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Effect of Al_2O_3/H_2O nanofluid on MWNT circular fin structures in a minichannel

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ABSTRACT

Surface imperfections such as pin fins and surface roughness in minichannels have proven to increase thermal performance. The use of nanofluid as the working medium in minichannels has also shown significant increase in thermal performance. To determine the heat removal ability of both multi-walled carbon nanotubes (MWNTs) grown in a silicon minichannel and the use of Al_2O_3/H_2O nanofluid at a volume concentration of 0.01% as the working medium, an experimental investigation was conducted. Minichannel devices containing two different MWNT structures – one fully coated surface of MWNTs and the other with a 6×12 (rows, columns) circular staggered fin array of MWNTs – were tested and compared to a minichannel device with no MWNTs. The performance is evaluated based on a constant heat flux applied to the silicon base versus the corresponding silicon base temperature. The experiment was performed at a volumetric flow rate of 80 mL/min for a range of power inputs and was conducted multiple times to understand the extended performance after nanoparticles sediment on the channel surface. It was observed that the sedimentation of Al_2O_3 nanoparticles on a channel surface with no MWNTs increases the surface roughness and the thermal performance. When using both nanofluid and the MWNTs structured surface, the thermal performance had little to no increase for all experimental runs compared to the experiment with using deionized water. With the nanoparticle residue on the initial bare channel surface, the experiment was then run using deionized water and improved thermal performance was achieved.

1. Introduction

With electronics innovating quickly into smaller more reliable devices, there is a need for improved heat removal at small scales. Electronics must sustain a low constant surface temperature in order to avoid overheating. The advancements in the electrical devices are limited to the absence of efficient methods to remove the heat that is generated.

Mini- and microchannels provide an effective way of cooling small surfaces because of their ability to dissipate high surface temperatures through convection. Nano-, micro-, and minichannels have a higher heat transfer surface area to fluid volume ratio than a conventional channel which enhances convection. The heat transfer coefficient increases as the channel's hydraulic diameter is reduced, enabling an excellent cooling apparatus. Although it has excellent cooling capabilities, these channels experience a high pressure drop across the channel. Several surface modifications proven to enhance the thermal performance even further includes varying the shape of the channel [1], oscillating the channels dimensions into a wavy channel [2,3], an increased surface roughness [4,5], applying small cavities on the channel walls [6–10], and adding pin fins to increase surface area [6,11–16]. Applying defects to the surfaces of the channel can increase mixing of the flow, improve wettability of the surface, and initiate nucleate boiling sooner allowing more heat to be carried away from the heated surface [17].

Because of carbon nanotubes (CNTs) excellent physical and thermal properties, many researchers have grown them on the surfaces of microchannels to act as fins. Flow boiling analysis of CNTs coated microchannels and water as the working fluid was conducted by [18–20]. In all cases there was an improvement of the critical heat flux due to the increased nucleation cites provided by the CNTs. Others investigated single phase flow using MWNTs on the surfaces of microchannels. Mo et al. [21] applied different heat rates to a silicon base channel and kept the pressure drop across the device constant. This work obtained up to a 23% higher input power while keeping the temperature of the transistor below a silicon microchannel containing no CNTs. Jakobski et al. [22] also applied CNTs to a silicon microchannel and obtained an increase in thermal performance. Shenoy et al. [23] investigated the effects of water flowing past two devices- one of a fully coated carpet of MWNTs on the surface and another of circular MWNT micro pin fins in a staggered array – and compared them to a bare minichannel. The results further validated the enhancement of the thermal performance of MWNTs and was able to obtain a higher inputted heat flux for a finned channel vs. both the bare channel and the fully carpeted channel with only a slight pressure drop at a given

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Nomenclature

A	flow area (m^2)
c_p	specific heat of constant pressure (J/kgK)
k	thermal conductivity (W/mK)
ΔP	total pressure drop (kPa)
q	applied heat flux (W/cm^2)
Q	applied heat (W)
T	temperature (°C)
ΔT	temperature difference (°C)
u	average axial velocity (m/s)
Δx	distance between thermocouples (m)
$\dot{V}$	volumetric flow rate (mL/min)

Greek symbols

ϕ	volume concentration (%)
ρ	density (kg/m^3)

Subscripts

Al_2O_3	alumina nanoparticles
b	base
H_2O	water
in	inlet
nf	nanofluid
out	outlet

temperature and two different flow rates. CNT fins have shown to be effective in increasing microchannel thermal performance.

The working fluid predominantly used through heat exchanger studies is water; however, other fluids such as dielectrics and nanofluids are also used. Dielectric fluids have a low boiling point and increases wetting properties to provide improved heat transfer in single phase flow but they undergo dry out and reverse flow problems [24–26]. Nanofluids are made up of small nanosized particles usually no bigger than 100 nm in size suspended in a base fluid such as water, ethylene glycol, engine oil, or refrigerant. These added nanoparticles have been found to increase thermo-physical properties such as thermal conductivity, thermal diffusivity, viscosity, and convection heat transfer compared to their base fluids [27]. Previous studies have investigated the parameters that can influence the thermal performance of nanofluids, specifically Al_2O_3. Parameters such as particle size [28,29], concentration [28,30–32], and the effect of fluid properties [33–35] have all been examined. A review of the effects of these parameters for Al_2O_3/H_2O based nanofluids is given in [36]. As the nanoparticle diameter is reduced (<5 nm), the effective thermal conductivity increases which significantly enhances the thermal conductivity. As particle diameter approaches the micron size, they do not remain suspended within the base fluid. These particles no longer have those chaotic, Brownian motion reducing the enhancement of the suspended particles. For flow boiling studies, increased concentration of nanoparticles provides enhanced critical heat flux and the wettability of the fluid is increased. This is mainly due to the surface defects created by the sedimentation and agglomeration of the nanoparticles as it reaches higher temperatures [27]. With increased volume concentration more sedimentation is left on the surface of the channel which increases the surface roughness [37,38] and the heat transfer coefficient. When further investigating the volume concentration, it seems that viscosity is not affected for concentrations below 1%. However, for viscosity at higher volume concentrations, a large increase is observed when a fluid sample is heated beyond a critical temperature. When it is cooled before it reaches the critical point, the viscosity remains very similar of that to water. This is known as the hysteresis phenomenon among researchers. Nanofluids can leave sedimentation of particles, fouling, erosion, and may even clog the channel over time [39]. Based on the literature, the effects of nanofluids can increase the thermal performance of a base channel and is affected by particle size and concentration.

Nanofluids are still an enigma to the world today. Some say the effects of enhancement of nanofluids are caused by the Brownian motion of the nanoparticle and or thermophoresis or thermal diffusion of the system. Brownian motion is the random drifting of particles suspended in a fluid and thermal diffusion is the mass flux induced by a thermal gradient [40–43]. Others claim the main reason for their ability to remove a vast amount of heat is due to the surface deficiencies created at high temperatures due to particle deposition [27]. Added surface roughness shows as a promising reason for enhanced heat transfer. Few researchers have investigated the use of both nanofluids and mechanically induced surface structures. Zhou [44] passed silver nanofluids of different volume concentrations suspended into a PVP solution through an array of drop shaped micro pin fins in a microchannel. About an 18% increase in performance was obtained compared to a base fluid with little difference in the pressure drop.

This paper considers two modes of enhancements – the use of micro pin fins and the use of nanofluids – to improve cooling to help understand if the main source of thermal enhancement in nanofluids is surface defects. A volume concentration of 0.01% of Al_2O_3 suspended in water flows through a minichannel at a rate of 80 mL/min with MWNTs grown on the bottom surface in a fully coated structure and a staggered array of circular micro pin fins. This is compared to a channel with no MWNTs. Because of sedimentation on the surface that occurs at higher temperatures, the experiments are conducted multiple times to understand the extended performance after nanoparticles collect on the channel surface for each device. Although two phase flows provide higher heat transfer when comparing to single phase flows and are ample for higher heat flux cases, this study focuses on the single phase flow and the nucleation phase of nanofluid through a minichannel coated with MWNTs on the surface.

2. Device fabrication

Three devices were fabricated and used for this experiment – (1) no MWNTs on the surface, (2) fully covered MWNTs on the surface, and (3) a 6 × 12 staggered array (6 rows and 12 columns) of circular fins made up of MWNTs. Fig. 1 is the device fabrication of the channels and their dimensions. A 1 mm thick silicon wafer, pre-coated with 500 nm of silicon dioxide, is sliced into a $55 \times 45\ mm^2$ rectangular plate. An octagonal hole is laser cut in the center of this piece where the widest and longest part of the channel is 25 and 35 mm, respectively. This silicon wafer piece is then bonded using thermal epoxy onto a 500 μm thick wafer of similar dimensions. To enclose the channel, a 1 mm thick Pyrex wafer with two drilled holes 1 mm in diameter and 31 mm apart at the center of the wafer is bonded also using thermal epoxy to the other side of the silicon wafer with the octagonal hole. Capillary tubing of 1 mm inner diameter is used then to form the inlet and outlet manifolds. This process is used for all the devices; however, for the channels with MWNTs, extra steps were taken. The MWNTs were grown using chemical vapor deposition at 775 °C with a ferrocene catalyst and a xylene source with a mixture of