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The Investigation of Rayleigh-Taylor Mixing with a Premixed Layer by BHR Turbulence Model

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Abstract. The Rayleigh-Taylor mixing with a premixed layer is investigated in the present study. A BHR-II turbulence model is employed to simulate the Rayleigh-Taylor mixing with different premixed layers. The implementation of the BHR-II model is described in detail and validated in canonical problems. Afterwards, the classic Rayleigh-Taylor instability (RTI) with a premixed layer is studied. Effects of density ratio, layer thickness and density profiles on the late time behaviour of classic RTI are analysed, and the results are also compared with ILES data. It turns out that the premixed layer delays the transition time of turbulent mixing. The late time behaviours of different premixed cases show a similar trend with the similarity of their distributions of turbulent kinetic energy. It is also shown that the premixed layer has little effect on the tilted angle in the canonical tilted rig case while the temporal evolution of the turbulent mixing at the early beginning is distinctly influenced by the premixed layer.

AMS subject classifications: 76F25, 76F55, 76T99

Key words: Turbulence model, Rayleigh-Taylor instability, premixed layer.

1 Introduction

Rayleigh-Taylor instability (RTI) exists widely in nature and industry. The knowledge of RTI extends our understanding of supernova core-collapse explosion, inertial confinement fusion and many other physical problems [1–4]. As a classical hydrodynamic instability, there have been quite a few studies on the RTI [5–13]. Turbulent mixing caused by this kind of instability is somehow a key issue in these problems. In classic RTI, there is an ideal interface between two fluids where the heavy fluid is resting on the light fluid. Then instability of the interface occurs and develops naturally. In many physical problems, the interface is always not a uniform and sharp surface and the mixing between two fluids occurs before the instability develops. An example is the ejecta generation

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from shocked metal interface. The fragments are well mixed with gas firstly. In this situation, the interface turns to be a layer with continuous density and volume fraction. The turbulent mixing induced by hydrodynamic instability with such a premixed layer has not been sufficiently investigated.

Theoretical methods have been widely used in the analysis of early evolution in RTI [14–21] when the perturbations are not significantly amplified and interaction between different scales is not strong. Linear stability analysis (LSA) and nonlinear stability analysis (NSA) have been proved efficient in this region. When there is a premixed layer with continuous density gradient, it is turned out that the growth rate decreases due to the characteristic thickness of the layer [15, 22].

Beyond this region, the strong nonlinear interaction between scales leads the flow to transition and turbulent state. Numerical simulations and experiments [23–32] are usually employed to study the behaviours at late time of RT mixing due to the complexity of turbulence. However, the influence of premixed layer on the transition and turbulent mixing is not clear until now. Although the computational ability has been enormously improved in the past twenty years, the direct numerical simulation (DNS) of RTI [34–36] is still an extremely difficult work, especially at high Reynolds number. An alternative method to investigate the turbulent mixing cause by RTI is the Reynolds average Navier-Stokes (RANS) models which had been improved for the multi-material mixing by the pioneering work of Besnard et al. [37]. Instead of buoyancy-drag model or traditional two-equation turbulence model [38, 39] (i.e., K-ε or K-L model), this kind of methods named by BHR is a multi-equation turbulence model that can capture the necessary physics in material mixing [40]. The BHR family of turbulence models has been designed and developed by Los Alamos National Laboratory for simulating various kinds of variable density turbulent mixing, including Kelvin-Helmholtz (KH), Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instability [41–44]. In contrast to the direct numerical simulation (DNS) and large eddy simulation (LES) method, the BHR turbulence model can save a large amount of computation while the efficiency of this model has been validated in many canonical problems.

BHR turbulence model has been developed for decades. There are a variety of modified versions for this kind of turbulence models [45–47] according to different closure methods of second order correlations and their transport equations. In present study, we focus on the BHR-II turbulence model which has been widely used in previous studies and its efficiency is also demonstrated [42, 43, 48]. We employ the BHR-II model to study the classic Rayleigh-Taylor and the canonical tilted rocket rig case with a premixed layer. The efficiency of BHR-II model for the instability of premixed layer is validated and the physical mechanism of the turbulent mixing caused by the Rayleigh-Taylor instability with a premixed layer is also investigated.

The paper is organized as follows. In Section 2, the governing equations of the BHR-II turbulence model is described in detail. Numerical method and implementation of our simulation are also introduced. The validation and analysis are presented in Section 3. In Subsection 3.1, our implementation is validated in two canonical cases, and the results