Application of Smoothed Particle Hydrodynamics method to interfacial two-phase flows

PhD abstract

Studying multiphase flows is crucial for gaining a better understanding and advancing current technology in various industrial processes and everyday life. In the realm of contemporary physics and engineering, numerical simulations play a vital role in aiding designers and technicians in this endeavour.

The Smoothed Particle Hydrodynamics (SPH) method employs particle-based discretisation, where each particle represents fluid properties and moves within the computational domain, mirroring the behaviour of the fluid. Interactions between particles are modelled using a smooth interpolating function, called kernel. In the field of Computational Fluid Dynamics (CFD), there exist various Eulerian approaches capable of solving multiphase flows. As a Lagrangian alternative, SPH has revealed to be a convenient option for selected classes of multiphase flows as it does not necessitate any specific measures to handle interface dynamics. Nevertheless, attention must be given to proper treatment of fluid density and viscosity changes across the interface, especially when the density and viscosity ratios are elevated.

Motivated by limited research on multiphase viscous flows in the current SPH literature, our aim is to assess the effectiveness of the model and the functionalities of the in-house code in managing these complex simulations. One of the goals is to define a proper expression for the viscous force within weakly compressible SPH (whose acronym is WCSPH). Hence, in this dissertation we propose a modified Violeau, Español and Revenga (mVER) formulation that is in accordance with the physical viscous force term in presence of the interface by implementing a suitable smoothing.

The new formulation is first validated against the steady state, single- and two-phase Poiseuille flow of known analytical solutions. An additional advantage of the Poiseuille flow benchmark is its physical simplicity, allowing us to focus on the assessment of the mVER formula. Since the new formulation has succeeded the first step, we considered the second benchmark, often encountered in the literature on multiphase flows, which is a gas bubble rising in liquid. In this study are considered two regimes of the bubble rise; they differ on the basis of the shape taken by the bubble when subjected to buoyancy and the shear effect, including at the interface. In the first regime the two fluid phases have relatively small difference in density and viscosity values, and the final bubble shape is ellipsoidal. In the second regime the density and viscosity ratios are much higher; consequently, the bubble is strongly deformed and assumes a so-called skirt shape. The first case, the ellipsoidal regime, has proved to be less challenging and we obtained a good agreement with the reference data in terms of the bubble rising velocity and final bubble shape, also measured using the circularity parameter. Utilising SPH to simulate the second regime, we have struggled to obtain the elongated skirt that was expected. As a positive outcome, the top part of the bubble had a shape comparable to the reference one. Moreover, the resulting rising velocity and the circularity parameters were close to the benchmark. Both cases have however showed an oscillatory behaviour of the rising velocity; this is a well-known issue that occurs in weakly compressible approaches.

The mVER formulation is also tested against more complex applications, including the sloshing phenomenon and the moon pool, a key feature in drill-ships and offshore platforms. It is an opening through the hull of vessels that allows underwater activity from on-board. Since the sloshing phenomenon has not been simulated before in our code, the sloshing tank benchmark is a natural preparatory study for the moon pool. Comparing our results with the reference analytical formulae stemming from the potential flow theory, we obtained good agreement for the wave height, while the sloshing force had a lower amplitude, because it manifested an inevitably viscous behaviour.

As the last application we studied the moon pool. Its presence influences the stability of ship motion, necessitating a thorough investigation, particularly for vessels like drill-ships frequently subjected to harsh open-sea conditions. Despite significant advancements in experimental analysis, CFD emerges as a viable and relatively convenient alternative, in some cases eliminating the need for complex and expensive towing tank laboratory studies. Considering this aspect, we have selected a recent reference in the literature, both experimental and computational, and implemented the same case in our SPH code. Notwithstanding the necessary simplifications, both in geometry (e.g., our moon pool is two-dimensional) and in the physical model (e.g., assuming periodic, rather than open, boundary conditions), the obtained dominant frequency of the sloshing flow inside the moon pool was comparable with the benchmark.

Still regarding the moon pool, we have also included a study on the recess which gives the moon pool the characteristic L-shape. Recently, the recess has demonstrated to be useful for assembling and putting in water tools and devices, particularly on drill-ships. Additionally, the recess affects the wave dynamics within the moon pool. We delve into the optimisation of the recess geometry, aiming to find the best solution, or a set of solutions, that minimise the wave height inside the moon pool. We have conducted the optimisation by coupling the SPH code with the software modeFRONTIER, provided by ESTECO SpA, and testing various flow conditions. Utilising the simplified moon pool already tested, we have firstly run a set of initial simulations by varying the recess height and length, as well as the frequency of the surface waves. Out of these simulations we can create a new predictive mathematical model using the response surface methodology. We explored this meta-model to compare as many new designs of the recess as we need to find the one (or ones) that performs best under the given flow conditions.

In the author's opinion, possible directions for future development are: (i) an investigation, in the WCSPH framework, of the relationship between the smoothing kernel expression and the observed oscillations of the solution; (ii) a further validation of the mVER formulation for new benchmarks, also applying other SPH software; (iii) a research on a physically sound and computationally efficient implementation of open boundary conditions.