***Original Research Article***

# Effect of Sinusoidal Excitation on Fluid Flow across a Cu-Mica Micro-channel


## ABSTRACT

Micro-fluidic devices integrated with on-chip control circuitry have been widely used in various biological and chemical synthesis applications. The objective of this paper is to investigate the effect of gravity, temperature, pulse width modulation (PWM), and sinusoidal excitations on the flow of methanol, ethanol, and chloroform through an indigenously fabricated Cu-Mica micro-channel for automatic identification of fluids. For PWM vibrations, chloroform takes comparatively lesser time to flow across the given micro-channel that verifies that the velocity of the fluids is not a monotonic function of the PWM frequency. For sinusoidal excitations, ethanol exhibits maximum velocity around the frequency 1.5 KHz. The minimum velocity is shown at 4.5 KHz. For methanol, maximum velocity observed is around 2.5 KHz and minimum at 3.5 KHz. Chloroform shows no visible effect of excitation in its flow velocity. As velocity profile for a given set of influencing factors is fluid dependent, micro-channel based sensors may be developed for automatic identification of liquids.


**Keywords:** Micro-channel, micro-fluids, PWM vibration, sinusoidal Excitation, velocity profile.

## 1. INTRODUCTION

Micro-fluidics posses broad range of applications in different fields due to low cost integration with on-chip systems, low power utilization, and higher sensitivity [1]. The electrical interrogation of micro-devices has led to the extensive exploration in usage of integrated on-chip systems, especially, micro-fluidics. Microelectronics devices integrated with micro-fluidics has various sensing applications like fluid sensor, flow control in liquids [2] [3]. These sensors have a number of applications in flow cytometry [4], wind estimations [5], gas chromatography [6], gas monitoring [7], wall-shear stress [8], and viscosity measurements [9]. These techniques include micro-fluidic device development such as valves, pumps, and micro-fluidic channels that result into lab-on chip micro-fluidics devices or micro machining analysis systems while integrated together [10-12].

Micro-fluidic devices integrated with on-chip control circuitry may be used in various biological or chemical synthesis applications for manipulating fluidic flow and precisely controlling its motion [13]. The miniaturized micro-channels has been also used for detection [14] [15], purification, fractionating [16-18], single cell sorting of DNA [14-19], and linear analysis of stretched DNA molecules [20] [21]. The selection criteria for choice of materials and suitable technique to fabricate micro-fluidics device depends on certain parameters such as capillary effects, surface to volume ratio, electro-osmotic flows, geometrical cross section of the channel [21]. Various fabrication techniques such as sacrificial layer etching, e-beam lithography, nano imprint lithography [22-25], photolithography, laser ablation, hot embossing, CVD set up, and micromachining [26] has already been employed for micro-channel fabrication by various researchers.

The objective of this paper is to investigate the effect of gravity, temperature, PWM vibrations, and sinusoidal excitations on the flow of selective fluids, such as, methanol, ethanol, and chloroform through an indigenously fabricated Cu-Mica micro-channel for automatic identification of fluids. This work also explains the basics of the factors responsible for the flow of micro-fluids through micro-channels. The details of pattern etching and basics of flow injection analysis are discussed in the following section. The methodology is presented in Section 3 followed by the results and conclusion in the subsequent sections.

## 2. MICRO-FLUIDIC FLOW PARAMETERS

The various factors responsible for the flow of micro-fluids are briefed as follows.

### 2.1 Reynolds number

This is a dimensionless parameter and used to determine the type of flow pattern. The value of Reynolds number depends upon the geometry of the channel and is given by

$$R_e = \frac{LV_{avg}\rho}{\mu}$$

where $L$ is the channel length, $\mu$ the viscosity, $\rho$ the fluid density, and $V_{\text{avg}}$ the average velocity of flow [27]. $R_e$ depends on material properties (density, viscosity), boundary conditions, and critical velocity. Reynolds number less than 25 is common in micro-fluidics. The flow may be laminar flow, turbulent, or transient depending upon the value of Reynolds number as shown in Table 1.

Laminar flow is a streamline flow in which smooth sliding of adjacent layers resembling a set of parallel layers takes place. The field of velocity vectors is constant with time. The flow rates are relatively

**TABLE 1:** Nature of fluid flow on basis of Reynolds number

| Range of $R_e$ | Nature of fluid flow |
|---|---|
| $R_e < 2300$ | Laminar Flow |
| $2300 < R_e < 4000$ | Transient Flow |
| $R_e > 4000$ | Turbulent Flow |

low and the Reynolds number value of such flow is less than 2300 [28]. The laminar flow at higher velocities is referred as turbulent flow. Reynolds number value for such flow is usually above 4000. The curling of field lines takes place leading to mixing of the adjacent layers in such a way that there occurs unpredictable development of the velocity vector field. The flow pattern is observed to be increasingly turbulent towards the higher velocities [27-29]. Transient flow is a periodic flow and termed as third flow regime in micro fluidics. This includes the surface waves and the acoustic waves. The Reynolds number value varies between the 2300 and 4000. Since micro channels are small in dimensions, Reynolds number $R_e$ is much less than 100 and often less than 1 in micro-fluidics which means the flow of micro-fluids is laminar without occurrence of any turbulence. However the fluid flow transition from laminar to turbulent can also occur due to its sensitivity to flow disturbances and channel imperfections. The extreme case of laminar flow is the Stokes flow which involves the creeping motion of fluid through channels at Reynolds number lesser than 1. This is due to greater effects of viscous forces acting relative to the inertial forces at low Reynolds number values. The micro-fluidic flow regime includes various types of flow such as a bubbly flow, slug /Taylor flow, churn flow, slug /annular flow and annular flow.

### 2.2 Viscosity

Viscosity of a fluid is the internal resistance to its flow. The property of posing a friction to the fluid flow is termed as the viscosity. It is necessary to determine the flow speed, since the fluids with low viscosity are faster in flow as compared to highly viscous fluids [30]. The Marangoni effects for gas-liquid interface cause hardening of the gas bubbles that attains by surrogate no-shear boundary condition or with a no slip boundary condition. These effects alter the pressure drop and theoretical calculation based on no shear at new interfaces in micro-fluidic network which require intense care for its use in practical applications.

### 2.3 Height of liquid

The amount of material drawn due to the capillary action is termed as height of liquid and is designated as *h*. Capillary action forms the basis of micro-fluidics since capillary pressure of a fluid flowing across a micro-channel depends upon the capillary action in which the adhesive intermolecular forces at liquid – substrate interface become more stronger than the cohesive intermolecular forces inside the liquid. Thus whenever fluid interacts with the micro-channel i.e. capillary interface, the surface tension induced causes the fluid flow advancing across the micro-channel [31]. Mathematically, height of liquid is expressed as

$$h = \frac{2\gamma \cos\theta}{g r \rho}$$

where $\gamma$ represents surface tension of fluid, $\theta$ is contact angle, $r$ is column radius, $g$ denotes the gravitational force, and $\rho$ is the density [32-36]. Fluid flow in capillaries of crossectional dimensions above 1mm forms a new fluidic system called milli-fluidic system. In milli-fluidic system the transition to turbulence when Reynolds number value reaches 1, can never be neglected. This is a limitation of milli-fluidic system as compared to other fluidic systems or even micro-fluidic systems [31].

## 3. METHODOLOGY

The methodology for investigating the effect of sinusoidal response of fluidic flow across Cu-Mica micro-channels is divided into two steps.

### 3.1 Micro-channel fabrication

Y-shaped micro-channels having length 3.6 cm were designed in Coral draw and transferred on a Cu-Mica board using screen printing. The channel width was fixed at 1 mm. Figure 1 shows the Snapshots of Cu-Mica micro-channels. The channel patterned Cu-Mica board was subjected to etching to obtain micro-channels with copper walling.

**Fig. 1:** Snapshots of Cu-Mica micro-channel at different elevations.

The etchant used for was pale yellow solution of ferric chloride ($FeCl_2$) and water in the ratio of 3:1. For accelerating the etching few drops of HCl were poured into the solution. The patterns of the micro-channels to be fabricated were transferred on a Cu-Mica board coated with swab coating after cleaning with acetone. The patterned Cu-Mica board was immersed in the etchant solution. For enhancing the rate of etching, the tray containing the etchant was gently moved in left- right direction followed by gentle movements in up/ down directions. The process was continued till the removal of unwanted copper from exposed areas of Cu-Mica board starts appearing. The complete etching took about 15 minutes. After etching, it was washed under running water first and then swab coated using acetone to ensure dirt free channel fabrication.

### 3.2 Analysis

Four different experiments were carried to investigate the effect of gravity, temperature, PWM vibrations, and sinusoidal excitations on the fluidic flow across Cu-Mica micro-channels. During first experiment, the effect of different elevations of the micro-channels ranging from 10° to 90° in the steps of 10° on the micro-fluidic flow has been investigated. Snapshots of different elevations of micro-channels varying from $10^{\circ}$ to $90^{\circ}$ had already been shown in Fig. 1. In the second experiment, the effect of temperature on fluidic flow across Cu-Mica micro-channels has been investigated. For conducting the experiments with the flow of ethanol, methanol and chloroform, the angle of elevation of the micro-channels was fixed at 40°. The flow of the liquids at different temperatures ranging from room temperature to 50°C was recorded using a digital movie camera placed in front of the micro-channels. The temperature was maintained by using an IR lamp based setup as shown in Fig.2.

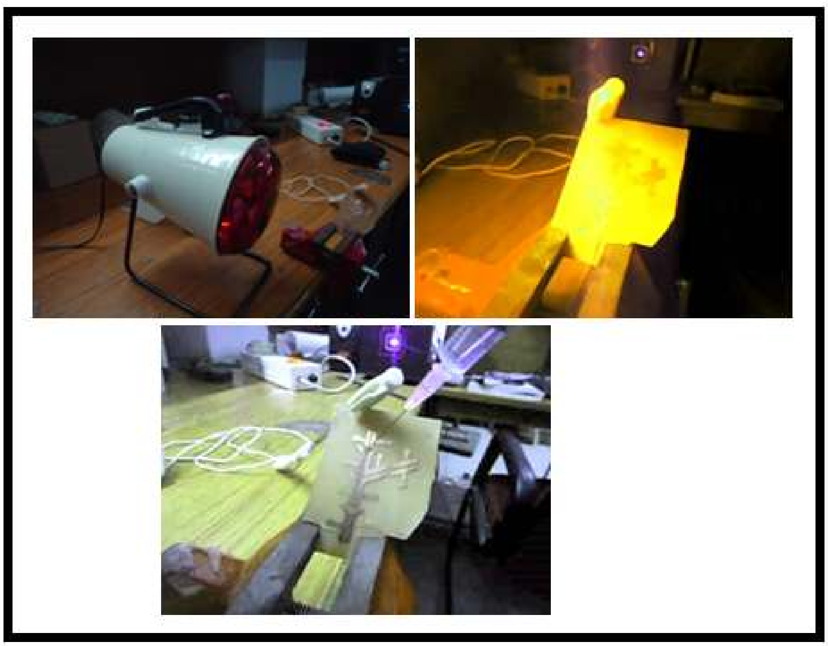

**Fig. 2:** Temperature control using IR lamp set up.

In the third experiment, the effect of PWM vibrations on fluidic flow across Cu-Mica micro-channels has been investigated. In this experiment the angle of elevation of the micro-channels was fixed at 25°.The instructions regarding the pulse durations were sent to the microcontroller system using a PC via serial programming interface. The frequency of the pulses was varied from 100 Hz to 5 KHz with a step of 500 Hz. PWM output of microcontroller was applied to the wide band speaker whose diaphragm acts as vibrator through a driver circuit. The speaker used with the sensitivity of 90 dB with $5\Omega$ impedance. The frequency response of speaker was 40 Hz to 20 KHz, $\pm 3\text{dB}$. The vibrations were coupled by fixing the diaphragm of the speaker to the bottom of the micro-fluidic system. The amplitude of the applied PWM signal was fixed at 5 volt. These steps are shown in Fig. 3.

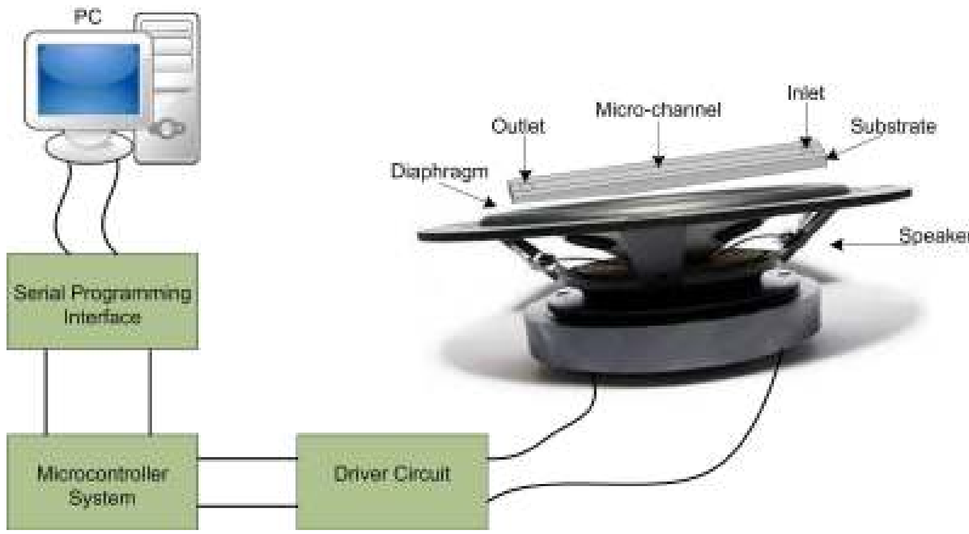


**Fig. 3**: Block diagram of the set up used for proposed investigations.

In the fourth experiment, the effect of sinusoidal excitations on the fluidic flow across Cu-Mica micro-channels has been investigated. The elevation of the micro-channels was fixed at 40° using a buncher. The sinusoidal excitations in the range of 100 Hz to 5 KHz with a step of 500 Hz were generated using a PC equipped with high quality sound card. The output of the sound card was applied to an audio amplifier and the amplified signal was coupled to the bottom of micro-channel by using a speaker as shown in Fig. 4.

**Fig. 4:** Set-up for evaluating the effect of sinusoidal excitations.

The audio sine wave at 100 Hz frequency was input and corresponding vibrations were produced. Micro-fluids were injected using metal syringe into micro-channel supplied with sine wave vibrations and the flow of fluid was recorded using a digital movie camera.

**Fig. 5:** Set-up for recording and analysis.

The flow pattern of other two fluids was also recorded in the same way. Then the sine wave generated at 500 Hz was applied as input to produce vibrations and flow pattern of each fluid was recorded at 500 Hz. This was repeated for different frequencies varying from 500 Hz to 5 KHz for each fluid and recorded for further proposed investigations as shown in Fig. 5. For injecting the fluids in the micro-channels, micro syringe was used called flow injection analysis (FIA) technique. It is a robust chemical analysis technique used for analysis of continuous fluid flows. FIA is preferred over conventional chemical analysis techniques due to its high reproducibility and sensitivity performance throughput capability that provides precise and fast analytical results with high degree of automation at low costs. It is also advantageous since it requires small amount of reagents for high resolution analysis [33] compared to conventional Flow analysis systems. For these experiments, the velocity was determined using stop-watch for 3.6 mm long micro-channel.

## 4. Results and Discussions

Although the first experiment is simple but significant, especially while comparing it with the results of our third experiment. The first experiment showed that speed of the micro-fluids increases with an increase in the angle of elevation. Chloroform shows flow velocity and it increases as the elevation angle increases. Ethanol shows minimum flow speed but ethanol and methanol shows maximum flow velocity around $80^{\circ}$and $90^{\circ}$ of elevation angles.

The analysis from the second experiment confirmed that fluid flow velocity is a function of temperature. The results showed that chloroform has maximum flow velocity at $50^{\circ}$C and minimum at the room temperature. The results of the third experiment are plotted in Fig. 6 as velocity profile for the three liquids. From the figure, it is clear that chloroform takes comparatively lesser time to flow across the micro-channel. In general, it may be expected that the velocity of the fluids is not a monotonic function of the frequency. The velocity profile with respect to frequency shows that the flow velocity increases with respect to the increase in frequency vibration. It is interesting to note that there are some frequencies for which ethanol and methanol do not show any movement irrespective of the applied vibration. Further, the investigations showed that methanol could not cross the channel even on the application of high frequency vibrations. On the other hand Ethanol started flowing above 2 KHz and the velocity increased with increase in frequency. Chloroform was observed to be the fastest moving fluid and its flow rate increases with increase in frequency. The maximum velocity was observed at 5 KHz and minimum velocity at 100 Hz. The similar results were obtained at 5 KHz frequency, while increasing the temperature from $30^{0}$C to $50^{0}$C. However the velocity flow increases but the trend was same, i.e, chloroform has maximum velocity and methanol showed minimum velocity.

**TABLE II:** Time and velocity computation of data recorded during analysis.

| Frequency (Hz) | Time (s) | | | Speed (cm/s) | | |
|---|---|---|---|---|---|---|
| | Ethanol | Methanol | Chloroform | Ethanol | Methanol | Chloroform |
| 100 | 7.2 | 5.7 | 1.0 | 0.333 | 0.421 | 2.40 |
| 500 | 4.6 | 3.2 | 1.0 | 0.522 | 0.750 | 2.40 |
| 1000 | 4.2 | 4.9 | 1.0 | 0.571 | 0.489 | 2.40 |
| 1500 | 3.8 | 5.4 | 1.0 | 0.631 | 0.444 | 2.40 |
| 2000 | 4.2 | 3.7 | 1.0 | 0.571 | 0.648 | 2.40 |
| 2500 | 7.0 | 3.6 | 1.0 | 0.343 | 0.666 | 2.40 |
| 3000 | 5.1 | 10.1 | 1.0 | 0.471 | 0.238 | 2.40 |
| 3500 | 5.0 | 13.1 | 1.0 | 0.480 | 0.183 | 2.40 |
| 4000 | 4.5 | 12.6 | 1.0 | 0.533 | 0.190 | 2.40 |
| 4500 | 9.2 | 11.4 | 1.0 | 0.261 | 0.211 | 2.40 |
| 5000 | 6.5 | 7.5 | 1.0 | 0.369 | 0.320 | 2.40 |

The results of the fourth experiment are tabulated in Table II and plotted as velocity profile as a function of frequency as shown in Fig. 7. From the plots it may be observed that maximum velocity was observed for ethanol around the frequency of the excitation at 1500 Hz. The minimum velocity is shown at 4500 Hz. Some peaks in the velocity were observed around 1 KHz, 1.5 KHz, and 2 KHz. For methanol, maximum velocity observed was around 2.5 KHz and minimum at 3.5 KHz. The peak velocities are observed around 500 Hz, 2 KHz and 2.5 KHz. Chloroform showed no visible effect of vibration in its velocity profile and remained constant at all frequencies of vibrations.

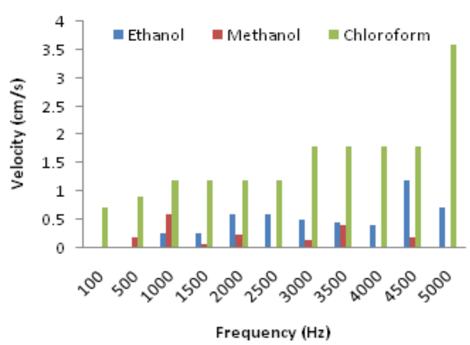


Fig. 6: Effect of PWM on fluid velocity at $50^0$C

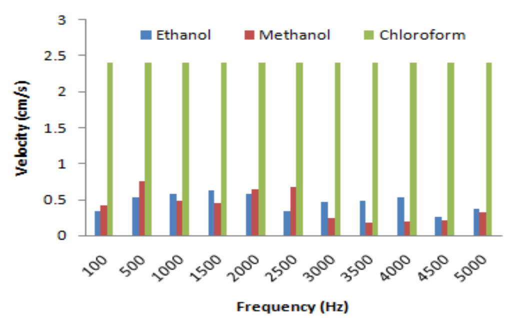


Fig. 7: Velocity plot for different fluids flowing across micro-channel at different frequencies

## 5. CONCLUSION

Investigations were carried out to study the effect of four different factors namely gravity, temperature, PWM vibrations and sinusoidal excitations on fluid flow across fabricated Cu- Mica micro-channels. The results of the first experiment showed that speed of the micro-fluids increases with an increase in the angle of elevation. Chloroform shows maximum speed and the acceleration is maximum around the elevation angles $60^{\circ}$-$90^{\circ}$. Ethanol shows minimum flow speed. Both ethanol and methanol show maximum acceleration around 80°-90° of elevation angles. The results of second experiment show that flow velocity of the liquids is a function of temperature. The chloroform shows maximum velocity at 50°C and minimum at the room temperature. The observations show that the acceleration is fluid dependent. The results of the third experiment show that the chloroform takes comparatively lesser time to flow across the given micro-channel. The velocity profile with respect to frequency shows maxima around 1 kHz and 3 kHz. The height of maxima goes on increasing with the frequency of vibration. The results of the fourth experiment showed that ethanol exhibits maximum velocity around the frequency of the excitation of 1.5 KHz. The minimum velocity is shown at 4.5 KHz. For methanol maximum velocity observed is around 2.5 KHz and minimum at 3.5 KHz. Chloroform showed no visible effect of vibration in its velocity profile and remained constant at all frequencies of vibrations. In conclusion, micro-channel based sensors may be developed for automatic identification of liquids. Thus, it can be concluded that sinusoidal excitation can control the fluid flow across a micro-channel. This technique offers a simple but influential alternate to the conventional microfluidic systems that may be employed in rapid-growing drug delivery applications in a controlled manner.

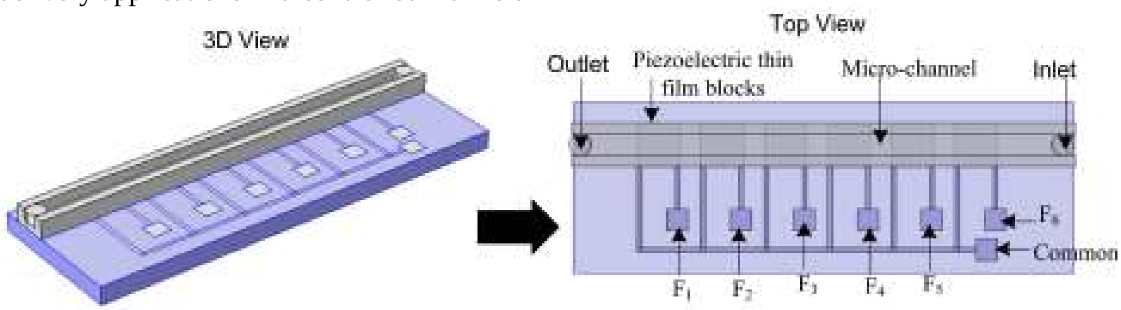


**Fig. 8:** Schematic showing different frequencies applied to microfluidic channel.

Figure 8 shows the schematic of the future work proposed by our team. In future work, different frequency signals, like, $F_1$, $F_2$, $F_3$ and so on, will be applied to the micro thin film piezoelectric blocks attached below the micro-channel. This concept may be helpful in moving the flow of the channel in a desired direction.

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