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**PHOENICS Case Study: PHOENICS Users**

# Numerical simulation of single droplet dynamics in three - phase flows using PHOENICS VOF 2022

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## Introduction

In this article the PHOENICS 3-phase VOF option is verified by its application to the liquid-lens and droplet-levitation cases reported by Tofighi and Yildiz (2013). These workers produced numerical results by using the Smoothed-Particle-Hydrodynamics (SPH) CFD method, which tracks free surfaces directly. The first test case involves the elongation of a circular droplet encompassed between two immiscible fluid layers, and the second case considers the levitation of a circular droplet initially at rest between two layers of immiscible fluids.

The implementation of the 3-phase VOF option in PHOENICS 2022 and its applications to rising-bubble cases was reported on in an earlier article by Ouazzani and Ludwig (2022). The purpose of this study is to demonstrate that this option behaves correctly for the three-phase test cases of Tofighi and Yildiz (2013), both with and without surface tension. The scope of the present study doesn't extend to investigating whether the PHOENICS results, or those published in the literature, are the most accurate.

## Liquid-Lens Application

This section presents the results obtained for the liquid-lens test case, and then compares them with the numerical results of Tofighi et al (2013). These workers, in turn, compared their results against the analytical solution for the equilibrium-lens diameter. The existence of an analytical solution means that this test case is very well suited for testing the accuracy of the proposed modelling scheme for three-phase flows. The computational domain for every simulation is taken to be a square with a side length of *l*. For test cases $V_1$, $V_2$ and $V_5$, Table 1 compares the PHOENICS results with those of Tofighi et al (2013) for the listed surface-tension coefficients.

| # | Surface tension $\sigma^{13}/\sigma^{12}$ ($\sigma^{13}=\sigma^{23}$) | Equilibrium lens diameter $d_a$ | Ratio $d_0/d_a$ ($d_0$ initial diameter of lens) | Ratio $d_f/d_a$ ($d_f$ final diameter of lens) **PHOENICS** | Ratio $d_f/d_a$ ($d_f$ final diameter of lens) **Tofighi** |
|---|---|---|---|---|---|
| $V_1$ | 0.8 | 0.4601 | 0.6527 | 0.9889 | 0.9939 |
| $V_3$ | 1.0 | 0.4159 | 0.7220 | 0.9890 | 0.9856 |
| $V_5$ | 1.2 | 0.3919 | 0.7663 | 0.9950 | 0.9865 |

**Table 1: Liquid Lens: Simulation parameters and results**

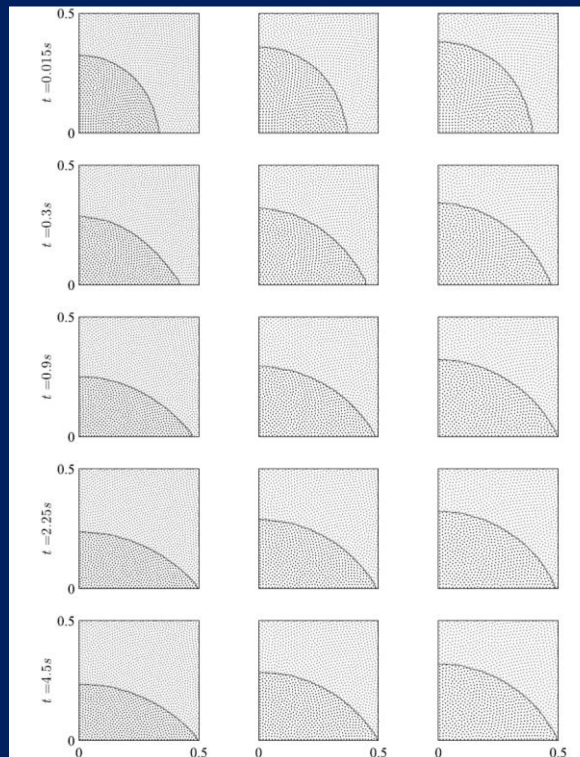
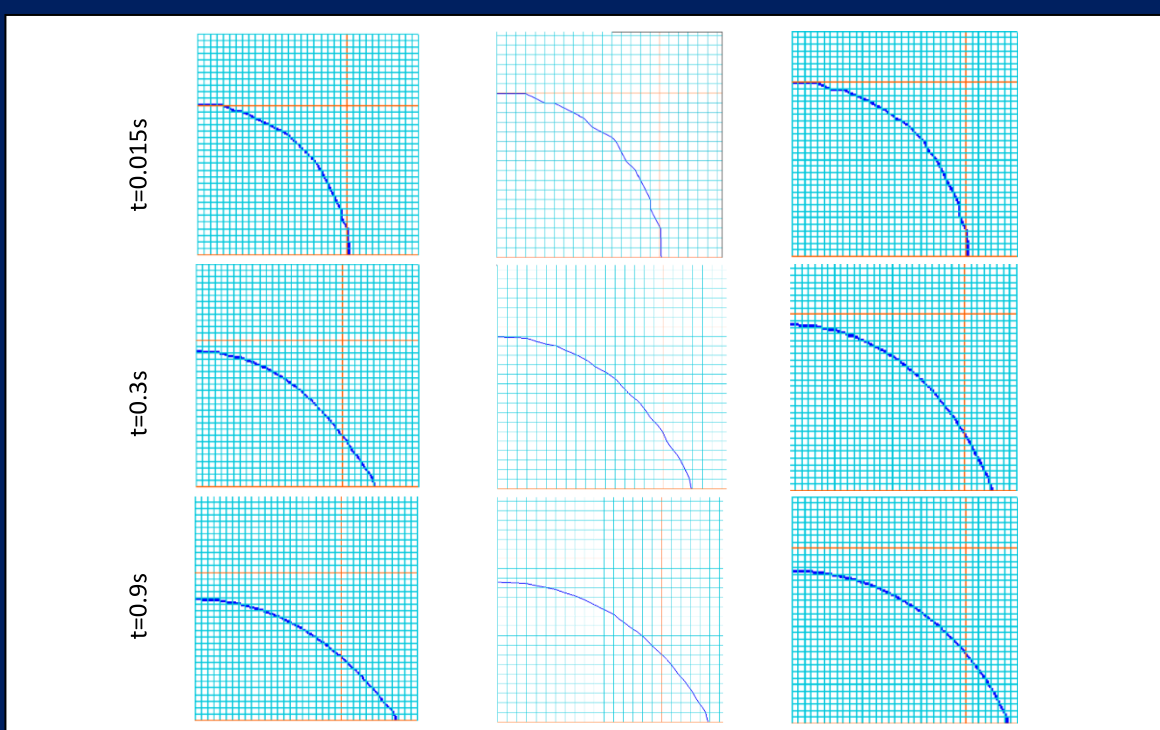



**Figure. 1. Tofighi & al (2013): Time snapshots of particle position and droplet boundary (0.5 level contour of colour function for droplet, phase 3). Both x and y axes are normalised with each test case's respective analytic equilibrium diameter. Only the top right quarter has been shown for brevity. Left column: case $V_1$; middle column: case $V_3$; right column: case $V_5$.**



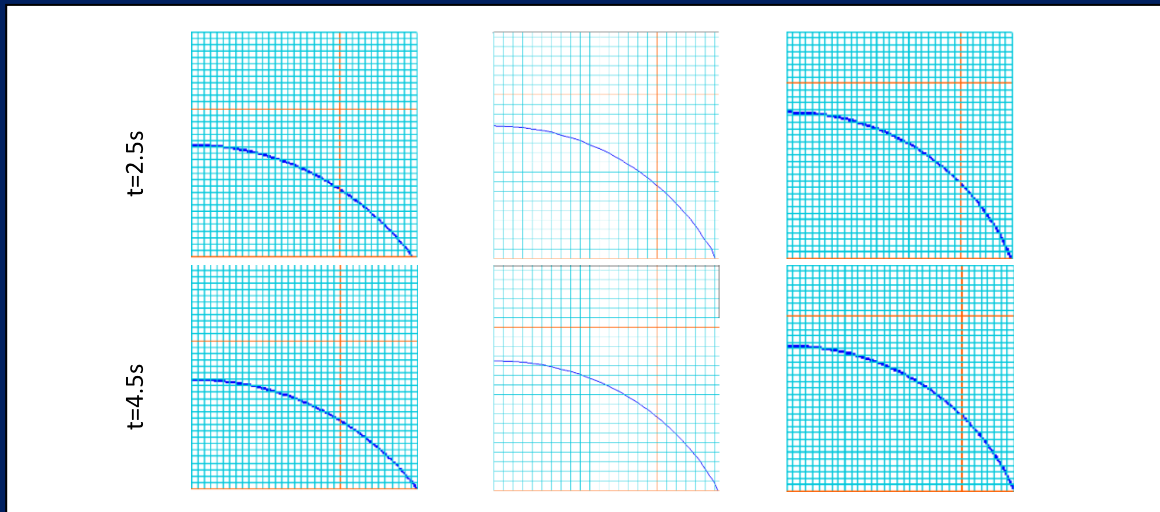



**Figure. 2. PHOENICS: Time snapshots of particle position and droplet boundary (0.5 level contour of color function for droplet, phase 3). Both x and y axes are normalised with each test case's respective analytic equilibrium diameter. Only the top right quarter has been shown for brevity. Left column: case $V_1$; middle column: case $V_3$; right column: case $V_5$.**

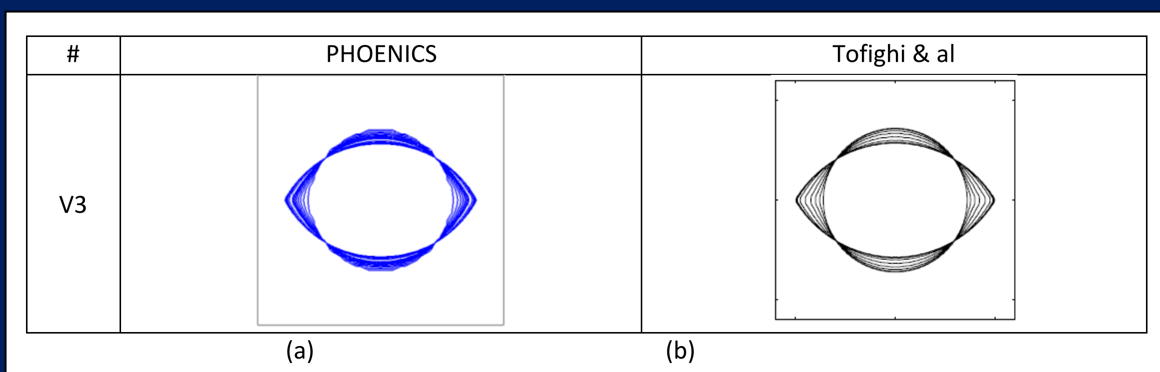



**Figure 3. Time snapshots of all phase boundaries (0.5 level contour of colour function of each phase) for case $V_3$. Droplet, phase 3. (a) PHOENICS results, (b) Tofighi et al results**.

## Droplet-levitation Application

This section presents the results of the levitation of a circular droplet, which is initially at rest between two layers of immiscible fluids. Droplet levitation presents a more challenging and dynamic problem to test the capabilities of the proposed three-phase formulation. In this case the droplet breaks free of the bottom surface, and then rises solely because of surface tension forces. No other body forces are present in the system.

Figure 4 provides time snapshots of droplet levitation for all three test cases considered here. These cases use different surface-tension coefficients, as shown in Table 2, which also provides a comparison of the maximum average vertical velocities predicted by PHOENICS and the SPH method of Tofighi et al. The average velocity, $u_{av} = \sum u_j/J$, where the summation is from j=1 to j=J.

As the droplet starts to break off from the bottom surface, Figure 4 shows that it experiences a deformation as a result of the surface tension force exerted. The ratio of $\sigma^{23}/\sigma^{13}$ has an important implication here because it directly influences the initial amount of the force exerted. This is better observable if the average velocity of all particles belonging to phase 3, J, is investigated. Figure 5 shows average vertical droplet velocity, $u_{av}$,y, for all the test cases. It is evident that larger surface tension ratios give rise to larger initial vertical velocity values.

| Test case | $\sigma^{23}/\sigma^{13}$ ($\sigma^{12} = \sigma^{13}$) | Maximum $u_{av,y}$ PHOENICS | Maximum $u_{av,y}$ Tofighi et al |
|---|---|---|---|
| L1 | 2.5 | 0.162 | 0.173 |
| L2 | 5 | 0.43 | 0.4186 |
| L3 | 10 | 0.856 | 0.8541 |

**Table 2: Simulation parameters and results for the droplet-levitation test case.**

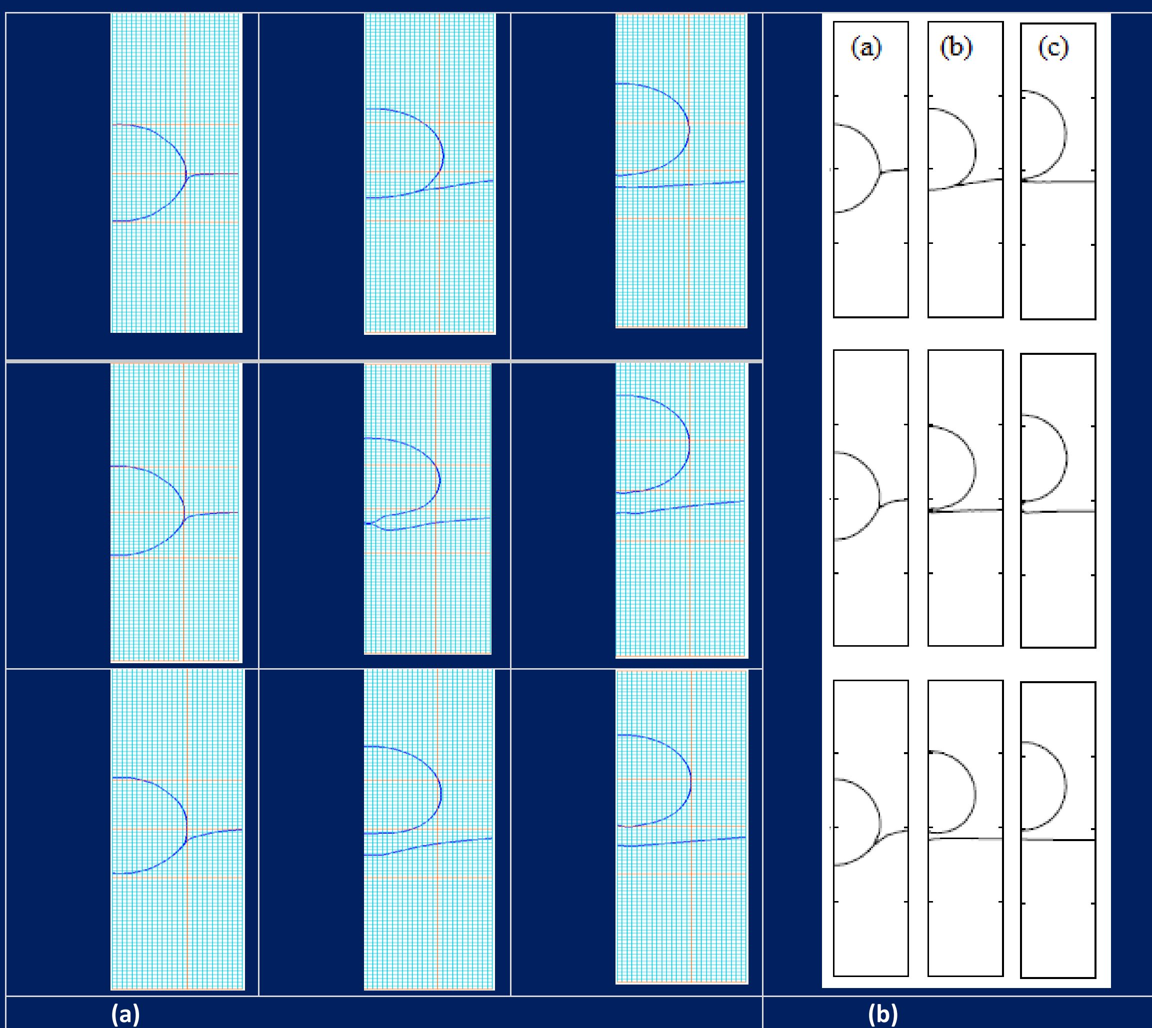
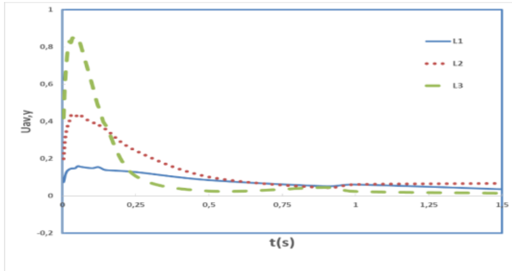
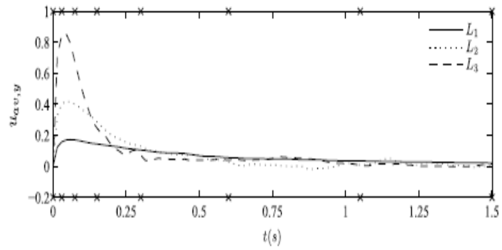



**Figure 4. Time snapshots of 0.5 level contour for all phases. Top row: case L1; middle row: case L2; bottom row: case L3; column letters (a) through (c) are at times 0.03, 0.6 and 4.5 s. (a) PHOENICS. (b) Tofighi & al.**




(a)




(b)

**Figure 5. Average vertical velocity of particles in droplet phase versus time for test cases L1, L2 and L3. (a) PHOENICS results, (b) Tofighi & al results.**

Figure 5 makes a comparison between the PHOENICS results and those Tofighi & al. It can be seen that there is quite good agreement, and both codes predict the same trend. Since Tofighi & al used an SPH method with high-resolution particles, it is not straightforward to equate the particle numbers of the SPH method to the mesh sizes used by PHOENICS. Therefore, the mesh sensitivity of the PHOENICS simulations should be investigated by using much finer meshes. A thorough study should also be done to investigate the effects of varying of parameters in the PHOENICS VOF method such as the smoothing level, Dirac-function cutoff, number of sweeps, etc. However, one can already see that the results obtained using the PHOENICS 3-phase VOF method are consistent and in good agreement with both the SPH method and analytical solutions.

## Concluding Remarks

The PHOENICS 3-phase VOF method has been applied to the liquid-lens and droplet-levitation test cases and the predicted results compared well with the analytical and numerical results reported in the literature. Further investigation of these cases is suggested so as to investigate the effects of mesh sensitivity and various model parameters on the solutions.

## References

J.Ouazanni, J.C.Ludwig, PHOENICS VOF – Application to a rising bubble in two and three-phase systems, PHOENICS Newsletter, Summer (2022).

N. Tofighi, M. Yildiz, Numerical simulation of single droplet dynamics in three-phase flows using ISPH, Computers and Mathematics with Applications 66, 525–536, (2013).