NUMERICAL MODELLING OF INTERMITTENCY REGION IN TURBULENT STRATIFIED AIR-WATER FLOWS

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Abstract The present work deals with the modelling of turbulent air-water flows, where the phases are separated by a deformable, but non-broken interface. We use a "mesoscopic" level of description, i.e. we aim to model the probabilty α of finding the water phase at a given point of the flow. The evolution equation for the function α is solved with the use of the conservative level-set method.

MODEL FOR THE INTERMITTENCY REGION IN TWO-PHASE FLOWS

The exact position of air-water interface can be described by the indicator function, cf. Ref. [1]

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

However, in the Reynolds-averaged (RANS) methods the ensemble averaging operator $\langle\cdot\rangle$ is applied to all equations of motions leading to simplified, statistical description of the turbulent flow. The same procedure applies in the case of two-phase flows. After averaging of the indication function we obtain a smoothed 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. The region were $0 < \alpha < 1$ is called the intermittency region or the surface layer. In Refs. [3, 5] a closure for the evolution equation of α in the one-fluid approach was proposed and tested against direct numerical simulations data.

The starting point of the proposed model was the averaged equation for the position of the interface which can be written as

$$\frac{\partial\alpha}{\partial t} + \langle\mathbf{u}\rangle\cdot\nabla\alpha = -\langle\mathbf{u}'\cdot\nabla\chi\rangle \tag{2}$$

where the $\mathbf{u} = \mathbf{u}_w\chi + \mathbf{u}_a(1-\chi)$ is the one-fluid velocity vector, $\mathbf{u}_w$ is the velocity of the water phase and $\mathbf{u}_a$ is the velocity of the air phase and $\mathbf{u}'$ is the velocity fluctuation.

In Refs. [3, 5] we proposed to model the uclosed term $\langle\mathbf{u}'\cdot\nabla\chi\rangle$ in Eq. (2) by two counteracting terms: diffusion of α due to the influence of turbulent eddies which disturb the surface and its contraction due to the stabilizing effects of gravity and the surface tension

$$\frac{\partial\alpha}{\partial t} + \langle\mathbf{u}\rangle\cdot\nabla\alpha = \nabla\cdot(D_t\nabla\alpha) + \nabla\cdot[C_c\alpha(1-\alpha)\hat{\mathbf{n}}] \tag{3}$$

where $\hat{\mathbf{n}} = -\nabla\alpha/|\nabla\alpha|$ is a vector normal to the isosurface of α, D_t and C_c are model coefficients. The coefficients where estimated in Ref. [5] as $D_t = C_\mu qL$ and $C_c = C_t q$ where q is the characteristic velocity scale of the turbulent eddies, and L is their characteristic length scale. The ratio D_t/C_c determines the width of the intermittency layer, defined as the region where the probability of finding surface equals 99.7%. This fact can be connected with the empirical diagram from [1] which presents widths of intermittency layers for different air-water regimes as function of L and q.

The validity of the modelling assumption (4) was tested in [5] against direct simulations data of eddies approaching the interface, cf. Fig. 1. Initially flat surface was first deformed by the eddies and next, as the structure splits into two eddies travelling in opposite direction, the surface started to stabilize. For this case we defined the width of the intermittency layer as the difference between the highest and the lowest position of the interface, $t-b$, in the computational domain. Fig. 2 presents evolution of the top t and bottom b limits of the surface layer as they evolve in time. In *a priori* tests performed in Ref. [5] a reasonable agreement between the $-\langle\mathbf{u}'\cdot\nabla\chi\rangle$ correlation and the RHS side of Eq. (4) was obtained.

NUMERICAL METHOD

Equation (4) with the contraction and diffusion terms is analogous to the one used in the conservative level-set method [4]. Therein both terms have numerical function of keeping the particular shape of α, or "thickness of the interface" constant in time. In our case the shape of α results from the ensebmle averaging of fluctuating surface and depends on the characteristic velocity and lenght scales of turbulent eddies deforming the surface.

The solver for α equation was implemented into the second-order accurate finite volume flow solver FASTEST with existing two-phase module based on interface capturing VOF method, see Ref. [7]. Numerical implementation of the α equation solver, tests and further results are described in detail in Ref. [6]. We only mention here that solution of Eq. (4) is split into two steps. In the first step we carry out the advection of the α function in the averaged velocity field obtained

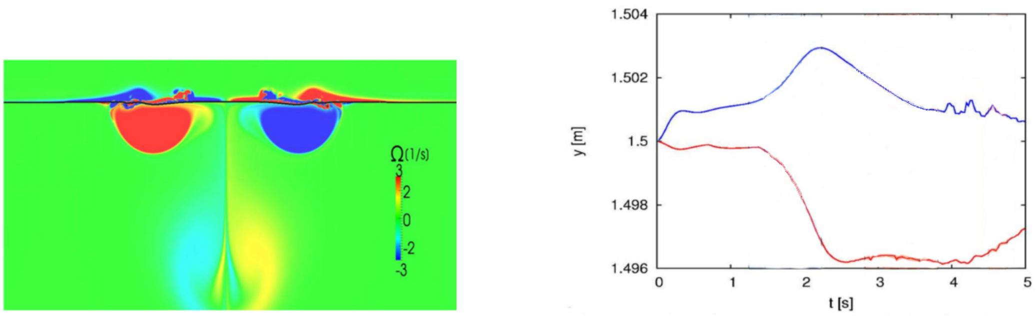

Figure 1. a) Vorticity module of two eddy structures reaching and deforming the interface, from Ref. [5], b) Top and bottom limits of the intermittency region, Ref. [5].

from the RANS solver. In this step implicit second order scheme is used for discretization in time and the second order MUSCL flux limiter is used within a deferred correction to keep bounded function [4]. In the second step, the evolution of the intermittency region is reconstructed with the use of reinitialization equation

$$\frac{\partial \alpha}{\partial \tau} = \nabla \cdot (D_t \nabla \alpha) + \nabla \cdot [C_c \alpha (1-\alpha)\hat{\mathbf{n}}] \tag{4}$$

where τ is the artificial time. The coefficients D_t and C_c are determined from the Navier-Stokes solver and remain constant during the reinitialisation step. Eq. (4) is solved in time using explicit low-storage, third order accurate TVD Runge-Kutta scheme. Equation (4) is solved until the steady state is reached.

MODELLING OF THE INTERMITTENCY LAYER

The work in progress includes application of the numerical scheme for the α equation to account for the evolution of the surface layer. The data of kinetic energy and the eddy length scale from *a priori* tests described in [5] will be delievered to the solver, profiles of α and the resulting width of intermittency layer will be calculated and compared with the *a priori* data. Next, the solver will be applied to the case of homogeneous turbulence interacting with free surface. Results of computations will be compared to the DNS data of [2].

The width of the surface layer largely influences turbulent statistics in the water side. Flat surface damps the surface-normal fluctuations acting analogously to the impermeable wall. When the eddies are strong enough to disturb the surface, this blocking effect is, in turn, reduced leading to more 3D picture of the flow. This problem will be further discussed and modelling ideas for the RANS solver will be presented.

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