Return to Menu

Lattice Boltzmann Method for Spacecraft Propellant Slosh Simulation

Project Manager(s)/Lead(s)

Joseph Powers/EV41
(256) 544–8513

Jeb Orr/ESSSA, EV41
(256) 961–0150

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The modeling and prediction of the behavior of fluids in microgravity continues to be a challenge in the design of spacecraft systems. In the microgravity environment, hydrodynamic regimes can be described by the nondimensional parameter of Bond number (*Bo*), characterizing the relative magnitude of the gravitational acceleration versus the capillary forces present in the liquid.

At very low Bond numbers ($Bo < 10$), the hydrodynamics are dominated by the surface tension and a qualitative change in behavior is observed. Liquid-free surface interfaces become characteristically curved, and most propellants approach a near zero contact angle with solid objects (such as tank walls). The dominant time scale of the liquid dynamics increases into the tens or hundreds of seconds, and characteristic flow velocities and the Mach number are very small. In these conditions, computational fluid mechanics (CFM) approaches are required to predict the motion of the bulk fluid mass and its effect on the spacecraft when displaced from equilibrium.

The lattice Boltzmann method (LBM) has recently emerged as a promising alternative to traditional approaches to CFM. Using this approach, the continuum fluid transport phenomena, i.e., the Navier-Stokes equations, can be approximated as a solution of a discretized nonlinear difference equation based upon the kinetic theory of gases.

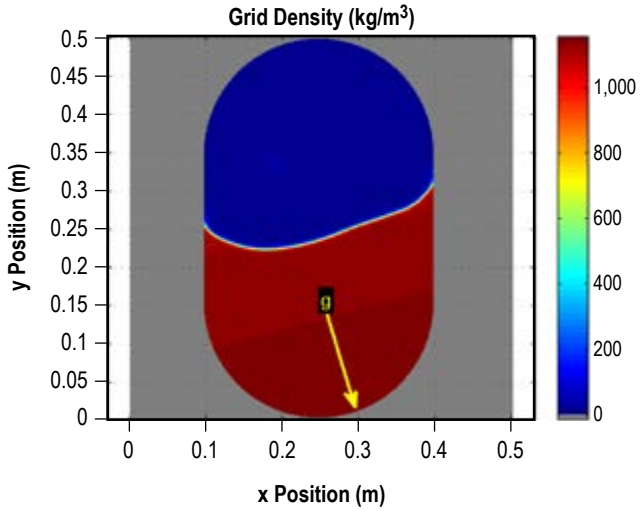

Figure 1: Fluid sloshing at $Bo = 20$ (0.001 *g*).

While the LBM is typically restricted to low velocity flows, it does provide several unique advantages over traditional solvers: (1) The meshing of complex geometry is performed on a regular lattice of fluid cells, each having uniform volume in the fluid domain. As such, computations involving flux across the boundary of adjacent cells are considerably simplified; (2) The LBM has the advantage of data locality; LBM flow solvers are not required to solve a global continuity equation at each time step; and (3) The LBM is relatively simple to implement and computationally efficient.

A scalable, proof-of-concept computational approach to the simulation of propellant tank sloshing dynamics in microgravity has been developed (fig. 1). We use the lattice Boltzmann equation to approximate the behavior of two-phase, single-component isothermal flows at very low Bond numbers. Through the use of a nonideal gas equation of state and a modified multiple relaxation time collision operator,[1] the proposed method can simulate thermodynamically consistent phase transitions at temperatures and density ratios consistent with typical spacecraft cryogenic propellants; e.g., liquid oxygen. Determination of the tank forces and moments relies upon the global momentum conservation of the fluid domain, and a parametric wall-wetting model allows tuning of the free surface contact angle.

In our formulation, a pseudopotential model with a real gas equation of state is used.[2] The pseudopotential model is a diffuse interface model; i.e., the interface appears in the lattice as a density gradient over a few cells or tens of cells. This increases the required minimum lattice resolution to obtain sharp interface definition if required by the application. Disadvantages of the pseudopotential model include the interdependency of the interface thickness, the surface tension parameters, and the high interface forces required to maintain a stable interface. The latter tends to yield spurious currents, which degrade the stability. Of course, the basic Lattice Boltzmann equation is isothermal; convective effects, which can be important in cryogenic flows in zero-g, are not captured.

The computation, data processing, and visualization are implemented directly in MATLAB®. Extensive use of MATLAB's multidimensional array operators allows many of the necessary operations, such as advection, collision, and the calculation of body forces, to be accomplished without the use of nested loops. By relying on MATLAB's internally optimized matrix libraries for much of the large-scale multiplication and division operations, a considerable advantage in computational efficiency and code simplicity is realized. Verification of the multiphase LBM implementation was accomplished through comparison of numerical and theoretical results for known phenomena in surface tension dominated flows; e.g., droplet oscillation (fig. 2).

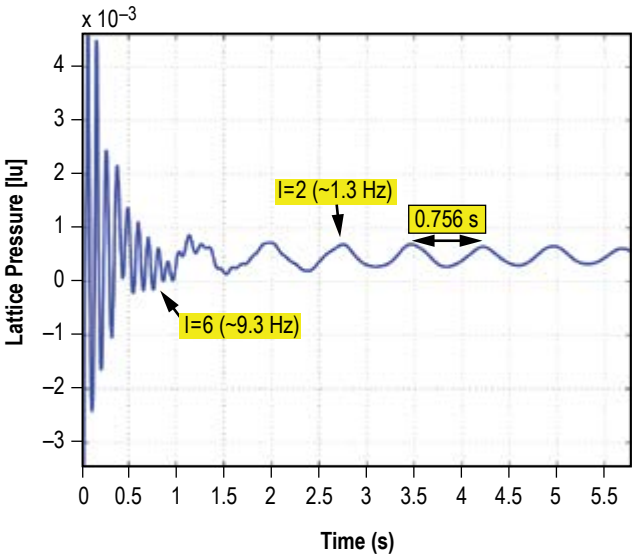

Figure 2: Analysis of oscillating droplet dynamics.

Anticipated Benefits

Rapid and accurate prediction of bulk fluid motion in spacecraft propellant tanks is crucial for analyzing the vehicle's dynamics and stability, especially during attitude control and thrusting maneuvers. In addition, the interaction of the propellant with tank hardware is particularly important in the design of propellant management devices. Since the lattice Boltzmann approach is computationally parallelizable, it may be possible to leverage emerging computing architectures to develop a fast, efficient multiphysics simulation of the coupled fluid-spacecraft dynamics.

These data can potentially reduce risk by allowing more accurate simulation predictions of an otherwise difficult-to-access flow regime.

Potential Applications

The present work was developed specifically to support analysis of the effects of propellant motion on the stability and dynamics of spacecraft, especially in the nonlinear regime and with respect to long time scales. However, the ability to model phase transitions using a real gas equation of state implies that it may be possible to directly incorporate thermal effects. In this case, the LBM may have applications to modeling and simulation of thermal management systems for cryogenic propellant storage, especially in those conditions relevant for long-duration space missions.

References

1. Lallemand, P.; and Luo, L.: "Theory of the Lattice Boltzmann Method: Dispersion, Dissipation, Isotropy, Galilean Invariance, and Stability," NASA/CR—2000–210103, NASA Langley Research Center, Institute for Computer Applications in Science and Engineering, 2000.

2. Yuan, P.; and Schafer, L.: "Equations of state in a lattice Boltzmann model," *Physics of Fluids*, Vol. 18, No. 4, p. 042101, doi: 10.1063/1.2187070, 2006.