**INDIAN INSTITUTE OF TECHNOLOGY, KHARAGPUR**
**End-Autumn Semester Examination 2023-24**

**Date of Examination: 21.11.2023 Session AN Duration 3 hrs**
**Subject No. : CH62049 Subject Name: Microscale Transport Process**
**Department/Center/School: Chemical Engineering**
**Specific charts, graph paper, log book etc., required: No**
**Special Instructions (if any): Assume any data you feel are missing**

**Q1.** Each question carries three marks, be brief **(3×3=9 Marks)**

(i) Is it true that for a droplet with a convex shape, the temperature induced Marangoni flow is always directed from a region with higher temperature to a region with lower temperature? Justify your statement analytically.

(ii) Starting with the z component of the Navier Stokes equation and the energy equation, highlight the special considerations for their use in microflows. Demonstrate how does the characteristic time for heating or cooling of a semi-infinite body change as the principal length scale is reduced in a micro-device?

(iii) Demonstrate with the help of relevant equations and concepts how surface roughness increases the inherent wetting characteristics of a substrate. Is it possible to explain the less than anticipated increase in hydrophobicity of a surface spin coated to form a thin film of Teflon to make it more hydrophobic?

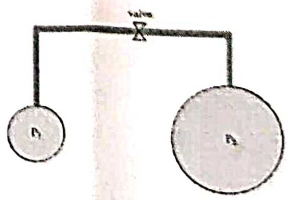
**Q2.** Each question carries one mark, be brief and precise **(1×10=10 Marks)**

(i) A vapor having a high thermal conductivity but low diffusion coefficient is being cooled in a chamber with a viewing port. Will you prescribe additional heating for the window to provide a clear view of the inside?

(ii) Explain the reasons behind using an additional thin layer of a hydrophobic substance on the dielectric in EWOD

(iii) Explain the use of oil in a closed digital microfluidic device handling biological material

(iv) Two small droplets of the same liquid are hypothetically connected to each other through an imaginary connection and a valve as shown in the figure. Explain, with proper reason, the direction of the flow, if any, when the valve is opened.




(v) Using appropriate equation show that the entropy generation is more for a system with higher temperature gradient.

(vi) For flow inside a mirochannel, the velocity is increased by a factor of two in one case, and in the other case the hydraulic diameter is decreased to get the same increase in velocity. Explain in which case the viscous dissipation will be more.

(vii) Write the basic assumptions of the lumped capacitance model. Do you think that this model is likely to be applicable in microsystems?

(viii) Explain why the voltage required to achieve contact angle decrease in EWOD is higher than in EW. Why EWOD is still preferred over EW?



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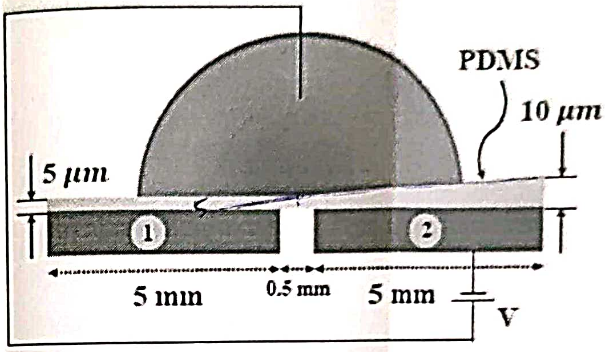
(ix) The constuctral theory of Bejan advocates bottom up approach. Do you agree with this statement and why?

(x) Explain what is meant by 'coffee ring effect' during evaporation.

**Q3.** Consider a droplet of water having a diameter = 5.5 mm sitting symmetrically over two electrodes, such that it covers half of each electrode. The electrodes are 5mm long with a gap of 0.5 mm in between them. The electrodes are covered with a thin, smooth layer of PDMS. The PDMS thickness on electrode 1 is 5 microns. However, the dielectric thickness on electrode 2 is varying linearly with a final thickness of 10 micron at the end. The equilibrium contact angle for the droplet surface is 100°. At an instant of time, electrode 2 is switched on while electrode 1 is kept at zero voltage. The droplet may try to move towards electrode 2 and beyond, while the other end is pinned on to its initial position on electrode 1 due to some surface inhomogeneity. The base radius of the droplet changes as per the following relation, where d is the dielectric thickness and V is the applied voltage. During spreading, the dielectric thickness may be taken as that corresponding to the final position of the contact line on the electrode. The effect of gravity may be neglected for this arrangement.




$$R_{Base} = R_{Initial} + 8.84\times10^{-10}\frac{V^{0.5}}{d}$$

(i) What potential is to be applied such that the advancing edge of the droplet reaches the end of the second (activated) electrode?

(ii) A droplet can move if the driving force is more than 2 micro Newton. Predict if the droplet can move beyond electrode 2 for the potential evaluated in part (i).

Given: Surface tension of the liquid $\sigma$ = 0.072N/m, $\rho$ = 1000 kg/m³, PDMS dielectric constant = 2.3, $\epsilon_0 = 8.854*10^{-12}$ C²/N m² **(2+4=6 Marks)**

**Q4.** In electrohydrodynamic atomization process, a capillary tip of radius 200 μm is placed at a distance of 1 cm from the ground electrode. Assume the interfacial tension as $10^{-2}$ N/m, and $\varepsilon_0\varepsilon_l \approx 10^{-10}$ coulomb²/(Joule-metre)?

i) What would be the magnitude of threshold voltage?

ii) The droplet thus generated will undergo acceleration or deceleration? How to estimate the magnitude?

iii) Will the droplet reach a terminal velocity? If so, how to estimate the magnitude of the velocity?

iv) What further changes in the droplet are expected on the flight towards the grounding plate?

v) For length scale to reach the tip (at a flow rate of 1 μL/s) as 1 mm, fluid viscosity as 1 cp, fluid density as 1gm/cc, ionic diffusivity as $10^{-9}$ m²/s, and Debye length as 0.01 μm, estimate the time scale of bulk charge relaxation of double layer, hydrodynamic timescale, and the viscous timescale, and infer from these timescales whether a cone develops in this case.

vi) When AC voltage is applied to implement the atomization, what should be the upper limit of frequency based on above information, such that a quasi-steady Taylor cone is produced in each half cycle? What happens to the Taylor cone, if the supply frequency exceeds the upper limit?

Relevant equations: $\varepsilon_0 \varepsilon_l \frac{V^2}{2d^2} \sim \frac{\sigma}{R}$; The voltage in volts is equal to the energy in joules, divided by the charge in coulombs.

**2×6 = 12 Marks**

**Q5.** Consider a particle with radius 100 nm and zeta potential = -5 mV in aqueous solution with $10^{-3}$ molar KCl solution at room temperature. Assuming Debye-Huckel approximation to be valid, calculate the Debye layer thickness. How does the thickness compare with the radius of the particle? What would be the velocity of the particle under an electric field of 100 Volt/cm?

$$\partial_z^2 \phi(z) = 2\frac{(Ze)^2 C_0}{\epsilon k_B T}\phi(z)$$

$\varepsilon = 80 \times 8.85 \times 10^{-12}$ coulomb$^2$/(N-m$^2$);

$k_B = 1.38 \times 10^{-23}$ J/K;

$e = 1.6 \times 10^{-19}$ coulomb;

$\mu = 10^{-3}$ Pa-s for water

**5 Marks**

**Q6.** Write in not more than three sentences and/or plots and/or equations

i) The importance of capillary, Bond, and Weber numbers

ii) Difference between Rayleigh instability and coulombic instability in the electrospray process

iii) Under what circumstances the electrospray process gets changed to electrospinning process, and what the common anomalies are with electrospinning?

iv) Difference between dripping and squeezing mode for droplet generation

**2×4 = 8 Marks**

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**Relations and Formulae**

$$\rho\frac{D\vec{w}}{Dt}=\rho\left(\frac{\partial}{\partial t}+\vec{w}\cdot div\right)\vec{w}=-grad\,p+\mu\nabla^2\vec{w}+\vec{k} \qquad \Delta P=\sigma_{lv}\left(\frac{1}{r_1}+\frac{1}{r_2}\right)=\sigma_{lv}K$$

$$\cos\theta_Y=\frac{\sigma_{sv}-\sigma_{sl}}{\sigma_{lv}}$$

**The non-dimensional form of the z component (flow direction) of the equation of motion for flow through a duct**

$$v^*\frac{\partial w^*}{\partial y^*}+w^*\frac{\partial w^*}{\partial z^*}=-\frac{\partial p}{\partial z^*}+\frac{\partial}{\partial y^*}\left[\eta^*\frac{\partial w^*}{\partial y^*}\right]+\frac{1}{\mathrm{Re}^2}\frac{\partial}{\partial z^*}\left[\eta^*\frac{\partial w^*}{\partial z^*}\right]$$

$$v^*\frac{\partial T^*}{\partial y^*}+w^*\frac{\partial T^*}{\partial z^*}=\frac{1}{\mathrm{Pr}}\frac{\partial}{\partial y^*}\left[\lambda^*\frac{\partial T^*}{\partial y^*}\right]+ +\frac{1}{\mathrm{PrRe}^2}\frac{\partial}{\partial z^*}\left[\lambda^*\frac{\partial T^*}{\partial z^*}\right]+\frac{\mathrm{Ec}}{\mathrm{Re}^2}\Phi^*$$

$$\zeta\approx\frac{2-\beta}{\beta}\Lambda$$

$$\Delta p=\left(C_f\frac{l}{d_h}+\zeta\,\mathrm{Re}\right)\frac{\rho v^2}{2}\frac{\mathrm{Re}}{d_h^2} \qquad w(x=0)=\zeta\left(\frac{\partial w}{\partial x}\right)_{y=0} \qquad Gr=\frac{g\beta s^3\left(T_{w1}-T_{w2}\right)}{v^2} \qquad Kn=\frac{\Lambda}{L}$$

$$\rho c_p\frac{dT}{dt}=\frac{dp}{dt}+\varepsilon-div\left(k\,grad\,T\right) \qquad Bo=\frac{\rho g R^2}{\sigma} \qquad \frac{ds}{dt}=\frac{1}{T}\left\{\frac{\varepsilon}{\rho}-\frac{1}{\rho}div\,\vec{q}\right\}$$

**Le (=Sc/Pr) = $\alpha/D$, ($\alpha=k/\rho c_p$).** **$Ec/Re^2 = v^2/(c_p\Delta T\, d^2)$, $Ec = w_r^2/c_p\Delta T$** $\quad \lambda=\frac{kT}{\sqrt{2}\,p\sigma} \quad \Lambda=\frac{1}{\sqrt{2}n\sigma}$

$$F_{Driving}=2\gamma w\sin\left(\frac{\theta_R+\theta_L}{2}\right)\left(\cos\theta_R-\cos\theta_L\right) \qquad \sigma_{sl}^{eff}(U)=\sigma_{sl}-\frac{\varepsilon_0\varepsilon_d}{2d}U^2$$

$$\cos\theta=\cos\theta_0+\frac{\epsilon_0\epsilon_r}{2d\sigma}V^2\ ;\ \cos\theta=\cos\theta_Y+\frac{\varepsilon_0\varepsilon_d}{2d\sigma_{lv}}U^2$$

$$\frac{1}{C_{eq}}=\frac{1}{C_1}+\frac{1}{C_2}\ ;\quad \cos\theta_W=r\cos\theta\ ,\quad \cos\theta_C=f\cos\theta+(1-f)\cos\theta_0 \qquad Ma=\frac{\Delta\gamma R}{\rho\nu\alpha}$$

The volume and surface area of a spherical cap can be expressed as

$$V(a,\theta)=\frac{\pi}{3}\frac{a^3}{\sin^3\theta}\left(2-3\cos\theta+\cos^3\theta\right)$$

Where V is the volume of the droplet, a is the base (wetted) radius; R is the radius of the entire spherical droplet and θ is the contact angle. The surface area can be expressed as

$$S(a,\theta)=\frac{2\pi a^2}{1+\cos\theta}$$