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NUMERICAL STUDY OF CORNER MENISCUS RISE IN THE INTERSTICE OF CIRCULAR CAPILLARIES

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ABSTRACT

The capillary rise phenomenon is studied by conducting a numerical simulation for the liquid rise inside the interstices. The interstice geometry is formed by combining three circular tubes. Due to the increase in the surface area within the interstices, the surface tension force is elevated, resulting in a higher rate of rise, which can find applications in various industrial contexts. We have utilized a Volume of Fluid (VoF) phase-fraction-based interface capturing approach. Using a surface tension model, we modified the OpenFOAM solver by incorporating the Kistler dynamic contact angle model. The fluid is considered incompressible and isothermal. The diameters of the micro capillaries are 300 μm, 400 μm, and 500 μm, with a length of 10 cm. Two different regimes are observed during the corner rise: the inertial regime, where inertial forces are dominant, and the gravitational regime during later time periods. We have verified that the numerical results show the corner height rise varying as a power of ¾ of time, which is in good agreement with the theory developed for the inertial period.

KEYWORDS
Interstice capillary, dynamic contact angle (DCA), capillary rise, corner meniscus, inertial regime, gravitational regime.

INTRODUCTION

Capillarity is a significant phenomenon which can be seen in various places and has applications in textile industries, ink-jet printing, oil and natural gas industries for its extraction. It can be observed in natural processes also like flow though porous media such as in soils, the suction of water through roots and leaves of a tree etc. The driving force in the capillary action is the surface tension force which acts at the inter-facial length of triple contact line i.e. interface where solid, liquid and gaseous states come in contact. The capillary rise was first described by Lucas-Washburn and they derived the expression for capillary bulk meniscus rise in circular capillaries. The rise inside the square capillary, which has 90° corner angle, was investigated by Dong et. al.[1] They developed a theory for the corner rise inside square capillary tube. Winjhrost et. al.[2] performed the experiments in a circular and square cross section capillaries and observed the effects of surfactants mixed in liquid. Numerical study was carried out by Gurumurthy et. al [3]. They used the VoF model method for simulations with adaptive mesh for their simulations. Gurumurthy et. al.[4] used static contact angle model and showed the effects of viscosity on the liquid rise in a square capillary.

GOVERNING EQUATIONS

The two-phase flow is modelled using the Volume-of-Fluid (VOF) method. The basic idea in the VOF method is to treat the two incompressible, immiscible fluids as one mixed fluid which includes both the fluids. This idea is achieved by defining a mixed fluid using an phase function α, which represents the volume fraction of the denser fluid in a cell. A cell with $\alpha = 1$ is completely filled with liquid, and $\alpha = 0$ with gas. Values in-between $(0 < \alpha < 1)$ indicates the presence of the liquid-gas interface in the cell. Under incompressible and isothermal conditions, the governing equations are:

$$\nabla \cdot U = 0 \tag{1}$$

$$\rho \left(\frac{\partial U}{\partial t} + U \cdot \nabla U \right) = -\nabla P + \nabla \cdot \tau + \rho g + F_\sigma \tag{2}$$

where U is the represents the velocity field, P the pressure field, and g is the gravitational field. Here, the term F_σ represents the volumetric form of the capillary force. The properties (ρ, μ) of this mixed fluid are calculated from the volume weighted averages of the individual phases as given below:

$$\phi = \alpha\phi_1 + (1\alpha)\phi_2 \tag{3}$$

where, ϕ is the phase fraction value in a cell. The distribution of the indicator function α is governed by the advection equation,

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha U) = 0 \tag{4}$$

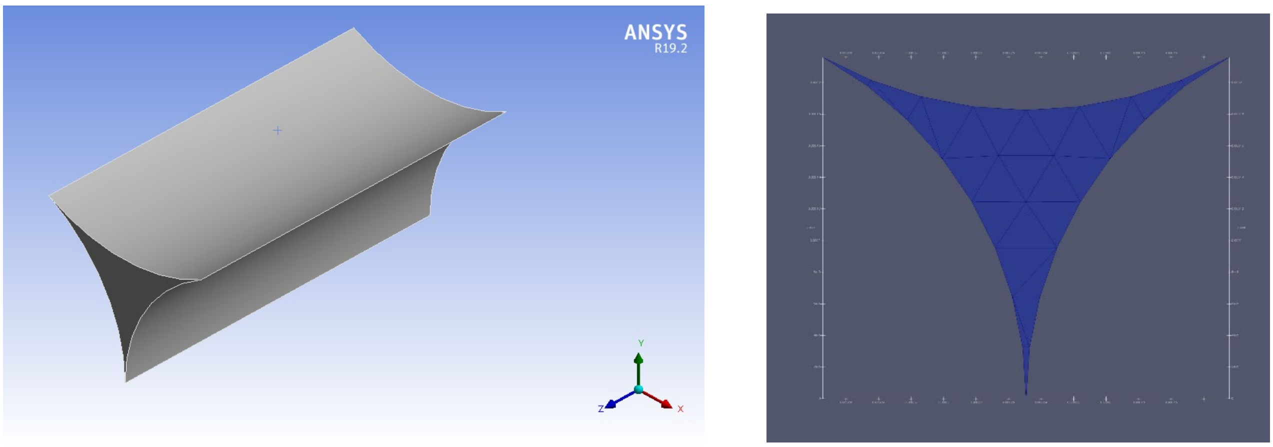
The volumetric form of the capillary force is written as

$$F_\sigma = \sigma\kappa\nabla\alpha \tag{5}$$

where, κ is the curvature of the liquid-gas interface. The gradient term $\nabla\alpha$ in above equation ensures that the capillary force acts only in the interface region.

GEOMETRY AND MESHING

A 3-D interstice geometry is created and mesh is generated in ANSYS Fluent 19.2 and the simulations were run in OpenFOAM platform using HPCE.



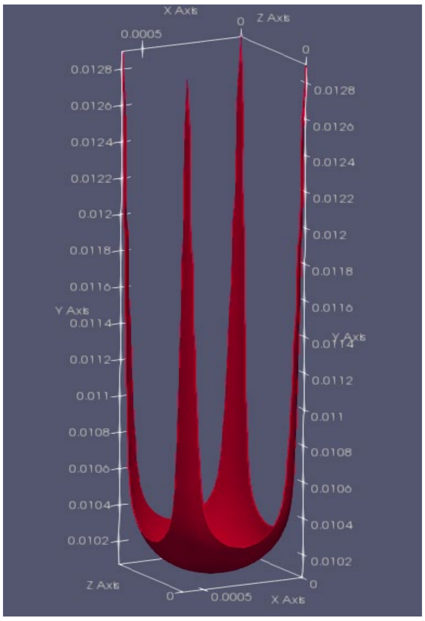
(a) (b)

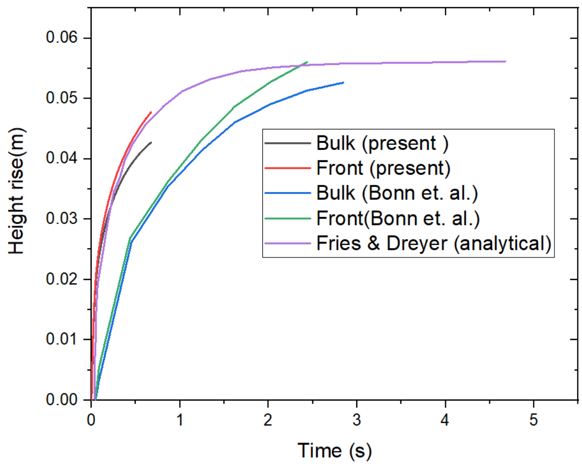
Fig 1: (a) 3-D geometry of interstice (b) Cross sectional view of interstice

We used the PIMPLE scheme. The time step size used is 10^{-6} such that the Courant number doesn't go beyond one. The maximum value for interface courant number is 1. The top of the interstice has atmospheric boundary conditions. No-slip condition is implemented on the walls and at the bottom, zero fluid velocity is given.

VALIDATION

A square capillary geometry of width 0.6 mm is created. A static contact angle is used as 15° for the validation case in a square capillary.



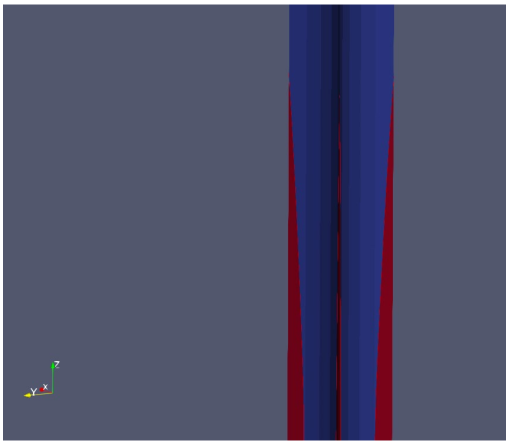


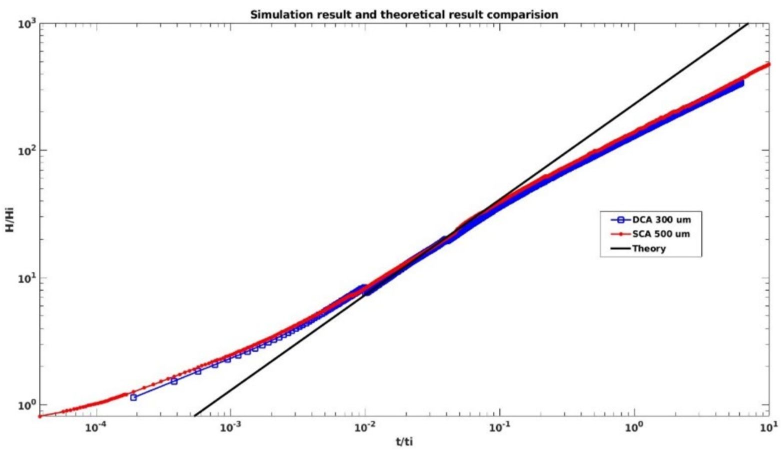
(a) (b)

Fig 2 : Corner rise of Square capillary at t = 3.35 s. (b) Height vs time plot for square capillary

RESULTS

Below are the figures that shows the corner rise in 3 corners inside the interstice. For DCA simulations, 10° advancing and 5° receding contact angle is used for glass and water combination.





(a) (b)

Fig. 3 (a) corner meniscus in interstice (b) Dimensionless Corner height vs dimensionless time plot.

The red color shows the liquid in figure (a). The figure (b) is the plot between dimensionless Height vs dimensionless time for 300 µm and 500 µm which is in good agreement with theory which shows height varies with time as $t^{3/4}$.

REFERENCES

[1]M. Dong, I. Chatzis, **The imbibition and flow of a wetting liquid along the corners of a square capillary tube**, *J.of Colloid and Interface Science*, 1995; 172 : 278–288.

[2] Rozeline Wijnhorst, Thijs Christiaan de Goede, Daniel Bonn, Noushine Shahidzadeh, **Surfactant Effects on the Dynamics of Capillary Rise and Finger Formation in Square Capillaries,** *Langmuir*, 2020; 36:13784–13792

[3]Vignesh Thammanna Gurumurthy, Daniel Rettenmaier, Ilia V.Roisman, Cameron Tropea, Stephen Garoff, **Computations of spontaneous rise of a rivulet in a corner of a vertical square capillary**, *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 2018; 544: 118–126.

[4]Vignesh Thammanna Gurumurthy, Ilia V.Roisman, Cameron Tropea, Stephen Garoff, **Spontaneous rise in open rectangular channels under gravity**, *Journal of Colloid and Interface Science,* 2018, 527:151–158