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The generality of the standard 2D TFM approach in predicting bubbling fluidized bed hydrodynamics

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ABSTRACT

Hydrodynamic simulations of a pseudo-2D bubbling fluidized bed were carried out and compared to experiments conducted over a wide range of flow conditions. The primary purpose of this study was to assess the generality of the standard 2D Two Fluid Model (TFM) closed by the Kinetic Theory of Granular Flows (KTGF) which is regularly used in the literature to simulate bubbling fluidized beds. Comparisons of the bed expansion ratio over wide ranges of fluidization velocity, bed loading and particle size showed systematic differences between simulations and experiments, indicating that the generality of this modelling approach is questionable. More detailed flow velocity measurements collected via Particle Image Velocimetry (PIV) showed that the model greatly over-predicts flow velocities in the bed. Subsequent 3D simulations showed this over-prediction to be the result of 2D simulations neglecting the wall friction at the front and back walls of the pseudo-2D bed.

1. Introduction

Since the kinetic theory of granular flows (KTGF) [1,2] was first proposed three decades ago, fundamental hydrodynamic simulations of bubbling fluidized beds have been regularly carried out within the research community. Naturally, validation efforts soon followed to show that the two fluid model (TFM) closed by the KTGF could give reasonable representations of reality even though only relatively coarse 2D grids were affordable at the time.

As computational power increased, finer meshes could be employed and validation studies against lab-scale physical models could be completed in 2D [3–8] and in 3D [9,10] with less numerical uncertainty. In general, results were encouraging, but rarely achieved a completely satisfactory match. The primary source of uncertainty quoted lies in the formulation of the various closure models incorporated into the KTGF.

Despite numerous uncertainties still remaining in terms of hydrodynamic modelling, significant research efforts have recently been invested in extending the KTGF to reactive flows [11–15]. Incorporation of chemical reactions significantly increases the complexity of the system due to the close coupling between hydrodynamics and chemical kinetics [16] and, due to this close coupling, predictions of overall reactor performance are highly dependent on accurate simulation of the underlying hydrodynamics.

Studies attempting to validate reactive fluidized bed simulations are rare and limited by the lack of sufficiently detailed or generic experimental data. One study completed on a chemical looping combustion system found that a 2D TFM KTGF approach could not reproduce a counter-intuitive experimental trend extracted over a range of fluidization velocities [15]. The qualitative failure of the numerical model drew attention to the sensitivity of reactive fluidized bed systems and the unexpected non-linear effects that can become highly influential. In this case, the fine length scales at the gas inlet together with the 2D assumption were responsible for the discrepancy. Inaccuracies in the hydrodynamic response of the model to changes in the fluidization velocity therefore led to a reactive fluidized bed model that was not generally applicable.

Generality is the ultimate aim of any fundamental predictive model. If the model is used to meet aims such as prototyping, design, optimization and scale-up, adequate generality is implicitly assumed since the model will inevitably be used to simulate conditions far removed from those under which it was validated. A model responding incorrectly to changes in any one of the multitude of design and operating variables defining a fluidized bed reactor (such as the example given in the previous paragraph) can therefore lead to dangerously erroneous conclusions.

When considering the importance of generality in the field of simulation based engineering, it is surprising that the vast majority of validation studies are focussed on one or a very limited number of flow situations. After all, adequate validation in a single case, even when completed in great detail, is no guarantee of generality throughout the parameter space defined by the numerous flow variables involved.

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List of symbols

Main symbol definitions

α	Volume fraction
ϕ	Kinetic energy transfer rate (kg/m.s^3)
γ	Dissipation rate (kg/m.s^3)
Θ_s	Granular temperature (m^2/s^2)
ρ	Density (kg/m^2)
ς	Specularity coefficient
$\bar{\bar{\tau}}$	Stress tensor (kg/m.s^2)
$\vec{\tau}_s$	Particle shear force at the wall (N)
$\vec{v}$	Velocity vector (m/s)
∇	Del operator/Gradient (1/m)
d	Diameter (m)
$\vec{g}$	Gravity vector (m/s^2)
$g_{0,ss}$	Radial distribution function
H	Bed height (m)
$\bar{\bar{I}}$	Identity tensor
K	Momentum exchange coefficient (kg/m^3.s)
k	Diffusion coefficient (kg/m.s)
p	Pressure (Pa)
t	Time (s)
$\vec{U}_{s,\parallel}$	Particle velocity parallel to wall (m/s)

Sub- and superscript definitions

0	Initial/static
Θ_s	Granular temperature
exp	Experiment
g	Gas
gs	Inter-phase
max	Maximum packing
s	Solids
sim	Simulation

Abbreviations

ANOVA	Analysis of variance by interaction effect
CCD	Charge-coupled device
CFD	Computational fluid dynamics
d	Particle diameter
H	Initial static bed height
KTGF	Kinetic theory of granular flows
L	Linear effect
LED	Light emitting diode
PIV/DIA	Particle image velocimetry combined with digital image analysis
Q	Quadratic effect
RMS	Root mean square
SS	Sum of squares
TFM	Two fluid model
U	Fluidization velocity

Recent work completed on different modelling strategies for fluidized bed reactors [17,18] identified clear systematic discrepancies between 1D, 2D and 3D modelling approaches within a parameter space defined by fluidization velocity, reactor temperature, solids loading and particle size. Although trends were predicted to be qualitatively similar, quantitative discrepancies tended to constantly increase with changes in certain flow variables. These works therefore showed the importance of defining any systematic differences between model and experiment before attempting to use such a model for purposes of simulation based engineering. If the model cannot be made to be fully generic, fixed boundaries on its range of applicability at least have to be determined.

For this reason, a thorough and systematic validation campaign is required to evaluate the performance of various fluidized bed reactor models with a specific focus on generality. Care should also be taken to structure the validation studies in such a way that the four primary sets of physical phenomena – hydrodynamics, species transfer, heat transfer and reaction kinetics – are decoupled so as to avoid non-linear coupled effects which hinder the useful interpretation of data.

The present work is the first step in such a campaign. It will evaluate the hydrodynamic generality of the widely used 2D TFM KTGF approach to simulating bubbling fluidization over a wide range of fluidization velocities, solids loadings and particle sizes.

The paper first gives an overview of the experimental, simulation and data processing methods employed. Results are then presented in the form a grid independence study, a generality study, some visual qualitative comparisons between simulations and experiments, and some more detailed solids velocity comparisons. Finally, some conclusions are drawn from the results.

2. Experiments

2.1. Experimental setup

The experimental setup (Fig. 1) consisted of a pseudo-2D fluidized bed column with a height of 1.5 m, a width of 0.3 m and a depth of 0.015 m. The front plate of the column was made from glass to allow for visual access to the bed as required by the experimental technique used in this study (Particle Image Velocimetry combined with Digital Image Analysis—PIV/DIA). A metallic black plate was used at the back in order to reduce light reflections when recording images.

A porous plate with 40 μm average pore size and 3 mm thickness was used as the gas distributor. Mass flow controllers were used to control the gas inlet flow rate and the column was equipped with an expanding metallic freeboard at the top in order to prevent elutriation of fine particles at higher flowrates.

Humidified air was used to fluidize spherical glass beads with a density of 2500 kg/m^3. Five different particle size distributions were studied: 70–110, 100–200, 200–300, 300–400 & 400–600 μm. More details about the size distributions are given in Table 1.

A high speed CCD camera (Lavision model Image Pro HS4M) was used to film the bed from the front for two purposes: determining the expanded bed height by means of image analysis and determining the particle velocity field based on PIV/DIA. Lighting was supplied by four LED lamps.

2.2. Particle image velocimetry

PIV is a non-invasive optical measurement technique that determines the particle velocity from two images recorded in short succession. The two images are analysed by first dividing each image into N × N interrogation areas and then applying a cross correlation to determine the average particle displacement in each interrogation area.

As recommended in a previous study [19], the filmed area was decreased with particle size in order to always afford 2–3 pixels for each individual particle. Under this limitation, the resolution of the camera (2016 × 2016 pixels) was sufficient to cover the entire 0.3 m bed width for the 350 and 500 μm particle sizes, but only 2/3 of the bed width for the 250 μm particles. The bed also expanded to more than 0.3 m for most of the cases studied requiring a vertical displacement of the camera to cover the whole bed height. Image pairs were collected at a frequency of 4 Hz with a time delay of 2–4 ms between the two images in each pair. The commercial software package Davis was used for post-processing the images and for determining the particle velocity fields.