International Journal of Research in Advent Technology, Vol.6, No.7, July 2018
E-ISSN: 2321-9637
Available online at www.ijrat.org

Analysis of Heat Transfer Parameters in Microchannel Fluid Flow

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Abstract: In an electronic components high processing power in compact chips results in large heat dissipation. The aim of this work is to study and analyse the parameters of liquids for microscale heat transfer as it is an emerging trend from research point of view. Further the range of coolants for microscale heat transfer can vary from water, ethylene glycol, liquid metal to nanofluids. Heat transfer in microchannel using nanofluid as coolants highly efficient as it has higher heat dissipation capacity than water used as coolant. Microchannel cooling with liquid metal poses tough challenge with regard to corrosion and blocking problems in the cooling systems.

In present study, the microchannel of rectangular geometry was fabricated by EDM and CuO nanofluid and water were made to flow through rectangular microchannels and their Reynolds number and Nusselt number were evaluated experimentally and compared. Heat transfer coefficient for CuO and water was determined both theoretically (COMSOL multiphysics software) and experimentally & it was found out that heat transfer coefficient and thermal conductivity of CuO nanofluid is 116% and 40% respectively more than that of water in rectangular microchannel.

Index Terms- microchannel; nanofluid; COMSOL; nusselt number; reynold number

1. INTRODUCTION

In the past few decades, there has been a lot of advancement in new technologies e.g electronics, computer technologies, communication, etc. The growth of these will lead to increasing power and large storage data in small size chips due to which the thermal management of these devices becomes a big problem[1]. An optical device is another area which also experienced a same problem of thermal management. These devices have reached the current limits of air-cooling technologies. Some applications require heat flux beyond the limit of 100W/cm^2 which will demand the advanced cooling solutions. To encounter these problems the liquid cooling technology is widely used now a days. Examples of heat transferfluids are heating and coolingsystems in buildings and industrial process heating, transportation industry and cooling systems in textile, pulp and paper, petro chemical, chemical, food, and other processing plants[5]. The thermal conductivity is an important factor of these fluids in the development of energy-efficient heat transfer equipment. Significant higher thermal conductivities are needed than presently available fluids to develop advanced heat transfer fluids. Because of the low thermal conductivity of conventional heat transfer fluids major improvements in cooling capabilities have been limited despite the considerable previous research and efforts for development on heat transfer enhancement. However, it is well known that metals in solid form at room temperature have high orders of magnitude of thermal conductivities than fluids.The thermal conductivity of copper is 700 times more than that of water and 3000 times more than that of engine oil at room temperature. The metallic liquids have much greater thermal conductivity than non-metallic liquids. Therefore, the fluids that contain suspended solid metallic particles are expected to be enhanced thermal conductivities as compared to conventional heat transfer fluids. Normal liquids like water do not posses as much high heat dissipation rate as required. Heat transfer properties of conventional heat transfer fluids are poor compared to most solids[4]. Therefore, the microchannel heat sinks using liquid fluids in the thermal management of electronic and optical devices are very efficient[3]. The microchannels have been studied for about three decades.

1.1 Microchannels

Microchannels are channels with a hydraulic diameter below 1 mm. Microchannel heat exchangers can be made from metal, ceramic and even low-cost plastics. These are manufactured in different shapes such as rectangular, trapezoidal, etc. by different techniques such as micromolding,micromilling, silicon etching or electroplating. Thick metal substrate requires in micromilling and micromolding processes, the heat sink is manufactured and then combined with the package of chip through thermal interface materials. The high area tovolume ratio and large area enhancement made microchannel heat sinks as very effective for dissipation of heat from devices such as integrated circuits. Generally liquid coolants instead of gaseous coolants are used in microchannel heat sinks which give higher heat transfer coefficients. Microchannels are widely used because of smaller size, less coolant inventory and larger heat transfer area as compared to traditional heat transfer. Also these have high convective heat transfer coefficient and as channel size reduce the pressure drop across the channel also reduces or low[8].They can be used for various applications :

1)Automotive and air space 2)Heat Pumps 3)Refrigeration air conditioning 4)Cooling of gas turbine bladed 5)Infrared detectors 6)Microelectronics 7)Heat recovery ventilators 8)Power industries

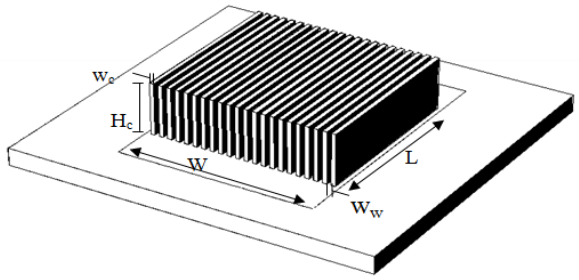

Figure 1 Schematic of microchannel geometry

1.2 Nanofluid

Nanofluid is a fluid containing nanometer-sized particles called nanoparticles. Nanofluids are made by putting nanoparticles (size < 100nm) made of metal, oxides, carbides or carbon nanotubes, etc (e.g. copper, copper oxide, aluminium oxide) in base fluid. These have unique mechanical, electrical, optical, magnetic and thermal properties. These are very much efficient as these have high thermal conductivity, high heat transfer coefficient and more thermal capacity than ordinary coolants. In solid-liquid mixtures particles abrasive action of the particles causes erosion of pipelines, clog flow channels, settle rapidly, cause severe pressure drop and also form layer on the surface which reduces thermal capacity of the fluid. By flowing coolant with the help of micro pump through the microchannels will also increase heat dissipation rate. Nanocrystalline particles are produced and dispersed in the fluid by heating the substance to be dispersed in a vacuum while passing a thin layer of fluid near the heated substance. Nanofluids are used in many applications due to their novel properties.

2. CFD MODEL OF MICROCHANNEL HEAT SINK

Computational Fluid Dynamics (CFD) modelling of thermal performance of rectangular microchannel heat sink with proposed nanofluid and water as working fluid has been formulated. CFD is the science of predicting heat and mass transfer, fluid flow and related phenomena by solving simultaneous set of governing numerical equations.

a) Conservation of mass
b) Conservation of energy
c) Conservation of momentum
d) Effects of body forces

The governing equations which constitute the hydrodynamic and thermal behaviour of the system are explained. The various initial and boundary conditions required for simulation studies are described in detail. Rectangular microchannel having same dimensions as that of actual experimental test setup was modelled and simulated using COMSOL Multiphysics software in single phase flow. COMSOL Multiphysics is a finite element technique which solves multiple variations of Navier Stokes equations to model flows in all velocity regimes under proposed boundary conditions. This includes modelling of low velocity fluids (stokes flow), weakly compressible flow and laminar compressible flow, turbulent flow, etc. It helps to analyse all the variables in the Navier Stokes equations and flow terms in laminar/turbulent models. Based on model variables from other couples physics interface can be included and use as is the application. The software has the ability to create 2-D modelling and 3-D geometries in which full analysis can be done as shown in figure 2 & 3.

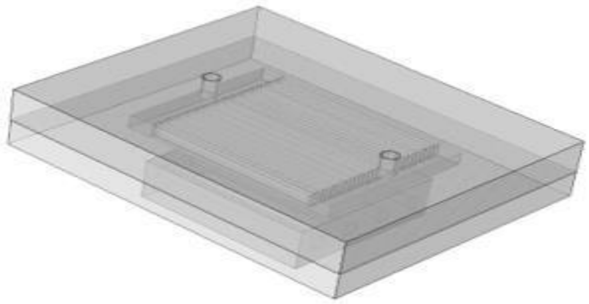

Figure 2 Structure of Microchannel heat sink

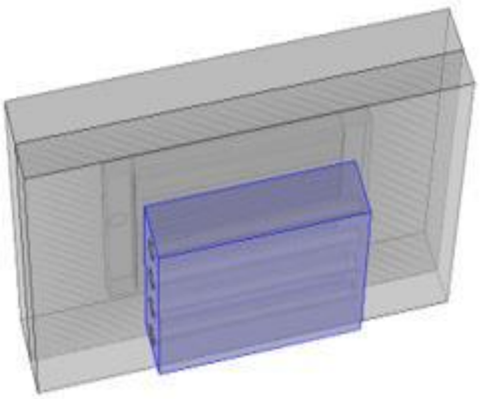

Figure3 Constant heat flux region of Rectangular microchannel

2.1 Description of model

The simulation software COMSOL Multiphysics was used to study the flow of fluid, heat transfer and associated physical phenomena for the microchannel heat sink considered in the study. A set of mathematical model equations based on laws of conservation was solved using this software in order to obtain the flow variables throughout the computational domain. By comparing simulation results with available experimental results the validation of the simulation analyses was achieved. The 3-D MCHS having same geometrical parameters as of experimental setup was analysed using de-ionised water and copper oxide nanofluids as the cooling fluids[5]. After that comparison of experimental and simulation results have been done between water and proposed nanofluids using different parameters

2.2 Meshing of Microchannel Design

The Microchannels has been designed and simulated with the help of structural mechanics physics of the MEMS Tool: COMSOL. To get the optimized result we designed three different shapes with varying dimensions of microchannel using water and copper oxide based nanofluid as heat cooling fluids. The output has been studied and the local convective heat transfer coefficient and corresponding Nusselt number along the channel from Newton's law of cooling were obtained. The proposed design was simulated after completing the system with Physics control meshing as shown in figure 4.

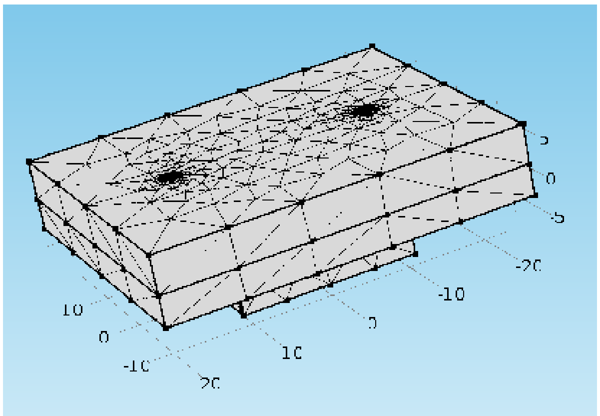

Figure 4 Meshed microchannel design of rectangular microchannel[2]

The estimated liquid temperatures along the channel with the measured wall temperature data along the channel and liquid temperatures at the inlet and outlet are calculated as: -

$h= -[k(T_s-T_v)^{-1}]\ [dt(dx)^{-1}]$

$Nu = hD_h(k)^{-1}$

D_h= Area/ wetted perimeter

Area = 4*height of channel*width of channel
Wetted perimeter = 2*height of channel + width of channel

It was observed that the convection heat transfer rate is proportional to the temperature difference and is conveniently expressed by Newton's Law of cooling as:-

$Q_{conv} = h\,(T_S - T_\infty)$

The Navier Stokes Equations for laminar fluid flow through channels are represented as follows:-
Continuity equation:-
$\nabla T = \nabla .(k\nabla T) + Q$

Equation for heat transfer in solids:-
$(u\,.\nabla) = \nabla .[-\rho l + \mu(\nabla\mu + (\nabla\mu)\mathrm{T}) - 2/3\mu(\nabla\,.\,\mu)\,]` + F$
$\nabla .(\rho\mu) = 0$

2.3 Simulation Analysis

Based upon geometrical parameters and carrier fluids the simulation study helps in deciding the direction for the different simulations. Five different velocities corresponding to Reynolds number were decided as different fluids have different Reynolds number based upon their viscosities. But little change in viscosity due to micro-concentration of nanoparticles was observed. Also all these velocities fall in the laminar flow range through the channel and practically viable. The different graph between heat transfer coefficient, Nusselt number along different Reynolds number is plotted and discussed. The analysis was carried out on the different velocities and corresponding to the Reynolds number.

2.4 Governing Equations

Following are the governing equations which are used for numerical analysis:-
Continuity equations
$\nabla .(\rho u) = 0$

Momentum equations
$(u.\nabla)u = \nabla .[-pI + \mu(\nabla u + (\nabla u)^{T - \frac{2}{3}\mu(\nabla .u)I}) + F]$

Energy equations fluid
$\rho C_p u.\nabla T = \nabla .(k\nabla T) + Q + Q_{vh} + W_p$

For Solid,
$\rho C_p u.\nabla T = \nabla .(K\nabla t) + Q$

Initial value
u = 0, P = 0, T = 293.15K

Fluid walls:
Boundary condition
No Slip, u = 0

Inlet:

$u = -u_0 n$=Normal inflow velocity
$T = T_0$= 295.15K = inlet temperature

For flow in a circular tube, the Reynolds number is defined as

Re = $\rho V_{avg} D/\mu = V_{avg} D/v$

whereV_{avg} is the average flow velocity, D is the diameter of the tube, and v is the kinematic viscosity of the fluid.

For flow through non-circular tubes, the Reynolds number as well as the Nusselt number, and the friction factor are based on the hydraulic diameter D_h defined as

$D_h = 4A_C/$p

where A_c is area of cross section of the tube and p is its perimeter. The hydraulic diameter is defined such that it reduces to ordinary diameter D for circular tubes. The constant surface flux condition is assumed and the analysis considering the surface heat flux has been explained below.

In case of $\dot{q}_s$= constant, the rate of heat transfer can also be expressed as

$Q = \dot{q}_s A_s = \dot{m}(T_e - T_i)$ Watt

Then the mean fluid temperature at the tube exit becomes

$T_e = T_i + \frac{\dot{q}s\,As}{\dot{m}Cp}$

In case of constant surface heat flux, the mean fluid temperature increases linearly in the flow direction, as surface area increases in the flow direction.

The surface temperature in the case of constant surface heat flux $\dot{q}s$ can be determined from

$\dot{q}_s$ = h (T_s- T_m)

$T_s = T_m + \dot{q}_s/h$

In the fully developed flow region, the surface temperature T_s also increase linearly in the flow direction since this is constant and thus T_s - T_m= constant

The steady flow energy equation can be applied as

$\dot{m}c_p dT_m = \dot{q}$(pdx)

$dT_m/dx = \dot{q}_s P/\dot{m}c_p$= constant

P is the perimeter, also note that both $\dot{q}_s$and h are constants, differentiating with respect to x

$dT_m/dx = dT_s/dx$

In the fully developed region, the requirement that the dimensionless temperature profile remains unchanged, thus establishes

$\partial/(T_s - T_m/T_s - T_m)$=0 ,$1/T_s - T_m(\partial T_s/\partial x - \partial T/\partial x)$=0, $\partial T/\partial x = dT_s/dx$

Since T_s -T_m=constant, Combining all above equations

$\partial T/\partial x = dT_s/dx = dT_m/dx = \dot{q}_s P/\dot{m}c_p$= constant

Thus the shape of the temperature profile does not change along the direction.

3. EXPERIMENTAL SETUP AND DESIGN

Improper heat dissipation will cause many problems in different condition and the overheating can cause severe damage to the components of Computer i.e. integrated circuits in Central Processing Unit. Heat sinks are used for proper heat dissipation rate and to prevent overheating e.g. fans used in CPU. Heat dissipation is not much effective as the thermal conductivity of air is low. Same is the case with gases, which due to low thermal capacity gets heated. In given volume limited amount of surface area can be accommodated for conventional heat sinks, and as a result, in order to provide the necessary convection surface area of the conventional heat sink must be large[9].

To increase the convective heat transfer rates liquid coolant e.g. water can be used using microchannel heat sink. Water has high convective heat transfer coefficient but low thermal conductivity also. Therefore, nanofluids with microchannel heat sink are very effective because they show high thermal conductivity than water as the volume concentration of nanofluids increases. Particles inside the nanofluids increases heat transfer area so, hydraulic diameter of channel can be reduced to obtain high heat transfer coefficient. The efficiency of the nanofluids used for cooling depends upon convection in fluids, conduction in solids and volume concentration of nanoparticles used. Due to small microchannel passage for single phase flow, the heat transfer coefficient is high[6]. Hence, to improve the efficiency of the microelectronics cooling systems it is necessary to have a better knowledge of heat transfer characteristics and micro scale liquid flow characteristics. With this motivation, various number of experiments and theoretical studies were carried out by using copper oxide nanofluids. Different parameters were studied at different flow rates like convective heat transfer coefficient, Reynolds number, Nusselt number, heat flow rate, inlet and outlet temperature and best range of flow rate was find out by considering maximum heat flow rate, less thermal resistance and minimum base temperature.The experimental setup have the following parts:

1. Pumping unit
2.Microchannel
3.Cover
4.Thermal sensors
5Data acquisition system
6.Heating unit with power regulation
7.Source of fluid
8.Water bath
9.Processing and display unit
10.Sink of fluid

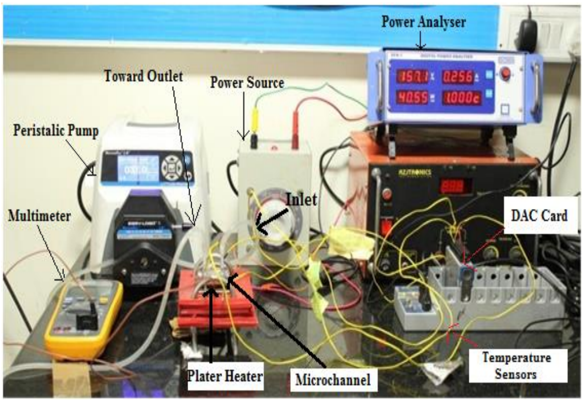

Figure 5.*Experimental Setup*

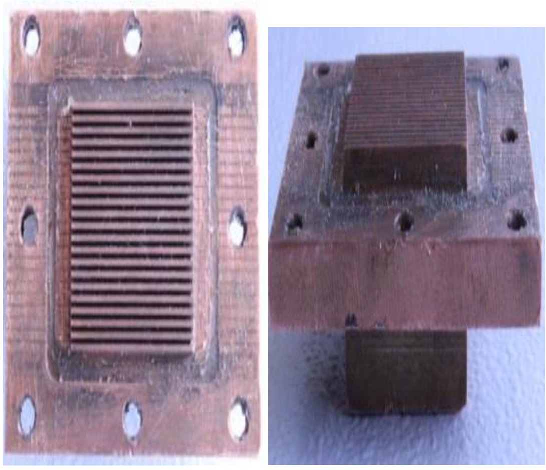

Figure 6. Microchannel 3D and fabricated models

4.RESULTS AND DISCUSSION

Heat transfer coefficient reached upto 5633W/m^{2}K and 5366W/m^{2}K in case of CuO nanofluids when calculated theoretically in COMSOL Multiphysics software and experimentally respectively at same flow rate or velocity and heat. This difference in theoretical and experimental results is due to the various losses in actual conditions like friction loss or pressure drop (due to roughness), heat loss to ambient as it is not possible to make perfect adiabatic setup, etc. Similarly, for water it goes upto 3976W/m^{2}K and 2486W/m^{2}K in theoretical and experimental results as shown in Table 1.

Velocity (m/s)	**h_{water}(W/m^2 K) theoretical**	**h_{water}(W/m^2 K) experimental**	**h_{CuO}(W/m^2 K) theoretical**	**h_{CuO}(W/m^2 K) experimental**
0.0472	1642.9	760	2327.4	885
0.0943	2726.7	1064	3862.8	1246
0.1415	3455.5	1222	4895.4	1401
0.1886	3946.7	1235	5591.2	1560
0.2358	4280.9	1361	6064.6	1621
0.0472	1629.9	835	2309	991
0.0943	2710.9	1162	3840.5	1486
0.1415	3440.8	1646	4874.4	1743
0.1886	3933.8	1700	5572.9	1782
0.2358	4269.4	1754	6048.3	1858
0.0472	1568.5	1025	2222	1177
0.0943	2559.2	1687	3625.6	1772
0.1415	3230.3	2099	4576.2	3071
0.1886	3679	2139	5211.9	4824
0.2358	3976.8	2486	5633.8	5366

Table 1 Heat transfer coefficient for water and nanofliud theoretical and experimental results

Width of channel (mm)	Height of channel (mm)	Width of substrate (mm)	Height of substrate (mm)	Length of microchannel (mm)	Number of channel
W_c	h_c	W_s	H_s	L	n
0.5	4	37.5	10	20	21

Table 2. Dimensions of Microchannel

v (m/s)	**Q (Watt)**	**T_{mean}**	**T_{wall}**	**ΔT**	**Re**	**Nu**
0.0472	25	18.37	7.91	7.91	47	0.9
0.0943	25	15.9	5.62	5.62	94	1.3
0.1415	25	14.84	5.00	5.00	141	1.5
0.1886	25	14.08	4.49	4.49	188	1.6

0.2358	25	13.71	4.32	4.32	234	1.7
0.0472	50	25.56	14.14	14.14	47	1.0
0.0943	50	22.65	9.43	9.43	94	1.6
0.1415	50	20.60	8.04	8.04	141	1.8
0.1886	50	18.96	7.86	7.86	188	1.9
0.2358	50	20.31	7.54	7.54	234	1.9
0.0472	75	33.07	17.85	17.85	47	1.2
0.0943	75	28.18	11.86	11.86	94	1.9
0.1415	75	24.74	6.84	6.84	141	3.2
0.1886	75	22.94	4.36	4.36	188	5.1
0.2358	75	22.30	3.92	3.92	234	5.6

Table3. Experimental values of Reynold and Nusselt numbers for CuO nanofluid

v (m/s)	Q (Watt)	T_{mean}	T_{wall}	ΔT	Re	Nu
0.0472	25	25.18	34.4	9.22	47	1.1
0.0943	25	22.31	28.89	6.58	94	1.6
0.1415	25	21.07	26.8	5.73	141	1.8
0.1886	25	20.44	26.11	5.67	188	1.8
0.2358	25	19.83	24.97	5.15	234	2.0
0.0472	50	28.57	45.35	16.78	47	1.2
0.0943	50	23.81	35.86	12.05	94	1.7
0.1415	50	21.81	30.32	8.51	141	2.4
0.1886	50	20.65	28.89	8.24	188	2.5
0.2358	50	19.87	27.85	7.99	234	2.6
0.0472	75	26.24	46.74	20.50	47	1.5
0.0943	75	17.97	30.42	12.45	94	2.5
0.1415	75	14.85	24.86	10.01	141	3.1
0.1886	75	13.44	23.26	9.82	188	3.2
0.2358	75	11.19	19.64	8.45	234	3.7

Table4. Experimental values of Reynold and Nusselt numbers for water

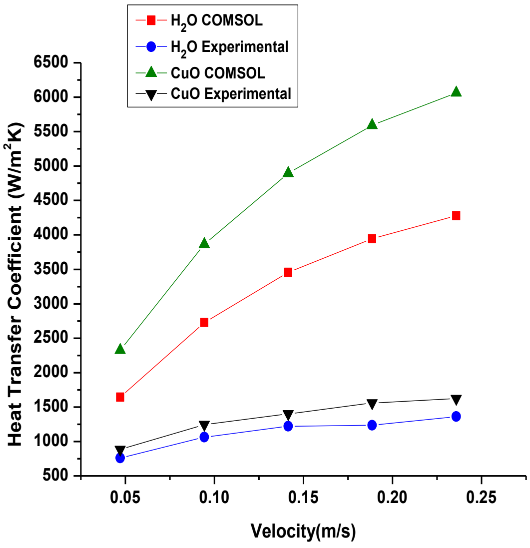

Figure 7. Velocity vs Heat transfer coefficient for water and CuO nanofluid at 25W

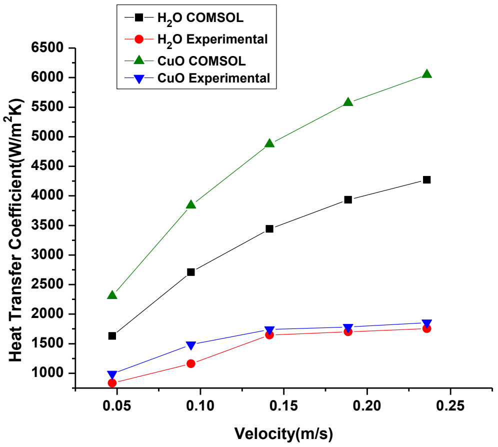

Figure8. Velocity vs Heat transfer coefficient for water and CuO nanofluid at 50W

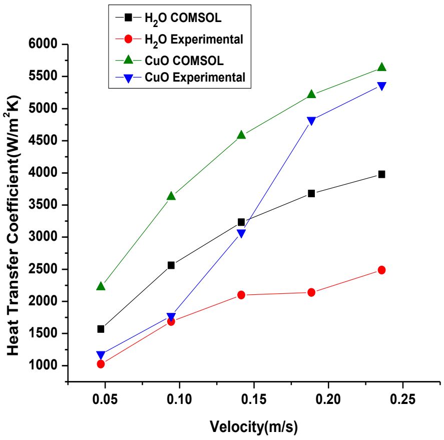

Figure 9. Velocity vs Heat transfer coefficient for water and CuO nanofluid at 75W

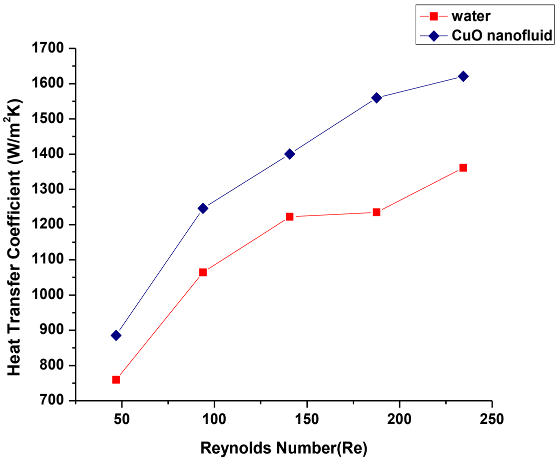

Figure10. Heat transfer coefficient vs Reynolds number at 25W

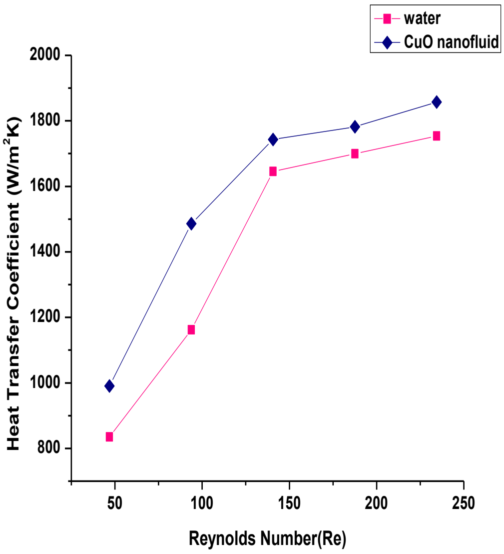

Figure11. Heat transfer coefficient vs Reynolds number at50W

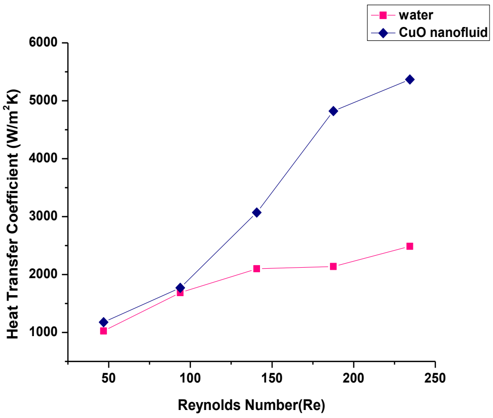

Figure12. Heat transfer coefficient vs Reynolds number at 75W

In figure 10 and 11, it can be seen that at same heat as the Reynolds number increases there will be increase in heat transfer coefficient which is more for CuO nanofluid as compared to water. In figure 12, the value of heat transfer coefficient for CuO is very high compared to other results which show at high temperature fluid results into excellent results.

The Reynolds number and Nusselt number values were compared which is very important and it was seen that Nusselt number varies as Reynolds number increases which conclude the dependence of Nusselt number upon Reynolds number. The plots comparing water and CuO nanofluid are plotted against Reynolds number at heat 75W.For water, the Nusselt number is in the range of 1.1-3.7 but for proposed nanofluid its value is in the range of 0.9-5.6 as shown in figure13.

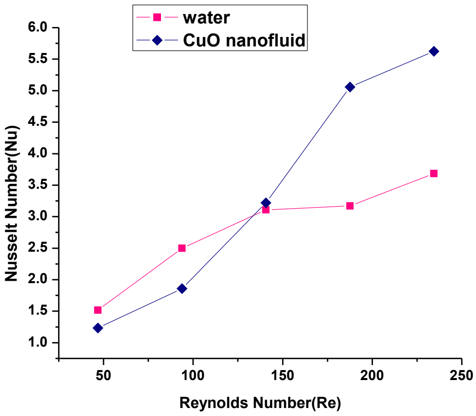

Figure13 Nusselt number Vs Reynolds number for water and CuO nanofluid at 75W

The thermal gradient was high in case of water thus more temperature non-uniformity throughout the fluid and less heat transfer coefficient which results into low Nusselt number. On the other hand, nanofluids have less thermal gradient throughout the fluid and thus more temperature uniformity due to high thermal conductivity than water. This lead to more heat transfer coefficient and high Nusselt number.

At low Reynolds number the value of Nusselt number is less for CuO nanofluid than water because of high thermal conductivity of nanofluid than water but as Reynolds number increased the value of Nusselt number also increased because the heat transfer coefficient increased with Reynolds number as discussed above. Therefore, the Nusselt number is very high (200% of Nu_{water}) for CuO nanofluid as compared to water.

5. CONCLUSION

In this research study, the effect of various parameters on heat transfer coefficient, Nusselt number, Reynolds number, temperature has been studied. It was found lack in performance of systems due to loss of energy in form of heat during experimental and numerical analysis. The microchannel of rectangular geometry was fabricated and CuO nanofluid was prepared to act as heat carrying agent. Both fluids i.e. water and CuO nanofluid passed through the channels and has found excellent results of CuO nanofluid as compared to water. From the present study following conclusion can be drawn:

1)Enhancement of thermal conductivity is 40% more in CuO nanofluid than water.
2)High heat transfer coefficient of 5366 W/m^2K can be achieved by using CuO rectangular microchannel which is 116% more than that of water.
3)With increase in heat flux and Reynolds number there is enhancement in heat transfer coefficient of both water and CuO nanofluid.
4)At low Reynold number the value of Nusselt number is less for CuO nanofluid than water because of high thermal conductivity of nanofluids. At increased Reynolds number the Nusselt number of CuO nanofluids is more than water.
5)Nusselt number is low for CuO nanofluid even though its heat transfer coefficient is high because of high thermal conductivity of CuO nanofluid reduces the value of Nusselt number. At higher heat transfer coefficient the Nusselt number of CuO nanofluids is as high as 200% than Nusselt number of water.

6 FUTURE SCOPE

This study deals with heat transfer and fluid flow analysis of water and nanofluids in rectangular microchannels. The liquid cooling using microchannel heat sink is a promising future technology for high heat transfer coefficient. This study has the following future scope:

1)The present work can further be extended to analyse the wear aspects of radiator material due to the nanoparticles being added to the base fluid
2)Ethylene glycol, propylene glycol and their mixtures with water can be chosen as a base fluid and further research could be done and proper suspensions can be selected to enhance the heat transfer performance.
3)The nanofluids can further be used with different aspect ratios of microchannel of different shapes.
4)Different aspects of nanofluids for stability and life can be considered for further study.
5)Effect of nanofluid on double layer microchannels could be studied to improve more heat transfer coefficient
6)The problem of freezing where the ambient temperature is less than the melting-point temperature of liquid coolant is less available in the literature.
7)Effect of formation of thermal boundarylayer on heat transfer rate with increasing length in microchannels using liquidcoolant can be studied.

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