NUMERICAL SIMULATION OF LIQUID-GAS STRATIFIED FLOWS USING TWO-PHASE EULERIAN APPROACH

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Safety studies related to Pressurized Water Reactor life duration and Pressurized Thermal Shock need CFD investigations using direct contact condensation on water-steam free surfaces much larger than cells size. Those Large Interface Simulations (LIS) require a special full set of models [1] which has been recently implemented and validated in the multiphase finite-volume NEPTUNE_CFD code [3]. The method allows for the location of the free surface and calculates momentum and turbulence exchanges.

Governing equations

*The two-fluid model solves 2*3 balance equations : momentum, mass and energy conservation for each phase and uses 2*2 additional balance equations for k-ε model in each phase. LIS models modify the classical momentum and energy balance :*

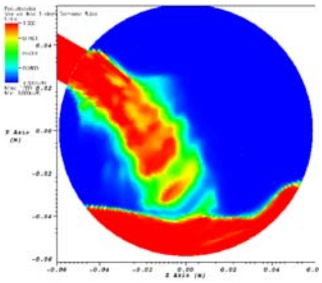
$$\frac{\partial \alpha_k \rho_k \underline{V}_k}{\partial t} + \nabla.\left(\alpha_k \rho_k \underline{V}_k \underline{V}_k\right) = -\alpha_k \underline{\nabla} P + \underline{M}_k^{LIS} + \alpha_k \rho_k \underline{g} + \nabla.\left[\alpha_k\left(\underline{\underline{\tau}}_k + \underline{\underline{\tau}}_k^T\right)\right]$$

$$\frac{\partial \alpha_k \rho_k K_k}{\partial t} + \nabla.\left(\alpha_k \rho_k \underline{V}_k K_k\right) = \frac{\partial}{\partial x_j}\left[\alpha_k \frac{\mu_k^T}{\sigma_K}\frac{\partial K_k}{\partial x_j}\right] + \alpha_k \rho_k \left(PROD_k - \varepsilon_k\right) + \Pi_K^{LIS}$$

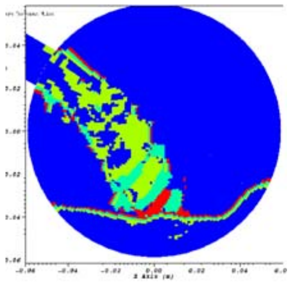
$$\frac{\partial \alpha_k \rho_k \varepsilon_k}{\partial t} + \nabla.\left(\alpha_k \rho_k \underline{V}_k \varepsilon_k\right) = \frac{\partial}{\partial x_j}\left[\alpha_k \frac{\mu_k^T}{\sigma_\varepsilon}\frac{\partial \varepsilon_k}{\partial x_j}\right] + \alpha_k \rho_k \frac{\varepsilon_k}{K_k}\left(C_{\varepsilon 1} PROD_k - C_{\varepsilon 2}\varepsilon_k\right) + \Pi_\varepsilon^{LIS}$$

Three-cell Large Interface description

The analysis of the liquid fraction field, using refined gradient method allows the location of "stratified"(ST) cells. "Gas" (STG) and "Liquid" (STL) neighbouring cells selection ends up the construction of the three-cell interface. Next figure presents, on the left a cut of the liquid fraction map in a jet, on the right the three-cell corresponding structure.



STG: red
ST: blue
STL: green
Others: dark



LIS closure laws

The momentum exchange $\underline{M}_k$ in "stratified" cells is calculated in the tangential direction $\underline{\tau}$ of the interface assuming wall-function-like friction equilibrium. The Liquid (resp. gas) velocity is taken in the STL (resp. STG) cell. The interface velocity, V_i, is solution of the system:

$$\underline{M}_G^{LIS} = a_i \rho_{Gu} u{*}_G^2\, \underline{t} = -\underline{M}_L^{LIS} = -a_i \rho_L u{*}_L^2\, \underline{t},\ \text{with } \underline{t} = \underline{\tau}/\left|\underline{\tau}\right| \text{ the tangential direction}$$

$$\underline{\tau} = (\underline{U}_L^{STL} - \underline{U}_G^{STG}) - (\underline{U}_L^{STL} - \underline{U}_G^{STG})\underline{n}\underline{n}, \qquad \underline{n} = \nabla\alpha_1 / a_i \text{ and } a_i = \left|\nabla\alpha_1\right|$$

$$u{*}_G^2 = F^{wf}\left(\left|\underline{U}_G^{STG}.\underline{\tau}\right| - V_i, \nu_G, \delta_{G-i}\right) \qquad u{*}_L^2 = F^{wf}\left(\left|\underline{U}_L^{STL}.\underline{\tau}\right| - V_i, \nu_L, \delta_{L-i}\right)$$

Production terms in K and ε equations also satisfy wall-function theory:

$$\Pi_k^{LIS} = \frac{\rho_k u{*}_k^3}{\kappa \delta_{k-i}}, \Pi_\varepsilon^{LIS} = \mu_k^T 4\kappa \left(\frac{u{*}_k}{\delta_{k-i}}\right)^3, \text{ and } \delta_{k-i} \text{ the distance between phase } k \text{ to interface}$$

Basic validation : Fabre et al. air-water channel [2]

Air and water are injected in a rectangular channel (10cm high and 13m long), with constant mass flow rates. The flow stratified. Mean velocities and turbulent measurements are compared with NEPTUNE_CFD simulation using LIS or a more basic model. The blue frontier denotes the interface position. A good agreement for both mean and fluctuating velocities is crucial for on going development of mass and energy transfer

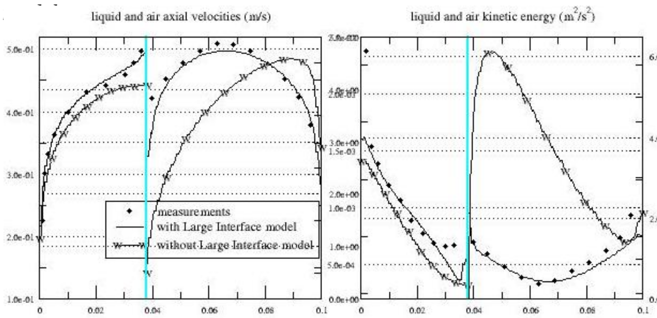
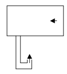


Fig 1: Comparison of the LIS model with air-water channel measurements

An industrial application: the vortex simulation



In the framework of nuclear studies evaluating loss of priming in safety pumps, we use NEPTUNE_CFD to simulate the vortex generation and gas entrainment.

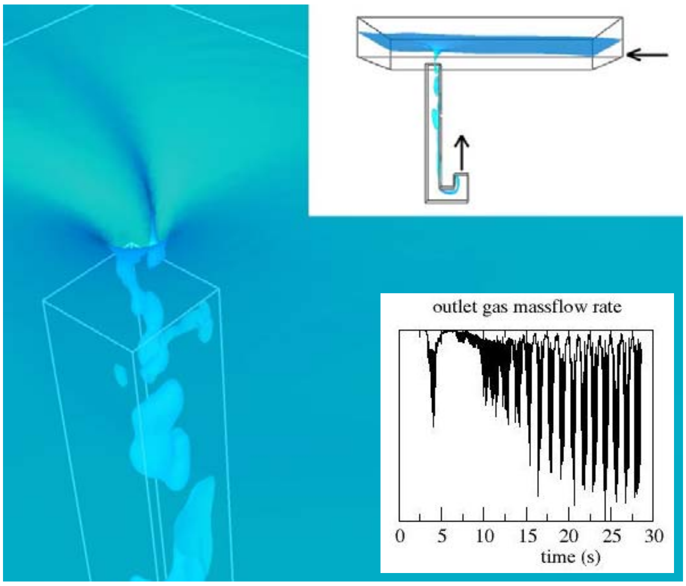


Fig 2: Simulation of a water-gas vortex using the LIS model. Inlet and outlet liquid flow rates are equal. The figure shows the iso-surface (a_L=0.5) of the liquid volumetric fraction. A large deformation of the free surface and bubbles generation can be observed near the extraction duct. The gas outlet mass flow rate shape denotes the oscillations of the phenomenon.

[1] P. Coste, J. Pouvreau, C. Morel, J. Laviéville, M. Boucker, A. Martin, "Modeling Turbulence and Friction around a Large Interface in a Three-Dimensional Two-Velocity Eulerian Code", 12th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-12), Pittsburg, Pennsylvannia, USA Sept 30-Oct 4, 2007.

[2] J. Fabre, L. Masbernat, C. Suzanne, "Stratified Flows, Part 1:Local Structure", Multiphase Science and Technology, 3, 1987, pp. 285-301.

[3] A. Guelfi, D. Bestion, M. Boucker, P. Fillion, M. Grandotto, J.-M. Hérard, E. Hervieu, P. Péturaud, "Neptune – A new software platform for advanced nuclear thermal hydraulics", Nuclear Science and Engeneering, vol. 156, 207, pp. 281-324.

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