Exergy Analysis in a Minichannel with Nanofluid

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***Abstract*— Due to its better heat transfer properties and compatibility, forced convection in minichannel might be one of the most popular methods for the thermal management of electronic equipment. Using various approaches, the channel's performance may be increased even more. The most obvious method is to enhance the working fluid's thermophysical characteristics. This may be accomplished by substituting a nanofluid for the working fluid. Due to their unique properties of increased thermal conductivity, nanofluids perform better than water. The optimum design of minichannel that gives maximum possible heat transfer with minimum pressure drop can be performed by quantifying the thermodynamic losses through exergy analysis. In this work, experimental studies were performed in a single rectangular channel with a hydraulic diameter of 591 µm and an aspect ratio of 0.135. Nanofluid was prepared by dispersing Al_2O_3 nanoparticles in De-Ionised water. The single-phase flow experiments were conducted and the exergy and heat transfer characteristics have been determined using nanofluid with varying concentrations (0.01 vol % to 0.3 vol %) and compared the results with that of base fluid (water). The output exergy, exergy efficiency, and exergy gain rise as the volume percentage of nanoparticles increases and decreases as the mass flow rate increases. At a flow rate of 42.75 ml/min, the greatest exergy efficiency was determined to be 52.75 percent for 0.3 vol. percent Al_2O_3–water nanofluid. At 0.3 vol. percent nanofluid, the highest exergy gain was discovered. The most critical characteristics that contribute to the exergy gain are determined to be the output fluid temperature and pressure that are decrease through the micro channel.**

Keywords — Exergy, Minichannel, Nanofluid, pH, Hydraulic diameter, Volume fraction

I. INTRODUCTION

The high heat-carrying capacity and compatibility make mini channels a more promising technology for thermal management for electronic components. Due to the enhanced thermal characteristics of nanofluid, it is widely accepted as a working fluid in heat transfer devices. The heat dissipation capacity of microchannels increases with a decrease in hydraulic diameter. Electronic chip cooling using a microchannel heat exchanger was first put forward by Tuckerman and Pease [1]. They fabricated microchannels with water as the working fluid on silicon chips and were able to remove heat flux of 790 W/cm^2 without phase change with a penalty in pressure drop of 1.94 bar. They found that channels with a dense package and large surface area to volume ratio have higher heat carrying capacity than a conventional cooling device. Morini *et al* [2] carried out several types of research in single-phase microchannel heat exchangers. Although heat transferred in single-phase flow through microchannel is high when compared to conventional channels, the temperature rises along the length of the channel limit the heat transfer capability and has overcome by flow boiling in microchannels. Lazarek and Black [3] investigated the heat transfer characteristics of flow in an evaporator of channel size 3.1mm using R-113 as the fluid. They obtained the sub-cooled and saturated data along with the constant heat transfer coefficient in single-phase flow. But the heat transfer coefficient was found to be independent of entry length. Dewan and Saivastava [4] reviewed heat transfer enhancement through flow disruption in microchannels. It has been observed that the flow disruption techniques are effective for heat transfer enhancement with lower penalties of increased pressure drop. The Reynolds numbers were less than 600, and the flow remained firmly in the laminar flow regime. Dehghan et al. [5] numerically studied heat transfer enhancement of micro channel using converging flow passages. They found that when tapering increases, pumping power 8 decreases and Nusselt number increases. The optimum heat transfer performance is found for a width–tapered ratio of 0.5. The conventional theory was found to be able to predict the flow in microchannels channels. Adams *et al.* [6] experimentally investigated single-phase forced convective heat transfer characteristics in circular microchannels of hydraulic diameter 760µm and 1090 µm, using water as the working fluid. The deviation increased with increasing Re and decreasing channel diameter, and the experimental Nusselt number was substantially greater than that derived using traditional correlations.

Due to the presence of suspended nanoparticles with high thermal conductivity, nanofluids outperform traditional fluids in terms of thermal performance. Nanoparticles offer unique features that nanofluids potentially take use of, such as a large surface area to volume ratio, dimension-dependent physical properties, and reduced kinetic energy. At the same time, a greater surface area improves and stabilises nanoparticle dispersion in base fluids. Nanofluids have a higher stability than microfluids. The notion of employing metallic particles to enhance the thermal characteristics of fluids was first presented by Flockhart et al [7]. Mapa et al. [8] investigated the impact of nanofluids in a small heat exchanger. Their studies used water as the working fluid and water and nanofluid with concentrations of 0.01 percent and 0.02 percent volume to assess heat transfer performance in the heat exchanger. They came to the conclusion that nanofluids improve heat transmission and lower the thickness of the thermal barrier layer. Garud et al. [9] examined the convective heat transfer of a CNT–water nanofluid in a micro-channel with a hydraulic diameter of 355 m and Reynolds numbers ranging from 2 to 17 for particle concentrations of 1.1 to 4.4 percent in a micro-channel with a hydraulic diameter of 355 m. At the maximum concentration, the CNT–water nanofluid had a higher heat transfer coefficient.

Heat transfer analysis is the most common way to describe thermal systems. Rant [9] coined the phrase Exergy in 1956, and it refers to the Greek terms ex (external) and ergos (hence) (work). Available energy, or simply availability, is another word for the same thing. Exergy has the characteristic that it is conserved only when all processes occurring in a system and the environment are reversible. When an irreversible process happens, exergy is lost. Exergy analysis considers the thermodynamic values of various energy forms and quantities, such as work and heat. The exergy transfer associated with heat transfer, on the other hand, is dependent on the temperature at which it happens in relation to the ambient temperature. There are several types of research works on exergy analysis in mini/microchannels. whereas simple microchannel devices had the lowest. Zhipeng et al. [11] used a computer simulation model to conduct an entropy generation investigation of nanofluids flow in microchannel. They claimed that microchannels with high aspect ratios had a narrower Reynolds number operating range.

2 EXPERIMENTAL FACILITY

A microchannel test facility has been fabricated and single-phase experiments were conducted to study the exergic performance and fluid flow and heat transfer characteristics in minichannel. The experiments were carried out initially using base fluid (water) and then with the nanofluids. This chapter discusses the detailed experimental setups and the procedures used to conduct the experiments. There are several equations used throughout the experiments which are also included in this chapter.

2.1 Experimental Setup

The experimental setup consists of a combination of several components. The schematic diagram of the experimental facility is shown in Fig 1

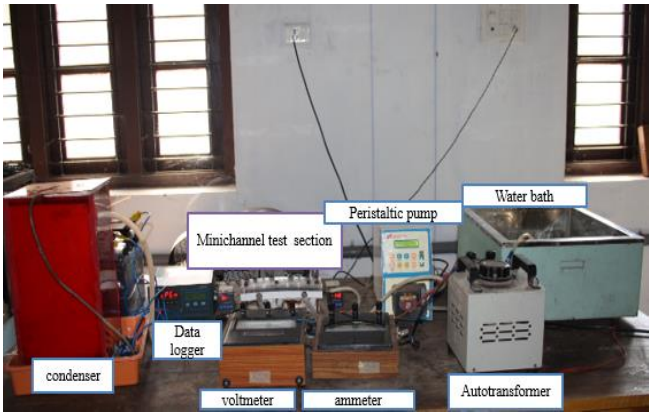

Fig. 1 Schematic diagram of the experimental facility

The experimental facility consists of a water bath (2kW, 10L capacity), a peristaltic pump (14 to 450 ml/min), minichannel test section, a data logger, an autotransformer (0-250 V), aftercooler, and two pressure transmitters (EQ-PT1000-2). The channel bottom surface temperature was measured using three K-type (Chromic/Alumel) mineral insulated thermocouples placed at holes drilled 2.5 mm below the channel bottom surface. Inlet and outlet fluid temperatures were measured by two thermocouples placed at the inlet and outlet plenum of the PTFE housing. The pressure drop across the channel was measured using differential pressure transducers connected at the inlet and outlet plenum of PTFE housing.

2.2 Nanofluid Preparation

Nanofluids can be prepared by single-step or two-step methods. The two-step method is widely used for the preparation of nanofluid. In the two steps, method nanoparticles are first produced as dry powders by chemical or physical methods. Then the nano-sized powder will be dispersed into a base fluid with the help of a magnetic stirrer, ultrasonic shaker, etc. It is critical to create stable nanofluids. Surfactants are one of the most common methods for ensuring the stability of nanoparticles in fluids. The current study techniques employed **Al_2O_3** nanoparticles (particle size 30-50 nm) and water is used as the base fluid. After calculating the weight of nanoparticles necessary for the production of nanofluid at a particular volume concentration, nanoparticles were mixed in the base fluid. Al_2O_3 nanofluids of three different volume concentrations in the range of 0.01, 0.1, 0.3, % were prepared for the present work. There is a chance of agglomeration of nanoparticles while it is suspended in the base fluidTo avoid this, all nanofluid test samples were treated to a magnetic stirring procedure followed by 5 hours of ultrasonic vibration. A drop of Triton-X-100 was employed as a surfactant to create stable aluminium oxide nanofluids.

3 DATA DEDUCTION

3.1 Single Phase Flow

The pressure drop across the inlet and exit manifolds was measured by using two pressure transmitters connected at the exit and inlet manifolds. The resulting pressure drop measured is a combination of entrance and exit loss and core frictional loss. Therefore, the net pressure drop along the channel was calculated as,

$$\Delta P = \Delta P_{experimental} - (K_c + K_e)\frac{1}{2}\rho u^2 \quad (1)$$

Where K_c and K_e are the entrance and exit loss coefficients respectively. The values of exit and entrance loss coefficients are obtained from Shah and Sekulic [67]. The values of these coefficients depend on the ratio of the channel to plenum flow area and the Reynolds number. The values are given in Table 3.1

The Fanning friction factor was determined using the equation,

$$f = \frac{\Delta P D_h}{2L\rho u^2} \quad (2)$$

Where hydraulic diameter,

$$D_h = \frac{4HW}{2(H+W)} \quad (3)$$

Reynolds number Re,

$$Re = \frac{\rho u D_h}{\mu} \quad (4)$$

Where u is the mean fluid velocity along the channel and is given by,

$$u = \frac{\dot{m}}{\rho A_c} \quad (5)$$

The heat removed by water,

$$Q = \dot{m} c_p (T_{out} - T_{in}) \quad (6)$$

Net heat input to the channel per unit area,

$$q'' = \frac{\dot{m} c_p (T_{out} - T_{in})}{A_s} = \frac{\dot{m} c_p (T_{out} - T_{in})}{(2H_c + W_c) L_c} \quad (7)$$

The local heat transfer coefficient is given by,

$$h = \frac{q''}{T_w - T_{out}} \quad (8)$$

where T_w the surface temperature at each thermocouple location and T_{out} is the fluid outlet temperature the Nusselt number is given by

$$Nu = \frac{h D_h}{K_f} \quad (9)$$

Where K_f is the thermal conductivity of the fluid. The thermophysical characteristics of water were determined using the arithmetic mean of the intake and exit temperatures in the single-phase tests.

$$T_m = \frac{T_{in} + T_{out}}{2}$$

3.2 EXERGY ANALYSIS

In the case of a heat transfer device like minichannel, the exergy represents the maximum amount of heat that could be extracted from the cooling surface. This is calculated using the measured values of mass flow rate, pressure drop, and thermocouple readings.

Heat carried away by the fluid,

$$\dot{Q} = \dot{m}\, c\, (T_{out} - T_{in}) \quad (10)$$

The average wall temperature at the base of the copper microchannel is calculated using the 1-D steady-state heat conduction assumption and is expressed as follows:

$$T_w = T_c - (\dot{Q} t / k_{cu} A_{pl}) \quad (11)$$

T_c is the average thermocouple temperature reading, $t$is the distance from the channel bottom to the thermocouple position, which is 2.5 mm, k_{cu} is copper's thermal conductivity, and A_{pl} is the polycarbonate housing's platform area.

The minichannel heat sink is modeled as a one-stream heat exchanger with continuous heat input as illustrated in Fig.2.

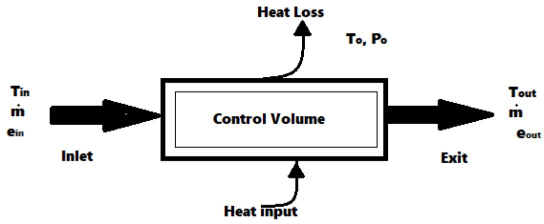

Fig. 2 Schematic representation of the interaction between the minichannel heat sink and the environment.

where T_{in}, T_{out}, ex_{in}, and e_{out} are the temperatures and specific exergies of the flow at the inlet and exit, respectively. P_o is the ambient pressure (atmospheric pressure). Based on the control volume illustrated in Fig. 3.6, the exergy balance under the steady-state condition is

$$0 = \left(1 - \frac{T_0}{T_w}\right)\dot{Q} - W_{cv} + \dot{m}e_{in} - \dot{m}e_{out} - i_{cv}$$

where T_o and T_W are ambient and average wall temperatures respectively. W_{cv} is the work done by the control volume, $\dot{m}$ is the mass flow rate, i_{cv} is the rate of change in irreversibility.

Minichannel is a steady flow device; the outlet exergy of the minichannel can find out by the equation

$$Ex_{out} = \dot{m}\,(h_{out} - h_o) - T_o\,(S_{out} - S_o)$$

$$Ex_{out} = C_p\left[(T_{out} - T_o) - T_o \ln\left(\frac{T_{out}}{T_o}\right)\right]$$

4 RESULTS AND DISCUSSION

Experiments were conducted for analyzing the exergic performance and single-phase fluid flow and heat transfer characteristics in minichannels using base fluid and nanofluids. This chapter discusses the effects of volume concentration and mass flow rate on the thermal and exergy performance of the minichannel. The exergy efficiency of the channel mainly depends on the pressure drop across the channel and outlet fluid temperature

4.1 Heat transfer characteristics of nanofluids

Experiments have been performed using nanofluid as the coolant. Nanofluids at different particle volume concentrations have been used to study the influence of the volume concentration of nanofluids on exergy and heat transfer coefficient. Fig. 3 shows the variation of outlet temperature of the fluid with mass flow rate for different concentrations of Al_2O_3–water nanofluid and its comparison with base fluid (water). It is found that the outlet fluid temperature increases with the augmentation of particle volume concentration and decreases with an increase in mass flow rate. The maximum outlet temperature of the fluid was found for 0.3 vol.% at a flow rate of 42.75 ml/min. Compared to water nanofluids remove more heat from the base of the heater core of the minichannel and keep the base temperature (average wall temperature) minimum. This might be due to an increase in the thermal conductivity of nanofluid.

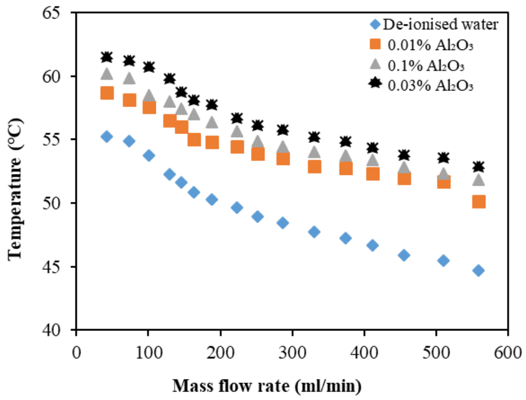

Fig. 3 Variation of outlet temperature of fluid with mass flow rate for different volume concentrations of nanofluid.

As demonstrated in Fig. 4, the pressure loss rises with flow rate and nanofluid volume percentage. The pressure loss increases as the mass flow rate and nanofluid volume concentration increase. At 588 ml/min flow rate (equivalent to 18,754 Pa) and 0.3 vol. percent concentrations, the greatest pressure decrease was observed. Comparing water and nanofluid, the pressure drop increased by 39% while using nanofluid.

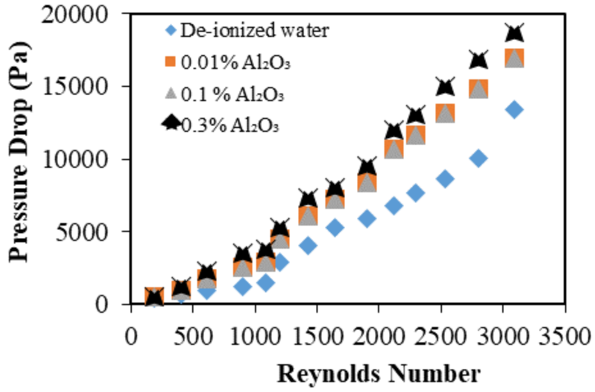

Fig. 4 Variation of pressure drop at different volume concentration

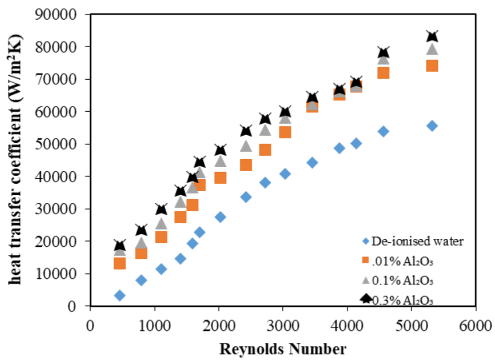

Fig. 5 Variation of heat transfer coefficient with Reynolds number

Fig. 5 shows the variation of single-phase heat transfer coefficient with Reynolds number for water and nanofluids. The trend is the same for both fluids with a considerable increase in heat transfer coefficient while using nanofluid. Increasing the concentration of nanoparticles tends to increase the heat transfer coefficient. This increase in heat transfer coefficient might be attributed to an increase in nanofluid thermal conductivity.

The maximum value heat transfer coefficient is found to be at higher flow rates. Compared to water the heat transfer coefficient of nanofluid is augmented by 50% at 0.3% volume concentration

4.2 Exergy Analysis of Minichannel with Nanofluid

The outlet exergy of the minichannel has been computed and shown in Fig 6 for various volume fractions and volume flow rates.

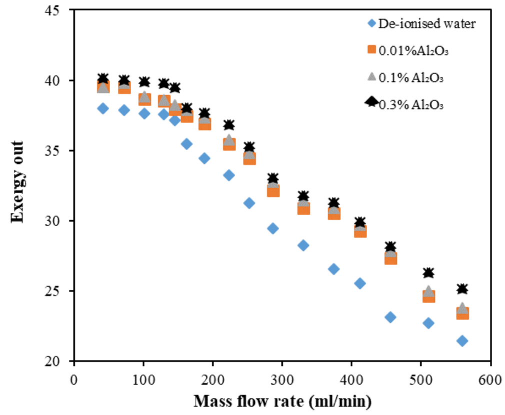

Fig. 6 Variation of outlet exergy at a different volume concentration of nanofluid

The outlet exergy of the microchannel employing nanofluid was greater than that of water, as measured. The output exergy rose as the volume percentages of nanofluid increased and dropped as the mass flow rate increased. When nanofluid was used as a coolant, the output exergy rose by 10%.

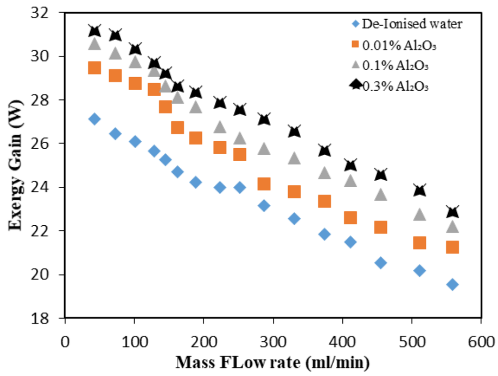

Fig. 7 Variation of exergy gain at different volume flow rates of nanofluid

When doing exergy analysis, exergy gain should also be included and is plotted in fig 7. As the volume fractions of nanofluid rise, the gain in exergy increases. It's also clear that when the volume flow rate rises, exergy gain declines. With a flow rate of 42.75 ml/min and a value of 31.186 W, the maximum exergy gain was obtained for 0.3 vol. percent. However, for 588 ml/min flow rate and 0.3 vol.% volume concentration, the maximum improvement of exergy gain was 15.01% concerning water

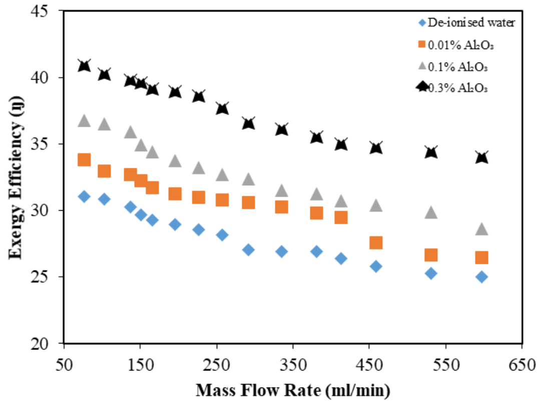

Fig. 8 Variation of exergy efficiency with mass flow rate for different volume concentrations of nanofluid

The exergy efficiency improves as the nanoparticle volume concentration increases, but it decreases when the flow rate is increased. For the volume fraction of 0.3 percent, exergy efficiency was highest (40.86 percent) at 52.75 ml/min flow rate. When nanofluid is used, exergy efficiency improves by around 31%. The exergy efficiency depends on the pumping power required to force the fluid into the minichannel and the outlet exergy. As the volume concentration of nanofluid increases, the outlet exergy increases at the expense of increased pumping power. Which leads to an increase in exergy efficiency. Similarly, as the mass flow rate of the fluid increases the outlet exergy decreases, and the pumping power required to force the fluid increases which also leads decrement in exergy efficiency.

From the above experiment, the results show that the exergy efficiency mainly depends on the pumping power required and outlet fluid temperature. For a given mass flow rate as the volume, concentration increases the thermodynamic like parameters exergy gain, exergy out, and exergy efficiency increase by the expense of pressure drop.

II. CONCLUSION

Optimum design of minichannel that gives maximum possible heat transfer with minimum pressure drop can be performed through exergy analysis. Second law analysis along with fluid flow and heat transfer analysis of single-phase flow for water and nanofluids in a rectangular minichannel were conducted experimentally. The effect of nanofluid concentration on exergic and heat transfer characteristics in minichannels were analyzed by experimenting with different volume fraction.

- Exergy gain, exergy out, and exergy efficiency increased with the increase of nanoparticle volume concentration. For a given volume flow rate, outlet fluid temperature increases, and at the same time wall temperature of minichannel decreases by the expense of pumping power with the rise of nanoparticle volume concentration.
- Exergy efficiency improved by 31% while using nanofluid of 0.3% of volume concentration.
- Even at a large volume percentage, nanofluid had outstanding stability. The thermal conductivity of the nanofluid rose as the volume concentration of nanoparticles increased.
- As the flow rate is increased, the friction factor decreases, but volume fractions of nanofluid rise.
- For all ranges of Reynolds number heat transfer coefficient of minichannel with nanofluids was higher than that of water.
- 50% improvement in the heat transfer coefficient is observed for nanofluid with 0.3% volume concentration by the expense of only a 39% rise in pressure drop compared to water.

The exergy efficiency and heat transfer coefficient were improved while using nanofluid with higher volume concentrations and so is recommended as a coolant in minichannel.

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