# The behaviour of nanofluids flooded in printed mini channels when excited by a small electrical potential

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**Abstract:** This work sought to observe the response of a nanofluid put along in an electrical circuit while seeing the behaviour of the fluid. Would the nanofluids have a characteristic of an electrolyte? Two mini channels were constructed using additive manufacturing approach. The nanofluids were flooded in the channels where they were connected in series with a generic resistor in a low voltage circuit. The fluids' behaviours were observed through the recorded voltage drops at the resistor and also at the channel's start and end points, respectively. The results showed minute currents were flowing in the circuit as the fluids recorded high resistances. Therefore, the nanofluids are naturally high resistance electrolytes. However, the real nature of the fluids exposed to electrical potentials for a longer duration is unknown.

**Keywords:** mini channel; hydraulic diameter; carbon nanotube; carbon nanofibre; electrical conductivity; 3D printing; high resistance electrolyte.

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## 1 Introduction

Experimental channels (ECs) are canals that deliver chemical samples or analytes. The channels can be fabricated in polymers, silicon, glass, and metals. As such, the corresponding dimensions of the channel should be exceedingly small.

There are various processes used to fabricate an EC that include surface micromachining, moulding, bulk micromachining, embossing and micro cutting. In general, there are two types of ECs. One is a channel for fluid control, and the other one is for heat transfer.

The ECs have essential applications in micro-devices. It is due to their high surface-to-volume ratio and their small volumes (Sharp et al., 2002). The fluid flow and heat transfer in ECs have various applications in electronics, bioengineering, advanced fuel cells, and micro heat exchangers.

Carbon nanotubes (CNTs) are allotropes of carbon called graphene with a cylindrical nanostructure that have such unusual properties. Graphene is a columnar microstructure which densely packed single, with a hexagonal layer of carbon-bonded atoms

(Ryglowski, 2009). Graphene microstructure orientation gives CNTs their unique strength, electrical and thermal properties. CNTs are a human-made form of carbon (Yazid et al., 2016).

A nanofluid comprises of the solid particles with average size of less than 100 nm dispersing in a base fluid with poor thermal conductivity such as water, ethylene glycol or engine oils. Normally, these solid particles are metal oxides or carbon-based nanotubes.

Two different assemblies and structures of CNTs have been discovered and investigated. Radushkevich-Lukyanovich first created bundles of multi-walled nanotubes (MWCNTs) type of carbon nanotube in 1951, then single-walled nanotubes (SWCNT) by Iijima-Ichihashi in 1993.

Their shapes distinguish these two kinds of carbon nanotubes. The SWCNT is made by rolling a graphene sheet into a seamless cylinder. It forms MWCNT when there are more rolled-up graphene sheets. The primary synthesis methods for SWCNT and MWCNT are the arc discharge, laser ablation, chemical vapour deposition, diffusion, and premixed flame methods.

One crucial characteristic and property of CNTs is high thermal conductivity. They have unique mechanical and thermophysical properties such as anomalous thermal conductivity and heat capacity due to non-uniform particle distribution in the carrier fluid (Al-Sharafi et al., 2016).

Among nanoparticles, CNT has the highest thermal conductivity. Macroscopic assemblies of CNTs seem to be advantageous as lightweight and highly conductive wires. Nanofluids are considered as a passive technique, but also a promising way for advanced thermal fluid science. Any efforts to deploy them as heat transfer fluids by dispersing them into any kinds of base fluids is called CNT nanofluids (Sarafraz et al., 2015).

This work sought to observe the behaviour of nanofluids flooded in constricted channels by exciting them with a low electrical potential. As carbon itself is obviously conductive, we hypothesise that the nanofluids will conduct currents. Are the nanofluids possess a characteristic of an electrolyte?

## 2 Background

### *2.1 The electrical properties*

There is a linear relationship between electric potential or voltage ($V$) with the current flows ($I$). The electrical resistance ($R$) is a constant independent variable of the voltage and the current. Consequently, this relationship is defined as $V = IR$.

Electrical resistivity is a measure of the quantity of a given material to prevent the flow of electric current. Electrical conductivity is a measure of the amount of material to conduct a current. In other words, electrical conductivity is the reciprocal of electrical resistivity.

Conductivity is the ability of a solution of any materials to make a flow of an electric current. In aqueous solutions, the current is carried by cations and anions. In metals, however, the current is carried by electrons. Electricity depends on some circumstances of the solutions.

In electrolysis process, conductivity can be measured by applying an alternating electrical current to two electrodes while the electrodes are immersed in a solution. Thus, the voltage quantity can be measured. During this process, the solution acts as an electrical conductor. The positively charged ions will move to the negative electrode while the negatively charged ions will advance to the positive electrode.

When a potential is applied across metals or solid substances, the result of the electric field causes electrons to move towards the positive sides due to the lattice of atoms in the metal material, described as the positive ionic lattice. Each lattice atoms of that metal have an outer shell of electrons. The outer shell of electrons moves freely. Thus, it can be separated from their parent atoms and travel through the lattice.

## *2.2 The channel*

Channels are human-made systems. The transport processes occur across the channel walls. Meanwhile, the bulk flow takes place through the cross-sectional area of the channel. Thus, the channel cross-section acts as a duct to transport fluid to or away from the channel walls.

A channel aims to fulfil two objectives. First is to bring fluid into close contact with the channel walls. Second is to deliver liquid to the walls and remove fluid away from the walls as the transport process is achieved.

The rate of the transport process of the fluids depends on the surface area. For a circular tube, the surface area is varied with the diameter. Meanwhile, the flow rate depends on the cross-sectional area. Thus, this varies linearly with the square diameter. It suggests that the tube surface area to volume ratio changes as the reciprocal of the diameter. When the diameter decreases, surface area to volume ratio increases. The diameter that affects the channel is called the hydraulic diameter (Kandlikar et al., 2006).

**Table 1** The channel classification scheme

| *No.* | *Channel type* | *Hydraulic diameter, $D_H$* |
|---|---|---|
| 1 | Conventional channel | $D_H > 3$ mm |
| 2 | Mini channel | 200 μm < $D_H \leq 3$ mm |
| 3 | Micro-channel | 100 μm < $D_H \leq 200$ μm |
| 4 | Transitional micro-channel | 1 μm < $D_H \leq 10$ μm |
| 5 | Transitional nano-channel | 0.1 μm ≤ $D_H \leq 1$ μm |
| 6 | Nano-channel | $D_H \leq 0.1$ μm |

*Source:* Kandlikar et al. (2006)

The channel classification is based on the hydraulic diameter. A smaller channel size has different effects on different processes. Table 1 lists the classification with its respective hydraulic diameter range. Equation (1) defines the hydraulic diameter, $D_H$ of a rectangular channel where $B$ is the width and $C$ is the depth of the channel.

$$D_H = \frac{2BC}{B + C} \tag{1}$$

## 3 Methods

### *3.1 Nanofluid preparation*

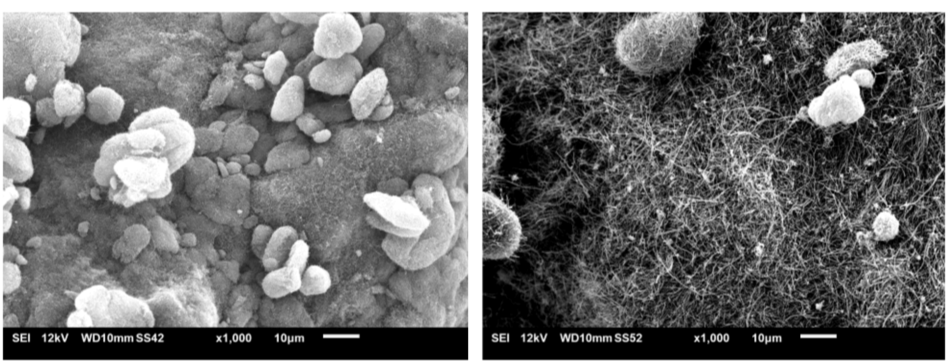
The sample preparation needs to be done by several steps with an accurate selection of CNT and carbon nanofibre (CNF). Properties of commercial CNT and CNF is shown in Table 2. The nanocarbon particles used in this study is multiwalled carbon nanotube (MWCNT-OH) from the industrial grade multi-walled CNT that has been functionalised with –OH, purchased from Nanostructured & Amorphous Materials, Inc. (Nanoamor). Meanwhile, CNF used is from Pyrograf III carbon nanofibre, high heat treated 24 (CNF HHT24) grade, which has been treated to high heat treatment temperature up to 3,000°C.

**Table 2** The properties found in commercial CNT and CNF

| *No.* | *Properties* | *CNT nanoamor* | *CNF HHT-24* |
|---|---|---|---|
| 1 | Manufacturer | Nanostructured and Amorphous Materials, Inc. | Pyrograf Products, Inc. |
| 2 | Purity (%) | 90 | 98 |
| 3 | Outer diameter (*nm*) | 10–30 | 100 |
| 4 | Form | Powder | Powder |
| 5 | Colour | Black | Black |

Figure 1 shows the scanning electron microscope (SEM) images of the CNT and CNF. The notable difference between the two materials is that CNF has been restructured from its original CNT structure. In short, CNF is the derivative of CNT. The nanofluids of this work are made up of CNT and CNF as the primary ingredients.

**Figure 1** SEM images of (a) CNT and (b) CNF




(a) (b)

Notes: The striking difference between the two is that CNF is the derivative of CNT and it is reshaped such that the tubes are stacked on top of each other, making it more robust.

In preparing for the CNF-based nanofluid, the CNF powder was mixed with the base fluids containing ethylene glycol and deionised water to synthesise the CNF-based electrode. The reason for using ethylene glycol (EG) and deionised water (DW) as the base fluid was because they are the primary liquid base for convective heat transfer (Selvam et al., 2016).

The polyvinylpyrrolidone from Sigma-Aldrich Co. was chosen as a surface activator to allow smooth dispersion of nanoparticles in nanofluids. The preparation of nanofluids is carried out using a two-step method preparation process. Preparation of nanofluids is accomplished by performing ratio calculation by setting the variable of weight percentage from 0.1wt% to 1.0wt% with the base fluid ratio of DW:EG equals 90:10% wt.

It is suggested that a 30:70 mixture would improve electrical conductivity of the f-HEG nanofluids (Kole and Dey, 2013). Having low electrolyte concentration would elevate the electrical conductivity of nanofluids (Sarojini et al., 2013) that should be measured under varying volume fractions and at different temperatures (Baby and Ramaprabhu, 2010). On the contrary, it is suggested that the electrical conductivity would suffer a drop as the weight content decreases to about 1% wt (Glory et al., 2008).

The suspension was homogenised for five minutes by using digital homogeniser LHG-15 at 10,000 rpm rotational speed. Then, the nanofluids sample undergoes ultrasonication process at 25°C using ultrasonic for about five minutes at 37 kHz frequency. The nanofluid dispersion and stability are then be observed by stability test rig (STR) as to make sure the nanofluid is in the stable condition and well homogenised (Abidin et al., 2016, Abdullah et al., 2016b).

The resulting suspension was homogenised by using digital homogeniser LHG-15 with a speed of 10,000 rpm for about five minutes to ensure that the solid particles inside the suspension are uniformly dispersed. Next, the sample undergoes ultrasonication cleaning process using an ultrasonic cleaner for about 15 minutes at 25°C at the highest frequency.

The nanofluid dispersion and stability are then be tested by Stability Test Rig as to make sure the nanofluid is in the stable condition and do not have any agglomeration (Abdullah et al., 2016a, Idrus et al., 2015).

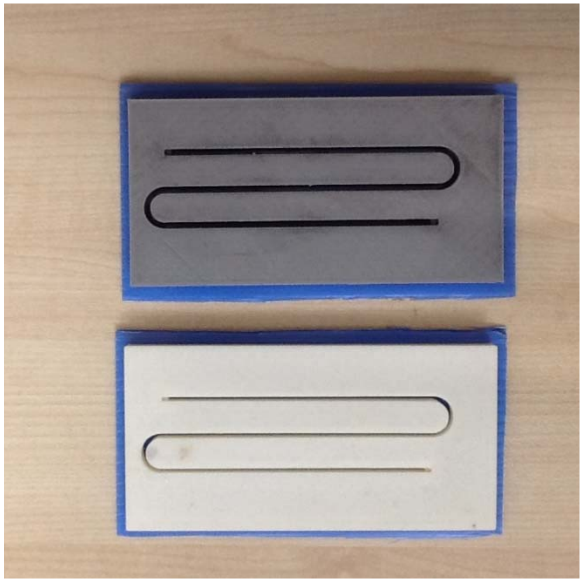
In this work, there are three CNT-based and another three CNF-based liquids. The samples have different values of concentration % wt for each sample fluid, which are: CNF\0.3, CNF\0.6, CNF\0.9, CNT\0.3, CNT\0.6, CNT\0.7.

### *3.2 Channel construction by 3D printing*

The channels were fabricated using Vagler 3D printer. Before the channel was printed, their shape must be drawn. The outline of the channels is of an S-shape. SolidWorks was utilised to construct the channels in the 3D model. The model was later being sliced into a large number of horizontal layers. The model was saved as a file and was uploaded to the 3D printer's processor.

Upon initiation, the printer would read every slice and print each of the slices using the fused deposition modelling approach. The printed parts (see Figure 2) were made of a plastic material, the acrylonitrile-butadiene-styrene (ABS). The ABS can withstand harsh use and hot conditions. It is also much stronger than the Polylactic acid.

**Figure 2** The mini-channels were produced through 3D-printing using ABS filament (see online version for colours)



Notes: Channel-1 (above, grey) has a hydraulic diameter of 2.86 nm while channel-2 (below, white) has a hydraulic diameter of 1.67 nm.

**Table 3** The channel's primary dimensions

| *Channel no.* | *Length (mm)* | *Width (mm)* | *Depth (mm)* | *Hydraulic diameter (mm)* |
|---|---|---|---|---|
| 1 | 284 | 2 | 5 | 2.86 |
| 2 | 284 | 1 | 5 | 1.67 |

Note: Based on the values of the hydraulic diameter, we categorise our channels as mini channels, according to the listing of Table 1.

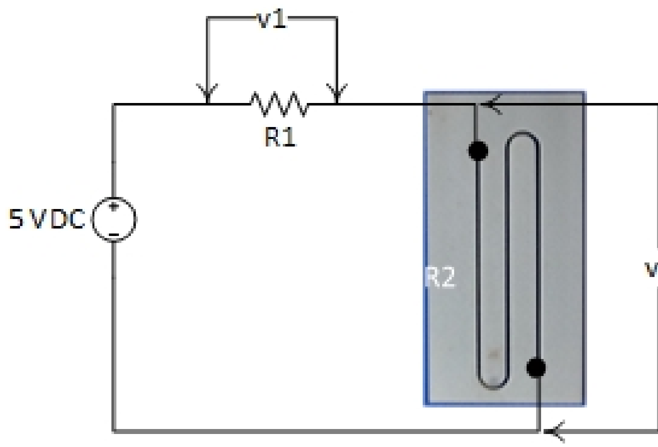
Table 3 lists the channel dimensions. Channel-2 is much smaller than channel-1, regarding, the hydraulic diameter. Both of the channels are categorised as mini channels as their hydraulic diameter falls within the range shown in Table 1.

### *3.3 Measurement technique*

The nature of the nanofluids is that their viscosities are affected when exposed to the open. The channels, on the other hand, are canals that hold the fluid while the surface of the liquid has direct contact with the environment. Reactions to the ambient air will cause the fluid to change state from the original to a more viscous liquid. As a result, the test for each liquid type was conducted rapidly. The measurement was recorded as quickly as possible to ensure the data collected represent the original state of the fluids and to avoid degradation.

A direct current power supply of low voltage was used to provide the potential across the circuit depicted in Figure 3. The schematic shows the 5 V power supply, the standard resistor ($R_1$), the channel that holds the fluid resistance ($R_2$), and how the electrical measurement would be carried out.

**Figure 3** The schematic used to run the tests (see online version for colours)




Notes: A low voltage supply would induce stress to the flooded channel ($R_1$) so that how the fluid would respond to the electrical potential across it may be observed. There is a standard resistor ($R_2$) connected in series with the channel. It works as a transducer that would confirm the existence of current flow in the circuit by measuring the voltage across it.

Instead of using a potentiometer, this work chose to use some standard resistors to represent $R_1$. Five resistors of a distinct resistance were chosen to be used in the tests. The main disadvantage of using a potentiometer is that the adjusted resistance is unknown unless it is measured after unplugging it from the circuit. Although one can construct as circuit so that a potentiometer's resistance may be known without unpluggin it from the circuit but the practice adds to circuit complexity.

The equipment used in assessing the samples' electrical responses was digilent analogue discovery (DAD), AMPROBE PM51A multimeter, a generic digital multimeter, and general model analogue and digital multimeters. The DAD provides USB oscilloscope and an adjustable power supply. As such, the software interfaced supply voltage and measurement are from the DAD. The generic multimeter was used to check for circuit continuity.

The first phase of this work was to measure and record the resistance of the samples. The second stage was to measure and to register the assortment of standard colour-coded resistors. Later, the system was assembled where the channels were put side by side along with a breadboard where the standards resistors were plugged in. The USB DAD was connected to a computer. A graphical user interface allows the user to perform measurement settings and data recording.

## 4 Results and discussion

### *4.1 Direct resistant measurement*

Each of nanofluid samples was flooded in the channels. It took about 5 mL of syringe volume to pump a sample into the channel. Some of the fluid might spill out of the channel. Once the channel was completely filled, the measurement procedure was to take place. Table 4 has each set of data uniquely belong to a sample. Only one-time measurement was recorded because the sample quantity was limited. Once the measurement procedure was done, the sample was not reused because its characteristic had changed when exposed to the open.

**Table 4** The resistances obtained by direct measurement using a multimeter on the channel flooded with the samples of nanofluids at room temperature

| *No.* | *Sample* | *Concentration (% wt)* | *Resistance (MΩ), channel-1* | *Resistance (MΩ), channel-2* |
|---|---|---|---|---|
| 1 | CNT | 0.3 | 7.14 | 4.55 |
| 2 | CNT | 0.6 | 6.90 | 6.12 |
| 3 | CNT | 0.7 | 7.07 | 5.97 |
| 4 | CNF | 0.3 | 3.78 | 4.47 |
| 5 | CNF | 0.6 | 2.20 | 4.39 |
| 6 | CNF | 0.9 | 2.64 | 1.67 |

For readings on channel-1, CNT of 0.3% wt recorded the highest resistance of 7.14 MΩ while the lowest resistance recorded was 2.2 MΩ for CNF of 0.6% wt. Similarly, for readings on channel-2, CNT of 0.6% wt recorded the highest resistance of 6.12 MΩ while the lowest value recorded was 1.67 MΩ for CNF of 0.9% wt.

It was evident that 0.6% wt of both CNT and CNF groups, in overall, showed inconsistent outcomes. On channel-1, CNF and CNT exhibited the lowest resistance. On channel-2, however, the groups revealed a mixed result where it was the highest resistance for CNT but a middling for CNF. The phenomenon was clearly abnormal and the reason behind this occurrence was unknown. It was suspected the sample might have been degraded after being exposed to the environment for some time.

From the trend seen in Table 4, it is noted that readings on channel-1 yielded higher resistance as compared to the readings on channel-2. There is an indication that the resistance is proportional to the hydraulic diameter, hence (2). The percent weight, however, did not show any sign of a relationship.

$$R_{nanofluid} \propto D_H \tag{2}$$

**Table 5** The resistances were obtained by direct measurement using a multimeter on the simple network that consisted of a power supply and an assortment of resistors

| *No.* | *Colour-coded resistance (Ω)* | *Actual resistance (Ω), $R_1$* | *Current (mA)* |
|---|---|---|---|
| 1 | 15 | 18.40 | Overcurrent |
| 2 | 39 | 40.90 | 120.80 |
| 3 | 56 | 56.50 | 87.70 |
| 4 | 220 | 217.20 | 22.90 |
| 5 | 470 | 466.00 | 10.70 |
| 6 | 1000 | 994.00 | 5.02 |

Note: The actual resistors and the current that flowed through each of the resistors were measured and recorded, given the power supply.

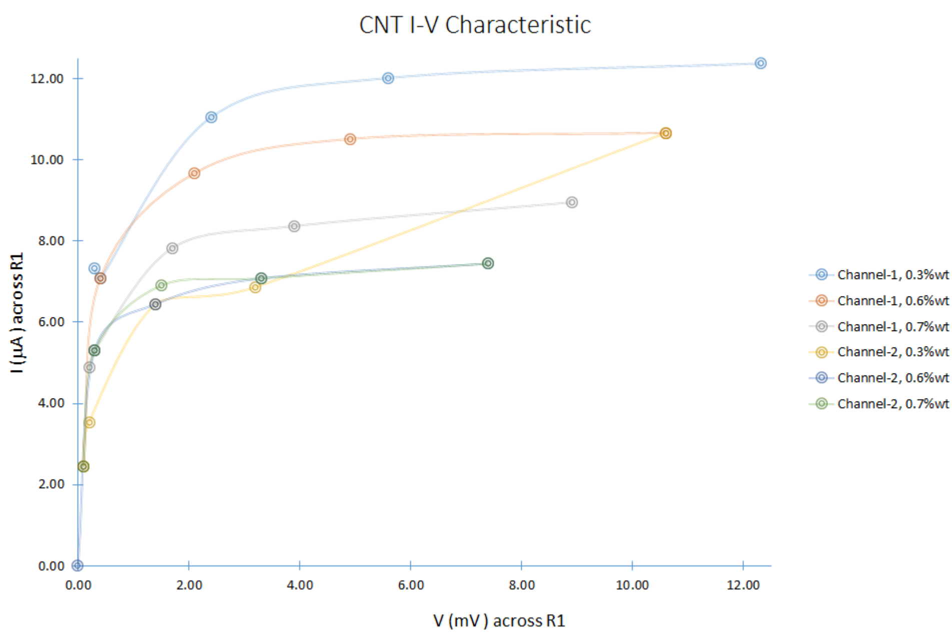
The listing of the resistor in Table 5 is a code-coded type that its resistance is known by decoding the stripes of colours found on its body. The resistant, however, is typical but not actual. So, determining the real resistant value was done by direct measurement on the resistor itself.

Once the real value of resistant was found, a 5 VDC power supply was connected to each of the resistors, individually. A voltage drop across the resistor was read and recorded. The current that flowed through the resistor was obtained by dividing the voltage drop by the actual resistant. The results indicate that the 15 Ω resistor had an overcurrent. Thus, it was taken out from the experimental procedure for the next tests.

## *4.2 Voltage and current measurement*

The tests were conducted to observe the electrical behaviour of the samples that responded to an electrical potential. The standard resistor acts as a transducer that senses the voltage drop across it. If there is reading then is a current flow of the circuit. The sample acts as semi electrolyte where the voltage drop across the filled channel should exist. Each of the standard resistors was connected in series with the channel where the voltage across each part was read and recorded.

**Figure 4** CNT – the relationship between the potentials across $R_1$ and the resistants when the channels were flooded with CNT of 0.3% wt, 0.6% wt, and 0.7% wt, respectively (see online version for colours)

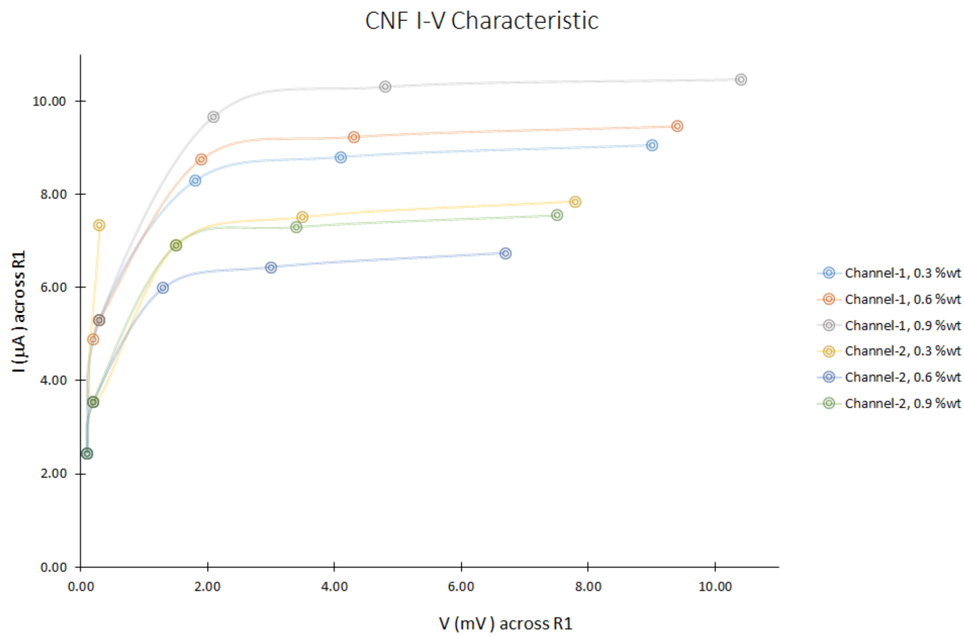



Note: The flooded channels acted as a resistor module, $R_2$.

Figure 4 displays the current-voltage (I-V) characteristic for CNT of 0.3% wt, 0.6% wt, and 0.7% wt, respectively. Since the sample has high resistance, the voltage drop across the channel was not observable. The only observable potential was found across $R_1$ because of very small resistance relative to $R_2$. The results implied that as the resistance of $R_2$ increased the voltage drop across it increased as well. At the same time, the potential across $R_2$ decreased.

The current, however, did not exhibit a drastic change. In all tests, the electrical current showed increment as the voltage drop increased until it reached a saturation region when the voltage drop started to increase from 2.00 mV and beyond.

**Figure 5** CNF – the relationship between the potentials across $R_1$ and the resistants when the channels were flooded with CNF of 0.3% wt, 0.6% wt, and 0.9% wt, respectively (see online version for colours)




Note: Similarly, the flooded channels acted as a resistor module, $R_2$.

In short, the curves displayed in Figure 5 summarise the behaviour of the nanofluids of different concentration when excited by a low voltage power source. Tiny currents were recorded flowing in the circuit. The phenomenon was apparently due to a low potential and a very high overall circuit resistance.

When tested on channel-1, the sample of CNTs exhibited increased in the current flow as the liquid concentration decreased ($i_{max,min} \approx 9$ µA, $\Delta i_{max} \rightarrow 13$ µA). Also, CNFs exhibited increased in the current flow as the liquid concentration decreased ($i_{max,min} \approx 9$ µA, $\Delta i_{max} \rightarrow 11$ µA).

Similarly, when tested on channel-2, the sample of all CNTs and CNFs allowed some current to flow in the circuit (6 µA $< i_{max} <$ 8 µA), except CNT of 0.3% wt allowed the largest current ($i_{max} >$ 10 µA). It was evident that minute current was flowing in the circuit proving that the nanofluids were naturally electrolytic of high resistant.

The current would reach a maximum value and eventually settled in saturation. More current was seen flowing in channel-1 as compared to channel-2. Thus, there is a clear indication that the current is somewhat proportional to the hydraulic diameter, hence (3).

$$i_{nanofluid} \propto D_H \quad (3)$$

## 5 Conclusions

Observing the behaviour of nanofluids flooded in constricted channels was performed by exciting these fluids with a low electrical potential. The idea was to prove our hypothesis that currents should flow through them because carbon is naturally a semiconductor. The results showed small electrical current flowed in the circuit as the fluids recorded high resistances. In fact, more currents flow in channel-1 as compared to channel-2. Therefore, the nanofluids are naturally high resistance electrolytes. However, the real nature of the fluids exposed to electrical potentials for a longer duration is unknown.

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