TWO-PHASE-FLOW THEORETICAL AND NUMERICAL MODELS FOR HYDRAULIC JUMPS, INCLUDING AIR ENTRAINMENT

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Hydraulic jumps have attracted wide attention for centuries now, not only because of its importance in designing stilling basins and other engineering works, but also because of its fascinating complexity. The outstanding features of hydraulic jumps can be summarized as follows: a) important turbulence intensities (often called macroturbulence); b) strong curvature of streamlines (i.e., non-hydrostatic pressure distribution); c) noticeable air entrainment into the water column through the free surface; and d) conspicuous presence of a roller of horizontal axis in the upper portion of the flow. In spite of the general impression that the hydraulic jump is a well-known flow phenomenon, detailed theoretical and numerical models of *all* the internal flow features in hydraulic jumps, for *all* Froude numbers, have yet to be developed.

The objective of this paper is to characterize mean flow, turbulence and air entrainment in hydraulic jumps through numerical means, in two and three dimensions, using the two-phase flow theory. In this endeavor, two-phase flow models are implemented in a state-of-the-art code, which is arguably the only code in the world which features air incorporation through the free surface. In addition, the code does not incorporate any assumption about hydrostaticity (i.e., “streamline curvature” is considered explicitly), it embeds a very accurate treatment for the free surface through the true VOF (volume-of-fluid) method, and has an option for the simulation of two-way coupling between phases.

The paper starts by briefly discussing mathematical models for dilute mixtures, departing from the two-fluid-model equations of motion (multi-phase flow theory). These equations can be obtained via ensemble averaging of the exact conservation equations for each phase in a multi-phase flow. In this work, mixture equations are integrated as a surrogate for the liquid flow. For the gas, we solve mass and simplified momentum equations. In addition, we exploit a model for air incorporation to the mass of water through the free surface based on the local turbulence level. The implementation in the code allows for the coupling or uncoupling of phases in the solution.

Numerical simulations undertaken in two and three dimensions, using a k - ε model and a Large-eddy-simulation approach (LES), are reported. The results are compared with very recent observations of mean flow and turbulence in hydraulic jumps (Liu et al., 2004). Liu et al. obtained time series of water velocity with the help of a microADV in different points of the central vertical plane, within the jump and several sections further downstream. Experiments were conducted for three different Froude numbers (2, 2.5 and 3.32). Liu et al. presented their results as vertical distributions of mean velocity and turbulence statistics.

Results obtained with the model for a Froude number of 2 are discussed in different sections. First, a careful analysis of mesh convergence in a two-dimensional configuration, using the k-ε model, is presented. Then, 3D simulations are discussed. Although the 3D simulation had to resign resolution (and consequently grid convergence) in the longitudinal direction, it is shown that the 2D and 3D numerical results do not differ too much; further, they confirmed the essentially 2D nature of the flow. Comparisons between the numerical results and the experimental data included three different variables: hydraulic jump length, and velocity and turbulent kinetic energy vertical distributions.

The estimated value of the hydraulic jump length of 3.5 ft (or 6.2 if divided by y_2) agrees notably well with the value of 3.7 measured by Liu et al. (approximately 6.6 in dimensionless form). Model predictions in terms of the mean flow also agree well with measurements, identifying the increase of the jump wedge width. The model offered a satisfactory prediction of the turbulent kinetic energy in different verticals, too.

After the comparison with data, the paper presents 2D fields and profiles of air fraction (volume of gas per volume of mixture). The computed air faction profiles agree qualitatively with distributions reported elsewhere. Unfortunately, Liu et al. did not provide gas concentrations in their paper to make comparison with.

Runs were repeated turning on and off the air entrainment option, and including and disregarding the phases coupling. The numerical results in terms of velocity distributions using the coupled model were virtually the same as those turning off that coupling, whereas the differences in air concentrations were minor. This is due to the dilute character of the mixture.

Finally, a snapshot of the free surface location obtained with LES is presented, showing a satisfactory description of the motion of fluid parcels in that region.

The agreement with data is considered satisfactory thanks to the use of non-hydrostatic models and an efficient treatment for the free surface, based on VOF. The air-incorporation model implemented is shown to provide a credible description of the physics in a hydraulic jump. This effort, based a global analysis of hydraulic jumps is believed to be unprecedented.