A Study of Heat Transfer in Microchannels Using Aluminium Oxide Nanofluids

A Dissertation Submitted
in partial fulfilment of requirements
for the degree of

Master of Engineering

in

Thermal Engineering

Submitted by

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DEPARTMENT OF MECHANICAL ENGINEERING

TIET, PATIALA

JUNE, 2018

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CERTIFICATE

I hereby declare that the thesis report entitled **"Study of Heat Transfer in Microchannels Using Aluminium 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 **TIET, Patiala** under the supervision of **Mr. Sumeet Sharma** (Associate Professor, M.E.D) and **Dr. D. Gangacharyulu** (Professor, Ch.E.D). 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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Declaration

I, **ARUN VIR SINGH,** hereby declare that the thesis, entitled **"A STUDY OF HEAT TRANSFER IN MICROCHANNELS USING ALUMINIUM OXIDE NANOFLUIDS"**, submitted to **Mechanical Engineering Department, TIET,** in partial fulfilment of the requirements for the award of the degree of **Master of Engineering** in **Thermal Engineering** is a record of original and independent research work done by me during the period 2016-2018, under the supervision and guidance of **Mr. Sumeet Sharma,** Associate Professor, Mechanical Engineering Department and **Dr. D. Gangacharyulu,** Professor, Department of chemical Engineering. The work contained in this thesis has not been previously submitted to meet the requirements for a degree or diploma at this or any higher education institution.

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Acknowledgements

I would like to express my deep sense of gratitude to Mr. Sumeet Sharma, Associate Professor, Mechanical Engineering Department, TIET, Patiala, India & Dr. D. Gangacharyulu, Professor, Chemical engineering department, TIET , Patiala, India for their invaluable suggestions, excellent supervision, constant encouragement, thought provoking discussions and unabashed inspiration in nurturing the work and during the preparation of manuscript throughout the research work.

I offer my special regards to Mrs. Harkirat Kaur, Research Scholars, Department of Chemical Engineering, TIET, Patiala, India, for providing their immense support in performing the experimental and developing a base in this field work throughout my research work.

I am grateful to Mr. Amit Kamboj, Laboratory Attendant, Department of Chemical Engineering, TIET, Patiala for providing me all the lab facilities for the successful completion of my thesis work.

Above all, I thank to THE GOD, for all his blessings and kindness at every step of my life.

26/7/18

ARUN VIR SINGH

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 (0.2%, 0.3%, 0.6% (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 35% for 0.6% (vol.) concentration and Prandtl number increased by 24% maximum. However Reynolds number had decreased by maximum of 21% for 0.5ml/min flow rate and least decrease by 13% for 2ml/min flow rate. However, microchannels give the high surface to volume ratio of $8.05mm^{-1}$. 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
$m\cdot$	= 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

φ	= Particle volume concentration, % [vol.]
ρ	= Density, kg/m^3
μ	= Dynamic viscosity, N-s/m^2
ν	= kinematic viscosity, m^{2}s
Ω	= 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

1.1 Introduction

Recently a lot of advancement has been made by microelectronics industry, resulting in development of high heat generating microelectronic devices. The heat generated by these devices which is an important issue for consideration of their use in industry or everyday activities. High heat buildup in microelectronic devices can not only hamper its performance but can also damage the device. Hence finding solution to this heat buildup is an important but challenging task. Now this heat disscipation task can either be achieved by increasing surface to volume ratio of heat exchangers or by employing better coolants or by both the methods.the problem here with conventional coolants like water, oils, ethylene glycols is that that they have been proved futile due to their low thermal conductivity that leads to poor heat disscipation and slows down the device. Thus, in 1873 it was put forward by J.C Maxwell [1] that to increase the thermal conductivity of base fluid, very small solid particles must be added to the base fluid which can lead to higher heat disscipation [2]. This happens due to higher heat capacity of very small solid particles as compared to base fluid and gives a boost to the heat capacity as well as thermal conductivity of base fluids [3]. However experiments have also shown that addition of micro particles and millimeter sized particles to base fluids also leads to problems like abrasive wearing of pipeline, channel clogging, sedimentation and pressure drop. The above problems has put a restriction on their use in industry.To bypass these problems the use of nanoparticles was introduced, later with advancement in nanotechnology and nano industry the use of nanoparticles picked up momentum for their use in research. Nanoparticles are fine powdery particles and are smaller than 100nm in size.In 1993 to increase the thermal conductivity of liquid Masuda et al [4] used ultra fine particles and later in 1995 the use of nanoparticles was proposed by choi[5].The nanopartciles can be metallic as well as non metallic like Al_2O_3, CuO, SiO2, TiO2, Cu, Ni, Al, ZnO[6]. Nanofluids are prepared by dispersing nanoparticles in base fluid.

Nanoparticles are prepared by dispersing nanaoparticles which have high thermal conductivity in base fluid. Nanoparticles smaller than 100nm in size less dispersed into base fluid. The unique advantage that dilute nanofluid suspension gives over colloidal solution is that it has high heat transfer surface between nanoparticles and fluids. Nanofluids find application in areas such as nano drug delivery, transportation, electronics industry, cooling applications in industry, heating of buildings, pollution reduction, nuclear cooling, application in biomedical, reducing friction, solar absorption, energy storage, magnetic sealing etc [7].

Microelectronics industry is continuously progressing towards betterment. The focus is on heat disscipation in small spaces. This challenge can be effectively tackled by using small scale heat exchangers paired with high heat capacity coolants. Microchannels are introduced as small scale heat exchangers and it is paired with high heat capacity nanoparticles [8]. Thus the pair meets the demand.

Microsized flow passasges having hydraulic Diameter range between 10 micrometer to 200 micrometers are called microchannels. Microchannels consists of high surface area to volume ratio enabling higher heat transfer rates. Microchannels can fit in very small spaces owing to their small size. It can fit into small spaces where heat generation is more and where conventional methods fail to disscipate the heat. Many researchers [9] [10] [11] have done experimentation for studying the heat transfer through microchannels using nanofluids. The experiments carried out by these researchers have shown increased thermal conductivity upto 790W/cm^2 and the maximum temperature can rise upto 71^{o}C higher than that of water [12].In the microchannels shown in figure 1.1 small channels which can be seen have hydraulic Diameter ranging from 10mm – 200mm. Microchannels are generally manufacteured on silicon wafers because of simple process of stereo lithography and ease of manufacturing. Although this method is easier but it has a drawback related to manucaturing accuracy and thus it leads to discrepancy between theoretical and experimental results.Hence due to this drawback a new method of cnc wire cutting on aluminium is generally utilized. The revolutionary work of tuckerman and Pease[13] in 1981 gave a boost to the microchannels research. After this the research focus shifted to design implementation from 1986-1988. This was further followed by understanding the design fundamentals of flow of fluid through microchannels during the period of 1992-2002 and then the interest shifted towards practical application in 2002.

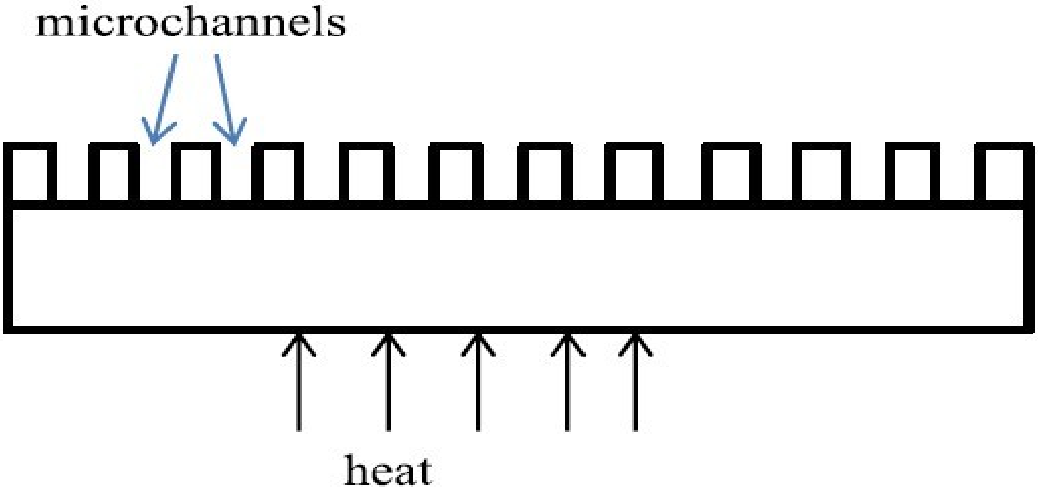


Fig 1.1:Microchannels

During the period after the focus shifted towards validating the research work which had already bee done. From the findings of Satish. G. Kandlikar [8] it has been found that for practical use more research needs to be done in microchannel area. Most of the literature available [10] [14] [15] [9] used silicon microchannels. Aluminium microchannels are used very less in the available literature. The quantity of experimental work available is also very less.Most of the work that is available in the field of microchannels are either either optimizations or numerical investigation. Very less researchers [9] [16] [6] [12] have done experimental work in this area.In the experimental research done by the researchers they have discovered that heat carrying capacity as well as pressure drop increases with increase in Reynolds number. They also tested the agglomeration of nanoparticles. Researchers such as Wu et al [9] tested the agglomeration formation of nanoparticles in microchannels, he found out that no deposition was formed with inlet temperatures in the range of 25^0C – 30^0C and oulet temperatures in the range of 30^0C – 40^0C but at temperatures beyond these ranges a very high deposition of particles has been observed. Thus room temperature has been chosen to carry out experimental work.The impact of various shapes of microchannels on friction factor has been studied by Gunnasegaran et al. [12]. From this study rectangular cross section is selected for microchannels.

OBJECTIVES 1.2

Both nanofluids and microchannels find significant applicability in electronics and thus the examination of their thermal performance remains an area of chief concern.Following objectives are outlined for the research work :-

- To find the variation of heat transfer coefficient of aliminium oxide – water based nanofluids and with flow rate.
- To compare the heat transfer coefficient of alumiunium oxide – water based nanofluids with the water at various combinations of particle volume concentrations and flow rates.
- To find the variation of Reynolds number as well as Prandtl number with particle volume concentration of nanofluids.

CHAPTER 2

LITERATURE REVIEW

The beginning part of this chapter provides information on microchannel and nanofluids and the remaining part sheds light on the work of scientists and researchers on the thermal charecteristics of microchannels and nanofluids. A review of available literature in the area of microchannels and nanofluids is done.

2.1 NANOFLUIDS

Nanofluids are fluids that are prepared by dispersing high conducting nanoparticles having size less than 100 mm in the base fluid. This leads to an increase in thermal conductivity due to increase in surface to volume ratio, also nanoparticles have Brownian motion and nanoparticles collide with each other this leads to an increased heat transfer rate of base fluid. At higher temperatures there is increased brownoan motion [17] because of which the viscousity varies inversely with temperature at elevated temperature, this again leads to an increased conductivity. In recent years many articles [7] [18] [19] on nanofluids have been published and these envolve both experimental and theoretical work.

2.2 MATERIALS FOR NANOFLUIDS

Very small particles with size less than 100mm and high thermal conductivity as compared to base fluid is dispersed in base fluid thus making nanofluids. Thus high thermal conductivity as compared to base fluid is the criterion for selection of material of nanoparticle.

Following are the commonly used base fluids and nanoparticles:-

1) Base fluids:-
    a) Water
    b) Oil
    c) Ethylene glycol

2) Nanoparticles:-
   a) Metal oxides
   b) Metallic particles
   c) Carbon nanotubes

2.3 PREPARATION OF NANOFLUIDS

Folllowing two methods are used for preparing nanoparticles:-

1) Two – step method
2) One - step method

2.3.1 Two - step method

This is the most popular method of preparing nanofluids. As the name suggests two steps are followed in this method to prepare nanofluids. In the first step the firstly the nanoparticles in the form of dry powder is manufactured by various chemical and physical methods. Now in the second step the nanoparticles are dispersed in the base fluid by processes such as ultrasonication etc. Two –step method is much more cheaper as well as economical for preparation of nanfluids as compared to one – step method. Since nanofluids prepared by this method has a high tend to agglomerate much more easily hence it leads to lower stability of nanofluids because of which one – step method was developed.

2.3.2 One – step method

As the name suggests one – step method envoles just a single step for preparing the nanfluid. Physical vapour condensation methods were developed by Eastman et al [20] for preparing ethylene glycol and copper nanofluids. In one – step method both manufacturing as well as dispersion of nanoparticles occurs in single step. In this method agglomeration formation is greatly reduced since processes of drying, dispersion and transportation are avoided. Preparation of nanofluids by one step method is very costly and thus not suited to large scale production of nanofluids, also there is difficulty in explaining the exact behavior of nanfluids due to left over particles of incomplete reaction. Usage of chemical methods has got a boost since it has higher production.

2.3.3 OTHER METHODS

Copper oxide nanofluid was prepared by Zhu et al [21] using a novel method called precursor transformation along with microwave and ultrasonic irraDiametertion. For preparation of copper nanofluids a new called microfluidic microreactor was developed by wei et al. In this method microstructure and properties are varied by adjustment of flow rate additive etc.

2.4 APPLICATIONS

2.4.1 APPLICATION IN ELECTRONICS

Modern electronic devices are not only very compact but also suffer from poor heat disccipation due to closed environment. Due to high heat generation in electronic chips it can lead to low performance of the device or the excessive heat can also damage the device. It is a very difficult process to disccipate all the heat generated by these electronic chips efficiently. There are basically two methods for effectively disscipating heat from these devices. In the first method the design of the cooling system is optimized for better performance of the cooling system. The second method envolves usage of hogh heat conducting nanfluids as coolants. Nanofluids have high heat conducting ability as compared to conventional coolants, also nanolfuids have high heat carrying capacity as compared to base fluids.

2.4.2 APPLICATION IN AUTOMOBILE

Nanofluids can be used as a coolant in the cooling system of the automobiles engines and also heavy duty engines and thus can significantly increase the performance and life of the engines. Nanofluids boosts the rate of heat transfer and this leads to decreased complexity of cooling jackets as well as reduced weight. This leads to much more compacter designs as well as reduced weight of raDiametertors and hence high fuel economy and higher performance.

2.4.3 HEATING OF BUILDINGS AND POLLUTION CONTROL

Heating of buildings in colder regions by using nanolfuids was examined by Kulkarni et al [22]. For heating purposes ethylene glycol nanofluids were used as the heat transfer fluid.The work of kulkarni et al has shown that by using nanofluids in heat exchangers, significant reduction in volume flow rates and mass flow rates can be achieved and thus resulting in reduced required pumping power. Using nanofluids smaller and much more compact cooling systems can be designed which are capable to deliver similar energy as that of largescale systems.

2.4.4 NUCLEAR COOLING SYSTEMS

MIT researchers are trying to find the applications of nanofluids in the area of nuclear science.There are three main areas of interest :- a) In high power density light H_2O reactor,during major accidents, it can be used as a coolant. b) Pressurized H_2O reactors. c) For core cooling as a coolant during emergency.

2.4.5 SPACE AND DEFENCE

The space stations and space crafts have restricted spaces in them thus space applications require very efficient cooling systems that can be accommodated in a very limited space. This restriction of space crafts and space stations gives direction towards light weight cooling solutions which have small and compact designs. This can really make space travel more economical than it is today. The high hest carrying capacity of the nanofluids lends them extremely usable in defence machineries such as missiles,tanks,subamarines,high power lasers etc. Thus nanofluids are extremely usable in areas which require light weight systems,compact spaces as well as high heat transfer rates.

2.4.6 SOLAR ENERGY ABSORPTION

Solar energy is the energy that is obtained from solar radiation reaching the surface of the earth. This energy obtained from solar radiation is one of the best forms of non conventional forms of energy and it is also available in abundance. A technology known as direct absorption solar collector is quite popular. Due to low absorption capability of collecting fluid the efficiency is on the lower side. To overcome this drawback, nanofluids are being employed. Many experminets were carried out by Otanicar et al [23] by employing nanofluids as heat transfer fluid and found an increase in efficiency of 5% of solar collector.

2.4.7 MISCELLANEOUS APPLICATIONS

Apart from the above main applications of nanofluids,it can also find applications in fields such as microbial fuel cell, reactors, automobile brake fluids, drug delivery etc.

2.5 CHALLENGES IN THE AREA OF NANOFLUIDS

Nanoparticles can find applications in various areas but due to long term difficulties they find limted usage in the longer term.

Nanofluids have high heat transfer rates as compared to conventional coolants still there use very much limited because:-

a) There is discrepancy between practical and theoretical aspects as found by many scientists.
b) Nanofluid have a high tendency to form agglomerates due high vaander waal forces that exists between the particles.however many method have been developed to mitigate these.
c) At higher temperatures sedimentation of particles occur.
d) Nanofluids with higher nanoparticles concentration have higher viscousity which leads to higher pumping power thus affecting efficiency of the pumps.
e) Preparation of nanofluids is not very economical and envoles high costs.

2.6 NANOFLUIDS STABILITY

A major factor that affects the usability of nanofluids is the stability of nanofluids. Sedimentation and agglomeration leads to blocking of the passages and also thermal conductivity of nanofluids suffer due to this. Hence examination of stability of nanofluids is a major concern.

2.6.1 STABILITY MECHANISM

During and after dispersion the particles start to stcik to each other and this leads to agglomeration and further settling down of this agglomerate leads to reduced heat transfer and clogging of pipes. This restricts the use of nanofluids. Landau and Verway have described that to examine the stability of nanofluids summation of van der waal forces and electrical double layer forces. Here van der waal forces arise due to the Brownian motion of the particles. If the van der waals forces are much more pronounced as compared to the repulsive forces the particles will adhere to each other and agglomeration will occur while the stability is maintained if the repulsive forces are much more pronounced as compared to the van der waals forces then particles will not adhere to each other and agglomeration will not occur,so nano fluids remain stable. The repulsive forces are thus required to be more dominant.

The stability of the nanofluids can be enhanced by the addition of additives and surfactants in nanofluids. Addition of surfactants and additives in nanofluids alters the two forces discussed earlier that is van der waals forces and electric repulsive forces thus increasing the stability of nanofluids. The surfactants and additives also affect the thermal property of the nanofluids hence they are required to be used in limited quantity. Surfactants and additives enhances the stability of nanofluids for a longer period of time.

2.6.2 ANALYSIS OF STABILITY

There are various physical and chemical processes [7] to enhance the stability of nanofluids. These methods are discussed here in brief:-

a) Zeta potential analysis
b) Spectral absorbency analysis
c) Sedimentation and centrifugation

The above three methods can be together used to do a stability test of nanofluids. These methods not only tell about the behavior of nanofluids but also act as a test of the stability of nanofluids.

If the coolants used in heat exchanging devices have better heat conduction ability, it can pave the way for much more sophisted designs for heat exchanging devices such as requirement of low space,light weight etc. Nano fluids are hand in glove with these requirements and thus they can be regarded as the future in this area. Concentration as well as size of the nanoparticles greatly affect thermal properties of the nanofluid. There are many challenges that are faced for making the nanofluids comeericially viable. This area of research is expanding everday and novel methods are being developed which will eventually lead to better stability of nanofluids without compromising the coolant quality.

2.7 MICROCHANNELS

Microlelectronics devices are very small in shape but they generate a lot of heat in a small area. To disscipate heat generated from microlectronic devices very small heat exchanging devices are required that can not only fit into small spaces but also are light weight. Microchannels are hand in glove with these requirements. Microchannels are small heat exchanging devices which comsists of very small passages through which coolants or heat exchanging fluid flows. These small microchannel passages have very high surface to volume ratio which allows very high heat transfer rates from small spaces. Microchannels can lent themselves useful in applications where there are restrictions of weight and space. These small passages have hydraulic Diameter ranging from 10µm - 200µm .

Tuckerman and Pease [13] in 1981 gave a boost to the research in the area of microchannels and gave the direction in which the research is to be done. Till 1988 the focus of the researchers was on design as well as implementation of microchannels technology. After thorough analysis of design and implementation the the focus of the researchers shifted towards studying the flow behavior through small microchannel passages. From 1990 – 2000 a lot of work was done by researchers using experiments but they could not find a solution or answer the problem of applying the continuum theory to the flow of liquid. Then there was a researcher Xu et al [24] who finally found the solution for the problem of applicability of continuum theory to flow of fluid in microchannel by ignoring the exit and entry effects. Afterwards a researcher Palm [25] found that research done till then was still not conclusive related to the application of continuum theory in fluid flow through microchannels. Then Qu and Mudawar [26], Stienke and Kandliker [27] confirmed the applicability of continuum theory for fluid flow in microchannels through experimental data. Afterwards lee et al [28] while carefully considering boundary conditions validated the continuum theory for flow of fluid in microchannels. The applicability of contiunuum theory is verified for single phase flow through microchannels. No verification has been made for two phase flow yet. This experimental work envolves single phase flow.

Fig 2.1 Straight flow channel

As can be seen from the figure nanofluid enters from one side and exits from the other and while flowing through the microchannels the heat transfer takes place from the system in which it is installed to the nanofluid. It is a straight flow type microchannel. Nanofluid enters from one side and exits from other while absorbing heat generated by the system.

2.7.1 CLASSIFICATION OF MICROCHANNELS

Classification of microchannels is based on two factors: a) Hydraulic Diameter of the channel b) Cross - sectional area of the channel.

Table 2.1 classification of microchannel by Mehndale et al

Sno.	Hydraulic Diameter	Nomenclature
1	Dh>3mm	Conventional channel
2	3mm 2: Dh > 200 µm	Minichannels
3	200 µm2:Dh> 10 µm	Microchannels
4	10 µm 2: Dh > 0.1 µm	Transitional microchannels
5	0.1 µm 2: Dh	Molecular nanochannels

Classification on the basis of hydraulic Diameter was given by Mahendale et al.The classification given by Mahendale et al is shown in table 2.1. Another classification was given by gunnasegaran et al based on cross sectional geometry of microchannels.

Another classification of microchannels is based on flow directions of nanofluid.they are:- a) Split flow type b) Straight flow type. The following figure shows both types of microchannels.

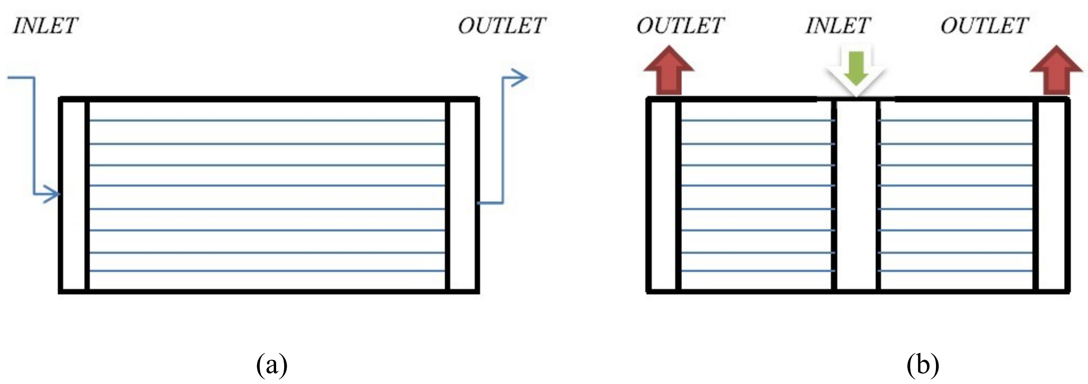
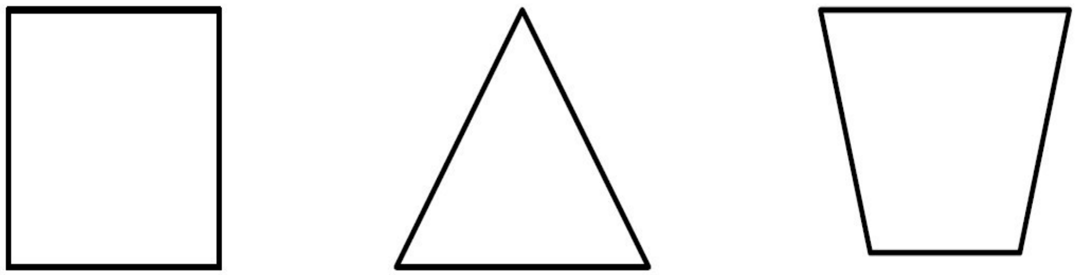


Fig 2.2 Microchannel classification

Gunnasegaran et al. did a classification of microchannels in his research based on the geometry of the microchannels which can be trapezoidal, triangular and rectangular and compared the performance of these geometries.

Gunnasegaran et al gave the following classification.



(a) (b) (c)

Fig 2.3 (a) rectangular (b) triangular (c) trapezoidal

The choice of cross sectional geometry of the microchannel for this research work was made on the basis of the classification given by Gunnasegaran et al. Since rectangular microchannels easier to manufacture, and also it is cheapest costwise as compared to microchannels of other geometrical shapes. Also rectangular cross sectional geometry of microchannels can be manufactured in a number of ways. Novel methods of lithography techniques were shown by monica et al [14]. The methods of dry wetching and wet wetching were shown by them.

a) Wet chemical etching.
b) Dry etching technique techniques.
    - Optical lithography
    - Deep reactive ion itching
    - Reactive ion itching

The shape of the microchannel can change to sinusoidal shape instead of rectangular shape if the wet itching method is continued for a longer duration of time. This cannot be ignored as during experiments flow of nanofluid receives extra resistance due to this. In the figure shown monica et al [14] shows the shape distortion from rectangular to sinusoidal.

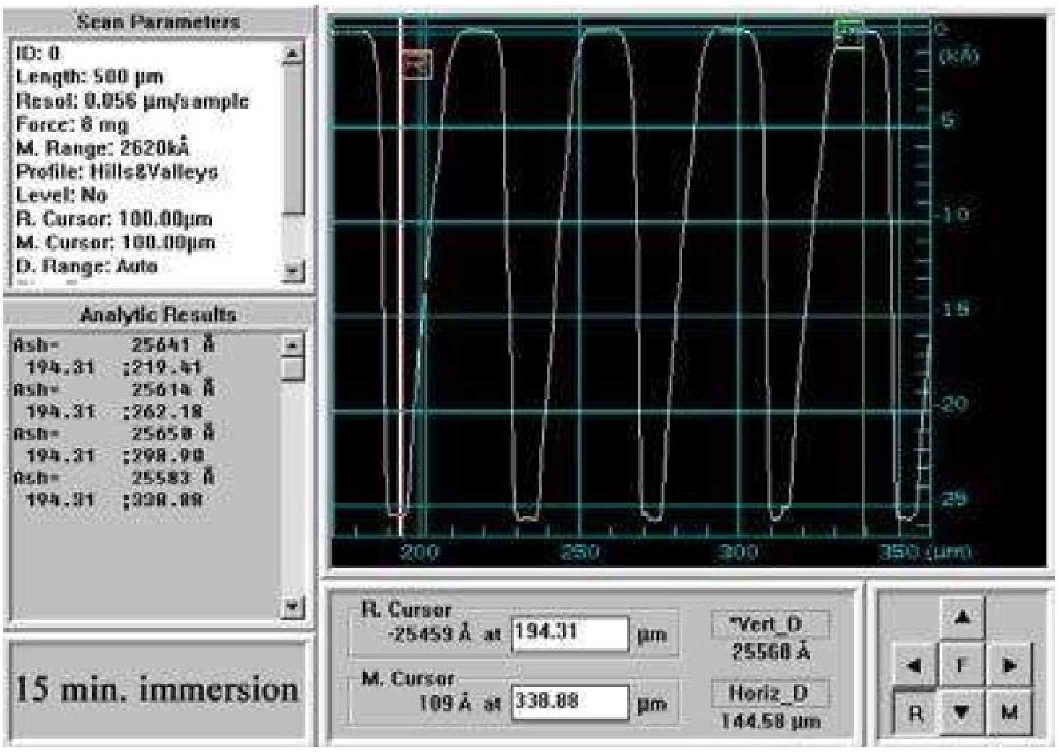


Fig 2.4: 15mm dispersion of microchannel with depth 2.1µm

A more dimensioned structure is obtained in reactive ion itching as compared towet itching process because of vertical delivery of recative ions. Microchannels manufactured by this method have very good surface and it does not have any effect on flow of fluid.

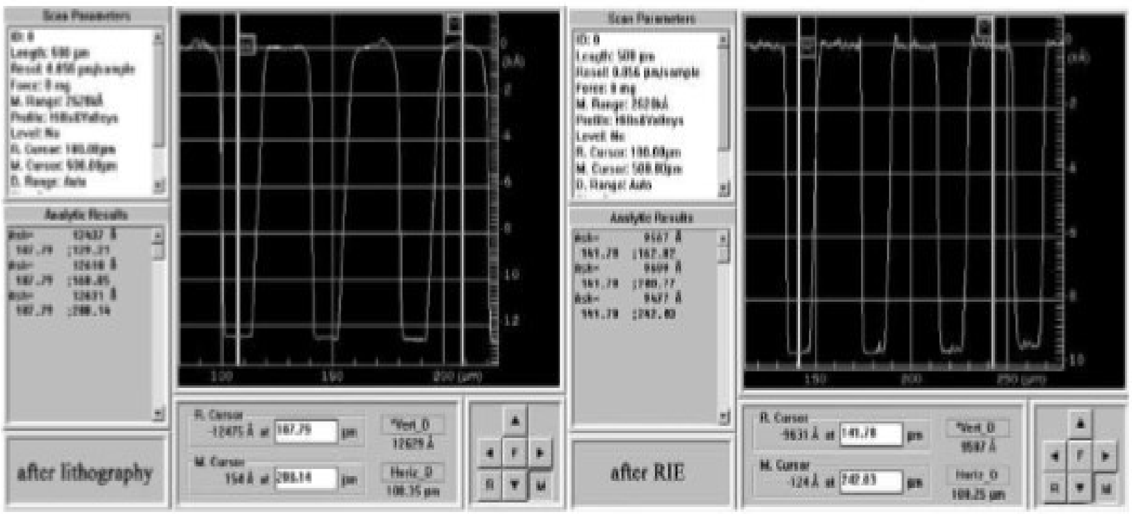


Fig 2.5: Microchannel fabricated by RI technique

Figures shown above indicate that RIE technique of fabrication produces much better dimensioned structure with much better accuracy of the process and also better flow conditions. Microchannels produced by this process have low depth. Hence this method is not very suited tp practical applications. To bypass this limitation a novel method was developed by which microchannels with a depth of 200 mm could be manufactured.This new method is called deep reactive ion itching. This method with metal mask layer. This is the main drawback of this method.

The techniques discussed have a high requirement for knowledge as well a lot of practice to manufacture microchannels since it envolves time dependent chemical reactions. These time dependent chemical recations are not very easily controlled. Also these methods have drawbacks as discussed earlier. To avoid this high level of difficulty a novel method for manufacturing of microchannel is selected. This method is known as CNC wire cutting.In CNC wire cutting a .018 mm size of wire is used to make a cut of .025 mm. CNC wire cutting is more economical, has better availability and the time consumed to manufacture is significantly less as compared to other methods.

2.7.2 APPLICATIONS OF MICROCHANNELS

Microchannel usability in various areas has significantly improved thanks to rapid advancement in manufacturing technology which makes them usable in wide varities application conditions [29]. This has led to rapid adoption of microchannel technology in various areas such as :-

a) In film deposition for thermal control
b) Automobile applications
c) Bioengineering applications
d) In cooling system of gas turbine
e) Refrigeration and air conditioning
f) Infrared sensors and laser mirrors
g) Applications in superconductors
h) Application in microelectronics
i) Power and manufacturing industries

2.8 LITERATURE REVIEW

Many researchers have done work in the field of nanofluids nad microchannels.The available literatue sheds light on the behavior of nanofluids such as their thermal properties, their stability and also their applicability in various areas. A large quantity of work is available in the field of microchannels where emphasis has been on behavior of flow, boiling of flow and on validating the applicability of continuum theory to the flow of nanofluid through the microchannels. This literature review will shed light on the work done in the field of microchannels and nanofluids till now. It will better equip us for understanding the field of nanofluids and microchannels and form the foundation for this research work.

Yu et al. Studied the nanofluids behavior and properties . From the studies performed they discussed in details the various aspects of nanofluids such as a) Application of nanofluids b) Various methods for checking the stability of nanofluids and c) Methods of preparation of nanofluids. They also discussed in detail about the one – step and two – step methods of preparation for nanofluids. In this discussion they have stated that one – step method for preparing the nanofluids provides better stability of nanofluids as compared to two – step method because of various factors such as a) No need for storage in one – step method b) The requirement to transport is avoided c) drying dispersion of nanofluid is also not required.Newer methods like phase transfer method,preparation of Cu nanofluids by continuous flow microfluidic microreactor. Methods to examine the stability of nanofluids:- a) Zeta potential method b) Sedimentation and centrifugation c) Spectral absorbency analysis. From the stated processes it was found that sedimentation and centrifugation is the best process to examine the stability of nanofluids. Applications of nanofluids have also been given. Stability enhancing methodologies have been described in detail.

Choi et al. has written that fluids that provide high heat transfer rates are required in the area of highly efficient fluids for their progression.Choi et al performed experiments with copper – H_2O and Al – H_2O nanofluids as heat coolants. They found that thermal conductivity of nanofluids as compared to base fluids is significantly better. Another observation was that the heat transfer rate could be doubled without much increment in pumping power needed to pass the nanofluid through heat exchanger.

Wu et al. did experiments using aluminium oxide – water based nanofluids and microchannels of silicon (hydraulic Diameter = 194.5 nm and relative roughness = $2.2*10^{-5}$). They used spherical shaped nanoparticles. The mean size of the particles was 56 nm and the volume fraction they took for the work were .26% and .15%. The nanofluids were prepared by two – step method. The nanofluids were prepared by dispersing the nanoparticles in distilled water which acts as the base fluid. This mixture is then kept in ultrasonic ultrasonic oscillator and ultrasonic oscillation is done for 90 minutes.

They kept the nanofluid for 10 days and after 10 days they examined the nanofluid for agglomeration. During this examination they found that no agglomeration had taken place and nanofluid was largely stable. The parameters they used for their work are a) Inlet temperature of the nanofluid (In the range of 25^0C – 35^0C) b) Flow rate (In the range of$4.5*10^{-8}$ m^3/sec – $2.6*10^{-7}$ m^3/sec). The apparatus used for the work were sytem through fluid flow occurs,test section data acquiring system. They also studied how the factor such as volume concentration, Reynolds number and Prandtl number affected the heat transfer behavior, friction in fluid and pumping power required were studied. They found that the results obtained from the experiments were consistent with the results obtained from theoretical procedure. Hence this proved the correctness of the results obtained from the experiments. Figure 2.6 shows the Diagram of testing section. In case of zero heating power condition the flow was controlled by adjustment of liquid valves.

Following was inferred from the results obtained from the experiments:

The work envolved studying the heat transfer as well as pressure drop behavior at different volume flow rates. Now according the study and the results obtained from experimentation they found that if the rate of volume flow was increased then both coefficient of heat transfer as well as pressure drop also increased in case of nanofluids as well as water. It was further found that water has slightly lower coefficient of heat transfer as well as slightly lower pressure drop as compared to nanofluids. Also this gap between water and nanofluids further widened with increase in concentration. This proves the superiority of water as coolant fluid as compared to water. It was also observed that friction factor varies inversely as Reynolds number for laminar flow.

It was observed that Nusselt no. varies inversely as Prandtl no., concentration and Reynolds no. Now this observation proves the superiority of aluminium oxide – water nanofluid as compared to water alone when paired with sislicon microchannels.In nanofluids particles are in contact with the microchannel wall as result of Brownian motion of the nanoparticles. As these nanopartciles have high heat transfer capabilities thus this leads high heat transfer rates. Nusselt no is affected by both Reynolds no and Prandtl no. When all other variables are constant Nusselt no varies directly with Prandtl no. which represents the nanolfuids at various temperatures.

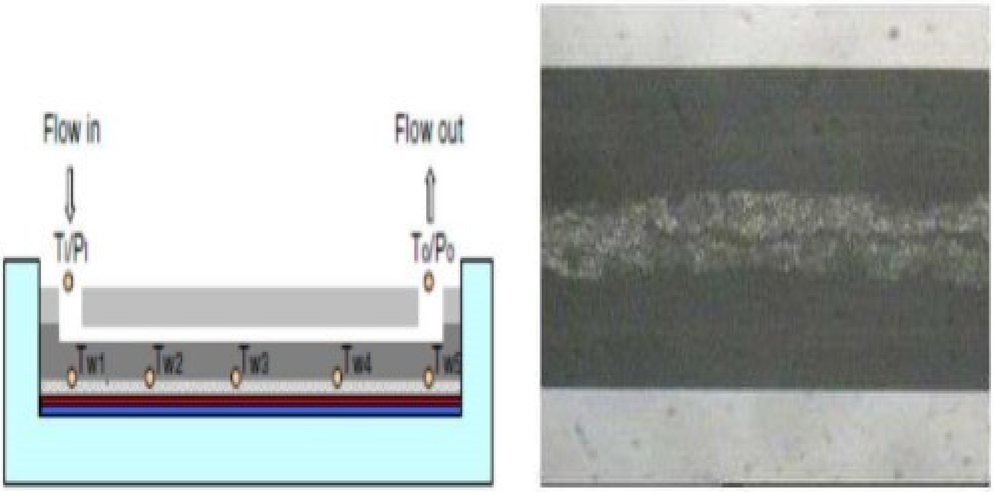


Fig 2.6: a) Microchannel section b) Nanofluids deposition in microchannels

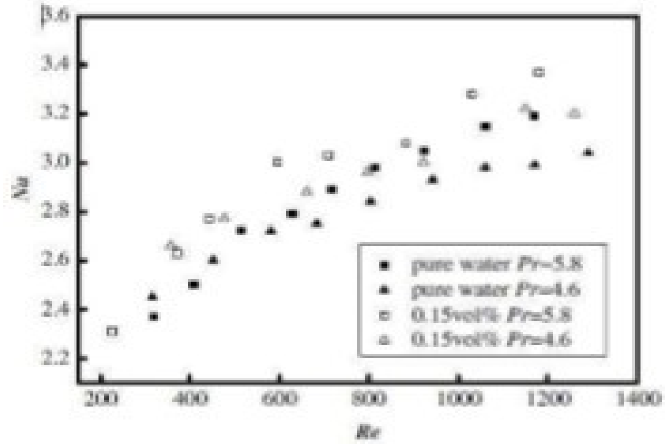


Fig 2.7: variation of Nusselt number with Reynolds number and Prandtl number

The relationship between thermal resistance and pumping power was also studies in this work and it was found that an inverse relationship exists between thermal resistance and pumping power. Then he increased the temperature and studied the nanofluid behavior at high temperature with help of charge coupled device camera and magnifying microscope. At high temperature (above boiling point for nanofluid under study) the stability of nanofluid is affected very badly and particles start to stick to each other and settle down. Thus at high temperatures there is aquestion of stability of nanofluids as the agglomeration starts to occur at such high temperatures.

Gunnasegaran et al. for the research work took various geometries of microchannels with diffirent aspect ratios performed a numerical simulation on flow of fluid through each of them. From this study it was determined how various geometries of microchannels and aspects ratios influence the pressure drop as well as friction factor in the flow. In this numerical study finite volume method was chosen for numerical investigation with grid size of $2.5*10^5$ cells. The different crosssections used in the study are triangular cross section,rectangular cross section and trapezoidal cross section.

The variables in this study are:- a) For rectangular geometry: width of the cross section as well as height of the cross section, b) For trapezoidal geometry: width of the bottom,width of the top,height and length of the geometry and c) For triangular geometry: top width,triangular angle and height of the triangular geometry.

The following observations were inferred from the numerical investigation:-

Reynolds number varies directly with Poiseulle number. This direct variation is although not a straight line variation this is because of the reason that at low values of Reynolds no. higher amount of heat is transferred to the water which leads to reduced pressure drop as well as viscousity. In terms of poisuelle no triangular geometry ranks at the top and then follows trapezoidal geometry and rectangular geometry ranks third and last. For rectangular geometry poisueille no and friction factor varies directly with width to height rato. For trapezoidal channel the design variables of significance are ratio of height to top width,the ratio of bottom to top width and ratio of length to hydraulic Diameter. The flow resistance varies inversely with the ratio of length to hydraulic Diameter, varies inersely as height to top width and varies directly as ratio of bottom to top width. The flow variables variables vary as triangular angle of the triangle geometry of microchannel. The values obtained from numerical method is found to be consistent with the theoretical results. In this study a distinction has been made between the behavior of flow through different geometries of microchannels.

Singh et al. performed experiments to study the heat transfer through microchannels using nanofluids. In this study two microchannels were used. One had hydraulic Diameter of 218 nm and the other has the hydraulic Diameter of 303 nm. Both the microchannels were manufactured by the process of wet ion itching on silicon wafer. In the apparatus there was facilities such as facility for temperature measurement of the lower wall as well as for providing the flow passage. The size of the nanoparticles are 45 nm.The various samples that were prepared for experimentation were 1 % by volume,.5% by volume and .25% by volume. These sample were stabilized by proper procedure. Water and ethylene glycol are used as fluids in which nanofluids are prepared. In this study emphasis was laid on viscousity as well as thermal conductivity.it was also studied how the various factors such as size of the particles, size of the channel, base fluids and volume concentration influence results. Dispersion is found to be characteristic of significance for which it was found that it occurred due to particle movement caused by shear. It was also observed that heat transfer behavior was directly related volume concentration and inversely related to viscousity of the base fluid.

Monica et al. has presented lithography techniques as novel method of manufacturing microchannels. The direction for this research has been obtained from the ability of nanofluids to get

Paired with not one but large number of nanofluids. The value of Reynolds no should be lower side to so as the flow is always laminar in behavior. The properties of nanofluids at micro - level is distinct from the properties of same nanofluid at macro – level. This variation in the properties of the nanfluids at micro level and macro level occurs because of viscous resistance, disscipation of energy as well as surface tension. The microchannels were manufactured using silicon wafer by 3 methods:-

a) Reactive ion itching
b) Wet chemical itching
c) Optical lithography

It was observed that reactive ion itching method is best for manufacturing of microchannels as it provides high accuracy. The depth of microchannels was measured by transmission electronic microscopy with the help of profilo – meter.

Mondragon et al. performed experiments using silica - nanofluids,alumina – nanofluids and carbon –nanotubes. The parameters used in the study were specific heat,thermal conductivity and viscousity. Nanofluids were prepared by dispersing nanoparticles in water. In this study the most stable nanofluids were selected based on the value of prandtl number. These nanofluids requires lesser pumping power and thus higher pump efficiency and also they provided the best rate of heat transfer. Different samples were prepared with volume concentration in the range of .5% by vol – 5% by volume. The properties of samples were found at different temperatures of 40^0C, 60^0C and 80^0C.

Different models were used in this study. The observations made from the experimental work were:-

- Low volume concentration of nanofluid did not affect the thermal performance much.
- Thermal performance varies directly with concentration.
- Increasing the temperature upto 600^0C resulted in increase in therma performance but after 600^0C the performance starts to decrease.
- The specific heat varies directly as temperature and varies inversely as volume concentration because of reduced thermal conductivity at higher volume concentrations.
- Viscousity of nanofluid caries directly as volume concentration whereas it varies inversely with temperature.

Salman et al. conducted the experiments with silicon dioxide – water based nanofluids. They also studies these nanofluids theoretically. The size of the nanoparticles was 30nm. The volume concentration of different samples is in the range .5 vol % - 1.0 vol % . These calculations are based on a certain formulae.

Two – step method was used for preparing the nanofluids.then 30 minutes of ultrasonication was done in the Ultrasonicator. Volume of each sample was 100 ml. After 5 hours nanofluids was examined for stability and it was reported that no agglomeration has occurred and nanofluid was largely stable. This study envoled finding how the nusselt no is affected by volume concentration as well as Prandtl no.

The apparatus on which experiments were done has following components:-

- Heater
- System for pressuring
- System for acquisition of data

A high pressure tank containing nitrogen was used to provide the flow of nanofluids.Heat was generated by a heaterwhich consisted of 5k – type thermocouple. These thermocouples were spaced by an equal distance of 30mm. They were placed along the length of the tube. Their function was controlling the heat generated as well as measurement of temperature. Two thermocouple spaced by 3 mm were used to record the external temperature at both inlet as wellas outlet. The friction factor was also found for both aluminium oxide – water nanofluids as well as silicon dioxide – water nanofluids. The volume concentration for both the nanofluids sample was taken as 1 by vol %. The Reynolds no was from 90 to 800.The results were verified with theoretical model of full developed flow with nusselt no of 4.36.The heat generation is constant.

It was observed that Nusselt number reaches 4.36 when Reynolds number has a high value because of unpredictable behavior of flow in the in the microtube. It was also observed that volume concentrations of .5 by % volume as well as 1 by % volume silicon dioxide nanofluids has the highest value of Nusselt number as compared to both water as well as aluminium oxide nanofluids. A 22% increase in heat transfer rate was observed as compared to water.

Sun et al. conducted the experiments to study heat transfer behavior of ferric oxide – water nanofluids. They prepared various samples of different samples of nanofluids with different volume concentrations.the samples with various volume contrations were.1 % by vol,.2 % by vol,.3 % by vol,.4 % by volume. The particle size of ferric oxide nanoparticle was 50 nm.Stability was examined after adding dispesants. It was observed that sodium dodecyl benzene sulfonate alongside volume concentration of .1 % by volume is the most stable. The apparatus consists of copper tube and grooved copper tube with internal Diameter of 8.6mm and 8.2mm. Two different samples were prepared one consisting of dispersant and other one lacking the dispersant. These samples of nanofluids were made to flow through the tubes.

The following was observed from the experimentation:-

- Heat transfer coefficient varies directly as mass fraction and also it was lesser in non grooved tube at constant Re no.
- Heat transfer coefficient varies directly as Re no.
- Friction factor varies directly with mass fraction.
- Heat transfer was higher in grooved copper tube.

Li et al. conducted experiments to find the heat transfer behavior aluminium oxide – water nanofluids.The mean size of the nanoparticles was 30 nm. Various samples were used in this study with different volume concentration.The volume concentration used in the study were 1 % by vol,2 % by vol,3 % by vol,4 % by vol. The microchannels used were dimple plus protruded as well as dimple.It was observed how the volume concentration, arrangement of microchannels and heat transfer behavior affected the results. Two types of microchannel was used:-

a) Staggered geometrical arrangement
b) Aligned geometrical arrangement.

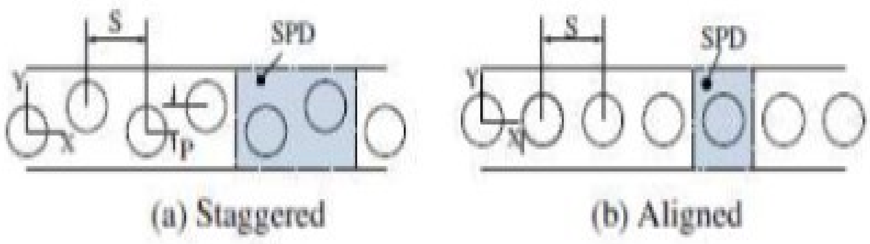


Fig 2.8: Staggered and aligned geometry

It was also observed that the factors such as volume conc., geometry of the microchannel, heat transfer behavior and velocity at inlet affects the results. The following observations were made:-

- It was observed that friction factor,Nu no and heat transfer rate varies directly with heat transfer coefficient.
- It was also observed that Nu no,friction factor and thermal performance of dimple microchannels or dimple plus protruded microchannels for staggered geometry was higher than that of aligned geometry.
- The dimple plus protruded microchannel had lower performance as compared to dimple microchannel.

Kim et al. conducted experiments using manifold microchannel heat sinks with forced air cooling. This research work envolved observing how microchannel geometry affects heat transfer through manifold microchannel heat sink. The study also envolved finding the best design for heat sink and also comparison of manifold microchannel heat sink and traditional manifold heat sink. There is also a difference between geometries of the two. The inlet width of manifold was 4 mm and outlet width was .9 mm.

The apparatus has following system:-

a) System for data acquisition
b) A power supply
c) Inlet portion

The first manifold was operated first and following observations were made:-

- Thermal resistance of microchannel is independent of the width of microchannel if the pumping power was increased
- Thermal resistance varies inversely as pumping power.
- Thermal resistance dercreased when width of microchannel was reduced.

Chein et al. experimentally found that in microchannel temperature of the wall was lower as well as rate of heat transfer was higher.In this study they used copper oxide – water nanofluids and did not use dispersion additives.Various samples were prepared with different volume concentration in the range of .2 % by vol to .4 % by volume.

The following was observed in the sudy:-

- It was found that at lower flow rates the heat disscipation was higher for nanolfuids as compared to water.
- At higher flow rates the the disctinction is quite negligible.
- Value of temperature of wall was consistenet theoretically as well as experimentally.
- Pressure drop was higher for higher volume concentration.

Satish G Kandlikar. described in detail all the advancements that have been made in field of microchannels. This study was more of a review of the literature available in this field. It discusses the advancements and developments that have been made that helps understand the various processes that takes place in two – phased liquid flow and single – phased liquid flow. It also describes their use in heat disscipating appliacations. It also gives the areas in which further research can be done:-

- Increasing the heat disscipation rate in single phase heat transfer.
- Utilization of flow boiling in microchannel heat sinks.
- He also described that continuum models are verified to work in flow through microchannels.

Saxena et al. has given novel methods for manufacturing of microchannels much more quickly. Laser induce plasma machining is a new method described by him for manufacturing of microchannels. Using this method many materials such as polymers, ceramics, brittle materials as well as hard to process materials can be processed. This method employs an optical system for coverting the laser point into a line. Thus by this methodology microchannels can be manufactured by avoiding scanning as in the regular case.

The scheme of the method is shown and experimental work is conducted on aluminium. Further by varying various variables such as no of exposures,pulp energy and frequency the width of channel as well as the depth of the channel can be changed. The efficiency of laser induced plasma micromachining has been shown to become twenty times.

Zhang et al. chose two different desgns of microchannel for this study and examined these for heat disscipation.The two different types of designs chosen for this study are :- a) U – shaped microchannel b) Straight microchannel design. In this study results are evaluated using numerical methods are employed to find the results. These obtained results then verified by using experimental results.

The first and foremost objective of this study is to further advance these systems and further the applicability of these methods in other systems that are similar to these system. Parametric modeling method is employed to model variables such as pressure drop, thermal resistances well as temperature. Consideration is given to design parameters and conditions of operation such as no of channels, dimension of each channel, rate of flow.

The comprehensive analysis given in this study provides a deep insight into how the different design parameters affect the heat disscipation in straight shaped designed microchannels as well as in U – shaped microchannel. This study also provides significant directions for choosing the various design variables for designing of microchannel heat exchangers.

Dylan et al. has provided method for improving the heat transfer for conventional heat exchangers as well as for compact heat sinks. The main method discussed in this study envolved a) swirl flow b) electric fields c) vibration d) vibration e) inlet region f) boundary layer and g) transition of flow h) secondary flow and i) mixers.

In this study it was found if the heat disscipation increasing methods useful for microchannels.

The methods which proved good in case of microchannels can find applicability in case of other single phase cooling situations.

Manay et al. [31] carried out a numerical study for finding out the heat transfer behavior and pressure drop in case of aluminium oxide nanofluids as well as copper oxide nanofluids. They took samples of different volume concentrations for this study. The samples of various volume concentrations used in this study were :- 0 %,.5 %,1 %,1.5 % and 2 %. The results obtained from numerical study were verified using results obtained from analysis of the literature.

The method of finite volume was employed for solving the mathematical equations . These equations were prepared using heat transfer and mixture model analysis applied to flow. Results are expressed in the form of Nu no, pressure drop and heat transfer. To validate the mixture model they compared this model with Eulerian method and agreement was found.

The following observations were made in this study:-

- The heat disscipation ability of nanofluids was significantly higher than that of base fluid.
- The Nu no varies directly as volume concentration and Re no.
- Copper oxide nanofluids have better heat disscipation ability than aluminium oxide nanoparticles.
- Nanaoparticles have negligible affect on friction factor.
- Friction factor varies as Re no.

Farsad et al. [32] numerically studied flow of nanofluids through microchannels and corresponding heat transfer. They conducted their numerical study on the commericial software FLUENT.

In this study the input temperature was chosen as 22^0C and pressure for the input was chosen as 1 – bar. Only one rate of flow of volume was chosen for this study. The chosen rate of flow of volume in this study was .3 ml/min. The flow velocity was .212m/sec. The different samples prepared of various concentrations are 0 %,2 %,4 %,6 %,8 %. Aluminium oxide – water based nanofluids are used in this study.

The following observations were made in this study:-

- Rate of heat transfer varies directly as rate of volume flow.
- Rate of heat transfer also varies directly with volume concentration.
- Heat transfer was better in case of metal nanofluids than the metal – oxide based nanofluids.

Mohammed et al. [33] studied the heat transfer in triangular geometry of microchannels. They used various nanofluids at the same volume concentration of 2 %. The different nanoparticles used in this study were :- a) Aluminium oxide b) Silver c) copper oxide d) titanium dioxide e) Silicon dioxide f) Diametermond

The following observations were made in this study :-

- The best heat disscipation rate was found in the case of Diametermond and the worst was found in the case of Al_2O_3.
- CuO and TiO_2 have similar heat disscipation capacity.
- Pressure drop was observed in case of nanofluids.
- Maximum pressure drop was in case of SiO_2.
- Silver nanolfluids have the lowest drop in pressure.
- Silver nanofluid has no shear wall stress.
- Copper oxide nanofluids has negligible shear wall stress.
- Silicon dioxide has the maximum shear wall stress.

Hamid et al. [34] numerically studied microchannels using the method of finite volume.In this study aluminium oxide – water nanofluids and copper oxide – water nanofluids were used as heat exchanging fluids. In this study it was studied how the factors such as performance index, efficiency of microchannel and pumping power were affected by phenomenons such as brownan motion and variables such as Re no and volume concentration.

In this study it was observed that :-

- Performance index and efficiency of counter flow microchannel heat exchanger varied direcly as Re no.
- Pumping power also increases with increase in Re no.
- Performance index as well as pumping power are independent of volume concentration.

Xi et al. [35] performed experimental investigations using trapezoidal geometry microchannels.The following observations were made in this study :-

Factors such as :-

- inlet manifolds.
- Design of inlet manifolds.
- Location of the inlet manifold
- Length of the inlet manifold
- Length of the outlet manifold.

Above factors affect the flow.

Chein et al. [36] conducted experiments for silicon microchannels.copper nanoparticles are employed to prepare nanofluids. The dimensions of two different geometries that were used as the microchannels are a) $W_{ch} = w_{fin} = 100$ µm b) $L_{ch} = 300$ µm c) $W_{ch} = W_{fin} = 57$ µm d) $L_{ch} = 365$ µm.

The following observations were made in this study :-

- Microchannels provide high surface to volume ratio which leads to higher heat transfer rates.
- There was no significant change in drop in pressure.

Hrishikesh et al. [37] comprehensively studied how various parameters such as material of the nanoparticle, volume concentration, size of the particle, temperature as well as base fluid affects the heat transfer behavior in the microchannels. In this study it was observed that :-

- Rate of heat transfer varies inversely as size of nanoparticles.
- Thermal conductivity varies directly as temperature.
- Metal oxides have lower thermal conductivity as compared to metal.

Table 2.2: Results of Hrishikesh et al.

Particle material	Base liquid	Temp (°C)	Particle size (nm)	Particle volume fraction (%)	Enhancement (%)	Enhancement predicted by Hamilton-Crosser model

Al_2O_3	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

Tanaz et al. [38] carried out experimental investigation using silicon microchannels. The main objective of this study was to find how the geometry of the microchannel effects the heat disscipation. In this study seven distinct microchannels were considered for study. The width of the microchannels lies in the range 100 µm - 580 µm. The depth of the microchannels was kept at 400 µm for all the microchannels. Fluorinert was the fluid that was employed in this study.

The following observations were made in this study :-

- Above microchannel width of 400 µm the heat transfer coefficient was not dependent on width of the microchannel.
- Heat transfer behavior was found to be dependent on cross section of the microchannel.

Manay et al. [39] carried out experiments to find how the heat transfer in microchannel was afftected by height of the microchannel. Nanofluids used by them were titanium dioxide based nanofluids. Five different samples of different volume concentrations were prepared by them. The volume concentrations were .5 %,1 %,1.5 %,2 %. The different heights of the microchannels were 200 µm, 300 µm, 400 µm, 500 µm. Heat flux of 80 kw/m^2 was supplied to the microchannels.

The following obersvations were made in this study :-

- Heat transfer coefficient varies inversely as height of the microchannel.
- Heat transfer coefficient varies directly as drop in pressure.
- Heat transfer coeffiecient varies directly as volume concentrations of nanofluids.
- Titanium dioxide nanoparticles have negligible effect on drop in pressure.

Wu et al. [40] carried out numerical study of flow through microchannel by using aluminium oxide – water nanofluid. The following observations were made in this study :-

- Al_2O_3 – H_2O nanofluids enhances the heat transfer coefficient and reduces thermal resistance.
- Pumping power varies directly as inlet velocity.

Solovitz et al. [41] gave a model based on which design of microchannel manifold could be advanced. They observed that flow through microchannel lacked uniformity. To find a solution to this problem they devised a model base on which the design of manifold of the microchannel could be modified in such a way so as the non – uniformity of flow in the microchannel could be eliminated.

The following observations were made in the study :-

- The speed of flow was within 3 % SD of mean velocity.
- Non-uniformity of velocity was observed for high values of Re no.
- Tappered manifold designs significantly reduced the uniformity of microchannels.

Chein et al. [42] carried out numerical study to find out how the temperature as well flow is affected by the placing of the inlet or outlet manifold. In this study finite volume analysis was used . Placings aside, all the manifolds have same dimensions.

The following observed in this study :-

- When fluid flow is vertical to the manifold,in this case there was more uniformity.

Xuan et al. used hot wire process to find the thermal conductivity of copper – water nanofluid. It was also observed how the various factors such as volume concentration, particle size affected the thermal conductivity. The following was observed based on this study :-

- For volume concentration ranging between 2.5% - 7.5%,the thermal conductivity became 1.24 – 1.78 times.

CHAPTER 3

EXPERIMENTAL METHODOLOGY AND SETUP

The studies done till now which have used nanofluids as coolant clearly point to the fact that nanofluids provides higher and better heat transfer rates as compared conventional coolants such as oil,ethylene glycol and water. This is due to the fact that these conventional coolants have lower thermal conductivity as compared metals. A large quantity work has been done in field of nanofluids and microchannels but most of these studies envolves numerical investigation. More experimental investigation needs to be done in this area.In all the experimental studies microchannels were used as the heat sinks.In this work experimental investigation has been carried out to study the thermal behavior in microchannels by employing nanofluids as heat transfer fluids. In this study aluminium oxide – water based nanolfuids are employed. These nanofluids are prepared by two – step method of preparation of nanofluids. The microchannels were manufactured by CNC wire cutting methodology.

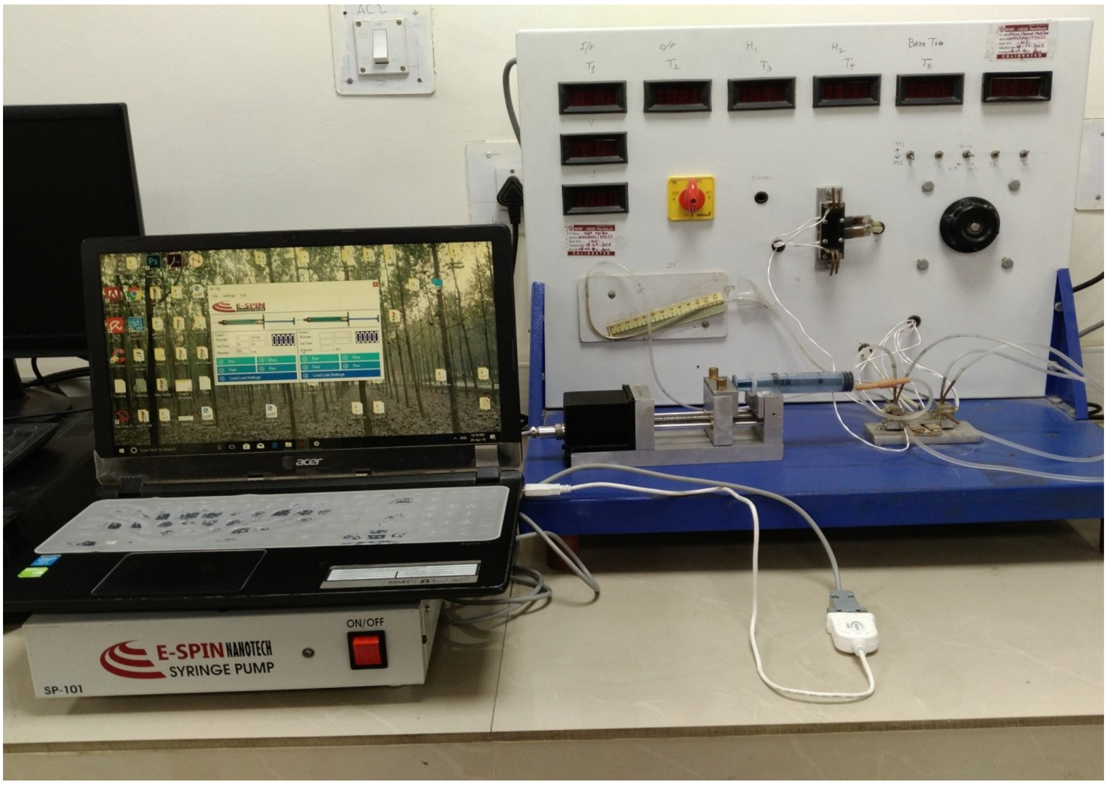


Fig 3.1 Experimental setup

3.1 EXPERIMENTAL LAYOUT

The directions for making the experimental setup was obtained from the literature review which described the effect of aluminium oxide – water nanofluids on the heat idsscipation capacity of microchannels [10]. Experimental apparatus was designed at T.I.E.T Patiala and manufactured at the Global instrument company ambala Haryana.

The experimental apparatus is comprised of the following components :-

- Controller of syringe pumps
- Syringe pumps
- Displays for temperature
- Displays for voltage
- Display for current
- Inclined manometer
- Pt – 100 temperature sensors
- Syringe pump
- Reservior
- Computer
- Heater
- 20 ml syringe
- Connecting cables
- Power supply

Rate of flow through the microchannels was controlled by computer operated syringe pumps. Flow meters were needed in this study since syringe pumps already provide highly precise flow rates. Thus highly accurate rate of flow was achievable by syringe pumps. The heat flux for heating of the microchannels was provided by the heater installed in the setup. This heat flux was controlled by carrying the current and voltage. Further the current and voltage were controlled by a dimmerstat provided in the setup. The nanofluids after pasing through the microchannels go into the reservoir. In this study single pass flow is considered. However the study could also be conducted using continuous flow. The main issue of leakage in microchannels is solved by using grease paper.

The various temperature sensors are as follows :-

- Inlet and outlet temperature sensors :- T_1,T_2,T_3.
- Temperature of the heated wall :- T_4.
- Temperature of the reservoir :- T_5.

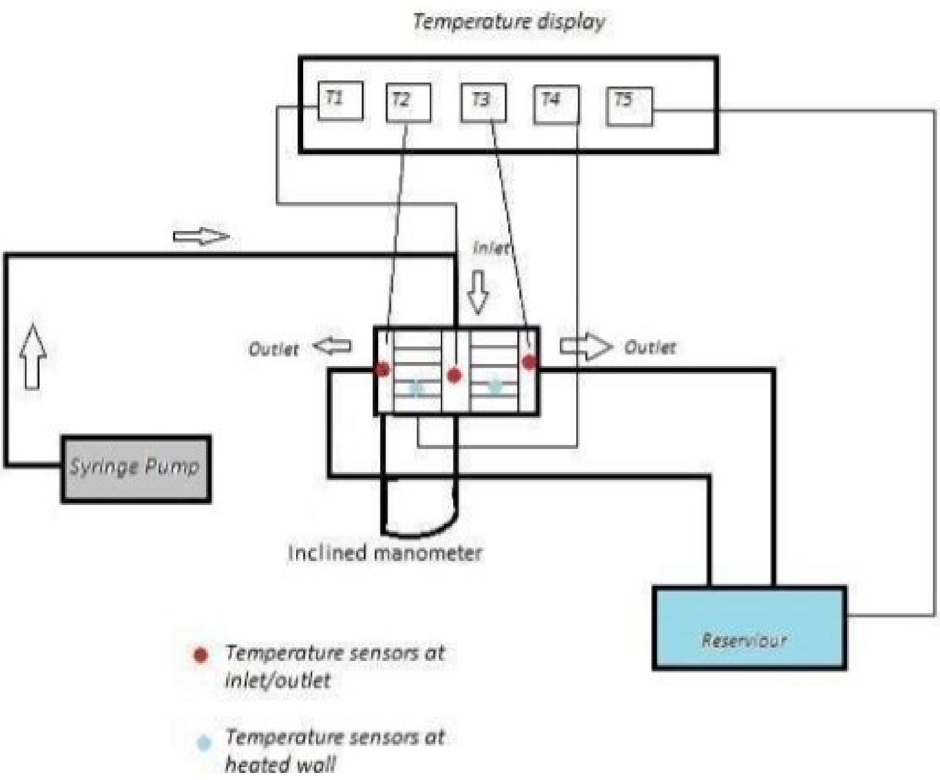


Fig 3.2 layout of setup

3.2 DESCRIPTION OF VARIOUS DEVICES

Following is the description of various device used in the experiment :-

3.2.1 Syringe pump

They form the main part of the experimental apparatus.Syringe pumps are devices that cause the nanofluids to flow through the microchannels. They provide the required pressure to flow the nanofluids through the microchannels. Syringe pumps can provide constant flow rates through the microchannels ofr set duration of time with very high degree of accuracy. Since syringe pumps are highly accurate, there is no requirement of flow meter in the passage. The syringe pumps used in this study have been procured from E-spin nanotech, Kanpur, UP.

The following table provides the specification of the syringe pumps :-

Table 3.1 Configuration of syringe

CONFIGURATION	
Type of pass	Single pass
Syringe Diameter	20mm
Maximum flow rate (with 20 ml syringe)	2 ml/min
Control unit	Separated 1. USB to serial cable 2. Serial converter 3. Serial cable (for connecting syringe pump controller to RS-232 converter) 4. Syringe pump controller 5. 4 pin connector
Syringe	20 ml
Voltage	220 V, AC, 50 Hz

Fig 3.3 is the image of a syringe pump.The various connections of the pump system is shown in fig 3.4.Fig 3.5 shows the software interface

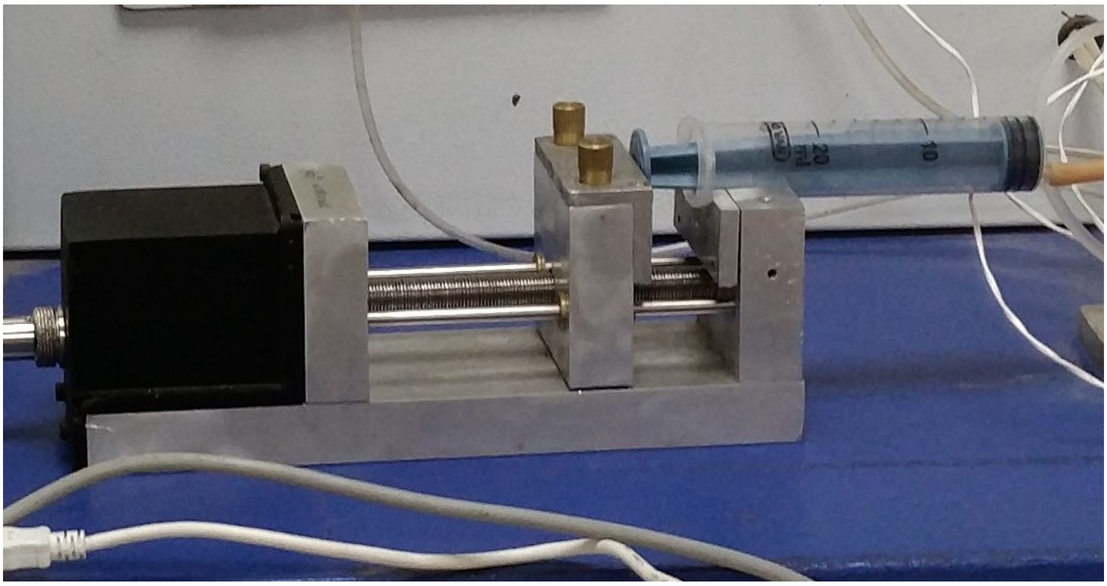


Fig 3.3 syringe pump

Fig 3.4 various connection on pump comtroller

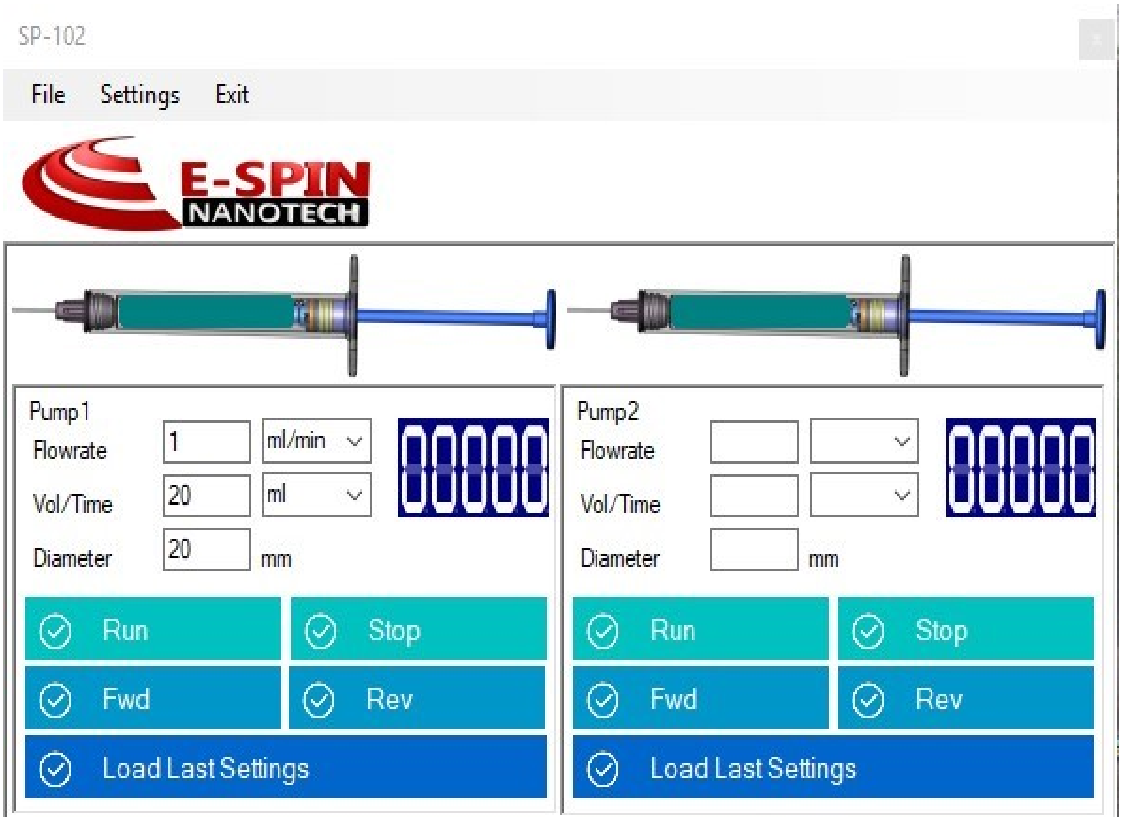


Fig 3.5 software interface

The syringe pumps are computer controlled and are operated through software interface which is installed on the computer from CD provided with the syringe pumps.The name of the software installed on the computer for operating the syringe pumps is SP – 102. Various inputs are feeded into the software and the syringe pumps work according to these inputs.The various input parameters required to be feeded into the software before operation are :- a) Diameter of syringe b) rate of volume flow c) Volume of the syringe d) Time duration for which the experiment is to run.According to the feeded inputs the computer computes the revolutions per minute of the motor. This information is then fed to the syringe pump controller. The controller then provides input to the syringe pump.

3.2.2 DESCRIPTION OF MICROCHANNELS

Small channels with hudraulic Diameter in the range of 10 µm to 200 µm are known as microchannels. Microchannels can have various geometries and cross sections. Different geometry of microchannels have different type of effect on heat transfer. The microchannel geometry used in this study is rectangular geometry. Microchannels can be manufactured using various methods. CNC wire cutting is one such method which is used manufacturing microchannels used in this study. The material of the microchannel used in this study is aluminium. There are three temperature sensors, two temperature sensors are at the outlet and one temperature sensor is at the inlet. To prevent leakage from top surface grease paper is used.

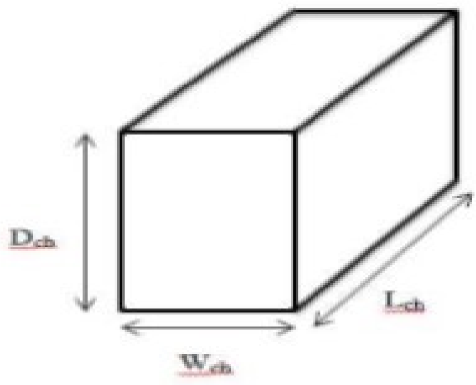


Fig 3.6 Microchannel Geometry

The table shows the dimensions of the microchannels Table 3.2

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

The major conern in fabrication of microchannel revolves around availability of cost effective fabrication facilities. Enough time was invested in finding out the best alternatives for cost effective manufacturing facility and following best alternatives were chosen :-

- CNC wire cutting technique was found to be the most cost effective technique for manufacturing of microchannels and was also available at location from where transportation was also viable.
- The width of the microchannel was chosen as .25 mm since it is the limiting width which can be produced from CNC wire cutting.
- Only rectangular geometry of microchannel can be manufactured by CNC wire cutting this fixes the geometry of microchannel.

- Kandlikar et al [43] has shown that highest heat transfer occurs corresponding to aspect ratio of 8. This leads to depth of microchannel as 2 mm.
- The Diameter for inlet and outlet manifold pipes is fixed to 2.5 millimetre due to availability constraint.

3.2.3 HEATERS

The heater used in the study is a low watt heater with a adjustable variate.These low watt heater have a wattage rating of only 35 W. These heater are highly effective in adjusting the heat fluc to the microchannels. The heat flux can be controlled with help of a adjustable variate. Using these heaters the temperature can be kept at a constant 40^0 C . The temperature can be increased further by adjusting the variate. These heater allows us to maintain the temperature in required range successfully.

3.2.4 DESCRIPTION OF TEMPERATURE SENSORS

The temperature sensors employed in this study are PT – 100. These temperature sensors are highly accurate temperature sensors for the measurements of temperature. These temperature sensors encapsulate the concept of resistance thermometers. The concept is that the resistivity of sensor changes with change in temperature. These temperature sensors are also more preferred as compared to thermo – couple sensors due to high precision. The description of PT – 100 is as follows :-

- PT = Platinum
- 100 = Resistance of the sensor i.e 100 **Ω**

6 temperature sensors were at following locations :-

- 3 – for flow temp
- 2 – for wall temp
- 1 – Reservior

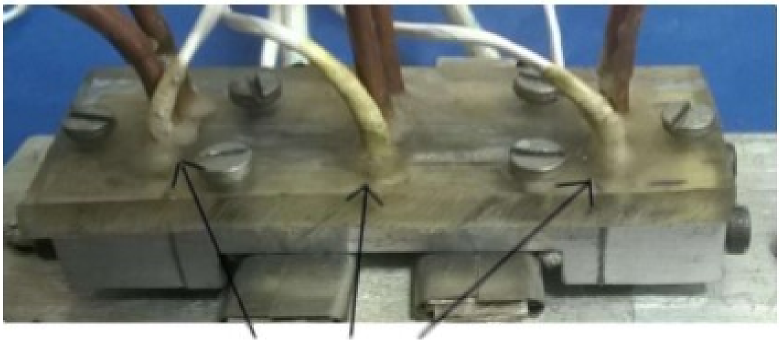


Fig 3.7 temperature sensors

3.2.5 DETAILS ABOUT CALIBRATION

The calibration was done at NIIRT – Lab situated at Industrial area, Panchkula,Haryana. The calibration is valid for one year from the date on which calibration was done. The calibration was done and the report was provided. Fig 3.8 shows stamp of calibration on the experimental apparatus.

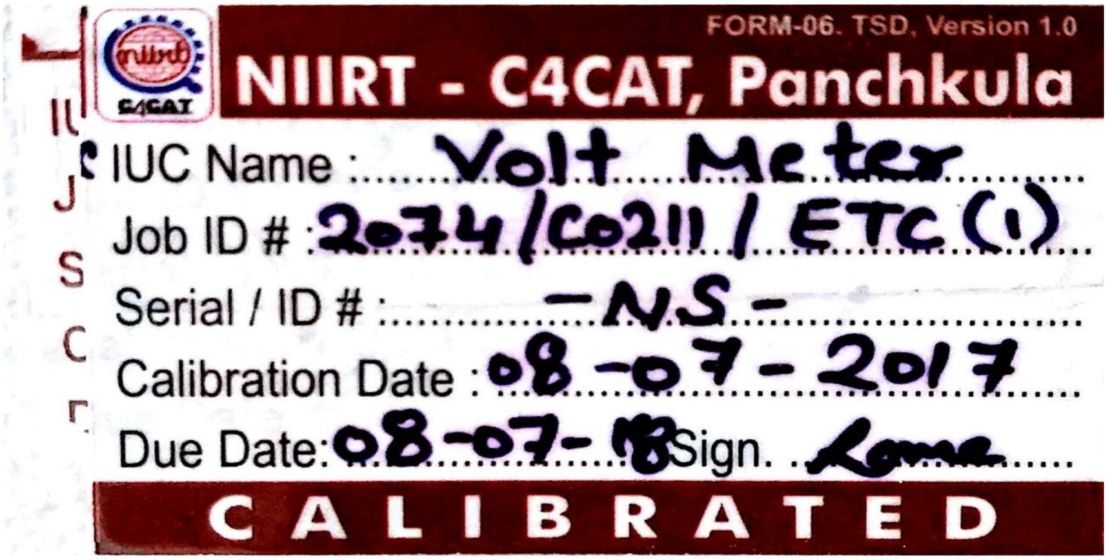


Fig 3.8 Calibration stamp

3.3 NANOFLUIDS PREPARATION

Nanofluids can be prepared by the following two methods :-

- One – step method
- Two step method

In this study two – step method has been employed for preparation of nanofluids. The two – step process of preparation of nanofluids has the following steps :-

- Preparation if nanofluids
- Dispersion of nanofluids in the base fluid

Table 3.3 Specs of nanoparticles

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

In this study for preparing the nanofluids, nanoparticles were dispersed in the DI water which acts as the base fluid. Four different samples were prepared with volume concentrations of 0 %, .2 %, .3 %, .6 %. Four distinct volume flow rates are chosen for each of the volume concentrations. The four distinct volume flow rates are .5 ml/min, 1 ml/min, 1.5 ml/min and 2 ml/min. In this study surfactants and additives were not added to nanofluids as these can alster the properties of the nanolfuids. Aluminium oxide – water nanofluids have higher stability and thus experimentation with them was much more comfortable. Ultra – sonication is done for 90 min to increase the stability nanofluids.

3.3.1 APPARATUS

- Ultrasonic oscillator
- Measuring flask
- 2 beakers of 150 ml each
- Hot plate magnetic stirrer
- Spatula
- Magnetic bead

Fig of these apparatus is shown in following pages

Fig 3.9 apparatus for nanofluids preparation

Fig 3.10 hot plate magnetic stirrer

Fig 3.11 ultrasonicator

For calculating the weight of nanoparticles required for preparing different samples of nanofluids mixture formulae was used which is stated in formule section. The required weight of nanoparticles for making each sample of nanofluids was first calculated using this formulae and then the next step of mixing the nanoparticles with base fluid was done followed by ultrasonication.

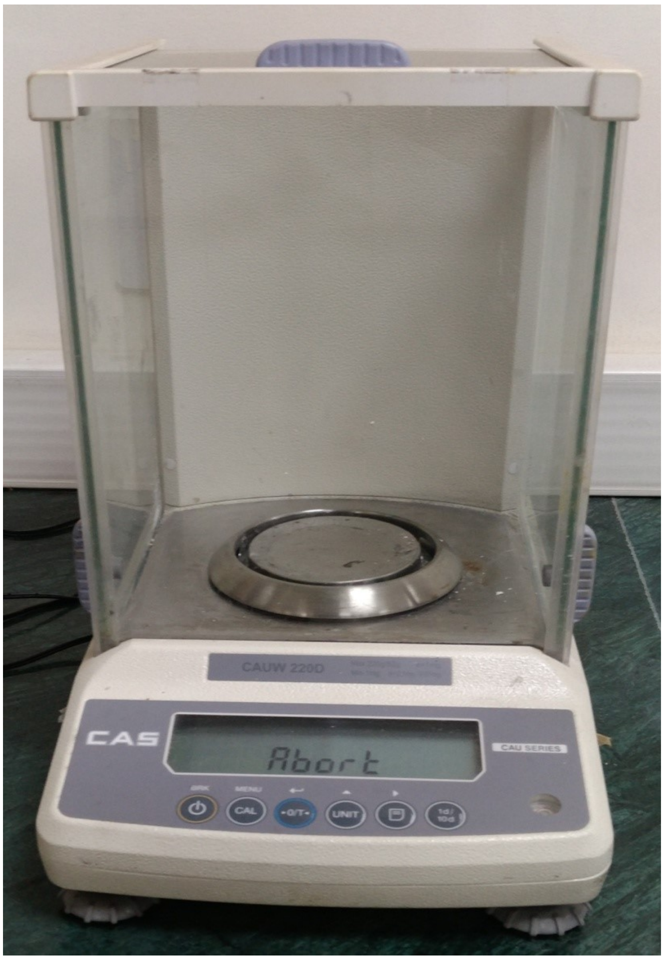


Fig 3.12 High precision weighing machine

The weight of the nanoparticles, precision weighing m/c was used. DI water was taken in a predetermined quantity and was put into a beaker. A magnetic bead is placed in the beaker and then it is placed on a hot plate magnetic stirrer. The hot plate magnetic stirrer was maintained at room temp. Following are the few steps that have to be kept in mind while following the above procedure :-

- High temperature has an effect on the stability of nanoparticles, therefore a close eye is need to be kept on the temperature.
- It should be made sure that nanoparticles nanoparticles are put into the beaker in one go. There should be slow pouring of the nanoparticles into the beaker with waiting in between two pouring, so that nanoparticles get enough time to scatter in the base fluid.
- The nanopartciles should be poured into the base fluid with constant stirring.

- Magnetic stirring is done for 20 min and after this the beaker containing nanolfuid is removed from the hote plate magnetic stirrer.
- After stirring for 20 min in the hot plate magnetic stirrer the beaker is placed into ultrasonicator and ultrasonication is done for 90 min.
- Before using the ultrasonicator it should be made sure that the water level in the ultrasonicator is according to the specification of the ultrasonictor. If the water level is not correct than water should be filled into ultrasonicator.
- The temperature of the beaker increases with time period of ultrasonication thus the temperature should be checked regularly to ensure that the temperature is not too high as high temperature leads to instability and agglomeration in nanofluids.
- After 90 min of ultrasonication remove the beaker from the ultrasonicator and switch off the ultrasonicator.

3.4 METHODOLOGY

The experimental apparatus consists of the following components :-

- Syringe pumps
- Syringe pump controller
- Microchannel
- Other needables

Our main center of attention is the microchannels which are made of aluminium and all the experimentation is carried out on the microchannel. The number of temperatures sensors and there location on microchannel has been discussed previously. The readings were taken in the following manner: -

- Readings with DI water as coolant fluid is taken.
- Nanofluids DI water is replaced by nanofluids and the processes is repeated.

The variables in this study are volume flow rate, volume concentration. The values of the parameters for which the readings were taken are shown in table 3.4.

Table 3.4 shows the parameters

Flow rate(ml/min)	0.5	1	1.5	2
Conc .(vol %)	0	0.2	0.3	0.6

The experimental procedure envolced following steps :-

- Microchannel assembly is switched on and temperature is set with dimmerstat.
- Pt – 100 temperature sensors were employed at various places for temperature recording.
- The data regarding flow rate, volume of the syringe and Diameter of the syringe is feeded into software interface.
- After feeding of the data into the software interface press run button and the nanolfuid will begin flowing through the microchannels.
- Wait is done for so that steady state is reached and then temperature readings are noted down.
- DI water is used to prevent corrosion.
- Readings were taken in each experiment by fixing concentration and then varying the the concentration from .2 ml/min to .6 ml/min in increasing order.
- For each sample four experiments are conducted corresponding to each flow rate.
- For 1ml/min of volume flow rate 20 ml syringe was used and in case of 1.5 ml/min of volume flow rate as well as 2 ml/min of volume flow rate 50 ml syringle was sufficient.
- Value of temperature is noted down for all the different combinations of volume concentration and volume flow rate.
- Same process was followed for all the experiments envolving different volume concentrations.

3.5 FORMULAE USED

Various different experiments were conducted in this study. For each of the experiments similar process was followed. Firstly the experiments are conducted by using distilled water and temperature readings are taken by conducting the experiments for four different flow rates. Then distilled water was replaced by nanofluids. Four different samples of nanofluid were prepared and temperature readings were taken for each experiment corresponding to four different flow rates. The following equations are used in this experiment :-

Hydraulic Diameter is very important variable in this experimental study and it is calculated by the following equation :-

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

Where D_h = hydraulic Diameter

P = Perimeter of microchannel

A_c = area of cross section

Reynolds no :- It is defined as the ratio of inertia force to viscous force and it is calculated according to the following formulae :-

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

Where

V = avg flow vel.

ϑ = Kinematic viscousity

D_h = Hydraulic Diameter

The average velocity can be calculated using the following formulae :-

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

Where,

N = no of microchannels

P = density of nanofluid

The heat transferred to working fluid is given by the formulae :-

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

Here,

C_p = specific heat

T_0 = outlet temperature

T_i = inlet temperature

The mean temperature difference which is required for further calculations can be calculated using the formulae :-

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

Here,

T_1, T_2, T_3, T_4, T_5 = temperature at various positions in the microchannel.

Heat transfer coefficient has been calcylated by using the following formulae :-

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

Where,

H = convective heat transfer coefficient

A_w = surface area of single microchannel passage through which heat transfer occurs.

In this study the microchannels have double side flow, thus for calculating overall heat transfer coefficient following formulae can be used :-

$$\frac{1}{UA} = \frac{1}{h_1 A_1} + \frac{1}{h_2 A_2}$$

Here,

U = overall heat transfer coefficient

h_1 = heat transfer coefficient on first side

h_2 = heat transfer coefficient on the second side

A_1 = heat transfer area of the first side

A_2 = heat transfer area of the second side

The various formulae used for calculating the thermo – physical properties of nanofluids are discussed below :-

- Thermal conductivity is calculated using the following formulae [9] :-

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

- Dynamic viscousity can be calculated by following formulae [9] :-

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

- Formulae for specific heat [9] :-

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

- For calculating density following formulae was used [9] :-

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

ρ = density

ϕ = volume concentration

μ_f =viscouity of base fluid

μ_{nf} = viscousity of nanofluid

k = thermal conductivity

Nusselt number :- It is defined as the ratio of rate of convective heat transfer to the the rate of conductive heat transfer. The Nusselt no is calculated by the following formulae :-

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

Prandtl number :- It is defined as the ratio of momentum diffusivity to thermal diffusivity. It is calculated by the following formulae :-

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

CHAPTER 4

RESULTS AND DISCUSSIONS

The value of heat transfer coefficient was calculated for various particle volume concentrations as well flow rates and this variation of heat transfer coefficient with particle volume concentration as well as volume flow rates is then plotted on a graph. Heat transfer coefficient for distilled water is calculated at four different volume flow rates and the results were then graphically compared with the nanofluids. Also the effect of Reynolds number and Nusselt number is also studied on the heat transfer coefficient. The results are represented in the form of graphs with requiste discussion.

4.1 HEAT TRANSFER

4.1.1 HEAT TRANSFER COEFFICIENT

This study was conducted with a view to enhance the heat transfer coefficient in the microchannels by utilization of nanofluids as heat transfer fluid. For this purpose alimunium oxide – water based nanofluids were prepared in four different samples with different volume concentrations.

There are two ways to increase the heat transfer coefficient in the microchannels by :-

- By increasing the particle volume concentration of nanofluids.
- By increasing the volume flow rate of the nanofluids through the microchannels.

The heat transfer capability of the heat transfer fluid can be increased by using nanofluids. The volume flow rate can be increased with help of high precision computer controlled syringe pumps.

Since the microchannels used in this study have two way flow, thus an over all heat transfer coefficient is calculated for various combinations of particle volume concentration and volume flow rate. The graphical comparison is shown in fig 4.1:-

The main results from the above experiment are :-

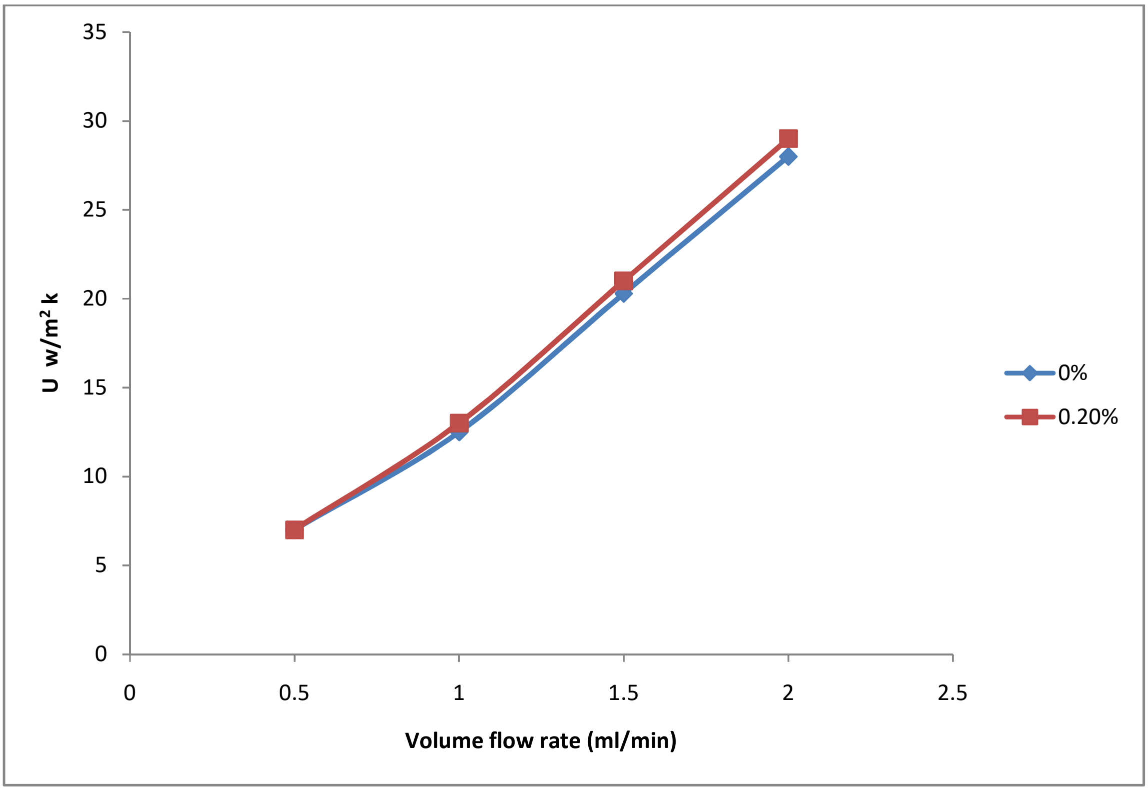


Fig 4.1 Results for .2 % volume concentration

- The experiment was conducted by using nanofluid of .2 % volume concentration as the heat transfer fluid.
- The above graph represents the variation of heat transfer coefficient with volume flow rate.
- The results are compared with that obtained by using water as the cooling fluid.
- From the above graph it can be seen that the trend of heat transfer coefficient with the volume flow rate is consistent for both water as well as aluminiumoxide – water based nanofluid.
- The difference between heat transfer coefficient in case aluminium oxide – water based nanodluid in comparison to water is not very high.

  Here it is clear that for sample of .2 % volume concentration there has been an increase in the heat transfer coefficient but at this volume concentration it is not a very significant increase.

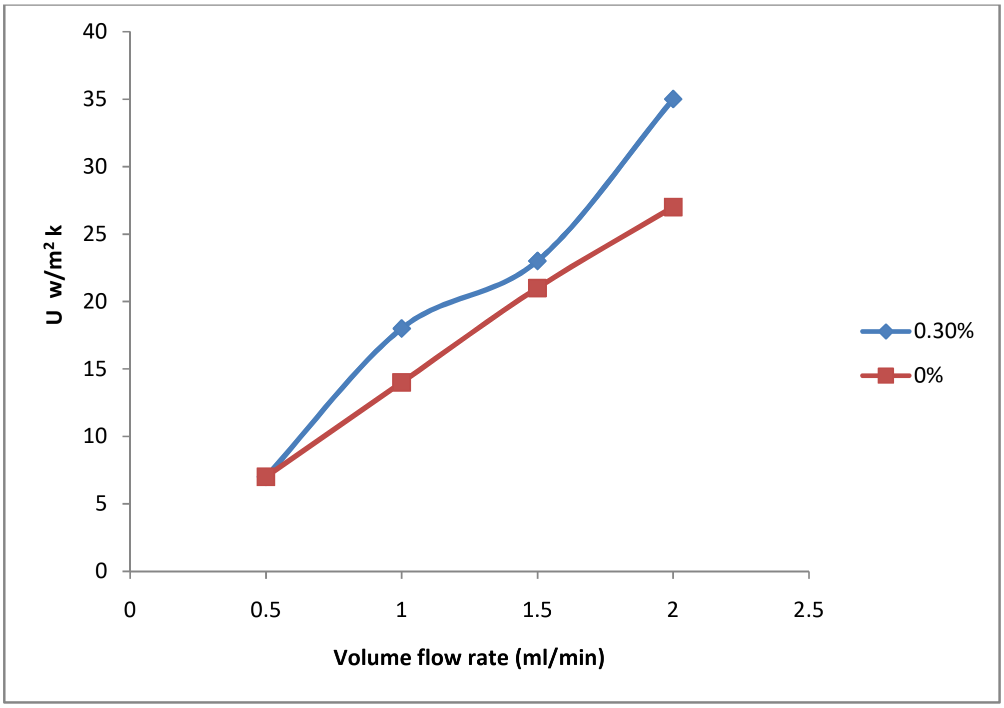


Fig 4.2 Results for .3 % volume concentration

The above graph shows the results of experiments that were conducted for finding the heat transfer coefficient at four different flow rates by using aluminium oxide – water nanolfuids with volume concentration of .3 % by volume.

- The results obtained are compared with that obtained with water as cooling fluid.
- The trend for heat transfer coefficient as shown in the above graph is similar to that obtained in case of .2 % volume concentration as well as the results that are obtained in case of water.
- The heat transfer coefficient is continuously increasing with increase in volume flow rates which clearly shows that heat transfer coefficient increases with increase in volume flow rate.
- By using aluminium oxide – water based nanofluid of volume concentration .3 % a greater increase of heat transfer coefficient is noticed as compared to .2 % volume concentration of nanofluid.

The above results in case of .3 % volume concentration imply that heat transfer coefficient increases with increase in volume flow rate as well as volume concentration.

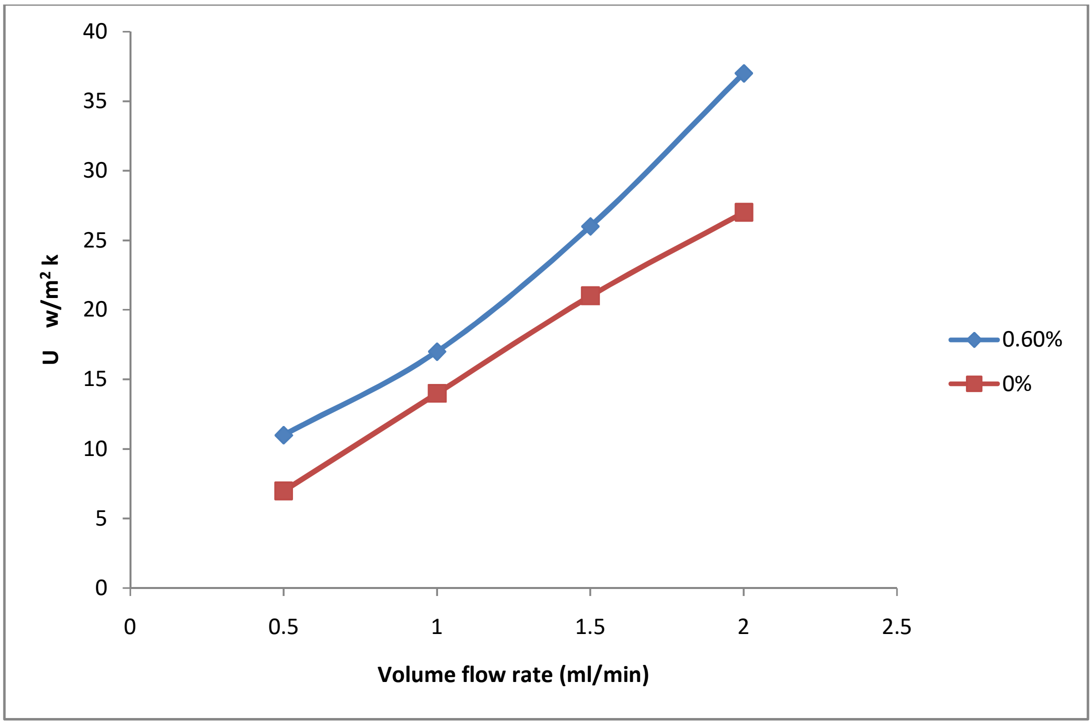


Fig 4.3 Results for .6 % volume concentration

- The above graph shows the results of experiments that were conducted for finding the heat transfer coefficient at four different flow rates by using aluminium oxide – water nanolfuids with volume concentration of .6 % by volume.
- The above graph represents the variation of heat transfer coefficient with volume flow rate.
- The results obtained are compared with that obtained with water as cooling fluid.
- The trend for heat transfer coefficient as shown in the above graph is similar to that obtained in case of .2 % volume concentration and .3 % volume concentration as well as the results that are obtained in case of water.
- The heat transfer coefficient is continuously increasing with increase in volume flow rates which clearly shows that heat transfer coefficient increases with increase in volume flow rate at this concentration.
- By using aluminium oxide – water based nanofluid of volume concentration .6 % a greater increase of heat transfer coefficient is noticed as compared to .3 % volume concentration and .3 % volume concentration of nanofluid as well water.

From the results obtained from the experimentation performed by using different combinations of volume flow rate and aluminium oxide – nanofluid volume concentration, the following can be concluded :-

- With increase in volume flow rate , the heat transfer coefficient always increases for every concentration of nanofluids as well as water.
- The heat transfer rate also increases with the volume concentration of the nanofluids that is at higher concentration of the aluminium oxide – water based nanofluids the heat transfer coefficient is also higher.
- Thus high heat transfer coefficient is obtained by using higher volume concentration of nanofluids as well as higher flow rates.

4.2 PRANDTL NUMBER

Prandtl no is a property of a very high significance of the nanofluids. It has a significant effect on the heat transfer characteristics of the nanofluids. Thus it is imperitive to find how the Prandtl no is afftected by the volume concentration of the nanofluid.

Prandtl no is defined as following :-

It is the ratio of momentum diffusivity to thermal diffusivity.

The prandtl no is the property of the fluid and its value relies on dynamic viscousity, thermal conductivity as well as specific heat of the nanofluids. The value of these three variables is reliant on volume concentration as well as temperature. Fig 4.4 shows the represents the variation of Prandtl no with volume concentration of the nanofluid. From the this trend it is interpreted that the Prandtl no varies directly with particle volume concentration of the aluminium oxide – water based nanofluids. It provides a strong case for the usage of nanofluids. Based on calculations done in this study it is shown that prandtl no can be boosted by 24 % by using higher particle volume concentration. Thus by using aluminium oxide – water based nanofluids of high concentrations a better value of Prandtl no can be obtained. Now viscosity as well as thermal conductivity varies directly with particle volume concentration of the aluminium oxide – water based nanofluids but the specific heat of nanofluids varies inversely with the particle volume concentration. The viscosity has a much more profound effect on the value of Prandtl no as compared to other variables, thus it is imperitive that the value of the Prandtl no becomes higher with higher values viscosity. Thus the viscosity overshadows the role of thermal conductivity in determining the value of Prandtl no.

Hence it also points to the fact that thermal diffusivity varies directly with particle volume concentrations of the aluminuim oxide – water based nanofluids. Vajjha et al [44] has given the variation of Prandtl no of the nanofluids with the temperature. In the study they have used copper oxide, silicon dioxide as well as alumiunium oxide nanoparticles based nanofluids. Particle volume concentration of .6 % was chosen for this study. They have shown that prandtl no varies directly with temperature.

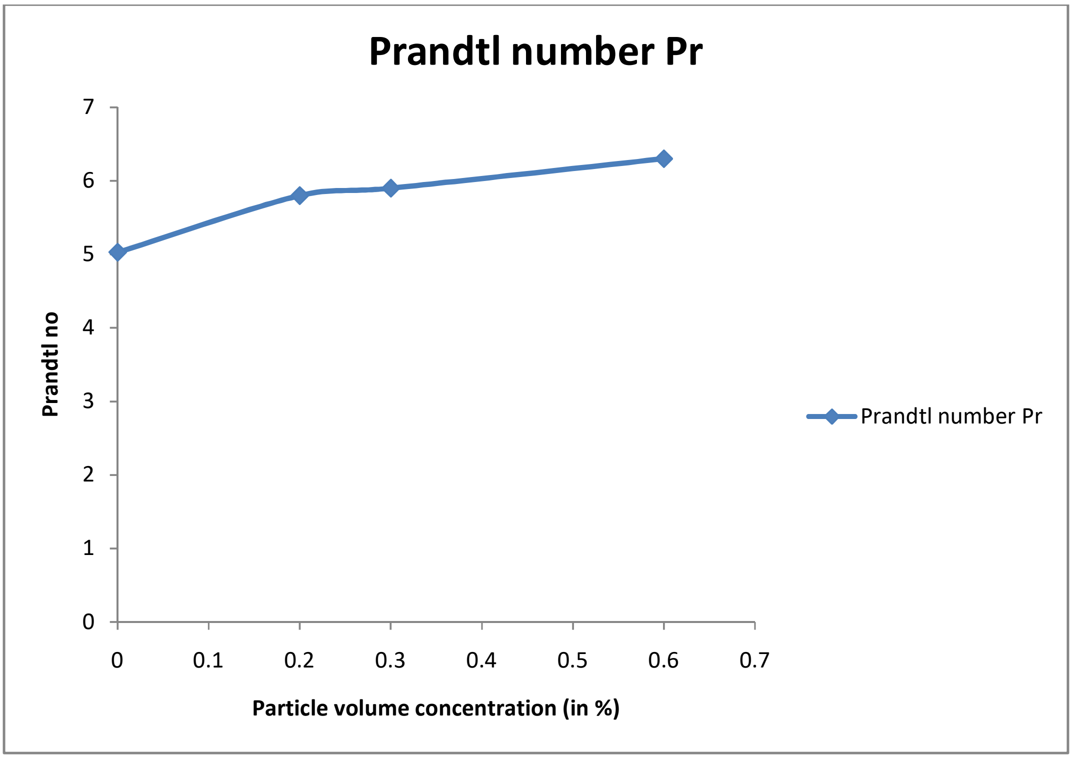


Fig 4.4 Prandtl number variation with concentration

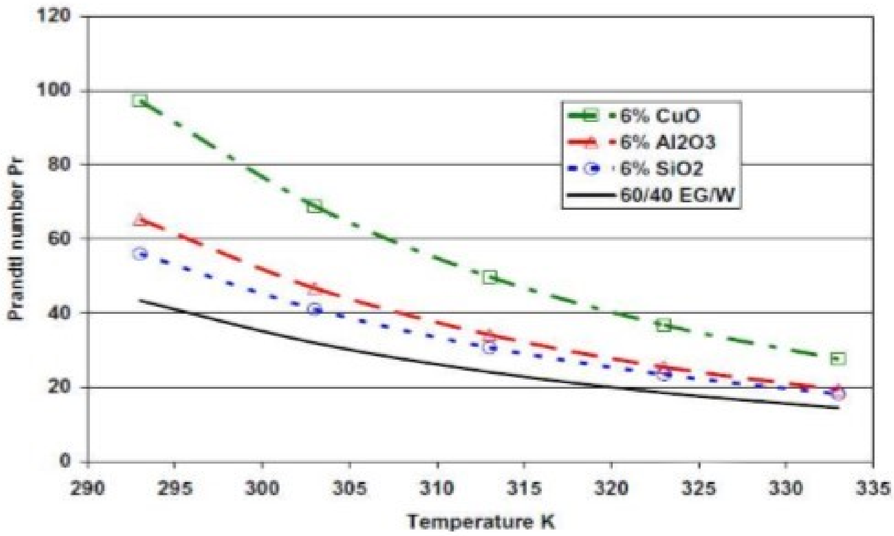


Fig 4.5: Temperature dependency of Prandtl number [44]

4.3 REYNOLDS NUMBER

Reynolds no can be defined as follows :-

It is the ratio of inertia force to viscous force. A higher viscosity of the fluid increases the required pumpimp power. It is a very important thermo – physical property of the nanofluid. It is therefore imperitive to find how the Reynolds no varies with volume concentration of the nanofluids. For keeping the experimental conditions similar for experimentation with different samples of nanofluids the variables such as velocity as well as Diameter are fixed. In the graph it is observed that the Reynolds no varies inversely with particle volume concentration for each value of volume flow rate. The viscosity of nanofluids vary directly with particle volume concentration of nanofluid. However there is a significant increment in the value of the viscousity as compared to the increment in the density and this leads to the viscous force overshadowing the inertia force. This further leads to decrement in the value of Reynolds no.

In the preceding two passages discussing about the Prandtl number and Reynolds number, it has been presented that increasing particle volume concentrations of the nanofluids leads to higher value of Prandtl no but lower values for Reynolds no. Thus at greater particle volume concentrations the value of Prandtl is greater but at lesser particle volume concentrations the value of Reynolds no is greater. Hence it becomes imperitive to consider both Reynolds no and Prandtl no to find the best balance as both have a positive effect on heat transfer.

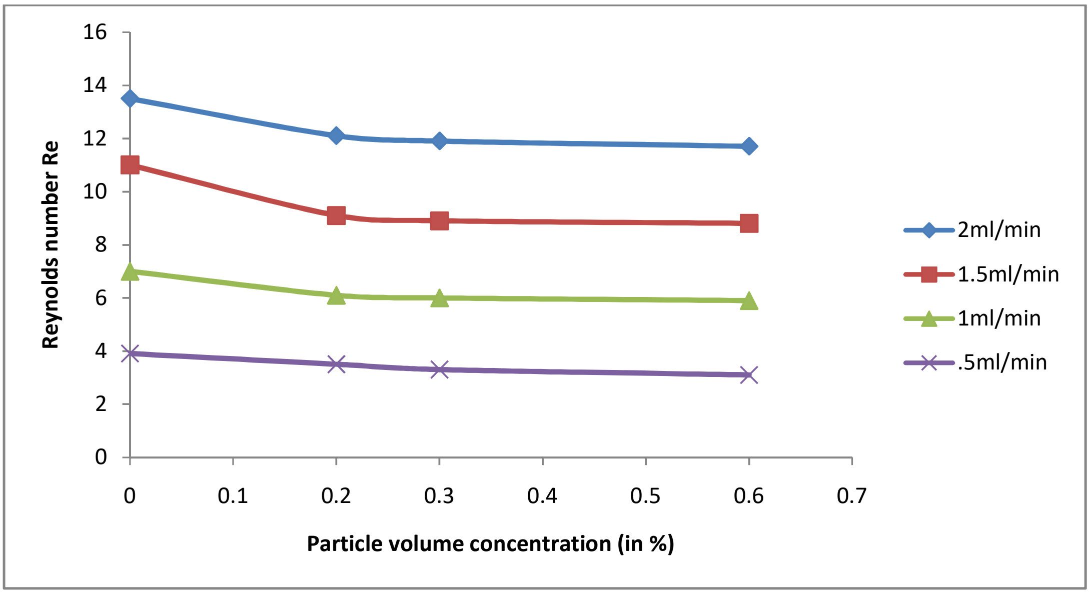


Fig 4.6 Reynolds no variation with conc.

CHAPTER 5

CONCLUSIONS

In this study experiments have been conducted to find the effect of aluminium oxide – water based nanofluids on the heat transfer through through microchannels.The microchannels used in this study are split flow type microchannels. Experiments were conducted by employing pure water and alumiunium oxide – water based nanofluids as cooling fluids. Various samples of nanofluids that were prepared had the particle volume concentrations of .2 %,.3 % and .6 % by volume. The four different volume flow rates used in this study are .5 ml/min,1 ml/min,1.5 ml/min,2 ml/min.

5.1 THERMO – PHYSICAL PROPERTIES

- As compared to water the aluminium oxide – water based nanofluids showed better thermo – physical properties. The nanofluids showed a higher and better thermal conductivity which has been a major area of interest for many researchers. A significant increment of 5.75 % is observed as compared to water at the particle volume concentration of .6 % for alumiunium oxide – water based nanofluid.
- Wu et al [9] has given a method for calculating the specific heat of the nanofluid and this method has been used in this study as well. The nanofluids have lower specific heat as compared to water. Also specific heat varies inversely with particle volume concentration of the nanofluid.
- Viscosity of the nanofluids vary directly with particle volume concentration of the nanofluids. A higher viscousity tends to elevate the required pumping power for fluid flow through the microchannels.

5.2 Heat transfer through microchannels

The heat transfer through microchannels has been observed at different combinations of particle volume concentrations of nanofluids and volume flow rates. The variation of various variables such as Reynolds no, heat transfer coefficient, Prandtl no with volume flow rate as well particle volume concentration is established.

- In this study it has been observed that Reynolds number varies inversely with particle volume concentration. A decrement of 19 % is observed for nanofluids as compared to water in case of particle volume concentration of .6 % by volume.
- Heat transfer coefficient has seen an increment of 35 % for nanofluids of .6 % particle volume concentration at the volume flow rate of 2 ml/min. The temperature readings are taken for each combination of particle volume concentration and volume flow rate.
- The value of Prandtl no depends upon particle volume concentration as well as temperature. It can be defined as the ratio of momentum diffusivity to thermal diffusivity. The prandtl number positively affects the heat transfer through microchannels. It varies directly with particle volume concentration. An increment of 25 % in Prandtl nmber is observed in case of nanofluid as compared to water.

CHAPTER 6

FUTURE SCOPE

In this study experiments were conducted by using aluminium oxide – water based nanofluids as cooling fluid. A split flow type microchannel is used as a heat exchanger. Four different samples of aluminium oxide – water based nanofluids were prepared with particle volume concentrations of .2 %, 3 % and .6 % by volume. Four different flow rates were used Although quite a bit of research has been done in the field of microchannels and nanofluids but still there is a long way to go till nanofluids and microchannels find practical applications. Following are the main areas of consideration for future research :-

- During experimental study researchers often find inconsistencies in the experimental and theoretical results which is one of the prominent problems researchers face even to this day. Thus there is need to develop new methodology to deal with this problem. Due to this descrepancies between experimental as well as theoretical results it has become imperitive to find out what factors play a role in creating this discrepancy.
- For practical applications of nanofluids, stability of nanofluids plays a major role. Thus it is an important area where future research can be focused. New methodologies can we developed for preparing the nanofluids which could make the nanofluids more stable without changing the thermal characterisitics of the nanofluids.Stability of the nanofluids can be enhanced by stability increasing substances that are added to the nanofluids. This are also represents an area where further investigative studies can be carried out and better such substances can prepared or can be found.
- Roughnes effects in microchannels can lead to various phenomenons such as eddies and recirculation. Today researchers are using numerical investigative techniques to find out the effect of these phenomenons. But problem lies in the experimentally validating the findings obtained from the numerical research.

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