Ocean Engineering 126 (2016) 432–466

Contents lists available at ScienceDirect

Ocean Engineering

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

Evaluation of a new scaling term in preconditioning schemes for computations of compressible cavitating and ventilated flows

Cong-Tu Ha, Warn-Gyu Park*

School of Mechanical Engineering, Pusan National University, Busan 609-735, South Korea

ARTICLE INFO

Keywords:
Cavitation
Ventilation
Multi-phase mixture flow
Compressible flow
Preconditioning
Dual-time stepping

ABSTRACT

This paper presents the application of a dual-time stepping scheme to the computation of unsteady cavitating and ventilated flows. The flows are modeled for multidimensional problems based on fully-compressible multi-component, multi-phase mixture Navier–Stokes equations. In order to handle the sharp discontinuity flows that previously developed preconditioning methods fail to do, the dual-time stepping scheme introduces a modified preconditioning parameter. This preconditioning parameter is defined using a "pressure-based" form so that accurate, efficient, and robust computations can be performed without dependence on the Mach number. The system of equations is solved on multi-block structured curvilinear grids with a high-resolution upwind scheme. Both the convergence performance and validation of the computational results are examined for various test cases including inviscid gaseous mixture flows in a tube, two-phase shock tube problem, free-surface flow in a nozzle, single-phase water flow, cavitating flows, transonic water flow, and ventilated flows over underwater vehicles. The results obtained with the modified form are in good agreement with the exact solutions and experimental data. In terms of accuracy, efficiency, and robustness, the modified form is strongly recommended for use in mixture flow computations when sharp discontinuities are present.

1. Introduction

Cavitation is known as the formation of vapor cavities as the local pressure drops below the saturation pressure. This phenomenon can be observed in a wide variety of industrial and military applications. Representative examples include flows over ship propellers, in heat exchangers, over underwater vehicles, and in turbines and pumps. Performance alteration, noise, vibration, and erosion are some of the pronounced effects of the cavitation phenomenon. However, for high-speed underwater vehicles, the reduction in drag associated with natural super-cavity flows or ventilated noncondensable gaseous flows may have great potential benefit (Ahn et al., 2010, Kawakami et al., 2009).

In general, the modeling of cavitating flows can be categorized into three approaches, namely (1) single-phase approach, (2) homogeneous approach, and (3) multi-fluid approach. In the first approach, only one set of conservations for the mass and momentum for the single-phase, supplemented by the equations of state (EOS) for liquid and vapor phases is employed (Esfahanian et al., 2012; Heul et al., 2000; Song and He, 1998). If the local pressure is greater than the saturation pressure, the local density is forced to equal to that of the liquid phase, and if the pressure is lower than the saturation pressure, the local density is forced to equal to that of the vapor phase. As the name of this method suggests, only a single state can exist at a particular location. Therefore, it is known that the single-phase approach cannot distinguish between liquid and vapor in regions where both exist. In the homogeneous approach (Ahuja et al., 2001; Edwards, 2001; Lindau et al., 2001; Owis and Nayfeh, 2003; Zhang and Khoo, 2014), the multi-phase mixture is assumed to be in mechanical and thermodynamic equilibrium, allowing the velocity slip among phases to be neglected. For these assumptions, the homogeneous approach also consists of only one set of conservations of momentum and energy for the mixture, supplemented by the EOS and conservations of mass with mass transfer terms (Merkle et al., 1998) for all the phases. The final approach (LeMartelot et al., 2014; Petitpas et al., 2011; Saurel et al., 2008) deals with the multi-fluid models. In this approach, the individual fluids are considered to flow freely with their own velocities, temperatures, and pressures. Along with the closure relations, multiple set of equations needs to be solved. Each set consists of conservations of mass with mass transfer terms, momentum, and energy for the corresponding fluid. Of the two later approaches, the homogeneous approach would be preferable for the application to cavitating and ventilated flows in which the phases are well mixed and no slip occurs. In addition, this approach is much more efficient than the multi-fluid

* Corresponding author.
E-mail address: wgpark@pusan.ac.kr (W.-G. Park).

http://dx.doi.org/10.1016/j.oceaneng.2016.09.029
Received 2 September 2015; Received in revised form 13 September 2016; Accepted 14 September 2016

one and is therefore applied in this study.

The primary difficulty in the application of density-based methods to compressible multi-phase flows at low-speed is associated with the large disparity in the characteristic waves. A common technique to overcome this difficulty is to use preconditioning techniques. The idea of the preconditioning is to modify the time-dependent terms by multiplying the vector of the time derivatives by a properly defined matrix. This matrix uses a preconditioning parameter that is defined such that it slows the acoustic wave down toward the convective wave, thus reducing the disparity (Choi and Merkle, 1993; Lee, 1996; Jafaria et al., 2015; Lindau et al., 2003; Rong and Wei, 2014; Turkel, 1999; Venkateswaran et al., 2002). We refer to this as the "convective-based" form. This form again uses a cutoff value to prevent the preconditioner from becoming singular, which is discussed in the following sections. For steady computations, the accuracy and improvement of the convergence rates of this technique over the non-preconditioning scheme have been well examined for both compressible single-phase (Anker and Mayer, 2004; Bas et al., 2014; Li et al., 2014; Reed, 1995; Tyliszczak and Deconinck, 2013; Volpe, 1993; Weiss and Smith, 1995) and compressible multi-phase mixture computations (Lindau et al., 2001; Owis and Neyfeh, 2003). The use of preconditioning matrices alters the time accuracy of the original form of the governing equations; it is therefore applicable only in steady-state simulations. In order to apply the preconditioning strategy to unsteady problems, a dual time-stepping technique (Jameson, 1991) that involves a pseudo-time marching process within each physical-time step can be applied. Dailey and Pletcher (1996) implemented a multigrid for a preconditioned dual-time step scheme and obtained the time-accurate solutions for the impulsively started lid driven cavity and pulsatile channel flow. Their results compare favorably with the exact solutions. Improvements of computational efficiency for unsteady flows, however, showed a dependence on the choice of the physical-time step size. Pandya et al. (2003) presented their implementation of the preconditioned dual-time scheme for several steady flow tests and also found that their solution is dependent on the choice of physical-time steps. Turkel and Vatsa (2005) performed the dual-time stepping calculations for a vortex motion and compared their results with the exact ones. However, the comparison is not clear because they introduced many problem-dependent parameters for the adjustment of the pseudo-time and the preconditioning parameter. Alkishriwi et al. (2006) examined their solution of the turbulent flow around a cylinder using an implicit dual-time stepping and showed good agreement with experiments. However, this comparison was made only for a steady state. Housman et al. (2009) performed a dual time stepping scheme for a steady injection of gas into a closed vessel and then compared their time-accuracy solutions for the total mass with the exact solutions. The results again indicated a problem dependence. More recently, Campobasso and Drofelnik (2012) presented a mixed dissipation term to alleviate the problem dependences that were observed in the previous studies (Dailey and Pletcher, 1996; Housman et al., 2009; Pandya et al., 2003). This mixed dissipation term uses two preconditioning parameters in a way such that the amount of the numerical dissipation is controlled to obtain an accurate solution for unsteady flows. The predictive capability and the computational performance of their proposed method were examined by presenting the analysis of a time-dependent flow associated with the vortex shedding behind a circular cylinder. In the examinations of dual-time stepping schemes which have been described earlier, at least to our knowledge, the accuracy assessment of the dual-time stepping scheme has not been well demonstrated. There is a lack of studies that clearly demonstrate the effects of the problem-dependent parameters such as the cutoff value (Turkel, 1993; Lee et al., 1997) and the convergence criterion on the time accuracy of the numerical solution. It will be shown for the tests considered here that reasonably correct solutions for convergence are only obtained with an appropriate choice for the cutoff value. In addition, when dealing with discontinuity flows, such as two-phase shock tube problems and ventilated flows containing very high flow gradients near the noncondensable gas/water contact regions, we found the convective-based form to lack robustness owing to incorrect scaling of numerical dissipation, which induces large errors in the pressure, temperature, and velocity computations near the discontinuity. As a result, the numerical scheme fails to converge after just one or several iterations. To our knowledge, such numerical issues have not been dealt with in previous studies. It is, therefore, our motivation to look for an alternative form to circumvent these issues.

The outline of the paper is as follows. This section is followed by brief presentations of the governing equations for the multi-component multi-phase mixtures as well as their relevant closure relations. Section 3 presents the preconditioning system with the modified preconditioning parameter. Section 4 describes the numerical implementation. The validation of the numerical scheme and some representative examples are then presented and discussed in Section 5. The paper ends with final remarks and a brief description of future work.

2. Governing equations

The three-dimensional, dimensionless forms of the fully-compressible multi-component, multi-phase mixture Navier–Stokes equations are written in generalized curvilinear coordinates (ξ, η, ζ) as follows:

$$\Gamma_e \frac{\partial \hat{Q}}{\partial t} + \frac{\partial \hat{E}}{\partial \xi} + \frac{\partial \hat{F}}{\partial \eta} + \frac{\partial \hat{G}}{\partial \zeta} - \frac{\partial \hat{E}^v}{\partial \xi} - \frac{\partial \hat{F}^v}{\partial \eta} - \frac{\partial \hat{G}^v}{\partial \zeta} = \hat{S} \tag{1}$$

where

$$\hat{Q} = \frac{Q}{J} = \frac{1}{J}\begin{pmatrix} p \\ u \\ v \\ w \\ T \\ Y_v \\ Y_g \end{pmatrix}, \quad \hat{E} = \frac{1}{J}\begin{pmatrix} Y_l\rho_m U \\ \rho_m u U + \xi_x p \\ \rho_m v U + \xi_y p \\ \rho_m w U + \xi_z p \\ \rho_m h_0 U \\ Y_v\rho_m U \\ Y_g\rho_m U \end{pmatrix}, \quad \hat{F} = \frac{1}{J}\begin{pmatrix} Y_l\rho_m V \\ \rho_m u V + \eta_x p \\ \rho_m v V + \eta_y p \\ \rho_m w V + \eta_y p \\ \rho_m h_0 V \\ Y_v\rho_m V \\ Y_g\rho_m V \end{pmatrix}, \quad \hat{G} = \frac{1}{J}\begin{pmatrix} Y_l\rho_m W \\ \rho_m u W + \zeta_x p \\ \rho_m v W + \zeta_y p \\ \rho_m w W + \zeta_y p \\ \rho_m h_0 W \\ Y_v\rho_m W \\ Y_g\rho_m W \end{pmatrix},$$