

# Study of Capillary Filling Dynamics in a Microtube

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A project report submitted in the partial fulfillment of the requirements for the degree of

**B. Tech**

**(Mechanical Engineering)**

*By*

**Swati Sahoo**

Roll no- 107MEo45

*Under the supervision of*

**Dr Ashok ku. Satapathy**

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NIT, Rourkela



**Department of Mechanical Engineering**

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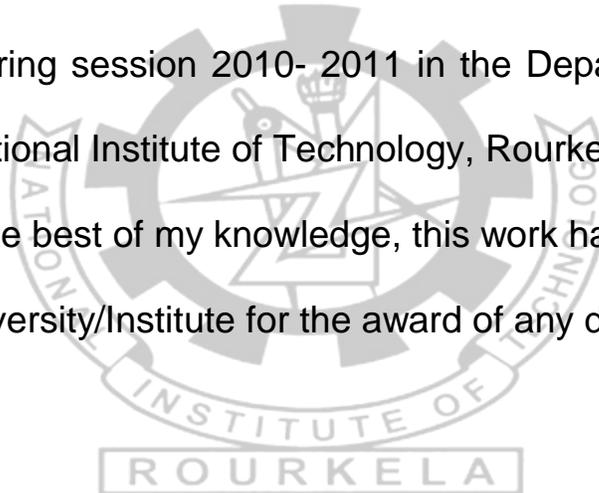
**May 2011**

# National Institute of Technology Rourkela

## C E R T I F I C A T E

This is to certify that the work in this thesis entitled “Study of Capillary filling dynamics in a microtube” by **Swati Sahoo**, has been carried out under my supervision in partial fulfillment of the requirements for the degree of **Bachelor of Technology** in ***Mechanical Engineering*** during session 2010- 2011 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of my knowledge, this work has not been submitted to any other University/Institute for the award of any degree or diploma.



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# ABSTRACT

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*Capillary filling dynamics in a microtube and different aspects of this type of flow has remained a long-acting problem in the last decade considering its numerous applications in various fields. In this study, an attempt has been made to study the influence of certain parameters on the equilibrium height attained by the liquid in the microtube. Lucas Washburn equation has been modified using the concept of phase change and vapour recoil and also accommodating the entrance effects in terms of added mass. The formulated governing equation was used to study the effect of parameters such as: phase change, different temperature difference across the interface and properties of the liquid numerically using MATLAB. Two different liquids water and ether has been used in the analysis. It was found that phase change by evaporation resulted in lowering of liquid rise. Also the oscillations in water were found to be damped more than those in ether. It was also seen that as capillary radius increases the temperature difference required to cause oscillations decreases and the oscillations take a longer time to decay. A larger contact angle implied a slower flow. The effect of a 'dynamic contact angle', as the fluid propagates inside the tube leads to a larger displacement at a given instant of time.*

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# CHAPTER 1

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## **INTRODUCTION**

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Microfluidics deals with the behavior of fluids in the sub millimeter range and its study requires different approach from the conventional ones used for macrofluidics though fundamental physics for both remains the same. Thus the differences and deviations between microfluidics and macrofluidics in various aspects have been studied widely. It is a multidisciplinary field including engineering, physics, chemistry, micro technology and biotechnology .Numerous applications of microfluidic devices in diverse fields like biomedical science, MEMS devices, lab on a chip technology, micro scale heat exchanger and micro heat pipes has made the study of the subject both relevant as well as significant.

Since the introduction of micro channel fluid flow as an effective means of cooling of electronic equipments, both experimental investigations and numerical predictions have been undertaken to study the microscale transport phenomena. Deviations of the results obtained by theoretical simulations from the experimental observation have resulted in modification of existing theories. Interpretation of findings and subsequent changes have led to a better understanding of various phenomena occurring in micro channel flow and of different factors affecting the flow characteristics.

The behavior of fluids at microscale[1] level differs from 'macrofluidic' behavior because surface tension, energy dissipation, and fluidic resistance become the dominating factors in microscale level.

Microfluidics studies how these factors change and how they can be exploited for new uses in various fields. Advances in microfluidics technology have revolutionized molecular biology procedures for enzymatic analysis , DNA analysis and proteomics.

It is used in the creation of microfluidic biochips which is used in clinical pathology and whose function is to integrate detection, sample pre-treatment and sample preparation on one chip. Biochips are mainly

used for immediate point-of-care diagnosis of diseases. In addition, microfluidics-based devices, capable of continuous sampling and real-time testing of air/water samples for biochemical toxins and other dangerous pathogens, can serve as an always-on "bio-smoke alarm" for early warning

Another application of microfluidics is micro heat pipe. Understanding the two-phase flow behavior and thin film evaporation in microchannels is the key to developing microchannel heat pipes for high-power microprocessors.

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# CHAPTER 2

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## LITERATURE SURVEY

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Peng et al. experimentally studied the flow of water in rectangular micro channels with hydraulic diameters in the range of 0.13 to 0.37 mm and aspect ratios from 0.3 to 1.0. The channels were machined on stainless steel substrate. According to the results the flow transition occurs at Reynolds number 200–700 which is very different from the conventional results. The transitional Reynolds number is observed to diminish with reductions in microchannel dimensions.

Pfahler et al. investigated the flow characteristics of different fluids in microchannels including nitrogen and helium gases, isopropyl liquid and silicone oil. The microchannels were fabricated on silicon wafer by etching method. It was observed that for the smaller microchannels, the test results deviated from the prediction of conventional theories.

Mohiuddin Mala et al. measured pressure gradients of water flow in microtubes with diameters in the range of 0.05 to 0.254 mm and the results indicated that for the larger microtubes with inner diameter above 150  $\mu\text{m}$ , the experimental results roughly matched the prediction of conventional theories. For the smaller microtubes, larger deviations were observed. With increase in  $Re$ , the differences between the experimental findings and the conventional theory predictions increased. This increasing difference was accounted for early transition from laminar to turbulent flow.

Stanley carried out some experiments of the single-phase and two phase liquid flow in microchannels machined on aluminum plate. The hydraulic diameters of the microchannels varied from 0.056 to 0.26 mm. Based on the experimental data, for water flow, it was stated that no transition occurred at any size of channels at any Reynolds numbers, from 2 to 10000.

Gas liquid two phase flow regimes were studied by different investigators and the various regimes as observed experimentally in case of microchannels were different from that of macroscale predictions.

Guy Ramon and Alexander Oron extended the Lucas-Washburn equation to account for the phase change and interfacial mass transfer due to phase change – evaporation or condensation.

The augmented equation developed contained contributions related to mass loss/gain and also an additional effective force, vapor recoil which occurs as a result of the velocity jump at the interface. Several properties of the system behavior were altered due to the phase change.

A number of studies were conducted in straight- walled ducts having a variety of cross sectional shapes. Ducts having unusual cross-sections or stream wise variations in cross section were considered. Among different geometries that were investigated, circular, trapezoidal and triangular cross sections were given more importance than others.

A generalized model for heat, mass transport and particle dynamics near an evaporating

meniscus was proposed by PAN and WANG. The evaporation on the meniscus, vapor diffusion in vapor/air domain, buoyant convection and particle dynamics were coupled together.

Deryagin et al [2] demonstrated liquid pressure reduction in the thin-film region due to disjoining pressure. Potash and Wayner [3] concluded that the variation of disjoining pressure and capillary pressure along the meniscus provides the necessary pressure gradient for liquid supply into the thin-film region. Wayner et al [4] discussed the effects of disjoining pressure on liquid supply as well as its role in suppressing evaporation. An augmented Young–Laplace equation was obtained for force balance on the thin film by introduction of a disjoining pressure. Schonberg et al.[5] investigated the thin film by ignoring  $P_c$ . Hallinan et al.[6] and DasGupta et al.[7] developed a fourth-order ordinary differential equation for solving the augmented Young–Laplace equation and obtained the thickness profile of the extended meniscus. The influence of superheat on the thin-film profile was discussed. Park et al. [8] proposed a mathematical model which included the vapor region and a slip boundary condition. It was concluded that the pressure gradient in the vapor region significantly affected the thin-film profile. Wee [9] discussed the effects of liquid polarity, slip boundary and thermo capillary effects on the thinfilm profile. The polarity effect was found to elongate the transition region while suppressing evaporation. Recently, binary liquids [10] have been found to induce a distillation-driven

capillary stress to counteract the thermo capillary stress, leading to an elongation in thin-film length. Atomistic simulations by Freund [11] showed that the thermal resistance at the solid-liquid interface is significant in very thin films. The menisci in more complex geometries have also been studied. Stephan and Busse [12] calculated the heat and mass transfer in the microregion and then combined the solution with the macroscopic meniscus within open grooves. Xu and Carey [13] conducted a combined analytical and experimental investigation on the liquid flow in V grooves and emphasized the importance of disjoining pressure on the overall heat transfer. Ma and Peterson [14] proposed a mathematical model for the evaporation heat transfer coefficient and temperature variation along the axial direction of a groove, which led to a better understanding of the axial heat transfer coefficient and temperature distribution on grooved surfaces. Morris [15] suggested a universal relationship between heat flow, contact angle, interface curvature, superheat and material properties, which can be extended to different geometries. Recently, thin-film evaporation in a microchannel was studied [16].

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# CHAPTER 3

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# THEORY

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One of the characteristic features of microfluidics is the dominance of surface effects due to the large surface to bulk ratio on the micrometer scale. A prominent class of surface effects are known as capillary effects particularly strong in microchannels having bore diameters equal to or less than about 50  $\mu\text{m}$ .

The capillary effects[17] can be understood by studying Gibbs free energy  $G$ , the energy of systems where the thermodynamic control parameters are pressure  $p$ , temperature  $T$ , and particle number  $N$ . In particular we shall be interested in equilibrium or quasi-equilibrium situations, where the Gibbs free energy is at a minimum.

## Surface Tension:

Surface tension is a property that relates to the surface or interfaces and depends on the state of the substance on both sides of the interface.

The surface tension of an interface is defined as the Gibbs free energy per area for fixed pressure and temperature,

$$\Upsilon = \left( \frac{\partial G}{\partial A} \right)_{p, t} \quad (1)$$

A microscopic model for surface tension between a liquid and a gas is sketched in fig.2.

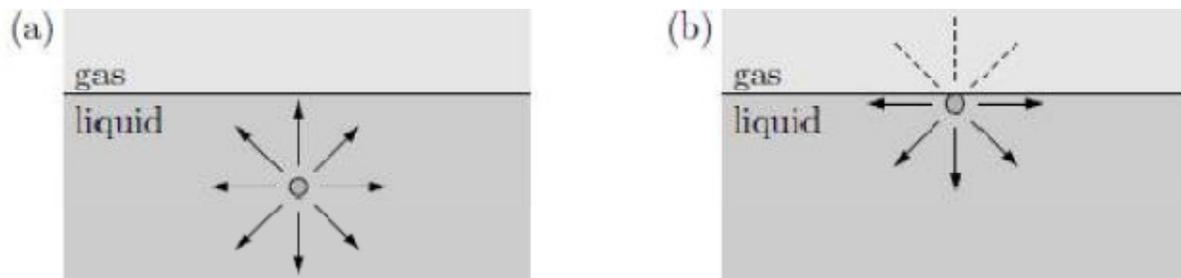


Fig 2: The origin of surface tension for a liquid-gas interface. (a) A molecule in the bulk of the liquid forms chemical bonds (arrows) with the neighboring molecules surrounding it. (b) A molecule at the surface of the liquid misses the chemical bonds in the direction of the surface (dashed lines).

Consequently, the energy of surface molecules is higher than that of bulk molecules, and the formation of such an interface costs energy.

A molecule in the bulk forms chemical bonds with the neighboring thus gaining a certain amount of binding energy. A molecule at the surface cannot form as many bonds since there are almost no molecules in the gas. This lack of chemical bonds results in a higher energy for the surface molecules. This is exactly the surface tension: it costs energy to form a surface. Using this model it is easy to estimate the order of magnitude of surface tension for a liquid-gas interface.

Surface tension can also be interpreted as a force per length having the unit  $\text{N/m} = \text{J/m}^2$ . This can be seen by considering a flat rectangular surface of length  $L$  and width  $w$ . If we keep the width constant while stretching the surface the amount  $\Delta L$  from  $L$  to  $L + \Delta L$ , an external force  $F$  must act to supply the work  $\Delta G = F\Delta L$  necessary for creating the new surface area  $w\Delta L$  containing the energy  $\Delta G = \gamma w\Delta L$

$$\frac{F}{w} = \frac{1}{w} \frac{\Delta G}{\Delta L} = \frac{1}{w} \frac{\Upsilon w \Delta L}{\Delta L} = \Upsilon \quad (2)$$

### **The Young Laplace pressure across curved interfaces:**

An important consequence of a non-zero surface tension is the presence of the so-called Young Laplace pressure drop ( $\Delta p_{\text{surf}}$ ) across a curved interface in thermodynamic equilibrium. If we disregard any influence of gravity there will only be two contributions to the change  $\Delta G$  of the free energy of the system: an increase in surface energy  $G_{\text{surf}}$  due to an increased area, and a decrease in pressure-volume energy  $G_{pV}$  due to the increase in volume. It is important to note the sign convention used here: the pressure is highest in the convex medium, i.e., the medium in which the centre of curvature lies.

### **Contact angle:**

Another fundamental concept in the theory of surface effects in microfluidics is the contact angle that appears at the contact line between three different phases, typically the solid wall of a channel and two immiscible fluids inside that channel. The two concepts, contact angle and surface tension, allow for understanding the capillary forces that act on two-fluid flows inside microchannels in lab-on-a-chip systems.

### **Definition of the contact angle**

The contact angle  $\theta$  is defined as the angle between the solid-liquid and the liquid-gas interface at the contact line where three immiscible phases meet, as illustrated in Fig. 3(a).

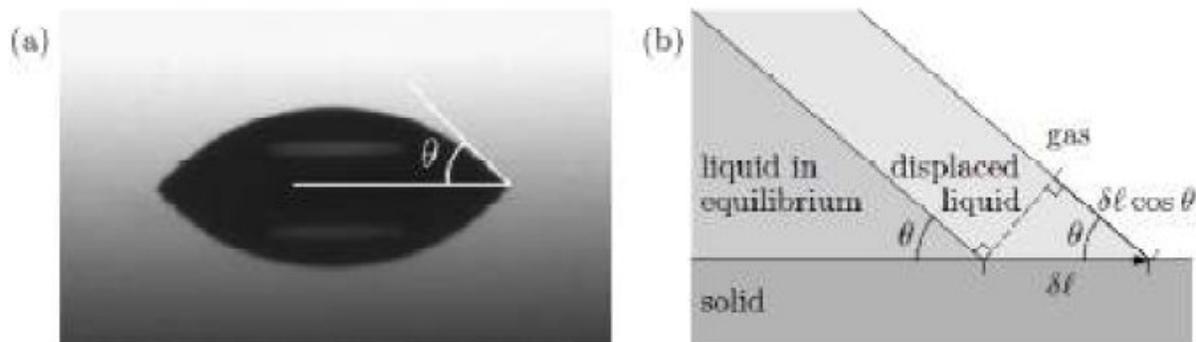


Fig 3 (a) The contact angle  $\theta$  is defined as the angle between the solid-liquid and the liquid-gas interface at the contact line. (b) A sketch of the small displacement  $\delta l$  of the contact line away from the equilibrium position. The change of the interface areas are proportional to  $+\delta l$ ,  $+\delta l \cos \theta$ , and  $-\delta l$  for the solid-liquid, liquid-gas, and solid-gas interface, respectively

In equilibrium  $\theta$  is determined by the three surface tensions  $\gamma_{sl}$ ,  $\gamma_{lg}$ , and  $\gamma_{sg}$  for the solid-liquid, liquid-gas and solid-gas interfaces by Young's equation to be discussed in the following subsection. Whereas the contact angle is well-defined in equilibrium it turns out to depend in a complicated way on the dynamical state of a moving contact line. One can for example observe that the contact angle at the advancing edge of a moving liquid drop on a substrate is different from that at the receding edge.

### **Young's equation; surface tensions and contact angle**

To derive an expression for the contact angle in equilibrium we again use the free energy minimum condition. We consider the system sketched in Fig. 3(b), where in equilibrium a flat interface between a liquid and a gas forms the angle  $\theta$  with the surface of a solid substrate. Imagine now that the liquid-gas interface is tilted an infinitesimal angle around an axis parallel to the contact line and placed far away from the substrate interface. As a result the contact line is

moved the distance  $\delta l$  while keeping the contact angle  $\theta$ . To order  $\delta l$  the only change in free energy comes from the changes in interface areas near the contact line. It is easy to see from Fig. 3(b) that the changes of the interface areas are proportional to  $+\delta l$ ,  $+\delta l \cos \theta$ , and  $-\delta l$  for the solid-liquid, liquid-gas, and solid-gas interface, respectively. The energy balance at the interface gives,

$$\cos \theta = \frac{\Upsilon_{sg} - \Upsilon_{sl}}{\Upsilon_{lg}} \quad (3)$$

### **Capillary rise:**

In the previous discussion gravity was neglected, an approximation that turns out to be very good in many cases for various microfluidic systems. The equilibrium shape of any liquid will be determined by minimizing the free energy  $G$  consisting of the surface energy and the gravitational potential energy of the bulk, with constant volume constraint. The equilibrium shape for a free liquid drop in zero gravity is a sphere, since the sphere has the minimal area for a given volume. Gravity does not influence the shape of free water-air interfaces in microfluidic systems of sizes  $a$  well below 1 mm. This insight can be used to analyze the so-called capillary rise that happens in narrow, vertically standing microchannels. The shape problem is governed by a characteristic length, the so-called capillary length  $l_{cap}$ ,

$$l_{cap} = \sqrt{\frac{\Upsilon}{\rho g}} \quad (4)$$

Capillary rise can be observed as sketched in Fig. 4(b) by dipping one end of a narrow open ended tube into some liquid. The liquid will rise inside the tube until it reaches equilibrium at some height  $H$  above the zero level  $z = 0$  defined as the flat liquid level far away from the tube.

The task is to determine  $H$ .

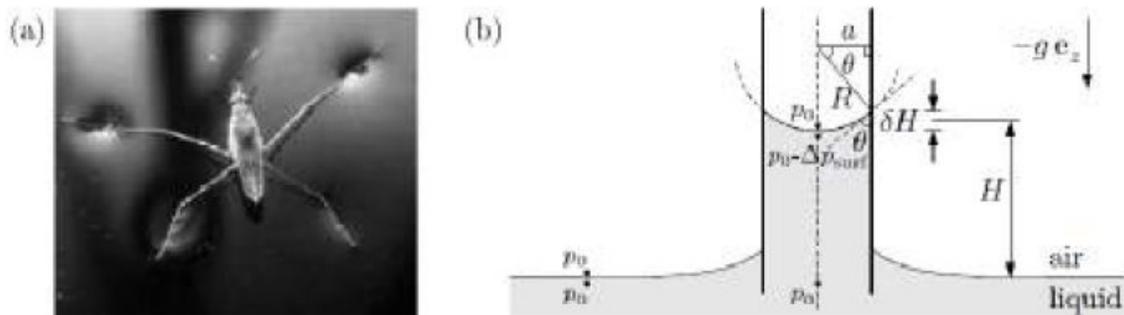


Figure 4(a): The importance of surface tension for microsystems illustrated by an insect able to walk on water. The gravitational force is balanced by the surface tension of the water-air interface. (b) Capillary rise in a vertically standing cylindrical microchannel.

Systems with contact angles  $\theta < 90^\circ$  are called hydrophilic (water loving) while those with  $\theta > 90^\circ$  are called hydrophobic (water fearing).

### **Capillary rise height:**

For simplicity we consider a vertically placed micro-tube with a circular cross section of radius  $a \ll l_{cap}$ . The contact angle of the tube-liquid-air system is denoted  $\theta$  and the surface tension of the liquid-air interface is called  $\Upsilon$ . Because  $a \ll l_{cap}$  and because the tube is circular the

liquid-air surface of minimal energy inside the tube will be spherical. Thus the two radii of curvature are identical, and from the geometry of Fig. 4(b) we find,

$$R_1 = R_2 = R = a/\cos \theta \quad (5)$$

Because the liquid-air interface is curved, a Young Laplace pressure drop  $\Delta p_{\text{surf}}$  will be present across it.

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# CHAPTER 4

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## THEORETICAL FORMULATION

For a microtube of radius  $R$ , with instantaneous axial length (averaged over the cross section) occupied by the fluid as  $l$ , the governing equation of fluid motion can be written as:

$$\frac{d}{dt} \left( (M_a + \rho\pi R^2 l) \frac{dl}{dt} \right) = P\sigma \cos \theta - F_D \quad (6)$$

where  $\rho$  is density of the fluid,  $P$  is the wetted perimeter,  $\sigma$  is the surface tension coefficient,  $\theta$  is the contact angle, and  $F_D$  is the viscous drag force. Eqn. (6) represents the Newtonian equation of motion of the liquid column in the capillary. The first term in the right hand side of eqn. (6) represents the surface tension force and the second term represents a viscous drag force. The term  $M_a$  in eqn. (6) is a so-called added mass. In fluid mechanics, added mass or virtual mass is the inertia added to a system because an accelerating or decelerating body must move some volume of surrounding fluid as it moves through it, since the object and fluid cannot occupy the same physical space simultaneously:

$$\text{Added mass} \quad m_0 = \frac{3\rho\pi R^3}{8}$$

In case of phase change, another force comes into play. This is called vapor recoil. When the liquid changes to vapor at the liquid-vapor interface, due to the large difference in the densities, the velocity increases considerably to keep the mass flux continuous at the interface. The kinematic boundary condition at the interface requires that

$u = \left( \frac{dl}{dt} + \frac{j}{\rho} \right)$  where  $j$  is the interfacial mass flux due to evaporation. Hence the governing equation of fluid motion can be written as:-

$$\frac{d}{dt} \left( (M_a + \rho \pi R^2 l) \left( \frac{dl}{dt} + \frac{j}{\rho} \right) \right) = P \sigma \cos \theta - F_D - \frac{j^2}{\rho_v} \quad (7)$$

$$\text{Vapor recoil} = \frac{j^2}{\rho_v}$$

The resulting mass flux[18] may be approximated using kinetic theory which in linearized form reads;

$j = k * (t_l - t_v)$  where  $t_l, t_v$  denotes the temperature at the interface and the vapour respectively

$$k = \frac{\alpha \rho_v L}{T_v^{3/2}} \left( \frac{M_w}{2\pi R_g} \right)^{1/2} \quad (8)$$

Here  $R_g$  is the universal gas constant,  $M_w$  is the molecular mass of the liquid, and  $\alpha$  is the accommodation coefficient, taken here as unity.

### Governing equation of the capillary filling in the microtube :-

Thus, the governing equation of the capillary filling in the microtube with temperature difference across the interface is:-

$$\frac{d^2l}{dt^2} = \left( \frac{2\sigma}{R} - g - \left( \frac{8\mu l_1}{R^2} + \rho\pi R^2 l_2 \right) \left( l_2 + \frac{j}{\rho} \right) - \left( \frac{j^2}{\rho v} \right) \right) / (\rho\pi R^2 \left( \frac{3R}{8} + l_1 \right)) \quad (9)$$

The Radius of curvature is a function of contact angle  $\theta$  which in turn depends on the exact properties of the fluids and the solids in which they are in contact:

$$R = \frac{a}{\cos\theta} \quad (10)$$

Hence the equation becomes:-

$$\frac{d^2l}{dt^2} = \left( \frac{2\sigma \cos\theta}{a} - g - \left( \frac{8\mu l_1 \cos^2\theta}{a^2} + \rho\pi \left( \frac{a}{\cos\theta} \right)^2 l_2 \right) \left( l_2 + \frac{j}{\rho} \right) - \left( \frac{j^2}{\rho v} \right) \right) / (\rho\pi \left( \frac{a}{\cos\theta} \right)^2 \left( \frac{3a}{8\cos\theta} + l_1 \right)) \quad (11)$$

The angle used in the above case is static contact angle.

### Concept of dynamic contact angle:-

The capillary effect in the microtube results in formation of a tri-junction due to interaction of solid-liquid, liquid-gas and solid-gas interface. In order to model the moving contact lines, one needs to assess the physical phenomena influencing the capillary action. The contact angle is not static but is in fact dynamic as it depends on velocity.

The apparent dynamic contact angle  $\theta_d$  that the liquid forms with the solid surface is closely

described by a universal scaling relationship[19] at low speeds , known as Tanner ' s law:-

$$\theta \propto Ca^{1/3}$$

$$\text{where } Ca = \frac{\mu u}{\sigma} \quad \mu = \text{viscosity} \quad u = \text{velocity of contact line} \quad (12)$$

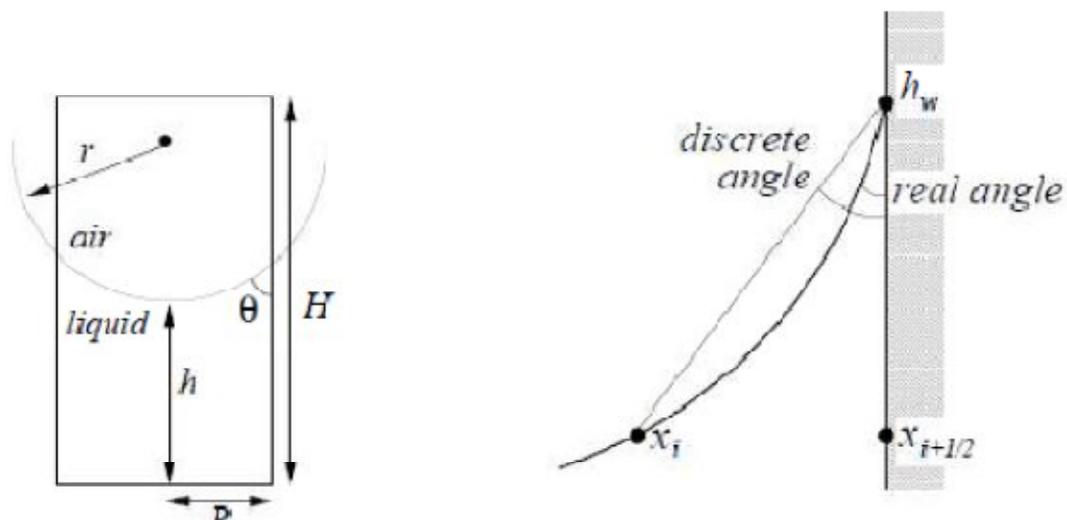


Fig 5:-In equilibrium the meniscus is shaped spherical and the discrete contact angle is larger than in theory

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## CHAPTER 5

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## Results and discussion

Problem data (for water):-

Capillary radius	0.5mm
Fluid density ( $\rho$ )	1000 kg/ m <sup>3</sup>
Surface tension coefficient ( $\sigma$ )	0.072 N/m
Coefficient of viscosity ( $\mu$ )	0.001
Static Contact angle( $\theta$ )	30 deg
Latent heat of vaporization (L)	2360kJ/kg
Mw	0.018(kg/mol)

Ether

Capillary radius	0.2mm
Surface tension( $\sigma$ )	0.016N/m
Density( $\rho$ )	708 kg/ m <sup>3</sup>
Viscosity( $\mu$ )	2.23e-4
Static Contact Angle( $\theta$ )	0
Vapour Density( $\rho_v$ )	3.12 kg/m <sup>3</sup>
Latent heat of vaporization (L)	377KJ/kg
Mw	0.074(kg/mol)

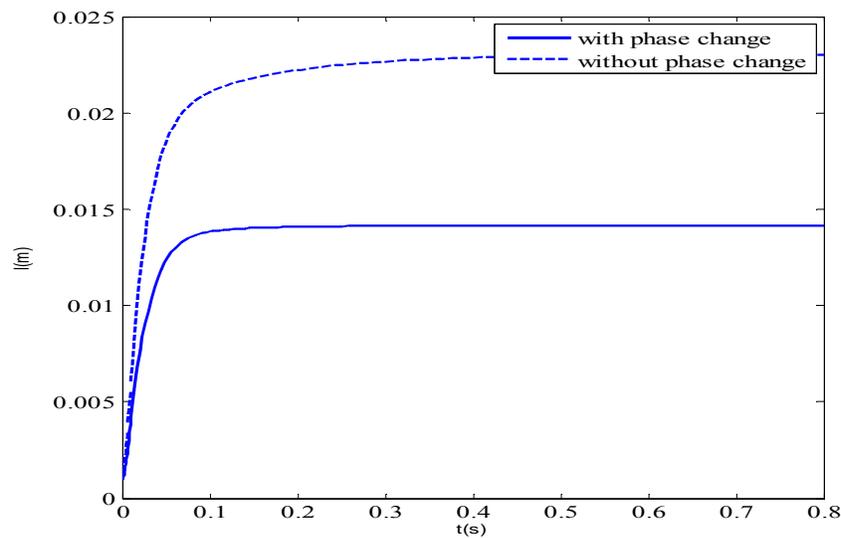


Fig-6 Time course of displacement of fluid into the tube with and without phase change consideration

Fig-6 depicts advancement of the meniscus in the micro tube as a function of time. It can be observed from Fig. 6 that the displacement decreases if there is phase change.

The effect of phase change is induced because of temperature difference between liquid and the vapor in the tube. This results in vapor recoil as discussed in chapter 4. As is seen in equation (7), vapor recoil always induces a pressure in the negative direction, thus opposing the flow. Thus the motion of the interface will be slower than with no phase change.

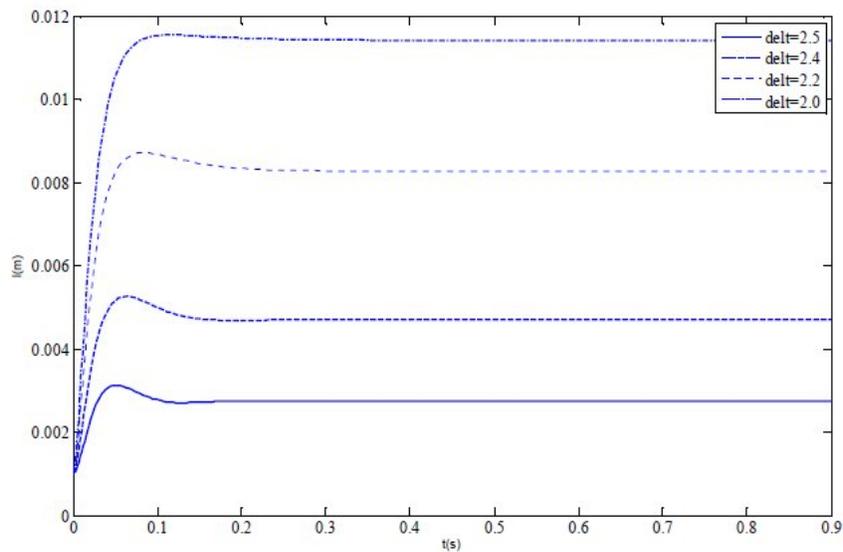


Fig 7:-Time course of displacement of fluid into the tube for ether for different temperature differences across the interface. ( $\Delta T = T_I - T_v$ ; where  $T_I$  is the temperature of the interface and  $T_v$  is the temperature of the vapour)

The effect of temperature difference which induces phase change is apparent as it affects the frequency and amplitude of oscillations. Fig7 depicts that as the temperature difference across the interface increases, there is a decrease in the displacement of the meniscus. This indicates that due to increase in temperature difference, evaporation increases, thus the vapour recoil term ( $j > 0$ ) increases which opposes the capillary flow.

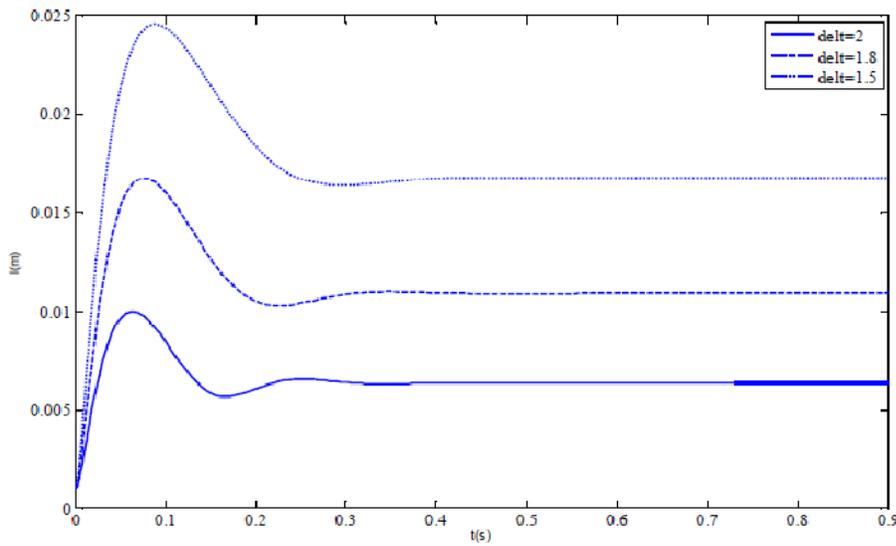


Fig-8 :-Time course of displacement of fluid into the tube for water for different temperature differences across the interface.

It is seen that ether oscillates faster than water due to the lower surface tension of ether and the oscillations in case of water decays faster than ether possibly due to the higher viscosity of water which causes higher damping effect.

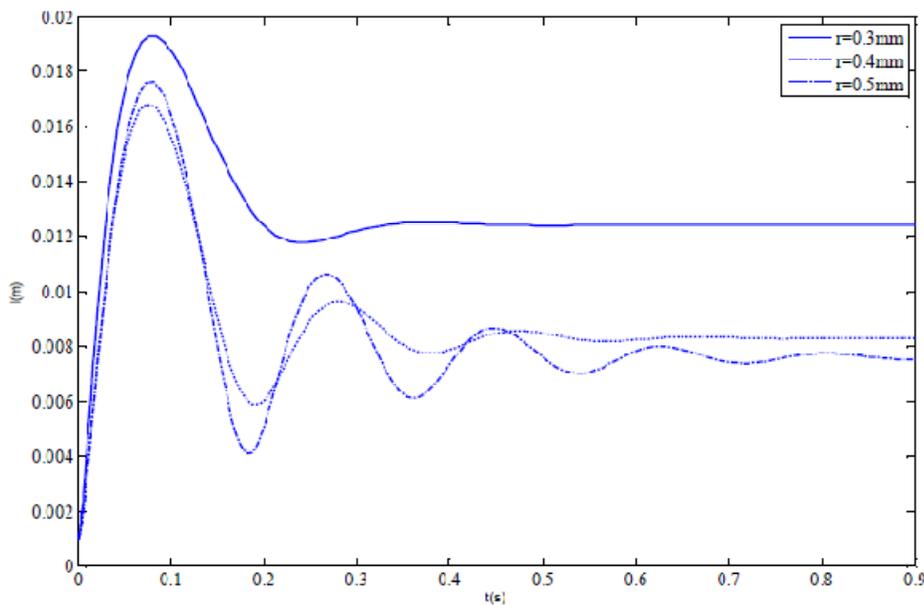


Fig-9: Time course of displacement of fluid into the channel for ether for different capillary radius  $R$  of the microtube.

This shows that as radius increases the displacement decreases. This is also seen in the governing equation (9) which shows that displacement is inversely proportional to radius. As radius increases, the driving force which is the surface tension reduces, hence it's motion is retarded.

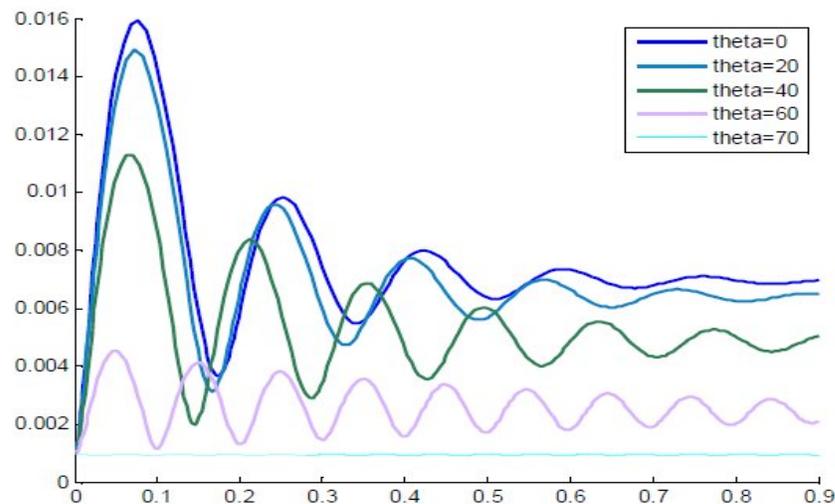


Fig. 10 Effect of contact angle in the time course of fluid front flowing into a microtube

Effect of Contact Angle:-Figure 10 shows the effect of the contact angle when fluid flows in a microtube.

A larger contact angle implies a slower flow.

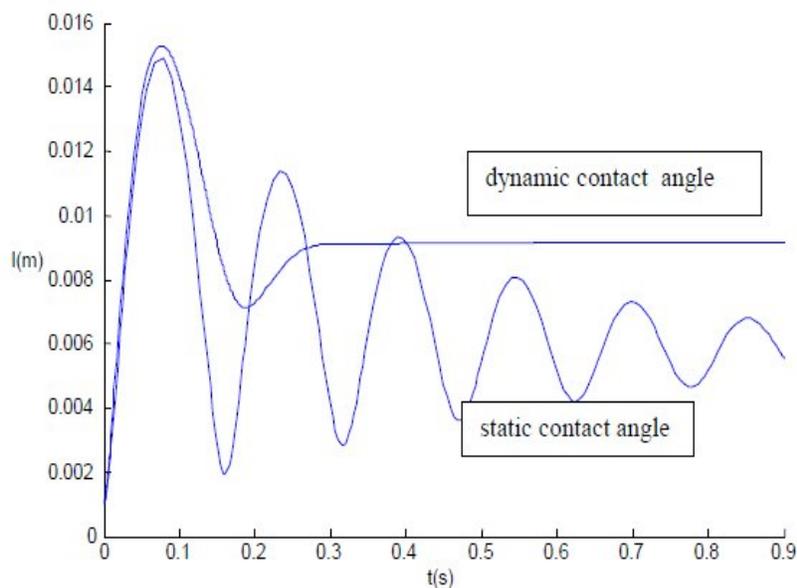


Fig.11:-Time course of displacement of fluid into the microtube for dynamic contact angle and static contact angle.

Fig. 11 depicts the effect of a 'dynamic contact angle, as the fluid propagates inside the tube. Since velocity decreases as time increases hence according to tanner's law, capillary number also decreases and hence consequently apparent angle also decreases. But since surface tension force depends on cosine of the angle, hence displacement increases with time in comparison with static contact angle.

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# CHAPTER 6

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## CONCLUSIONS

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The following conclusions were drawn from the results analyzed in the previous chapter

- There is a decrease in displacement due to evaporation which is due to the increase vapor pressure on the liquid vapor interface.
- The system is found to always possess a stable equilibrium state when the temperature jump across the interface is confined to a certain range
- To achieve a particular equilibrium height during phase change, a higher value of temperature difference is required for water than for ether due to higher density of water and consequently high mass transfer.
- Oscillations decay faster in water due to its higher viscosity and higher damping coefficient than ether, other factors remaining constant.
- Ether oscillates faster than water and due to lower surface tension it has smaller amplitude of motion.
- Higher static angles implies slower flow.
- It's also found that as temperature difference increases, the displacement decreases due to increase in vapor recoil.
- Dynamic contact angle leads to a larger displacement at a given instant of time.
- Higher capillary radius means driving force i.e. surface tension is less, hence displacement reduces.
- The range of applicability of the present theory is limited in terms of the rate of phase change.

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## REFERENCES

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