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A priori study for the modelling of velocity–interface correlations in the stratified air–water flows

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ABSTRACT

This work concerns the modelling of stratified two-phase turbulent flows with interfaces. We consider an equation for an intermittency function $\alpha(\mathbf{x}, t)$ which denotes the probability of finding an interface at a given time t and a given point $\mathbf{x}$. In Wacławczyk and Oberlack (2011) a model for the unclosed terms in this equation was proposed. Here, we investigate the performance of this model by a priori tests, and finally, based on the a priori data discuss its possible modification and improvements.

1. Introduction

In the present work we investigate stratified turbulent air–water flows where the phases are separated by a deformable, but non-broken interface. We consider the statistical approach where the ensemble averaging of physical quantities, including these connected with the fluctuating interface, is performed. After the averaging we do not deal with a sharp boundary between the two phases but receive a layer where the probability of the surface position is non-zero. In the present paper correlations between the velocity and fluctuating surface based on the a priori data are investigated. At the beginning, we refer to the work of Brocchini and Peregrine (2001a,b) where the intermittency function α denoting the probability of finding the water phase at a given point of the flow and at the given time was considered. The region where $0 < \alpha < 1$ is called the "intermittency region" or the "surface layer", cf. Fig. 1a. Brocchini and Peregrine (2001a,b) classify different regimes of the interface deformations created due to the stochastic forcing of turbulent eddies using two turbulence-related quantities: the typical length scale of the turbulent "blobs" reaching the surface denoted by L and the intensity of the turbulent fluctuations $q = \sqrt{2k/3}$, where k is the turbulent kinetic energy. Those authors divided the $L - q$ diagram into various flow regimes, cf. Fig. 1b and, based on experimental observations, introduced a coefficient $\mathscr{A}$ specific for each flow regime, associated with a thickness of the intermittency region which in the wavy region is the difference between the measured position of the highest crests t and the deepest troughs b

$$t - b = 2\mathscr{A}L(q) \tag{1}$$

The influence of turbulence on the surface deformations was further investigated experimentally e.g. in Smolentsev and Miraghaie (2005) and numerically by direct simulations of steady isotropic turbulence interacting with the free surface, cf. (Guo and Shen, 2009). In Guo and Shen (2009) several flow cases with different r.m.s. of the surface elevations (η_{rms}) due to the action of the turbulent eddies were investigated. As it was observed, the surface suppresses the normal velocity component which introduces high anisotropy to the Reynolds-stresses and produces the characteristic, dominantly 2D pancake-like eddy-structures in the surface vicinity. However, with increasing η_{rms} the surface-normal fluctuations are less suppressed and the turbulence structure in the surface vicinity resembles more this in the bulk flow, i.e. tends to isotropic state. The same observation was confirmed by experimental data in Smolentsev and Miraghaie (2005). These works show that important physics may be overlooked if the "surface layer" is simply replaced by a mean interface and unclosed velocity–interface interactions terms are neglected. We address recent contributions of Toutant et al. (2009a), Toutant et al. (2009b) (cf. also Labourasse et al. (2007)) and Yapalparvi and Protas (2012). In Toutant et al. (2009a) the continuous intermittency region was considered in the LES context. The region is created through the filtering operation and the authors called such description "a mesoscopic level". A closure for subgrid terms, including

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the velocity–interface interaction term at the mesoscopic level is proposed using the scale similarity hypothesis. Next, a macroscopic level was created where the interface was again considered as a discontinuity and the interfacial transfer terms were taken into account through appropriate boundary conditions (this step requires additional modelling assumptions).

The problem of averaging of equations describing two-phase flows in the RANS context was addressed recently in Yapalparvi and Protas (2012). The starting point was again the "intermittency region" created as a result of averaging. Then, the "sharp effective boundary" was defined giving rise to unclosed terms in the mass and momentum equations. An algebraic model for the particular case of spherical droplets falling on the free surface was proposed therein.

In contrast to the two latter approaches Wacławczyk and Oberlack (2011a,b) addressed the "mesoscopic" level of description and proposed a closure for the evolution equation of α within the intermittency zone. The resulting model contains two terms: diffusion responsible for the spreading of the intermittency region and the contraction term. It was argued in Wacławczyk and Oberlack (2011a) that the former term results from the disturbing action of turbulent eddies deforming the surface and the latter from the stabilising action of gravity and/or the surface tension. The pdf distribution and its integral i.e. the function α are particular solutions of the proposed model for the intermittency region. We mention yet another recent work (Skartlien et al., 2014) where a phenomenological, algebraic formula for the pdf of the surface position was proposed by analogy to the Boltzmann distribution. Next, the proposal was generalised to the case of breaking/entrainment by a proper prolongation of the function. Another, dual-scale modelling approach in the LES context was proposed in Herrmann (2013). Therein, the interface was transported on two meshes: a coarser mesh related to the width of the LES filter and a finer mesh that assures the exact representation of the interface. A model for subgrid component of the velocity induced by subfilter surface tension forces by analogy to the spring-dumper system was further proposed in Herrmann (2013).

The new contribution of the present work are the a priori tests of the modelling assumptions proposed in Wacławczyk and Oberlack (2011a,b). We consider a 2D vortex impinging on the initially undeformed air–water surface. We calculate the profiles of α function and other ensemble and surface-averaged statistics across the intermittency region. We compare the exact terms with the predictions of the model proposed in Wacławczyk and Oberlack (2011a,b). Moreover, we extend the approach towards the Favre-averaged quantities which allows to couple the model for the function α with the Favre-averaged mass and momentum equations. We also propose modifications which improve the performance of the model from Wacławczyk and Oberlack (2011a,b). These are other, new contributions of the present work. The a priori study of statistics across the thin intermittency zone may also serve as a database for the development of other modelling approaches on the macroscopic level.

The present paper is structured as follows. In Section 2, the model proposal from Wacławczyk and Oberlack (2011a,b) is recalled and its extension towards Favre-averaged quantities is proposed. In Section 3 some details of numerical method and the chosen test case are presented. Results of a priori tests and a modified model proposal is given in Section 4. This is followed by the summary and conclusions.

2. Model for the evolution of the surface layer

We first introduce a phase indicator function

$$\chi(\mathbf{x},t) = \begin{cases} 1 & \text{if the water phase is present at } \mathbf{x} \text{ and } t \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

The gradient of the phase indicator function can be written as the following integral over the surface $\mathcal{S}$ (Welch and Wilson, 2000)

$$\chi(\mathbf{x},t) = -\int\int_{\mathcal{S}} \mathbf{n}\delta(\mathbf{x}-\mathbf{x}_s(\lambda,\mu))A(\lambda,\mu)\mathrm{d}\lambda\mathrm{d}\mu \quad (3)$$

where $\mathbf{n}$ is the unitary surface-normal vector, directed towards the gas phase and $A(\lambda,\mu)\mathrm{d}\lambda\mathrm{d}\mu$ is the surface element. The surface is parameterized with a 2-dimensional coordinate system (λ,μ) and the term $\mathbf{x}_s(\lambda,\mu)$ denotes a point at the surface. Next, the ensemble average operator $\langle\cdot\rangle$ is defined as an average over independent realisations of the field $Q^{(n)}(\mathbf{x},t)$

$$\langle Q(\mathbf{x},t)\rangle = \lim_{N\to\infty}\frac{1}{N}\sum_{n=1}^{N}Q^{(n)}(\mathbf{x},t) \quad (4)$$

The operator (4) is applied to the phase indicator function χ. As a result we obtain a function $\alpha = \langle\chi(\mathbf{x},t)\rangle$ which takes the values between 0 and 1 and denotes the probability of finding the water phase at the given point $\mathbf{x}$ at time t, cf. Fig. 1a. The starting point is the averaged equation for the position of the interface which can be written as

$$\frac{\partial\alpha}{\partial t} + \langle\mathbf{u}\rangle\cdot\nabla\alpha + \langle\mathbf{u}'\cdot\nabla\chi\rangle = 0 \quad (5)$$

or, alternatively formulated with the use of the surface averages, cf. (Pope, 1988)

$$\frac{\partial\alpha}{\partial t} + \langle\mathbf{u}\rangle\cdot\nabla\alpha = \langle\mathbf{u}'\cdot\mathbf{n}\rangle_s\Sigma \quad (6)$$

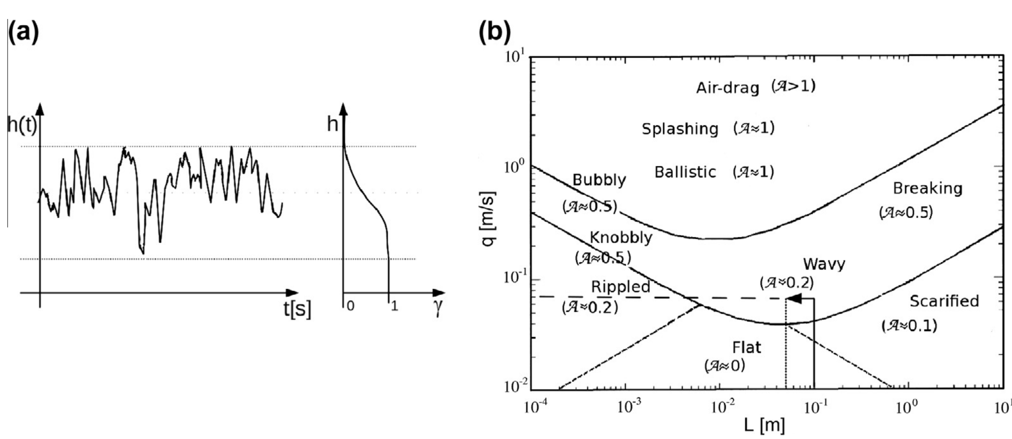

Fig. 1. (a) A sketch of the measurements of instantaneous water height and the corresponding *intermittency zone*, and (b) $(L-q)$-plane diagram from Brocchini and Peregrine (2001b). Values of q and L calculated during the current simulation are indicated on the diagram by lines with arrows.