Progress in Nuclear Energy 109 (2018) 130–144

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Numerical simulation of Rayleigh-Taylor Instability with periodic boundary condition using MPS method

Kailun Guo[a,b], Ronghua Chen[a,b,*], Yonglin Li[a,b], Wenxi Tian[a,b], Guanghui Su[a,b], Suizheng Qiu[a,b]

[a] School of Nuclear Science and Technology, Xi'an Jiaotong University, No. 28, Xianning West road, Xi'an, 710049, China
[b] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, No. 28, Xianning West road, Xi'an, 710049, China

ARTICLE INFO

Keywords:
Multiphase moving particle semi-implicit (MMPS) method
Rayleigh-Taylor instability(RTI)
Multiphase flow
Periodic boundary condition
Initial velocity disturbance arrangement

ABSTRACT

The Multiphase Moving Particle Semi-implicit(MMPS) method is adopted to simulate the Rayleigh-Taylor Instability (RTI) process in an incompressible viscous two-phase immiscible fluid. To eliminate influences of the initial disturbance arrangement and boundary conditions in RTI simulations, the initial velocity distribution is deduced and the periodic boundary condition is developed in this paper. The RTI cases in this paper include those with single-mode disturbance and multimode disturbance. For the single-mode RTI process, cases with different initial disturbance wavelengths, different Atwood numbers and different surface tension coefficients are simulated. Results are quantitatively compared with analytical solutions in a linear growth stage and the simulation results fit well with the theoretical results. The long-term development of simulations is presented for investigating changes in the topology of rising bubbles and falling spikes in RTI, and the steady velocity conforms well with that calculate by theoretical solution. What's more, the multimode RTI processes are also simulated in this paper, and bubbles' competition and mergence process can be observed.

1. Introduction

The Rayleigh-Taylor Instability (RTI) occurs at the interface of different fluids with density difference. If there is a pressure gradient from lighter fluid towards heavier fluid at the normal direction of the interface (equivalent to the gravity from heavier fluid towards lighter fluid), small disturbance will grow over time, this kind of interface instability is defined as the Rayleigh-Taylor Instability. When shock waves pass through the interface of two fluids with density difference, fluid at the interface will obtain an instantaneous acceleration, the interface instability will also happen, and this kind of interface instability is defined as the Rayleigh-Meshkov Instability (RMI). In nature and industries, the interface instability of stratified fluids are extremely important processes, RTI and RMI play important roles in some stages of stellar evolution, fragmentation of the gas film, crystallization of underground salt dome and the ignition stage of Inertial Confinement Fusion (ICF) (Meyer-ter-Vehn, 2009).

In nuclear reactor severe accidents, RTI is an important influence factor (Kim and Corradini, 1988). In vapor explosion accident, the pressure vessel has broken, molten corium with high temperature, high density and high viscosity leaks into the cooling water tank. During the interaction of molten corium and coolant, the interface instability happens, these will lead to the fragmentation of the gas film near the molten corium, then the molten corium bursts forth and fragment. Heat transfer between molten corium and coolant increases during these processes which finally lead to the vapor explosion. The uncertainty of severe accidents increases due to the interface instability, thus the interface instability becomes an important influence factor in Fuel Coolant Interaction (FCI) process, and it is necessary to do some researches on these phenomena.

Studies on RTI have been carried out for decades, especially in recent years. Due to the ICF ignition and FCI process have become hot topics of research, the study of RTI has entered a high growth stage, this phenomenon has obtained more and more attentions.

Through experimental and theoretical studies, development of RTI can be broadly divided into the initial stage, linear stage and nonlinear stage (Kull, 1991). In the initial stage of RTI, the lighter fluid and heavier fluid invade into each other, but the amplitude of growing disturbance is small, there are only weak disturbances at the interface, so the influence of RTI in this stage can be ignored. With the development of the instability, more and more fluid exchange area, but the interface can be still observed clearly. The amplitude of the disturbance at the interface changes, and the growth of the amplitude follows the exponential law. This stage is considered as the linear growth stage of RTI. When the amplitude of the disturbance is larger than the 10% of the initial disturbance wavelength, the RTI is generally considered to be

* Corresponding author. School of Nuclear Science and Technology, Xi'an Jiaotong University, No. 28, Xianning West road, Xi'an, 710049, China.
E-mail address: rhchen@mail.xjtu.edu.cn (R. Chen).

https://doi.org/10.1016/j.pnucene.2018.08.008
Received 11 December 2017; Received in revised form 22 May 2018; Accepted 6 August 2018

Nomenclature

C	dimensionless modified matrix/color function/Courant number/constant number
D	dimension number
$\vec{F}$	force vector
G	Gaussian kernel function
H	hyperbolic kernel function/height, m
L	length, m
N	number of neighboring particles
$\vec{N}$	degree of irregularity of particles distribution
W	generalized kernel function/width, m
$\vec{g}$	gravity acceleration, m/s^2
h	amplitude, m
k	wave number of the disturbance
l_0	particle average distance, m
n	particle number density
p	pressure, Pa
t	time, s
u	particle velocity, m/s
$\vec{u}$	particle velocity vector
r	distance between particles, m
$\vec{r}$	particle location vector
x,y,z	position in each direction

Greek letters

ϕ	physical quantity
α	compressibility of fluid
κ	local curvature
λ	wavelength, m
μ	dynamic viscosity, Pa•s
ξ	dynamic parameter
ρ	density, kg/m^3
σ	surface tension coefficient, N/m

Superscript/subscript

0	initial condition
1	fluid phase 1/constant in Eq. (32)
2	fluid phase 2/constant in Eq. (33)
i	No. of target particles
j	No. of neighboring particles
S	surface tension
ave	average value
min	minimum value
*	temporal value

the non-linear growth stage (Jacobs and Catton, 2006). The non-linear stage can be further divided into steady growth stage, irregular non-linear growth stage and turbulent mixing stage (Dimonte, 2000). In the steady growth stage, the initial disturbances at the interface rapidly develop into bubbles (lighter fluids flow into heavier fluids) and spikes (heavier fluids invade into lighter fluids) which both develop with the terminal velocity. Another interface instability, Kelvin-Helmholtz Instability (KHI) will happen during this process, thus the KHI can be regarded as a kind of phenomenon that along with the RTI. The top of bubbles and spikes will roll up when the KHI appears, and the shape of them transforms like “mushrooms”. In the multimode disturbance RTI, bubbles will compete and merge with each other, “mushrooms” will break, the interface becomes complicated and hardly to predict. The RTI finally grows into the turbulent mixing stage.

Experimental researches laid the foundation of the field of interface instability. Taylor first observed the single bubble's rising at a constant speed in a RTI experiment (Taylor, 1950). In 1973, Ratafia observed the formation of bubbles and spikes, he first found the rolling up of spikes' top (formation of “mushrooms”) due to the KHI (Ratafia, 1973). Since 1980s, many elaborate and creative researches has been carried out with the demand of the high-tech field such as ICF. Ken Read adopted a vertical acceleration vessel to study the variation of the interface during RTI in 1984 (Read, 1992). Dimonte & Schneider used straight line engine to accelerate the interface and they got the characteristic of the RTI under the complicate acceleration (Dimonte et al., 2007). Dalziel et al. (Dalziel, 2000) isolated two fluids with plate, and the process of RTI under the gravity was studied. In the field of nuclear reactor severe accidents field, lots of researches on FCI have also been carried out since 1990s. Dinh et al. (1999) carried out some researches on the jet breaking in FCI process. In recent years, Hyo Heo et al. (2015) poured molten Wood metal into water to study different influential factor in FCI. The liquid-liquid injection experiment was carried out by Shimpei Satio (Saito et al., 2015) to study the influences of density ratio and viscosity ratio on the FCI process. All these researches have shown that the interface instability is an important impact factor in jet breaking behavior of FCI process, RTI can be observed in these experiments.

In numerical simulations of RTI, Youngs (1984), Glimm (Glimm and Li, 1988) and Li Xiaolin (Li, 1993) used Interface Tracking, MAC and Level Set method to simulate the RTI in 2D and 3D, respectively. The Front Tracking, VOF and LBM methods are the most common approaches in RTI simulations. In recent years, the DNS is also adopted in RTI simulation with the development of computer technology (Reckinger et al., 2016). There are also a series numerical research about RTI using meshless method, which are mainly refer to those particle methods such as Smoothed Particle Hydrodynamics (SPH) and Moving Particle Semi-implicit method (MPS). But the RTI simulations carried out by these particle methods are mainly adopted to validate different multiphase flow algorithms of each researcher. Simulation results in these researches lack of rigorous theoretical analysis and always show poor agreement with the existing RTI theory. For example, Jie Liu et al. (2005) used MPS-FVM method to simulate the RTI with single-mode disturbance, he compared his simulation results with the theoretical solution in linear growth stage. He concluded that when the surface tension force was not involved in the simulation, simulation results were far from the theoretical solution, but when the surface tension force was considered, the situation can be improved. In Shakibaeinia's paper (Shakibaeinia and Jin, 2012), he adopted the explicit multiphase algorithm similar to that in SPH to calculate the fluid field pressure, and a RTI simulation with upwards disturbance was simulated. The results were compared with those calculated by VOF, but deviations were shown between these two methods. Jeong used the pressure gradient model based on sum of neighbor particles' pressure (Jeong et al., 2013) to simulate the same RTI case as Liu's in reference (Liu et al., 2005), but the interface deformation in his paper was significantly slower than Liu's results. There is a widespread problem in all of the studies above: the initial disturbances in previous simulations of the RTI processes using particle methods are all displacement disturbances formed by particles along interfaces. The resolution of the interface can't be high enough to describe irregular shape (e.g. a Cosine wave shape) due to the characteristic of the Lagrange particle method. This leads to a large different between the results of particle methods and those of grid methods or the theoretical solution, especially in the early stage of RTI. The shape of the disturbance in the linear stage of RTI is closer to the square wave rather than the Cosine wave (Liu et al., 2005; Shakibaeinia and Jin, 2012). What's more, the boundary conditions in the literature above are all set as the no-slip boundary, but in many other RTI numerical researches with grid methods, boundary conditions are often set as the periodic boundary and free-slip