Paper Based Microfluidics: Demonstration of Capillary Flows and Fluid Viscosity Determination

1.Aim

To study the dynamics of capillary flow in paper-based microfluidic devices and estimate the viscosity of an unknown solution. Capillary flows in paper serve as a model for flow through porous media.

2. Objectives

The proposed experiment has the following objectives:

- **Power law:** Analyse flow behaviour through straight channels of the width of a few millimetres (1-3 mm) on paper. Add a drop of fluid and measure the imbibed length at different time instants to establish a power law dependency between length and time. Check if it follows the Lucas Washburn (LW) law.
- **Role of fluid viscosity:** Analyse the flow behaviour for different concentrations of glycerol in water. The viscosity of the solution increases with increasing concentration of glycerol. Determine the proportionality constant (k) and the power law index (n) for each solution using Lucy Washburn equation.
- **Viscosity Estimation:** Construct a calibration curve by plotting the obtained proportionality constants against the corresponding viscosities and concentrations of glycerol. This curve will enable the estimation of the viscosity of an unknown fluid and also unknown concentration of glycerol in water.

3. Materials Required

- Micro pipette (10-100µL) or use a dispenser to load and dispense 10 to 20 microliters
- Printed Whatman filter paper with straight hydrophilic channels supplied by Kaappon Analytics India Pvt. Ltd (KAIPL).
- Distilled water
- Glycerol solutions (0%, 10%, 30%,50%,70%,90% by volume)
- Mobile phone with rear camera
- Dye supplied by KAIPL, which will ensure that the hydrophobic barriers remain intact. Alternatively, you can use Red Brill ink after diluting it twenty fold for example take 1m l and make it 20 ml by adding water.
- Mobile phone stand (optional)

4. Theory

Capillary flows are those induced by capillary forces i.e. surface tension forces. Paper is a porous substrate consisting of several fibres interwoven together. The pore sizes are typically in the range of 10-25 µm depending on the paper being used. At these scales, surface tension effects are important and are responsible for creating pressure gradients across gas -liquid interfaces which can drive the flow. These devices leverage the intrinsic capillary properties of porous papers, enabling fluid transport without the need for external pumps and purely by surface tension effects. Understanding these flows will help in making paper-based devices for point-of-care applications in health care and environmental monitoring.

When a drop is placed on the paper, it spreads in all direction of paper radially (Fig. 1). The paper substrate is patterned to have unidirectional flow by rendering portions of the paper hydrophobic by suitable treatment as shown in Fig. 2. Kaappon Analytics with its patented technology fabricate these paper-based microfluidic devices of various shapes and designs. Aqueous solutions will flow only through the hydrophilic portions, as the hydrophobic portions create a barrier for aqueous solutions. The hydrophobic portions contain a polymeric material, and hence, care should be taken to ensure that the liquid does not react and dissolve the hydrophobic polymer material.

Lucas Washburn Law

The Lucas Washburn equation describes the flow in a single capillary microchannel. It relates the penetration length to time in a single capillary. It assumes negligible inertial forces as the flow is characterised by a low Reynolds number (creeping flow). The surface forces are responsible for generating the pressure gradient.

When the capillary walls are hydrophilic, the curvature of the liquid-air interface leads to a pressure gradient across the channel as shown in Fig. 3. The pressure difference across the interface ΔP_c called the capillary pressure is given by Young's Laplace law

$$\Delta P_c = \mathrm{P}_2 - P_1 = \frac{2\sigma}{R_c} \tag{1}$$

Where R_c is the radius of curvature. This is expressed in terms of the contact angle θ between the penetrating liquid and the pore size as

$$R_c \ = \frac{r_p}{cos\theta} \tag{2}$$

where r_p is the radius of the pore of the paper.

For a cylindrical pore, the velocity profile is given by the Hagen-Poiseuille equation and this results in a flow rate Q

$$Q = -\frac{\pi r_p^4}{8\mu}\frac{\mathrm{dP}}{\mathrm{dx}} \tag{3}$$

where, μ is the viscosity of the liquid, and $\frac{dP}{dx}$ is the pressure gradient in the direction of flow. The pressure gradient is written as

$$\frac{dP}{dx} = \frac{(P_1 - P_2)}{L} \tag{4}$$

where L is the penetration length. Here, P_2 is the pressure at the left of the interface and P_2 is the pressure at the channel inlet and pressure outside the channel is atmospheric pressureP_{atm}.

The flow rate Q can be written as the product of cross-sectional area (πr_p^2) and the average velocity $\frac{dL}{dt}$. Using this in equation 3 and 4 results in

$$\frac{dL}{dt} = \frac{r_p \sigma cos\theta}{4\mu L} \tag{5}$$

On integrating, we get the relation between the penetration length (L) of a liquid in a capillary and time (t) as

$$L^2 = kt \tag{6}$$

$$L=\sqrt{(kt)} \tag{7}$$

where k is the coefficient of proportionality

$$k = \frac{r_p \sigma cos\theta}{2\mu} \tag{8}$$

Taking the logarithm of the above relation gives

$$ln(L) = 1/2 \ ln(t) + 1/2 \ ln(k) \tag{9}$$

The intercept of the length versus time on a log-log plot gives the proportionality constant which depends on the fluid properties and the slope is n represents the index. This is a constant (n = 0.5) if the system follows Lucas Washburn equation.

For flow in a paper substrate, the flow takes a longer time for a given length due to interconnected pores which give rise to a tortuous medium. Using the Lucy Washburn equation, we hypothesize that the flow in a paper substrate can be expressed using a generalized power law

$$L = (kt)^n \tag{10}$$

The exponent n can be different from single capillary ($n = 0.5$), due to the tortuous medium. Hence, the n depends on the paper characteristics.

5. Methodology

Reagent preparation:

1. Prepare a different concentrations of glycerol water solutions using distilled water (Volume percentage: 10, 30, 50, 70, 90%)
2. Mix 30μL of stock dye with 1 ml of each mixture to aid the visualisation of capillary flow. Higher concentrations result in the barrier being broken.

Methods:

1. Place the paper-based device on a flat surface with the hydrophilic channels facing up.
2. Fix the phone/camera at a suitable height such that the entire channel, including the loading zone, is in the field of view of the camera and start the video.
3. Take a 10% glycerol: water solution using Pasteur pipette (or ink filler) till the first expansion as shown in Fig.4a. Gently, dispense the solution to the circular hydrophilic region (shown in Fig.2). The dye is used to help visualise the advancing front in the channel. While injecting the fluid ensure that the tip of the filler does not touch the paper.
4. Maintain the environment undisturbed while you observe the movement of fluid along the channel and capture the video till the fluid has reached the channel end or for a maximum of 5 minutes when the liquid flow is very slow.
5. Similarly, record the video for other glycerol water mixtures and the unknown mixture.

6. Results and analysis

1. The length of the liquid that is penetrated is measured at various time instants by analysing the video. This is done using the website eleif.net, for measuring length penetrated at various time instants after calibration.
2. The time t = 0 s, is when the dye enters the rectangular channel. Take the snapshot of the video for different time instants (t = 0, 10, 20, 30, 60, 120, 180, 240, 300s) as shown in Fig. 4b.
3. If the website is used, the length of the scale bar (1 cm) should be used as a reference line. Now, measure the length of the rectangular channel till which the liquid (red dye) has reached.
4. Plot a log-log graph for the length of the wetting front (penetration length) versus time. The steps involved are shown in Fig. 5. On the log-log graph, plot the trend line, find the slope (n) and intercept ($\log(k)$) using power law representation. The intercept gives the proportionality constant, and the slope tells us how closely it follows the Lucas Washburn equation.
5. Repeat this for solutions with different concentrations of glycerol. Estimate k and n for different solutions.
6. Plot the proportionality constant k with respect to known values of viscosity for different concentrations of glycerol. A decreasing curve is obtained and this is used as a calibration graph. Fit the data in a trendline and obtain the regression equation.
7. Using the regression equation and k obtained from log-log graph, we can estimate viscosity of unknown solution.

A sample of data for 50% glycerol-water is given in Table 1. The corresponding plots are given by Fig. 6 and Fig. 7.

Table 1 Measured values of penetration length at different times

Time as per the video(s)	**Time since entering channel (s)**	**Length covered(cm)**	**log (t)**	**log (L)**
20	0	0		
25	5	0.7	1.3979	-0.1549
30	10	0.85	1.4771	-0.0705
40	20	1.25	1.6020	0.0969
50	30	1.5	1.6989	0.1760
80	60	1.96	1.9030	0.2922
110	90	2.17	2.0413	0.3364
140	120	2.31	2.1461	0.3636
200	180	2.4	2.3010	0.3802
260	240	2.52	2.4149	0.4014
320	300	2.56	2.5051	0.4082

Table 2 Experimental n and k values for two different concentrations with their viscocity values

% glycerol	n avg	k avg *1000	Viscosity (mPa)
0	0.3279	24.06326	1
10	0.4134	21	1.383
20	0.29705	20.66675	1.985
30	0.3811	14.82302	2.996
40	0.2952	10.70576	3.02
50	0.33245	8.667854	8.365
60	0.29765	3.614456	16
70	0.35675	1.216229	35.132
80	0.6107	1.761705	91.455
90	0.42325	0.522502	302.7

Figures

Fig. 1 Radial flow of liquid on a paper

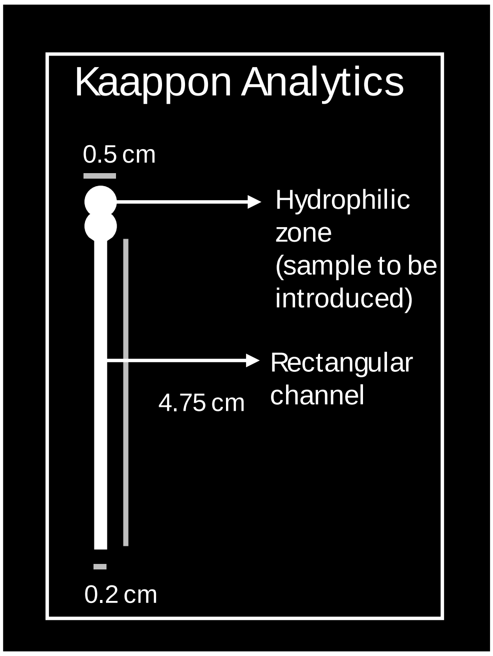


Fig.2 Design of hydrophilic channels (white) surrounded by hydrophobic barriers (black) to enable unidirectional flow. The circular portion is the area where the liquid is loaded

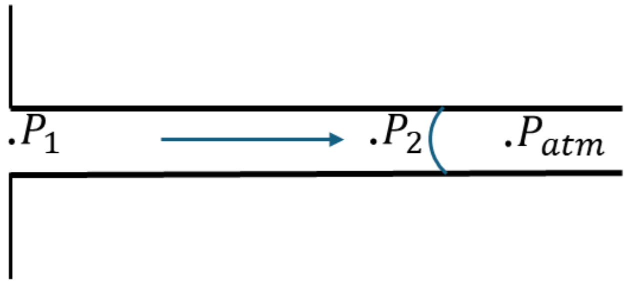


Fig. 3 $P_1 = Patm > P_2$ which causes pressure gradient ΔP_c across the channel

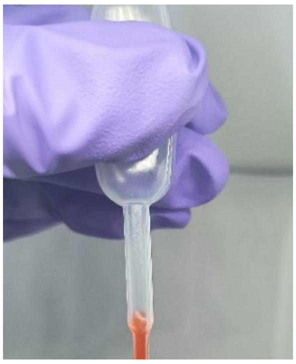
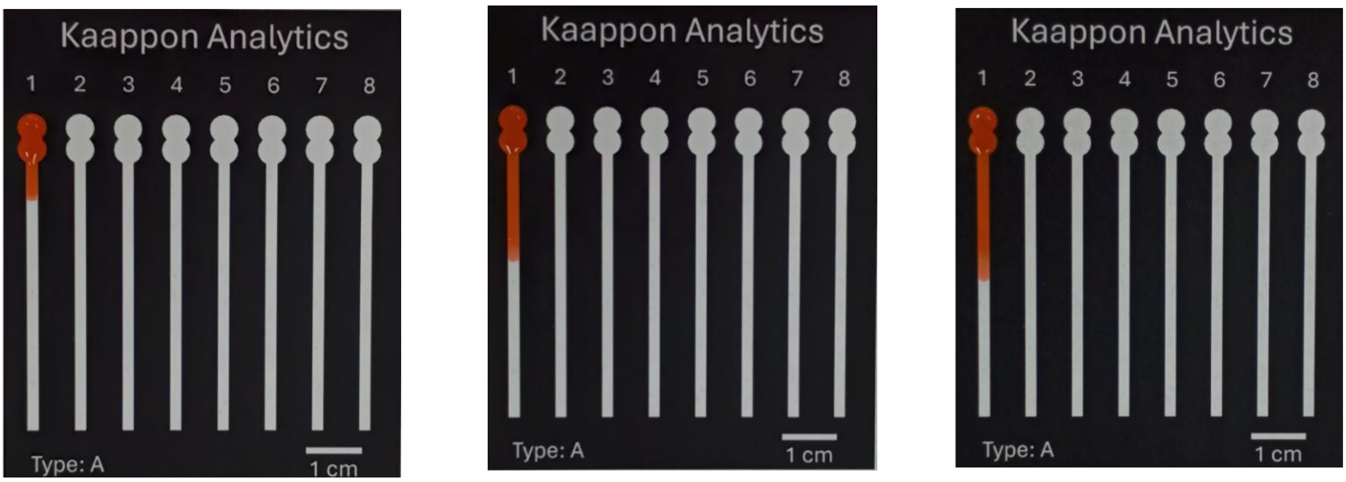


Fig 4a Filler depicting the level of liquid from the tip up to the first expansion. This should be added at the top circle without touching the paper.



t= 5s **t= 60s** **t= 120s**

Fig. 4b A water droplet with red dye spreading along the first hydrophilic channel of the strip at different time instants

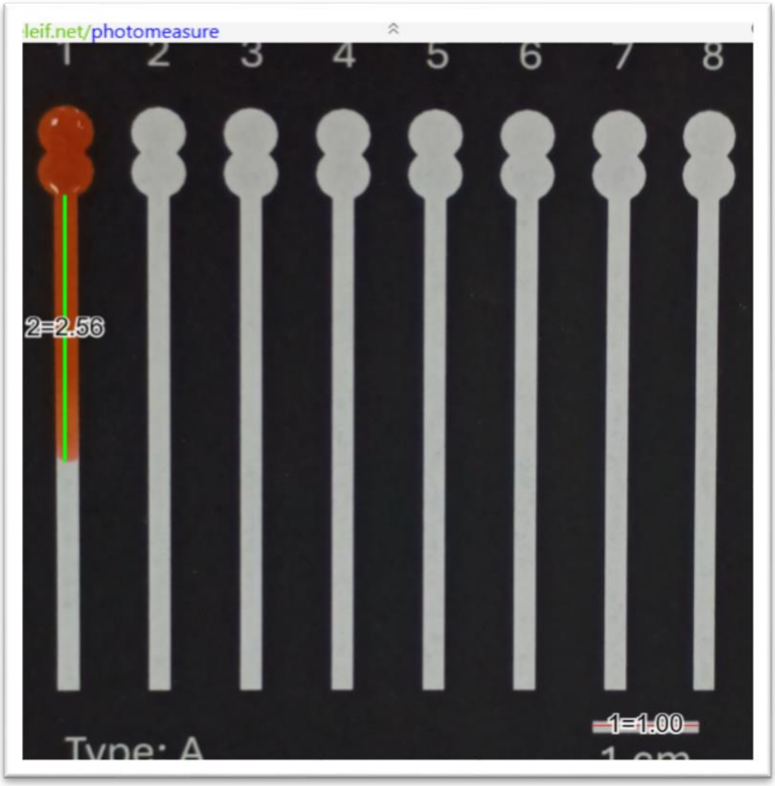


Fig. 5 Measurement of the length of the advancing liquid front by comparing with reference length 1cm given at bottom

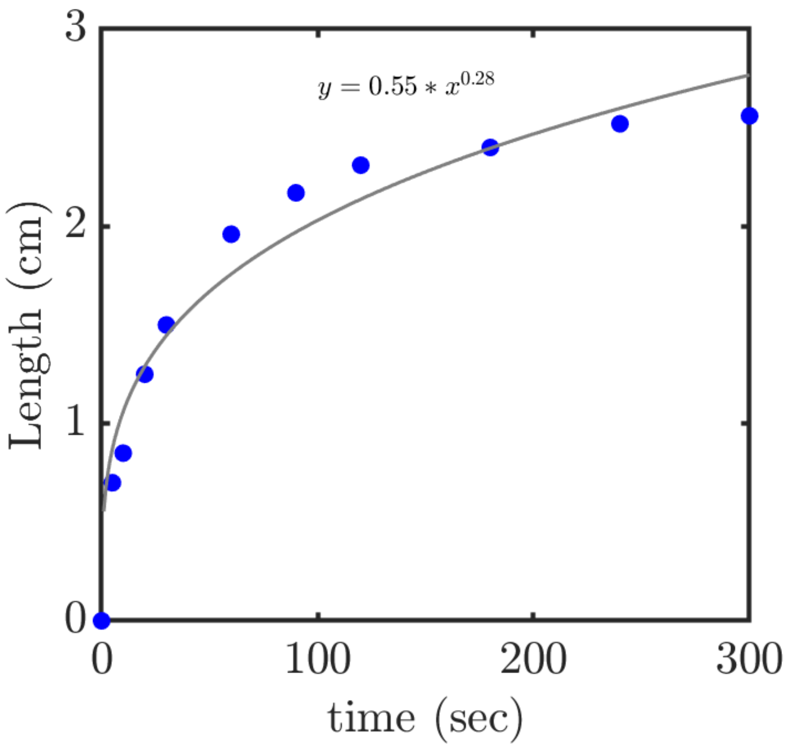


Fig. 6 Penetration length vs time plot

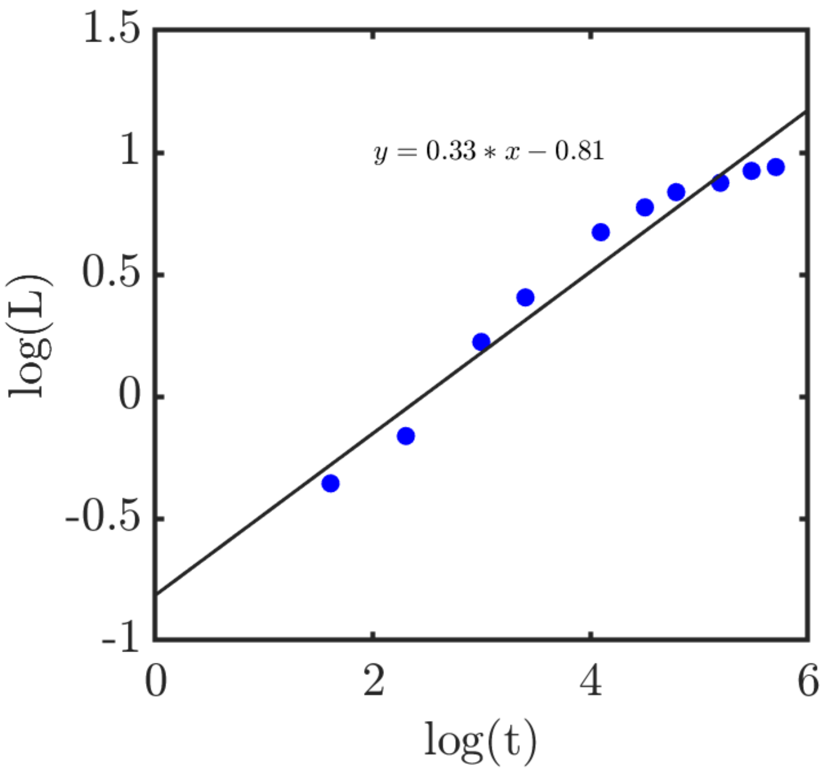


Fig. 7 Log-log graph plotted for length vs time

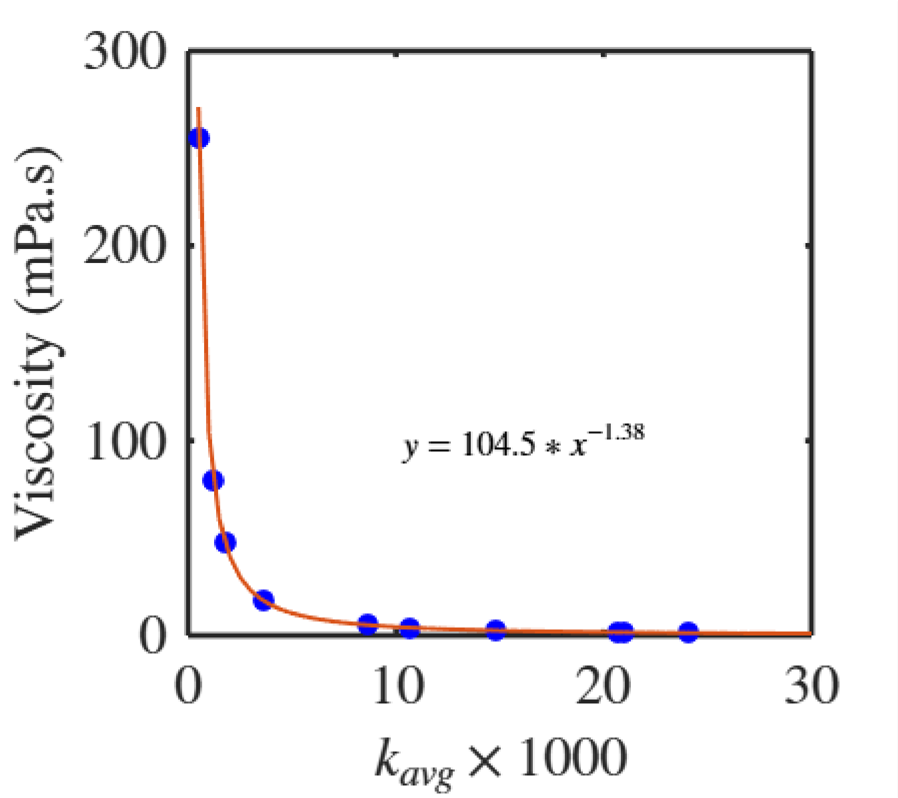


Fig. 8 Proportionality constant *k* vs Viscosity graph