PHOENICS Newsletter

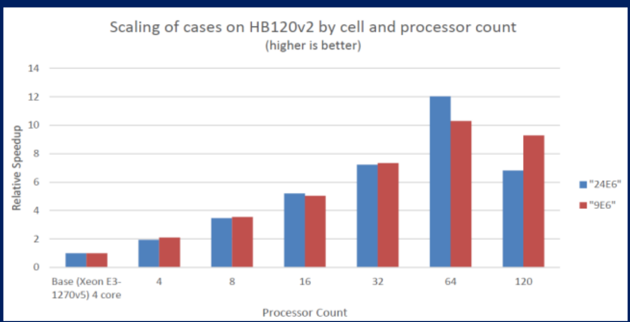
CHAM

Dear Reader

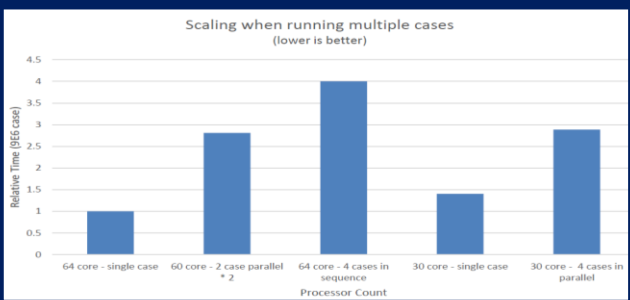
*Why not try **PHOENICS On the Cloud**? Experiment with your requirements on a pay-as-you-go basis. In addition to accessing the benefits of PHOENICS, you can decide what Virtual Machines, ranging from dual to 120 core on the Microsoft Azure Marketplace, best suit:*

https://azuremarketplace.microsoft.com/en-us/marketplace/apps/concentrationheatandmomentumlimited1616154387047.phoenics.

Scaling for sample cases of 9 million and 24 million computational cells run on a multi-processor system is shown on Graph 1 and similar benefits when running multiple cases simultaneously on Graph 2.



Graph 1



Graph 2

Are you seeking a career change and challenge?

If you are passionate about, and have in-depth experience of, CFD, and would like to create and develop a, new, position why not send your CV, and cover letter, to hr@cham.co.uk? You must be legally entitled to work in the UK without restrictions. See:

https://www.cham.co.uk/careers_description_Consultancy_Engineer.php for a full job description.

Kind Regards

Colleen Spalding, Managing Director

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Summer 2022

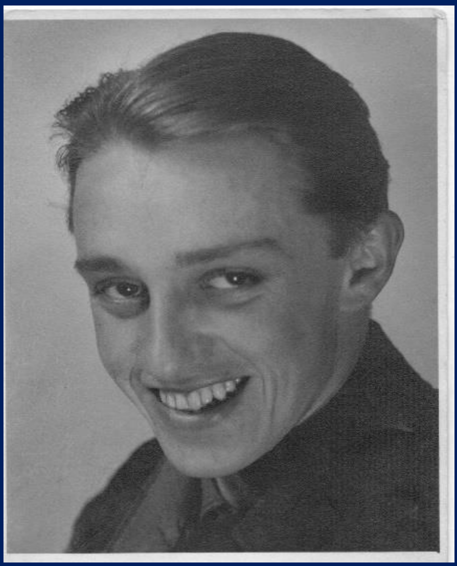
Brian Spalding FRS FREng *January 09 2023 will be Brian's Centenary.*

It would have been marked by a Conference, a Journal article, a mention in various scientific publications and various parties and gatherings.

He would have enjoyed the Conferences, lectures, and articles more than the parties.

In lieu of the above, there will be a special edition of the PHOENICS Newsletter which will contain memories provided by:

1) *Those who knew him in any capacity (scientific, family, personal).*
2) *Those who did not know him personally but knew of him through his work or other reasons.*
3) *Any who want to make a contribution.*



This is intended as a memorial to a man who was a scientist, an academic, a mentor, a free thinker, a father of CFD, a poet, an intellectual. Contributions can be what their authors want them to be. They can, of course, be scientific but they do not need to be.

Brian wrote poetry so if you came across him in that context, if you met him at a Conference, if he was your PhD supervisor, if you met him on his, or your, travels, if you did not meet him but read and were influenced by his work – any connexion is relevant.

Articles do not have to be long – a sentence, a paragraph, anything which paints a picture of someone who made a major contribution across so many aspects of life for 70 years.

For the Newsletter to be issued in January it is necessary to receive material as quickly as possible.

Please contact me, or send me your memories, at:

newsletter@cham.co.uk

or by surface mail to:

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England

If you have photos of Brian with you, in a group, anywhere, they would be most welcome as would any tapes, CDs, videos or anything with him speaking whether it be a lecture or at a dinner. More recordings of him, and of his voice, which could be shared on the website would be most welcome.

PHOENICS-2022: New Features and Improvements

1) 3-PHASE Volume of Fluid (VOF)

VOF, a free-surface modelling technique, solves a conservation equation for the volume fraction of heavy fluid using specialised techniques to preserve a very sharp interface. VOF features in PHOENICS include THINC-WLIC (Tangent of Hyperbola for INterface Capturing, Weighted Line Interface Calculation), CICSAM, HRIC etc.

3-Phase VOF, the latest addition, allows 3 distinct phases by solving an additional conservation equation; combinations are:

1) gas/liquid/gas,
2) liquid/gas/liquid,
3) liquid/liquid/liquid or gas/gas/gas.

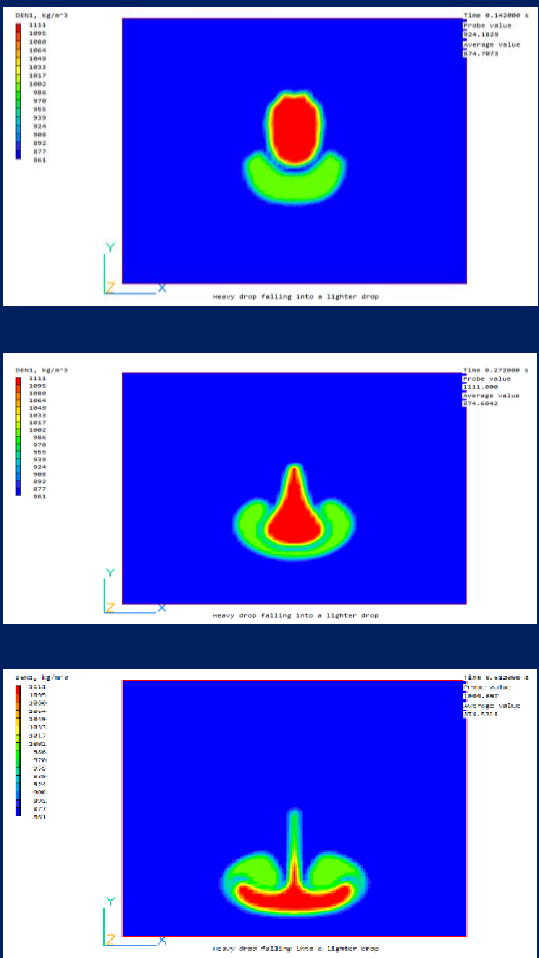
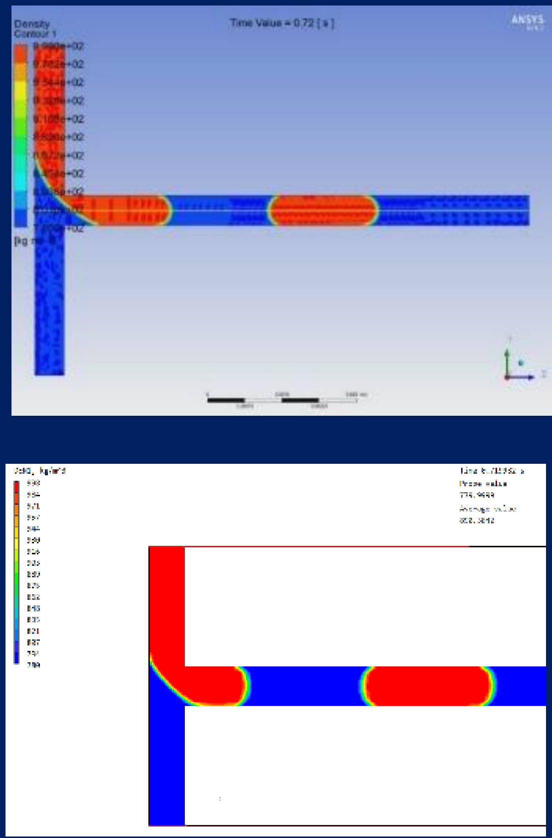


Figure: A heavy drop falling into a lighter one

All PHOENICS VOF models solve temperature-dependent cases, with proper treatment of temperature in each phase and in any immersed solids. Added options make surface tension a linear function of temperature, or use the Langmuir equation of state which includes a scalar as well as temperature. A constant static contact angle can be specified to model wall adhesion effects

Comparisons with Ansys © were made for water / kerosene slug flow. Comparative results were excellent as can be seen below.



2) Non-Newtonian fluid Models

PHOENICS may now contain more built-in options to model viscous non-Newtonian fluids than any other CFD code.

Seven, additional, non-Newtonian models are coded into PHOENICS-2022 equipping it with a wide range of menu-driven models including standard versions of: Power-law, Sisko, Cross, Carreau, Carreau-Yusada (CY), Powell-Eyring, Bingham Plastic, Herschel Bulkley, Casson and Ellis. These models facilitate simulation of an extensive range of fluids including blood, clay, foods, greases, mud, polymers, sewage sludge, and slurries. PHOENICS can successfully model all of these - **and more**.

The models are documented in POLIS and validated via library cases for tube flow. Optional functions have been provided, documented and tested for temperature-dependent rheology used by PHOENICS to handle variants of Power-law/Cross/ Carreau/CY fluids. PHOENICS results for all fluid types compare favourably with analytical and/or numerical solutions, including those for the Graetz problem for heat transfer to a polymer melt with viscous dissipation at high Brinkman number.

This PHOENICS upgrade include the Papanastasiou regularisation for viscoplastic fluids, which improves the convergence rate when simulating the flow of these fluids, especially at high Hedstrom/Yield numbers.

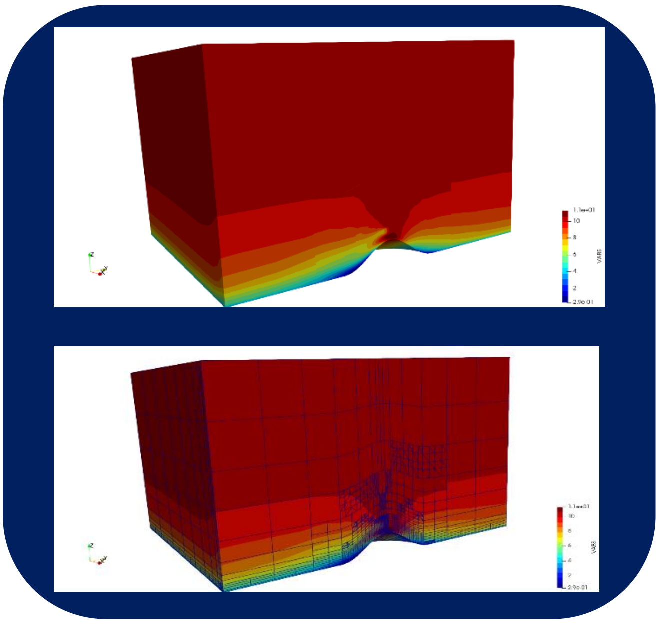
3) USP-BFC Wind Farm Unstructured Terrain Model

CHAM has supplied PHOENICS for windfarm use since the mid-1990s. PHOENICS powers WindSim the "wind farm design software based on Computational Fluid Dynamics" & is used by the Norwegian Company WindSim (originally Vector AS).

CHAM created an unstructured PHOENICS version for WindSim with a terrain-following BFC (Body-Fitted-Coordinate) grid as the unstructured mesh starting point. Local grid refinement allows great reduction of cell numbers compared to a traditional structured BFC mesh. The resulting grid can incorporate local refinements near ground plane and around wind turbines (represented as actuator discs using **InForm**) and the code can run in parallel.

In-Form supplements PHOENICS Input Language (PIL) and facilitates input of problem-defining data. It allows users to express requirements through algebraic formulae for:

space and time discretization,	material properties,
initial values,	sources,
boundary conditions,	body shapes and motions,
special print-out features	



4) Sutherland's Law for thermal conductivity

Practical engineering can posit problems involving noticeable temperature changes in the field of flow which requires a model for thermal conductivity and viscosity.

Where viscosity depends only on temperature Sutherland's law, in PHOENICS, provides an additional option for calculating temperature-dependent thermal conductivity of a gas. Values of constants for several common gases are included.

The law based on idealized intermolecular-force potential is:

$$\mu = \mu_o \frac{T_o + C}{T + C} \left(\frac{T}{T_o}\right)^{3/2}$$

5) IPSA (inter-Phase-Slip Algorithm)

IPSA has been available in, used by, and built into, PHOENICS since 1981. It was developed by Brian Spalding:

"After developing a satisfactory calculation method for single-phase problems, Spalding turned his attention to multi-phase flows, for which he proposed the inter-phase-slip algorithm (IPSA), in which each phase is assumed to form a continuum, interpenetrating other phases. At each location, each phase has a volume fraction and its own velocity and temperature field. The transport equations for each phase contain terms representing inter-phase transfers. Thus, any velocity difference (the slip) between other phases creates a shear-force term, while temperature differences lead to inter-phase heat transfer."

https://royalsocietypublishing.org/doi/10.1098/rsbm.2018.0024

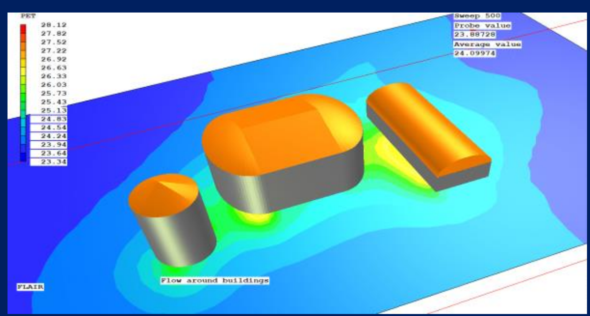
A new IPSA capability has been added to PHOENICS-2022. In the current model a fluidised bed is characterised by four different flow regimes, namely: dense, sub-dense, sub-dilute and dilute. A blending function is introduced to provide a smooth transition between the various regimes.

7) PET & TSI Improvements to FLAIR

PET (Physiolgal Equivalent Temperature) is a thermal comfort index based on a prognostic model of the human energy balance that computes skin and body core temperature, sweat rate and, as an auxiliary variable, clothing temperature.

PET is based on the Munich Energy-balance Model for Individuals (MEMI) and used to model the impact of heat, wind, etc on the body to create a comfortable human environment.

TSI (Thermal Sensations Index) is an empirical model adopted by public housing projects in Hong Kong where its prevalence can be explained by its user-friendly nature. It considers five climatic factors — air temperature, horizontal solar radiation, wind speed, relative humidity and mean radiant temperature — at a given location and time. A simplified version has been implemented in PHOENICS, according to BEAM Plus New Buildings Version 2.0.



Flow Around a Group of Buildings

PHOENICS VOF – Applied to a Rising Bubble in 2 & 3 Phases

by Jalil Ouazzani, ArcoFluid, Bordeaux, France, Zaim Ouazzani, ArcoFluid Consulting LLC, Orlando, USA, and John Ludwig Concentration Heat and Momentum Limited (CHAM), London, UK.

Introduction

This article reports on the extension of the existing PHOENICS VOF (volume of fluid) option to simulate three phase flows, such as those encountered in applications involving three different immiscible fluids. Examples include systems involving combinations of liquids and gases with differing densities, like those found in the water/oil/air interfaces of an oilfield separator and the liquid-steel/liquid-slag/gas interfaces of a gas-stirred metallurgical ladle. The extension to three fluids involves the solution of a conservation equation for an additional colour (or indicator) function, C_3, to represent the third phase; and a modification of the surface-tension force in the mixture momentum equation to handle the three distinct fluids.

The PHOENICS 3-phase VOF implementation is tested by its application to two rising bubble cases, one for a bubble rising in a liquid column, and the other for a bubble rising in a column with two stratified liquids. The first case is important for verifying that the VOF extension produces results that are in agreement with published numerical results for the simpler two-phase system. The second test case is qualitative in the sense that it simulates a full three-phase system to investigate the bubble rise in response to changes in the physical properties of each phase.

Theoretical Considerations

The transport equation for C_3 has the same form as the existing colour function C_1 used in two-phase VOF simulations, i.e.:

$$\frac{\partial C_3}{\partial t} + \nabla \cdot V C_3 = 0 \qquad (1)$$

The option exists in PHOENICS to solve this equation in conservative or in non-conservative form, depending on the physical problem. The following algebraic equation enforces volume continuity and links two colour functions: $\sum_{n=1}^{3} C_n = 1$, where C_n is the colour function of phase n.

The **physical properties** of the resulting mixture are computed under the above constraint by using equations of the form: $\phi = \sum_{n=1}^{3} C_n \phi_n$, where ϕ denotes the density, kinematic viscosity, specific heat capacity, thermal conductivity and volumetric expansion coefficient.

The PHOENICS two-phase VOF method uses the standard continuous surface force (CSF) approach of Brackbill et al (1992) to introduce **surface-tension forces** into the momentum equations in form of an equivalent body force, which in case of a two-phase system, takes the following form: $\mathbf{f}_{cap} = \sigma\kappa_i\delta\mathbf{n}_i$, where σ is interfacial tension, $\mathbf{n}_i = -\nabla C_i/|\nabla C_i|$ is unit normal vector at the interface pointing out of the i-phase, with C_i the colour function of the i-phase, $\delta = |\nabla C_i|$ is the Dirac delta function centred at the interface and $\kappa_i = -(\nabla \cdot \mathbf{n}_i)$ is the interface curvature.

The drawback of the CSF approach is that for different densities of adjacent phases, the capillary force introduced into the momentum equations produces an unsymmetrical distribution of the acceleration field relative to the interface location. For example, the acceleration $\mathbf{f}_{cap}/\rho$, where ρ is the local VOF phase density, is much higher in a less dense phase and vice versa. The CSF approach will lead to a thinning or thickening of the smooth transitional region between phases, depending on the direction of the vector $\mathbf{f}_{cap}$. If $\mathbf{f}_{cap}$ is pointing into a less dense phase, then the interface tends to thicken with time, whereas if it is pointing into a denser phase, the interface will become thinner with time. This problem has been resolved by Brackbill et al (1992) for two-phase systems by using density scaling of the CSF (DS-CSF), as follows:

$$f_{cap} = -\sigma\kappa_i\nabla C_i \frac{\rho}{\langle\rho\rangle} \qquad (2)$$

where $\langle\rho\rangle = (\rho_1 + \rho_2)/2$ is the average density between adjacent phases 1 and 2. This practice results in a symmetric distribution of the acceleration with respect to the interface.

In this work, by following Tofighi and Yildiz (2013), the DS-CSF has been extended to three phases by splitting the resulting capillary force into three constituents, one per phase. Each of these phase-specific forces is given by equation (2) above, but instead of using interfacial surface tensions, three phase-specific surface tensions σ_n (where n = 1,2, 3) are used in these forces. This approach is valid only for three-phase systems, as will be discussed later. When focusing on a given phase n, the idea of density scaling is to treat the two others as a single n-adjacent phase with spatially varying density.

By analogy with a two-phase system, but using now the density of the n-adjacent phase for the DS-CSF, the capillary force for a three-phase system can be computed as:

$$f_{cap} = \sum_{n=1}^{3} f_{ncap} = -\sum_{n=1}^{3} \sigma_n\kappa_n\nabla C_n \frac{\rho}{\langle\rho\rangle_\alpha} \qquad (3)$$

where $\mathbf{f}_{n,cap}$ is the equivalent of $\mathbf{f}_{cap}$ for phase n with $\langle\rho\rangle_n = (\rho_n + \rho_{n\text{-adjacent}})/2$.

This formulation redistributes the surface forces across interfaces in such a way as to produce a symmetric acceleration. It remains to define the values of phase-specific surface tensions. The idea is based on the decomposition of the resulting force vector into three constituent phase-specific forces (see Tofighi and Yildiz (2013)). These phase-specific forces are then treated individually in the same manner as surface forces in two-phase systems, where only one type of interface is possible. For this purpose, the interfacial tension between phases n and β is expressed through artificially introduced phase-specific surface tensions, so that $\sigma_{n\beta} = \sigma_n + \sigma_\beta$ where:

$$\begin{cases} \sigma_1 = 0.5(\sigma_{12} + \sigma_{13} - \sigma_{23}) \\ \sigma_2 = 0.5(\sigma_{12} + \sigma_{23} - \sigma_{13}) \\ \sigma_3 = 0.5(\sigma_{13} + \sigma_{23} - \sigma_{12}) \end{cases} \quad (4)$$

One difficulty in three phase systems is the possibility of direct contact between all phases. However, these situations are accounted for automatically by the foregoing capillary-force decomposition into the sum of phase-specific capillary forces.

Application to the 2-phase system of a bubble rising in liquid

The flow considered is a two-dimensional bubble rising in a column of liquid, as defined by Hysing et al. (2009) as test case 2. This case is representative of industrial applications because it concerns a bubble with a density much lower than that of the surrounding fluid. The solution domain is illustrated in Figure 1; and the liquid (phase 1) properties are taken as ρ_1=1000 kg/m^3 and μ_1=10 Ns/m^2. The gas (phase 2) properties are set to ρ_2=1 kg/m^3 and μ_2=0.1 Ns/m^2. The surface tension and gravitational acceleration are set to σ=1.96 N/m and g=0.98 m/s^2, respectively.

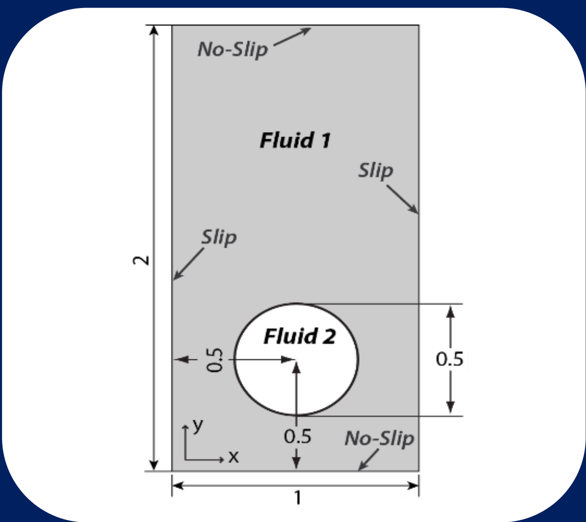


Figure 1. Configuration and boundary conditions for 2D bubble benchmark

The task is to predict the vertical position of the following parameters: the bubble centroid, the bubble rise velocity, the bubble circularity/sphericity, the bubble area and the surface perimeter. The PHOENICS predictions of these parameters are then compared with the numerical results of other workers. The circularity is the inverse ratio of the bubble surface perimeter P_b to the perimeter of the area-equivalent circle in two dimensions P_a. It takes the value of unity at the beginning of the computation and decreases as the bubble deforms.

PHOENICS VOF simulations were performed to cover a time duration of 3 seconds using a uniform mesh size h in each coordinate direction, as defined by h =1/40,1/80,1/160 and 320. For comparison, simulations were made using the CICSAM and THINC interface-resolution schemes for discretization of the nonlinear convective term in the transport equation for the colour function.

Results are presented in Figures 2 - 5. Figures 2a and 2b show snapshots of the time evolution of the bubble at grid resolution 320. Figure 3 shows the bubble shape obtained with PHOENICS for a grid resolution 320 at time t = 3s, together with numerical results obtained by Gamet et al (2018) using InterFoam and InterIsoFoam. Figure 4 compares the results obtained for PHOENICS VOF-CICSAM with those using PHOENICS VOF-THINC. It shows centre of mass, the rise velocity and circularity at grid resolutions of 40, 80, 160 and 320. Figure 5 shows results for PHOENICS VOF-CICSAM compared with results obtained with PHOENICS VOF-THINC for centre of mass, rise velocity and circularity at resolution 320.

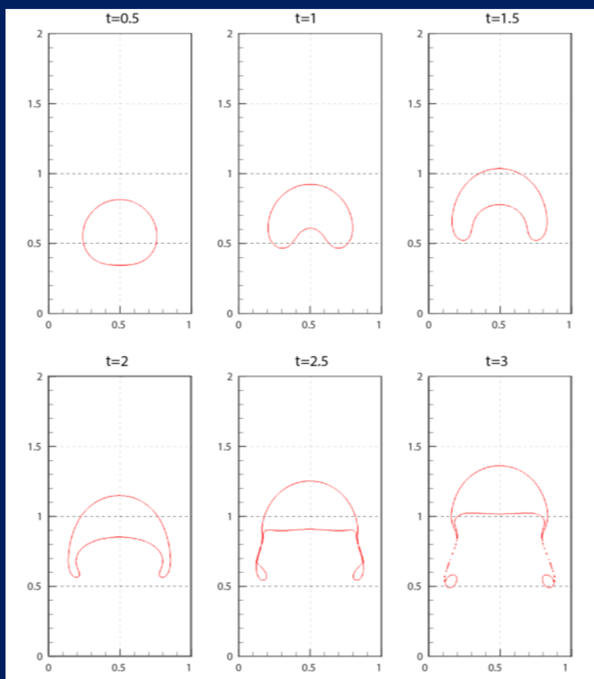


Figure 2a. Time evolution of bubble shapes (for PHOENICS VOF-THINC) at resolution 160×320 (lines contours).

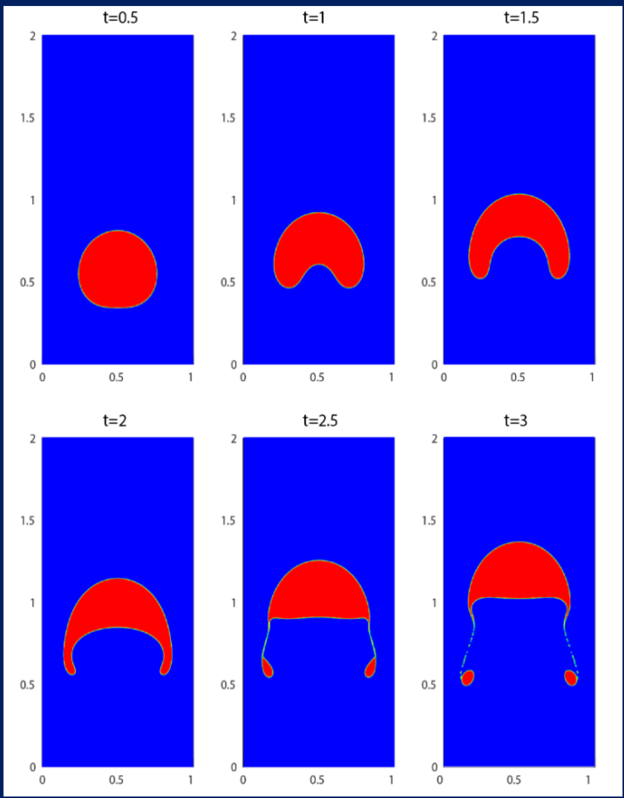


Figure 2b. Time evolution of bubble shapes (for PHOENICS VOF-THINC) at resolution 160×320 (filled colour contours).

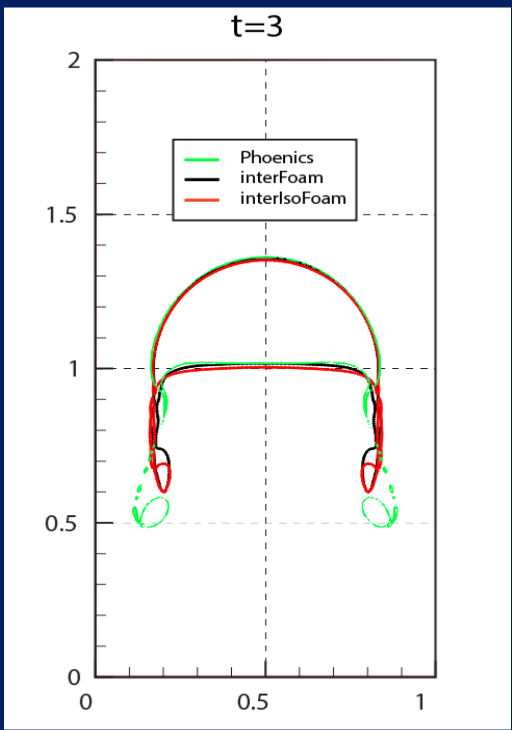


Figure 3. Comparison of bubble shapes 0.
at final time t = 3 s for PHOENICS (1/h=320), InterFoam (1/h=160) and InterIsoFoam (1/h=160).

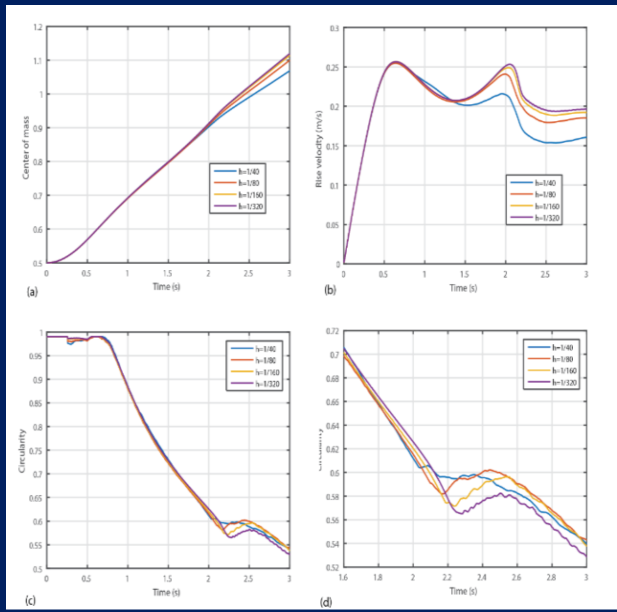


Figure 4. Time evolution of center of mass (a), rise velocity (b), circularity (c) and close-up of the circularity (d) for PHOENICS VOF-CICSAM at different resolutions.

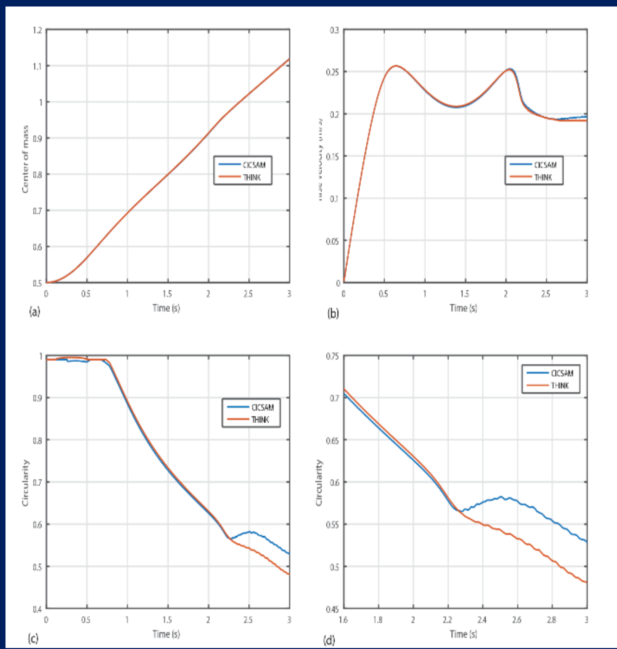


Figure 5. Time evolution of center of mass (a), rise velocity (b), circularity (c) and close-up of the circularity (d) for PHOENICS VOF-CICSAM (blue) and VOF-THINC (red) at resolution grid 320.

The comparisons reveal the good behaviour of PHOENICS, whether using the CICSAM or THINC VOF method. Moreover, the results compare well with other published results. A thorough study can still be done to investigate the effect of varying several parameters in the PHOENICS VOF method, such as the smoothing level, Dirac function cutoff, number of sweeps, etc.

Application to the 3-phase system of a bubble rising through 2 stratified liquids

In this section, we consider a bubble rising due to buoyancy through two stratified liquids of differing density. The surface tension, viscosity, and gravity are taken into consideration. The computational domain takes a square shape Ω = [0.0, 1.0] × [0.0, 1.0], and at time zero, the bubble (phase 1) has an elliptic shape defined by $(\left((x-0.5)/a\right)^2 + \left((y-0.325)/b\right)^2 = 1$, with major and minor axes a=0.15 and b=0.075, respectively. Phases 2 and 3 are located above and below the horizontal line y = 0.5 with densities of 1000 and 1500 kg/m^3, respectively.

Gravity acts along the negative vertical direction with a magnitude of 9.8 m/s^2. Computations are performed on a 200 × 200 cell grid using three different sets of physical properties, as indicated in Table 1.

Case #	Density (Kg/ m^3)	Dynamic Viscosities Pa.s (μ_1,μ_2,μ_3)	Surface tension N/m ($\sigma_{12},\sigma_{13},\sigma_{23}$)
1	1	(0.0,1.0,2.0)	(0.5,0.5,1.0)
2	1000	(0.0,10.0,20.0)	(0.5,0.5,1.0)
3	1500	(0.0,1.0,2.0)	(50.0,50.0,100.0)

Table 1: Case numbers and physical parameters

The numerical results at four different times (t = 0.02, 0.12, 0.28, 0.5 s) are presented in Figure 6. The bubble rises due to buoyancy, and it can be seen that its shape tends to break up as it moves upwards. This is because the surface force isn't large enough to maintain the circular shape. The effects of viscosity attenuate the rising velocity of the bubble, as well as its shape.

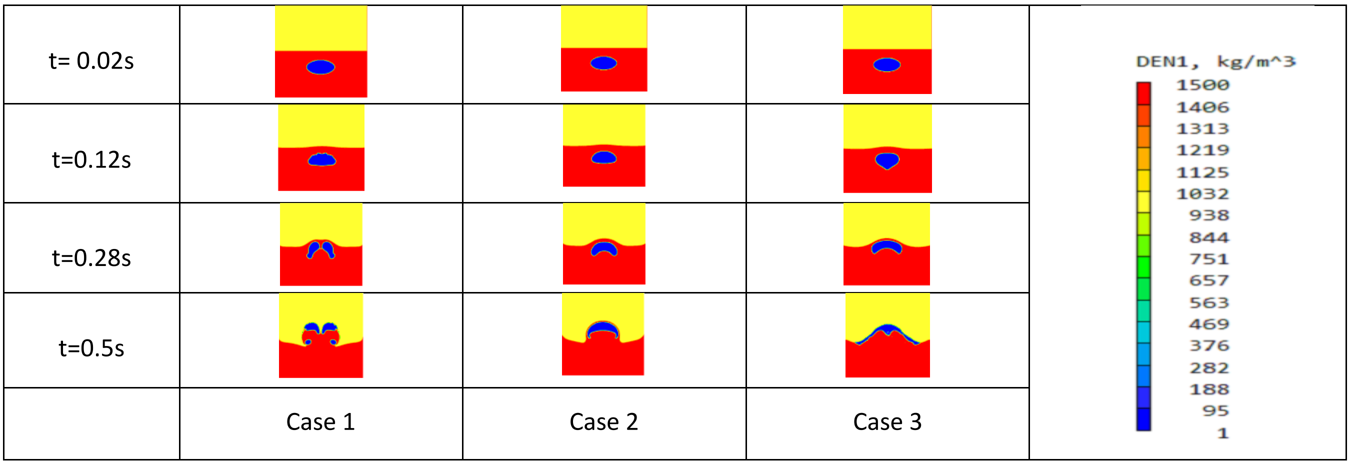


Figure 6 Density contours in the 3-fluid rising-bubble problem.

The Reynolds number for cases 1, 2, and 3 are 8267.43, 82.67, and 82.67, respectively. The larger the Reynolds number, the more distortion the bubble should experience. The second case employs higher dynamic viscosities than the other cases, thereby decreasing the Reynolds number. Figure 6 shows that the bubble is subject to less distortion for Case 2. A comparison between the results of Case 1 (left column) and Case 3 (right column) shows the effects of surface tension. In the results of Case 3, it can be seen that the bubble doesn't split up because of the enlarged surface tension relative to Case 1. For Case 3, Figure 6 shows that the bubble eventually becomes fully immersed in the fluid of phase 2.

Concluding remarks

The PHOENICS VOF option has been extended to simulate flows involving three different immiscible fluids. The implementation has been verified successfully for the two-phase system of a bubble rising through a column of liquid. A three-phase system was also investigated by observing the behaviour of a bubble rising in a column with two stratified liquids. The bubble motion and distortion were studied qualitatively in response to changes in the physical properties of each fluid. Future work will be aimed at quantitative verification of a three-phase system by comparison with published numerical results.

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

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

By Jalil Ouazzani – ArcoFluid – Bordeaux France.

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 σ^{13}/σ^{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

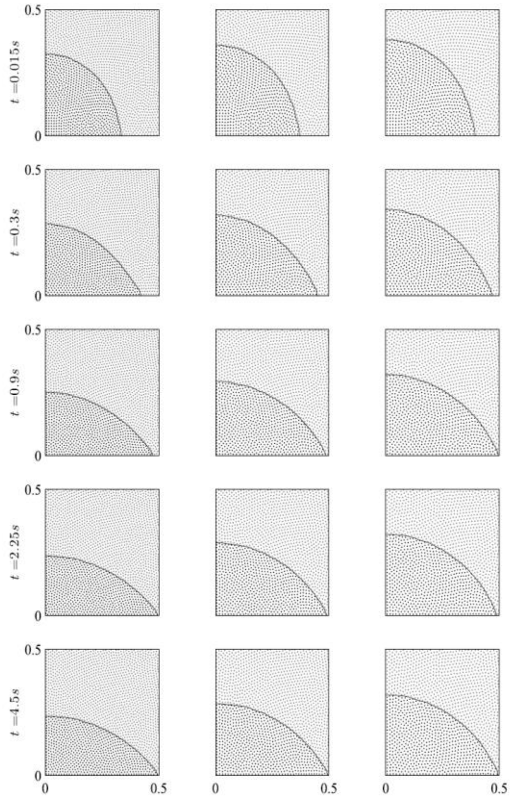


Figure. 1. Tofighi & al (2013): Time snapshots of particle position and droplet boundary (0.5 level contour of colour function for droplet, phase 3). Both x and y axes are normalised with each test case's respective analytic equilibrium diameter. Only the top right quarter has been shown for brevity.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

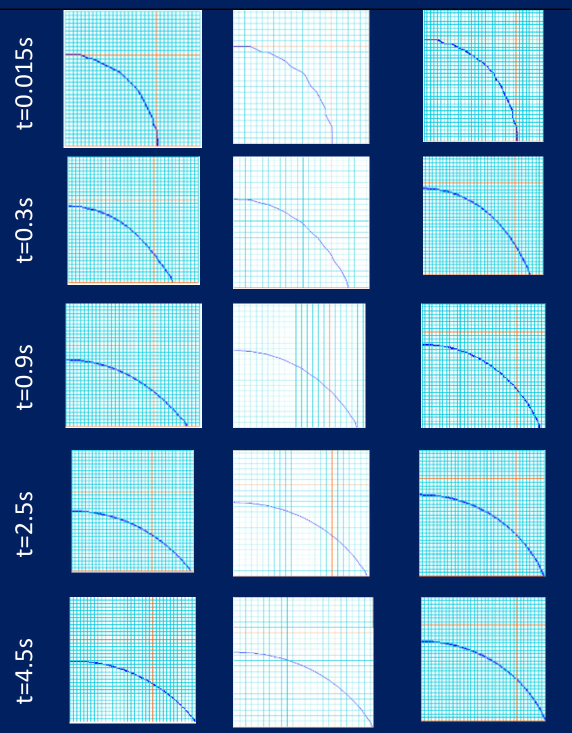


Figure. 2. PHOENICS: Time snapshots of particle position and droplet boundary (0.5 level contour of color function for droplet, phase 3). Both x and y axes are normalised with each test case's respective analytic equilibrium diameter. Only the top right quarter has been shown for brevity. Left column: case V1; middle column: case V3; right column: case V5.

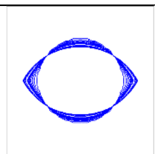
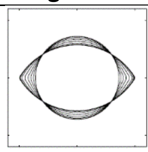
#	Phoenics	Tofighi & al
V3		

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

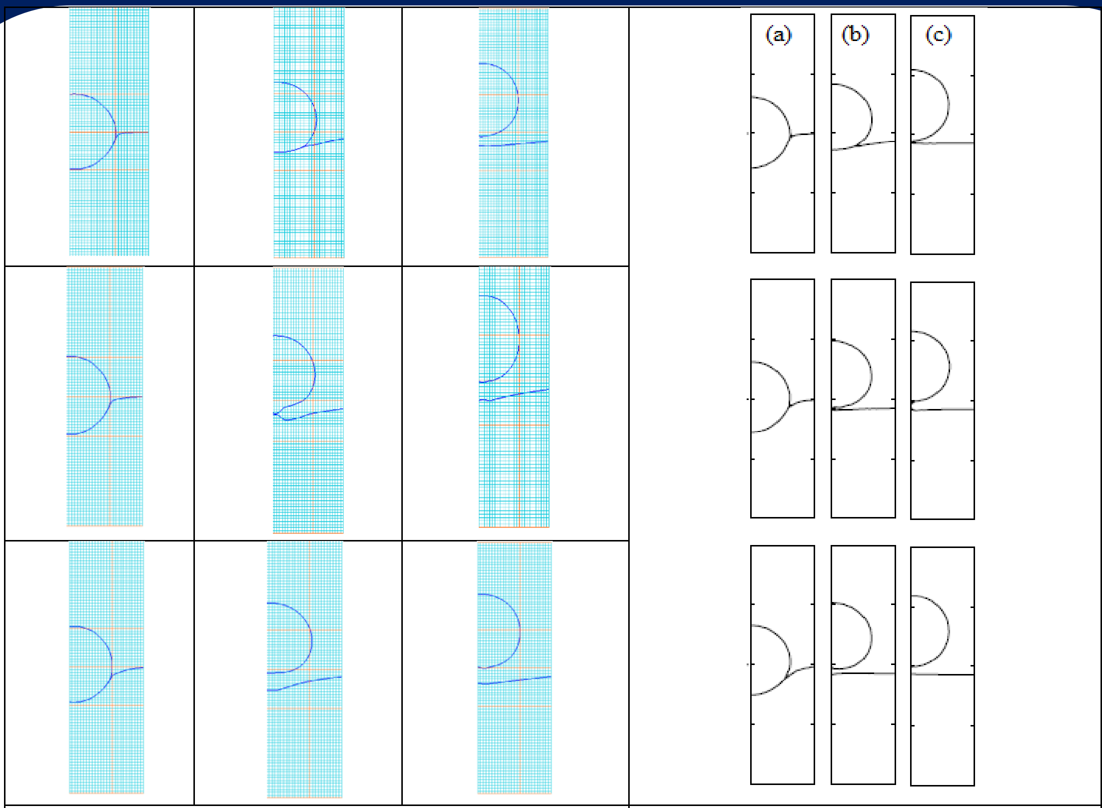
This section presents the results of the levitation of a circular droplet, which is initially at rest between two layers of immiscible fluids. Droplet levitation presents a more challenging and dynamic problem to test the capabilities of the proposed three-phase formulation. In this case the droplet 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 σ^{23}/σ^{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.

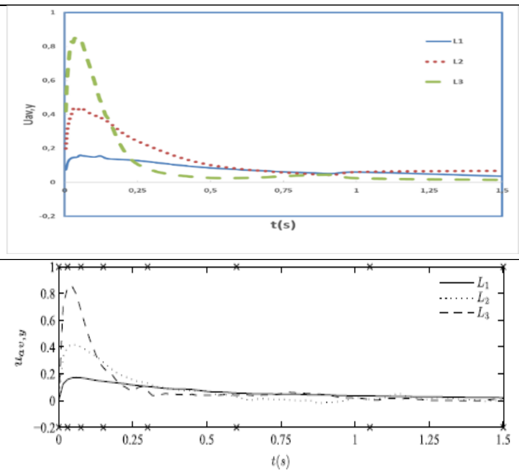
Test case	σ^{23}/σ^{13} ($\sigma^{12} = \sigma^{13}$)	Maximum $u_{av,y}$ PHOENICS	Maximum $u_{av,y}$ Tofighi et al
L1	2.5	0.162	0.173
L2	5	0.43	0.4186
L3	10	0.856	0.8541

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



(a) (b)

Fig. 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 results, (b) Tofighi et al results.



(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 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 fairly 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

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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).

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