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ORIGINAL ARTICLE

Environmental multi-phase fluid mechanics: what, why, how, where to?

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1 Introduction

In April 2009, the Springer journal *Environmental Fluid Mechanics* published a special issue on "Recent Advances on Multi-Phase Flows of Environmental Importance" (*Env. Fluid Mech.*, Vol. 9, No. 2, 2009), edited by the same authors of this editorial [1]. That issue featured six high-calibre papers devoted to a range of multi-phase flow topics relevant to environmental and geophysical flows [2–7]; it is believed that these papers provided a complete picture of the state of the art on the observation and modelling of multi-phase-flows. The significance and impact of these scientific contributions may be arguably quantified in terms of citations. For the last 7 years, the special issue articles were cited between 132 and 236 times altogether (as of May 21, 2016) depending upon the database, representing an average of 2.7–4.8 citations per paper per year. Further, some of those papers have inspired, and have served as a backbone of other recent contributions. Arguably, all these articles did significantly contribute to our scientific knowledge on multi-phase flows.

Based on the success of that special issue, it was decided to update the state of the art on the subject with the edition of a new one. Distinguished researchers were invited to contribute in this new edition. The current issue contains eight papers (including this editorial) accepted after a rigorous peer-review process from initially ten manuscripts agreed to be submitted to the special issue. The deadline for paper submission was 1 June

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2015, but papers were received as late as December 2015. Still, the review process was rapid albeit thorough.

Before discussing the topics and contributions of the papers of the new special issue, we present in the following section some important concepts associated with environmental multi-phase flows.

2 Why multi-phase flows are so important in the environment?

Multi-phase flows are pervasive in many industrial and environmental processes. For instance, multi-phase flows appear in rockets (flows in solid-boosters); in pipes associated with cooling systems in power plants; in nuclear reactors; in sewage treatment plants, just to mention a few [8].

Civil and environmental engineers have been pioneers in the use, manipulation, and prediction of the behaviour of multi-phase flows [9, 10]. Consider for instance the enormous contributions of hydraulic engineers to the design of aeration devices for wastewater ponds, the use of bubble plumes for breaking waves in harbors, the control of erosion and deposition processes of sediment in rivers and coastal areas, or the management of massive debris produced by mining activities during the Golden Rush in California. In all these cases, engineers needed not only to devise methods to measure fluxes of water and transport rates of the so-called “disperse phase” (i.e., either bubbles or solid particles) in the environment, but also they needed to develop mathematical tools for their prediction. These predictions were initially done mostly with simple, practical regressions, and they prove to be relatively successful. It is evident that the environmental applications of multiphase flows date back to more than a century, and that civil/hydraulic engineers have contributed to the knowledge of the field.

In Figs. 1 and 2, two examples of multi-phase flows associated with civil engineering are presented. In Fig. 1, the breaking tidal bore of the Qiantang River, China, is shown on 12 October 2014 at Meilvba. The tidal bore propagates from right to left and, in the figure, some important air entrainment can be observed. In Fig. 2, sediment deposits in the Jioujhize River bed, Taiping Mountain, Taiwan, can be seen on 5 January 2016. A wide range of sediment sizes is noticed, which indicates the complexity of the phenomenon. Questions of interest in both cases are, among many others: (a) What is the air–water mass transport rate induced by the tidal bore roller?; (b) Where in the river reach the particles of a given size deposit?; (c) What is the distribution of particle concentrations in the vertical direction in the second case?; (d) What is the relation between the level of turbulence close to the bed and the sediment entrainment from the bottom; (e) Which sizes take part of the sediment entrainment into suspension?

Following with this perspective, applications on multi-phase flows from the nuclear, mechanical, and aerospace engineering have allowed for the development of novel theories in the last five decades, which are currently known as the “two-fluid model.” In this model, mass and momentum equations (and sometimes energy) are solved for *all* phases. Simultaneously, novel experimental devices coming from the science of fluid mechanics and from hydraulics have allowed for faster, more accurate and reliable measurements of flow variables. Therefore, with the important theoretical and experimental contributions, civil engineers are now in a tremendously-advantageous position, because they have been dealing with multi-phase flows for more than a century [11].

As examples of such privileged situation, dual-tip conductivity probes have allowed to observe the two-phase flow in hydraulic jumps, as presented for instance in Murzyn and

Fig. 1 Aeration of the breaking tidal bore of the Qiantang River, China, on 12 October 2014 at Meilvba–Tidal bore propagation from *right* to *left*—note the strong aeration of the bore roller (foreground) and the City of Hangzhou in the background

Fig. 2 Sediment deposits in the Jioujhize River bed, Taiping Mountain, Taiwan on 5 January 2016—note the coarse sediment materials deposited after the last flood flow, looking upstream

Chanson [4] (published in the first edition of the special issue). In this work, vertical profiles of air concentrations, bubble frequencies, bubble chord lengths, velocities and turbulence intensities were reported and discussed. In addition, particle image velocimetry and particle tracking velocimetry were used by Muste et al. [2] (also published in the first edition of the special issue) to determine the water and particle velocities in a sediment-laden flow in open channels. The "two-fluid" model equations have allowed for detailed analyses of multi-phase flows under non-dilute conditions. It has been shown by Jha and

Bombardelli [12] that the standard models of sediment transport cannot reproduce well the concentrations of sediment in open channels for non-dilute conditions, found to occur at concentration values larger than 2–5% by volume.

There is a direct impact of recent innovations on the experimental, theoretical and numerical fronts in the civil/hydraulic engineering field on the analysis and prediction of two-phase flows of environmental importance. This is a strong justification for this special issue.

3 Papers of the special issue

The papers of the special issue include contributions of experimental, theoretical and numerical nature, employing a wide set of tools to attack a variety of problems. Among the experimental works, Wang and Murzyn [13] investigated flow patterns and turbulence statistics in hydraulic jumps with the use of a dual-tip phase-detection probe. The study reports interesting results regarding the time-averaged air concentration in different cross sections. Interfacial velocities, length scales, etc. are presented in the vertical direction. It also investigates the time-dependent zone of impingement of the hydraulic jump through the use of video images. Zhang and Chanson [14] also addressed air–water flows but on spillways, both smooth and stepped. Analytical solutions are compared against new experimental data to focus on the differences in air entrainment between model and prototype. Variables such as the ratio of air diffusivity and diffusivity of momentum are studied and its variation with the Reynolds number is analysed. Lubin and Chanson [15] addressed the similarities and differences of tidal bores, surges and hydraulic jumps, carefully indicating ranges of bubble radii, Froude number definition and instances where flow analogies can help the research.

Regarding solid–water flows, Khosronejad et al. [16] present an interesting study of the transport of sediment in suspension in bendway weirs using numerical methods. The simulations were developed with an Unsteady Reynolds-Averaged Navier–Stokes solver developed at the Saint Anthony Falls Laboratory and they included the evolution of the bed morphology and interaction with the hydraulic structures. González et al.'s [17] paper is another numerical work devoted to direct numerical simulations of the problem of particle motion as bedload, discussing interesting aspects of the issue of intermittency. Interestingly, Lyu et al. [18] devoted their efforts to study debris flows, at a different scale and using macroscopic tools as opposed to the previous paper. Finally, Imran et al. [19] addressed the issue of scaling in the simulation of saline and particulate density currents, which nicely resonates with the paper by Zhang and Chanson [14] on air–water flows. Their conclusions into which type of current can be scaled up from physical models has a potential to influence the way studies are interpreted and undertaken.

Overall, it is possible to conclude that the progress in the field has been steady and considerable so far, but that many more challenges remain. The issue of scaling of two-phase flows is an unsolved one; cases of non-dilute conditions still require more work and clarification. New experimental devices and numerical models will be needed to address the latter case.

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