and in aircraft generates the need for highly efficient cooling system which has high heat flux capacity. This presenting a vision for lighter weight of cooling systems due to compact and simple designs of heat exchangers, which further makes space travel cheaper than present. The high critical heat flux capacity make nanofluids capable of being used in military systems such as in submarines, high power diode lasers etc. thus nanofluids has the potential to be used in the areas where components should be lighter weight and power density is more.

#### **2.4.6 Solar absorption**

Solar energy is the best non-conventional source of energy available in abundance. Direct absorption solar collector is well established technology. But the efficiency is very low due to poor absorption capacity of collector fluid. Recently this technology has been pooled with nanofluidic technology. Otanicar *et al* [23] performed experiments on direct absorption solar collector with nanofluids as working fluid and reported 5% increase in efficiency of solar thermal collectors.

#### **2.4.7 Miscellaneous**

Along with these major applications of nanofluids, they has much more application in different fields for e.g. Nanodrug delivery, in microreactors, as vehicular brake fluids, nanofluids based microbial fuel cell etc.

## **2.5 Challenges of nanofluids**

However with these great applications of nanofluids, still their use is limited due to the discrepancies in their long term use. Nanofluids though have their thermal conductivity more than the conventional fluids; still the use is hindered by the following reasons:

1. Disagreement of theoretical and practical measurements by many researchers group.
2. Stability of nanofluids, nanofluids have very low stability due to strong van-der Waal forces between the particles which make them to agglomerate. However physical and chemical methods have been developed to increase the stability e.g. ultra sonication, addition of additives and surfactants.
3. Manufacturing cost is another parameter in their use. Cost of manufacturing is high which make them costlier than the base fluids..
4. Increase in viscosity of nanofluids as compared to base fluid with increase in concentration, which increases the pumping power.
5. Sedimentation of particles at higher temperatures.

## **2.6 Stability of nanofluids**

Stability of nanofluids is the major concern for their commercial use. Particle agglomeration and settlement not only chokes the passages but also decreases the thermal conductivity of nanofluids. Hence the investigation of nanofluids stability study is important.

### **2.6.1 Stability mechanism**

In dispersion the particles adhere to each other and form agglomerates of increasing size, which further settles down and clogs the passages; this questions the credibility of nanofluids in practical use. According to Derjaguin, Verwey, Landau, and Overbeek (DVLO) the stability of particle is determined by sum of electrical double layer repulsive force and van der Waal forces between the particles which arises due to their Brownian motion. When the van der Waal forces dominant over the electrical repulsive forces particle stick to each other and form agglomerates, when the electrical repulsive forces are more than van der Waal forces particles do not aggregate and stability is maintained. So, for stability the electric repulsive forces should be more than the

attractive van der Waal forces. These forces can be modified by adding surfactants and additives in nanofluids and the stability can be enhanced, for e.g. Zinc oxide nanoparticles with PMAA shows good compatibility with polar solvents. Surfactants and reagents increase the stability of nanofluids for more duration but they also affect the thermal properties of nanofluids. They should be used in metered and limited quantity.

## **2.6.2 Stability analysis**

Stability of nanofluids can be evaluated by different chemical and physical methods. These methods are described here very shortly and can be read in detailed from reference [7].

1. Sedimentation and centrifugation.
2. Zeta potential analysis.
3. Spectral absorbency analysis.

These methods help in evaluating the stability of nanofluids and many behavioral properties can be predicted from stability. All above three methods can be combined to investigate the stability of nanofluids.

Nanofluids with more thermal conductivity than the base fluids are the future cooling fluids because of simpler designs and smaller heat exchangers devices that can be made by using enhancement advantage of thermal properties of nanofluids. Particle size and concentration greatly affects the thermal properties of nanofluids. With the challenges (discussed above) in nanofluids commercialization. This field is growing day by day and new methods of improvement are discovered, we hope in near future we will be having more stable nanofluids without compromising on their thermal properties.

## **2.7 Microchannels**

As the size of devices become smaller, heat dissipation and thermal control of these devices can be accomplished by using microchannels passages. The small passages of microchannels provide high surface to volume ratio that enable efficient heat dissipation from small very small spaces. Microchannels have application in the devices where the designs have space and weight constraint. Microchannels are the passages which have their hydraulic diameter between 10-200

$\mu\text{m}$ . After the research work of Tuckerman and Pease[13] in 1981 the field of microchannel get the direction to research upon. Many researchers diverted their concentration to the new means of heat dissipation and work on design and implementation gets started, continues till 1988. After design and implementation the researchers researched upon the fundamental understanding of flow characteristics in microchannels. The experimental research work of many researchers in 1990s still cannot solve the question of credibility of continuum theory to the liquid flow. Later Xu *et al* [24] neglecting the entrance and exit effects, validated the applicability of conventional theory in microchannel. However later the study by Palm [25] concluded that the research of that time is still inconclusive regarding the applicability of continuum theory in microchannels. The researchers Qu and Mudawar [26] , Steinke and Kandlikar [27] presented the experimental data that confirms the validity of continuum theory in microchannels. Later Lee *et al* [28] validated the applicability of continuum theory in microchannels with careful consideration on boundary conditions during experiment. Hence the validation of continuum theory has been accepted in single phase flow in microchannels. Two phase flow is still in under active research and conclusion has to be made yet. Single phase flow is considered in this experimental work.

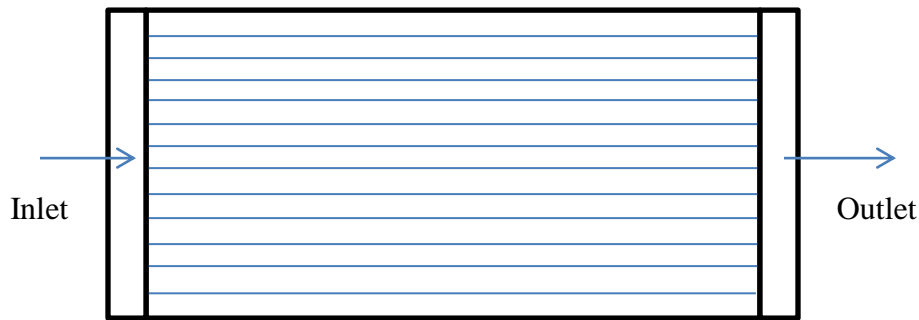


Figure 2.1: Straight flow microchannels

As we can see from the figure flow enters from one side and goes out from other side taking up the heat generated by the system upon which it is fitted. This type of microchannels is called straight flow microchannels. Fluid flow enters from one side take up the heat and goes out from other side.

### 2.7.1 Classification of microchannels

Microchannels are classified on the basis of cross sectional area of the channel, hydraulic diameter of the channel. Mehandale *et al* had given the classification criteria on the basis of

hydraulic diameter. His classification is given in the following Table 2.1. Gunnasegaran *et al* made the classification on the basis of cross sectional geometry of microchannels.

Sno.	Hydraulic diameter	Nomenclature
1	$D_h > 3\text{mm}$	Conventional channel
2	$3\text{mm} \geq D_h > 200 \mu\text{m}$	Minichannels
3	$200 \mu\text{m} \geq D_h > 10 \mu\text{m}$	Microchannels
4	$10 \mu\text{m} \geq D_h > 0.1 \mu\text{m}$	Transitional microchannels
5	$0.1 \mu\text{m} \geq D_h$	Molecular nanochannels

Table 2.1: Classification of microchannels by. Mehandale et al.

Microchannels are also classified by the fluid flow directions also i. e split flow type and straight flow type. The following Figure shows the classification of microchannels as straight flow type and split type.

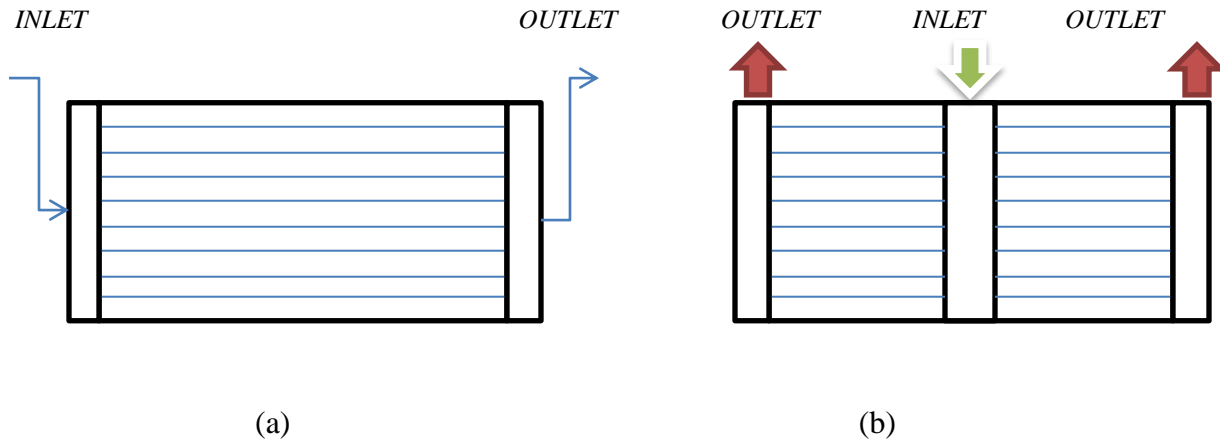


Figure 2.2: Microchannel classification, a) straight flow type, b) split flow type

Gunnasegaran *et al* classified the microchannels in his work on the basis of their geometry: rectangular, triangular and trapezoidal microchannels. He compared the performance of microchannels in his work.

Classification by Gunnasegaran *et al* is shown below:

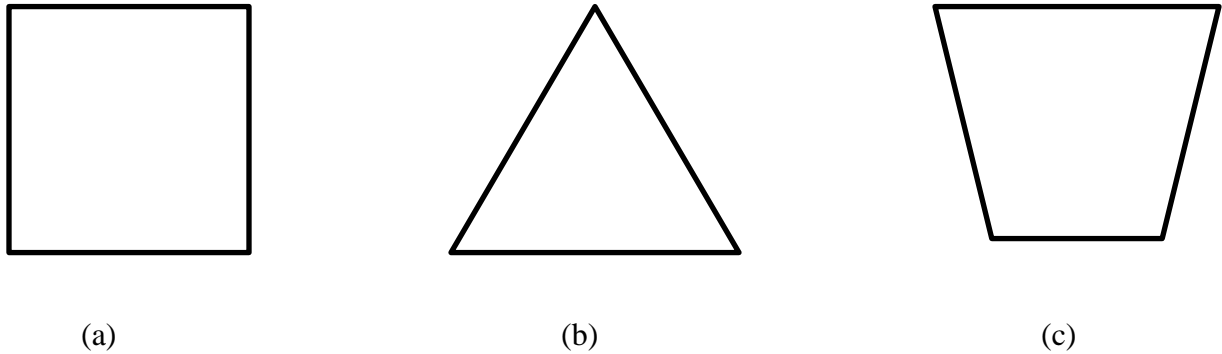


Figure 2.3: a) rectangular microchannel, b) triangular microchannel, c) trapezoidal microchannel

This classification of the channels on the basis of cross sectional geometry helped to choose the microchannel for the research work. Rectangular microchannels are easy to manufacture, cheaper in cost than any other channel and can be manufactured by number of ways. Monica *et al* [14] presented new method of lithographic techniques. They represented the wet etching and dry etching techniques to fabricate microchannels as follows.

1. Dry etching techniques
  - i. Optical lithography.
  - ii. Reactive ion etching.
  - iii. Deep reactive ion etching.
2. Wet chemical etching.

Wet chemical etching for longer time distorts the shape of rectangular microchannels and shape changed to sinusoidal one rather than rectangular profile, which cannot be neglected for experimental processes as it gives the extra resistance to the fluid flow, this distortion of shape from rectangular to sinusoidal is shown by Monica *et al* [14] in the figure below.

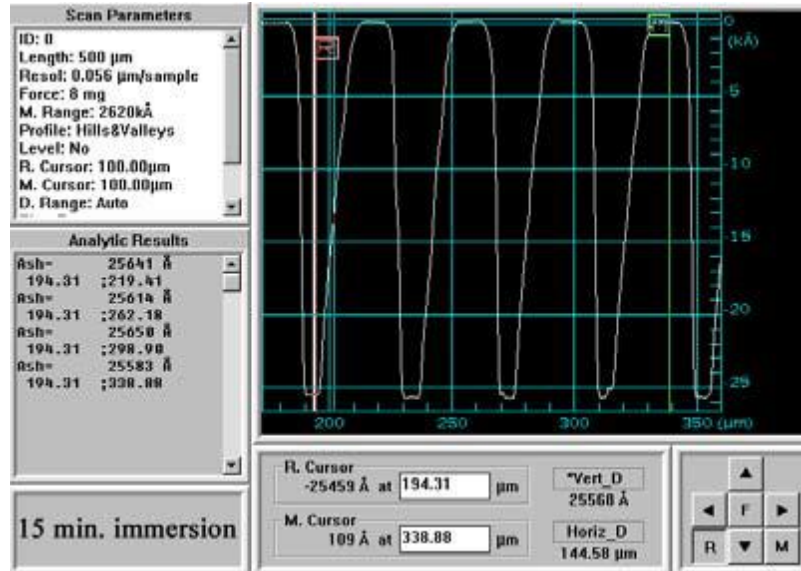


Figure 2.4: 15 min dispersion of microchannel with depth of 2.1 μm

Reactive ion etching, in contrast to wet etching produces more dimensioned structure due to almost vertical delivery of reactive ions [14]. The surface quality of etched microchannel by this technique is very good and will not affect the fluid flow.

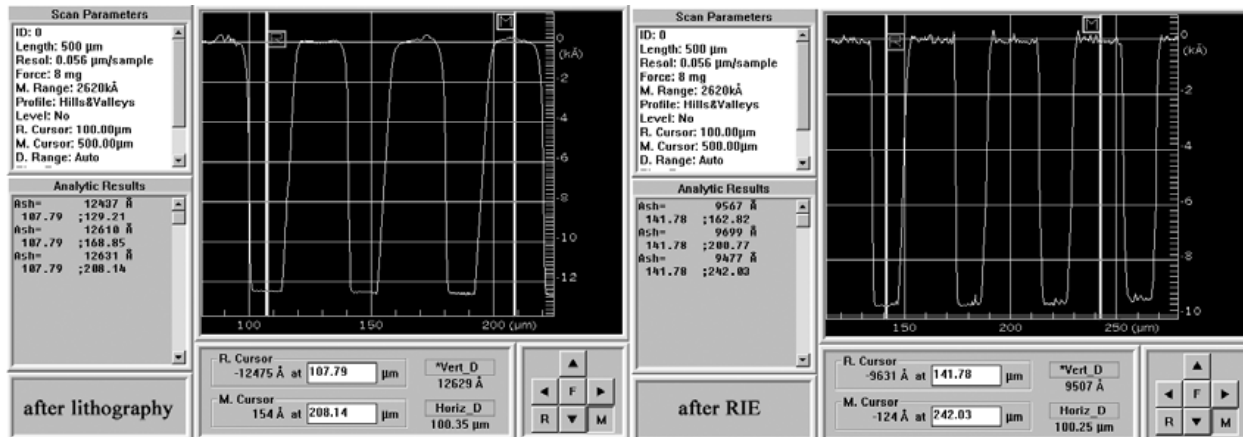


Figure 2.5: Microchannel fabricated by RIE technique

From the above figures we can say that microchannel fabricated by RIE technique has more dimensioned structure, more is the accuracy in the process, better flow conditions. However these methods are not convenient for practical applications due to small depths of microchannels, hence they developed the new method, deep reactive ion etching (DRIE), which can make the silicon wafers as deep as 200 μm. But the main drawback of this method is that it should be used with metal mask layer.

Manufacture these microchannels by these techniques require very good knowledge and practice to manufacture it due to involvement of time dependent chemical reactions, which are very hard to control and these methods have their own drawbacks as discussed above. So, not going to this level of difficulty a new method of channel fabrication has been selected i.e. CNC wire cutting. This CNC wire cutting is cheaper, easily available, takes less time in manufacture. CNC wire cut uses the wire of 0.018mm to produce the cut of 0.025mm.

As the manufacturing science is growing it parallels the microchannel development which makes it feasible to use in different fields according to their constraints. The practical applications of microchannels have been growing since its evolution in early 21 century. And some of them are as follows.

### **2.7.2 Applications of microchannels**

- In space –

Today it costs ₹ 14,33,103 to send 1 kg of load to space. [29] Heavy circuitry is needed in launch vehicles and space crafts which produce a lot of heat and as microchannels provide us higher surface to volume ratio and can more heat by any other heat exchanger of same size with lesser weight.

- Automotive.
- Bioengineering.
- Cooling of gas turbine blades
- Power and process industries
- Refrigeration and air conditioning
- Infrared detectors and powerful laser mirrors and
- Superconductors
- Microelectronics
- Thermal control of film deposition.

## 2.8 Previous Literature review

Many researchers have done work on nanofluids and their applications, stability, thermal properties. Numerous works has been done on microchannels in understanding the flow behavior, flow boiling and on proving the validation of continuum theory. This chapter provides the brief knowledge of previous work done in nanofluids and microchannels. This helps us to understand the subject in better way and act as directive for this research work.

**Choi et al.** revealed that in the advancement of energy efficient fluids, thermal conductivity plays a vital role. They conducted experiments on Cu/water and Alumina/water nanofluids and showed that the thermal conductivity of nanofluids was significantly higher than that of base fluid. They also concluded that the rate of heat transfer could be increased by factor of 2 without significant increase in the pumping power required for the circulation of fluid through heat exchanger.

**Yu et al** studied the nanofluids and presented a review. In their review they gave information about the nanofluids, there preparation methods, there stability checking methods and applications. They represented the two-step and one step method. He concluded that one step method preparation has higher stability then two-step method due to elimination of storage, transportation, drying dispersion of nanofluids is avoided. He also highlighted other novel methods like continuous flow microfluidic microreactor to synthesize copper nanofluids, phase transfer method etc. The stability evaluation methods: sedimentation and centrifugation, zeta potential method, spectral absorbency analysis. Among these methods sedimentation and centrifugation method is the simplest method to analyze the stability. The ways of enhancing the stability has also been discussed and these are use of surfactant, surface modification techniques etc. have been discussed. In the last section the applications of the nanofluids has been highlighted.

**Wu et al** performed experimental investigations on  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids in silicon microchannel (with hydraulic diameter 194.5 nm, relative roughness  $2.2 \times 10^{-5}$ ). The nanofluids have spherical particles with average size of 56nm with the volume fractions taken in the experiment were 0.15%, 0.26%. The nanofluids were synthesized by employing two-step method. The nanoparticles were dispersed in DI water which is vibrated by the ultrasonic

disrupter for 90 min. 10 days stay of prepared nanofluids was given to check the agglomeration of the particles, and it was seen there was very less or negligible deposition of nanoparticles occur. The parameters incorporated in experiment were - inlet and outlet temperatures range of nanofluids 25°-35° C and 30°-40°C resp. and flow rates used were  $4.5 \times 10^{-8}$  -  $2.6 \times 10^{-7} \text{ m}^3/\text{s}$ . The experimental setup consists of fluid flow system, test section and data acquisition system. The effect of Reynolds number, Prandtl number and volume concentration on heat transfer characteristics, fluid friction, pumping power were studied and the agreement of the experimental results with the theoretical results was obtained, which proves the validity of experimental results. The detailed picture of test section is given in Figure 2.6. Under zero heating power condition the flow was regulated by adjusting the liquid valves.

*Experimental results show the following observations;* By varying the volume flow rate the pressure drop and heat transfer characteristics were observed and it is concluded that with increase in the volume flow rates pressure drop and heat transfer coefficient increases for both water and nanofluids but nanofluids has slightly more pressure drop and heat transfer coefficient than water, which also increases with the concentration increase, this observation proves the contribution of nanoparticles in heat transfer at higher flow rates also. By increasing the laminar Reynolds number (190-1020) it is seen that friction factor decreases. The effect of Reynolds number, concentration, and Prandtl number on Nusselt number is studied and it is found that with increase in Reynolds number and concentration (at Prandtl number 5.8) the Nusselt number increases(Figure 2.7) which again gives the evidence of increased heat transfer with  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids in silicon microchannel. The increase in heat transfer coeff. With concentration is explained as: due to more particles in Brownian motion there is more interaction with the channel wall, because of more conductivity of these particles more heat transfer occurred. Not the Reynolds number and concentration affects the Nusselt number but Prandtl number also influences it. The direct relation is observed between the two numbers i.e. with increase in Prandtl number keeping all other parameter constant there is increase in Nusselt number which shows the contribution of nanofluids at low and high temperatures both (Fig 2.7).

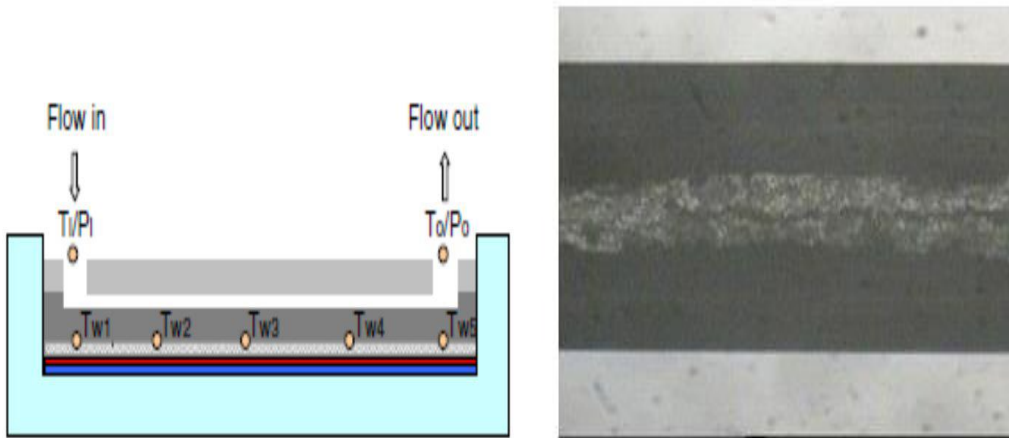


Figure 2.6: a) microchannel section, b) nanofluids deposition in microchannels

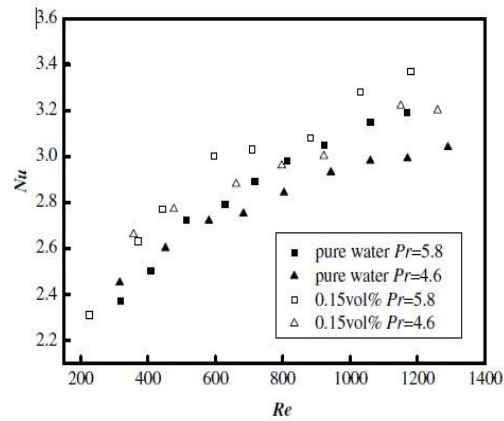


Figure 2.7: Variation of Nusselt number with Reynolds number and Prandtl number

The pumping power and thermal resistance is also considered in this experiment and observation of decreased thermal resistance with increase of pumping power was made. When the temperature was increased slowly (75°-121°C) with the help of CCD camera and magnification microscope it is observed that as the boiling commences the nanoparticles severely settle down and adhesion to the channel wall starts (Fig 2.6). This makes the use of nanofluids for high temperature a questionable issue.

**Gunnasegaran *et al*** did the numerical simulation on the fluid flow to determine the effect of different cross section on the pressure drop and friction factor of the flow in the microchannels of different cross section by taking the different aspect ratios of each type of microchannel. The Finite volume method was used with the grid of  $2.5 \times 10^5$  computational cells. The cross sections

studied were rectangular, trapezoidal, triangular with the parameters used were-  $w_c$ ,  $h_c$  (width and height of rectangular section channel),  $b$ ,  $a$ ,  $h$ ,  $L_c$  (bottom width, top width, height and the length of the trapezoidal section channel,  $a$ ,  $\beta$ ,  $h$ (width of top, triangular angle, height) of triangular section microchannel. Based on the simulated test following results were concluded. The Poiseuille number increases with the increase in the Reynolds number, the variation is not linear due to the fact that at low Reynolds number water absorbs more heat and this decreases its viscosity and pressure drop. The rectangular section channel has lowest Poiseuille number then comes trapezoidal and highest is of triangular. As the  $w_c/h_c$  ratio (in rectangular cross section) increases the Poiseuille number and friction factor also increases. The ratio of height-to-top width ratio ( $H/a$ ), the bottom-to-top width ratio ( $b/a$ ), and length-to-hydraulic diameter ratio ( $L/D_h$ ) are the important design parameters for trapezoidal microchannels. The flow resistance decreases as  $L/D_h$ ,  $H/a$  increases while  $b/a$  decreases. The tip angle of the triangular shaped microchannel affects the flow parameters in direct proportion. The verification of the simulated results is cross checked with the formula available in the literature and the agreement between both is found. This study gives the clear comparison between the different types of microchannels used widely.

**Singh *et al*** carried out the experimental about the heat transfer behavior of nanofluids in the microchannels. Two microchannels with hydraulic diameters 218 and 303  $\mu\text{m}$  are fabricated by wet etching process on silicon wafer. The experimental setup was provided with temperature measurements along the bottom wall temperature and provision of flow in the microchannel. Alumina nanofluids of concentration 0.25 vol. %, 0.5 vol. %, and 1 vol. % with 45 nm are prepared, done stabilizing and characterized by standard methods. The study analyses the thermal conductivity and viscosity. The base fluids used were water and ethylene glycol. The effect of volume fraction, channel size, particle size, and base fluids are presented and analyzed. An important phenomenon of dispersion is observed. Shear induced particle migration is identified to be the reason of difference for dispersion of particles. It was found that better heat transfer characteristics can be obtained by higher concentration of nanofluids and by low viscous base fluids.

**Monica *et al*** proposed the new methods of microchannel fabrication by relying on lithographic techniques. The originality aspects of the work had come from the unique design of the

microchannels able to handle a large range of the nanofluidics applications. The fluid behavior at microscale is different as that of the macroscale behavior due to energy dissipation, surface tension, and fluidic resistance Reynolds number is also taken into account, which should be very low so that the flow remains laminar. The microchannels from silicon wafers were fabricated by three processes i.e. wet chemical etching, optical lithography, and reactive ion etching (RIE). It was found that the RIE gives the precise microchannel shape than wet etching. The profilometer is used to measure the microchannel's depth, by means of transmission electron microscopy (TEM). The nanorods were investigated by TEM to observe their lateral and vertical alignment.

**Mondragon *et al*** carried out the experiments to measure the thermal conductivity, viscosity, specific heat of three basic water based nanofluids of silica, alumina, and carbon nanotubes. Well dispersed nanofluids were prepared by dispersing the powder into the water and the commercial nanofluids obtained in the form of suspension. The main aim of this study was to optimize the Prandtl number in order to select stable nanofluids that provide the best thermal performance with lower pump power. In the research various models were applied to find the thermophysical properties of the different nanofluids at temperatures of 40,60,80°C of different concentrations ranging from 0.5 to 5 %vol. the suitability of different models such as – for thermal conductivity -Maxwell, Rayleigh, Fricke, Nanet al., Hamilton and Crosser , Krischer, Mixture model , Yu and Choi, Xue, Bruggeman, Leon et al. The following results were inferred from the experiment that the thermal conductivity had negligible increase at lower concentrations(0.1%vol), to get the higher thermal conductivity the concentration should be higher also the thermal conductivity increase upto the temp of 600°C and then decrease monotonically. The specific heat as expected increases with the increase in temperature and decreases with increase in concentration, due to the fact that the thermal conductivity of the solid content is low as that of the liquid. Then comes the viscosity which as per the general rule increases with the solid content and decreases with temperature according to the models available. At last the Prandtl number was calculated in order to optimize the pumping power and it was observed that viscous penetration is dominant over the thermal penetrations. The trend showed was similar to that of the viscosity.

**Salman *et al*** carried out the experimental and theoretical study on the two most commonly used nanoparticles i.e. and SiO<sub>2</sub> with water as the base fluid of size 30nm and the different fractions involved in the experimentation were ranging from 0.5%-1% which is calculated by the mixture

formula. The nanofluids were prepared by two-step method and then mixed in ultra-sonic vibrator for 30 min each 100ml, the nanofluids were then kept still for 5 hours and no coagulation and sedimentation was observed. In this experimental work the effect of Reynolds number and concentration on Nusselt number was studied. The experimental setup consists of three main parts – pressuring system, data acquisition system, and heating system. Pressurized nitrogen tank was used to pressurize the nanofluid/water tank which provided the smooth flow with the help of pressure control valves and flow meters, the constant heat flux was provided by the heating system which incorporates 5 k-type thermocouples placed each at 30 mm distance along the length of microtube to control the heating and measuring the temperature. The outside temperature was measured by two thermocouples placed at 3mm from microtube at inlet and outlet ports. The friction factor was measured for  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  with particle concentration of 1% and Reynolds number range from 90-800. The results were compared with conventional theory of fully developed flow with  $\text{Nu}=4.36$  and constant heat flux and it is seen that the Reynolds number value reach 4.36 at higher Reynolds number this is due to the uncertainty of the flow regime inside the tube. Furthermore it is seen that 0.5% and 1% particle concentration  $\text{SiO}_2$  shows the highest Nusselt number followed by  $\text{Al}_2\text{O}_3$  and plain water. It is seen that there was 22% enhancement in heat transfer coefficient as compared to water.

**Sun *et al*** experimentally studied the heat transfer characteristics of  $\text{Fe}_2\text{O}_3$  -water based nanofluids at different fractions, with and without dispersants. They prepared the mass fractions of 0.1%, 0.2%, 0.3%, 0.4% with  $\text{Fe}_2\text{O}_3$  particles of average size of 50 nm. Different dispersants were added and stability was checked. It was found that sodium dodecyl benzene sulfonate (SDBS) with concentration of 0.1% shows the maximum stability. Two samples were prepared on with dispersant and other without dispersant were prepared and flowed through the inner grooved copper tube and copper tube with internal diameters of 8.22 mm and 8.66mm. it has been seen that the convective heat transfer coefficient was increased as the mass fraction increased and it was more in copper grooved tube at constant Reynolds number. At constant Reynolds number heat transfer coefficient increased with Reynolds number. The heat transfer characteristics were better in inner grooved copper tube. However the increased mass fraction increases the friction factor.

**Li et al** did the experimental study on heat transfer characteristic of  $\text{Al}_2\text{O}_3$ -water based nanofluids of average diameter of 30 nm with the concentrations of 1%, 2%, 3%, 4%, in the dimple and dimple+protruded microchannel. The effects of concentration of nanoparticles, geometrical pattern of microchannel and heat transfer characteristic were studied in detail. The microchannels were fabricated in staggered and aligned geometry.

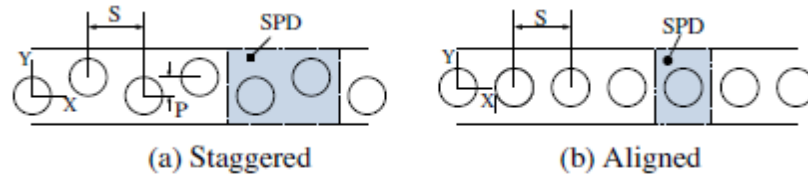


Figure 2.8: Staggered and aligned geometry

The effects of nanoparticle volume fraction (0–3%), inlet velocity  $U$  ( $1.2\text{--}8.7\text{ m/s}^{-1}$ ) and geometrical structure of microchannel on flow and heat transfer characteristics are studied in detail. The results show that the relative Fanning friction factor  $f/f_0$ , Nusselt number  $Nu/Nu_0$  and thermal performance TP increase with the increase of  $U$  for nanofluids.  $f/f_0$  and  $Nu/Nu_0$  and TP of dimple/protrusion aligned arrangement is lower than that of staggered arrangement, especially in the dimpled + protrusion microchannel. The integrated performance of dimpled microchannel is better than that of dimpled + protrusioned ones for  $\text{Al}_2\text{O}_3$  –water nanofluids at the same condition.

**Kim et al** did a study of manifold microchannel (MMC) heat sinks for forced air cooling experimentally. The study was focused on investigation of the effects of geometrical parameters on the thermal performance of the manifold microchannel heat sinks for optimal design and the comparison of thermal resistance of MMC and TMC. MMC differ from TMC in dimensions and geometry. The two manifolds with inlet/outlet channel width -4mm and 0.9mm were made and different thickness to width ratio was incorporated in experiment.

The experimental setup consists of entry section, a power supplier and data acquisition systems, an orifice flow meter. The manifold 1 was first used and it is seen that of 4 mm. As expected, the thermal resistances of heat sinks were significantly reduced with increasing the pumping power regardless of the microchannel width. The thermal resistances were also reduced as-the microchannel width decreased. Then manifold 2 was used and the same pattern was observed but

the thermal resistance with manifold 2 of microchannel is twice that of manifold 1. The pressure drop of the microchannel was decreased greatly by using a manifold without higher loss in the heat transfer. The pumping power was also reduced by 35% than that of TMC.

**Chein *et al*** did the experiments to verify the assumption that the wall temperature in micro channel was obtained less and more heat dissipation. To check the assumption they performed the experiment on CuO-H<sub>2</sub>O mixtures without any dispersant agent. The volume fraction used was in the range of 0.2-0.4%. It was observed that the heat transfer rates were higher using nanofluids rather than the water at low flow rates but at higher flow rate the volume flow rate dominates over the increased conductivity of nanofluids. The wall temp was agreed with the theoretical predictions but in higher flow rates the results did not completely agree. With increase in the volume concentration there is very little increase in pressure drop across the microchannel as compared with the pure water.

**Satish G. Kandlikar** reviewed the literature available and made a thorough study to briefly explain the development in the field of microchannels. This survey article provides a historical perspective of the progress made in understanding the underlying mechanisms in single-phase liquid flow and two-phase flow boiling processes and their use in high heat flux removal applications. Future research directions for (i) further enhancing the single-phase heat transfer performance and (ii) enabling practical implementation of flow boiling in microchannel heat exchangers are outlined. He also stated that in single-phase liquid flow in microchannels, it is now well accepted that the continuum models are applicable.

**Saxena *et al*** has presented the new technique to fabricate microchannels on surfaces with high-speed and by using a multimaterial process, namely, laser induced plasma micromachining (LIPMM). The process has the potential to machine metals, ceramics, polymers, and other transparent, brittle, and hard-to-machine materials. The presented technique uses an optical system to modify the laser spot into the shape of a line, to fabricate microchannels directly without scanning as in the case of a regular circular spot. The process schematics are shown, and micromachining experiments on polished aluminum are discussed. Moreover, it is shown that the depth and width of the channels may be varied by changing process parameters like the pulse energy, pulse frequency, and number of exposures. The productivity of LIPMM has been

enhanced by a factor of 20, by using an optical system to modify the beam focal spot shape and size.

**Zhang *et al*** has taken the two different configurations of multiple microchannel heat sinks, with fluid flow, are investigated for heat removal: straight and U-shaped channel designs. Numerical models are utilized to study the multiphysics behavior in the microchannels and these are validated by comparisons with experimental results. The main focus of this work is on the design and optimization of these systems and to outline the methodology that may be used for other similar thermal systems. Three responses, including thermal resistance, pressure drop, and maximum temperature, are parametrically modeled with respect to various design variables and operating conditions such as dimensions of the channels, total number of channels, and flow rate. The detailed investigations presented in this paper not only provide a comprehensive understanding of the influences of the design variables on the heat transfer performance in both the straight and U-shaped microchannel systems but also offer useful guidelines for the selection of design parameters in the heat sink designs.

**Dylan *et al*** [30] has proposed the thermal design criteria for extraordinary performance of devices cooled by microchannel heat sink. Simple thermal design criteria governing the general placement of components on devices to be cooled by microchannel heat sink are developed and presented. These thermal criteria are not meant to supersede connection and other important design criteria but are intended as a necessary and valuable supplement. Full-scale numerical simulations of a device with a realistic power map cooled by microchannel heat sink prove the effectiveness of the criteria, showing large reduction in maximum operating temperature and harmful temperature gradients. The simulations further show that the device and microchannel heat sink can dissipate a comparatively high amount of power, with little thermal danger, when design considers the criteria developed herein.

**Satish G. Kandlikar** presented the single-phase heat transfer enhancement technique for conventional channels and compact heat exchanges. The major techniques which include flow transition, breakup of boundary layer, entrance region, vibration, electric fields, swirl flow, secondary flow and mixers were discussed in the paper. In the present paper, the applicability of these techniques for single-phase flows in microchannels and Minichannels was evaluated. The

microchannel and minichannels single-phase heat transfer enhancement devices would extend the applicability of single-phase cooling for critical applications.

**Manay et al** [31] in 2012 numerically investigated the heat transfer characteristics and pressure drop of  $\text{Al}_2\text{O}_3$  and  $\text{CuO}$  particles with volume fractions of 0%, 0.5%, 1.0%, 1.5% and 2.0%. The numerically obtained results were matched with literature available. Finite volume method is used to calculate the equations of heat transfer and mixture model was used to simulate the nanofluids flow. Results were represented in the terms of Nusselt number, heat transfer and pressure drop. The agreement of mixture model and Eulerian-Eulerian method was there, this proves the validation of numerical model chosen by author. The presence of particles in the base fluid increases the thermal conductivity remarkably. The Nusselt number increases with increase in particle concentration and Reynolds number.  $\text{CuO}$  provides higher heat transfer than  $\text{Al}_2\text{O}_3$  particles. Also it is observed that adding the particles does not increase the friction factor remarkably. However, friction factor increases but in small proportions. Friction factor decreases with increase in Reynolds number.

**Farsad et al** [32] in 2011 did the numerical simulation of microchannels using nanofluids as cooling agent on commercial software FLUENT. The choose  $22^\circ\text{C}$  as input temperature, with 1 bar input pressure having volumetric flow rate of 0.3ml/min with velocity of 0.212 m/s. the concentrations employed are 0%, 2%, 4%, 6%, 8% of  $\text{Al}_2\text{O}_3$ . The results show that heat transfer coefficient increases with increase in volumetric flow rates. Heat transfer increases with increase in concentration. The thermal performance with metals increased as compared to their oxide counter parts.

**Mohammed et al** [33] in 2011 performed the experiment with triangular microchannels using different nanofluids at the concentration of 2%. They performed experiments with diamond  $\text{Al}_2\text{O}_3$ , Ag,  $\text{CuO}$ ,  $\text{TiO}_2$ ,  $\text{SiO}_2$ . They found the following results with their experiments: diamond has highest heat transfer coefficients and alumina nanofluids have lowest heat transfer coefficients. Copper oxide and titanium dioxide has almost same heat transfer coefficient. With nanofluids there was slight drop in pressure. Silicon dioxide nanofluids exhibits highest pressure drop, while Ag- $\text{H}_2\text{O}$  has the least pressure drop. Ag- $\text{H}_2\text{O}$  shows no wall shear stress,  $\text{CuO-H}_2\text{O}$  shows very little wall shear stress; however  $\text{SiO}_2\text{-H}_2\text{O}$  shows highest wall shear stress. Last but

not the least it is concluded that diamond nanoparticles are used to achieve maximum heat transfer coefficient, while Ag nanoparticles recommended where lowest pressure drop is desired.

**Hamid** *et al* [34] in 2011 carried out the simulation on microchannels by using finite volume approach, taking  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  and  $\text{CuO-H}_2\text{O}$  nanofluids as fluid material. The effects of Brownian motion, Reynolds number and volume fraction effect on pumping power, performance index and efficiency of counterflow microchannel heat exchanger (CMHE) was evaluated. It was inferred that performance index and effectiveness of CMHE decreases with increase in Reynolds number. Moreover pumping power becomes more at higher Reynolds number. It was also concluded that pumping power and performance index are insensitive to volume fraction at lower and higher Reynolds number.

**Xi** *et al* [35] in 2008 conducted the experiment on trapezoidal microchannels. The analysis show that the uniformity of flow depends upon the design and shape of inlet manifolds, length and location of inlet and outlet and on inlet volumetric flow rates. The results show that there was significant rise in heat transfer rates in microchannels and this may due to laminar flow in microchannels, fluid-channel wall interactions, conduction and convection heat transfer through walls and within channel respectively.

**Chein** *et al* [36] performed the experimental study using silicon microchannel. The Cu particles were used to make nanofluids. Two geometries of microchannels were used with specification as;  $W_{ch} = W_{fin} = 100 \mu\text{m}$  and  $L_{ch} = 300 \mu\text{m}$ ,  $W_{ch} = W_{fin} = 57 \mu\text{m}$  and  $L_{ch} = 365 \mu\text{m}$ . Because of higher surface to volume ratio it was found that heat transfer performance was greatly increased in both channels when nanofluids were used. Moreover it was also seen there was no significant increase in extra pressure drop due to low concentration and small size of particles.

**Hrishikesh** *et al* [37] presented a study which consist of comprehensive experimental database of thermal conductivity variation with respect to the particle concentration, nanoparticle material, base fluid, particle size, temperature. Here only temperature variation is shown, like wise many other parameters were also evaluated. And it was found that particle size has effect on thermal conductivity, it increases almost inversely with the reduction in particle size. The small part of extensive data is shown here:

Particle material	Base liquid	Temp ( <sup>0</sup> C)	Particle size (nm)	Particle volume fraction (%)	Enhancement (%)	Enhancement predicted by Hamilton-Crosser model
Al <sub>2</sub> O <sub>3</sub>	Ethylene glycol	20	11	1	11.2	2.95
		30	11	1	12.5	2.95
		40	11	1	14	2.94
		50	11	1	16	2.94

Table 2.2: Results of Hrishikesh *et al*

Temperature increment increases the thermal conductivity of nanofluids. It also seen that thermal conductivity of nanofluids is relatively higher at lower volume fractions. The thermal conductivity of metal particles is higher than that of their oxides counterparts.

**Tannaz *et al*** [38] in 2009 performed experiments on silicon microchannels. The aim of their study was found out the effect of channel geometry on heat transfer coefficient. They fabricated seven different microchannels sections ranging their width from 100 to 5850  $\mu\text{m}$ , with depth same for all channels of 400 $\mu\text{m}$ . The fluid used was dielectric Fluorinert FC-77. It was seen that heat transfer coefficient is independent of channel width above 400  $\mu\text{m}$ , with similar flow regimes in these channels. Also the flow nucleate boiling behavior was also investigated in new type of microchannels with depths ranging from 100-250 $\mu\text{m}$ , width ranging from 100 to 1000 $\mu\text{m}$ . the study showed that cross sectional geometry of channels effects the boiling mechanisms and heat transfer coefficients in microchannels. The cross sectional area of 0.089  $\text{mm}^2$  or larger, nucleate flow boiling dominants and goes upto very high heat fluxes resulting in independence of heat transfer coefficient on channel geometry and dimension.

**Manay *et al*** [39] in 2016, conducted the experiments to study the effect of microchannel height on performance of nanofluids. They used TiO<sub>2</sub> particles and made five concentrations of 0.25%, 0.5%, 1.0%, 1.5%, 2.0% and keeping the microchannel heights of 200,300,400 and 500 $\mu\text{m}$ . a constant heat flux of 80 $\text{kw}/\text{m}^2$  was applied to the channels. In experiments it was found that an

increase in height of microchannels decreases the heat transfer coefficient and increases pressure drop. Also it was concluded that nanoparticle  $\text{TiO}_2$  do not cause excessive pressure drop as compared to water. Also heat transfer coefficient increases with increase in volume fraction.

**Wu et al** [40] in 2016, numerically investigated the effect of  $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$  nanofluids in improving the overall performance of microchannels heat exchanger. They found that alumina-water nanofluids decrease thermal resistance and increase the heat transfer coefficient. Decrease in volume specific heat capacity degrades the heat transfer benefit due to increase in thermal conductivity of alumina nanofluids. At higher inlet velocities the pumping power increases. At last it was concluded that alumina-water nanofluids is good choice for using as coolant in microchannels.

**Solovitz et al** [41] predicted an analytical model to optimize the manifold design of microchannels. They found the non-uniformity of flow in the microchannels and analytical model was given to optimize the manifold design to get almost uniform flow in the channels from entry to exit. They found the speed of laminar flow is uniformly distributed in the channel with standard deviation of 3% of overall mean velocity; however it was also seen that at higher Reynolds number some mal-distribution of velocities has been seen. New tapered design was suggested to lessen the mal-distribution of velocities due to irregular manifold designs.

**Chein et al** [42] numerically investigated the effects of inlet/outlet manifold positioning on flow behavior and temperature distribution. Finite volume method was incorporated by the author and computational domain is taken entire heat sink. All the inlet/outlet manifolds have same dimensions except the position of each set. They used averaged velocities and fluid temperature to quantify the temperature distribution and fluid flow in microchannels. They found that better uniformities are in arrangement, when coolant is supplied and exit vertically to the surface of manifolds.

**Xuan et al.** measured the thermal conductivity of  $\text{Cu}/\text{water}$  nanofluids with hot wire method. They studied the effect of various parameters such as particle volume fraction, size and properties of nanoparticles on the thermal conductivity and revealed that thermal conductivity was highly dependent on these parameters. They concluded that for 2.5 % to 7.5 % nanoparticle volume fraction, the thermal conductivity was increased by factor of 1.24 to 1.78.

# Chapter 3

## Experimental setup and methodology

Literature has revealed that nanofluids have greater thermal conductivity than water, oil and ethylene glycol; this is because of metals at have higher conductivity than these coolants. So far a lot of research has been done on nanofluids and microchannels, but little work has been done experimentally. Many researchers did numerical investigation and computational work on the behavior of thermal properties and flow behavior. However the field of microchannel has witnessed even lesser research than nanofluids. Experimental work was done in which microchannels were used as heat exchangers to dissipate heat at higher rates from small spaces. In research presented here, experimental work was carried out using microchannels as heat exchangers and nanofluids as coolant.  $Al_2O_3$  particles were used to make nanofluids by two-step method and aluminum microchannels were fabricated with CNC wire cutting. The effect on thermophysical performance of aluminum microchannels with alumina nanofluids has been investigated by making an appropriate experimental setup, which was entirely designed at the Thapar University and fabricated in Amabala, Haryana. The pictorial view of which is shown in Figure 3.1.

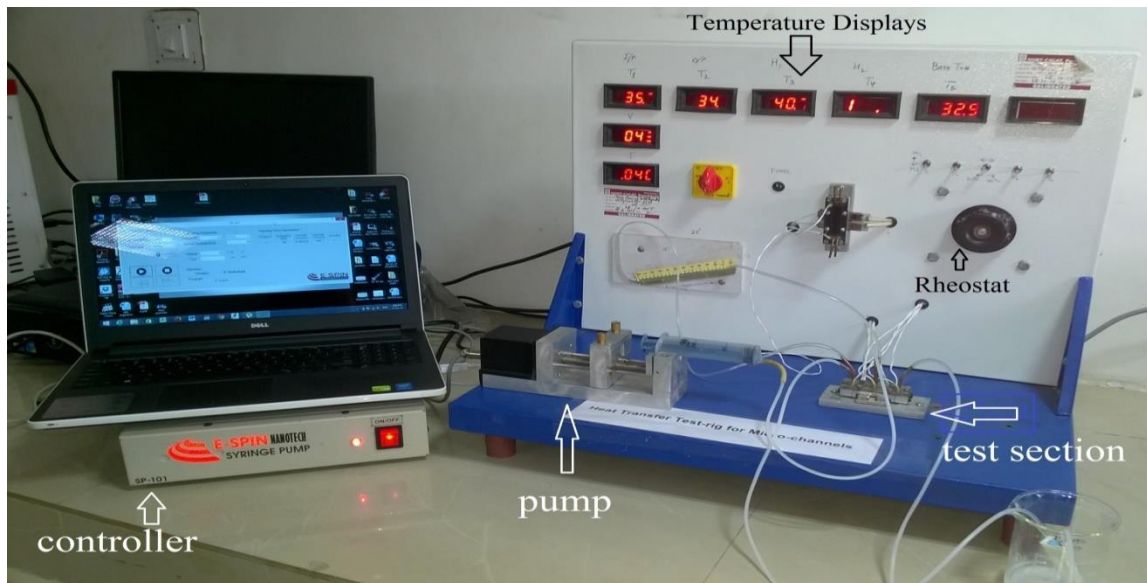


Figure 3.1: Experimental Setup

### 3.1 Layout of experimental setup

Experimental setup was made by taking the idea from the literature studied to investigate heat dissipation capacity of microchannels using  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids [10]. Experimental setup was fabricated by Global Instrument Company, Ambala, Haryana. Experimental setup consist of microchannels, syringe pump, syringe, PT-100 temperature sensors, temperature displays, heater, voltage and current display, reservoir, inclined manometer, controller system of syringe pump, computer. Figure 3.2 shows the layout of fabricated setup. Flow rate through the setup was regulated by the computer controlled syringe pumps, as syringe pumps are highly accurate there is no need of installing any flow meter in flow passage to double check the flow rate. The given heat to the microchannels is regulated by varying the current and voltage to the heater with the help of a dimmerstat. By regulating current and voltage power supply to the heater the heat generated by the heater can be regulated. A reservoir is used to collect heat extracted nanofluids which has passed from microchannels. The whole setup is single pass flow type; however there is also a provision to make the whole experiment in continuous flow system, with the help of controllers and another assembly of pumps. The major problem comes in fabrication is leakages in microchannel and upper acrylic covering which was rectified by applying grease paper in between microchannels and top acrylic sheet and tighten it by six screws. However, another method like putting rubber sheet between microchannels and the transparent acrylic sheet: acting like an adiabatic wall over the top surface of microchannels. Temperature sensors  $T_1$ ,  $T_2$ ,  $T_3$  are inlet and outlet temperature sensors,  $T_4$  is temperature of bottom wall which is in contact with heater.  $T_5$  shows the temperature of nanofluids collected in reservoir.

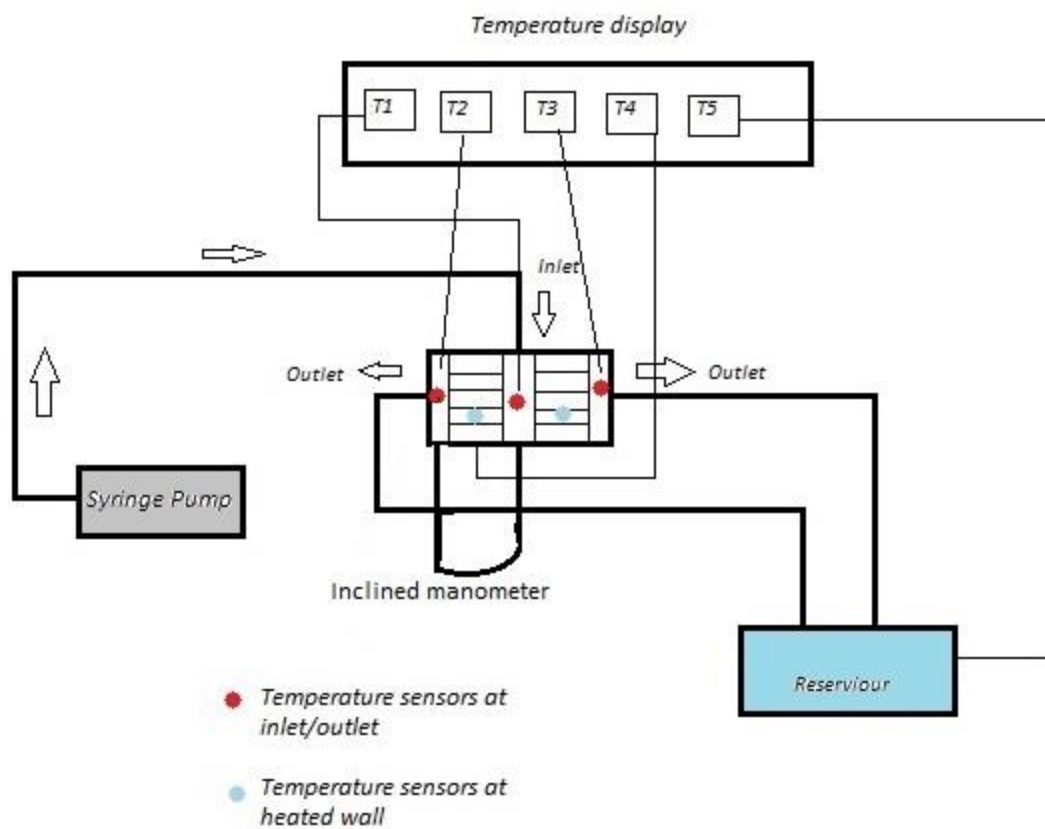


Figure 3.2: Layout of Experimental Setup

## 3.2 Specification and function of various equipments

Equipments used in experimentation and preparation of nanofluids are discussed below.

### 3.2.1 Syringe pump

Pumps are the major component in the setup since they are the driving force in an experiment. The accuracy of pumps is the utmost consideration in accuracy of overall experiment. Here the pumps used are syringe pump. Due to very low flow rate required in microchannels, syringe pumps have been selected for the purpose of pumping. Also to incorporate any flow meter in the flow passage can disturb the distribution and concentration of nanofluids used. Highly accurate syringe pumps purchased from E-Spin Nanotech, IIT Kanpur, Uttar Pradesh has been used here. The specification of pumps is as follows:

CONFIGURATION	
Type of pass	Single pass
Syringe diameter	20 mm
Maximum flow rate (with 20 ml syringe)	2 ml/min
Control unit	Separated <ol style="list-style-type: none"> <li>1. USB to serial cable</li> <li>2. Serial converter</li> <li>3. Serial cable ( for connecting syringe pump controller to RS-232 converter)</li> <li>4. Syringe pump controller</li> <li>5. 4 pin connector</li> </ol>
Syringe	20 ml
Voltage	220 V, AC, 50 Hz

Table 3.1: Configurations of Syringe pump

Figure 3.3 shows the syringe pump, Figure 3.4 shows different components of the syringe pump assembly and Figure 3.5 shows the connection assembly of whole of syringe pump drive. The syringe pumps software is installed in computer and correct connections were made as shown in Figure 3.5. In the software (SP-101) input parameters like baud rate, flow rate, syringe diameter and infusion/withdrawal are entered. The software calculates the rpm of motor of syringe pump required for desired flow rate and signals are sent to the controller. Control is connected to the motor of syringe pump, which regulate the rpm of motor.

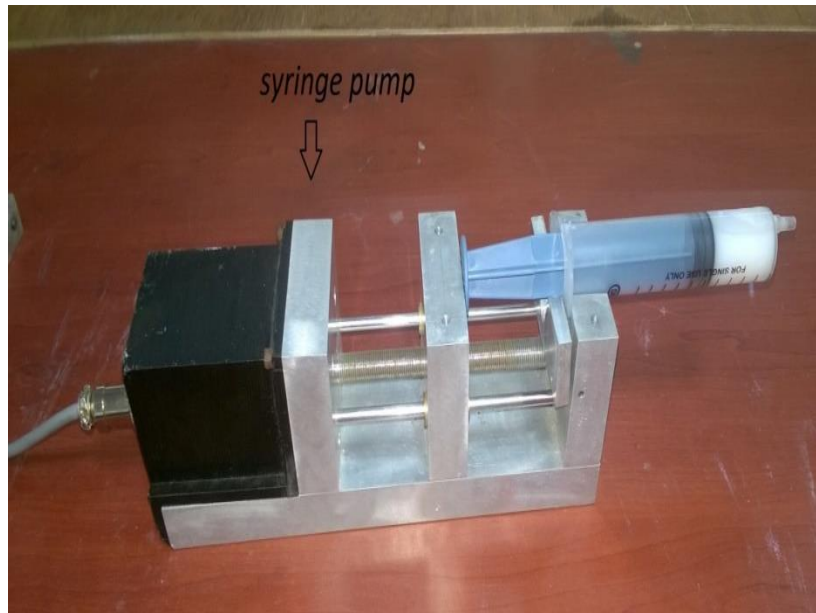


Figure 3.3: Syringe pump

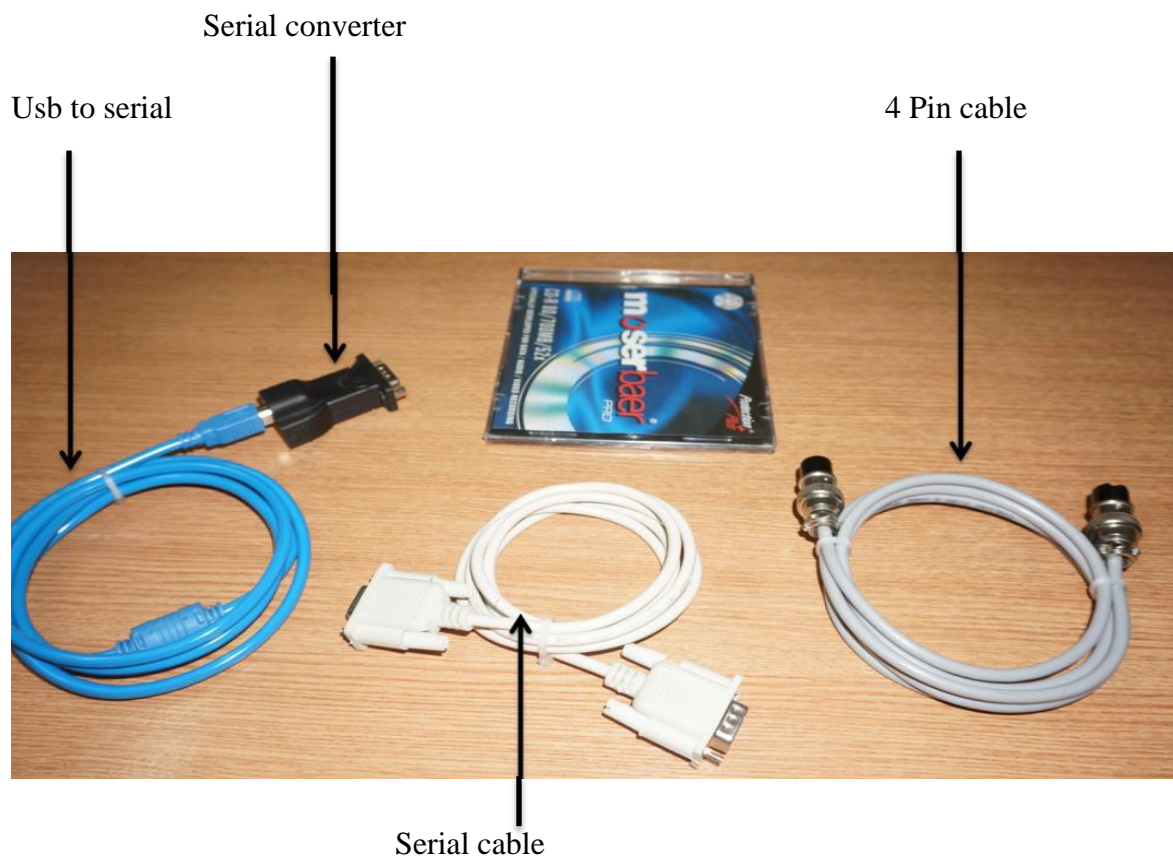


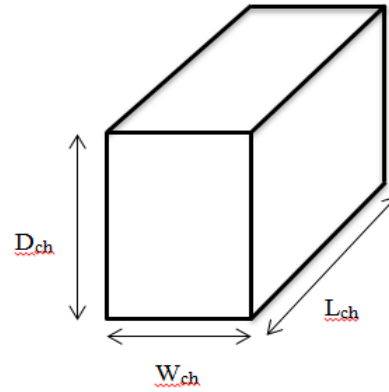
Figure 3.4: Components of the syringe pump assembly



Figure 3.5: Connection assembly

### 3.2.2 Microchannels

Microchannels are the passages with hydraulic diameters ranging from 10-200  $\mu\text{m}$ . Rectangular microchannels with dimensions  $W_{\text{ch}}$ ,  $D_{\text{ch}}$ ,  $L_{\text{ch}}$  as 25 $\mu\text{m}$ , 2000 $\mu\text{m}$  and 2cm respectively. Microchannels as discussed above can be made by many methods, here CNC wire cutting method has been adopted on aluminium microchannels having split type flow passage. Microchannels assembly is fitted with three temperature sensors, one at inlet and other two at two outlets. Beneath the microchannels a low capacity heater is fitted to heat the microchannels. To make the upper surface as adiabatic wall, acrylic sheet has been used with grease paper to make it leak proof. However other methods like using rubber sheet between channels upper surface and acrylic sheet can be used. Figure 3.6 show the microchannels dimensions and actual microchannels picture used in experiment. Pressure manometer is also connected to microchannels assembly half way because flow passage is half way in the microchannels and is symmetrical in both directions.



(a)

(b)

Figure 3.6: Microchannels section, (a) actual (b) geometrical

The dimensions of microchannels are given in the Table 3.1

$D_{ch}$	$W_{ch}$	$L_{ch}$	Number of channels
2mm	0.25mm	20mm (each side)	14

Table 3.2: Geometric Dimensions of microchannels

However, the main constraint in manufacturing of microchannels is the economical manufacturing facility in the nearby areas of Patiala. By investing time in searching the economical facility; CNC wire cut was found to be economical and less time consuming and available in nearby area within 80 km of Patiala. The least dimension of microchannel which can be made with the help of CNC wire cutting is 0.25mm. Hence the width gets fixed due to manufacturing constraint of wire and machining facility. Since CNC wire cutting can only produce rectangular cross sectional, hence shape of microchannel is selected. From Kandlikar et al [43] microchannels with aspect ratio of 8 shows maximum convective heat transfer, hence the depth of 2mm is selected.

The minimum size of pipe for inlet and outlet manifolds available in market is 2.5 mm. This constraint of pipe diameter has fixed the width of inlet and outlet plenums. However, three holes in the acrylic sheet for insertion of temperature sensor, inlet/outlet manifold and pressure manometer which should have considerable amount at least 1.5 mm if sheet material between them to avoid the leakages from these points. Hence the length of plenums is kept 15mm.

### 3.2.3 Heaters

A low wattage heaters are used to heat the microchannels is placed under microchannels with base of asbestos sheet, to prevent the heat loss to the base material. 35 W heaters with the variate have been used to regulate the heat to the microchannels. These low wattage heaters can maintain the temperature upto 40<sup>0</sup>C as required in the experiment. The power of heater can be increased by using rotary variate and temperature can be raised upto 100<sup>0</sup>C easily. Low power heaters with variable variate are used to double sure that temperature should not raise upto boiling point of water.

### 3.2.4 Temperature sensors

Highly sensitive PT-100 temperature sensors are used in the experiment; the total six sensors were used three for flow temperature measurement, two for heated base wall temperature, and one to measure the temperature of nanofluids at the reservoir. Pt-100 sensors work on principle of resistance thermometers, with change in temperature the resistivity of element changes, this change in resistivity correlates to the temperature change of fluid. Pt-100 sensors are used over thermocouples because of their higher accuracy and quick response time than thermocouples. In Pt-100 'Pt' stands for platinum and 100 stands for the resistance 100 $\Omega$  at 0<sup>0</sup>C. Another model Pt-1000 is also available in the market. Figure 3.7 shows the actual position of pt-100 sensors in microchannels.

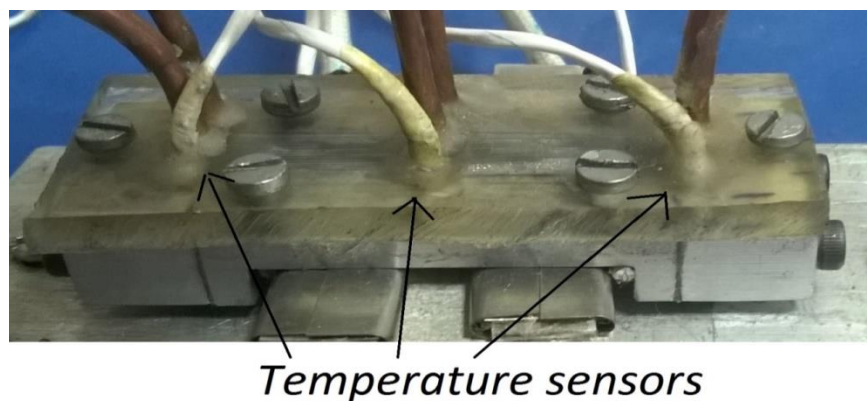


Figure 3.7: Pt-100 Temperature sensors

### 3.2.5 Calibration

Since there is no flow meter in the experimental setup, hence the calibration works reduces a lot. The calibration of temperature sensors was done by NIIRT-Centre for Calibration, Analysis, and Testing, Industrial area, Panchkula, Haryana. Figure 3.8 shows the stamp for calibration on the experimental setup.



Figure 3.8: Calibration certificate

### 3.3 Nanofluids Preparation Methodology

Nanofluids are prepared by two methods: one step method and two-step method. We have used two-step method because of its ease. Two-step method involves first preparing of nanoparticles and then dispersing them into the base fluid. The Aluminium oxide nanoparticles are purchased from Nanoshell Technologies, specification of particles is given in Table 4.

Particles used	Aluminium oxide
Appearance	White
Morphology	Spherical
Purity	99.9+%
Average particle size	Less than 80 nm
Thermal conductivity	36 W/mk

Table 3.3: Specifications of nanoparticles

SEM (spectral electron microscopy) was done on nanoparticles in SAI labs at Thapar University. The report of which is shown in Figure 3.9. In SEM 80 nm size has been detected.

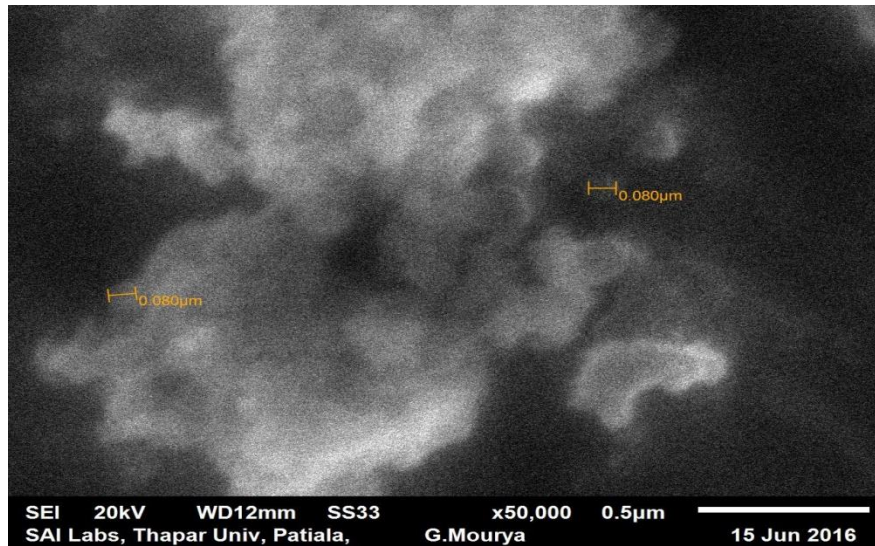


Figure 3.9: SEM

In present work double distilled water was used as base fluid in which nanoparticles were dispersed slowly. Four concentrations are chosen for experimental work: 0%, 0.1%, 0.25%, 0.5% at four different flow rates: 0.5 ml/min, 1.0 ml/min, 1.5 ml/min, and 2.0 ml/min. No surfactants were used in nanofluids as they affect the thermophysical properties of nanofluids. Also the  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  is stable for longer time and experiments can be done very easily with them. To make nanofluids more stable they are dipped in sonicator bath for 90 minutes. Followings steps were taken to make nanofluids.

### 3.3.1 Apparatus required

1. Two beakers (150ml each).
2. Spatula
3. Magnetic bead
4. Hot plate magnetic stirrer
5. Measuring flask
6. Ultrasonicator water bath.

Figure 3.10 and 3.11 shows the picture of these equipments used.



Figure 3.10: Apparatus required



(a)



(b)

Figure 3.11: (a) Magnetic stirrer, (b) Ultrasonic vibrator

The amount of alumina powder required was measured by using the formula given in following articles. Highly accurate precision weighing machine was used to measure the actual weight of particles used. Measured quantity (by measuring flask) of double distilled water was taken into beaker and kept on hot plate magnetic stirrer with magnetic bead dipped in it. Hot plate magnetic stirrer was switched on with temperature being kept at room temperature. The main precautions to be taken while pouring the particles into beaker are:

1. Check the temperature of base plate it should not raise high, as high temperature effects the stability and agglomeration of nanoparticles.
2. Always pour nanoparticles very slowly with small quantity into beaker. Do not pour them all in single go, as it can make agglomerations in the water nanoparticles should be poured in very less amount and then wait should be done to get those particles dissolved fully till next pouring.

After 20 minute magnetic stirring, nanofluids are taken for sonication in ultrasonic bath where 90 minutes sonication was done in view to make nanofluids more stable for longer time. Precautions are to be taken at sonication, since there is specified level of water in sonication bath; hence the care should be taken to fill the sonication bath upto the level specified in it. Secondly the temperature of water increases with sonication time. Higher temperature affects the stability and uniform dispersion of nanofluids. At higher temperature nanoparticles start to coagulate and settle down. Hence water level and temperature are the major factors to be considered during sonication. After sonication of 90 minutes nanofluids are now ready to use in experimentation.

### **3.3.2 Measurement of thermal conductivity**

Thermal conductivity was measured by KD2 Pro conductimeter. KD2 Pro measures the thermal conductivity by transient hot wire technique. A thin metallic wire is immersed in fluid whose temperature is to be measured. Transient hot wire techniques works on temperature/time response of wire for electrical signal pulse. To reduce the convective heat transfer inside the flask, needle should be kept vertical. To increase the accuracy of measurement any type of vibration and disturbance to the wire probe should be avoided. A gap of 5 minutes should be taken in two consecutive readings to make needle in equilibrium with environment, so it should not affect next readings.

KD2 Pro consists of a measuring needle and manually controlled micro-controller. KS-1 needle has the accuracy of  $\pm 5\%$ , used to measure the conductivity of nanofluids. One experiment cycle was completed in 90 seconds. The temperature of nanofluids was controlled by placing them in thermal bath, at Thapar University, Patiala. KD2 Pro based on following equation to calculate thermal conductivity.

$$k = \frac{q(\ln t_2 - \ln t_1)}{4\pi(\Delta T_2 - \Delta T_1)}$$

Where  $k$  is the thermal conductivity,  $q$  is the constant heat rate supplied.  $\Delta T_1$  and  $\Delta T_2$  are the temperature change at  $t_1$  and  $t_2$  time respectively. Figure 3.12 shows the picture of KD2 Pro. The test sample was poured in its glass tube; sensor needle was inserted in this glass tube. It is very important to ensure the vertical position of sensor needle, to minimize the convective heat transfer inside the glass tube. To carry out measurement at high temperatures the glass tube is inserted in thermostatic bath where temperature was controlled digitally. To reduce the free convection inside the tube the temperature difference of sensor needle temperature and fluid inside the tube it is to be taken care of.

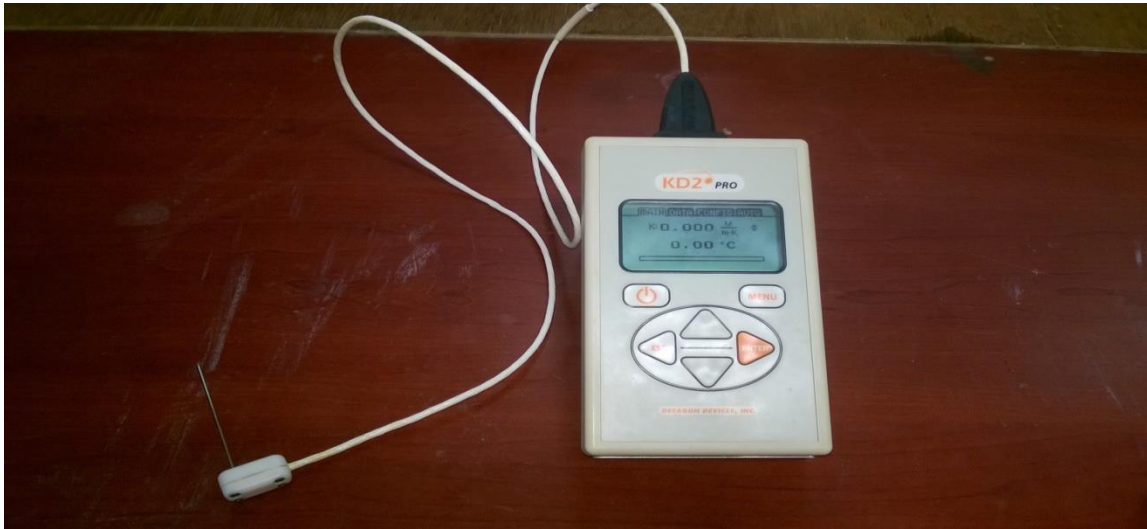


Figure 3.12: KD2-Pro Conductimeter.

It is also known that heat conductance is inversely proportional to characteristic dimension of probe hence it is important to make the probe stand vertically with no vibration and disturbance in it.

### 3.3.3 Measurement of viscosity

Viscosity of nanofluids is measured at different temperature ranging from 25<sup>0</sup> C to 50<sup>0</sup> C by using Brookfield viscometer DV II+ PRO, available at Thapar University. Viscometer measures viscosity by rotating spindle in fluid. The concept of two cylinders is used in viscometer with inner rotating cylinder and stationery outer cylinder, the gap between cylinders is filled with fluid. The torque required by the spindle to rotate is calculated and by calibrated spring which is connected to rotary transducer measures the viscous drag. By Brookfield viscometer viscosity is measured in Centipoise. Other factors like shear stress, shear rate etc. are also measured by this device.

Results obtained were compared with Einstein model [44] given as

$$\mu_{nf} = \mu_f \frac{1}{(1-\phi)^{2.5}}$$

Where  $\mu_{nf}$  is viscosity of nanofluids,  $\mu_f$  is viscosity of base fluid and  $\phi$  is nanofluid concentration



Figure 3.13: Brookfield Viscometer

### 3.4 Methodology

As described earlier experimental setup consist of microchannels, syringe pump, and other useful accessories. A cluster of single pass microchannels made on single piece of aluminium equipped with 3 temperature sensors are the main area of interest upon which study was conducted. To study the effects of nanofluids upon simple base fluid firstly experiments were performed with distilled water and then fluid was replaced with  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids. Main parameters in this study were concentration of nanofluids, flow inlet velocity. These are two main parameters in the study and numerical values of which is tabulated in Table 3.4. Flow rate was metered with high accuracy and precise computer controlled syringe pumps. There is no need of any flow measurement device in the flow passage.

Flow rate of fluid (ml/min)	0.5	1.0	1.5	2.0
Concentration of nanofluids ( $\phi$ )(%, vol)	0	0.1	0.25	0.50

Table 3.4: Parameters to be varied

Uniform flow from both sides of microchannels was ensured by height adjustment of outlet flow pipes. Temperature sensors were placed at different positions within microchannel: one at inlet plenum, two at both outlet plenums and two beneath the microchannel. The heating power of heaters, which were placed beneath the microchannels, is controlled by dimmerstat. Experiments were performed in following manner:

1. First the power supply was on and adjusted with dimmerstat.
2. Inlet and outlet fluid temperatures were measured by Pt-100 temperature sensors.
3. Flow rate of fluid was controlled by computer controlled syringe pump.
4. Double distilled water was taken, to avoid any corrosion and scaling on microchannels surface, in syringe and fitted on the pump. Experiment was run and reading of temperatures at inlet, outlet, bottom wall were noted (for all concentrations), readings of concentration 0.5% are shown in table 5.

5. Flow rate was increased in ascending order i.e. first experiment was done with 0.5 ml/min, then with 1.0, 1.5, 2.0 ml/min.
6. Experiments were run till the steady state was reached. 20 ml syringe is sufficient for flow rates upto 1.0 ml/min to reach steady state. For 1.5 and 2.0ml/min flow rates 50 ml syringe was used.
7. Temperatures were measured at different flow rates at single concentration, starting with 0%.
8. Now steps 4 to 7 were repeated by replacing double distilled water with 0.1%, 0.25%, 0.5% (vol.) aluminium oxide and water nanofluids.

### 3.5 Equations used

Experimental calculations were done for finding heat transfer coefficient for microchannels and then comparison is carried out with different fluids in similar conditions. Thermo physical properties like density, specific heat capacity, thermal conductivity, dynamic viscosity were taken at bulk mean temperature. The following equations have been used for the calculations:

Hydraulic diameter is the first parameter to be calculated to decide other parameters in microchannels and it is given by

$$D_h = \frac{4A_c}{P}$$

Where  $A_c$  is area of cross section,  $P$  is perimeter of microchannels.

Reynolds number represents the ratio of inertial force to the viscous force and is given by equation

$$Re = \frac{v * D_h}{\vartheta}$$

Here  $v$  is average velocity of flow inside microchannel,  $\vartheta$  is kinematic viscosity,  $v$  the average velocity of working fluid is obtained from following equation

$$v = \frac{\dot{m}}{N\rho A_c}$$

Here N is total number of microchannels;  $\rho$  is density of working fluid.

Q is the total heat removed by the fluid and is given as

$$Q = \dot{m}C_p(T_o - T_i)$$

Where  $C_p$  is the specific heat capacity of fluid,  $T_o$  is outlet temperature and  $T_i$  is the inlet temperature of fluid.

In order to calculate heat transfer coefficient for microchannels; mean temperature difference between walls and fluid flowing is to be known, which is obtained as

$$\Delta T_m = \frac{1}{5}(T_1 + T_2 + T_3 + T_4 + T_5) - \frac{1}{2}(T_i + T_o)$$

Where  $T_1, T_2, T_3, T_4, T_5$  are the temperatures measured by temperature sensors at different locations in microchannels.  $T_1$  is the temperature measured by sensor at inlet plenum wall.  $T_2, T_3$  are temperature at left and right plenum walls.  $T_4, T_5$  are the temperatures at bottom wall of microchannels.

Heat transfer coefficient in this study has been calculated by using the equation

$$h = \frac{Q}{N * A_w * \Delta T_m}$$

Where h is convective heat transfer coefficient,  $A_w$  is the area of heat transfer which is total area from where heat transfer is going on.

Since we are having two side flow in microchannels hence the overall heat transfer coefficient (U) is given as.

$$\frac{1}{UA} = \frac{1}{h_1A_1} + \frac{1}{h_2A_2}$$

Where A is the total heat transfer area,  $h_1$  is the heat transfer coefficient of one side,  $h_2$  is the heat transfer coefficient of another side,  $A_1, A_2$  is heat transfer areas of sides respectively.

Thermo physical properties of nanofluids; density, thermal conductivity, specific heat, dynamic viscosity are measured by using following formulas:

1. Density [9]

$$\rho_{nf} = (1 - \varphi)\rho_f + \varphi\rho_p$$

2. Specific heat [9]

$$(\rho C_p)_{nf} = (1 - \varphi)(\rho C_p)_f + \varphi(\rho C_p)_p$$

3. Dynamic viscosity [9]

$$\mu_{nf} = \mu_f \frac{1}{(1 - \varphi)^{2.5}}$$

4. Thermal conductivity [9]

$$k_{nf} = \frac{k_p + 2k_f + 2(k_p - k_f)\varphi}{k_p + 2k_f - (k_p - k_f)\varphi} k_f$$

Where  $\rho$  is the density,  $\varphi$  is particle volume fraction,  $\mu$  is dynamic viscosity,  $k$  is thermal conductivity. Subscripts p, nf, f stands for particle, nanofluids and base fluid respectively, all other symbols carry their usual meaning. Thermo physical properties of nanofluids are tabulated in Table 3.5.

Temperature, T (°C)	Particle volume fraction, $\varphi$ (%)	Density, $\rho$ (kg m <sup>-3</sup> )	Thermal conductivity, k (Wm <sup>-1</sup> K <sup>-1</sup> )	Viscosity, $\mu$ (kgm <sup>-1</sup> s <sup>-1</sup> )	Specific heat, C <sub>p</sub> (Jkg <sup>-1</sup> K <sup>-1</sup> )	Pr
30	0	995.8	0.618	0.00077	4178	5.02
30	0.10	998.67	0.622	0.00086	4165	5.38
30	0.25	1002.98	0.64	0.00091	4174	5.85
30	0.5	1010.17	0.653	0.00099	4112.46	6.23

Table 3.5: Thermophysical properties of nanofluids

Nusselt number represents the ratio of convective heat transfer rate to convective heat transfer given as

$$Nu = \frac{hD_h}{k}$$

Prandtl number ratio of momentum diffusivity to thermal diffusivity, is given as

$$Pr = \frac{\mu C_p}{k}$$

On calculations, the values of parameters are as obtained:

$$D_h = 0.4445\text{mm}$$

Reynolds number (Re) and other parameters which are dependent on flow rate are given in Table 3.5, which shows the values at 0.5% vol concentration.

Flow (ml/min)	Flow Velocity (m/s)	U (W/m <sup>2</sup> k)	Re	Pr
0.5	0.00595	7.12	3.62	5.02
1.0	0.01185	13.35	7.203	5.6
1.5	0.01785	24.373	10.6	5.85
2.0	0.02378	35	13.3	6.23

Table 3.6: Value of parameters, (0.5%, vol).

# Chapter 4

## Results and discussions

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Thermophysical quantities like thermal conductivity and viscosity of nanofluids are measured for different concentrations to study their effect with particle volume fraction. However the effect of temperature on density was also measured in temperature range from 25° C to 50°C. Effect of Reynolds number, Nusselt number, particle volume concentration is studied for convective heat coefficient. Results are shown with the aid of graphs with appropriate reason

### 4.1 Thermal conductivity

From the available literature it has been noticed that thermal conductivity is the most studied property of nanofluids. Thermal conductivity of nanofluids at various concentrations was measured and shown in Figure 23. From figure it is seen that thermal conductivity of nanofluids increases with increase in concentration. With respect to pure water (0%,vol.) thermal conductivity increase by 0.585%, 3.5%, 5.65% for 0.1%, 0.25%, 0.5% vol. concentration respectively. Pak and Cho [45] and Eastman et al [46] studied the effect on thermal conductivity of Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O and alumina-ethylene glycol and found the increment in thermal conductivity of nanofluids than the base fluid. Kamaldeep et al [47] investigated the effect of temperature on thermal conductivity of nanofluids and found that with increase in temperature thermal conductivity increases for all volume fractions of nanofluids. Thus from these two observations it can be said that thermal conductivity is the function of temperature and concentration. From the review by Yu and Xie [48] it can be suggested that particle size also effects the thermal conductivity of nanofluids. The degree of agglomeration of particles affects the thermal conductivity adversely.

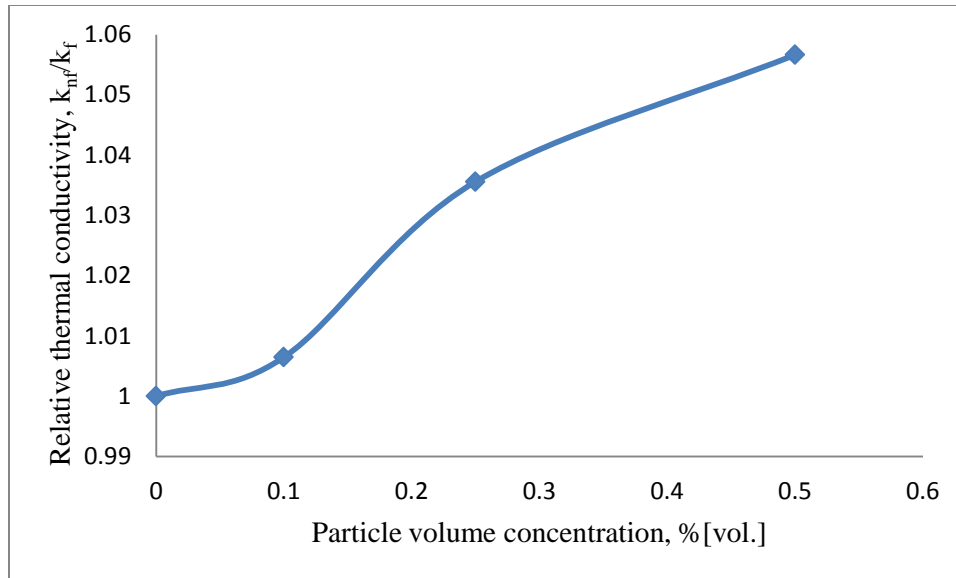


Figure 4.1: Relative thermal conductivity with particle volume concentration

It is seen from the Figure 4.1 that particle concentration of 0.1%,vol. doesn't provide any considerable enhancement in thermal conductivity of nanofluids. To obtain considerable enhancement in thermal conductivity the particle volume concentration was increased, therefore by increasing the particle volume concentration the thermal conductivity increased by 5.65% and this is due to presence of higher number high conductivity nano particles in base fluid and higher number of contacts between the particles.

## 4.2 Viscosity

Very few researchers have worked on viscosity behavior of nanofluids [49] [50]. In this study viscosity of nanofluids was measured at different temperature from 25°C – 50°C and the behavior was studied. It can be seen that with increase in temperature from 25 to 50°C the viscosity decreases because of more Brownian motion among particles due to energy gained by heating. Nanofluids have slightly higher viscosity than pure water due to presence of solid particles in them. However the increase in viscosity was overcome by heat transfer gains by nanofluids. Figure 4.2 shows the comparison of viscosity among pure water, nanofluids, and mathematical value calculated by Newton's model. Kamaldeep et al [47] also studied the effects of temperature on nanofluids and same pattern is observed i.e. with increase in temperature

viscosity of nanofluids decreases and nanofluids shows slight increase in viscosity in comparison to the pure water at same temperature.

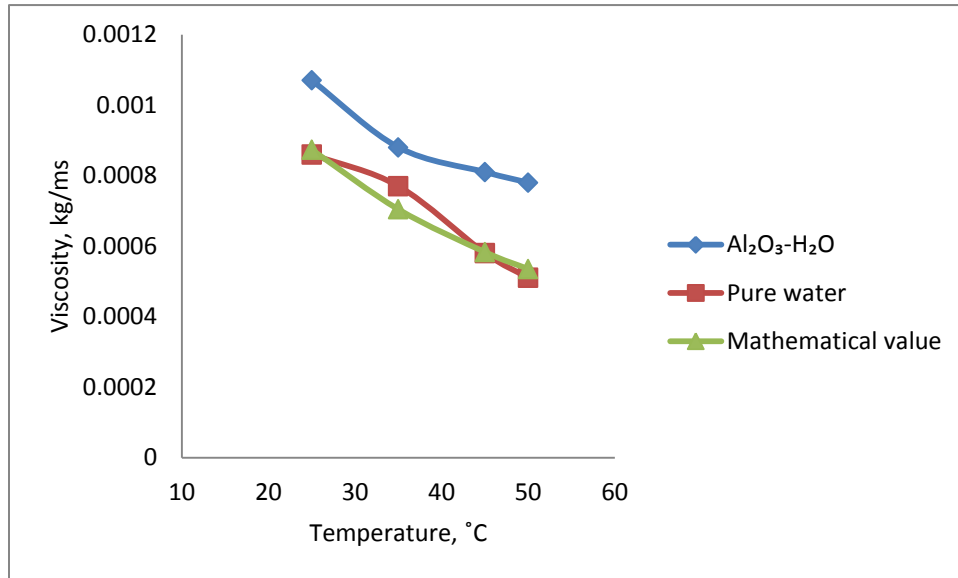


Figure 4.2: Viscosity variation with temperature

Relative viscosity of nanofluids with respect to particle volume concentration was measured. The plot is between relative viscosity and particle volume concentration is shown in Figure 4.3. From figure the obvious trend of viscosity increase with particle volume fraction increases.

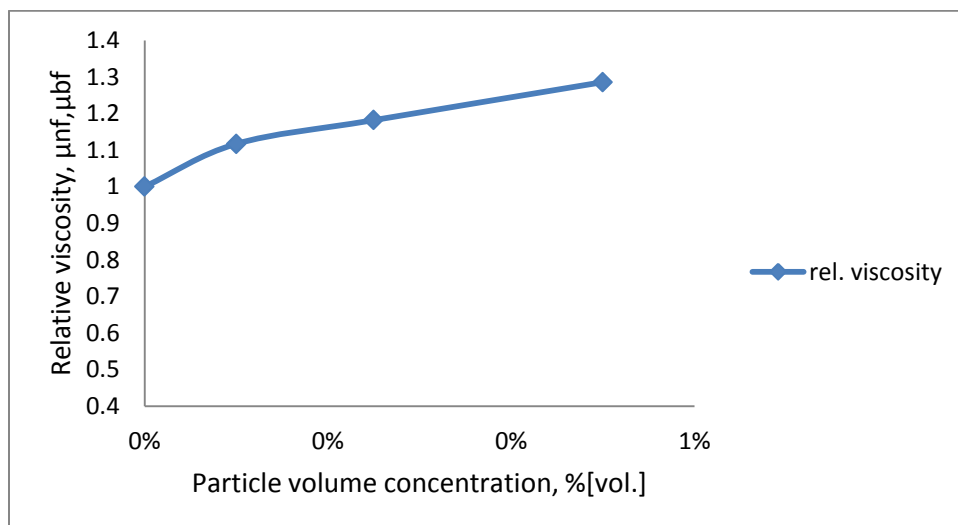


Figure 4.3: Relative viscosity with particle vol. concentration

## 4.3 Heat transfer

### 4.3.1 Heat transfer coefficient

Figure 4.4 shows the plot of heat transfer coefficient versus flow rate in ml/min of pure water and Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O nanofluids. Every effort has been made to increase the convective heat transfer coefficient to increase the heat transfer capacity of the coolant. Heat transfer coefficient can be increased either by increasing the flow velocity in the channels and by increasing the coolant heat carrying capacity. Heat capacity has been increased by using nanoparticles and velocity was increased by using syringe pumps. In split flow type microchannels convective heat transfer coefficient of both the sides was calculated and then the overall heat transfer coefficient was calculated for different flow and for different concentrations of nanofluids. Similar trend was noticed with all concentrations.

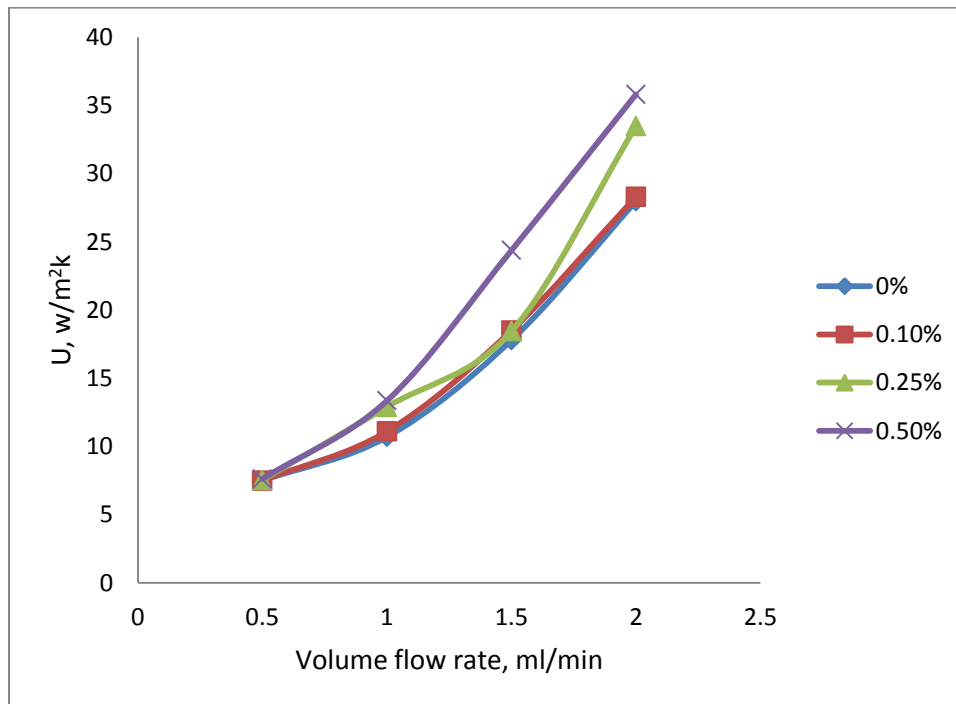


Figure 4.4: Variation of Overall heat coefficient with particle volume concentration

Two major observations were made which are as follows.

1. As flow rate of fluids increases there is an obvious increase in heat transfer coefficient in similar manner as volume flow rate is increasing.
2. At the same volume flow rate the heat transfer coefficient increase with increase in particle volume fraction as compared to pure water. This was due to presence of more number of higher thermal conductivity particles in fluid. As volume flow rate increased from 0.5ml/min to 2ml/min and particle volume concentration is varied from 0% to 0.5%.vol. the heat transfer coefficient is increased by 6.2 - 27%. This clearly shows that convective heat transfer can be enhanced in aluminium microchannels by using  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids instead of pure water.

Hence it is clear that by using nanoparticles in base fluids, an increase in convective heat transfer coefficient can be gained. This further makes the nanofluids feasible to extract more heat in comparison to base fluid with other parameters remaining same. The thermal diffusivity increases with increase in particle concentration which makes nanofluids to extract more heat.

### **4.3.2 Prandtl number**

Prandtl number, Reynolds number these are important function of thermophysical properties of nanofluids, which greatly affect the heat convective heat transfer coefficient. Hence it becomes important to study their variations. Prandtl number is the ratio of momentum diffusivity to the thermal diffusivity of a fluid and it is the only dimensionless number which is a property of fluid and depends on  $\mu$ ,  $C_p$  and  $k$ , which further depends upon temperature and  $\phi$ . Figure 4.5 shows how Prandtl number behaves on adding different fractions of nanoparticles in base fluid. It is seen from the figure that as the particle concentration increases Prandtl number increases for  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids. This backs the utility of nanofluids. From the observations it is seen that by using nanofluids Prandtl number increases by upto 24%. This considerable increase with concentration of 0.5% (vol.) suggests that to get more Prandtl number higher concentrations may be used. With increase in concentration of nanofluids viscosity, thermal conductivity increases but specific heat decreases. The viscosity changes are dominant over all other parameters change, therefore with change in concentration of nanofluids Prandtl number increases, overcoming the increasing effects of thermal conductivity. This suggests that thermal diffusion

increases with increase in concentration of nanofluids. Temperature dependency of nanofluids have been studied by [51]. They took CuO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> nanoparticles at 6% (by vol.) concentration and showed that Prandtl number decreases with increase in temperature (as shown in figure 4.6) because in this case viscosity variation dominates over specific heat capacity and thermal conductivity. This decreases the Prandtl number over temperature increase.

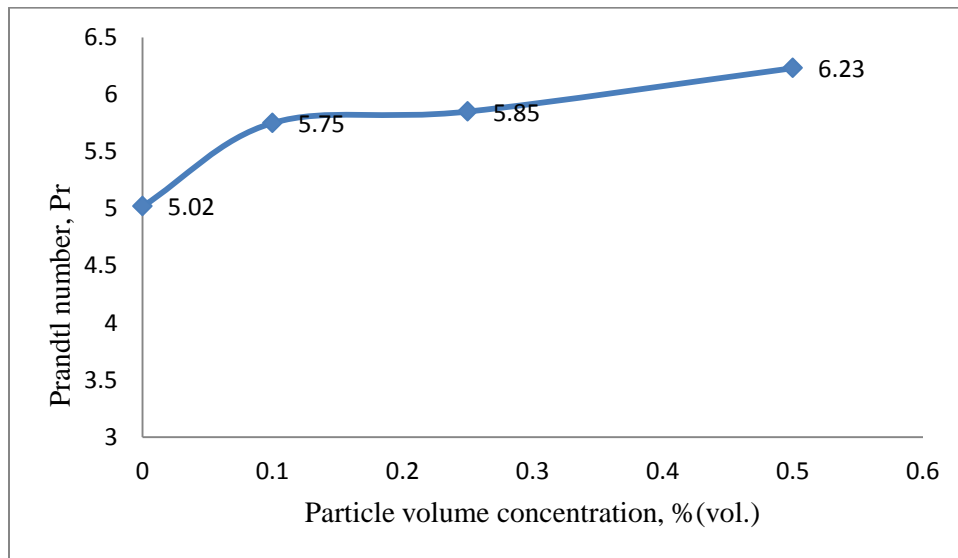


Figure 4.5: Prandtl number variation with particle volume concentration

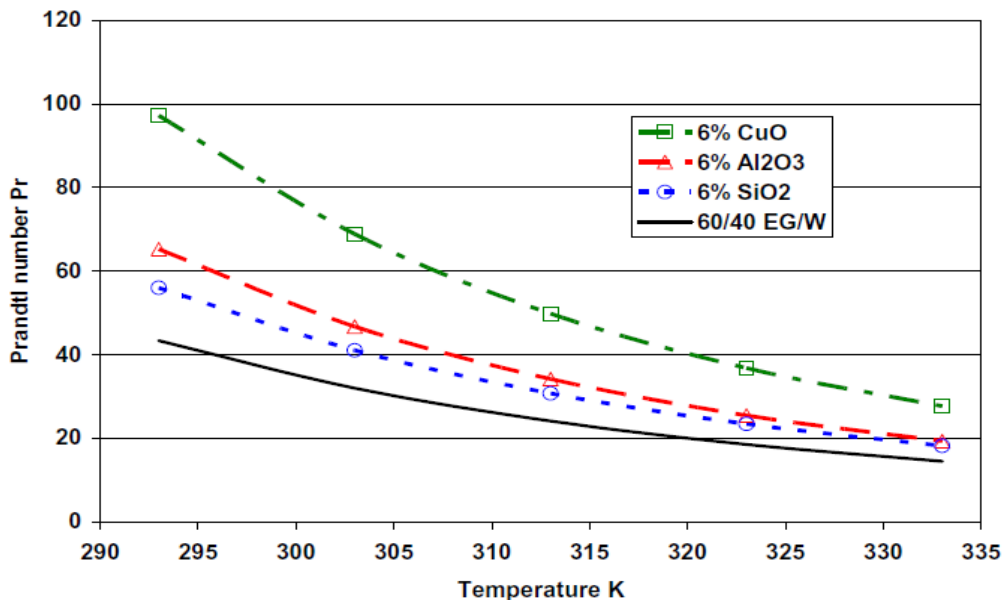


Figure 4.6 : Temperature dependency of Prandtl number [51]

### 4.3.3 Reynolds number

Reynolds number is the ratio of inertial force to the viscous force. The behavior of Reynolds number is studied with different flow rates. Figure 4.7 shows the variation of Reynolds number of different flow rates with particle volume concentration. The diameter and velocity are kept constant for different particle volume concentrations, to ensure same parameters. From the Figure 4.7 it is seen that there is gradual decrease in Reynolds number with increase in particle volume concentration for every flow rate. However maximum drop of 28% is seen for the flow rate of 0.5ml/min and least drop of 185 for 2ml/min flow rate. Increase in particle volume concentration in the base fluid increases viscosity and density of nanofluids. However there is less increase in density and considerable increase in viscosity of nanofluids, the viscous forces increases more than the inertial forces. Therefore at the end there is decrease in Reynolds number with increase in concentration of nanofluids could be encountered.

The analyses under the sections 4.3.2 and 4.3.2 show that thermophysical properties of nanofluids influences the Prandtl number and Reynolds number in contradicting manner. Higher concentrations of nanofluids are better for higher Prandtl number and heat transfers, whereas lower concentrations are desirable for higher Reynolds number to enhance heat transfers. Hence designing the equipment optimization of both the numbers should be done to get better results from nanofluids.

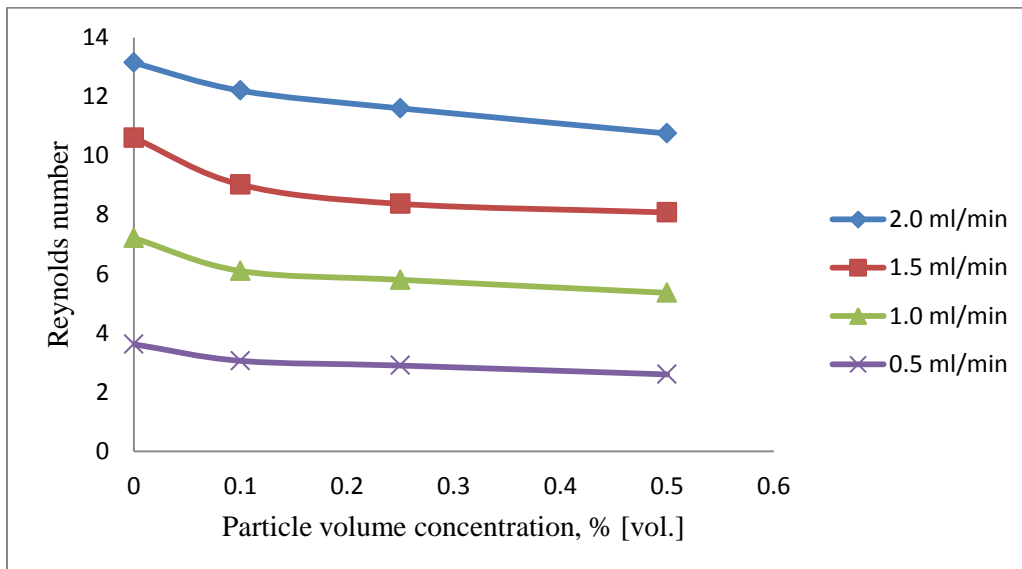


Figure 4.7: Reynolds number variation with concentration

# Chapter 5

## Conclusions

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Experimental work was performed on split flow microchannels to study the effects of  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids on thermophysical properties and performance of microchannels heat sink. Experimental work was performed using distilled water and  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids with different concentrations, 0.1%, 0.25% and 0.5% (vol.) as a coolant in microchannels. Experiments were carried out at 0.5 ml/min, 1.0 ml/min, 1.5 ml/min, 2.0 ml/min flow rates in laminar regime. Following conclusions were made from the experimental work.

### 5.1 Thermophysical properties of nanofluids

- Thermophysical properties of nanofluids got improved in comparison with the pure water. Thermal conductivity of nanoparticles got increased, which is the main focus of every study done on nanofluids. Enhancement of 5.65% with respect to pure water with concentration of 0.5% (vol.) of  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  is reported.
- Viscosity of nanofluids increases with increase in particle volume concentration i.e. least with pure water and maximum with 0.5% concentration. The viscosity increases leads to increase in pumping power. However, with increase in temperature viscosity of nanofluids decreases due to increased Brownian motion in particles.
- Specific heat capacity calculated by model quoted by Wu et al [9] in his research work, and it has been seen nanofluids have lesser specific heat than pure water due to presence of low heat capacity nanoparticles in them. It is also seen that specific heat decreases with increase in concentration of nanofluids.

### 5.2 Performance of microchannels

The performance of microchannels has been studied at different concentrations and at different flow rates. The parameters: heat transfer coefficient, Prandtl number are studied with respect to concentration and Reynolds number. Reynolds number has been kept in laminar regime.

- **Heat transfer coefficient:** the flow rate has been increased from 0.5ml/min to 2 ml/min and concentration is varied from 0.1% to 0.5%. With the increase in concentration of nanofluids heat transfer coefficient has been increased upto 27% with respect to the distilled water. This observation backs the utility of nanofluids in many heat exchanger applications where space and weight is constraint. It has been seen that for 0.1% concentration there is very less increase in heat transfer coefficient with increasing flow rates. However, higher concentrations of 0.25% and 0.5% show the considerable increase in heat transfer coefficient.
- **Prandtl number:** Prandtl number the ratio of momentum diffusion to thermal diffusion depends on  $\varphi$  and temperature. With increase in concentration Prandtl number increases, with respect to distilled water. Prandtl number increased with increase in concentration in almost same proportion for every concentration change. Increase of Prandtl number upto 22% for  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids shows the expected results [51]. Das et al [51] also studied the change of Prandtl number with different nanofluids and concluded that Prandtl number increases with increase in concentration for every nanofluid he used. With temperature Prandtl number increases due to viscosity dominance at higher temperatures.
- **Reynolds number:** Reynolds number with increase in particle volume concentration decrease. The decrease in Reynolds number by 18% from pure water to 0.5% (vol.) shows the considerable increase in viscosity overcoming the density effects.
- The results obtained showed that microchannels are proved vital in the field of heat transfer. Their higher surface to volume ratios gives high heat transfer coefficients, which carries more heat from small places.

# Chapter 6

## Future scope

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In the present work  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids were prepared with particle volume concentration of 0.1%, 0.25%, 0.5%. Thermophysical properties and performance of microchannels were studied. Microchannels and nanofluids have shown a positive approach in heat transfer field. But still a lot of research is needed for commercialization of nanofluids and microchannels. Some of major challenges have been summarized as:

- A. Roughness effects: The effect of roughness elements on heat transfer and friction factor is being studied by numerical models techniques. Simulations leave eddies and recirculation effects by rough surfaces; these effects are not accurately structured in numerical schemes. Experimental validation is required to get accurate results. Models should be developed in accordance with eddies and recirculation effects.
- B. Design optimizations techniques: The strip fin generations need more investigation geometrical. It is expected that numerical optimization techniques will be developed in near future.
- C. Due to lack of agreement on results in nanofluids by many researchers created a need for further study and experimentation to find out the factors causing difference in results.
- D. The stability of the suspensions is the key issue for research and practical applications. New methods and techniques should be developed to make nanofluids more stable without compromising on thermophysical properties of nanofluids.
- E. Nanofluids properties largely depend on the shape and size of additives. Thermal conductivity of nanofluids gets affected by degree of agglomeration of nanoparticles. Hence there would be more stable nanofluids for promising heat transfer coefficients.

## REFERENCES

- [1] Chein, R., and Chuang, J., 2007, “Experimental microchannel heat sink performance studies using nanofluids,” *Int. J. Therm. Sci.*, **46**(1), pp. 57–66.
- [2] MAXWELL, J. C., 1873, “Maxwell\_1873\_Treatise\_Preface.”
- [3] Mondragón, R., Segarra, C., Martínez-Cuenca, R., Juliá, J. E., and Jarque, J. C., 2013, “Experimental characterization and modeling of thermophysical properties of nanofluids at high temperature conditions for heat transfer applications,” *Powder Technol.*, **249**, pp. 516–529.
- [4] Masuda, H., Ebata, A., Teramae, K., and Hishinuma, N., 1993, “Alteration of Thermal Conductivity and Viscosity of Liquid by Dispersing Ultra-Fine Particles. Dispersion of  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$  and  $\text{TiO}_2$  Ultra-Fine Particles.,” *Netsu Bussei*, **7**(4), pp. 227–233.
- [5] Choi, S. U. S., 1995, “Enhancing thermal conductivity of fluids with nanoparticles,” *Proc. 1995 ASME Int. Mech. Eng. Congr. Expo.*, **66**, pp. 99–105.
- [6] Salman, B. H., Mohammed, H. A., and Kherbeet, A. S., 2014, “Numerical and experimental investigation of heat transfer enhancement in a microtube using nanofluids,” *Int. Commun. Heat Mass Transf.*, **59**, pp. 88–100.
- [7] Yu, W., and Xie, H., 2012, “A review on nanofluids: Preparation, stability mechanisms, and applications,” *J. Nanomater.*, **2012**.
- [8] Kandlikar, S. G., 2012, “History, Advances, and Challenges in Liquid Flow and Flow Boiling Heat Transfer in Microchannels: A Critical Review,” *J. Heat Transfer*, **134**(3), p. 034001.
- [9] Wu, X., Wu, H., and Cheng, P., 2009, “Pressure drop and heat transfer of  $\text{Al}_2\text{O}_3$ - $\text{H}_2\text{O}$  nanofluids through silicon microchannels,” *J. Micromechanics Microengineering*, **19**(1), p. 11.
- [10] Singh, P. K., Harikrishna, P. V., Sundararajan, T., and Das, S. K., 2012, “Experimental and numerical investigation into the hydrodynamics of nanofluids in microchannels,” *Exp.*

- Therm. Fluid Sci., **42**(December), pp. 174–186.
- [11] Mohammed, H. A., Bhaskaran, G., Shuaib, N. H., and Saidur, R., 2011, “Heat transfer and fluid flow characteristics in microchannels heat exchanger using nanofluids: A review,” *Renew. Sustain. Energy Rev.*, **15**(3), pp. 1502–1512.
- [12] Gunnasegaran, P., Mohammed, H., and Shuaib, N. H., 2009, “Pressure drop and friction factor for different shapes of microchannels,” *ICEE 2009 - Proceeding 2009 3rd Int. Conf. Energy Environ. Adv. Towar. Glob. Sustain.*, (December), pp. 418–426.
- [13] Tuckerman, D. B., and Pease, R. F. W., 1981, “High-performance heat sinking for VLSI,” *IEEE Electron Device Lett.*, **2**(5), pp. 126–129.
- [14] Nădăsan, M., and Manea, A., 2009, “Design and fabrication of the microchannels for microfluidics applications,” *UPB Sci. Bull. Ser. C Electr. Eng.*, **71**(4), pp. 125–134.
- [15] Lin, P. T., Zhang, J., Jaluria, Y., and Gea, H. C., 2012, “Design and Optimization of Multiple Microchannel Heat Transfer Systems Based on Multiple Prioritized Preferences,” *Vol. 3 38th Des. Autom. Conf. Parts A B*, **6**(March 2014), p. 789.
- [16] Mohammed, H. A., Gunnasegaran, P., and Shuaib, N. H., 2010, “Heat transfer in rectangular microchannels heat sink using nanofluids,” *Int. Commun. Heat Mass Transf.*, **37**(10), pp. 1496–1503.
- [17] Jang, S. P., and Choi, S. U. S., 2004, “Role of Brownian motion in the enhanced thermal conductivity of nanofluids,” *Appl. Phys. Lett.*, **84**(21), pp. 4316–4318.
- [18] Trisaksri, V., and Wongwises, S., 2007, “Critical review of heat transfer characteristics of nanofluids,” *Renew. Sustain. Energy Rev.*, **11**(3), pp. 512–523.
- [19] Wang, X. Q., and Mujumdar, A. S., 2008, “A review on nanofluids - Part II: Experiments and applications,” *Brazilian J. Chem. Eng.*, **25**(4), pp. 631–648.
- [20] Eastman, J. A., Choi, S. U. S., Li, S., Yu, W., and Thompson, L. J., 2001, “Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles,” *Appl. Phys. Lett.*, **78**(6), pp. 718–720.

- [21] Zhu, H. T., Zhang, C. Y., Tang, Y. M., and Wang, J. X., 2007, "Novel Synthesis and Thermal Conductivity of CuO Nanofluid," *J. Phys. Chem. C*, **111**(4), pp. 1646–1650.
- [22] Kulkarni, D. P., Das, D. K., and Vajjha, R. S., 2009, "Application of nanofluids in heating buildings and reducing pollution," *Appl. Energy*, **86**(12), pp. 2566–2573.
- [23] Otanicar, T. P., Phelan, P. E., Prasher, R. S., Rosengarten, G., and Taylor, R. A., 2010, "Nanofluid-based direct absorption solar collector," *J. Renew. Sustain. Energy*, **2**(3).
- [24] Xu, B., Ooti, K. T., Wong, N. T., and Choi, W. K., 2000, "Experimental investigation of flow friction for liquid flow in microchannels," *Int. Commun. Heat Mass Transf.*, **27**(8), pp. 1165–1176.
- [25] Taylor, P., 2001, "Heat transfer in microchannels," *Microscale Thermophys. Eng.*, **5**(3), pp. 155–175.
- [26] Qu, W., and Mudawar, I., 2002, "Experimental and numerical study of pressure drop and heat transfer in a single-phase micro-channel heat sink," *Int. J. Heat Mass Transf.*, **45**(12), pp. 2549–2565.
- [27] Steinke, M. E., and Kandlikar, S. G., 2006, "Single-phase liquid friction factors in microchannels," *Int. J. Therm. Sci.*, **45**(11), pp. 1073–1083.
- [28] Lee, P. S., Garimella, S. V., and Liu, D., 2005, "Investigation of heat transfer in rectangular microchannels," *Int. J. Heat Mass Transf.*, **48**(9), pp. 1688–1704.
- [29] Choi, S. U. S., and Eastman, J. A., 1995, "Enhancing thermal conductivity of fluids with nanoparticles," ASME International Mechanical Engineering Congress and Exposition, pp. 99–105.
- [30] Farnam, D., Sammakia, B., and Ghose, K., 2010, "Thermal Design Criteria for Extraordinary Performance of Devices Cooled by Microchannel Heat Sink," *J. Therm. Sci. Eng. Appl.*, **2**(4), p. 041001.
- [31] Manay, E., Sahin, B., Yilmaz, M., and Gelis, K., 2012, "Thermal Performance Analysis of Nanofluids in Microchannel Heat Sinks," *World Acad. Sci. Eng. Technol.*, **67**(7), pp. 100–

105.

- [32] Farsad, E., Abbasi, S. P., Zabihi, M. S., and Sabbaghzadeh, J., 2011, “Numerical simulation of heat transfer in a micro channel heat sinks using nanofluids,” *Heat Mass Transf. und Stoffuebertragung*, **47**(4), pp. 479–490.
- [33] Mohammed, H. A., Gunnasegaran, P., and Shuaib, N. H., 2011, “The impact of various nanofluid types on triangular microchannels heat sink cooling performance,” *Int. Commun. Heat Mass Transf.*, **38**(6), pp. 767–773.
- [34] Seyf, H. R., and Keshavarz Mohammadian, S., 2011, “Thermal and Hydraulic Performance of Counterflow Microchannel Heat Exchangers With and Without Nanofluids,” *J. Heat Transfer*, **133**(8), p. 081801.
- [35] Lu, X., and Nnanna, A. G. A., 2008, “IMECE2008-6 7932.”
- [36] Chein, R., and Huang, G., 2005, “Analysis of microchannel heat sink performance using nanofluids,” *Appl. Therm. Eng.*, **25**(17-18), pp. 3104–3114.
- [37] Patel, H. E., Sundararajan, T., and Das, S. K., 2010, “An experimental investigation into the thermal conductivity enhancement in oxide and metallic nanofluids,” *J. Nanoparticle Res.*, **12**(3), pp. 1015–1031.
- [38] Harirchian, T., and Garimella, S. V., 2009, “The critical role of channel cross-sectional area in microchannel flow boiling heat transfer,” *Int. J. Multiph. Flow*, **35**(10), pp. 904–913.
- [39] Manay, E., and Sahin, B., 2016, “The effect of microchannel height on performance of nanofluids,” *Int. J. Heat Mass Transf.*, **95**, pp. 307–320.
- [40] Wu, J., Zhao, J., Lei, J., and Liu, B., 2016, “Effectiveness of nanofluid on improving the performance of microchannel heat sink,” *Appl. Therm. Eng.*
- [41] Solovitz, S. a., and Mainka, J., 2011, “Manifold Design for Micro-Channel Cooling With Uniform Flow Distribution,” *J. Fluids Eng.*, **133**(5), p. 051103.
- [42] Chein, R., and Chen, J., 2009, “Numerical study of the inlet/outlet arrangement effect on

- microchannel heat sink performance,” *Int. J. Therm. Sci.*, **48**(8), pp. 1627–1638.
- [43] Kandlikar, S. G., Garimella, S., Li, D., Colin, S., and King, M. R., 2014, *Heat Transfer and Fluid Flow in Minichannels and Microchannels*.
- [44] Mahbubul, I. M., Saidur, R., and Amalina, M. A., 2012, “Latest developments on the viscosity of nanofluids,” *Int. J. Heat Mass Transf.*, **55**(4), pp. 874–885.
- [45] Pak, B. C., and Cho, Y. I., 1998, “Hydrodynamic and Heat Transfer Study of Dispersed Fluids With Submicron Metallic Oxide Particles,” *Exp. Heat Transf.*, **11**(2), pp. 151–170.
- [46] Eastman, J. a., Choi, S. U. S., Li, S., Thompson, L. J., and Lee, S., 1997, “Enhanced Thermal Conductivity through the Development of Nanofluids,” *MRS Proc.*, **457**, pp. 3–11.
- [47] Singh, K., Sharma, S., and Gangacharyulu, D., 2013, “Experimental Study of Thermophysical Properties of  $\text{Al}_2\text{O}_3$ /Water Nanofluid,” *Int. J. Res. Mech. Eng. Technol.*, **3**(2).
- [48] Yu, W., and Xie, H., 2012, “A Review on Nanofluids: Preparation, Stability Mechanisms, and Applications,” *J. Nanomater.*, **Article ID**(doi:10.1155/2012/435873), p. 17.
- [49] Pastoriza-Gallego, M. J., Casanova, C., Páramo, R., Barbés, B., Legido, J. L., and Piñeiro, M. M., 2009, “A study on stability and thermophysical properties (density and viscosity) of  $\text{Al}_2\text{O}_3$  in water nanofluid,” *J. Appl. Phys.*, **106**(6), p. 064301.
- [50] Ding, Y., Alias, H., Wen, D., and Williams, R. A., 2006, “Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids),” *Int. J. Heat Mass Transf.*, **49**(1-2), pp. 240–250.
- [51] Vajjha, R. S., and Das, D. K., 2012, “A review and analysis on influence of temperature and concentration of nanofluids on thermophysical properties, heat transfer and pumping power,” *Int. J. Heat Mass Transf.*, **55**(15-16), pp. 4063–4078.