MODELING AND COMPUTATIONAL INVESTIGATION ON THERMOHYDRAULIC CHARACTERIZATION OF MICROCHANNELS USED FOR COOLING OF TURBINE BLADES

DISSERTATION-II

Submitted In partial fulfillment of requirement for the award of the degree of

MASTER OF TECHNOLOGY IN THERMAL ENGINEERING

By

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APRIL 2017

CERTIFICATE

I hereby certify that the thesis work of dissertation-1 which is being presented here entitled "***Modelling and computational investigation on Thermohydraulic characterization of microchannels used for cooling of turbine blades***" in partial fulfillment of the requirement for the award of degree of **Master of Technology** and submitted in Department of Mechanical Engineering, Lovely Professional University, Punjab, is an authentic record of my own work carried out during period of Dissertation under the supervision of ***Mr. Aashish Sharma (Assistant Professor)***, Department of Mechanical Engineering (Thermal engineering), Lovely Professional University, Punjab.

The material presented in this thesis report has not been submitted by me anywhere for the award of any other degree or to any other institute.

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___The external viva-voce examination of the student was held on successfully _____

Signature of Examiner

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ACKNOWLEDGEMENT

I have taken my sincere efforts in this thesis work of dissertation-II, However, it would not have been possible without the kind support and help of many individuals and organization. I would like to extend my sincere thanks to all of them.

I am highly indebted to ***Mr*. *Aashish Sharma (Assistant Professor), Department of Mechanical Engineering, Lovely Professional University*** for his guidance and constant supervision as well as for providing all the necessary information regarding my thesis work & also for his support in discussing about the selected topic.

I want to extend my sincere gratitude to ***Mr. Ram Kunwar (Former Assistant Professor)*, *Department of Mechanical Engineering, Lovely Professional University*** for providing better understanding of mechanics of fluid flow in microchannels and the opportunity to implementation of idea into physical application.

I also want to show my deep appreciation to ***Dr. Raja Sekhar Dhondapati (Assistant Professor), Department of Mechanical Engineering, Lovely Professional University*** for providing guidance about heat transfer mechanics in microchannels and knowledge about the working interface of ***COMPUTATIONAL FLUID DYNAMICS*** software ***ICEM*** and ***FLUENT*** to perform the numerical analysis of this research.

Thanking You,

Jeet Prakash Sharma

11502396

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ABSTRACT

The increasing demand for the miniaturizing the instruments is the primary focus area as per making products light in weight , cost effective , faster in operation and more reliable has compelled all industries to develop new ways to face the upcoming challenges for designing and operation of the thermal system. Microchannel heat exchanger technology is emerging swiftly and finding its applications in all the technical areas of the world. Microchannel heat exchanger is said to be the future of heat exchanger technology as it is appearing as game changing technology in cooling applications.

A computational investigation that predict fluidic and thermal characteristics of flow of Liquid Nitrogen (LN_2) and Liquid Hydrogen (LH_2) at the temperature of 65 K in circular microchannels, diameter ranging from 1µm to 100µm and the length 0.1 meter. This study shows the effects of increasing mass flow rate (0.5 gram/sec to 10 gram/sec) over the wide range of diameters of microchannels. The flow of liquid nitrogen and liquid hydrogen in microchannels was considered as incompressible flow and fully turbulent additionally the effects of pressure drop over the wide range of Reynolds number and also the effects of heat transfer co-efficient over the long range of mass-flow rate were observed.

Microchannel offers some astonishing advantages in heat transfer applications because of their high surface to volume ratio small volume. Due to the large surface to volume ratio Microchannels are capable of providing very high rate heat transfer. This specific property of Microchannels can be used to develop some new and far better kinds of micro heat exchangers. Microchannels are being considered as in the next generation because of their excellent new emerging applications in the cooling technology in various sectors of the industries.

We here present Microchannels as the new cooling technique for the turbine blades and vanes. It’s within possible to use this technique at the large industrial scale and its application will exceed the limits which were set before.

TERMINOLOGY

Nomenclature

A	angle
A	area
a	height side
b	width side
c_p	Heat capacity
D	Diameter
f	Friction factor
g	gravitational constant
h	heat transfer coefficient
H	total head
k	Thermal conductivity
L_s	Slip length
m	mass
Nu	Nusselt number
P	Pressure drop
P_o	Poiseuille number
Pr	Prandtl number
q	Rate of heat transfer
q''	heat flux
Re	Reynolds number
T	Temperature
U	Flow velocity (vector)
u	Velocity compo. in x-direction
v	Velocity of fluid
Z	elevation head

Greek Symbols

ρ_l	Density of liquid
μ	Viscosity
α	Length ratio
τ	Shear stress

Subscripts

i or 1	Inlet
o or 2	Outlet
l	Liquid
s	Slip
h	Hydraulic
avg.	Average
x	local

1 INTRODUCTION

Nominally, microchannels could be defined as the channels or ducts whose diameter is less than 1 millimeter (mm) but greater than 1 micron (µ). Since the dimensions of Microchannel are very small, and the flow behavior in the microchannels does not happen to be same as in the macrochannels or in the normal pipes. Above 1 millimeter diameter, the channel exhibits the same flow behavior as the most of the macrochannels.

Microchannels offer very astonishing advantages in the heat transfer application because of its large surface to volume ratio [1] and its very small volume. Since the surface area of the Microchannel is very high as compare to their volume which directly leads to the high and rapid heat transfer rate and this property can be used to develop new and better kind of micro-heat exchanger. Theoretically, the efficiency of the micro-heat exchanger would happen to be excellent and it can be increased further by using the different low temperature fluids such as the cryogenic fluids.

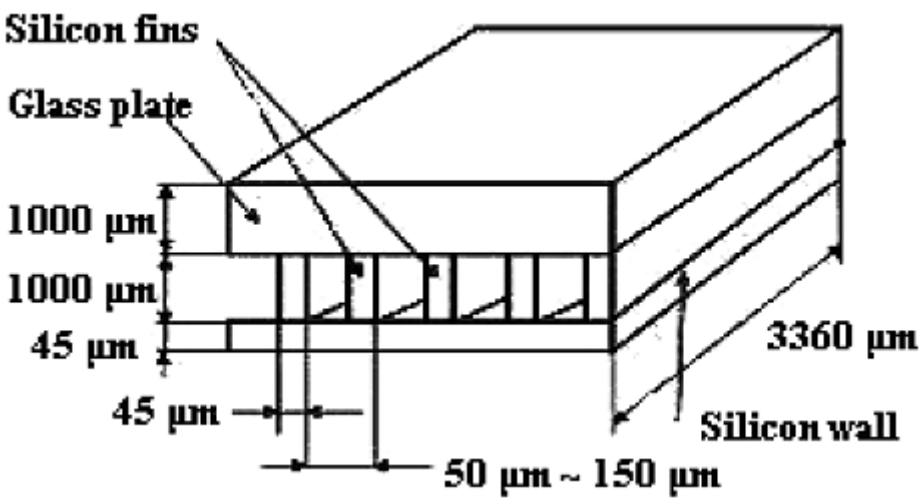

Figure 1: Micro heat exchanger [31]

The device shown in the figure (1) is known as the micro heat exchanger consists of rectangular microchannels. It is constructed with the thin silicon layer. The dimensions of microchannels are 45µm ×1000 µm. to allow the heat transfer with the ambient air, one of the faces (made of glass) of each exchanger is machined by ultrasonic machining so that only a thin silicon layer is conserved (45µm) with minimal fin thickness fixed to 45µmand the width of the channels adjustable in a range from 50 to 150µm.

1.1 Liquid flows in Microchannels

Flow characteristics of liquids and gases in microchannels are very different from the macrochannels and this difference of flow characteristics between microchannels and macrochannels [43] exist because of several reasons,

I. Flow on the small scale makes molecular effect such as wall slip more important and this wall slip effect also amplifies the resulting magnitude of certain ordinary continuum effects to the extreme.

II. The value of the critical Reynolds number is very different in microchannels than macrochannels. In microchannels the transition in to laminar flow occurs early as compare to the macro scale.

III. The heat transfer characteristics in the microchannels are not quite sure but in macrochannels they have been studied widely.

Let's consider an example of strain rate and the shear rate, the scale which is proportional to the velocity scale U_s and inverse proportional to the length scale L_s. Thus 100 mm/sec flow will experience a shear rate of 10^{-4} sec^{-1}.

$$\boxed{\tau = \mu \frac{d\boldsymbol{u}}{d\boldsymbol{x}}}$$

Where, τ = shear stress, μ = viscosity of fluid, $\frac{du}{dx}$ = velocity gradient

This effect becomes more interesting if one tends to keep maintaining the same volume flux while scaling down. The fluids which show Newtonian behavior at ordinary shear rate [45] can also show the non- Newtonian behavior at very light shear rates. The gradient of pressure drop becomes relatively large in the channels of small cross-section. For the constant value of volume flux, the pressure gradient increases by the factor of L_s^{-4}.

When the fluid flows in the duct the Electro-kinetic effects [44] occurs at the interface between the liquids and the solids such as glass due to chemical interaction. This happens because of induced charge distribution by an electrically charged double layer in a very sheer layer of fluid which stays close to the wall at the time of the application of an electric field to this layer and generates a body force strong enough of moving of fluid as if it seems like slipping over the surface of the wall. The molecular structure effects are absolutely different to the full extent in the gases and liquids. If the value of Knudsen

number is greater than 10^{-3}, non-equilibrium effects may start to occur. As the value of Knudsen number continues to increase, the continuum assumption and the field theory are no longer applicable.

1.2 Transition to turbulent flow

When the velocity of flow (V) is very low and the viscosity of the fluid (μ) flowing in the pipe is very high, the flow occurs at defined path along the stream line in a formation, this type of flow is known as the laminar flow. In laminar flow [46] the value of Reynolds number (Re) is very low, say 2000. However, if the viscosity of the fluid decreases and the velocity of the fluid continue to increase to a chaotic level simultaneously the value of Reynolds number gets very high and the eddy formation in the flow takes place, this type of flow is defined as the turbulent flow.

In year 1883, Reynolds discovered an intensive value of the velocity over which the aspect of the flow resistance goes under the alteration. The analogous dimensionless parameter to this critical value of velocity is known as the critical Reynolds number above which the distribution in the flow is not maintained. The value of critical Reynolds [47] number (Re) for macro-scale is 2040 or in some cases 2300 roughly. Once the flow is formed fully turbulent, the empirical relations can be used to correlate the friction factor and the Reynolds number for smooth pipes. There are two different theories which define the flow in micro-scale and macro-scale separately.

1.2.1 Laminar flow

Macroscale theory says that the product of the friction factor and the Reynolds number is a constant [48], which always will be 64 for a circular pipe flow. This theory is called as the classical theory of the fluid flow and it is only applicable in case of laminar flow.

$$\boldsymbol{f * Re = 64}$$

The Darcy equation gives the relation between the friction factor and the pressure drop, and this is also valid for only laminar flow,

$$\mathbf{\Delta P = \frac{\rho f L v^2}{2D}}$$

The Hagen-Poiseuille equation [49] also gives the pressure drop in laminar region and also is valid for turbulent region for incompressible flow,

$$\boldsymbol{\Delta P = \frac{128\mu LQ}{\Pi d^4}}$$

1.2.2 Turbulent flow

Reynolds performed the experiment and established the value of critical Reynolds number Re_{cr} to be approximately 2040 or 2300 and this value was generally accepted. Once the flow is fully turbulent, the empirical relations can be used to correlate friction factor and the Reynolds number for smooth pipes. This solution was proposed by Blassius [50] which is,

$$\boldsymbol{f = 0.3164Re^{-0.25}}$$

For flow in rough pipes, the solution departs from the Blassius relation for flow in turbulent region.

To compare the results of the theoretical theories and the experimental studies, a normalized friction factor C* [51] is defined as,

$$\boldsymbol{C^* = \frac{fRe\ exp.}{fRe\ theo.}}$$

Electro-viscous effects [52], [53] are the main possible cause of the greater value of frictional resistance and also dependency of flow resistance on flow geometry such as aspect ratio, thickness and hydraulic diameters have been observed. Both Papautsky et al. (1999) [54] and Pfahler et al. (1990) [55] acknowledge the difficulty of ensuring accurate size measurement and the corresponding difficulty of conclusively establishing a geometrical effect in their experiment. In one case, the departure from conventional macro-scale theoretical predictions was found to be dependent on both Reynolds number and hydraulic diameters of the trapezoidal channels by Qu et al. 2000 [56].

1.3 Microscale theory

When the flow is occurring in microchannels, the characteristics of the flow are not likely as the flow in normal pipe. The value of critical Reynolds number also changes or say

decreases which implies that the flow transition in to turbulent in micro channels happens very early as compare to the normal pipes.

The value of Critical Reynolds number for flow transition from laminar flow into turbulent flow in microchannel was reported for certain flow conditions by Hsieh et al, 2004 [57], Mala and Li, 1999 [8], Morini, 2004 [60], Peng et al, 1994 [61], 58) Liu and Garimella, 2004 [58], Pfund et al, 2000 [62], wu and little, 1983 & 1984 [63], [64] or consistent by Celata et al, 2006 & 2010 [65], [66], [67], Liu and Garimella, 2004 [68], sharp and Adrian, 2004 [7] with nominal value s for macroscale conduit flows such as 2000 for circular pipe flow by Darbyshire and Mullin, 1995 [69]. The ranges of the critical Reynolds number observed in the experiments of fluids flow in microchannels were dramatically lower than the nominal macroscale values. Such as 240 by Hsieh et al, 2004 [57], 200-700 by peng et al, 1994 [61], 400 by wu and little, 1983 [63], 300-900 by mala and li, 1999 [8], and values slightly lower than the macroscale value was observed by Pfund et al, 2000 [62].

On the safe side, it has been conclusively prove that whenever there is flow on the microscale, the flow behavior would not be the same as the macroscale, though the cause of the alteration in the flow behavior or the case of early transition to the turbulent flow have not been established yet. Most certainly, the inclusion or the exclusion of the entrance effect or the surface roughness of the microchannel could possibly be the cause of flow characteristics alteration. These effects can also vary the magnitude of the friction factor measured in experimental study.

1.4 Measurement of velocity in microchannels

Along with the growth of the microchannels researches, rapid and vast development of experiment technique for investigating flows in such devices is also in the way which also includes the modification of the experimental techniques applied to the macroscale. Measurement of velocity in microchannel is obtained by the using the field measurement technique [71] and bulk flow. Each technique has its own separate advantage that may make it suitable to providing a specific type of flow field information. Traditional typical methods used to measure bulk flow rate, include an in-line flow meter or the timed collection of the fluid at outlet and pressure taps located at the inlet and outlet or very simply at the inlet if the pressure at outlet is known. Sinton et al. [70] used Direct and

indirect technique for the electro-osmotic flow for the velocity measurements in microchannels.

1.5 Thermal aspect of microchannel

Thermal energy or heat energy is the physical representation of the ultimate manifestation of all forms of energy. Transfer of heat energy from one medium to another medium, one location to another location, and to attain all the challenges of accomplishing this transfer under different types of constraints have been the objective of heat transfer research. The heat transfer from the microchannels is quite high thus it proved a better option for to use it in any desired area of application. Microchannels and minichanels are the center of attraction for the development of the micro heat exchangers and the miniature refrigerator. Since the value of heat transfer coefficients are very high for single phase flow in the channels of very small diameter thus the flow boiling produces very large values. For example, in the single-phase flow, the value of heat transfer coefficient for laminar flow for flowing fluid water in a square channel of hydraulic diameter of 200μm is around 10,000W/m^2 ◦C, while the value of flow boiling heat transfer coefficients can be raised up to 100,000W/m^2 ◦C [32]. For the channels of larger hydraulic diameters, they can be incorporated with flow boiling at measurable or even larger heat transfer coefficients as compare to the single-phase flow systems. This characteristic becomes especially important for the point of view of the filtration needs to keep the channels clean.

1.6 Convection heat transfer

Heat transfer by convection provides a means of transferring heat quickly away heat exchange surface. Fluids employed in engineering systems and processes undergo the changes in their thermal states in heat exchangers. The basic equation for heat transfer by convection [72] is,

$$\boldsymbol{Q = hA(Ts - Tf)}$$

Where,

Q= heat transfer,

h= heat transfer co-efficient,

A= surface area

T_s= surface temperature,

T_f = outlet temperature

The basic focus was to increase the surface area to obtain the high rate of heat transfer. Shall and tube heat exchangers dominate the scene with their ability to scale up size. The era of compact heat exchangers began through the demand from the transportation sector basically automotive, aircraft, submarine and spacecraft.

High heat fluxes coupled with the small sized led to the smaller channel dimensions. The word 'micro' was used enthusiastically with the opening of its newest branch in the microscale heat transfer. The classification of small channel dimension was proposed by Menhendale [73], who divided the range from,

1 µm to 100 µm	*Microchannels*
100 µm to 1 mm	*Meso-channels*
1 mm to 6 mm	*Compact passages*
>6 mm	*Conventional channels*

Table 1: Classification of channels [32]

1.7 Microchannels in heat transfer devices

Since the microchannels have high thermal performance is the basic reason that they are being increasingly used process application of every single industry. The higher pumping power requirement are offset with the overall size and cost reduction. In the automobile and aero industry, micro channels have proved to be very valuable.

Micro-electronic engineers are conversing to their submicron-scale to micron-scale for their IC design and the mechanical engineers are very familiar with the microchannels in the micro heat exchangers and they have found the microchannels as a desirable compromise in micro-electronics cooling applications. In biomedical and the optical applications, transitional microchannels are often being employed.

The race is not over yet, with the mechanical engineers moving from comfortable confines of heat sink mounted on electronic device, various components and the assemblies to the critical regions of microchannels, partnering with the microelectronic engineers for their on chip fight to meet the new micron and submicron sizes and the thermal and fabrication challenges.

2 SCOPE OF STUDY

Microchannels are the modern and relatively more efficient heat exchangers and also said to be the future of heat exchangers. The ability of transferring the large amount of heat because of it high surface area to volume ratio and its lower value of volume sets them apart from the conventional heat exchangers.

2.1 Application of microchannels

Microchannel heat exchanger is a new developing technology in the field of heat transfer and it is finding its way across all the industries. Microchannels are useful in every field where high rate of heat transfer is required or the high velocity in the pipe flow comes to play.

Some of the important areas of application of microchannels are described as below,

1. **In Electronics sector**

   Microchannels heat exchangers are the biggest need of electronics industry in the current time. Since all the electronic applications suffers from the high rate of heat emission just like in a processor of the computer. A processor is the component of the computer which is nothing but the simple combination of the transistors and when computer is being operated, the processor comes under load and in such condition the transistors starts emitting heat. Simply if more efficient processor is desirable, more number of transistor have to be added but addition of large number of transistor also will emit large amount of heat which in turn will reduce the overall performance of the processor.

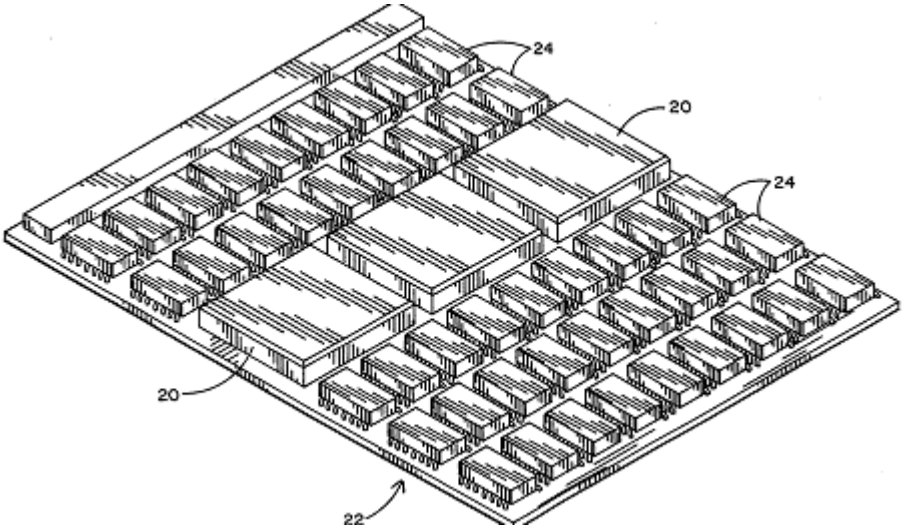

Figure 2: Microprocessor [33]

So it is quite obvious that the only thing stands before the getting the high performance from the electronic equipment is the thermal restrictions (high rate of heat generation) and this situation can be resolved by the use of **micro heat exchangers.**

It is observed that the fan in the computer is not as effective as the micro heat exchanger will be because of its high rate of cooling analogous to air conditioner is more effective in room as compare to fan in summer time.

2. In Cryosurgery

Cryosurgery is the process of removing the unwanted skin tissues from the human bodies after killing the tissues by injection of the cryogenic fluids into the tissues.

Cryosurgery is extremely complicated to perform thus it needs to miniaturize the cryoprobe to reduce the invasiveness. Cryosurgical treatment is performed for those who suffer from the small cancer problem. Basically liquid nitrogen, Dimethyl ether – propane and argon is used in the process of cryosurgery. Typically speaking, ultra-fine cryoprobe have been developed which have double layer stainless steel microtubes and the diameter less than 500 µm. In cryoprobe, very fine needle is used which accomplishes the purpose thus the application of microchannels comes into the scene.

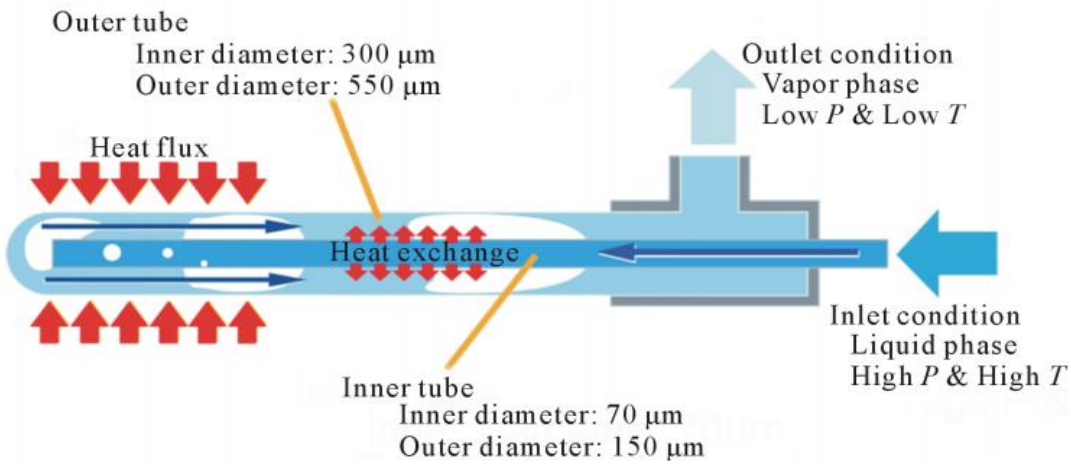

Figure 3: Ultrafine cryoprobe [34]

The fluid used in the injection process is cryogenic fluid which is stored at extremely low temperatures and will flow through the microtubes.

Study performed by Junnosuke Okajima, Atsuki Komiya, and Shigenao Maruyama [34] on the topic Evaluation of Characteristics of Phase Change Heat Transfer in Ultrafine Cryoprobe suggests that heat transfer co-efficient obtained from the micro-tube in cryotube was higher than the normal channels. Results imply that while cryogenic fluid flowing was nucleate boiling.

3. In Aerospace and Automotive industry

In aerospace and automotive industries, there is always requirement of high efficient heat exchangers to dissipate the heat. Currently heat exchangers are being made of pipe of significantly larger diameters and will occupy the larger space instead if the heat exchangers are made of microchannels for same dimension that will increase the number of microchannels inbuilt as compare to the pipes of the nominal diameters.

Increasing the number of microchannels will definitely increase the amount of surface area involved which intron increase the rate of heat transfer and will make the micro heat exchanger the more efficient as compare to the normal heat exchangers. Due to its compact size and low weight it can be employed in the aerospace industry as well as the automotive industry.

Microchannels are available in various types of geometries which can be employed in the manufacturing of the micro heat exchangers in order to get the desired shape and size of the heat exchangers according to the requirement.

4. In fuel processing application

Fuel processor is a critical element for the development of automotive fuel cell power system. One component fuel processor is gasoline vaporizer and its micro scale model was possible because of the microchannels.

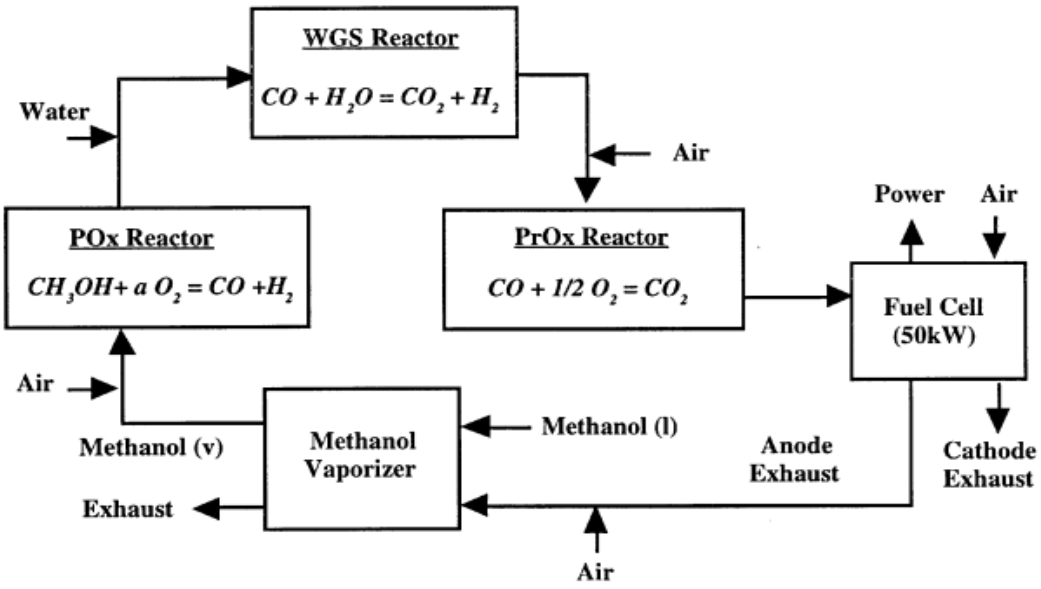

Figure 4: Complete fuel processing system [35]

Micro-chemical systems are well suited for designing and deploying compact reactors with millisecond reaction times because of the rapid heat transfer that result from integrated micro-chemical heat exchangers (Call et al., 1996; Srinivasan et al., 1996, Tonkovich et al., 1996, 1998a, b). Heat produced from the exothermic reaction is quickly removed through an efficient microchannel heat exchanger. These processes can be operated under near isothermal conditions to prevent hot spots, thermal run-away, and possible explosions.

5. In laser diodes

Laser technology made significant improvement to the amount of output power that can be produced high efficiency laser diode bars. Optical output powers greater than 120 W continuous wave from a single diode bar when packaged on a microchannel cooler have been demonstrated. The purpose of packaging a diode

bar is to deliver the necessary electrical current and remove the waste heat. More efficient the micro heat exchanger, more amount of heat will be removed and more efficient the laser will be. Thus wrapping the laser jacket with the micro heat exchanger will be more efficient to dissipate the heat that are emitting from the laser and now laser can work more efficiently.

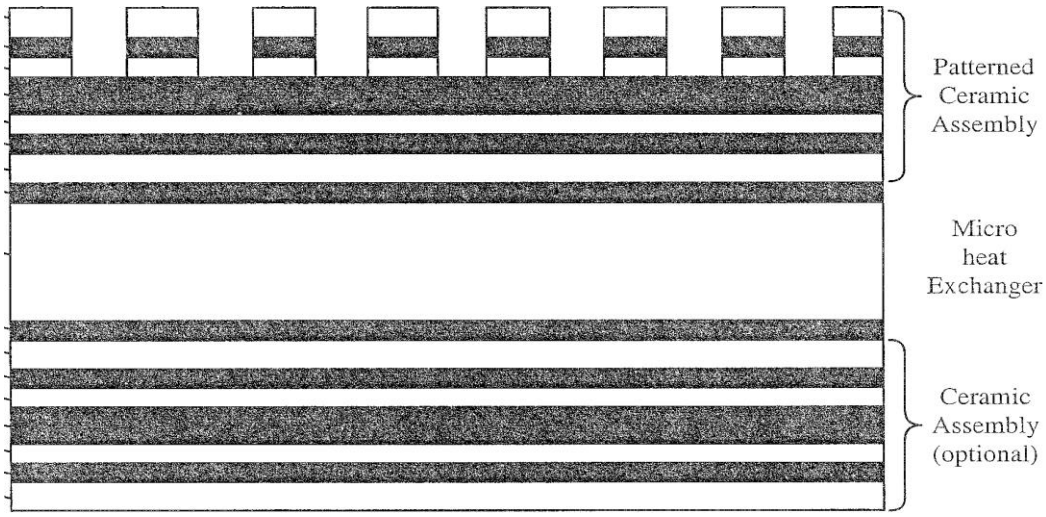

Figure 5: Cut-out side view of exemplary layers of a ceramic assembly fabricated using a bare ceramic approach [36]

A heat exchanging device comprising a thermally conductive material, wherein the heat exchanging device is configured to transfer heat from the thermally conductive material to a fluid flowing there through and a thermally conductive ceramic assembly thermally coupled to the heat exchanging device, wherein the ceramic assembly comprises:

i. a conductive layer
ii. a ceramic layer
iii. an active brazing alloy bonded between the conductive layer and the ceramic layer to form a joining layer, wherein the conductive layer and the joining layer are configured to form one or more electrically isolated conductive pads

6. In turbine blades and vanes

The efficiency of a steam turbine is directly proportional to the inlet temperature of the steam. It suggests that as the inlet temperature of the steam increases, the efficiency of the steam turbine also increases. However, due to thermal restrictions the inlet temperature of the steam can be increased up to a nominal

value which depends on the properties of the material of turbine blades and vanes because if the inlet temperature is continue to increase regardless the consideration of the blade material than it is very much possible that the blades and vanes will undergo deformation. To avoid such cases cooling in steam turbine is very important and since the microchannels can transfer to heat to a high rate thus it can be used an effective method of cooling which is not only easy to implement but also is very cheap as compare to the other cooling techniques that are being used at the current time.

3 RESEARCH OBJECTIVES

The main objective of this study is to determine Thermohydraulic characteristics of the flow in the microchannels so that the high heat transfer properties of the microchannels can be used in the cooling of the turbine blades.

Turbine blade is the individual component of the steam turbine which is responsible for the extracting the energy from the high temperature and high pressure produced by the combustor. To survive in these chaotic situation turbine blades is made of super-alloys and they use many different methods of cooling such as internal channels, boundary layer cooling and thermal barrier coating.

The one of the major problem caused in the turbine blade because of the high temperature is fatigue failure due to thermal stresses and also the high dynamic stresses caused by the blade vibration.

The modern gas turbine engine is focus on increased turbine inlet temperature in order to reduce the specific fuel consumption and increase the overall efficiency. However, operation at very high temperature reduces the life span of the blades and vanes. Moreover the allowable temperature of the cycle is limited by the melting point of the material. Therefore turbine blade cooling is necessary to reduce the temperature of the blade to acceptable level for increasing the thermal capability of the engine.

On increasing the turbine inlet temperature would get a substantial benefit in terms of work done by the cycle, which means more work done by the turbine. So more work done is available for wither creation of the thrust for aero-engine or running the propeller shaft which creates the thrust. It simply means that you can get more power output out of the single gas turbine engine [29].

The fundamentals of thermodynamics bore you down on the fact that you need cooling in the turbine because the material science cannot go beyond to a certain limit for providing the batter material and alloys which could withstand temperature beyond a certain limit which is roughly 1000 K.

That's why the additional techniques are required if we want to turbine blade temperature to go even higher and that's where the cooling technology comes into the play.

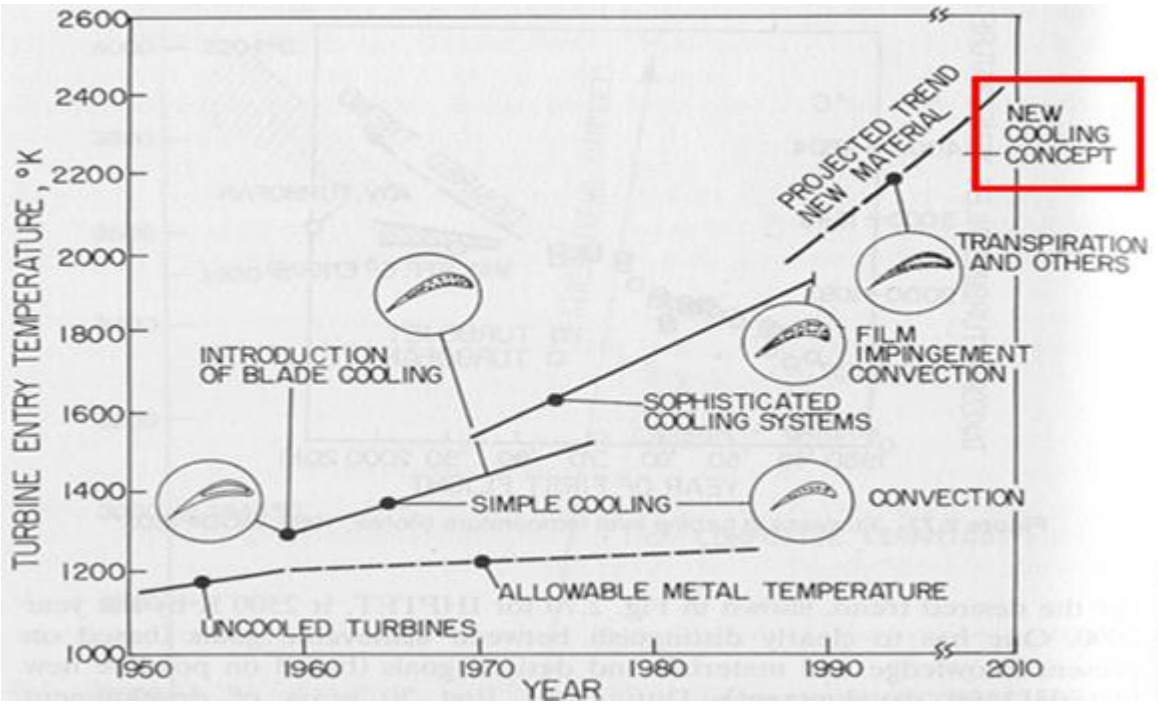

Figure 6: Comparison of various cooling techniques [36]

If see the graph, easily see that in the 1950s or so, the most of the blades were actually cool blades. But they could take up to about 1000 degree centigrade and then from onwards if we are aspiring towards higher turbine inlet temperature, we have to resort some kind of cooling technology beyond otherwise, the turbine inlet temperature could not be improved.

It is basically heat transfer technology coupled with engineering methods that the temperature could rise up to 1400 degree and then people realized that we need more complex cooling methods to go up to higher than 1400 degree. Hence today we are talking about more sophisticated cooling techniques which involve the film cooling and then injecting impingement cooling so on, which has taken the turbine inlet temperature up to 2000 degree.

While talking about the cooling of the turbine the first thing that comes into mind is water cooling. The processing of the turbine is hot; high pressure but the blade only feels the temperature. The blade feels the temperature which is not same as the turbine entry temperature.

Say, turbine inlet temperature is T_{01} and the blade exit temperature is $T_{02.}$ What blade would feel is an average of the 2 minutes of the rotating kinetic head which is *u*, mean square by twice c_p of gas which is passing through plus the degree of the reaction forces. So gas temperature is not what blade feels it will feel at temperature lower than a gas temperature so the cooling is not respect to the gas temperature but it is actually what blade actually feels.

Flow characteristics also play a very important role in the cooling techniques. As long as the flow is laminar the gas is flowing slowly and the rise in temperature of the blade will take place slowly, once it becomes turbulent, the gas temperature flows inside very quickly and then the blades start getting hugely heated up. So the cooling requirement indeed here is more even though the temperatures near the leading edge actually more.

4 LITERATURE REVIEW

In past few recent years, the scientists and the engineers are egger and very excited to investigate the flow characteristics and the heat transfer properties of the microchannels because of the fact that microchannels could be the “future compact heat exchangers”. As the dimension of the channels decreases from several hundred to 0.1 µm, the fluid behavior is strongly influenced by the wall effect, the friction factor, and the Reynolds numbers and of course the velocity of the fluid in the microchannels also plays an important role in the alteration of the flow and thermal behavior of the fluid in the microchannels.

Amirah M. Sahara, Mehmed R. Özdemira [1] conducted the computational and experimental investigation of single phase fluid flow and application of conjugate heat transfer boundary conditions on the rectangular cross-section microchannels fabricated by copper using fluent 14.5. The results of the study showed that, For a single phase flow using de-ionized water and for multiphase flow R134a as working fluid and the transition of flow from laminar regime to turbulent regime takes place at the valve of Reynolds number, Re = 1600- 2000. In addition they described that the Heat flux is non-uniformly distributed alongside of the channel length. The expected value of the friction factor was found to be significantly lesser than the prediction made by the conventional flow theory, for both laminar regime and turbulent regimes. These aspects of the study suggest that the flow in microchannels is not likely to be similar as the flow in pipes and macro-channels.

C. Rands, B.W. Webb, D. Maynes [2] Performed a study which was based the characterization of transition of the flow from laminar to into turbulent in the microchannels of with diameters in the range 16.6–32.2 µm over the Reynolds number range of 300–3400. The results of this study were surprisingly in agreement with the macro-scale theory. They found that the laminar flow was observed at low Reynolds number. The transition was observed at Reynolds number range of, Re= 2100–2500**.** The Fluid mixed mean temperature increases with the increasing value of Reynolds numbers and the Fluid viscosity is nearly independent of pressure over the range of pressure

explored. Maximum Fluid velocities 130 m/s was found to be causing the significant temperature rise.

Jaeseon Lee, Issam Mudawar [3] for the investigation of heat transfer characteristics of R134a in microchannels using heat sink as evaporator and also for the inspection of that how the heat transfer is associated with different mechanisms for low, medium and high qualities. As it turns out that the results of the study was very promising and they found a new relation which is valid for both water and R134. The results also indicated that the process of nucleate boiling takes place only at low qualities values such as, (Xe < 0.05) corresponding to low heat flux values. The High fluxes can produce medium quality like, (0.05 < Xe < 0.55) or high quality as (0.55 < Xe < 1.0) flows.

X. F. Peng, G. P. Peterson, B. X. Wang [4] Conducted an experiment on the Frictional flow characteristics by considering water as flowing fluid through rectangular microchannels to investigate the effect of hydraulic diameter and H/W ratio on Reynolds number. The dimension of the microchannels were as the hydraulic diameter D_h= 0.133mm- 0.367mm and the aspect ratio H/W= 0.333- 1. The study gave the promising results showing that the transition to turbulent occurs at very smaller Reynolds number. The transition Reynolds number was heavily dependent on the hydraulic diameters. If the microchannel size decreases, it would increase the value of friction factor and that would be higher than the predicted by the classical theory.

X. F. Peng, B. X. Wang, G. P. Peterson [5] experimented on the topic of Heat transfer characteristics of water flowing through microchannels to investigate the convective heat transfer in microchannels having hydraulic diameter 0.133- 0.367 mm also the investigation of friction factor and its dependency on H/W ratio. The results obtained by the experiment demonstrated that the laminar heat transfer seized at a range of Reynolds number, Re = 200-700. The convective heat transfer in fully turbulent regime was achieved at a value of Reynolds number, Re = 400-1500. It was seen that the transition Reynolds number diminished with reductions in the microchannel dimensions for laminar heat transfer the Nusselt number was proportional to the $Re^{0.62}$ which is different from the classical relationship. It demonstrated same relationship between the Nusselt number (Nu) and the Reynolds number (Re); however the empirical coefficient CHt was very abstracted.

Qu Weilin, Gh. Mohiuddin Mala, Li Dongqing [6] performed the experiment on Pressure-driven water flows in trapezoidal silicon microchannels. Experiment was conducted on trapezoidal section of hydraulic diameters in the range from 51 µm to 169 µm and the mass flow rate and the pressure drop across the microchannels were measured at steady state condition and also performed a comparison of flow friction. The comparison was made between the Pressure gradient obtained from the experimental data with pressure drop obtained from the classical laminar flow theory. According to the results of the experiments Experimental Pressure gradient and flow friction was higher than the classical laminar flow theory $fRe = 64$**.** At low Reynolds number the pressure gradient will show the liner relationship with Reynolds number, when the value of Reynolds number increased more than 500. The slope of pressure gradient and Reynolds number increases with Re. Roughness - viscosity model was used to measure the surface roughness of the microchannels.

K.V. Sharp [7] performed a study on Transition from laminar to turbulent flow in liquid filled Micro-tubes to investigate the transition to turbulent flow of the different polarities liquid in glass micro-tubes of diameters ranging 50- 247 µm. De-ionized water, methanol and 20% glycol was used as working fluid. According to the results of the study transition to turbulent occurs at Reynolds number 1800–2000. Continuum theory describes the flow behavior in microchannels better until the dimensions approaches to the slip at wall level. The macro-scale model could be applied for transitional value in microchannels with the example of water moving at speeds greater than 150 kmph through a tube whose diameter is less than that of a human hair.

Gh. Mohiuddin Mala, Dongqing Li [8] performed a study on the Flow characteristics of water in micro-tubes to investigate the flow characteristics of water in micro-tubes (fused silica and stainless steel). The effect of friction factor was observed on the flow with respect to Reynolds number while keeping the volumetric flow rate constant. Experiment was performed on the micro-tubes of diameter ranging 50- 254 µm for constant volumetric flow rate. The magnitude of pressure gradient needed to force the liquid flow through the micro-tubes is higher than the predicted value by the conventional flow theory for smaller values of Reynolds number (smaller Q). It was also seen that the conventional flow theory and the experimental data are in rough agreement with each other. If the value of Reynolds number (Re) increases than there a significant deviation

from conventional flow theory was seen and it was observed that the deviation increases as diameter of the tube decreases. Additionally the value of friction factor and the value of friction constant are much higher than conventional theory.

J. Judy, D. Mayne, B.W. Webb [9] Conducted a study on Characterization of frictional pressure drop for liquid flows through microchannels to explore the pressure drop required to make liquid flow in the microchannel of diameter ranging 15 - 150µm. Reynolds number range is 8- 2300, Working fluids used were distilled water, 2- propenol and methanol. Two different kinds of geometry of cross section is used :- (1) Circular (2) Square. In this particular investigation they calculated the frictional pressure drop for three different fluids in Reynolds number range of 15 to 150. There was no significant distinguishable deviation from macro-scale stokes theory. There was no evidence to support the transition to turbulence at Reynolds number less than 2000. Experimental results are in good agreement with classical theory of flow$f * Re = 64$.

Devid brutin, Lou nestedrist [10] studied the Experimental friction factor of liquid flow in micro-tubes to investigate the friction factor of the water flowing in the micro-tube made of fused silica. Water used in the experiment was of two types (1) Tap water (2) Distilled water. In this study Pressure drop and the flowing masses are also been measured for determining the flow characteristics by using transit method. Observation also been made on fluid wall interaction. Fluids ionic properties and roughness viscosity explanation also was provided. The results of the study depicted that Poiseuille number being related to the Reynolds number makes huge impact on the flow characteristics and to flow transition to turbulent. They found that Po is 27% higher than predicted by the conventional theory. When the roughness analysis was made the value found was 2nm. It was observed that Tap water contains more cations and anions than distilled water and when they come in contact with polarized surface will modify the velocity profile. In Surface polarizability analysis, experimental results agreed with the conventional theory. They learned that Fluid- surface interaction can used as an explanation of increase in the Poiseuille number by the fluid ionic coupling with the surface and so local viscosity modification.

Y. Sui, C.J. Teo, P.S. Lee, Y.T. Chew, C. Shu [11] conducted a study on Fluid flow and heat transfer in wavy microchannels to study the laminar liquid flow and heat transfer in 3D wavy microchannels of rectangular cross section. Study was performed to investigate

the heat transfer in microchannels to enhance the performance of the wavy micro heat exchanger. The assumptions made in the study was as follows,

(1) Time bound Steady state boundary conditions

(2) Flow is Incompressible

(3) Flow regime is Laminar

(4) Fluid properties are constant

(5) Viscous dissipation is negligible

(6) There is negligible radiative and natural convective heat transfer from the heat sink.

The results indicated that due to increase in relative waviness along the flow direction results in higher heat transfer performance because of generation of dean vortices in most electronic devices. The rate of heat dissipation over a chip is non-uniform, which ultimately results in hot regions and in turn comes in conciliation with the Credibility of the ICs, thus it leads it to the premature failures. Some better and Special kind of techniques must be taken into considerations on the account of while designing of heat sinks in order to remove the hot regions experiment carried out wavy microchannels at Re = 300- 400, under heat flux H_2 and temperature T and conjugate Conditions.

Yongping Chen, Chang bin zhang, Mingheng Sui, G.P. Peterson [12] performed the experiment on the topic describing the Role of surface roughness characterized by fractal geometry on laminar flow in microchannels. 3-D model of microchannels was used in the study. Laminar flow was numerically analyzed by taking the surface roughness effects in to accounts occurring by fractal geometry. The effects of relative roughness, Reynolds number, and the fractal dimension in laminar flow regime were experimented. The idea of Fractal geometry was firstly considered by Mandelbrot. It was for describing the disordered objects using fractal geometric dimensions and how it was Different from Euclidean geometry. The concept of fractal geometry tells about the dimensional parameters of the disordered and irregular objects such as porous media of fractal trees, natural coastlines and rough surfaces all can be non-integer related. Considered value of Reynolds number in the present experiments is Re= 1500. Since the Navier-Stokes equations was valid for flow in laminar region. The momentum and mass conservation equations can be used to model the concept. If the roughness is on the surface, it leads to the change in velocity profile for laminar flow basically in microchannels. It also can be

major cause of pressure drop along the length of rough and smooth microchannels. Results showed the drop in the rough channels is considerably more than as compare to the smooth channels. Results also demonstrated that the surface with large fractal geometric dimension leads to major pressure drop. The observed fluctuation characteristic in pressure drop is due to the generation of vortex. In a specific observation, the pressure gradient at the location of vortex is significantly larger than that of no vortex region. This suggests that the presence of irregularities (rough element) on the surface will result in the counter pressure distribution near to the surface and leads to increase in friction factor. Comparing was made for the Poiseuille number as a function of Reynolds number for different aspect ratios. The results suggested that the Poiseuille number was no longer remains constant with Reynolds number but it increases with Re linearly and this value is larger than classical value$f * Re = 64$.Which means that the vortex effect generated at low Re is much smaller than that at large Re. As the relative roughness increases, the flow over rough features generates more recirculation and flow separation which in turn increases in pressure drop in single phase.

Y. S. Muzychka, M. M. Yovanovich [13] experimented on the Laminar Forced Convection Heat Transfer considering the Region of Combined Entry for Ducts of Non-Circular cross-sections to develop a new model for predicting the Nusselt number in the non-circular ducts and channels. The model can predict the local and avg. Nusselt number and valid for both isothermal and Iso-flux condition. This model was of particular interest in developing the micro/mini heat exchangers. To resolve the complicacy of combined entry problem, the governing equation of three fundamental forces are used which is follows,

1-combined entry developing flow {incompressible and constant property $0 < Pr < \infty$}
2-The thermal entrance flow
3-Thermally fully developed flow

The approach used in this model was same as used in the model proposed by Churchill and Ozoe for circular duct. Fully developed flow limits were proposed by Muzychka for both the hydrodynamic and thermal boundaries. A new general model for the purpose of predicting the values of heat transfer coefficient in the region of combined entry for the non-circular shaped ducts was formulated. The valid conditions/ boundary conditions for this model was $0.1 < Pr < \infty$, $0 < Z < \infty$ For both the uniform wall and uniform heat flux

conditions. It was also valid for both local and mean Nusselt number. The result agreement with theories was observed up to ±15% for non-circular ducts. Very important observation of Yovanovich and Muzychka is, that the hydraulic diameter should not be the characteristics length scale for non-circular ducts in the laminar flows, but rather it can be the square root of the area of cross section. His results demonstrated that the product of the friction factor and Reynolds number is based upon the square root value of the cross sectional area. Huge data was reduced into a single curve which was merely a function of the aspect ratio the duct or channel. In the thermal entrance region of non-circular ducts the thermal boundary layer will be thin and it may be assumed to be developing in the region where the velocity gradient is linear.

Poh Seng Lee, Suresh Garimella, Dong Liu [14] conducted Investigation of heat transfer in rectangular microchannels. This test was conducted on the copper test piece congaing 10 microchannels in parallel. The depth of the microchannels was in the range of 194µm to 534µm with channel depth being 5 times of channel width in each case. The de-ionized water was used as test fluid for the range of Reynolds number approximately 300 to 3500. The results demonstrated that the experimental data obtained was seems to be in good agreement with the classical, continuum approach. The average deviation showed was less than 5%. Conventional heat transfer analysis also can be employed for these specific dimensions of the microchannels. The variation in Nusselt number was plotted as a function of Reynolds number. Results predicted that the variation in the Nusselt number was according to the variation in the Reynolds number microchannels of different sizes. With hydraulic diameters of D_h= 318 – 903µm performed an experimental investigation over a wide range of flow rates in which Single-phase flows in the thermally developing laminar regimes was considered. The results showed that heat transfer coefficient increases with the decreasing size of the channel at a given flow rate. The comparison was made between the experimental results and the conventional theories and then it was analyzed. The results and their applicability in predicting the heat transfer in microchannels. The final conclusion was, in the transitional regimes and turbulent regimes, the improved and precise correlations are needed to account for the developing conditions.

Ian Papautsky Bruce K. Gale, Swomitra Mohanty, Tim A. Ameelc [15] studied the effects of aspect ratio on laminar friction constant in rectangular microchannels are described. The experimental observation on the fluid property was performed my using micro-

machined surface of rectangular metallic pipette array, each array consist of 5-7 pipette. The dimensions are as; the Width of the microchannels is 150-500µm and the Heights 22.71 – 26.75µm. The Working fluid used in this experiment was water. Reynolds number range for this particular experiment was 10 – 100. Study displayed that several concepts that can be neglected in the macro scale theory can be still exist in the micro scale theory. This phenomenon could be transport effect in two or three dimension. One another investigated property of microscale is that of temperature variation in the transport fluid which is capable of causing a significant variation in the fluid viscosity. According to the results of the study the experiment was per formed considering the water as working fluid at room temperature. The value of Reynolds number was 0.001 to 10 and all the data was kept in terms of friction constant C* as a function of Reynolds number. Increase in friction constant compared to the macroscale theory of laminar flow and also observed the avg. C* for the experimental data, which was 1.1956. This value approximately 20% increase from the theoretical value. According to the uncertainty analysis, the average uncertainty for friction factor and Reynolds number to be 7.77% and 1.51 % respectively at low pressure and 5.61% and 0.13% at high pressure. The important observation was as the pressure and thus the Reynolds number and the flow rate increases, the friction factor decreases. Possible explanation for that was the change in channels height or width that might occur at high pressure by the elongation or the deflection of the channels sidewalls. With the help of classical stress-strain relationship, the elongation of the channels side walls was measured approximately 1 nm for the maximum fluid pressure. Large microchannels with the characteristics dimension of the order 100µm, produces the function constant very close to the theoretical prediction and it’s very possible that these dimension cannot be observed at microscale.

V.K. Dwivedi, R. Gopal, S. Ahmad[16] Performed an investigation on Fabrication of very smooth walls and bottoms of silicon microchannels for heat dissipation of semiconductor devices. In microchannel fabrication the fabrication of complete smooth walls and bottom formation has been very difficult task during micromachining of silicon due to its chemical etching. A new technology has been developed to fabricate the deep microchannels on silicon wafers to dissipate the great amount of heat generated by semiconductor device to improve its efficiency. Smooth walls and bottom of the dimension about 400 mm deep silicon microchannels was obtained after controlling the temperature, etchant composition and orientation submicron channel lengths dissipates 1

mW per gate. This points the heat dissipation of 250 Watt by a silicon ULSI circuit chip, which has near about quarter million gates. In this present work ternary silicon etchant based on KOH, water and 2-propanol was used for fabricating a defect free surface. Microchannel chip separation is extremely complicated because square shaped chip cannot be scribed with diamond tool due to its second crystal cleavage. If the chips are scribed with diamond tool self-cleavage propagation may occur and the reliability of the chip may lower. The results of this experiment displayed Microchannels were etched by changing the temperature of the etchant and the according to the observation made. The etchant temperature has considerable influence on the silicon etch rate. Result showed that etch rate of p-type silicon is more than n-type silicon in KOH- water and 2- propanol solution. It was also observed that the increases in the temperature from 65 to 85 degree Celsius improve the surface quality which infers that at higher temperatures i.e. 95 ºC there is considerable improvement in surface etching.

Errol arkilic[17] They worked on Slip flow in microchannels. Helium mass flow through microchannel was measured for inlet pressure ranging from 1.2 atm to 2.5 atm with the outlet pressure atmospheric. The dimension of the microchannels was taken as 52.25µm wide and 1.33µm deep and 7500µm long. The effects made by the slip velocity from the Navier stokes equation on the mass flow was investigated and with the measured results it was concluded that when the momentum transfer takes place from fluid to the wall of the channel, the no slip condition fails. The ratio of mean free path to the characteristics dimension is called as the Knudsen number. As the Knudsen number increases the exchange of energy and momentum b/w system and environment shows the behavior that can be used to discrete the molecular composition. Gaseous flow in microchannels was studied by the Pfahler and he found decrease in friction factor. In this type of flow which infers decrease in the momentum exchange between the microchannels and the operating fluids. In this study some assumptions was made which is as follows:-

1. Steady state flow was assumed.
2. Pressure drop associated with inlet and outlet contraction and expansion are ignored.
3. Fluid flow is assumed to be isothermal.
4. Fluid pressure is assumed to be the function of x.

According to the results of the study, the model that predicts an increase in the mass flow for given an inlet and outlet pressure for flow in microchannels is based on no-slip solution of Navier-Stokes equations. It's been shown in the results that for large value of Knudsen number the flow in microchannels cannot be modelled with no-slip condition. Results of the helium flow in the microchannel, including the initial assumptions, are justified.

J Pfahler, J Harley, H Bau [18] Studied Liquid Transport in Micron and Submicron Channels. An experimental study on the fluid flow in very small channel was performed for the purpose of demonstration of these channel's potential capacity of cooling the electronic devices and reactors. Area of the microchannels was 7200 to 80 square microns. Assumption was made that the exit press will be equal to the atmospheric pressure. In this experiment N-propenol was used as the working fluid and that was said that the de-ionized water cannot be used as working fluid because of the channel plugging which might be due to electrochemical reaction. Experiment was performed for the relatively large rectangular cross-section. It was seen that the experimental conclusions are in rough agreement with theoretical predictions made by conventional theory. The discrepancy in the results can be explained by the effects due to change in temperature and the change in the thermo-physical properties of the n-propanol and other experimental errors. The amplified trend of C with the rising value of Reynolds number can be allege to a evolution of the entrance length At the value of Reynolds number, Re = 300. Nearly 20% of the total channel length is occupied by the entrance length. There can be seen a significant depart from the fully developed flow assumption. According to the results, two different kinds of the behavior was found, (1) the results for the 17μm deep channels are found to be in rough agreement with theoretical prediction (2) However, in case of 8μm deep microchannels not only found that the magnitude of C is greater than theoretical prediction. Also found that the trend of differing the behavior of C, at larger Reynolds number from theoretical prediction.

V Jain, C X Lin [19] Worked upon Numerical modeling of three-dimensional compressible gas flow in microchannels. The study was conducted on a simulated numerical analysis on a 3D continuum model of nitrogen gas flow in the long microchannel with square shaped cross-section. Slip and no-slip boundary conditions were performed. The solution of governing equation was taken by the control volume method. The fluid flow thorough Microchannel is currently modeled using either the continuum approach or the non-continuum approach, which most commonly is known as molecular

approach. In the continuum model, the governing equations are solved for the macroscopic fluid properties by considering as a function of spatial coordinates and further it is used widely in the various fluid Flow applications. If the physical system's length scale decreases, the validity of the standard continuum approach may diminish. The local Knudsen number can be used to define the measure of the degree of the rarefaction of gasses encountered in flows through microchannels. By depicting as the value of Knudsen number increases, rarefaction effects become more important. The pressure drop in the microchannel occurs to overcome the generated shear stress and the frictional forces along the walls of the microchannel. It can be seen that as the pressure ratio (PR = Pin/ Pout) increases, the divergence in the distribution of pressure between the slip and the no-slip Wall conditions increase. The Knudsen number increases from inlet to outlet for compressible flow; however it decreases if the value of pressure ratio is increased. if the ratio of pressure was small, the distribution of pressure was close to linear for every flow condition because the effect of compressibility was negligible, however with the increase of the pressure ratio. The distribution of pressure tends to follow the nonlinear characteristics due to the compressibility effects and when the pressure ratio (PR) is larger than 1.5, the compressibility effects should be considered. Knudsen number starts increasing from inlet to outlet for the compressible flow, but it decreases as the pressure ratio increased.

I.Tiselj, G. Hetsroni, B. Mavko, A. Mosyak, E. Pogrebnyak, and Z. Segal [20] conducted the experiment which defines the effects of axial heat conduction of the heat transfer in micro-channels. This particular study focuses on the efficacy of axial heat flux of heat transfer process in the microchannels at low value of Reynolds number. In this experiment a module was made to perform a systematic study and to find the values of the axial heat flux. Numerical and Experimental analysis were done to obtain the characteristics of heat transfer for flowing fluid water, which flows through triangular silicon micro-channels having hydraulic diameters of 160μm. The range of Reynolds number was set to, Re= 32–64. In the roughness-viscosity model, the assumption was made that the velocity gradient close to the wall was decreased due to the roughness. The temperature gradient close to the wall was also decreased and thus the convective heat transfer was also decreased.

It was observed that Bulk temperature of the water, as well as the heated wall temperature does not change linearly along the length of the channel. The obtained experimental

results of temperature distribution over the heated wall are in agreement with the numerical predictions. The difference between the bulk water temperature and the temperatures on the wall becomes negative and the sign of the flux changes. Assumptions made in the study were as,

1. The transport processes are at steady state and 3-D
2. The flow is assumed as incompressible and in laminar regime
3. Thermal radiation into the channels is overlooked as compare to the convection
4. The physical properties does not depend upon the temperature
5. The properties of steel, water and silicon are specified for the collectors, chip and the Fluid at room temperature

Boundary conditions of silicon and steel temperature:-

1. For the collectors and chip the losses due to heat were specified as $qs = -h\,(Tf - Ta)$, assuming the heat transfer coefficient h=10 W/(m^2-K) at all outer boundaries
2. The approximate values of constant heat transfer coefficient are near enough because of the of the heat losses.
3. Thermal resistance was assumed to be zero between the steel collector's boundaries and the silicon chip.
4. According to the study's results, the axial heat flux has a maximum value close to the inlet collector and it reduces in the flow direction down to zero.
5. It remains negative in this region (i.e. it acts in direction Opposite to the flow).
6. The axial heat flux is positive, i.e. it acts in the flow direction.
7. The wall temperature decreases and the heat transfer takes place from the fluid to the silicon wafer.

Aristotel Popescu, James R. Welty, and David Pfund David Rector [21] conducted experiment on the measurements of the thermal characteristics in the rectangular microchannels. The paper describes the experimental study of heat transfer process for the high aspect ratio (width/depth). A single channel of having width of 10 mm was cut into polycarbonate spacers of different thicknesses which results in Channel depths of 128µm, 263µm and 521µm. In this study the constant heat flux Boundary condition was employed at the channel's surface. Refrigerant R-124 was used as working fluid for the Reynolds number range of Re = 300 – 900 and Prandtl number range of Pr = 3.6 – 3.8. The mass

flow rates through the system were varied from 20 ml/min to 60ml/min. The temperature of the fluid at the inlet of the micro-channel was approximately 10°C due to the heat losses. Results showed a very small or no deviation from the macroscale theory for the microchannels having hydraulic diameters greater than 500µm. The results for the aspect ratio of 80:1 showed a significant deviation from the conventional theory. The values of Experimental data for the local nusselt number were nearly 25% lesser than the predicted values of the conventional theory. The asymptotic value of Nusselt number for laminar flow regime was determined as, Nu= 5.63 and it was higher than the predicted value of the conventional theory, Nu= 5.31. There seems to be significant decrease in the values of the nusselt number for the smallest channel. The values of local Nusselt number were basically less than predicted values by the numerical model, however the differences were not very large, in the range of 0 – 10%. Local Nusselt numbers were obtained from experimental data was in good agreement with the conventional theory.

Xu B, Ooi K.T, Wong N.T, Choi W.K [22] performed an experimental study to investigate the flow friction for liquid flow in microchannels. The study was done on the microchannels having hydraulic diameter in the range of 30µm to 344µm at Reynolds numbers range from Re= 20 to 4000. According to the experimental investigations of Pfahler for the fluid flow in microchannels, the nitrogen gas & helium gas long with silicone oil and isopropyl liquid were used as flowing fluids to investigate the characteristics of fluid flow in the microchannels. It was also seen that the different fluids showed different phenomena. It was observed that the channels having large cross-sections are in rough agreement with the Navier-Stokes theory. It was also observed that if the channel depth is reduced than for the critical channel size, the characteristics of the experimental observations deviates from the theoretical predictions. Pressure drop was measured by including the losses at the entry and the exit due to varying cross-section of the microchannel. According to the conventional theory, the conservation of the mass flow and momentum flow, the co-relation between the friction coefficient and the Reynolds number in the fully developed laminar flow in the rectangular microchannels were proven to be in agreement with the equation at the Re smaller than 2300 is $f * Re$ =96(1 - 1.3553α + 1.9467α² - 1.7012α^3 + 0.9564α^4 - 0.2537α^5) and for classical theory, $f * Re = 64$. The experimental results showed that the same pattern is followed as for the Poiseuille flow for low Reynolds number, which ultimately tells that the flow in this region is laminar. At the high values of Reynolds number, the flow was observed in transitioning to

the turbulent and it happened at the value of Reynolds number of 1500, which is slightly earlier than observed in macroscale

Cheng Wang, Chun Yang, Nam-Trung Nguyen, K T Ooi [23] Electro-osmotic flow is defined as the motion of liquid which is induced by the application of the potential across to a porous medium, membrane, microchannel, capillary tube or any other fluid conduit. Since the electro osmotic velocities does not depends upon the size of the conduit, if the electrical double layers stays smaller than the characteristic length scale of the channel. Electro osmotic flow is originate by the Coulomb force which is induced by an electric field on net mobile electric charge in a solution. Since the chemical equilibrium between surfaces, an electrolyte solution typically tends to the interface acquiring a net fixed electrical charge.

A mobile ion's layer which is called as an electrical double layer or Debye layer forms in the region near the interface. When an electric field is applied, the net charge is induced in the double layer which moves the Coulomb force. Thus the resulting flow is named as the electro osmotic flow. This study is based on the pressure driven flows in the microchannels with two fluids having the electro-osmosis effect. The boundary conditions were as steady state, fully developed flow in laminar regime under the effect of pressure gradient. Analytical solutions were derived to relate the flow rates and the velocity profiles to the aspect ratio and the viscosity ratio for the liquid and the electrical field. This study consists of a pressure driven model having the electro-osmosis effect and linear approximation the analytic solution for the electric distribution. The solutions were obtained by solving the linear Poisson-Boltzmann equation. The modified solutions of the Navier-Stokes equation were described for the steady state and the fully developed laminar region. At liquid to liquid interface the solutions are in very good agreement with the conventional theory for the rectangular microchannels.

M. B. Bowers, I. Mudawart [24] Studied about the High boiling flux at the low flow rate and at low pressure drop in the minichanels and the microchannels heat sinks. Since the upcoming demand of the large heat dissipation of heat fluxes in electronic devices and in the miniature heat sinks were made. Heat sinks have the thin block of metal which has channels of small size for flowing the cooling fluid. It acts as the sink for the heat which is applied from the block surface. Experimental study was made for the pressure drop and

CHF in mini channels (D=2.54mm) and microchannels (D=510µm). Heat sinks of 1cm heated length were performed using R-113.

R-113 is known as chlorofluorocarbon produced as the derivative of methane, ethane and propane, its goes as name of Freon. Its basic properties are low toxicity, low reactivity, and low flammability. The heat sinks are characterized by the hydraulic diameters of the channels in the range of 90-550 µm. The small hydraulic diameter insures a slender thermal boundary layer and it gives a large value of heat transfer co-efficient. The high heat Fluxes dissipation is combined with the high pressure drops. Phillips made a computer code to predict both the laminar flow and turbulent flow association with the characteristics of pressure drop and heat transfer for different liquids and micro-channel sizes. The water flow produced the heat flux of 100 W/cm^{-2} in a 1 cm long channel with the pressure drop value of 0.69 bars.

The test conditions contains the sub-cooling temperature range from 10 to 32 ºc and low mass flow rate up to maximum 95 ml/min. Main factor for including the miniature heat sink was the lack of inlet sub-cooling effect on critical heat flux and also the superheated condition at outlet for the lowest mass flow rates. There are advantages to utilize the Miniature heat sinks of two phases over the single phase. The single phase heat sinks of miniature size compensate for the high value of surface heat fluxes by a big stream-wise rise in the temperature of coolant and a corresponding Stream-wise rise in the temperature of heat sink. The two phases basically depends upon the latent heat exchange which keeps the stream-wise uniformity for both, in the coolant and the heat sink temperatures at a level adopted by the saturation temperature of coolant. The results showed that the performance of the mini-channel was seen greater as compare to the microchannel because of the pressure drop having value less than 0.01 bars for comparable CHF. Tests were performed to investigate the cause and effects of velocity and inlet sub-cooling on CHF as well as to compare the thermal and hydrodynamic Performances of the two heat sinks.

Having the single phase condition, the pressure drop of the mini-channel were negligible ($\Delta P < 0.003$ bar), as were the micro-channel's ($\Delta P = 0.007$ bar), due to the low flow rate. The boiling curves are specified for the flow rate having value of 45 ml/min and inlet sub-cooling temperature values of 10, 20, and 30ºC. The curves for each sub-cooling converge at high fluxes and they produce the same values of CHF for each respective heat

sink. The microchannel produces a higher value of CHF than the mini-channel's CHF. Flow boiling in mini-channels and micro-channel heat sinks is an emphatic way of producing a high heat fluxes (q > 200 W /cm^2) which is coupled with low flow rates (Q, < 65 ml/min) and low pressure drops (ΔP < 0.35 bar). Single-phase microchannel needs a value of pressure drop of 1 bar to achieve a heat flux of 181 W/cm^2 by using water as flowing fluid, which has way more greater thermal properties than the dielectric liquid.

Manoj Moharana, Sameer Khandeka [25] Worked upon a topic of Optimum Nusselt number for the simultaneously developing internal flow by applying the conjugate conditions in a square cross-section of microchannel. In this case, a numerical analysis has been performed to understand the axial wall conduction effects along with the conjugate heat transfer boundary condition. It also incorporates the developing laminar floe regime and the heat transfer in square cross-section microchannel over the condition of constant heat flux. Imposition of heat flux condition is on the bottom of the wall. Rest of the wall substrate is exposed to the surroundings and was kept as adiabatic. Conduction parameter is defined as the ratio of axial heat transfer within the solid duct or tube due to axial temperature gradient in it to the energy flow carried by the fluid in the channel in the axial direction. According to the results of the study conductivity ratio, k_{sf} is the key factor in affecting the extent of axial conduction on the heat transport characteristics at the fluid–solid interface. Higher k_{sf} leads to severe axial back conduction, thus decreasing the average Nusselt number (Nu).

Wolfram Urbanek, Jay N Zemel, Haim H Bau [26] Conducted experiment on an investigation of the temperature dependence of Poiseuille numbers in microchannel flow. In this particular study they explored the temperature dependence of Poiseuille numbers and possibly molecular isomerism of the liquid. Working fluids used in this study were 1, 2 propenol, &1, 3 pentanol. Hydraulic diameters of the tubes were taken as 5, 12, 25µm. Temperature increase range was 0 to 85ºC. For isothermal, steady, incompressible, fully developed laminar flow, the product of fanning friction factor and Reynolds number is nothing but Poiseuille number. Poiseuille number is a pure constant which is independent of fluid material properties, velocity, and temperature or duct size. For circular duct (PO = 16) and for infinite parallel plates (Po = 24).

$$f * Re = Po$$

$$f = \frac{2\tau_w}{\rho U^2}$$

$$Re = \frac{\rho D_h U}{\mu}$$

According to the results of the study, for 1-propanol exhibits a larger temperature dependence than, for 2-propanol, 1- and 2-propanol. They have essentially the same slope, with that of 1-propanol perhaps slightly Steeper. 1-pentanol exhibits a slope similar to that of the propanol for T < 60ºC, however at higher temperatures increases sharply the measured values of densities are in agreement with the conventional theory. Since the kinematic viscosity is a stronger function of temperature at low temperature as compare to the density. It exhibited a Maximum deviation of 0.4%.

Ward E. TeGrotenhuis, Victoria S. Stenkamp, Benjamin Q. Roberts [27] conducted an experiment on miniaturization of an ammonia water- absorption cycle heat pump using microchannels. Conventional vapour compression cycle relies on the mechanical compressor to drive the cooling cycle but they draw power from the electric power from the engine. Which in turn reduces the engine efficiency so here is information on progress toward a 250-Wattscale breadboard of a miniaturized absorption cycle cooling system.

FJ do Nascimento, HLSL Leão, Ribatski [28] performed an experiment on an experimental study on flow boiling heat transfer of R134a in a microchannel-based heat sink. This study focuses on the evaluation of the flow boiling of R134a in the microchannels. Heat sink is composed of fifty parallel rectangular microchannels the cross-sectional dimension of the microchannels is width= 100µm, depth= 500µm, total length = 15 mm. The working fluid used in the study is refrigerant R134athe value of heat fluxes is 310 KW/mt^2, mass velocities ranging from 400 to 1500 kg/m^{2}s and temperatures of saturation are approximately 25 ºC at the microchannels outlet. Average heat transfer coefficients based on the heated area up to 36 kW/m^2 ºC were obtained. Ribatski addressed the basic advantages of heat exchangers typically based on microchannels over the heat exchangers based on large channels. It was seen that the ratio between the surface area in direct contact with the refrigerant with respect to the heat exchanger volume increases with decreasing value of the channel diameter. In 1965, Moore explained that in a microprocessor, the number of transistors would double approximately in the period of every 2 years, which later became known as Moore's law. As the transistor's number

increases in the processor, the consumption of energy by the microprocessor and also the heat dissipation increases with it. The big aim of the study is to provide a better understanding of the heat transfer mechanisms. In the two-phase flow, the behaviors of fluid at the time of convective boiling inside microchannels are very necessary for the design of reliable devices. The results show that with the increase of superheating, liquid sub-cooling at the heats sink inlet also increases. This trend follows the agreement with the results of Park and Thome.

5 PROBLEM BACKGROUND

Purpose of study is consist of two parts in which one defines the thermal aspect of characteristics of microchannels and second one defines the hydraulic aspect of the characteristics.

5.1 Heat transfer

The effect of the hydraulic diameter on the heat transfer can be seen in the figure,

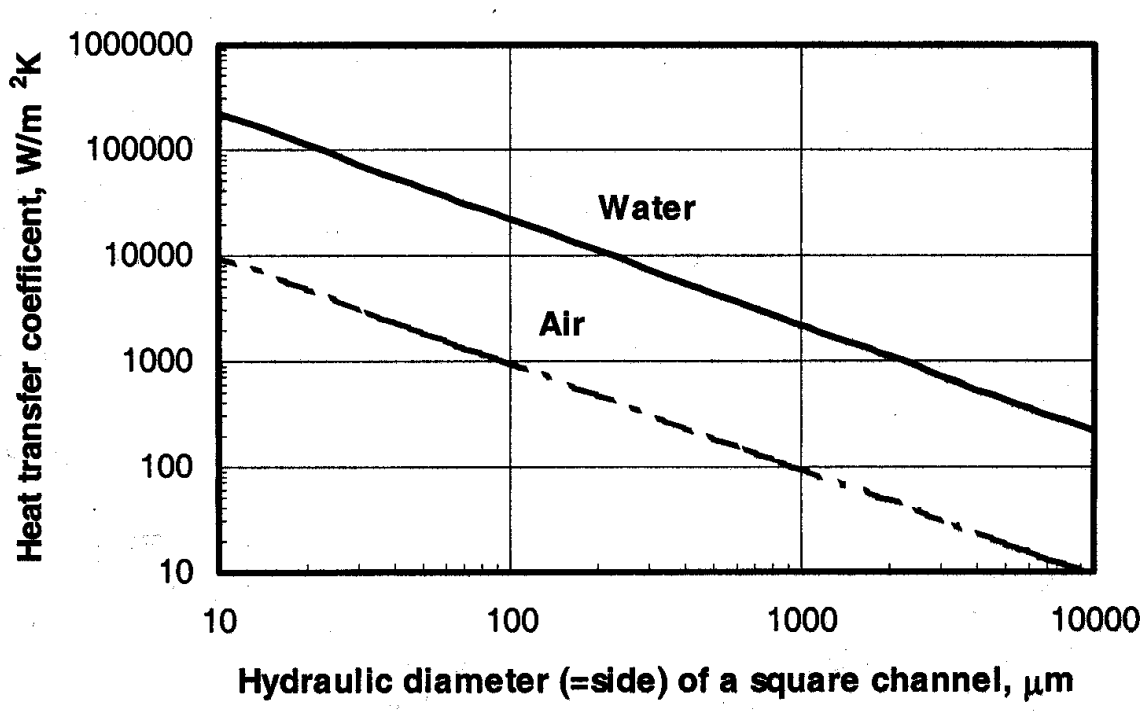

Figure 7: Graph between heat transfer co-efficient and hydraulic diameter for square channel [32]

The comparison of variation in heat transfer co-efficient with respect to the hydraulic diameter of a square channel for both water and air for laminar flow can be observed in the figure [2].

According to the shown figure, in laminar flow condition as the hydraulic diameter of the square channel increases, the value of heat transfer for both fluids air and water decreases linearly. However, it can be observed that the decrement in the heat transfer coefficient of air is more as compare to the water.

The heat transfer coefficient is unaffected by the flow Reynolds number in the fully developed laminar flow region. It's given by,

$$h = \frac{Nu * k}{D}$$

Where,

h=heat transfer co-efficient, Nu= nusselt number, k= thermal conductivity

5.2 Basic pressure drop

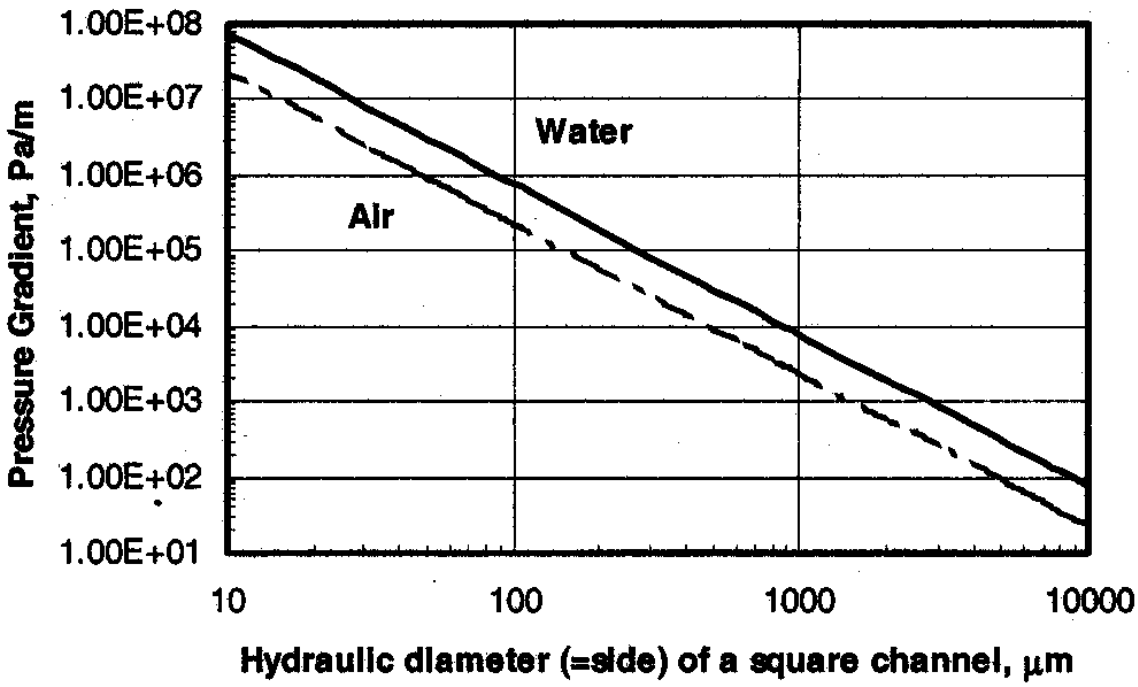

Figure 8: Graph between pressure drop and hydraulic diameter for square channel [32]

This figure above depicts the effect of hydraulic diameter variation on the pressure drop in square microchannels.

It can be seen that the friction factor (f) varies inversely with Reynolds number Re, however the product of friction factor and the Reynolds number ($f * Re$) remains constant during fully developed laminar flow. Frictional pressure drop per unit length for the flow of an incompressible fluid is given by the Darcy equation,

$$\Delta P = \frac{\rho f l v^2}{2D}$$

For fully developed laminar flow we can write,

$$\boldsymbol{f * Re = C}$$

5.3 Single phase liquid flow in microchannels

Single phase flow is expected to be unaffected for liquids, as the hydraulic diameter is reduced in range from 200 to 10µm.

Richter etched channels by KOH solution producing 54.7º side angles for the used triangular channels. The top width was between 28 and 182.7 µm, and the length of the flow channels was kept as 2 mm. the mass flow rate was between 0.01- 1000 µl/min and the flow behavior of the fluid was laminar with the value of Reynolds number less than 1.

Richter compared their results with the theoretical prediction using the channel friction factor and there was very good agreement over the entire range [37].

Pfahler concluded experiments with N- propanol in two different sizes of rectangular microchannels with the dimensions 1.7µm and 0.8µm deep and 100µm wide. Their results of the study showed that for all test sections, with the exception of smallest depth of 0.8µm, the conventional theory predicted the friction factor quite well [38].

5.4 Single phase gas flow in microchannels

The effect of rarefaction is expressed by Knudsen number,

$$\boldsymbol{Kn = \frac{\lambda}{D}}$$

Rarefaction is the phenomenon characterized by the reduction of the density of the substance. It's basically the inverse of compression.

At high value of Knudsen number, the continuum assumption of no slip at the wall no longer exists. Harley [11] provides the classification on the basis of Knudsen number. It has been observed that for all gases, the flow will enter into slip flow condition for microchannels.

For $Kn < 0.1$, rarefaction effects become important. In the slip flow region, where

$0.1 > Kn > 0.001$, which is generally the interest of the microchannels and the MEMS devices.

5.4.1 Dependence of type of flow on Knudsen number

range of Knudsen number	*type of flow*
0.001 ≥ Kn	Continuum flow: no rarefaction effect
0.1 > Kn > 0.001	Slip flow: rarefaction effects that can be modeled with a modified continuum theory are responsible for wall slip
10 >Kn > 0.1	Transition flow: a type of flow between slip flow and free molecular flow that is analyzed statistically i.e. with a Boltzmann equation
Kn > 10	Free molecular flow: motion of individual molecules must be modeled and then analyzed statistically

Table 2: Type of flow in microchannels based on Knudsen number [32]

5.5 Flow boiling in microchannels

Surface tension plays a very important role as the channels dimension becomes smaller. The fundamental issues related to the flow pattern in the microchannels and mini-channels was conducted by Kandlikar, which can be summarized as below,

i. The low patterns observed in the microchannels are strongly dependent of time, with a sequence of different flow patterns passing through the channel as a result of flow instability. The results are more pronounced in the microchannels.

ii. Flow reversal is commonly experienced in a channel along its length. studies have confirmed that the fluctuations results from the rapid expansion of a bubble into a slug, which pushes the liquid away both upstream as well as downstream of the flow.

5.6 Condensation in microchannels

Very little information is found in the condensation in microchannels. Condensation heat transfer is governed by the thickness of the liquid film at the coated wall.

In two phase flow condensation there are two mechanisms acting to decrease the film thickness: gravity and shear stress. Gravity should have less effect as the channels diameter is reduced. Shear stress could be expected to increase with decreasing diameter. Also surface tension force could be of importance. This can be seen from the Laplace equation for cylindrical pipe,

$$P_v - P_l = \frac{\sigma}{r}$$

If the tube radius is small there will be a noticeable pressure difference between the vapor and the liquid phase, which will influence the saturation temperature and also might tend to increase the film thickness.

5.7 Liquid nitrogen

Liquid nitrogen is simply nitrogen which exists in liquid state at extremely low temperature. Liquid nitrogen is colorless and transparent liquid with the density of 0.807 gram/ml at its boiling point which is typically 77 K. Liquid nitrogen is commonly referred by the designation LN_2. In chemical composition, liquid nitrogen is diatomic liquid, which suggests that liquid nitrogen in composes of two nitrogen atoms with the formation of a strong covalent bond. The basic and probably the important property lies in the fact that liquid nitrogen is a cryogenic fluid that is capable of causing the rapid freezing when comes in the contact of living tissue and also sets very fine bars when it comes to use of it as refrigerant.

The storage and transportation of liquid nitrogen is not very tricky if it is completely insulated from the ambient heat from the surrounding. It easily can be stored in vacuum flasks. The temperature needs to be held constant at 77 K for slow boiling and for slowing down the process of resulting the evolution of nitrogen. The temperature of liquid nitro can be reduced to the 63 K by placing it into a vacuum chamber.

It is has been stated by lots of experiments that liquid nitrogen is an excellent refrigerant and it boils immediately when comes in the contact of warmer objects considering the object in insulating nitrogen gas. This effect is called as Leiden frost effect, can be applied to any liquid in contact with an object significantly hotter than its boiling point.

Figure 9: Liquid nitrogen [40]

5.7.1 Production of liquid nitrogen

Liquid nitrogen is commercially produced by the process of cryogenic distillation of liquefied air and otherwise manner it also can be produced from the liquefaction of pure nitrogen extracted from the air by using pressure swing adsorption.

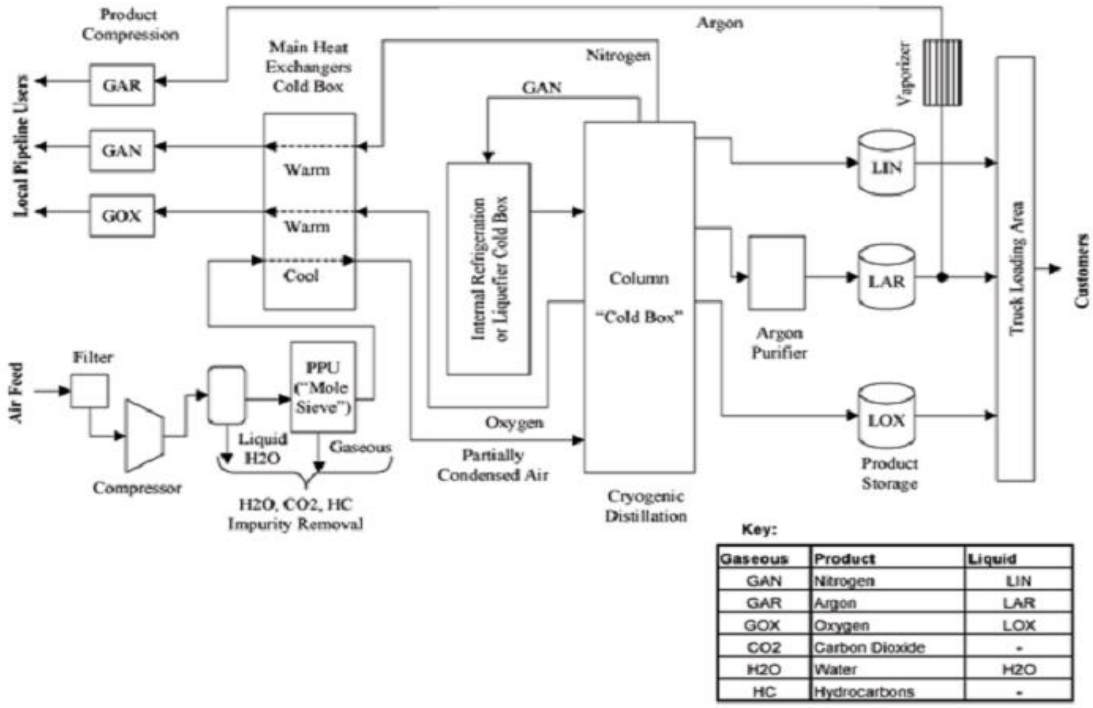

Figure 10: Production cycle of liquid nitrogen [39]

Later on, an air compressor is used to compress filtered air to high pressure then the high pressured gas is again cooled back to atmospheric temperature and allowed it to expand to a low pressure. The air expanding air cools sevenfold (vastly) due to joule-Thomson effect and oxygen, nitrogen and organ remaining are separated further by expansion and distillation.

One other advantage is that the small scale production of liquid nitrogen can be readily obtained by using the principle.

5.7.2 Physical and chemical properties of Liquid Nitrogen [41]

Chemical Formula	N_2
Molecular Weight	28.01
Boiling Point @ 1 atm	–320.5°F or –195.8°C
Freezing Point @ 1 atm	–346.0°F or –210.0°C
Critical Temperature –232.5°F	–146.9°C
Critical Pressure	33.5 atm
Density, Liquid @ BP, 1 atm 50.47 lb/scf	808.5 Kg/m3
Density, Gas @ 68°F (20°C), 1 atm 0.0725 lb/scf	1.16 Kg/m3
Specific Gravity, Gas (air=1) @ 68°F (20°C), 1 atm	0.967
Specific Gravity, Liquid (water=1) @ 68°F (20°C), 1 atm	0.808
Specific Volume @ 68°F (20°C), 1 atm	0.861 m3/kg
Latent Heat of Vaporization	199.1 kJ/kg
Expansion Ratio, Liquid to Gas, BP to 68°F (20°C)	1 to 694

5.7.3 Safety

While the handling the liquid nitrogen several safely issue can be considered as hazardous thus the precaution must be made at the time of working with liquid nitrogen. Due to the fact that liquid-to-gas expansion ratio of nitrogen at 20 °C is 1:694, an immense amount of force can be generated if the liquid nitrogen is rapidly vaporize in an enclosed stead.

An accident happened on January 12, 2006 at A&M University (Texas), the pressure relief valve of the liquid nitrogen was malfunctioned and as a result the large pressure build up which caused the tank failed catastrophically. The force of the explosion was so strong that tank was propelling through the ceiling.

One more thing is to consider is that since the extremely low temperature, carelessness in handling the liquid nitrogen might cause the cold burns. In that case the, the gloves or probably the operational suite must be wear. As the temperature of liquid nitrogen increases, it starts to evaporate and it reduces the oxygen concentration in the air and it might act as an asphyxiant. Nitrogen is colorless, odorless and tasteless and might produce asphyxia without any warning.

5.7.4 Uses

Liquid nitrogen is a wonderful substance that can be used in number of useful ways in various fields like medical, science experiments and even to make ice cream. Nitrogen is a gas which nearly comprises 78% of the air.

Only two other substances colder than liquid nitrogen are liquid hydrogen and liquid helium. Liquid nitrogen is a very good source of nitrogen gas because it does not require any pressurization. In addition, the ability of liquid nitrogen to maintain its temperature far below to the freezing point of water makes it more useful in various important applications, thus it is basically an open cycle refrigerant.

i. **As cryogenic refrigerant**

   Cryogenics is the process of producing and maintaining extremely low temperature for the preservation of substance which are most likely to alter their characteristics by temperature variation.

ii. **As vehicle fuel**

   One of the most important uses of liquid nitrogen is that it can be used as vehicle fuel. The operation principle is quite simple; heat from the atmosphere vaporizes liquid nitrogen under pressure and produced compressed nitrogen gas. This obtained compressed nitrogen gas a pneumatic or compressed gas drive motor with nitrogen gas as exhaust.

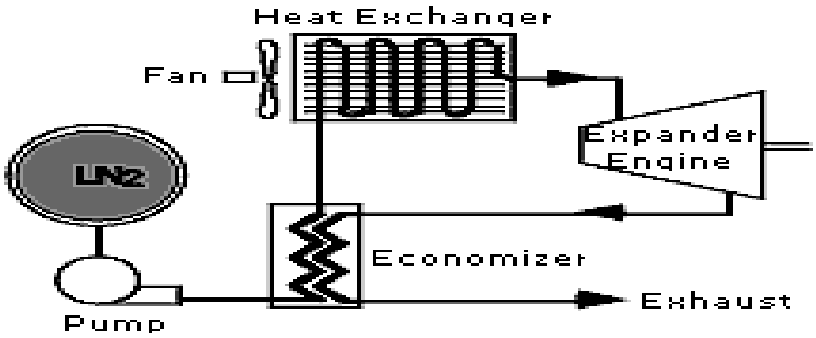

Figure 11: Flow of liquid nitrogen in a power generation cycle [40]

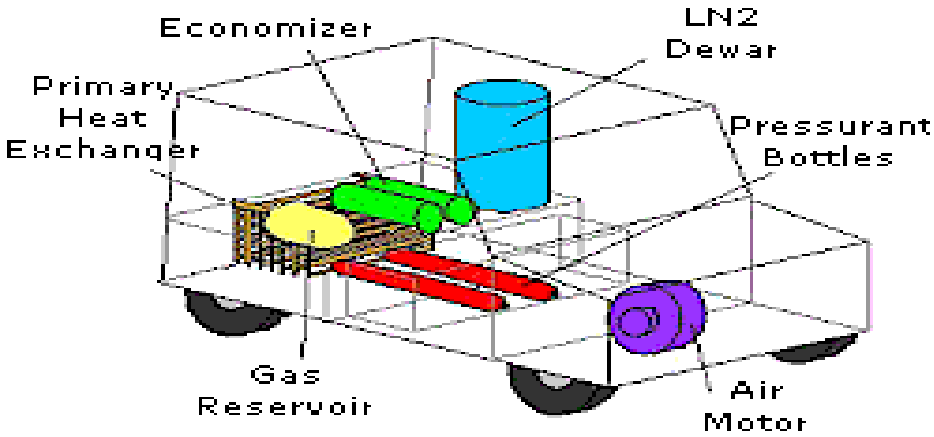

Figure 12: Liquid nitrogen as vehicle fuel [40]

iii. Wart removal

Because of the fact that any living human body cells that comes into contact with the liquid nitrogen can be instantly frozen and later they will die and fall apart. This process allows to the liquid nitrogen to be used in the effective treatment of wart removal or should be say the removal of small skin cancer.

iv. Frozen sperm

The process of freezing the sperm is quite in trend these days because of the preserving the promise of fertility for the future. Liquid nitrogen is also being used for this process because the temperature of the sperm needs to be maintained very low and this can be easily achieved by using the liquid nitrogen.

v. Cryotherapy

It is the process of removing the unwanted skin cells of the human body by damaging the cell with very low temperature where liquid nitrogen comes in play for producing very low temperature. There are lot of other uses of liquid nitrogen

in medical field like cryopreservation of blood and cryopreservation of animal genetic resources. Food transportation is also very big area of the using of liquid nitrogen.

One of other pretty interesting use of liquid nitrogen is for making the ice cream.

5.7.5 Advantages of Liquid Nitrogen

i. Liquid nitrogen is not combustible or toxic
ii. It is much lighter and takes very less time in refilling
iii. Have significantly better performance

5.7.6 Disadvantages of Liquid Nitrogen

i. liquid nitrogen is not available at public refuelling stations
ii. it requires lot of energy to convert nitrogen gas into liquid nitrogen

5.8 Liquid Hydrogen

Hydrogen happens to be the lightest element which exist in the periodic table with atomic number 1 and it has some astonishing quality in it in gaseous phase and as well as in liquid phase.

Hydrogen as only single electron in its outer cell and it has quite strong tendency to make a covalent bond it every other element most probably. In the most common case of water (H_2O) hydrogen makes two covalent bonds with single oxygen atom.

5.8.1 Physical properties of Hydrogen

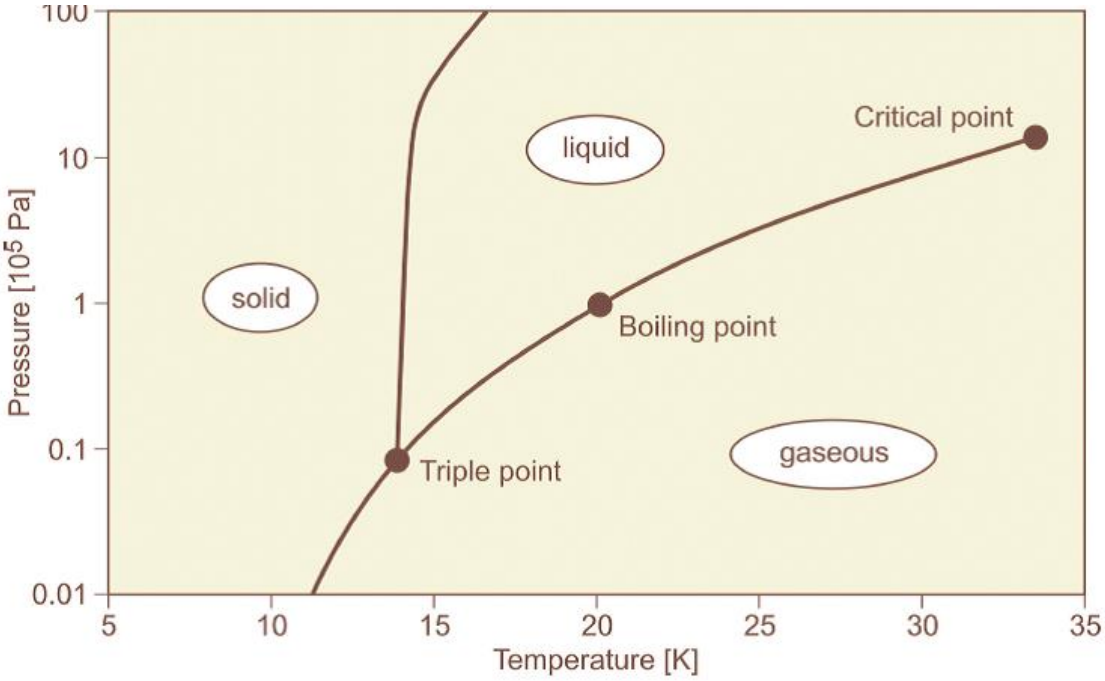

Figure 13: Properties of hydrogen [42]

Hydrogen is basically assumed as ideal gas over a wide range of temperature and at even very high range of pressures. At normal temperature and pressure conditions it is colorless, odorless, non-toxic, non-corrosive, non- metallic gas.

Between all the excellent qualities one of the fine quality is that it has low density, which makes it more practical for all the applications like either compress the hydrogen gas or change it to liquid state.

5.8.2 Chemical properties

Hydrogen is amazingly reactive with every other element with non-metals of high electro-negativity and with metals of low electro-negativity.

Electro-negativity is basically is a phenomenon of attraction of electrons towards the nucleus. The difference of electro-negativity of two elements defines the characteristics of the bond. If electro-negativity difference is 0, bond is non-polar covalent and higher valve of difference shows the polar form of covalent bond.

Hydrogen is flammable over a wide range of temperature and as a fuel is demonstrates very environment friendly, neat and clean substitute of petroleum if the movable storage is not the issue.

5.8.3 Liquid phase

Liquid hydrogen is the liquid form of hydrogen gas which obtained by liquefaction at below the critical temperature of hydrogen which is typically 33K. Liquid hydrogen basically exists in two forms called as Para-hydrogen 99.7% and ortho-hydrogen 0.3%.

5.8.4 Uses

The uses of liquid hydrogen are limited but important. Some of the important uses are as given follows,

I. Liquid hydrogen is basically used as the primary rocket fuel in aerospace industry. It helps the combustion with oxygen or fluorine.
II. Basically the more uses of hydrogen are in gaseous state, but the storage and the transportation is done in liquid state.
III. It is also used as for the manufacturing of polyethylene and polypropylene.
IV. One of the important uses of liquid hydrogen is to reduce metal oxides and prevent oxidation.
V. It is also used for the manufacturing of semiconductors.

5.9 Analytical methodology

According to the many previous researches, Microscale theory of fluid flow does not quite agree with the macroscale theory.

On the one hand, the macroscale theory suggests the three basic regions of fluid flow which is typically laminar, transition and turbulent. These regions are classified by the value of critical Reynolds number which happens to be 2040 or in some cases 2300. When the value of Reynolds number stays less than 2040 or 2300, flow is said to be laminar and if the value of Reynolds number goes over the critical value than the flow is called as turbulent. In turbulent region the fluid basically flows with chaotic velocity and the density of fluid decreases.

On the other hand microscale theory does not show the laminar region widely because diameter of the pipe (microchannel) is very less which in turn in the reason of less cross section area thus results in extremely high velocity in pipe (microchannel), due to this very high velocity laminar region and transition are very difficult to synthesize thus only remain the wide region of turbulent flow.

5.10 Fluid flow in microchannels

5.10.1 Turbulent flow

When in microchannels the flow of fluid occurs at extremely high velocity because of the very less cross sectional diameter of the microchannel it results in eddy formation in the flow which is responsible for the turbulent region generation and the flow in turbulent region with high velocity is called as turbulent flow.

In turbulent flow the velocity of the fluid fluctuates at some range and due to this fluctuation the constant velocity of the fluid disrupts and eddy formation takes place because of energy exchange between fluid particles.

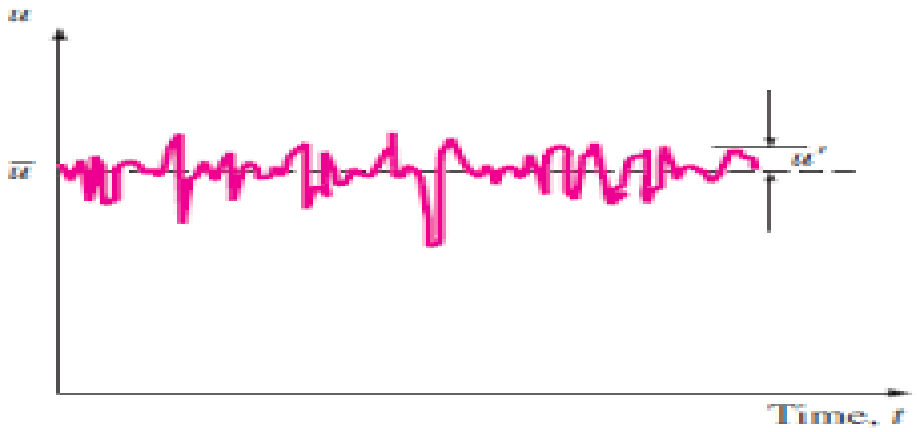

Figure 14: Turbulence in flow

5.10.2 Reynolds number

The first characteristic in fluid flow is the Reynolds number which is defined as,

$$\boldsymbol{Re} = \frac{\boldsymbol{\rho v d}}{\mu}$$

Or, it can also be written as,

$$\boldsymbol{Re} = \frac{\boldsymbol{inertial\ force}}{\boldsymbol{viscous\ force}}$$

Where, ρ= density of the fluid, v= velocity of the fluid

d = diameter of the pipe μ= viscosity of the fluid

5.10.3 Friction factor

When the turbulent flow in microchannels is occurring (considering the pipe is smooth), the noted Blassius corrected solution of friction factor can be used to calculate the friction factor which is,

$$\boldsymbol{f = 0.0791\ \mathrm{Re}^{-0.25}}$$

This friction factor is fanning friction factor, which is one-fourth of Darcy friction factor.

$$\Delta \boldsymbol{P} = \frac{\boldsymbol{128\mu LQ}}{\boldsymbol{\pi d4}}$$

5.10.4 Pressure drop

Pressure drop in the microchannels is calculated by the Hagen-Poiseuille equation for incompressible flow which is described as,

5.11 Heat transfer in microchannels

In many researches, the Nusselt number is tends to be increasing with increasing Reynolds number as depicted by the classical laminar flow theory. However, many other researchers showed that Nusselt number remains constant.

The classical theory says that the value of Nusselt number would be change according to the geometry of the pipe or in this case microchannel.

5.11.1 Nusselt number

Nusselt number is defined as the ratio of convective to conductive heat transfer normal to the boundary.

$$\boldsymbol{Nu = \frac{hd}{k}}$$

Where,

h= heat transfer co-efficient, d= diameter, k= thermal conductivity

The value of nusselt number for the flow in microchannels can be calculated by Chilton-Colburn analogy which is,

$$\boldsymbol{Nu = 0.125 \times fRe \times Pr^{0.33}}$$

5.11.2 Prandtl number

Prandtl is defined as the ratio of viscous diffusion rate to thermal diffusion rate.

$$\boldsymbol{Pr = \frac{\mu C}{k}}$$

Where,

μ= viscosity, C= specific heat, k= thermal conductivity

6 RESEARCH METHODOLOGY

The modern trend of turbine cooling is using various methods of the cooling which mainly classified into two major sections,

1. **Internal cooling:** where the heat is removed by the variation of convection configuration, where the high velocity of air flows and hits the turbine blades and the vanes.
2. **External cooling:** where cold air is injected through the film cooling holes on the external surface in order to create a thin cooling layer.

The present study is directed toward a new cooling technique for the turbine blades which is by using the microchannels on the surface of the blades. When the gas flows through the microchannels it will lose its heat there and cool down before flowing further. The flow rate of the air and the area of contact of the gas with the microchannels surface will play very important role in this technique. Considering the fact that microchannel has high area to volume ratio will results in higher rate of heat transfer, will probably result in efficient cooling of the turbine blade which will in turn increase the inlet temperature of the blade.

A computational analysis study with the help of CFD software, on the Thermohydraulic properties of the cooling medium will be performed and on the basis of collected data the accurate estimation whether the microchannels can be or cannot be used for the cooling of the turbine blade will be established. In present 2-D computational study, modeling and meshing of the pipe will be formulated by **ICEM** software and then solution will be converging on **FLUENT** solver.

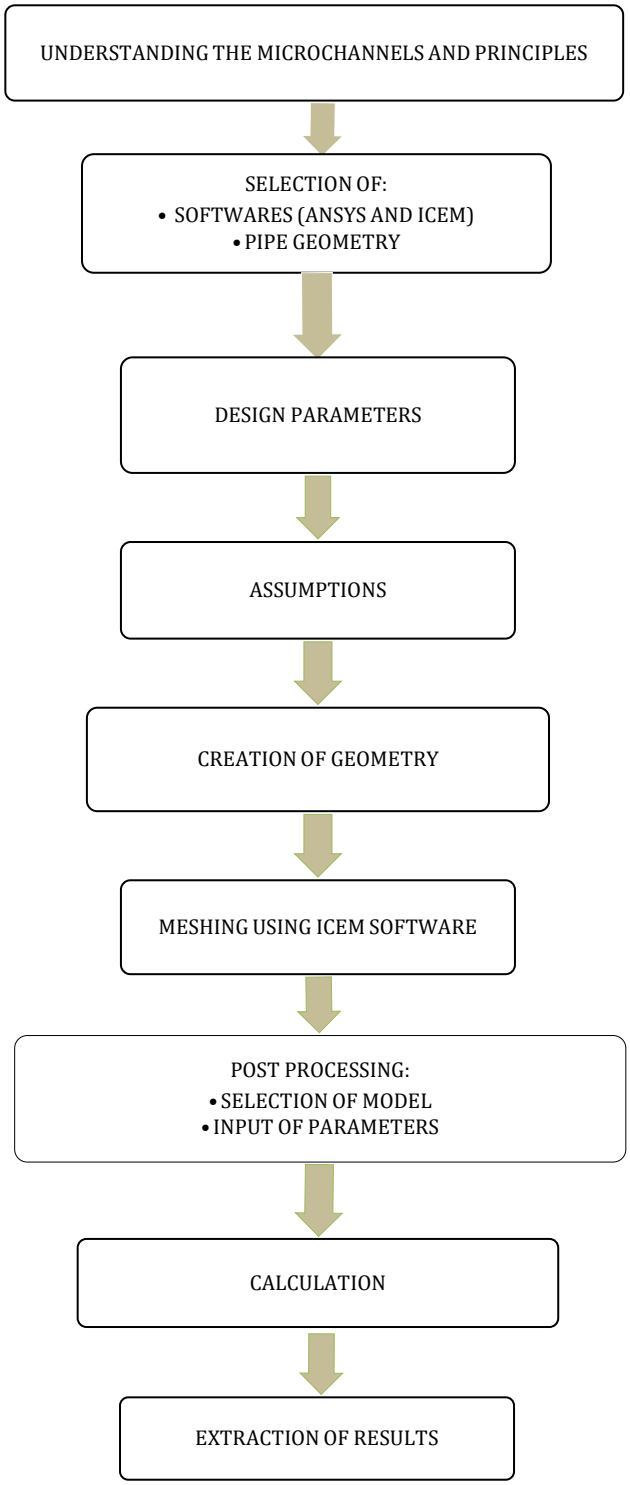

Figure 15: Flowchart of the methodology

6.1 Selection of Pipe geometry

The most conventional pipe geometry generally found is of circular cross section thus for the computational analysis a microchannel of circular cross-section is chosen.

6.2 Assumptions

In the present study, the following assumptions are considered:

i. The flow inside microchannels is incompressible

ii. Flow field is Turbulent

iii. Temperature distribution along the length of microchannel is constant

iv. Steady state

v. Microchannel surface is smooth

6.3 Design Parameters

Parameters	Air	Liquid Nitrogen	Liquid Hydrogen
Inlet temperature	300 K	65 K	25 K
Wall temperature	330 K	100 K	50
Hydraulic diameter	1µm – 100µm	1µm – 100µm	1µm – 100µm
Length of the microchannel	0.1 m	0.1 m	0.1 m
Range of mass flow rate	0.5 – 10 gram/sec	0.5 – 10 gram/sec	0.5 – 10 gram/sec

Table 3: Design parameters

6.4 Creation of Geometry and Meshing

A 2-dimensional axisymmetric model of circular cross-section geometry is created in ICEM design modeller and meshing is also done using Ansys ICEM CFD. The microchannels having hydraulic diameters of 1µm – 100µm were created. The length of the microchannels was kept constant as 0.1 m.

6.5 Post-processing

For the post processing of the simulation, the results were executed considering steady state, pressure based Navier stokes equations and turbulence model enabling the energy equation. The most commonly used model for turbulence are standard K-epsilon, standard wall fn, K-omega, Spart - allaras etc. model. Generally, K-epsilon model includes three models Standard, RNG and realizable model is used for viscous heating, buoyancy effect etc. The RNG models can be used for differential viscosity model where low Reynolds number is included under turbulence viscosity. In the present study, K-epsilon model with standard wall treatment is considered.

6.5.1 Selection of model and materials

i. Steady State

ii. Pressure based Navier stokes equation

iii. Energy Equation

iv. K-epsilon Model with standard wall function

v. Flowing Fluids: Air, liquid nitrogen, liquid hydrogen

vi. Solid Medium: Aluminium

6.5.2 Boundary Conditions

Inlet Condition:

Magnitude of mass flow rate: 0.5 – 10 gram/sec

Inlet Temperature: 300 K for air, 65 K for liquid nitrogen, 25 K for liquid hydrogen

6.6 Extraction of Results

The results of the CFD simulation were extracted for hydraulic diameter range of 1µm to 100µm over the mass flow rate range of 0.5 gram/sec to 10gram/sec for considered circular cross-section of microchannel. The results were in the form of temperature reduction. The variable considered was:

i. The variation of mass flow rate at constant diameter.
ii. The characterization of Pressure drop and Reynolds number.
iii. The characterization Nusselt number, heat transfer co-efficient and heat transfer rate.
iv. The characterization of wall shear stress

7 COMPUTATIONAL RESULTS

7.1 Velocity magnitude diagram

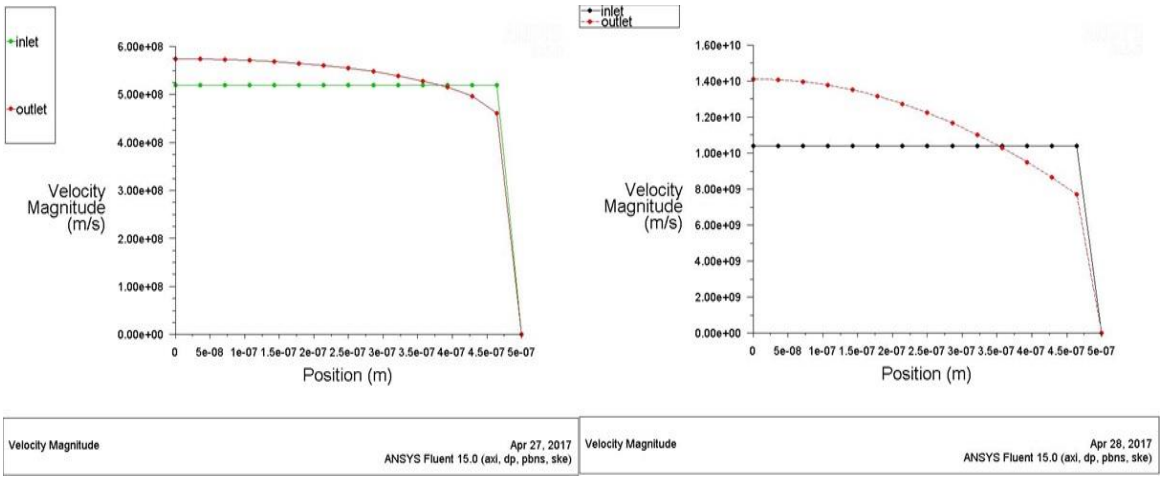

Figure 16: Velocity magnitude vs. position (for Air)

Above given figure (16) shows the velocity diagram for air at the mass flow rate of 0.5 gram/sec (left) and 10 gram/sec (right)

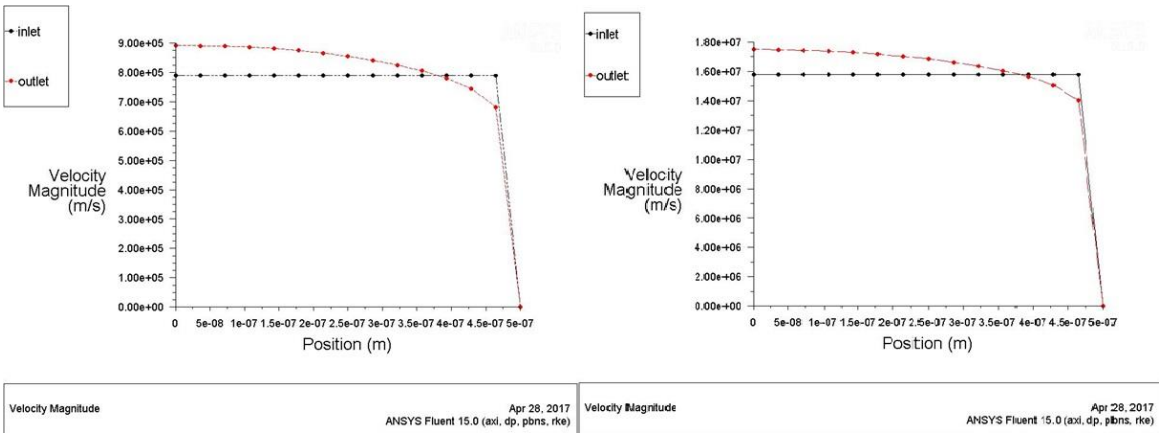

Figure 17: Velocity magnitude vs. position (for Liquid Nitrogen)

Above given figure (17) shows the velocity diagram for liquid nitrogen at the mass flow rate of 0.5 gram/sec (left) and 10 gram/sec (right)

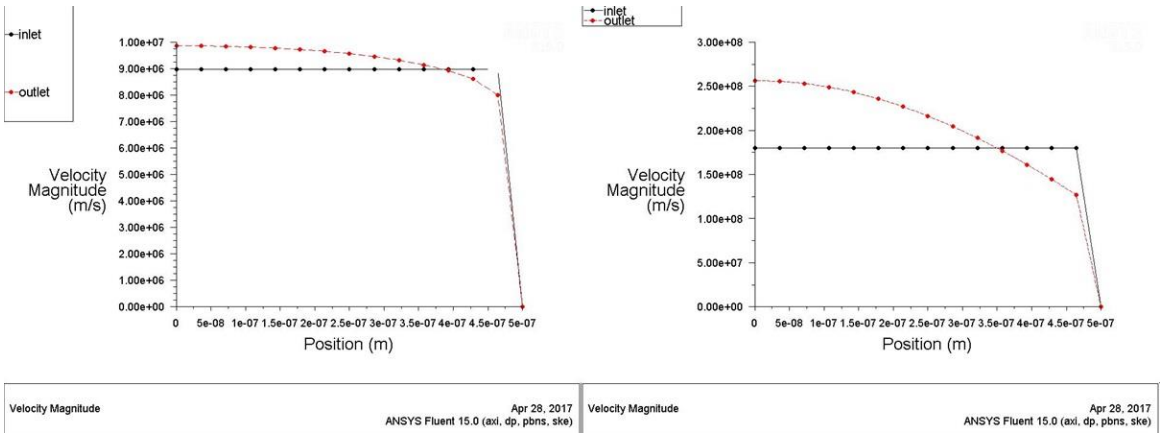

Figure 18: Velocity magnitude vs. position (for Liquid Hydrogen)

Above given figure (18) shows the velocity diagram for liquid hydrogen at the mass flow rate of 0.5 gram/sec (left) and 10 gram/sec (right)

7.2 Friction factor vs. Reynolds number

Friction factor is the quantity which plays a significant role in pressure drop during the flow in channel or duct. The graph is plotted between the friction factor and the Reynolds number.

This graph is plotted for varying mass flow rate from 0.5 gram/sec to 10 gram/sec on different diameters from 1µm to 100µm by keeping the length of the microchannel constant as 0.1 meter. The green line denotes the liquid hydrogen [LN_2], the red line denotes the liquid hydrogen [LH_2] and the blue line is showing the variation in friction factor for Air.

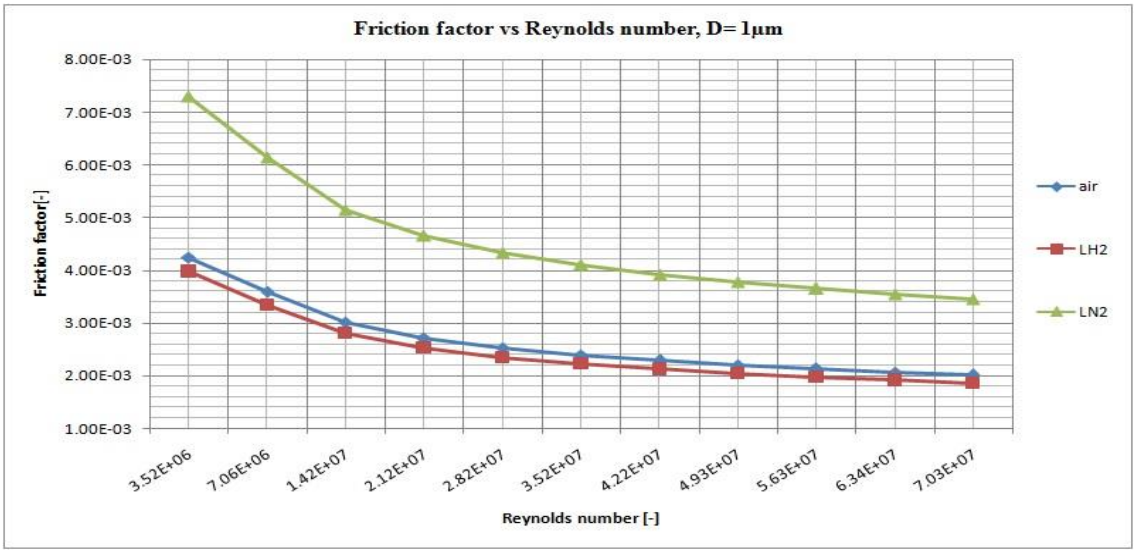

Figure 19: Graph between fanning friction factor and Reynolds number for circular microchannel, diameter = 1µm

This graph [19] shows the variation in friction factor against Reynolds number for the microchannels of 1µm diameter. It can be seen in the graph that the variation in the friction factor is reciprocal to the Reynolds number. As the value of Reynolds number keep on increasing the value of fanning friction factor keep on decreasing. This graph is in agreement with the conventional theory, which also suggests that on increasing the value of Reynolds number the value friction factor will decrease.

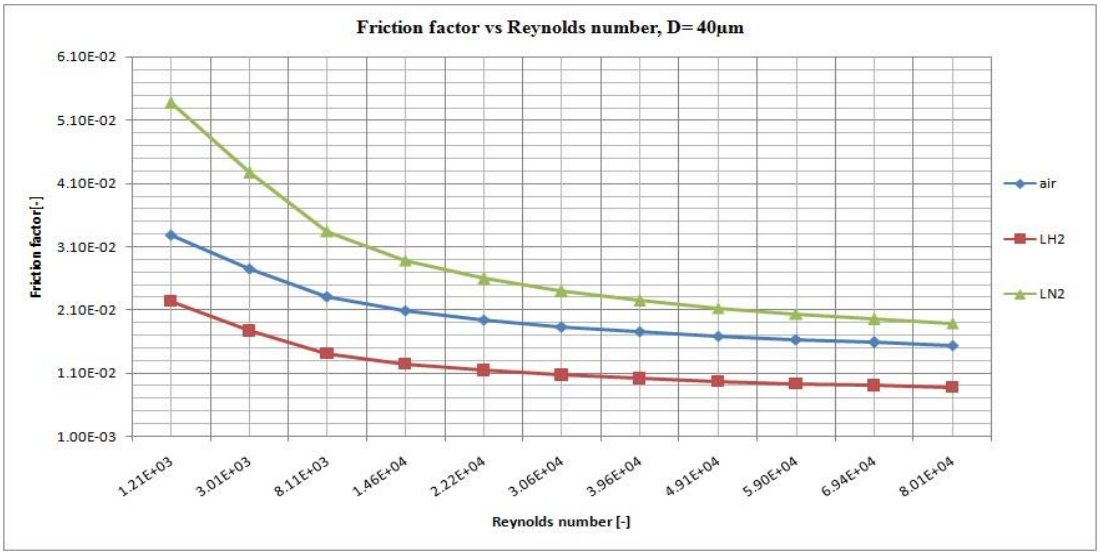

Figure 20: Graph between fanning friction factor and Reynolds number for circular microchannel, diameter = 40µm

This above given graph [20] is for the microchannel of 40µm and it also shows that friction factor decreases with the increasing value of Reynolds number and this graph is also in the agreement with the conventional theory. Additionally it can be observed that the liquid nitrogen shows the highest value of friction factor and liquid hydrogen displays the lowest value of friction factor among all three fluids. It can be observed from the figure that the variation in friction factor yields same as the conventional channels on the basis of moody chart. For varying mass flow rate range from 0.5 gram/ sec to 10 gram/ sec, it follows the exact same pattern as others for the rest of diameters and comes in completely in agreement with conventional behavior for friction factor.

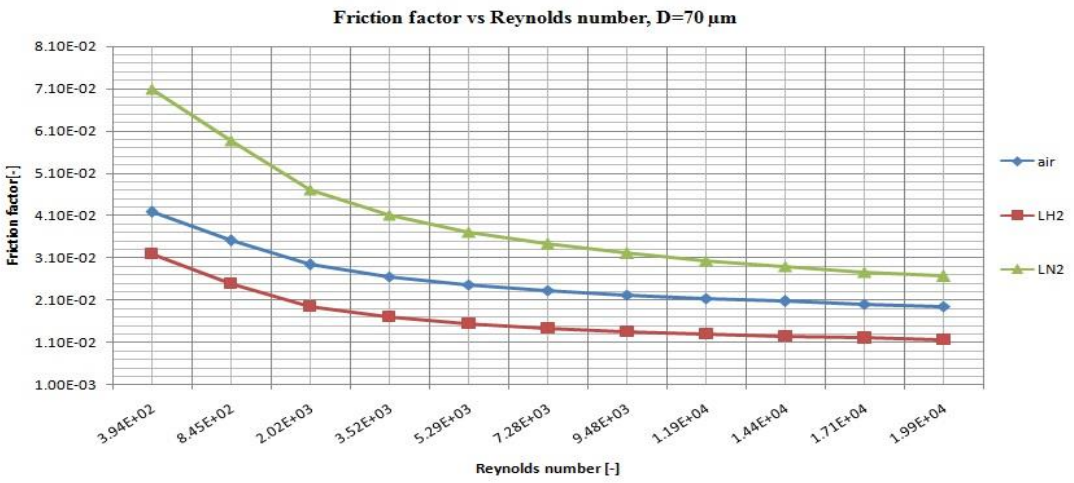

Figure 21: Graph between fanning friction factor and Reynolds number for circular microchannel, diameter = 70µm

In the above given graph [21] the same pattern is being followed by all three flowing fluids as the rest of the graphs and showing agreement with the conventional theory and compatibility with moody diagram for turbulent flow.

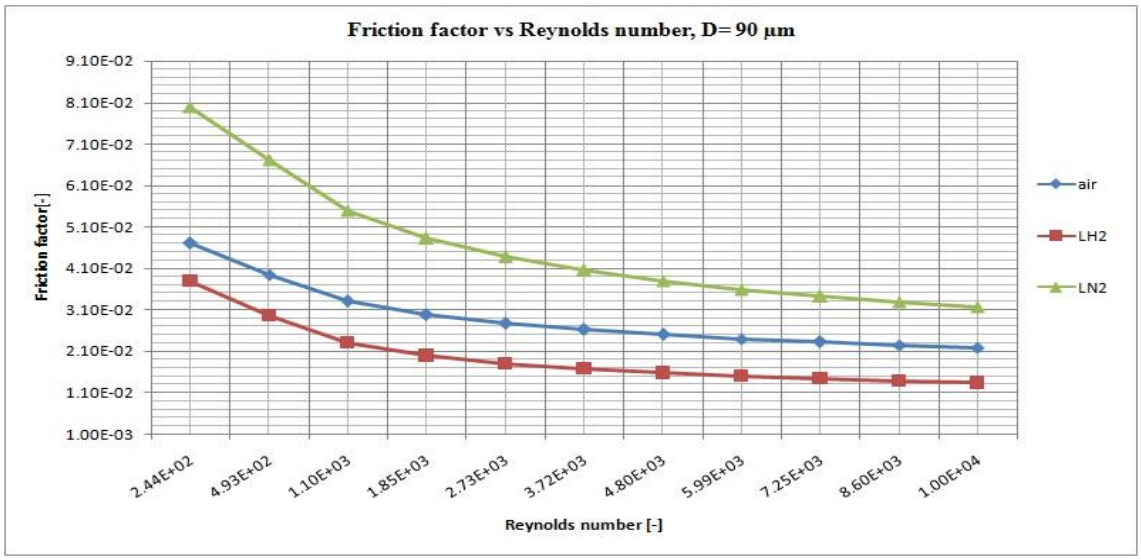

Figure 22: Graph between fanning friction factor and Reynolds number for circular microchannel, diameter = 90µm

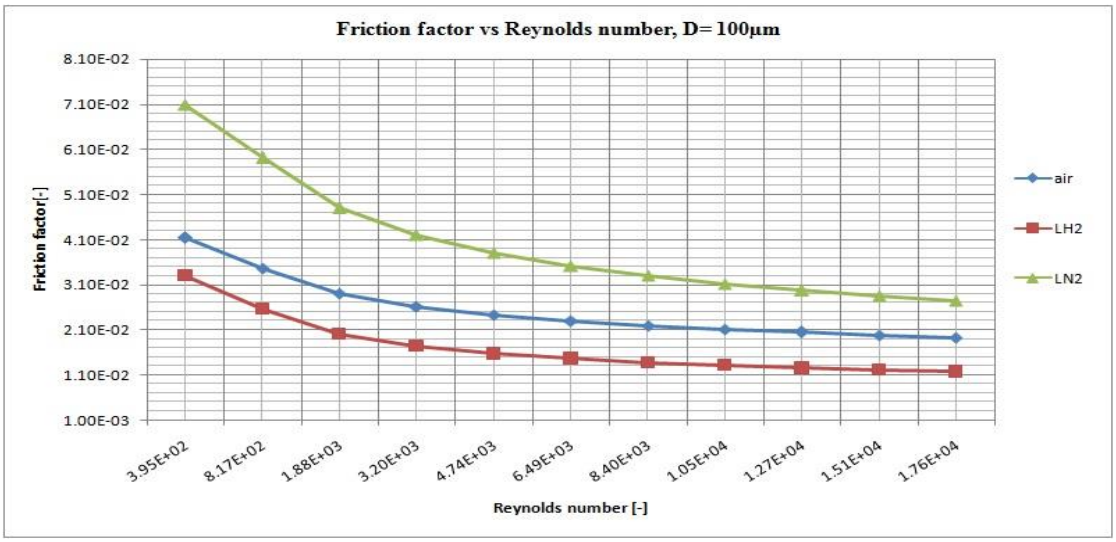

Figure 23: Graph between fanning friction factor and Reynolds number for circular microchannel, diameter = 100µm

Same pattern can been in the rest of the graphs of friction factor vs. Reynolds number which clearly justifies the fact that friction factor is reciprocal to the Reynolds number for flow in microchannels which is according to the conventional theory and follows the moody diagram in turbulent region. Thus the flow in microchannel is same as the conventional channel however the values of friction factor seems to be bit higher. Thus it can be seen from the friction factor vs. Reynolds number graphs that as the value of Reynolds number increases, the value of friction factor decreases for constant diameter. However, if the value of diameter is increased, the value of friction factor increases.

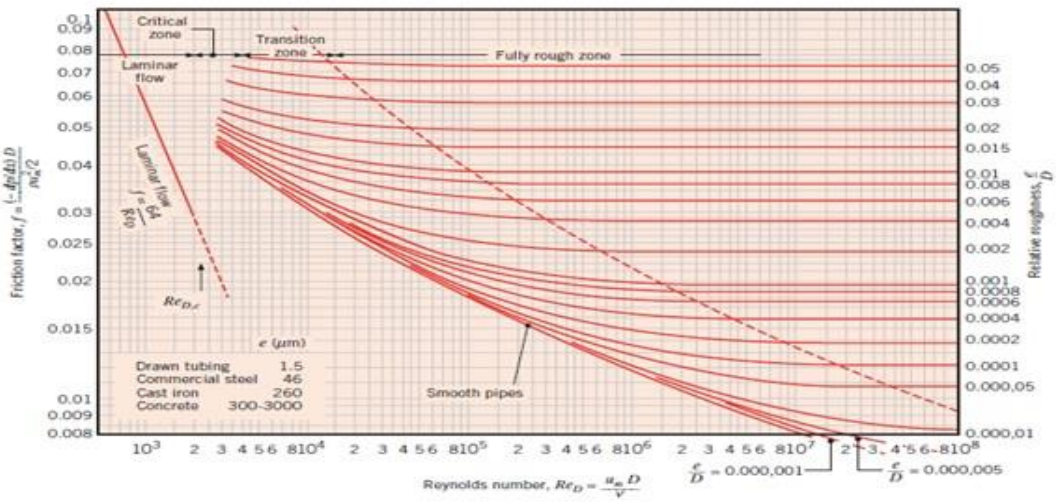

Figure 24: moody diagram showing the pattern of friction factor vs. Reynolds number (according to the conventional theory) [74]

The above given diagram [24] is known as the moody diagram which depicts the variation in the values of friction factor with the change in the values of Reynolds number in both, the laminar and the turbulent region. Moody diagram is standard graph to analyze the dependence of friction factor over the Reynolds number according to the conventional theory. It provides the information about the varying characteristics of friction factor as there is change in the value of Reynolds number and the aspect ratio of the channel. Friction factor calculated by the moody chart is basically in the form of Darcy friction factor which is 4 times of fanning friction factor.

7.3 Pressure drop vs. Reynolds number

Basically, there are three major components which have their contribution to the overall pressure drop in fluid flow in microchannels or duct. The losses at inlet and exit need to be quantified as the flow in microchannels takes place. While evaluating the hydrodynamic developing length care must be taken into account. Finally, the rest of the length possesses the frictional loss in fully developed flow.

In the graphs of Pressure drop vs. Reynolds number, the blue line indicates the liquid nitrogen [LN_2] and red line indicates the liquid hydrogen [LH_2] and the green line indicates the air.

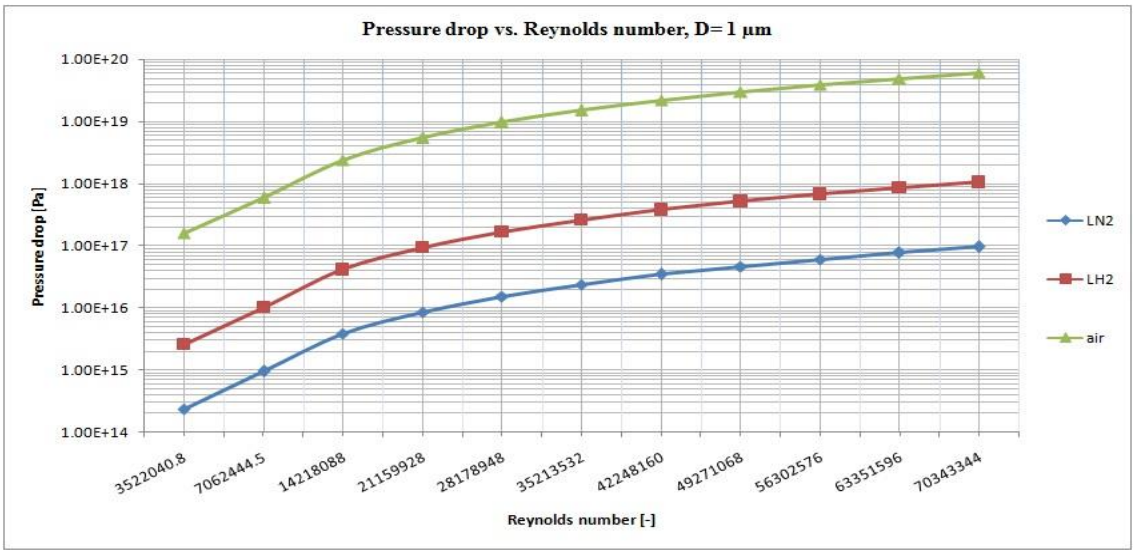

Figure 25: Graph between pressure drop and Reynolds number for circular microchannel, diameter = 1µm

This graph given above is plotted between the pressure drop and the Reynolds number for the varying value of mass-flow rate for the flow in microchannels of 1µm diameter. The range of the mass flow rate is from 0.5 gram/sec to 10 gram/sec. The graph depicts that as

the value of Reynolds number increases, the pressure drop also increases on a curve gradually, for the varying mass-flow rates. It can also be observed for the graph that all three flowing fluids are in excellent agreement with each other.

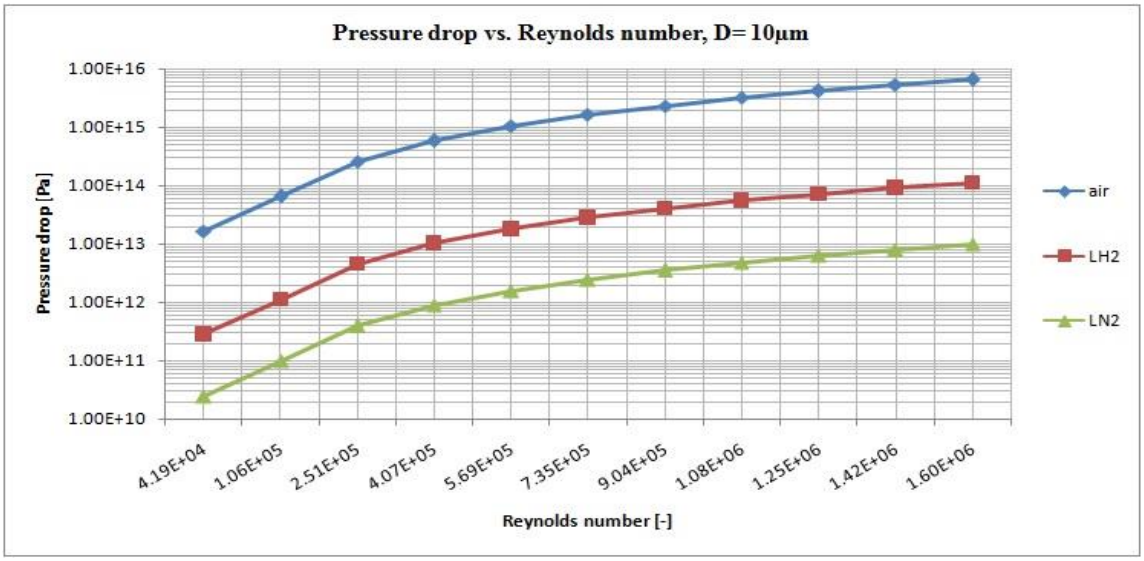

Figure 26: Graph between pressure drop and Reynolds number for circular microchannel, diameter = 10µm

Similar effect can be observe in the graph of 10µm diameter, that the shape of the curve does not changes and the value of pressure drop increases with the increasing value of Reynolds number. Graphs shows that the air yield the highest value for the pressure drop and liquid nitrogen yields the lowest value for a constant diameter among all three flowing fluids.

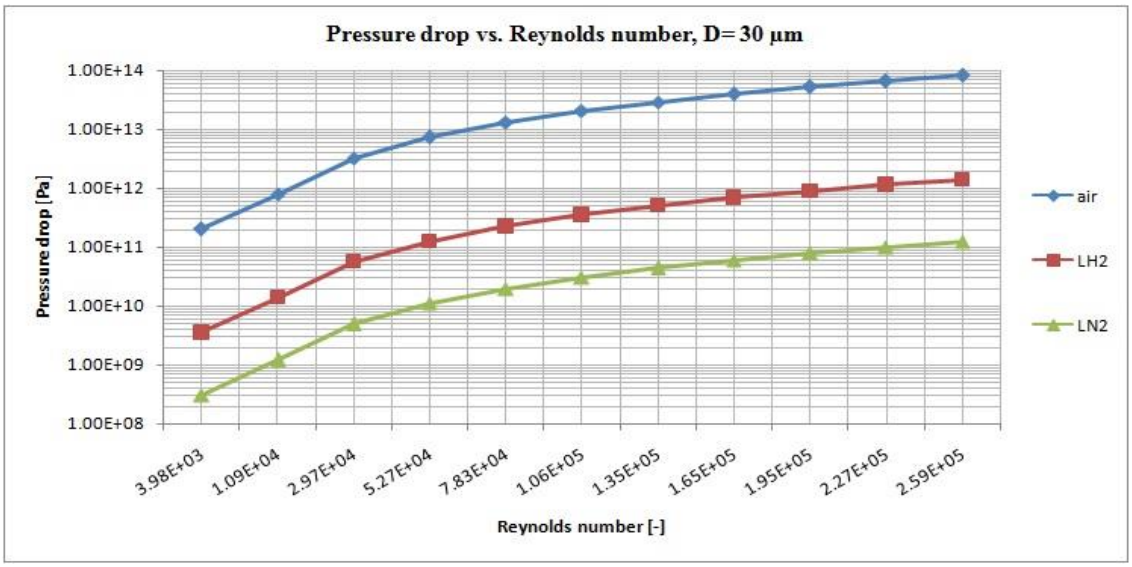

Figure 27: Graph between pressure drop and Reynolds number for circular microchannel, diameter = 30µm

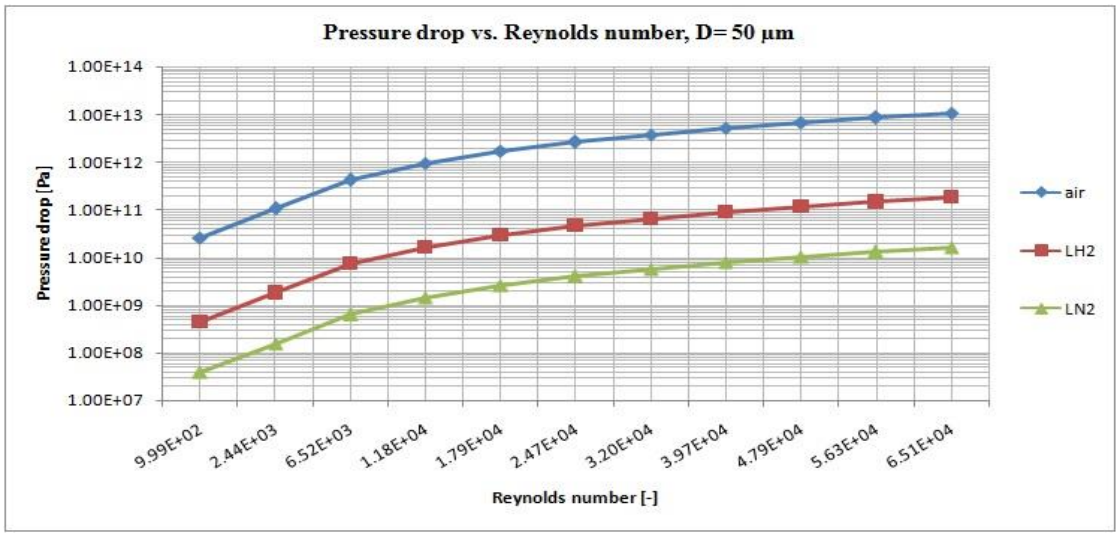

Figure 28: Graph between pressure drop and Reynolds number for circular microchannel, diameter = 50µm

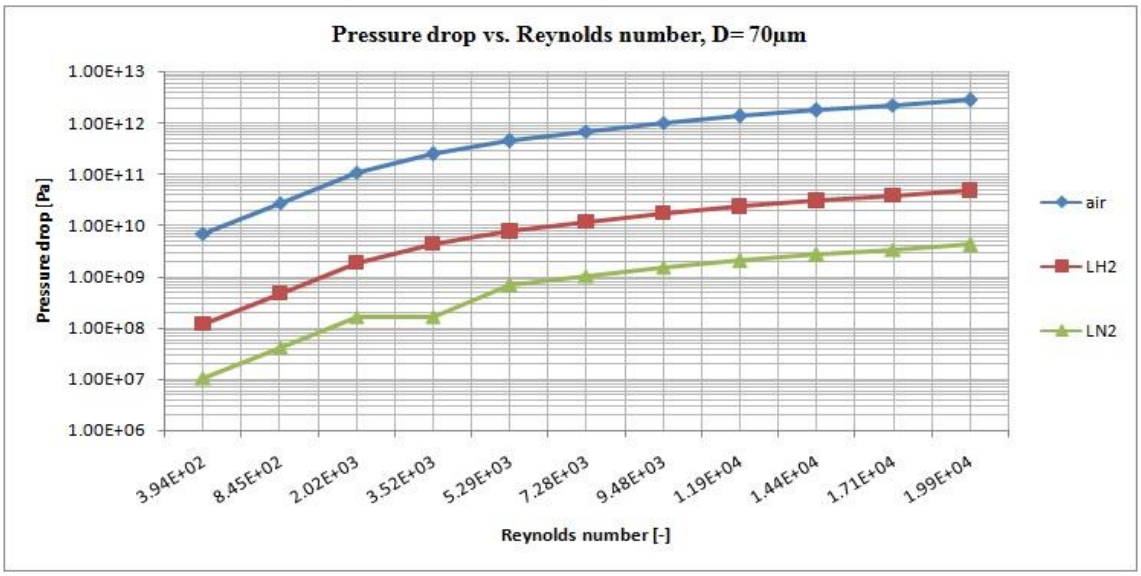

Figure 29: Graph between pressure drop and Reynolds number for circular microchannel, diameter = 70µm

it can be observed that as the value of Reynolds number (Re) for a particular hydraulic diameter increases with the increasing value of mass flow rate, the value of pressure drop also keep on increasing for all three flowing fluids. As result it can be predicted that by pressure drop being the function of mass flow rate, according to Bernoulli equation,

$$(P_1 - P_2) = \frac{\rho}{144}[(Z_2 - Z_1) + \frac{(V_2^2 - V_1^2)}{2g} + H_L$$

Change in pressure ∂P is due to change in velocity or mass flow rate which in turn shows its impeccable effect over flow behavior. Moreover it is deduced that as Reynolds number increases, the pressure drop in microchannel also will increase.

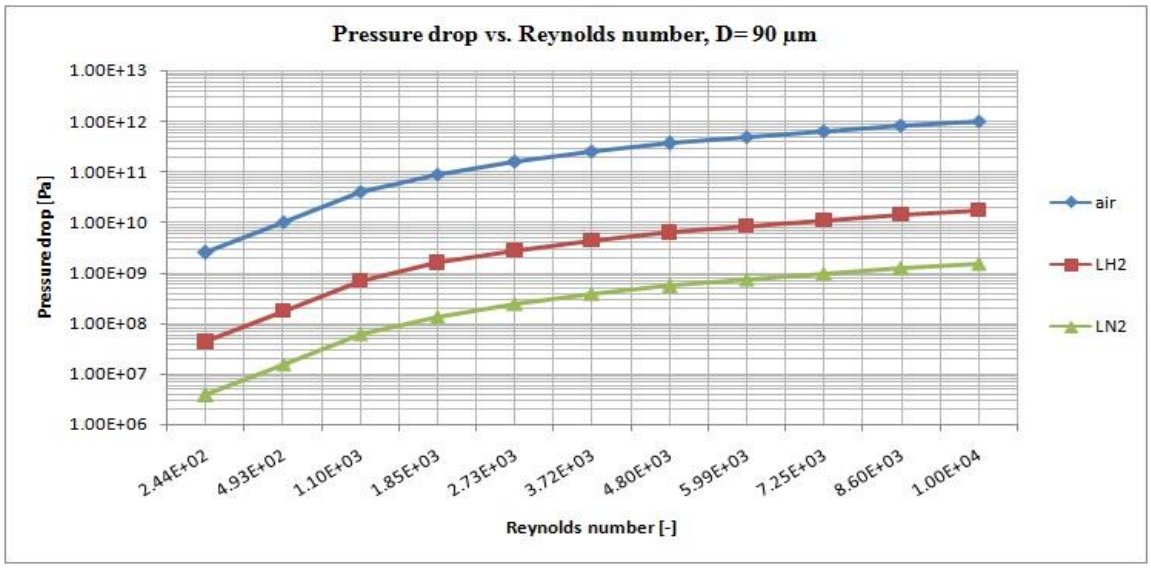

Figure 30: Graph between pressure drop and Reynolds number for circular microchannel, diameter = 90 µm

Ultimately rest of the graph of 10, 20, 40 and 50µm which are given, do follow the same pattern as the first and the value of pressure drop keep on increasing as the value of Reynolds number increases.

7.4 Nusselt number vs. Reynolds number

Heat transfer through convection bestows a mode for transferring the heat between fluid to fluid or fluid to solid quickly from the exchange surface. Fluids used in the processes and systems experiences a slight shift in their thermal virtues in heat exchanger. The general equation for convective heat transfer is,

$$Q = hA(T_s - T_f)$$

According to the conventional theory, the heat transfer co-efficient remains uninfluenced by the value of Reynolds number in the laminar regime of fully developed flow is suggested as,

$$h = \frac{Nu \times k}{D}$$

The nusselt number for the flow in microchannel can be calculated by Chilton-Colburn analogy given as,

$$Nu = 0.125 f Re \times Pr^{0.33}$$

The local convective heat transfer coefficient and local Nusselt number are defined as,

$$h_x = \frac{qA}{\mathrm{N\,A}_{ch}(T_{w,x} - T_x)}$$

The value of nusselt number depends upon the Reynolds number as well as the value of friction factor and the Prandtl number.

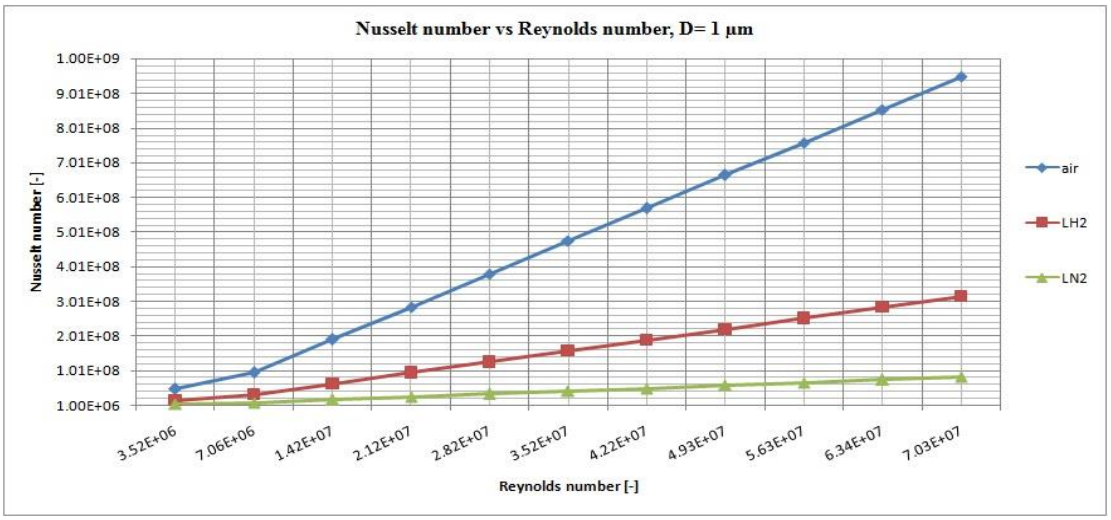

Figure 31: Graph between nusselt number and Reynolds number for circular microchannel, diameter = 1µm

This graph is plotted for the microchannel of 1µm diameter to evaluate the effects of nusselt number over the range of Reynolds number.

The flowing fluids, air, the liquid nitrogen and the liquid hydrogen showing the agreement with each other and it can be seen from the graph that the value of nusselt number is increasing with the increasing value of Reynolds number. It is also observed that the increment in the value of nusselt number is on a straight line at a slope and the air yields the higher values of nusselt number for a particular diameter as compare to the liquid nitrogen [LN_2] and liquid hydrogen [LH_2].

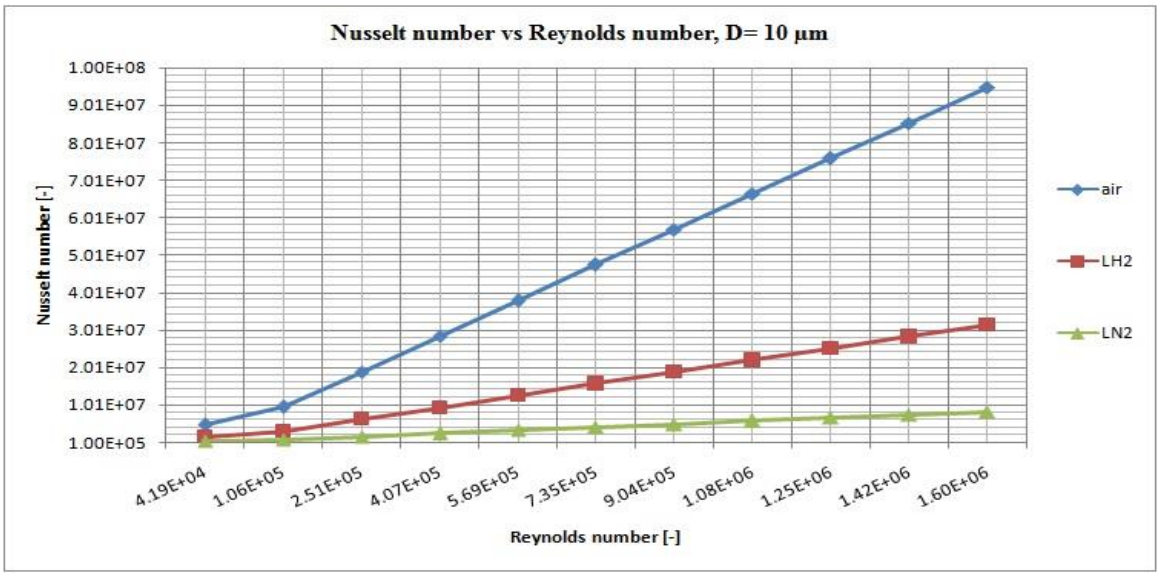

Figure 32: Graph between nusselt number and Reynolds number for circular microchannel, diameter = 10µm

It can be observed from the graphs that as the Reynolds number value increases with the increasing value of mass flow rate, Nusselt number increases. Figure shows that by increasing the Reynolds, the Nusselt number increases however it was also observed that for a particular value of mass flow rate if hydraulic diameter of the microchannel is increased than the value of Nusselt number decreases.

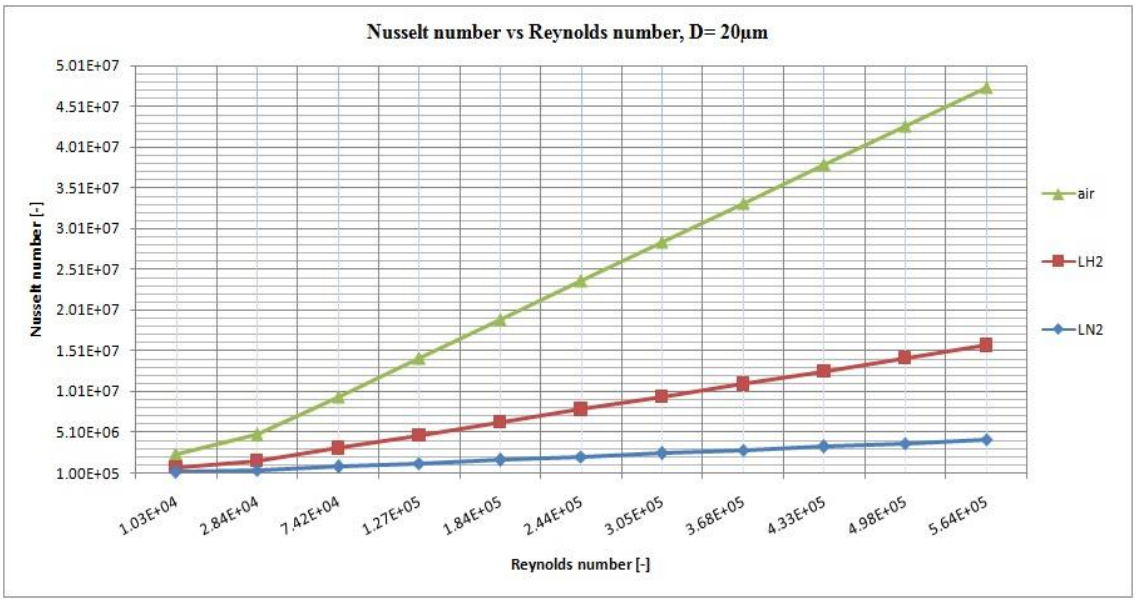

Figure 33: Graph between nusselt number and Reynolds number for circular microchannel, diameter = 20µm

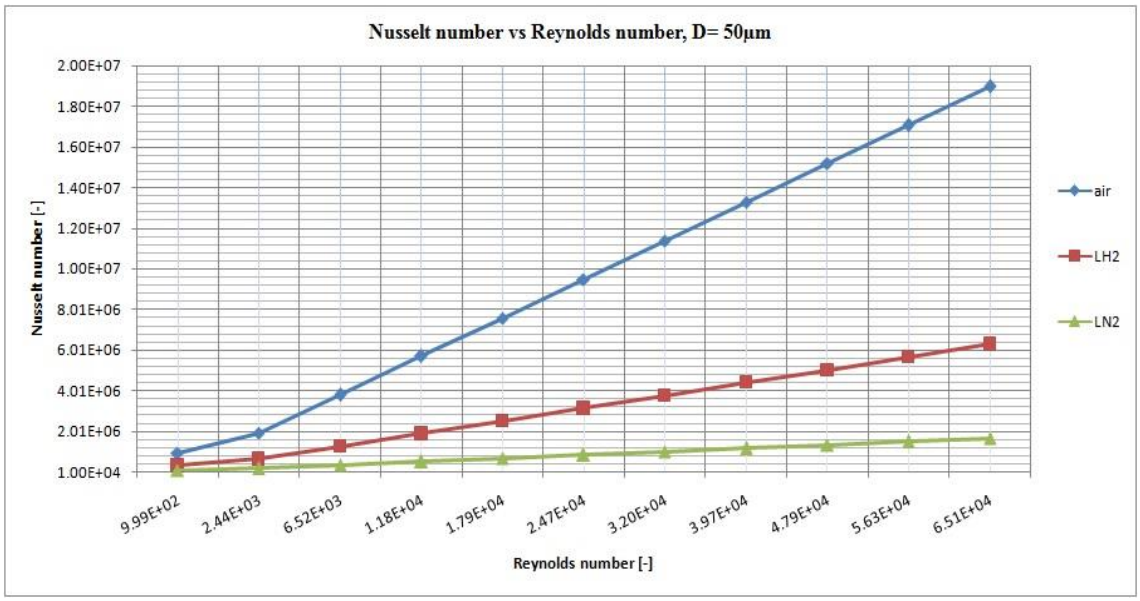

Figure 34: Graph between nusselt number and Reynolds number for circular microchannel, diameter = 50µm

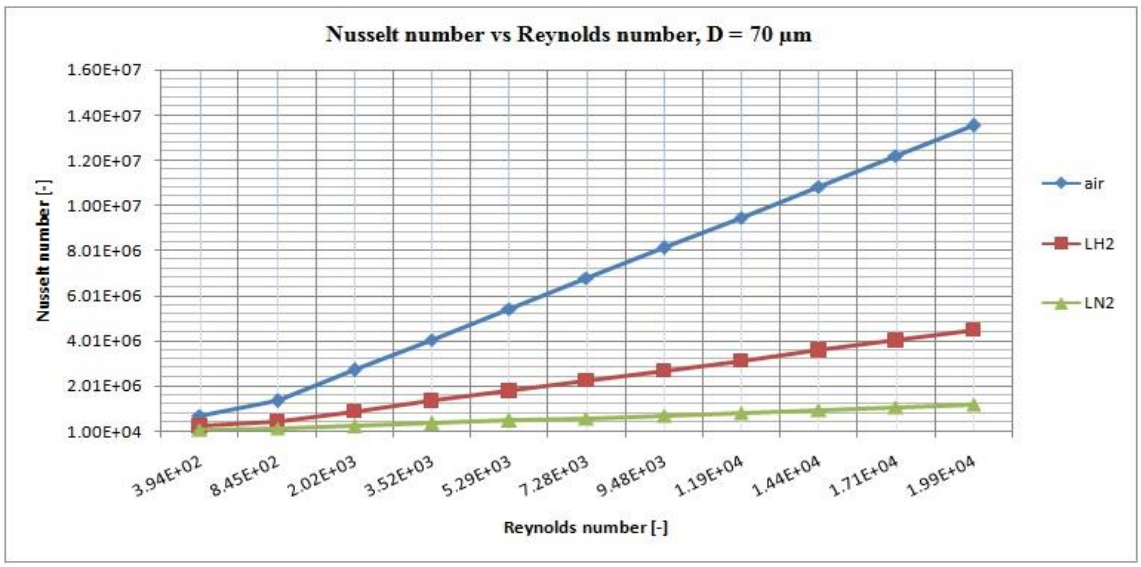

Figure 35: Graph between nusselt number and Reynolds number for circular microchannel, diameter = 70µm

The graphs given above can be seen to follow the same pattern as the graph for the microchannel of 1µm diameter. The value of diameter can be increased but every time that liquid hydrogen yields the higher value for every specific diameter as compare to the liquid nitrogen and the variation will always be on a straight line at a slope.

7.5 Heat transfer vs. mass flow rate

Heat transfer is the function of heat transfer co-efficient as well as the nusselt number. These graphs given below are drawn for the various diameters over the increasing values

of mass flow rate and it trying to find out the effects of mass flow rate over the heat transfer from microchannels.

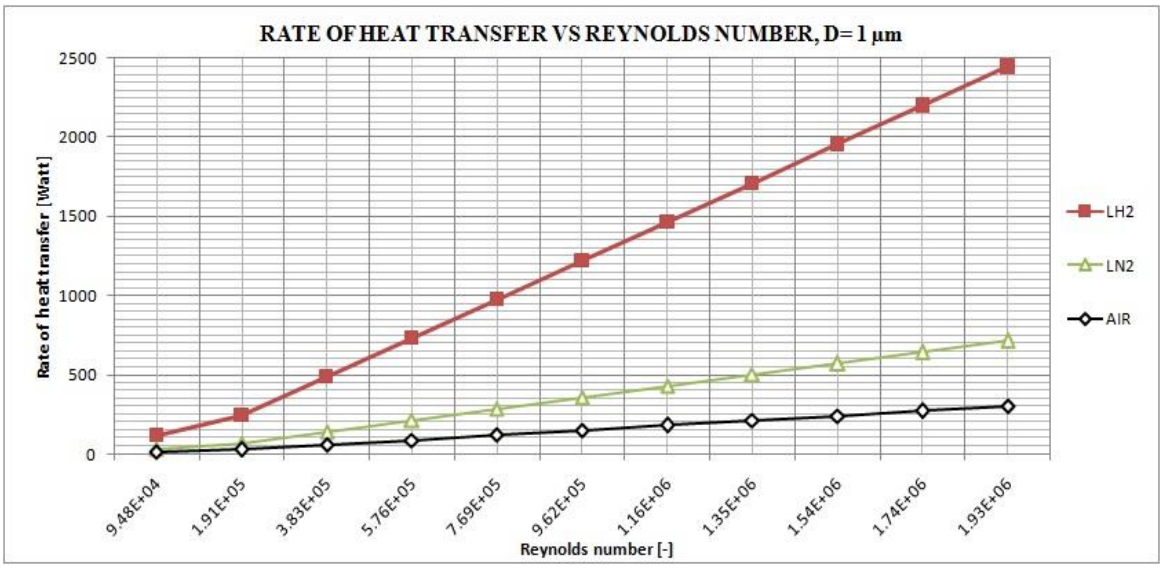

Figure 36: Graph between heat transfer and mass flow rate for circular microchannel, diameter = 1µm

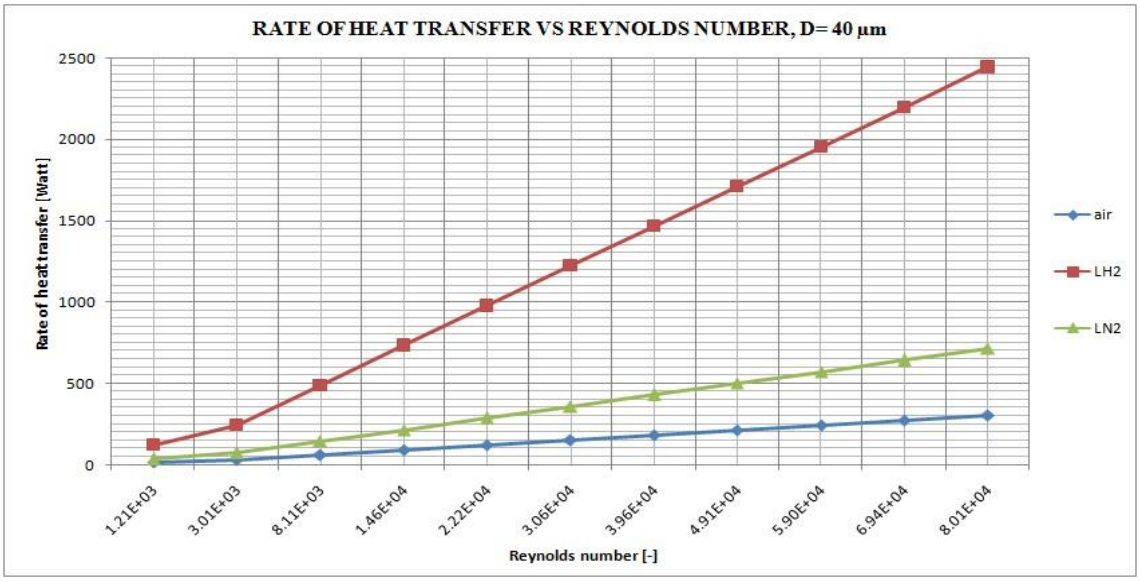

Figure 37: Graph between heat transfer and mass flow rate for circular microchannel, diameter = 40µm

These two graphs above are plotted between heat transfer and mass flow rate for diameter 1µm and 40µm. The Rate of heat transfer is on the vertical axis and the mass flow rates are plotted on the horizontal axis.

In the graphs, the blue line indicates the air and the red line indicated the liquid hydrogen and green line indicates the liquid nitrogen. It can be observed in the graphs that the

liquid hydrogen yields the higher heat transfer as compare to the liquid nitrogen and also the value of heat transfer increases with the incrasing value of mass flow rate.

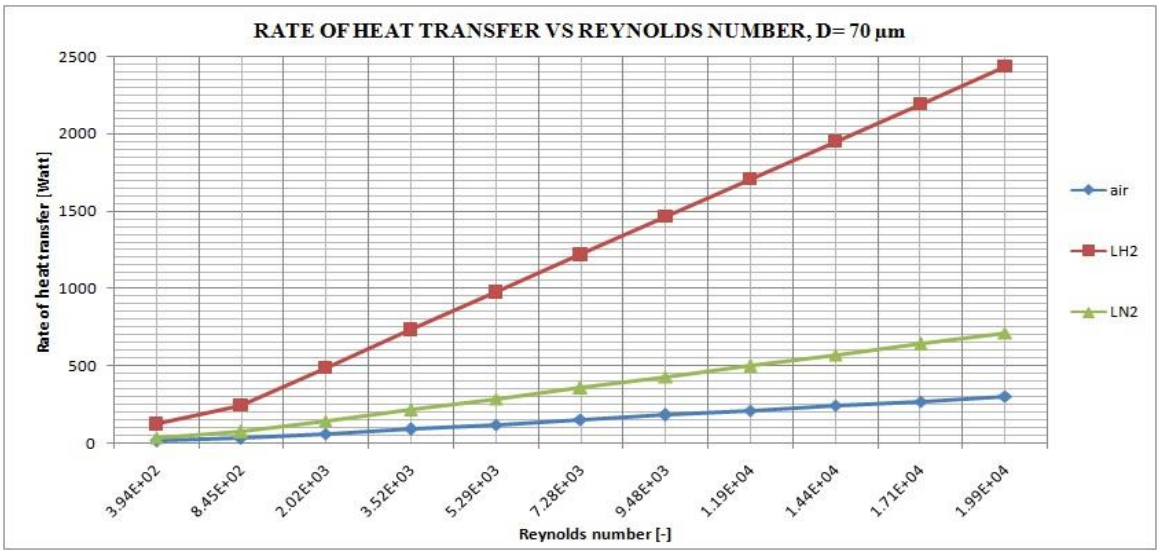

Figure 38: Graph between heat transfer and mass flow rate for circular microchannel, diameter = 70µm

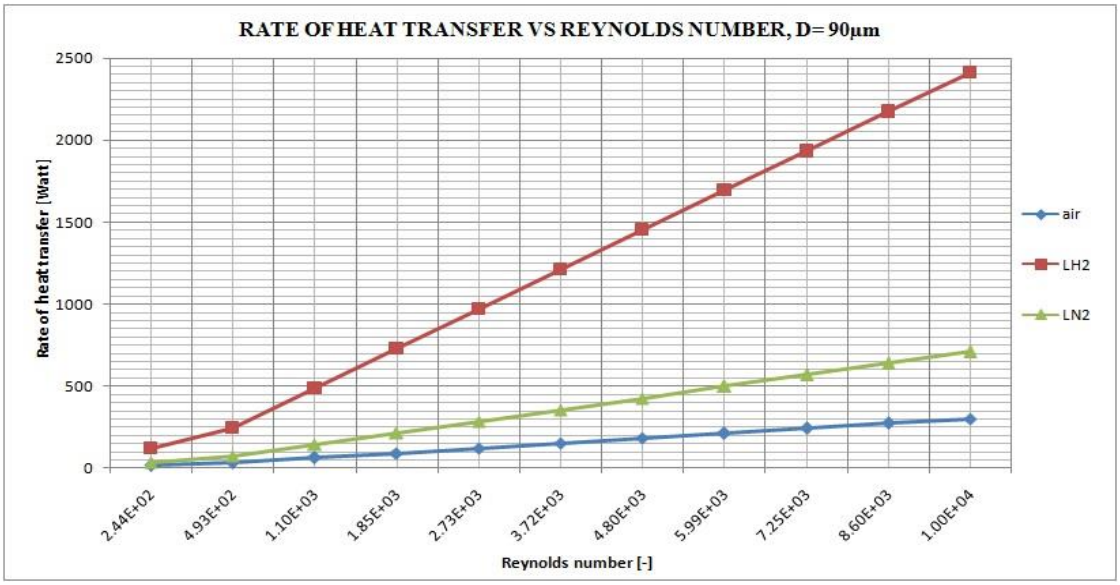

Figure 39: Graph between heat transfer and mass flow rate for circular microchannel, diameter = 90µm

It is also observed for the graphs that as the value of cross-section is increased, the value of heat transfer decreased for all three fluids. Since the cross-section is increasing and the length of the microchannels is constant thus for lesser diameter the area to volume ratio will be higher and for high value of diameter the area to volume ratio will be lower, so it suggests that for high surface area to volume ratio leads to the higher heat transfer.

7.6 Pressure drop vs. mass flow rate

Pressure drop and the mass flow rates are directly proportional which suggests that as the mass flow rate increases the pressure drop in the pipe flow also increases (conventional theory).

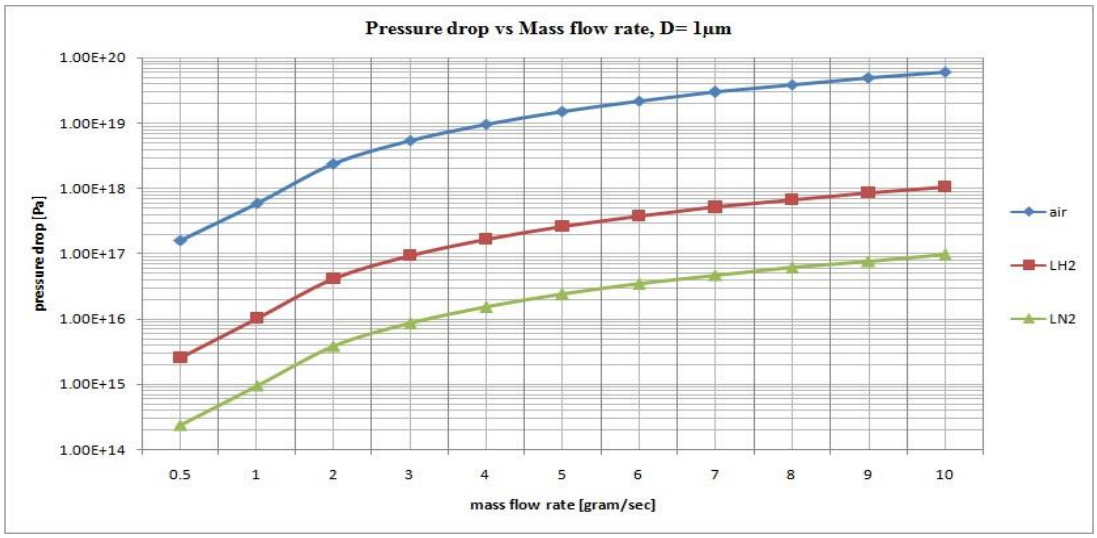

Figure 40: Graph between pressure drop and mass flow rate for circular microchannel, diameter = 1µm

This graph above is plotted for the liquid flow in microchannel of 1µm diameter. In the graph, the pressure drop is plotted on the vertical axis and the mass flow rate is on the horizontal axis. The given graph shows that as the values of mass-flow rate for a particular diameter increases, the value of pressure drop inside the microchannel also increases and it also can be seen that values of pressure drop for the air is greater as compare to the liquid nitrogen [LN_2] and liquid hydrogen [LH_2].

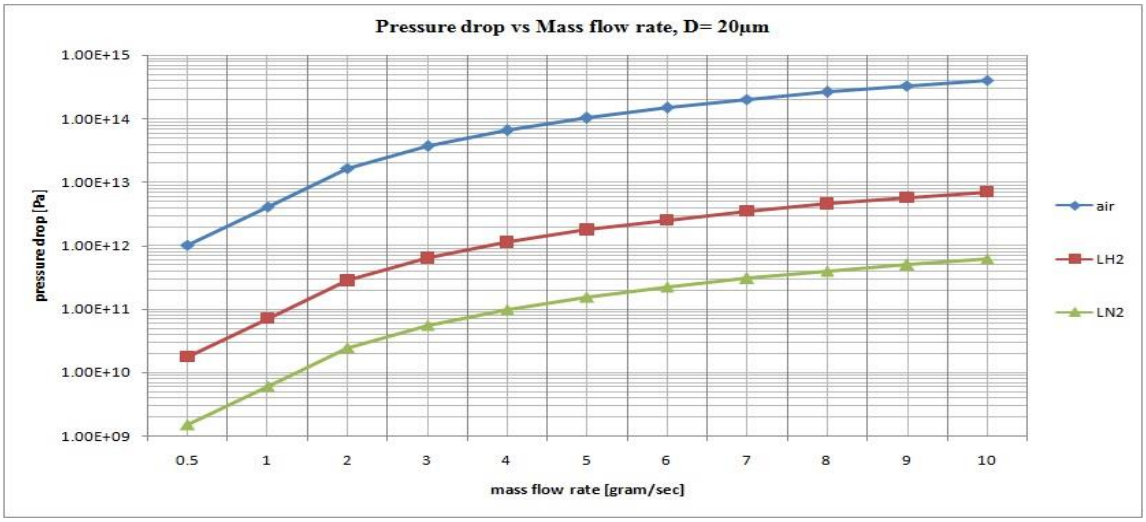

Figure 41: Graph between pressure drop and mass flow rate for circular microchannel, diameter = 20µm

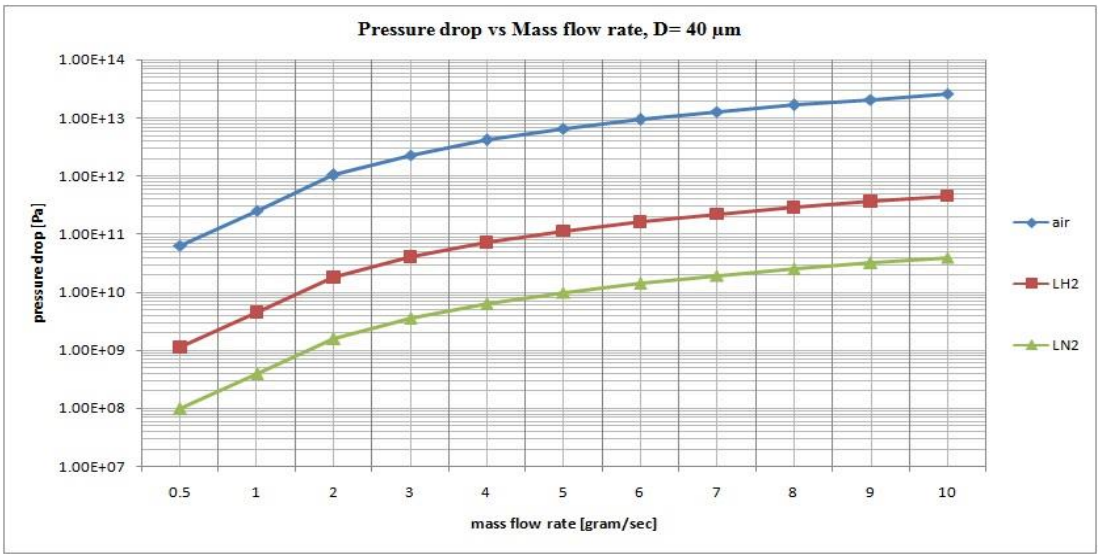

Figure 42: Graph between pressure drop and mass flow rate for circular microchannel, diameter = 40µm

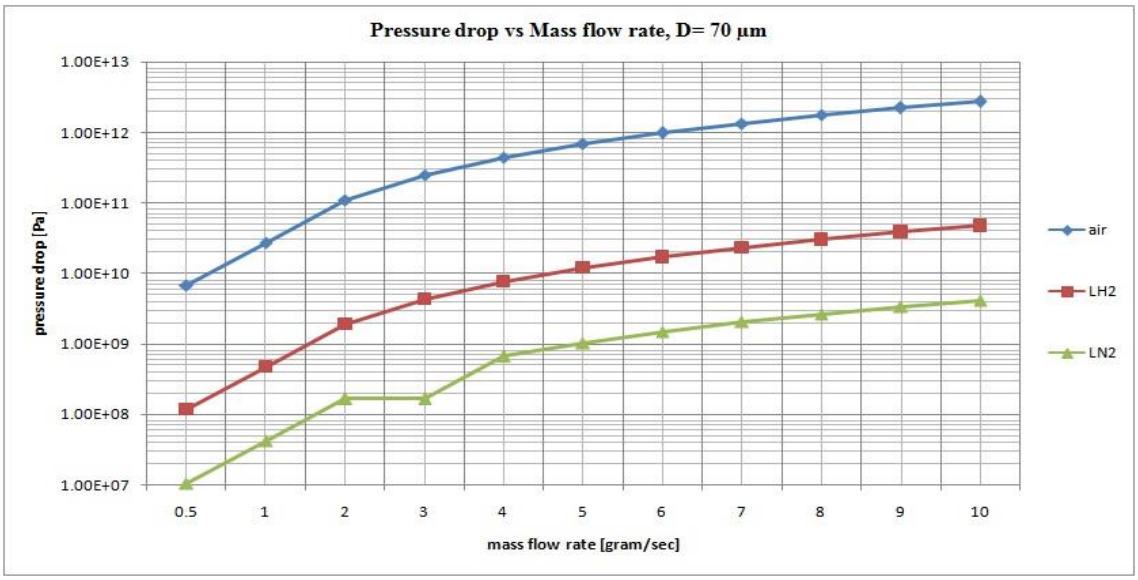

Figure 43: Graph between pressure drop and mass flow rate for circular microchannel, diameter = 70µm

However, it is seen that as the diameter microchannels is increased for a constant mass flow rate, the value of pressure drop decreases.

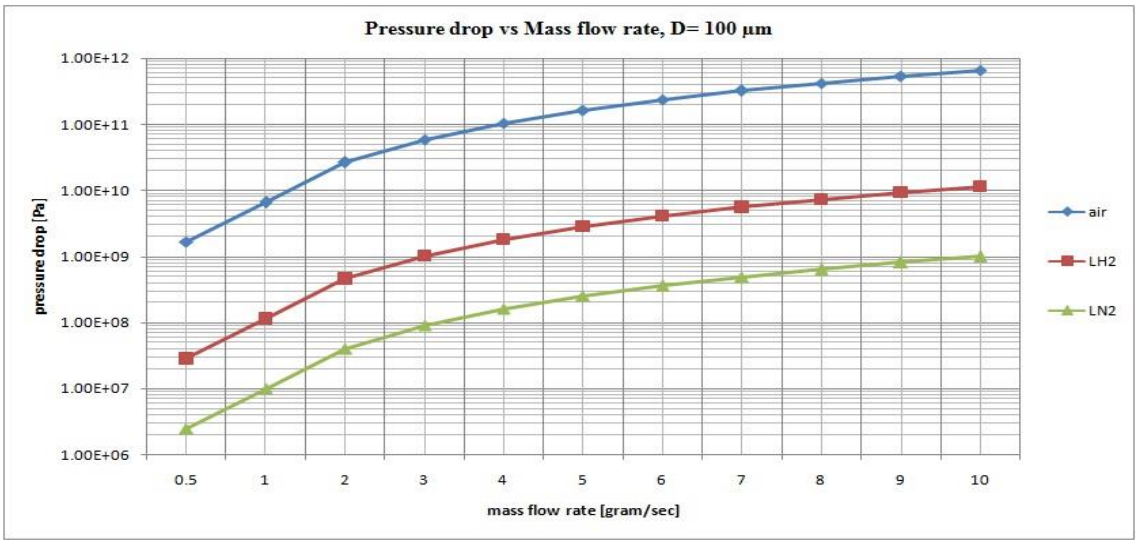

Figure 44: Graph between pressure drop and mass flow rate for circular microchannel, diameter = 100µm

In the other graphs that are plotted for the different diameters, it can be easily seen that in every graph that liquid nitrogen [LN_2] yield the higher pressure drop value for a particular diameter as compare to the liquid hydrogen [LH_2] for varying mass flow rate.

7.7 Heat transfer co-efficient vs. mass flow rate

Heat transfer co-efficient has the direct impact over the over the heat transfer through a microchannel. Since the fluid flowing in microchannels [air, LN_2 and LH_2] have the higher values of heat transfer co-efficient thus it is able to transfer the heat faster than pipes of larger diameters or say the conventional pipes.

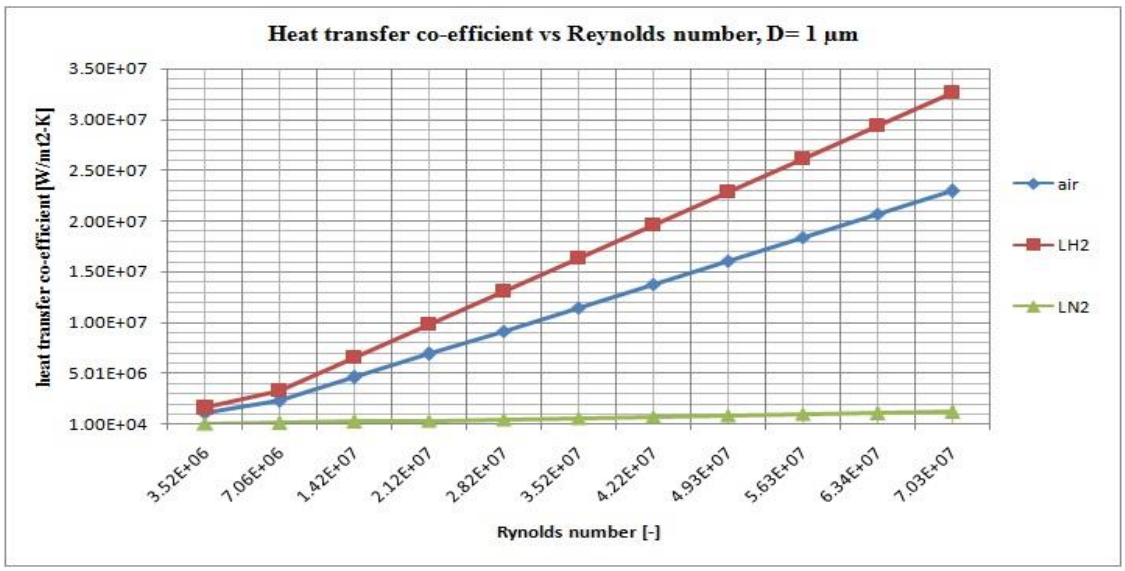

Figure 45: Graph between heat transfer co-efficient and mass flow rate for circular microchannel, diameter = 1µm

The above graph is been plotted against the heat transfer co-efficient and the mass flow rates for a microchannel of 1µm diameter and it is deduced that among all three fluid that are flowing inside the microchannels the liquid hydrogen [LH_2] has the higher values of heat transfer co-efficient as compare to the liquid nitrogen [LN_2] and air and air yield the lowest value at constant diameter for varying mass flow rate. However, it is observed that on increasing the diameter the value of heat transfer co-efficient decreases, if the mass flow rate is kept constant but the increasing mass flow rate at constant diameter is able to increase the value of heat transfer co-efficient very rapidly to much higher value.

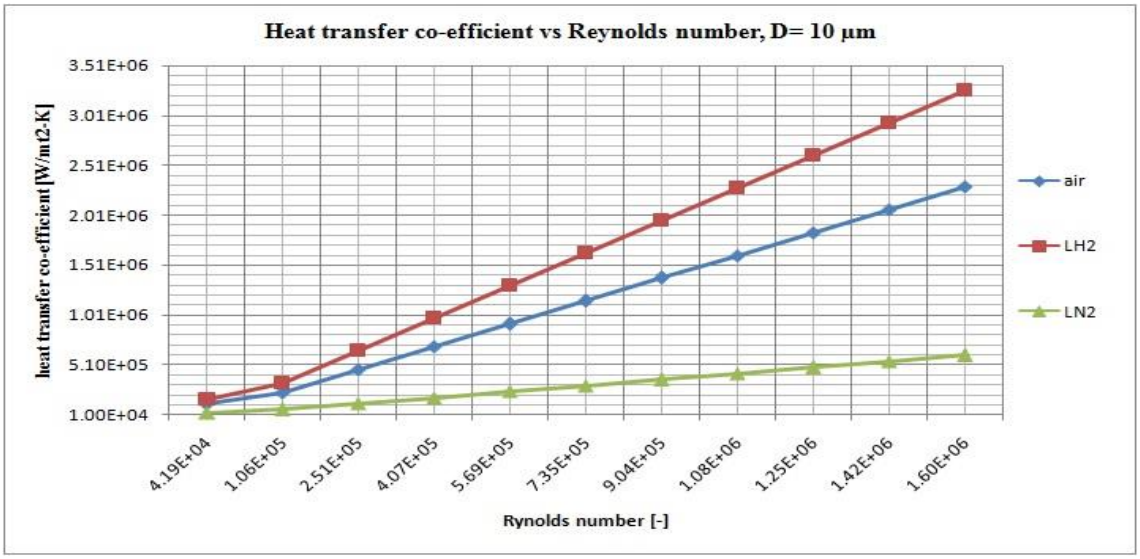

Figure 46: Graph between heat transfer co-efficient and mass flow rate for circular microchannel, diameter = 10µm

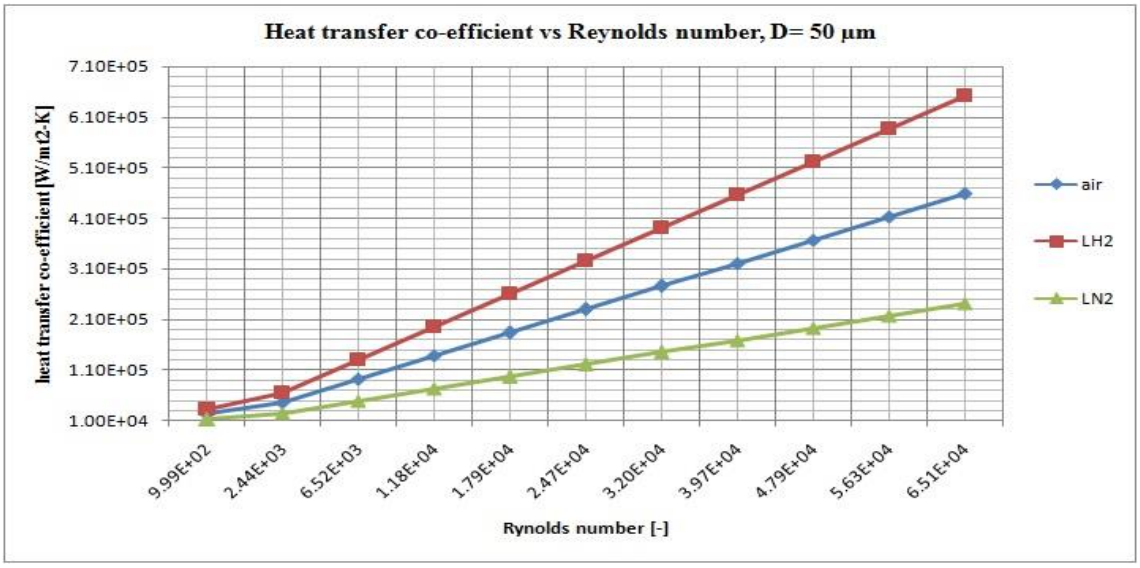

Figure 47: Graph between heat transfer co-efficient and mass flow rate for circular microchannel, diameter = 50µm

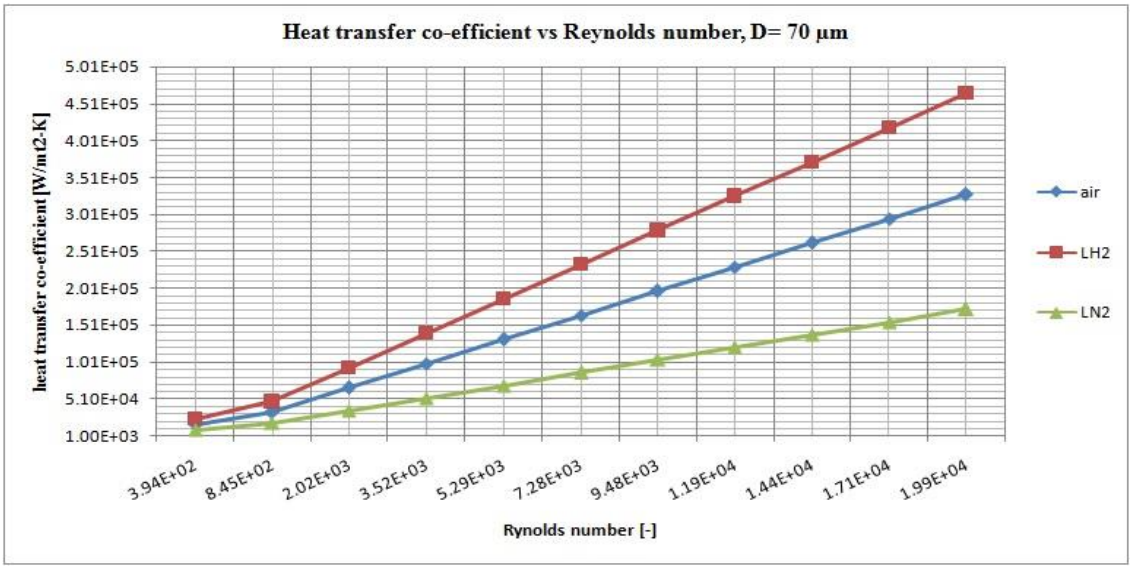

Figure 48: Graph between heat transfer co-efficient and mass flow rate for circular microchannel, diameter = 70µm

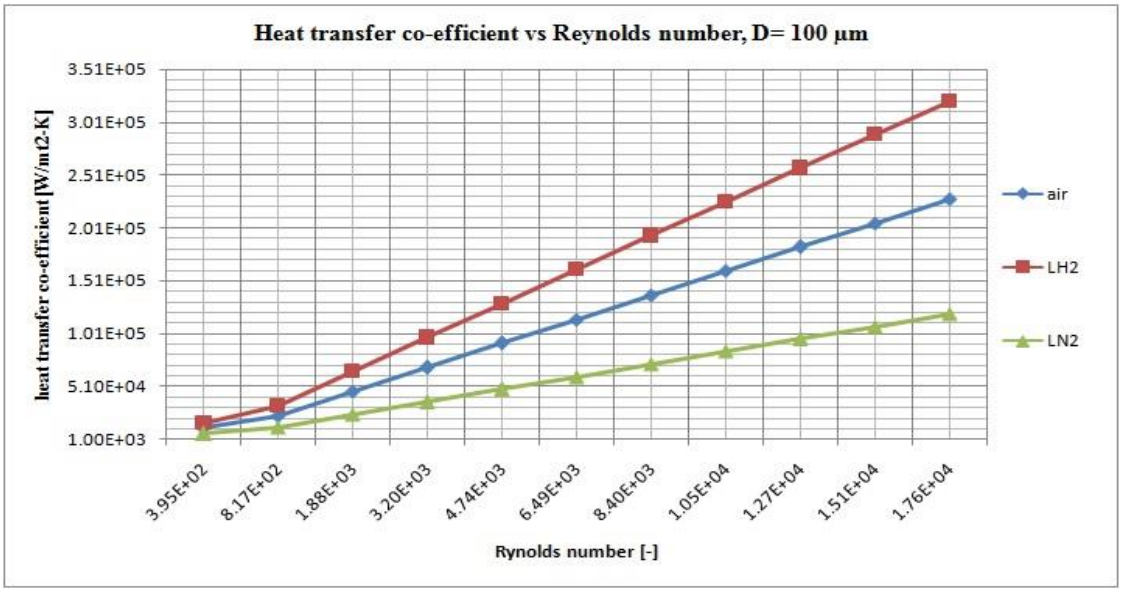

Figure 49: Graph between heat transfer co-efficient and mass flow rate for circular microchannel, diameter = 100µm

These graphs gives above are plotted for different diameters for flow in microchannel and in all the graphs the same pattern is been followed as the graph for the 1µm diameter thus it is safe to say that for the various values of diameters the liquid hydrogen [LH_2] will always yield the higher value of heat transfer co-efficient than liquid nitrogen [LN_2] and air.

7.8 Wall shear stress vs. Reynolds number

When the fluid moves along the solid boundary, it offers some resistance force which reduces the velocity of the fluid; however the viscosity plays the role of an important factor.

$$\mu = \frac{\tau}{\frac{\partial u}{\partial y}}$$

Where, τ is wall shear stress, μ is dynamic viscosity and $\frac{\partial u}{\partial y}$ is known as velocity gradient.

No slip phenomenon is defined when wall boundary does not offer any resistance to the fluid motion thus fluid will flow without friction at the wall contact.

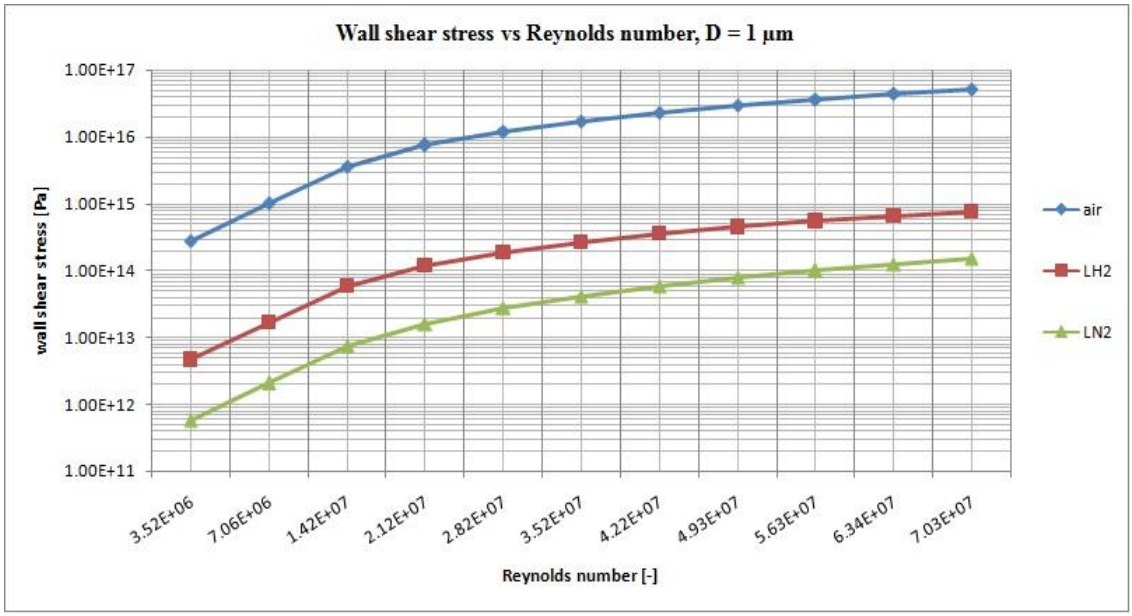

Figure 50: Graph between wall shear stress vs. Reynolds number for circular microchannel, diameter = 1µm

In the above given figure [47] shows the effect of increasing value of Reynolds number over the wall shear stress for hydraulic diameter of 1µm for the varying mass flow rate. It show that as the value of mass flow rate increases, Reynolds number increases and with the increasing value of Reynolds number, the value of wall shear stress increases. It is also observed that as the hydraulic diameter is increased, wall shear stress is decreased.

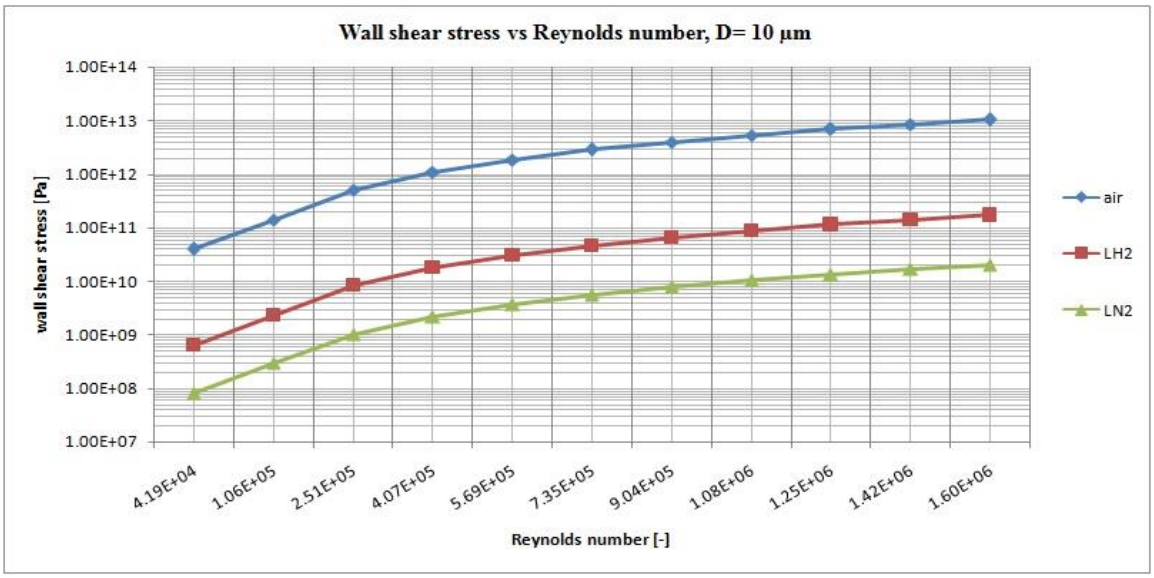

Figure 51: Graph between wall shear stress vs. Reynolds number for circular microchannel, diameter = 10µm

Wall shear stress graphs shows that the air yields the highest value of wall shear stress among all three flowing fluids and liquid nitrogen yields the lowest value. All the graphs of the wall shear stress against Reynolds number follow the shear thickening curve.

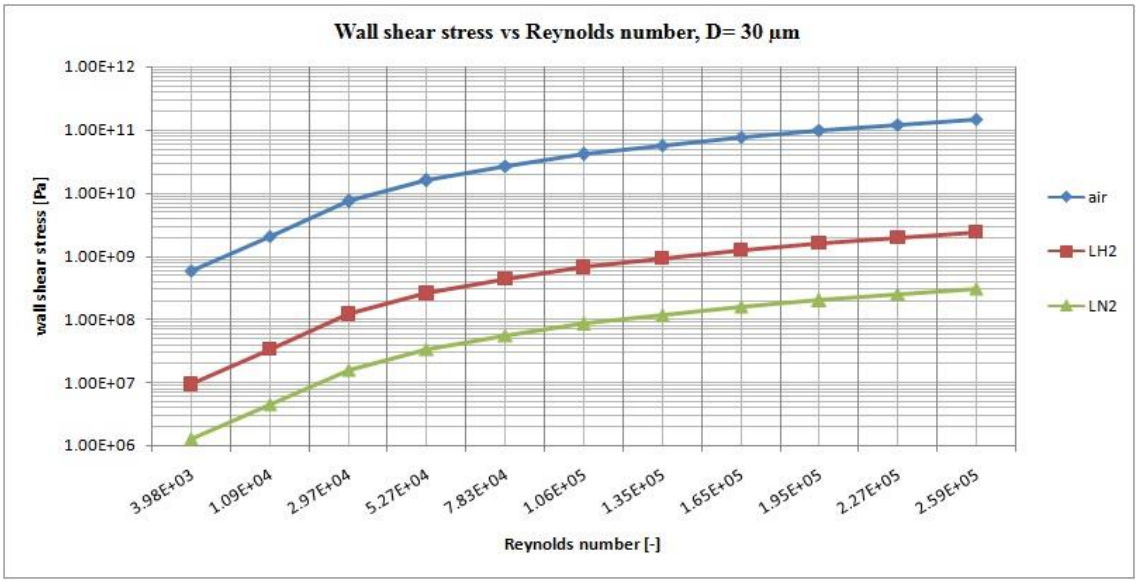

Figure 52: Graph between wall shear stress vs. Reynolds number for circular microchannel, diameter = 30µm

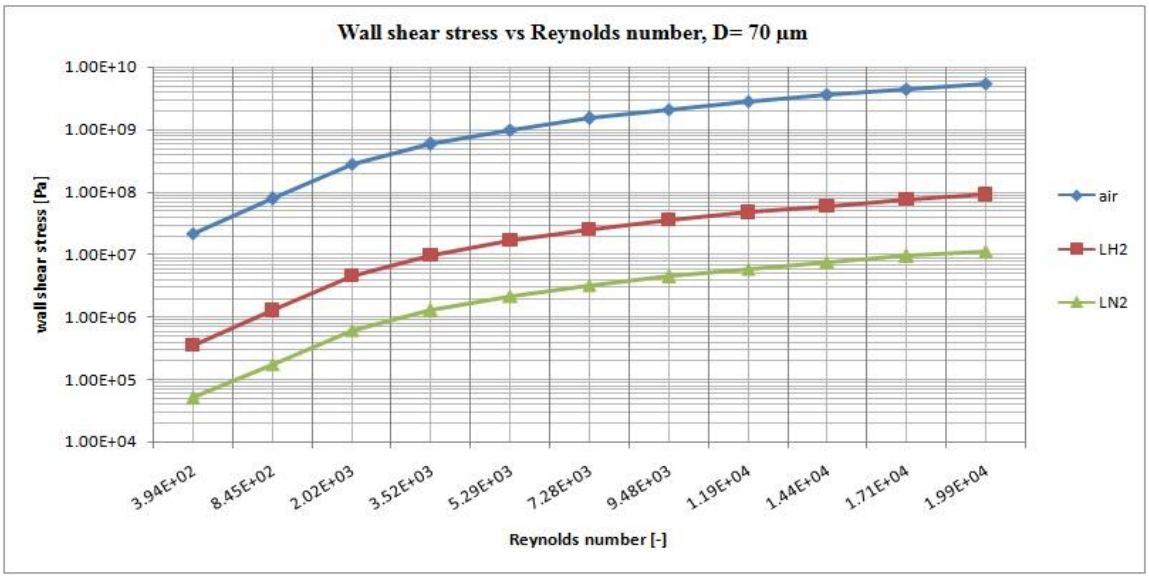

Figure 53: Graph between wall shear stress vs. Reynolds number for circular microchannel, diameter = 70µm

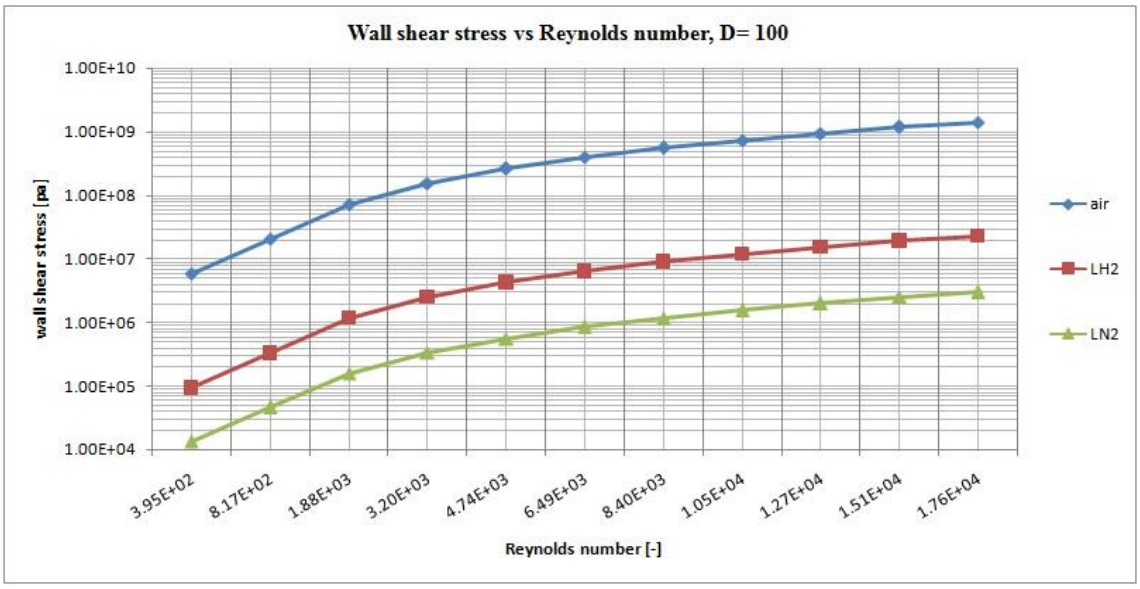

Figure 54: Graph between wall shear stress vs. Reynolds number for circular microchannel, diameter = 100µm

It can clearly be observed from the above graphs that as the wall shear stress is directly proportional of the Reynolds number for constant diameter over the varying mass flow rate. However, if the diameter is increased the value of wall shear stress decreases at constant value of mass flow rate.

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8 SUMMARY AND CONCLUSION

A computational investigation to understand the Thermohydraulic characteristics of fluid flow in microchannels by considering air, liquid nitrogen and liquid hydrogen as flowing fluid was carried out. For single-phase flow in turbulent flow regime, the fluid flow characteristics, in microchannels with hydraulic diameter range of 1µm to 100µm follows the classical flow theory. The friction factor behaviour for all three flowing fluids at varying mass flow rate in the range of 0.5 gram/sec to 10 gram/sec follows the same as for the conventional channel as seen according to the moody diagram. Pressure drop was found to be increasing with increasing Reynolds number though it decreased while increasing the diameter considering the mass flow rate as constant. It was observed that wall shear stress increases with increasing value of Reynolds number and follows shear thickening behaviour. However, wall shear stress was decreasing while increasing the diameter at constant mass flow rate. In the case of heat transfer characteristics, as the Reynolds number increased with increasing value of mass flow rate, the rate of heat transfer was also increasing but it does not shows much fluctuation in value of rate of heat transfer while increasing the diameter at constant mass flow rate. It was seen that nusselt number increases with increasing value of Reynolds number for all three flowing fluids. However, as the diameter increases, the value of nusselt number decreases if mass flow rate was kept constant.

Results of the study suggests the flowing,

1. Due to the fact that the diameter of the microchannels is very less, the velocity will be high which leads to turbulent flow.
2. Friction factor (fanning friction factor) is the function of Reynolds number and its variation depends on it, since the values of Reynolds number is very high it results in very low values of friction factor. It was observed that liquid nitrogen yields the highest value for the friction factor and liquid hydrogen yield the lowest value of friction factor.
3. Pressure drop will be very high inside the microchannels and it increases with increasing values of Reynolds number and mass flow rate as well at constant

diameter. It was seen that air yield the highest value of pressure drop as compare to the liquid nitrogen and liquid hydrogen.

4. Nusselt number is the function of friction factor, Reynolds number and the Prandtl number thus the values of Reynolds number affects the nusselt number the most and which further affects the heat transfer by affecting the heat transfer co-efficient. Additionally, the air yields the highest and liquid nitrogen yields the lowest value of the nusselt number.
5. It has been seen that the variation in Reynolds number on increasing the mass flow rate is higher in liquid hydrogen [LH_2] as compare to the liquid nitrogen [LN_2] and air.
6. Results show that the rate heat transfer is much higher in liquid hydrogen [LH_2] as compare to the liquid nitrogen [LN_2] and air.

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