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Influence of Rayleigh–Taylor Instability on Liquid Propellant Reorientation in a Low-Gravity Environment *

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A computational simulation is conducted to investigate the influence of Rayleigh–Taylor instability on liquid propellant reorientation flow dynamics for the tank of CZ-3A launch vehicle series fuel tanks in a low-gravity environment. The volume-of-fluid (VOF) method is used to simulate the free surface flow of gas-liquid. The process of the liquid propellant reorientation started from initially flat and curved interfaces are numerically studied. These two different initial conditions of the gas-liquid interface result in two modes of liquid flow. It is found that the Rayleigh–Taylor instability can be reduced evidently at the initial gas-liquid interface with a high curve during the process of liquid reorientation in a low-gravity environment.

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Free surface flows appear in various engineering applications such as the propellant management in spacecraft.[1] In recent years, NASA has planned The on-orbit management[2] of liquid hydrogen for the return to the moon:[3] the extended storage and handling of large quantities of liquid hydrogen on-orbit. The major objectives of liquid-propellant management during coasting flight are efficient engine restart capabilities and, in the case of cryogenics, an efficient venting mode to maintain tank pressurization control. Spacecraft must therefore complement methods to ensure that the liquid is located at the desired location in the tank even when effective gravity is directed adversely or in unknown directions. Similarly, if the tank is pressurized and must be vented periodically, methods are required to ensure that gas is positioned over the vent. A way to accomplish these objectives is to use an auxiliary thrusting system to provide a linear acceleration large enough to settle the liquid.[4] CZ-3A launch vehicle series[5,6] is the rocket series with the largest carrying capacity in China at present and the main large commercial rocket series. It is mainly used to launch the geostationary transfer orbit (GTO) payload. The low earth orbit (LEO) payload, sun synchronous orbit (SSO) payload as well as payloads flying to the moon and Mars can also be launched. With the CZ-3A launch vehicle series, a typical upper-stage vehicle, four 10-N and four 150-N thrusters are used to settle the propellant aft in the tank for engine venting and restarting. The worst case of propellant reorientation is that the liquid phase locates at the top of the tank, and gas at the bottom (relative to gravity vector direction). The equilibrium of the gas-liquid interface is unstable to certain perturbations or disturbances. The Rayleigh–Taylor instability will occur after the application of the reorientation thrust.

The Rayleigh–Taylor instability, or RT instability (after Lord Rayleigh and G. I. Taylor), is an instability of an interface between two fluids of different densities, which occurs when the lighter fluid is pushing the heavier fluid.[7] Consider that a heavy fluid is superposed over a light fluid in a gravitational field and surface tension is neglected, the interface between the fluids is catastrophically unstable. The heavier material moves down under the gravitational field, and the lighter material is displaced upwards. This was the setup as studied by Rayleigh.[8] The important insight by Taylor[9] was that he realized this situation is equivalent to the situation when the fluids are accelerated, with the lighter fluid accelerating into the heavier fluid.

The interfacial instability problem was classically studied for two-layer fluids of infinite length and thickness. However, the liquid propellant reorientation in a microgravity environment shows the case to have finite length and thickness gas-liquid layers with a high ratio of fluid densities. Many works have been carried out on the interfacial instability in recent years. Direct numerical simulation (DNS) was used to study flow characteristics after the interaction of a planar shock with a spherical media interface in each side of which the density was different by Fu *et al.*[10] Zhang *et al.*[11] investigated Rayleigh–Taylor instabilities using a specially-developed unsteady three-dimensional high-order spectral element method code. Numerical solution techniques for modeling the interfacial insta-

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bility of rocket propellant reorientation on computational meshes is required for the accurate simulation of interfacial physics in multi-fluid flows. In recent years, a number of methods have been developed for modeling such free surface flows,[]12 which can be classified primarily as Lagrangian or Eulerian-based. Eulerian-based methods are better suited for flows with complex topological changes and interface deformations. The volume-of-fluid (VOF) method[13] is an Eulerian-based method that has been widely used. It utilizes a volume fraction function to track the interface implicitly. In this method, a scalar function F is defined as the fraction of a cell volume occupied by fluid. F is assumed to be unity when a cell is fully occupied by the fluid and zero for an empty cell. Cells with values of $0 < F < 1$ contain a free surface.

In this Letter, we investigate the influence of Rayleigh–Taylor instability on liquid propellant reorientation flow dynamics for the tank of CZ-3A launch vehicle series. In the simulation, the actual parameter of the vehicle tank is used to provide guidance to the space engineering. The simulation model tank (Fig. 1) is a circular cylinder with spherical tops and bottoms. It has a radii of $R = 44$ cm and a length of $L = 145$ cm, respectively. The height of the cylinder part is 57 cm.

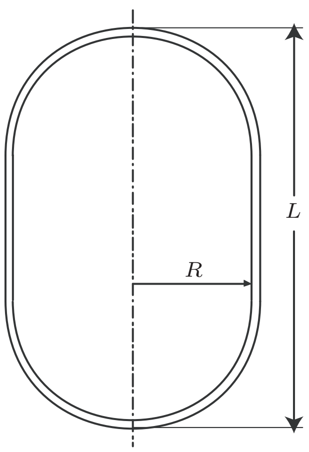

Fig. 1. Geometry of a liquid propellant tank.

UDMH was used as fuel liquid. The surface tension, density, and viscosity for UDMH are presented in Table 1. This liquid has a static contact angle of very near to 0° the container surfaces.

Table 1. UDMH properties at 293.15 K.

Liquid	σ (N/m)	ρ (kg/m^3)	μ (kg/m·s)
UDMH	24.18×10^{-3}	791.1	0.527×10^{-3}

For incompressible flows with constant properties, the continuity, momentum and VOF equations are given by

$$\nabla \cdot \boldsymbol{v} = 0, \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\nabla p + \mu \nabla^2 \boldsymbol{v} + \boldsymbol{f}_s + \rho \boldsymbol{a}, \quad (2)$$

$$\frac{\partial F}{\partial t} + \boldsymbol{v} \cdot \nabla F = 0. \quad (3)$$

The symbol $\boldsymbol{v}$ is the velocity vector; p, ρ, and μ represent the pressure, density, and viscosity of the mixture fluid, respectively. F is the VOF function. The term $\boldsymbol{a}$ denotes the residual acceleration of the aerodynamic drag acting on the spacecraft for the orbital maneuver course; $\boldsymbol{f}_s$ is the surface tension at the liquid-gas interface. Surface tension effect plays a significant role in the free surface flow problems in a micro-gravity environment. The continuum surface force (CSF) model[14] has been widely used to model surface tension. In the CSF model, surface tension effect is treated as a body force $\boldsymbol{f}_s$. It is distributed within a transition region of finite thickness at the interface, given by

$$\boldsymbol{f}_s = \sigma \kappa \boldsymbol{n} \delta(\boldsymbol{x}), \quad (4)$$

where σ is the coefficient of surface tension, κ the mean curvature, $\boldsymbol{n}$ the normal to the surface, and $\delta(\boldsymbol{x})$ a δ-function concentrated at the interface. In the context of the VOF method, the body force is given by

$$\boldsymbol{f}_s = \sigma \kappa \nabla F. \quad (5)$$

It is included in the momentum equation as a source term. This continuum treatment of the discontinuous change at the interface eases the implementation of the surface tension effect where only the VOF function is needed. In the problems with complex topological changes, the CSF model is superior to the conventional method in robustness and versatility. The term $\sigma \kappa \nabla F$ indicates that $\boldsymbol{f}_s$ is proportional to the curvature κ with the force acting along the normal direction of the interface. Contact angles are applied as a boundary condition at the contact line.[15] In the simulation, we set the contact angle $\theta_c = 0$. Boundary conditions for fluid along solid surfaces are the no-slip and no-penetration conditions.

An important step to verify the numerical model is to ensure that the discretization errors obtained on a chosen computational mesh are sufficiently low. Two separate grid sets have been constructed in our work: the coarse grid contained 3170 cells, the fine grid contained 7340 cells. The results for the fine and the coarse grid cases are close to each other. Converged solutions are obtained for both grid sizes. In order to obtain more accurate results we used the fine grid (7340 cells) for simulations of the following cases. In the studied cases, we chose the reorientation Bond number Bo conditions of 52.4, 393.0 and 786.0 ($Bo = \rho \boldsymbol{a} R^2/\mu$) corresponding to the thrust value 40 N, 300 N, and 600 N, which are available. We consider that the liquid fill level is 50%. The initial conditions of the gas-liquid interface prior to the application of the reorientation acceleration as flat and curved, respectively. In Fig. 2, the left one with a flat interface behaves as in the normal gravity field on earth; the right one has a curved interface, and the liquid phase is stabilized at the top of the tank at a Bond number of 10. Here the black area denotes liquid, the gray denotes gas.

The state of liquid flow dynamics after application of the reorientation thrust and impingement at the tank bottom is shown in Figs. 3 and 4.

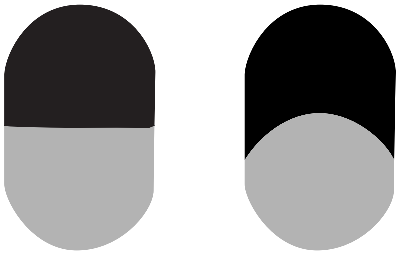

Fig. 2. Initial gas-liquid interface profiles prior to reorientation.

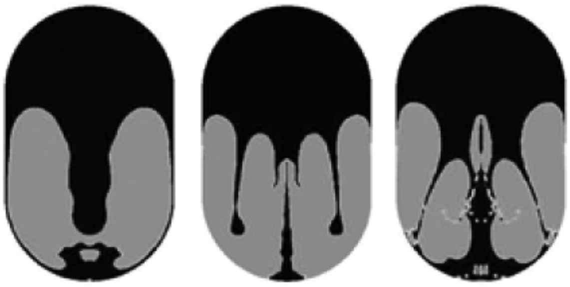

Fig. 3. Interface profiles during reorientation with initial flat interface (from left to right, reorientation Bo : $52.4, 393.0, 786.0$).

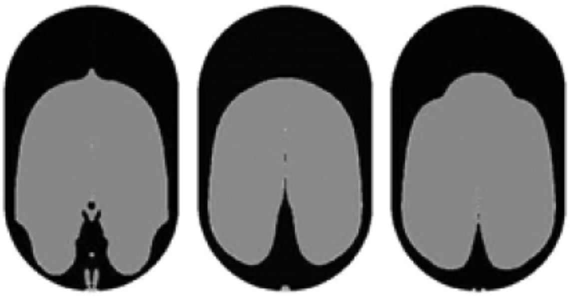

Fig. 4. Interface profiles during reorientation with initial curved interface with initial $Bo = 10.0$ (from left to right, reorientation Bo : $52.4, 393.0, 786.0$).

The two tests shown in Figs. 3 and 4 are conducted with the same reorientation parameters, and only the shapes of initial interface were different. Figure 3 shows that the reorientation flow is in spike along the tank centerline. With the Bond number increase, the Rayleigh–Taylor instability is magnified. The interface breaks up into more pieces and the wave number increases when the reorientation Bond number becomes larger. Figure 4 shows that all the reorientation flow is in a sheet along the tank walls even under the condition of the large reorientation Bond number ($Bo = 786.0$). After liquid impact at the tank bottom, the geyser initiates.

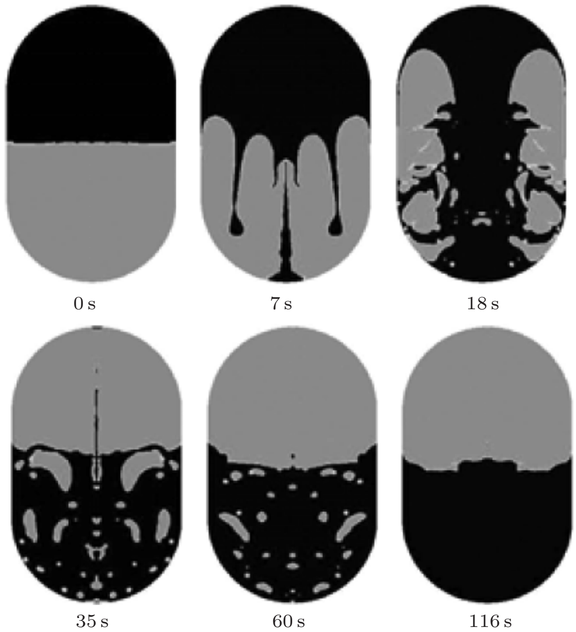

Fig. 5. Reorientation process with initial flat interface for $Bo = 393.0$.

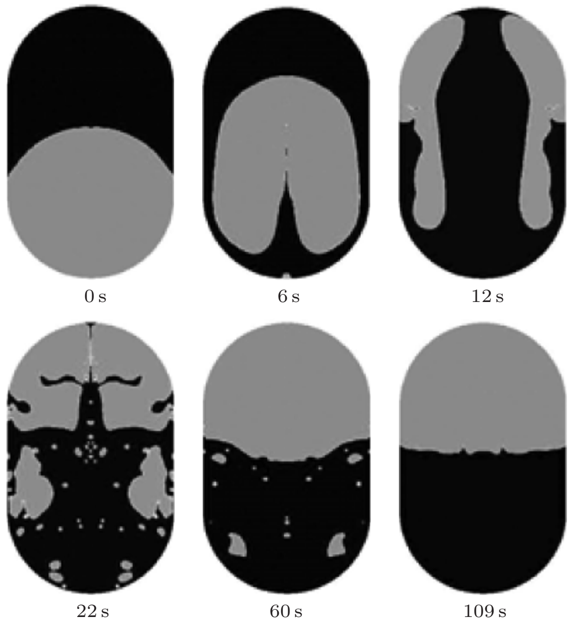

Fig. 6. Reorientation process with initial curved interface for $Bo = 393.0$.

Under the condition of the reorientation Bond number of 393.0, the specific reorientation flow process is shown in Figs. 5 and 6. Liquid rebounding or geysering occurs after impact on the tank bottom by the application of thrust. Then the interface broke up, gas-liquid mixed and bubbles generated from the liquid inside, finally gas eliminated from the liquid due to the reorientation acceleration. Figure 5 shows that the flow process is more chaotic and disorderly than that shown in Fig. 6. There are more bubbles generated, a stronger mix of gas-liquid, and a longer time will be taken to discharge the bubbles from the liquid when the reorientation process starts from the initial flat interface. In the Bond number of 52.4 and 786.0, the flow process is similar. We define the reorientation event time from the initiation of thrust as follows: T_1 is the time of liquid impact at the tank bottom; T_2 is the time when the tank top is clear of liquid; and T_3 the time of bubbles discharged from the liquid mostly.

Figure 7 shows that in all the cases the reorientation event time of the liquid reorientation process started from the initial curved interface is significantly less than the initial flat interface.

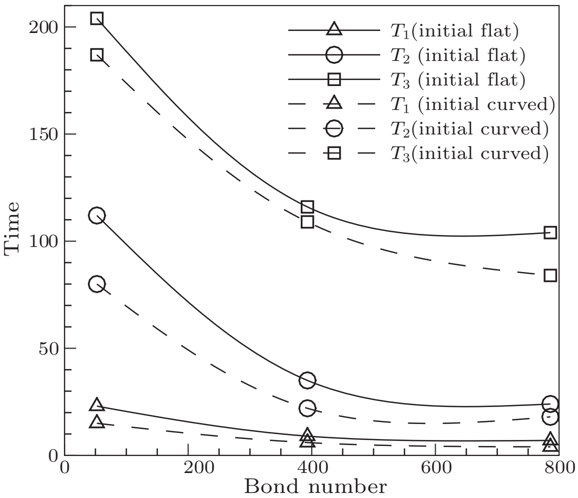

Fig. 7. Reorientation event time versus Bond number.

Both the cases are investigated for comparison with the drop-tower experiment results in future. In the ground, the gas-liquid interface is always flat in balanced. Thus, in order to simulate the reorientation process in the microgravity environment by drop-tower experiment, the reorientation thrust must apply at the time after a period of low Bond number drop to make the gas-liquid interface configuration approximated most nearly to its quiescent interfacial shape of liquid propellant at low-gravity in space.

In conclusion, the influence of Rayleigh–Taylor instability on the liquid propellant reorientation of on-orbit vehicle fuel tanks in a low-gravity environment has been studied. The numerical results indicate that during the reorientation process, the initial conditions of the gas-liquid interface will determine the flow mode of liquid in fuel tanks. An initial highly curved interface can evidently reduce the Rayleigh–Taylor instability of the gas-liquid system on liquid reorientation. The effect of the liquid fill level and the influence of thrust value on reorientation time and consumed impulse will be investigated and discussed in future.

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