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Validation of a two-fluid model on unsteady liquid–vapor water flows

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ABSTRACT

This paper is devoted to the validation of a two-fluid two-phase flow model in some highly unsteady situations involving strong rarefaction waves and shocks in water-vapor flows. The two-fluid model and its associated numerical method that were introduced in a previous work are first recalled, and details on the computational scheme and the verification of interfacial mass transfer terms are provided. Consistency with experimental data is checked in three configurations. First, a comparison with the speed of sound in a two-phase mixture is detailed. Afterwards, numerical approximations obtained with the two-fluid approach are discussed and compared with some experimental data documented in the Simpson water-hammer experiment and the high depressurization with flashing associated with Canon experiment.

1. Introduction

The development of models and associated numerical methods for the simulation of two-phase flows should be achieved in three distinct but evolutionary steps. The derivation of suitable models, both from a mathematical and physical point of view, is the first step that provides closed sets of equations involving non linear PDEs. Then numerical algorithms must be found that would provide convergent series of approximations towards solutions of the latter PDEs, and this corresponds to the verification process. Afterwards numerical results obtained with that set of PDEs must be compared with available experimental data, making sure that the mesh size is sufficiently small so that numerical approximations are no longer sensitive to a further mesh refinement. This last step is referred as the validation step; it is mandatory and is in fact the main objective of the whole approach. Once these three steps have been achieved with the most intense scrutiny, one may tackle the difficult problem of the quantification of uncertainities, but it would be meaningless to begin that work before the modeling/verification/validation steps had been completed, as recalled in [7] for instance.

We focus in this paper on water-vapor flows with mass transfer, with emphasis on water-hammer flows and thus on shock waves occurring in the transient, and on sudden depressurizations that might arise if some loss of fluid would happen in a coolant circuit. This of course requires the application of a two-phase flow model that can handle heat and mass transfer in highly unsteady situations. Actually, *the main aim in the current work is to scrutinize a few available validation test cases of unsteady two-phase flows*, and in that sense, this work may be seen as a sequel of the paper [32] where emphasis was put on the presentation of a two-fluid model, together with suitable numerical methods and their verification, while restricting to gas–liquid flows without any mass transfer.

Thus we will first recall and summarize herein the main characteristics concerning the two-fluid two-phase flow model that will be used, and its associated numerical method, and then we will investigate features linked with mass transfer. The two-phase flow model describes the dynamics of seven quantities: the statistical fractions, the mean densities, mean velocities and mean temperatures within each phase. The model and its main properties will be briefly recalled in Section 2. For further details on this class of two-fluid models, the reader is referred to [5,10,6,13,19,22–24,26,28,14,33,36,37] among others. Afterwards, we will rather quickly

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provide the main numerical tools that are used in the approximation of the two-fluid model in the Finite Volume code. Basically, the algorithm relies on the use of a fractional step method that complies with the entropy inequality, and it treats separately convective terms and relaxation terms. The most important properties and constraints will be briefly described, and a more detailed discussion on some possible way to cope with mass transfer between phases will follow. Obviously, other approaches might be considered as well, such as those introduced in [1,3,4,26,47,51] for instance. The last section will be devoted to the presentation of three distinct cases and associated comments.

2. The two-fluid model

The derivation of the two-fluid model which is described in the sequel relies on classical statistical averaging and closure laws, following a standard thermodynamical approach, the keystone of which is the entropy inequality. Many details and comments can be found in [24,33], and also in [19,35,36,28,10]. We would like to emphasize that:

- this particular model does not take the counterpart of single-phase Reynolds stresses into account (these are neglected). Some possible extensions in that direction are currently examined, but this remains beyond the scope of the present work, which basically aims at investigating some validation test cases;
- instantaneous single-phase equations of state rely of stiffened gas EOS. Thus a straightforward consequence is that averaged EOS may be written exactly as functions of the sole main unknowns (mean pressure, mean internal energy and mean density);
- some high-order statistical correlations involving pressure and velocity fluctuations are neglected. As underlined in [33], some non-trivial closure laws might be accounted for, while keeping the same entropy–entropy flux formulation, following the basic approach of Ristorcelli [44], but we also know that this would render the system of PDEs even more intricate ([8,52]); hence these extensions have not been examined in detail up to now.

Before going further on, we recall that the main specifications for the model derivation are such that:

- a physically relevant entropy inequality should hold for the smooth solutions of the whole model, including viscous terms and sources;
- the homogeneous model obtained by getting rid of viscous and source contributions should be hyperbolic for physically relevant phasic states (thus for positive densities, positive internal energies and positive statistical void fractions);
- unique and meaningful jump conditions should be associated with the latter homogeneous model.

2.1. Governing equations

We use classical notations in this paper. Thus $\alpha_k(x,t)$ will denote the statistical void fraction of phase $k = l, v$, so that:

$$\alpha_l(x,t) + \alpha_v(x,t) = 1$$

Variables ρ_k, U_k, P_k respectively stand for the mean density, the mean velocity, the mean pressure within phase k. We also define partial masses:

$$m_k = \alpha_k \rho_k$$

The total mean energy E_k within phase $k = l, v$ is defined as:

$$E_k = \rho_k \epsilon_k(P_k, \rho_k) + \rho_k U_k^2/2$$

where the function associated with the mean internal energy ϵ_k only depends on the mean pressure and the mean density (P_k, ρ_k).

We can now introduce the set of governing equations for the main unknown W:

$$W^t = (\alpha_v, m_l, m_v, m_l U_l, m_v U_v, \alpha_l E_l, \alpha_v E_v)$$

These governing equations of the two-fluid model read, for $k = l, v$:

$$\begin{aligned}
&\partial_t(\alpha_v) + V_{int}(W)\partial_x(\alpha_v) = \phi_v(W)\\
&\partial_t(m_k) + \partial_x(m_k U_k) = \Gamma_k(W)\\
&\partial_t(m_k U_k) + \partial_x\left(m_k U_k^2\right) + \partial_x(\alpha_k P_k) - \Pi_{int}(W)\partial_x(\alpha_k)\\
&= D_k(W) + \Gamma_k(W)\overline{U}_{int}(W)\\
&\partial_t(\alpha_k E_k) + \partial_x(\alpha_k U_k(E_k + P_k)) + \Pi_{int}(W)\partial_t(\alpha_k)\\
&= \psi_k(W) + \overline{U}_{int}(W)D_k(W) + \Gamma_k(W)\overline{H}_{int}(W)
\end{aligned} \quad (1)$$

setting: $\overline{U}_{int} = (U_l + U_v)/2$, and: $\overline{H}_{int} = U_l U_v/2$.

As it has been emphasized in [24,33] among other references, admissible closure laws for $\Pi_{int}(W)$ may be exhibited in order to comply with a physical entropy inequality. In practice, this means that, assuming a convex form for $V_{int}(W)$:

$$V_{int}(W) = \xi(W)U_l + (1 - \xi(W))U_v. \quad (2)$$

the closure law for $\Pi_{int}(W)$ should be of the form:

$$\Pi_{int}(W) = \chi(W)P_l + (1 - \chi(W))P_v \quad (3)$$

with:

$$\chi(W) = \frac{(1 - \xi(W))/T_l}{(1 - \xi(W))/T_l + \xi(W)/T_v} \quad (4)$$

The latter function $\chi(W)$depends on the mean temperatures T_k which are defined by:

$$1/T_k = \partial_{P_k}(S_k)/\partial_{P_k}(\epsilon_k)$$

where the $S_k(P_k, \rho_k)$ denote the mean phasic entropies that must comply with:

$$c_k^2 \partial_{P_k}(S_k) + \partial_{\rho_k}(S_k) = 0 \quad (5)$$

denoting:

$$c_k^2 = (\partial_{P_k}(\epsilon_k(P_k, \rho_k)))^{-1}\left(\frac{P_k}{(\rho_k)^2} - \partial_{\rho_k}(\epsilon_k(P_k, \rho_k))\right).$$

We also set:

$$\mu_k = \epsilon_k + P_k/\rho_k - T_k S_k$$

At this stage, it only remains to define the source terms $\Gamma_k(W), D_k(W), \psi_k(W)$, which respectively stand for the interfacial mass transfer, the drag effects and the interfacial heat transfer, but also the right-hand side in the governing equation of the statistical void fraction $\phi_k(W)$. The latter one arises due to the statistical averaging (see [19,33]). Obviously we have:

$$\sum_{k=l,v}\Gamma_k(W) = 0; \quad \sum_{k=l,v}\psi_k(W) = 0; \quad \sum_{k=l,v}D_k(W) = 0 \quad (6)$$

and also:

$$\sum_{k=l,v}\phi_k(W) = 0. \quad (7)$$

Closure laws for the former three $\Gamma_l(W), D_l(W), \psi_l(W)$ correspond to classical terms arising in the two-fluid literature, that is: