International Journal of Multiphase Flow 104 (2018) 322–337

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Review

Status and future developments of Large-Eddy Simulation of turbulent multi-fluid flows (LEIS and LESS)

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ARTICLE INFO

Article history:
Received 6 July 2017
Revised 14 February 2018
Accepted 22 February 2018
Available online 7 March 2018

Keywords:
LES
LEIS
LESS
Multi-fluid flow
ITM
Phase averaging/filtering

ABSTRACT

Current computational trends related to turbulent gas-liquid flow are discussed, together with the developments and open challenges needed to bring the discipline to a mature stage. The contribution presents the possibilities offered today by turbulent scale-resolving strategies (Large-Eddy Simulation, LES) to treat complex, multiphase flow topology in system components, and transcending more conventional kinetic energy dissipation-based models combined with phase-average approaches. The LES approach of turbulent gas-liquid flows introduced here under its sub-variants LESS and LEIS (Large-Eddy & Structures Simulation and Large-Eddy & Interface Simulation) is based on unifying the phase averaging concept and the turbulent-scale filtering operations into one single process. The paper is written in the spirit of a review, albeit it provides enough derivation details including the connection between the supergrid (resolved) and subgrid (unresolved) physics. A particular attention is paid here to the various attempts to model the underlying subgrid physics, including DNS-based model upscaling. A brief review of LEIS and LESS applications to phase-change heat transfer problems is provided, too. While the LESS variant based on the filtered multi-fluid equations is best suited for a range of problems in which one of the phases is dispersed in the other, LEIS provides further accuracy by directly predicting interface dynamics and turbulence motions down to the grid level. The paper addresses also the required developments for more complex multi-scale, multi-fluid flow problems, including a new approach termed as ARM, short for All-Regime Multiphase flow model.

1. Introduction

The computational multi-fluid flow scene has gone through successive transitions motivated by new, sometimes challenging needs and developments. The first real transition triggered in the 1980s focused on gradually removing the limitations of lumped-parameter 1D modeling (used essentially in the oil and gas and nuclear energy sectors) by further developing the phase-average approach (homogeneous and two-fluid models) for 3D turbulent flow problems. This is now state-of-the-art. The advent of the so-called Interface Tracking Methods (ITM) in the late 80s (Kataoka, 1986), which permit to better predict the shape of interfaces while minimizing the modeling assumptions, has somewhat shifted the interest towards a new era, known today as CMFD, short for Computational Multi-Fluid Dynamics. The most recent transition is now underway: it specifically centers on the use of these new simulation techniques (ITM) for practical, turbulent flow problems present in the energy and processes segment. This latest transition initiated in the 2000s has been marked by the gradual migration from the phase-average formulation to more refined interface tracking methods (ITMs), and from statistical Reynolds averaged modeling (RANS) to scale-resolving turbulence simulation including Large-Eddy Simulation (LES) and its sub-variants: dispersed-flow LES referred to here as LESS, short for Large-Eddy and Structure Simulation, and Interfacial-flow LES baptized LEIS (Lakehal, 2010), short for Large-Eddy and Interface Simulation. The migration was essentially motivated by the weaknesses of phase averaging to predict various (sometimes rather simple) types of topologies, e.g. stratifying slug flow, and also because statistical turbulence modeling is of limited predictive performance in the multiphase flow context. As it will be thoroughly discussed in this paper, the extensive investigation devoted to extending LES to multiphase gas-liquid flows raised specific questions as to the modeling of the unresolved flow physics, e.g. the contribution of the unresolved dispersed phase to the dissipation mechanism in LESS (Vaidheeswaran and Hibiki, 2017), and the asymptotic behavior of turbulence at the interface in LEIS (Reboux et al., 2006). These were central for the LESS and LEIS concepts and have to some extent benefited from DNS (Fulgosi et al., 2003; Tabib and Schwarz, 2011) and detailed experiments for model upscaling (Simiano et al., 2009), albeit not at the

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https://doi.org/10.1016/j.ijmultiphaseflow.2018.02.018
0301-9322/

same extent as what has been learnt from DNS of particle-laden flows (Elghobashi and Truesdell, 1993; Ferrante and Elghobashi, 2003).

LESS has been employed under the two-fluid and mixture model variants essentially for turbulent bubbly flows (Deen et al., 2001; Milelli et al., 2001; Lakehal et al., 2002; Lakehal, 2004). Other contributions appeared subsequently in the literature, using some form of LESS for a variety of dispersed gas liquid flows (Ničeno et al., 2008; Capecelatro and Desjardins, 2013; Ma et al., 2016; Yang et al., 2016). The derivation of the LESS equations can be found in the papers of Lakehal et al. (2002) and Sirignano (2005); the latter considered heat transfer and chemical reaction, too. LEIS has been applied to turbulent gas-liquid flows involving large-scale sheared interfaces, with problems ranging from spilling wave flows (Lakehal and Liovic, 2011) to steam injection in a water pool (Li et al., 2015). Lately, Lakehal et al. (2017) simulated a turbulent channel flow laden with resolved bubbles clustered near the wall. But the progress in hardware technology is helping LEIS gain in popularity in the jet-atomization community in particular (Buonfiglioli and Mendonça, 2005; Desjardins et al., 2010; Chesnel et al., 2011; Duret et al., 2013; Kaario et al., 2013; Jarrahbashi and Sirignano, 2014; Navarro-Martinez, 2014; Behzad et al., 2016; Hélie et al., 2016). LEIS is indeed capable of predicting primary breakup without necessarily introducing additional sub-grid scale models, which could be required for secondary breakup mechanisms (Klein et al., 2015). Full DNS of liquid jet primary and secondary breakup indeed requires massive mesh resolutions (Shinjo and Umemura, 2010).

We proceed by posing the issue of scale segregation in multi-fluid flows to make the analogy with conventional LES clear. In the second part we review the extension of LES to multi-fluid gas-liquid flows, from early-to-mid 2000s where the fundamentals of LES of gas-liquid flows was published for the first time, until the very recent developments in terms of model upscaling and novel predictive strategies. We then aboard the wide spectrum of multi-fluid flow modeling routes, from the microscopic description up to resolved-scale and unresolved-scale strategies. We then review past work on the derivation of each approach, from the concept of filtering to subgrid-scale modeling. Finally we discuss developments underway as to unifying the two approaches towards what we refer to as ARM, short for All-Regime Multiphase flow model. The paper does not address the use of LES for particle laden flows; a review is dedicated to the subject by Fox (2012).

2. Turbulent multi-fluid flows

2.1. Scale segregation

The notion of 'flow scales' in turbulent multi-fluid flow systems needs to be clarified prior to invoking computational techniques and models. To illustrate this notion, we proceed by analyzing the wave breaking flow depicted in Fig. 1 to which we could look at as a combination of turbulence scales interacting with the topology or interfacial scales. Here the interfacial sublayer is substantially sheared and interacts with the free surface causing intermittent high and low curvature areas. To what extent this phenomenon can be affected by the underlying turbulence is not clear, however, what matters when it comes to prediction is to avoid smoothing out interface deformations and turbulence structures. The flow regime evolves gradually from stratified with capillary waves to large-scale waves by the action of pressure and gas-shear by extracting kinetic energy from the mean flow; it ultimately breaks into small scales and dissipates its energy. Interfacial scales range therefore from the size of individual droplets/bubbles to the wave slope.

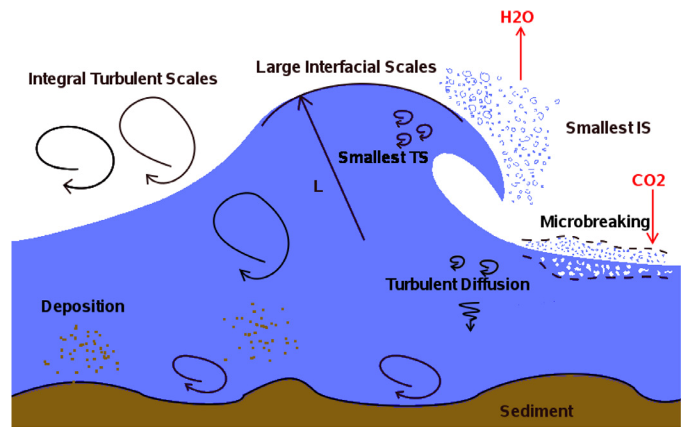

Fig. 1. Breaking wave flow.

Turbulence is generated at the interface by friction and subsequent to wave plunging (in addition to inflow and wall turbulence). The hydrodynamic instability caused by the shear between two adjacent flows is in effect a transition to turbulence and can be a major source of turbulence. A cascade process with the generation of smaller length scales occurs, until capillary action prevails. The spectrum of turbulence varies depending on the imposed flow conditions, ranging from low-frequency integral scales to high-frequency scales developing at the crest of the wave, near breaking. Dispersed droplets and bubbles created by wave entrainment and spilling - generating surface foam - disperse by reaction to turbulence. The picture is complete; it needs now to be translated in terms of modeling and simulation principles. The flow scenario discussed above requires tailored computational methods since it presents various facets in terms of topology: the dispersed mixed flow regions can only be treated using a phase-averaged formulation since the scales are unresolvable on typical CFD grids, while wave deformations can be simulated using ITM's since the interface is sufficiently large to be resolved in a typical grid.

2.2. Scale-resolving strategies

Considering topology changes, ITM's are best suited to locate the interface, not by following it in a Lagrangian sense, but by keeping track of its topology in an Eulerian sense through the evolution of an appropriate phase-indicator field or color function. Examples include the Level-Set method (Osher and Sethian, 1988) in which the interface is considered to be a level surface of a function that is defined over all space, and the VOF method (Hirt and Nichols, 1981), in which the location of the interface is captured by keeping track of the volume fraction of each computational cell in the grid with respect to one of the fluid phases. Phase-average process is in essence a filtering process since the portion of the spectrum associated with smaller interfacial scales is filtered out: it can thus be applied to treat mixed flows containing a dispersed phase whose exact topology is otherwise unresolvable on Eulerian grids, and can be performed under different forms, including multi-realization ensemble averaging, volume averaging, etc. As to turbulence, the big-picture distinguishes between (i) turbulence-scale resolving methods, including DNS (all the scales), LES (larger scales than the grid-imposed filter) and its sub-scale variants like Very-Large Eddy Simulation and Detached Eddy Simulation (V-LES and DES), and statistical time averaging based on the Reynolds averaged Navier–Stokes equations (RANS).

Clearly, modeling a specific flow involving a combination of topology and turbulence length scales requires combining specific computational techniques with selected models to cope with the