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A simple turbulent two-fluid model

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ABSTRACT

We present in this paper a simple turbulent two-phase flow model using the two-fluid approach. The model, which relies on the classical ensemble averaging, allows the computation of unsteady flows including shock waves, rarefaction waves, and contact discontinuities. It requires the definition of adequate source terms and interfacial quantities. The hyperbolic turbulent two-fluid model is such that unique jump conditions hold within each field. Closure laws for the interfacial velocity and the interfacial pressure comply with a physically relevant entropy inequality. Moreover, source terms that account for mass, momentum and energy interfacial transfer are in agreement with the entropy inequality. Particular attention is also given to the jump conditions when assuming a perfect gas equation of state within each phase; this enables us to recover expected bounds on the mean density through shock waves.

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1. Introduction

We propose herein a turbulent two-fluid model for the prediction of two-phase flows. Actually, though we use the classical ensemble averaging [1,2], we follow here the approach used in a recent series of papers. Our main goal is to derive a two-fluid two-phase flow model that accounts for Reynolds stress tensors in a very simple way, so that the fundamental properties invoked in [3] are preserved. This means that the following specifications are enforced:

- (i) the model should be such that one could retrieve the standard Baer–Nunziato model in the laminar case;
- (ii) an entropy inequality should hold for smooth solutions, and meanwhile it should provide some guidelines for closure laws associated with interfacial mass, momentum and energy transfer;
- (iii) unique jump conditions should be valid so that meaningful and unique shock waves might be predicted.

These requirements are mandatory if we intend to predict relevant shock solutions in two-phase flows, such as those that arise in vapour explosions or other similar situations, while using the standard verification and validation process (see [4] for instance). A class of two-fluid models that are capable to predict unsteady situations has emerged from the recent literature, either for gas-particle flows (see [5–9] for instance), or for water-vapour flows (see [10–12] among others). These

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models essentially differ from one another through the definition of the interface pressure–velocity couple. We will thus focus here on the approach suggested in [3], that gave some new enlightenment on the admissible closure laws that enable us to comply with both items (ii) and (iii) recalled above.

As we will see, the constraint (ii) will in turn provide some closure laws for the interfacial pressure (see equation (7)), whereas (iii) will enable us to define relevant closure laws for the interface velocity (see equation (6)).

Moreover, in order to account for turbulent effects in a rather simple way, we will rely on the single-phase proposal introduced in [13], which inherits from the earlier work described in [14–17]. As we will see, this will minimise the number of unknowns, and inlet/outlet boundary conditions, and meanwhile will allow complying with the above-mentioned requirements (i, ii, iii). We also emphasise that the present work should not be confused with the one of [18], which was mainly inspired by [19] and [3]. Actually, though it agrees with the former items (i) and (ii), the latter turbulent model [18] is not suitable for shock solutions. Indeed, jump conditions are not defined in a unique way, due to the occurrence of non-conservative products that are active in genuinely non-linear fields; as a result, different mesh-converged solutions issuing from distinct schemes may emerge in practical computations, as it is now quite well-known (see [15,20]).

The paper is organised as follows. We first provide the governing set of equations including source terms accounting for all possible transfers between phases. The choice of relevant interfacial velocity and pressure is discussed. Then we focus on the key property of the model, which is the entropy inequality. It is compared with the laminar case and we underline how turbulent energy affects the different relaxation terms. A third section discusses the main properties of the convective system: hyperbolicity, structure of fields and jump conditions. For simplicity, we restrict ourselves to the Baer–Nunziato closure in this section, but few remarks are given about other possible closures. Particular attention is given to the jump conditions when assuming a perfect gas equation of state within each phase. In that case, we show that density ratios are bounded through shock waves and that they are in agreement with the laminar frame. Moreover, turbulent energy ratios are bounded as well, unlike pressure ratios. The last section is devoted to a few remarks on the Riemann problem.

Though the derivation of the model is quite different, we will also address in section 3 the differences and similarities with the models proposed in [21].

2. Governing equations

The two-phase flow model has been obtained by a statistical averaging of the single-phase Navier–Stokes equations. One additional topological equation on the statistical void fraction is also needed (see [2]). For the sake of simplicity, we do not detail this averaging procedure here, but we underline the fact that the tensor involving turbulent effects is modelled following the approach of [13] for the single-phase Reynolds stress tensor. Thus the governing set of equations takes the form (when neglecting viscous terms):

$$\partial_t W + \partial_x F(W) + C(W)\partial_x W = S(W) \tag{1}$$

with W, $F(W)$, $S(W)$ in $\mathbb{R}^7$, and $C(W)$ in $\mathbb{R}^{7\times 7}$. The state variable W is:

$$W = \begin{pmatrix} \alpha_1 \\ \alpha_1\rho_1 \\ \alpha_2\rho_2 \\ \alpha_1\rho_1 u_1 \\ \alpha_2\rho_2 u_2 \\ \alpha_1 E_1 \\ \alpha_1 E_2 \end{pmatrix} \tag{2}$$

where α_k, ρ_k, u_k, p_k and E_k are respectively the statistical void fraction, the mean density, the mean velocity, the mean pressure and the mean total energy of phase k, $k = 1, 2$. The statistical void factions are such that:

$$\alpha_2 = 1 - \alpha_1$$

and the mean total energy E_k is given by:

$$E_k = \frac{1}{2}\rho_k u_k^2 + \rho_k \varepsilon_k + K_k$$

where $\varepsilon_k = \varepsilon_k(\rho_k, p_k)$ is the mean internal energy of phase k and K_k is the turbulent kinetic energy:

$$K_k = K_{k,0}\rho_k^{5/3} \tag{3}$$

(with $K_{k,0} > 0$). It is important to underline the fact that the mean internal energy only depends on the mean density and the mean pressure, which is a crude assumption on statistical thermodynamics. However, one can easily prove that it is verified in the case of simple Equation Of State (EOS) such as perfect gas or stiffened gas (see [22]). We define the set of admissible states Ω by:

$$\Omega = \left\{ W \in \mathbb{R}^7 \ ; \ \alpha_1 \in]0, 1[\ , \rho_k > 0, \varepsilon_k > 0 \right\} \tag{4}$$

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