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Study on the algorithm for solving two-fluid seven-equation two-pressure model

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ABSTRACT

Compared to the two-fluid single-pressure model, the two-fluid seven-equation two-pressure model has been proved to be well-posed (hyperbolic) due to its real characteristic values and exists a wide range of physical and industrial applications. In this paper, the partial differential equation system of the two-pressure model is discretized numerically using the finite volume integral method with staggered grids. The semi-implicit scheme is implemented to achieve accurate and stable numerical results. The source terms containing the heat and mass transfer, no instantaneous relaxation, wall drag and gravity field are included in this scheme. Eventually, the proposed numerical scheme is validated with several classical benchmark tests. The calculation results show that the proposed numerical scheme is accurate and robust in solving two-phase flows.

1. Introduction

In many industrial applications especially in the nuclear plant system, two-fluid (two-phase) flows exist widely and are the most important phenomenon. Accurate analysis of two-fluid flows is a subject of intense current interest and of great importance in research topics. There are many important models in literature for describing two-phase flows such as the homogeneous equilibrium model, the drift flux model and the two-fluid model.

The two-fluid six-equation model treating each phase as a separate fluid is assumed to have different velocity for each phase in the sense that this model is the most complete approximation for the two fluid flow. So current main reactor thermal-hydraulics analysis codes such as RALAP5, ATHLET, APROS, TRACE, TRAC, CATHENA and CATHARE, are all based on such six-equation model. However, due to an equilibrium pressure assumption, such model has been proved to be ill posed, which means that the initial value problem with the two-fluid model equation system is non-hyperbolic and has imaginary characteristic eigenvalues, leading to the wrong wave dynamic and numerical unphysical oscillations.

In order to overcome the ill-posed issue of two-fluid single-pressure model, there are three important ideas: implementation of the interfacial pressure term (Emonot et al., 2011), implementation of the virtual mass force term (Sloan et al., 1992) and application of the two-pressure model. The interfacial pressure differential term and the virtual mass force differential term are added into phasic momentum equations to restore the hyperbolicity. The present authors investigated the ill-posed characteristic and analyzed ill-posed regions of the two-fluid single-pressure model and the effect of the virtual mass force and the interfacial pressure on improving the ill-posedness (Chao et al., 2016). The results show that the appropriate virtual mass force and the appropriate interfacial pressure can well improve the ill-posedness of the six-equation model, and the appropriate combination of them can significantly improve the ill-posedness for most conditions of practical interest in reactor safety analyses. However such two-fluid six-equation single-pressure model cannot completely avoid the ill-posedness with the appropriate virtual mass force and the appropriate interfacial pressure, only the two-fluid two-pressure model in which each phase is assumed to have its own pressure, is a well-posed model in all situations.

Many researchers (Abgrall and Saurel, 2003; Banerjee and Chan, 1980; Berry et al., 2010; Chang and Liou, 2005; Chen et al., 1996; Chinnayya et al., 2004; Chung et al., 2001; Drew, 1983; Hancox et al., 1980; Hicks, 1981; Jin and Ishii, 2000; Lim et al., 2003; Long, 1956; Nguyen, 1983; Passman et al., 1983; PI et al., 2008; Ramshaw and Trapp, 1978; Ransom and Hicks, 1984, 1988; Ransom and Scofield, 1976; Rousseau and Ferch, 1979; Saurel, 1999; Saurel and Abgrall, 1999; Saurel and Gallouet, 1998) carried out the study of such two-pressure model due to the well-posed

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Nomenclature

Symbol

A	the cross-sectional area of the pipeline (m^2)
A_{int}	the interfacial area between two phases per unit volume (m^{-1})
C_{iD}	the interfacial drag coefficient between two phases
c_k	the phase k sound velocity ($m{\cdot}s^{-1}$)
D	the hydraulic diameter (m)
$F_{wall,gas}$	wall frictional force acting on gas phase ($N{\cdot}m^{-1}$)
$F_{wall,lquid}$	wall frictional force acting liquid phase ($N{\cdot}m^{-1}$)
$F_{liquid,gas}$	interfacial drag between two phases ($N{\cdot}m^{-1}$)
$f_{wall,k}$	the wall friction coefficient for phase k
g_x	the gravity acceleration in the direction of flow ($m{\cdot}s^{-2}$)
H_{ig}	interface-to-gas convective heat transfer coefficient per unit volume ($W{\cdot}m^{-3}{\cdot}K^{-1}$)
h_{ig}	convective heat transfer coefficient between the interface and the gas phase ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
h_{if}	the interface-to-liquid convective heat transfer coefficient ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
H_{if}	interface-to-liquid convective heat transfer coefficient per unit volume ($W{\cdot}m^{-3}{\cdot}K^{-1}$)
h_g^*	the gas specific enthalpy evaluated at the interfacial mass transfer condition ($J{\cdot}kg^{-1}$)
h_f^*	the liquid specific enthalpy evaluated at the interfacial mass transfer condition ($J{\cdot}kg^{-1}$)
P_g	gas pressure (Pa)
P_f	liquid pressure (Pa)
P_{int}	interfacial pressure (Pa)
Q_{ig}	interface-to-gas phase heat transfer per unit volume ($W{\cdot}m^{-3}$)
Q_{if}	interface-to-liquid phase heat transfer per unit volume ($W{\cdot}m^{-3}$)
T_k	temperature for phase k (K)
T^s	the saturation temperature under the interfacial pressure P_{int} (K)
U_g	vapour/gas specific internal energy ($J{\cdot}kg^{-1}$)
U_f	liquid specific internal energy ($J{\cdot}kg^{-1}$)
v_{int}	the interfacial velocity ($m{\cdot}s^{-1}$)
v_g	gas velocity ($m{\cdot}s^{-1}$)
v_f	liquid velocity ($m{\cdot}s^{-1}$)
V_L	volume of the control volume L (m^3)
Z_k	the phase k acoustic impedance ($kg{\cdot}m^{-2}{\cdot}s^{-1}$)
α_g	gas volume fraction
α_f	liquid volume fraction
ρ_g	gas density ($kg{\cdot}m^{-3}$)
ρ_f	liquid density ($kg{\cdot}m^{-3}$)
ρ_{int}	the interfacial density corresponds to the liquid saturated density with P_{int} ($kg{\cdot}m^{-3}$)
ρ_c	the continuous phase density ($kg{\cdot}m^{-3}$)
Γ_g	the net gas-liquid mass transfer per unit volume ($kg{\cdot}m^{-3}{\cdot}s^{-1}$)
μ	the pressure relaxation coefficient function ($Pa^{-1}{\cdot}s^{-1}$)
τ_P	the pressure relaxation time (s)
Δx	the length of the control volume (m)

Subscript

g	gas phase
f	liquid phase
int	phasic interface
k	gas phase (g) or liquid phase (f)
initial	initial condition

Acronyms

NUSOL	Nuclear Safety and Operation Laboratory, Xian Jiaotong University

advantage since 1976. Three two-pressure models are usually applied in the literature. One of them is a two-fluid two-pressure model with the surface tension (Chung et al., 2001; Ramshaw and Trapp, 1978). Furthermore, for stratified flows, slightly different pressures with the effect of the gravitational force are considered in the two-fluid two-pressure model (Banerjee and Chan, 1980; Hancox et al., 1980; Long, 1956; Rousseau and Ferch, 1979). This model is hyperbolic with the help of the gravity force. However, while the gravitational field vanishes, this two-pressure model will be reduced to a single-pressure model. All the researchers for the above two two-pressure models tried to gain the well-posed two-pressure model through algebraic means which seemed to be some limited successes and missing some key information for two-fluid flows. Last but not least, the most important two-pressure model is the two-fluid seven-equation model to which much attention has been devoted (Baer and Nunziato, 1986; Berry et al., 2010; Chen et al., 1996; Chinnayya et al., 2004; Hicks, 1981; Jin and Ishii, 2000; Lim et al., 2003; Nguyen, 1983; Passman et al., 1983; PI et al., 2008; Ransom and Hicks, 1984, 1988; Ransom and Scofield, 1976; Saurel, 1999; Saurel and Abgrall, 1999; Saurel and Gallouet, 1998). Such seven-equation model consists of six conservation partial differential equations (two mass equations, two momentum equations, two energy equations) and a volume fraction transport equation. With the seventh volume fraction transport equation, such seven-equation model admits seven real eigenvalues and is unconditionally hyperbolic (well-posed) in the sense of Hadamard (2014), Toro (2013). This seven-equation model will be studied in this paper.

In the last few decades, a volume of work has been conducted on the numerical computation of this seven-equation two-pressure model. There are three important ideas: finite volume method, finite element method and discrete equation method (DEM). Liang et al. (2014) presented the operator splitting approach to decompose the seven-equation model into the hyperbolic operator and the relaxation operators. They used Godunov scheme and the HLLC flux to gain the numerical scheme for solving such seven-equation model. But the relaxation parts were solved by the instantaneous relaxation procedures which meant that the relaxation coefficients were infinite. And the interfacial heat/mass transfer were ignored in his scheme. Zein et al. (2010) implemented the heat and mass transfer to model phase transitions. He also used the splitting approach and Godunov-type discretization to obtain the solution of this two-pressure model. Both the velocity and the pressure however were assumed to be in the instantaneous equilibrium too. Gallouët et al. (2004) proposed no instantaneous local equilibrium between phases to compute the seven-equation model which resulted in the different pressure and the velocity for each phase. Two finite volume methods based on Rusanov scheme and Godunov scheme were presented to solve such two-pressure model. The source terms such as relaxation terms, the phase change and gravity were calculated by a fractional step approach in his scheme. Ambroso et al. (2012) constructed a new approximate Riemann solver for the numerical approximation of the solutions of the seven-equation model. The interfacial drag force, gravity field and bounded relaxation pressure term were included in his numerical solver. Berry et al. (2010) and Abgrall