MICRO-413 (2024) / Inkjet Printing : Exercise 1 solutions

1) The first step to formulate an inkjet-printable ink is to study the relevant physical properties of the ink, e.g., viscosity, surface tension, density, etc., and ensure that stable and satellite-free droplets can be generated. As a first approximation, one can perform dimensionless analysis, where dimensionless numbers, i.e., Reynolds, Webber, Capillary, Z, and Oh, are calculated to predict jettability. Now, considering materials with physical properties given in table 1, answer the following questions.
   a) Assuming that you are printing the inks using a nozzle with a 60 µm opening, calculate the Ca and We numbers for droplet velocities of 1,2,3,4,5 and 8 m/s.
   b) Considered the printability window shown in Fig. 1, explain which inks are not printable and why?
   c) The inks outside the printability window in regions 1,2,3, and 4, indicated in Fig. 1, are not printable. Explain what limits the printability in each region.
   d) The dotted lines in Fig. 1 indicate Z numbers of 100, 10, 1, and 0.1. Label the figure with the Z number corresponding to each line.
   e) In some literature, it is indicated that materials with 1 < Z < 10 are printable. However, the Z number alone cannot guarantee the printability of ink. Explain why this is the case.

Table 1 Physical properties of target inks

Sample	Mass loading %	Density (g/cm3)	viscosity (mPa.s)	surface tension (mN/m)
water	0	1.000	1	72
Hexanol	0	0.814	4.3	24.5
Glycerol	0	1.260	141	64
Anisole	0	0.995	1	29.3
	0	1.110	16.1	47.3
triethylene glycol monomethyl ether	0	1.026	7.8	31.4
Silver ink	35	1.450	14	37

$$Re = \frac{inertia}{surface\ tension} = \frac{\rho v d}{\eta}$$

$$We = \frac{inertia}{viscous} = \frac{\rho v^2 d}{\sigma}$$

$$Ca = \frac{viscous}{surface\ tension} = \frac{\eta v}{\sigma}$$

$$Z = \frac{1}{oh} = \frac{Re}{\sqrt{We}} = \frac{\sqrt{\rho \sigma d}}{\eta}$$

a) Dimensionless analysis in Ca-We space

b) Glycerol is not printable due to its high viscosity, and water is at the limit of printability due to its low viscosity and high surface tension. Also, the jettability of other inks is affected at high Weber numbers when the droplet speed is too high.

c) Limitation of jettabilty:
   a. Region 1 high-Ca and low-We: Inertial force is not large enough to overcome the viscous forces; therefore, no droplets are generated.
   b. Region 2 Low-Ca and low-We: Inertial force is not large enough to overcome surface tension force; therefore, no droplets are generated.
   c. Region 3 high-Ca and We: Relatively viscous inks experience a large inertial force resulting in the emergence of large pillars from the nozzle. The large pillars break up due to Rayleigh instability, resulting in the formation of one or multiple satellite droplets.
   d. Region 4 low-Ca and high We: Inviscid inks experience a large inertial force resulting in multiple breakups at the liquid thread and spraying behavior.

d) The Z numbers are shown in Fig. 1

e) For fluids, not all of which are printable, it is possible that different combinations of densities, viscosities, and surface tensions result in the same Z number.

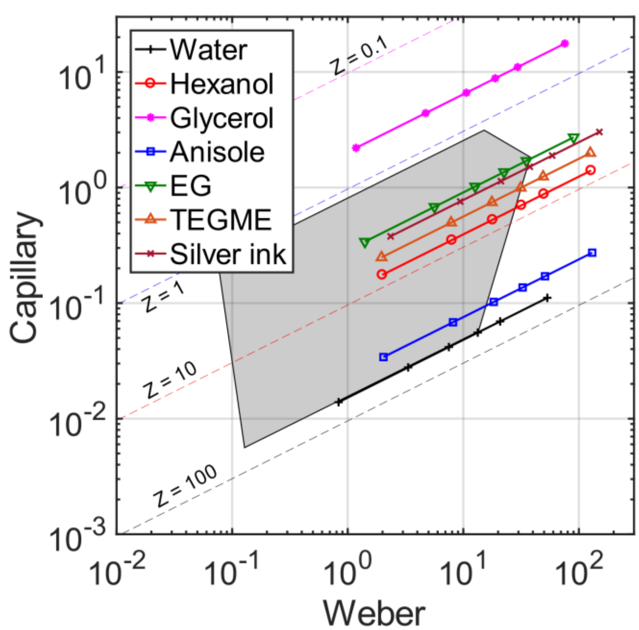
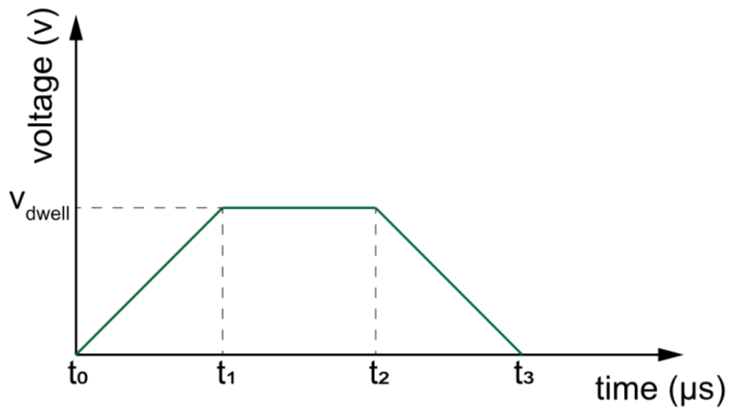
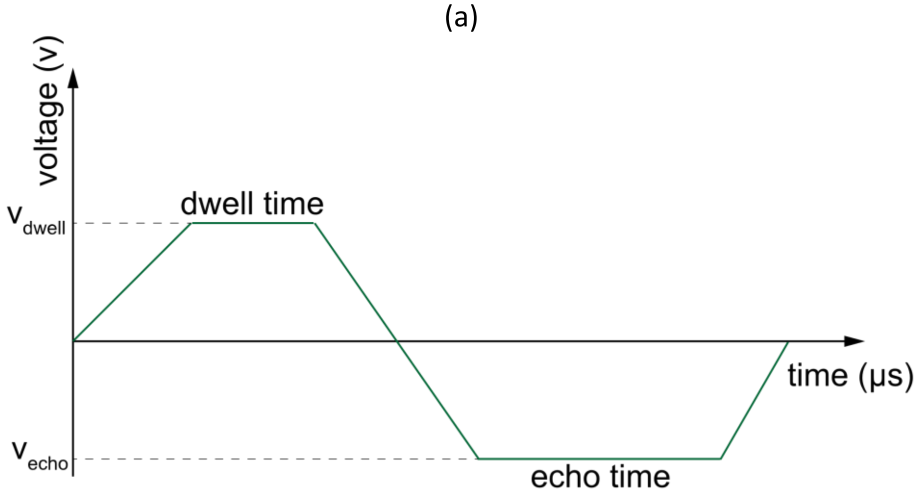


Fig. 1 Capillary / Webber map to determine jettability

2) The shape of the electric pulse that actuates the inkjet nozzle plays an essential role in forming satellite-free droplets. Considering the waveforms shown in Fig. 2, answer the following questions:
   a) Considering the unipolar waveform (Fig.2 (a)), sketch/draw the pressure wave propagation inside the capillary tube in Fig. 2 at different stages (B to H).
   b) What pulse length (i.e., dwell time) would result in the fastest droplet velocity considering a capillary with length l and sound speed in liquid to be c.
   c) For generating satellite-free droplets, it is more advantageous to use bipolar waveforms (Fig.2 (b)). Explain how a bipolar wave helps with the generation of satellite-free droplets.
   d) What would be the theoretical optimum ratio between the idle and echo times?



(a)



(b)

Fig. 2 Waveform used for actuation of the piezo-actuator (a) a unipolar waveform and (b) a bipolar waveform

a) Pressure waves traveling inside the capillary tube

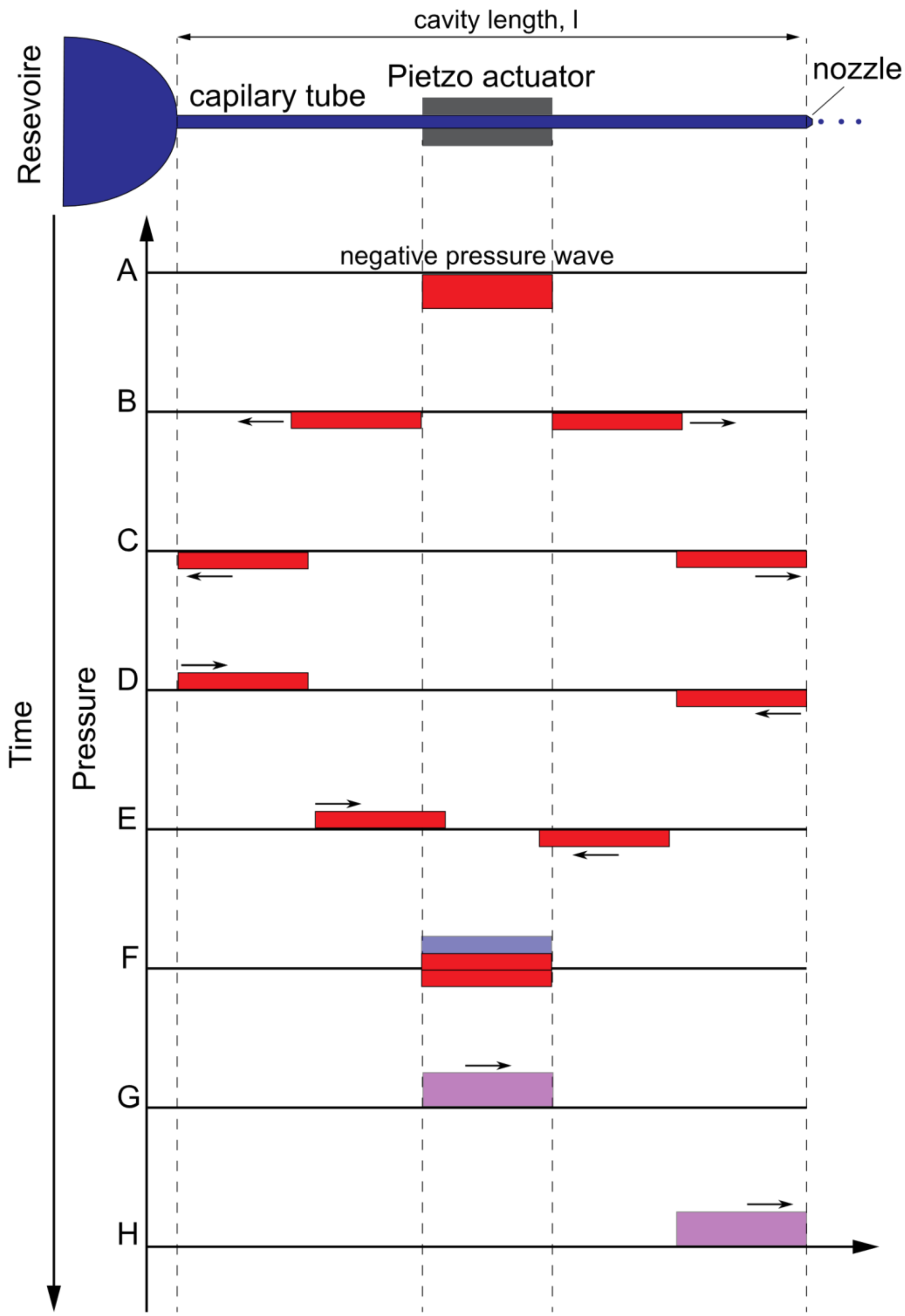


Fig.3 propagation of pressure waves generated by a unipolar waveform inside a capillary tube

b) The pulse length of $\frac{l}{c}$ results in the fastest droplet generation

c) A bipolar waveform is used to eliminate the residual acoustic oscillations remaining in the capillary tube after droplet ejections. The bipolar waveform also allows applying a high voltage difference without increasing the pulse amplitude too high.

d) The optimum time of the echo voltage is twice the dwell time, i.e., $\frac{2l}{c}$