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Revisiting low-fidelity two-fluid models for gas–solids transport

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A B S T R A C T

Two-phase gas–solids transport models are widely utilized for process design and automation in a broad range of industrial applications. Some of these applications include proppant transport in gaseous fracking fluids, air/gas drilling hydraulics, coal-gasification reactors and food processing units. Systems automation and real time process optimization stand to benefit a great deal from availability of efficient and accurate theoretical models for operations data processing. However, modeling two-phase pneumatic transport systems accurately requires a comprehensive understanding of gas–solids flow behavior. In this study we discuss the prevailing flow conditions and present a low-fidelity two-fluid model equation for particulate transport. The model equations are formulated in a manner that ensures the physical flux term remains conservative despite the inclusion of solids normal stress through the empirical formula for modulus of elasticity. A new set of Roe–Pike averages are presented for the resulting strictly hyperbolic flux term in the system of equations, which was used to develop a Roe-type approximate Riemann solver. The resulting scheme is stable regardless of the choice of flux-limiter. The model is evaluated by the prediction of experimental results from both pneumatic riser and air-drilling hydraulics systems. We demonstrate the effect and impact of numerical formulation and choice of numerical scheme on model predictions. We illustrate the capability of a low-fidelity one-dimensional two-fluid model in predicting relevant flow parameters in two-phase particulate systems accurately even under flow regimes involving counter-current flow.

1. Introduction

Particulate transport in fluid media is common in many industrial processes. Designing such processes to predefined capacity limits can be abstruce and highly dependent on the ability to model and simulate them. Furthermore, real-time mechanistic model simulation coupled to model parameter tuning algorithms that take advantage of available operations data is crucial for efficient process control automation. Process automation frameworks aid the seamless real-time optimization of engineering operations and industrial processes using measured operations data. Stand alone commercial and open-source simulators like FLUENT, Star-CCM+ and OpenFOAM are capable of modeling particulate transport at high fidelity. However, they are inefficient for real-time process optimization and capacity design as they are not built with the flexibility for dynamic data utilization while running perpetually on remote servers with little or no human interaction. Hence the need for lower fidelity models that are fast, accurate and robust.

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Some well known computational models, such as K-FIX [1], MULTIFIX [2,3], FORSIM [4], OLGA [5], TACITE [6], PLAC and TUFFP [7], TRAC [8], RELAP [9–11] and CATHARE [12] are examples of lower fidelity models for multiphase flow systems. However, these tend to suffer from frontal smearing, which ultimately affects parameter predictions, when applied to compressible two-phase particulate transport systems. This fact led some authors [13] to the conclusion that such lower fidelity models are incapable of making accurate parameter predictions when applied to two-phase particulate transport systems.

Toumi and Kumbaro [14] noted that the smearing of the fronts observed in the earlier models are due to the description of the mathematical model and the numerical method adopted. They presented an approximate Riemann solution on a modified set of isentropic equal pressure two-fluid model equation that included the virtual mass effect proposed by Drew and Lahey [15,16] in order to ensure hyperbolicity.

Tsuo and Gidaspow [13] presented a set of strictly hyperbolic model equations for gas–solids flow in circulating fluidized beds where the pressure gradient of the particulate phase is expressed in terms of an empirically determined modulus of elasticity. They simulated both one- and two-dimensional flow using an earlier extension of K-FIX by Syamlal [2] in an effort to replicate the experimental results of Luo [17,18]. Their one-dimensional numerical simulation showed signs of significant frontal smearing [13,19] and poor steady-state solids concentration (volume fraction) predictions. They concluded that one-dimensional models can not be used to predict solids concentrations accurately in two phase gas–solid transport even for vertical flow. They made particular reference to flow regimes that experience clustering and counter-current annular flow. Interestingly, their two-dimensional simulation results also indicated poor steady-state solids concentration predictions as well. However, they attributed the discrepancy in the numerical predictions relative to experimental measurements to the inaccuracies of the x-ray densitometer used in Luo's experiment [17] to measure the solids concentrations.

Syamlal [20] also presented a new set of two-fluid model equations that are hyperbolic under a wide range of flow conditions by including a bouyant force term that accounts for relative velocity between the fluid and solids phases. He expressed the flow equations using primitive variables and also showed through characteristic analysis, where various sets of flow equations lose hyperbolicity. However, Hou and Le Floch [21] have shown that numerical formulations such as those that employ primitive variables do not converge to the correct solution when discontinuities are present.

Hudson and Harris [22] also presented a high resolution scheme for gas–solids two-phase isentropic flow. Both of Gidaspow's [23] non-hyperbolic (Model A) and strictly hyperbolic (Model B) equations were evaluated. Model C, which is also non-hyperbolic was analyzed but not evaluated as it displayed a larger region of non-hyperbolicity relative to Model A. They utilized a conservative finite volume scheme and a Roe-type approximate Riemann solver. They presented a set of Roe–Pike averages for their system of equations and solved these equations using conserved variables. They however reported some instability in their numerical scheme which they attributed to sensitivity to the choice of flux-limiter used. It should be noted that the observation of numerical instabilities when solving strictly hyperbolic systems, as is the case for model B reported by Hudson and Harris, typically points to flaws in the applied numerical scheme.

Kamath and Du [24] presented an approximate Riemann solver for granular gas flow proposed by Goldshtein and Shapiro [25]. Kamath and Du presented a Roe-type algorithm for the hyperbolic system, which included non-conservative terms. The non-conservative terms introduce non-isentropic effects in acoustic-wave propagation within granular media and contribute to the Rankine–Hugoniot relations across discontinuities. They reported stable and accurate results for a one-dimensional test case for shocks with the flow features of a fluidized region downstream of the shock and a compacted solid-block region adjacent to the wall. They concluded that the Roe-type scheme they had presented may be relevant in the investigation of two-phase flows.

Ibraheem and Adewumi [26] also studied two-phase gas–solids transport for the initiation stage of hydrate formation and transport in natural gas pipelines. They utilized a conservative finite volume scheme and applied a Roe-type approximate Riemann solver using the set of Roe–Pike averages they had presented. While their model was reported stable, they had excluded any normal stresses associated with the solids phase completely.

While there have been many studies related to the construction of high resolution schemes for gas–solids two phase flow [20,22,24,27], there has not been enough effort in investigating the overarching benefit of improved resolution of discontinuous fronts on parameter predictions in gas–solids systems. In this study, we present a new set of Roe–Pike averages for a system of strictly hyperbolic two-fluid gas–solids flow model equation of the form of Gidaspow's Type-B model [23]. The resulting numerical scheme is insensitive to the choice of flux-limiters. We also show that the inaccuracies observed in parameter predictions in one-dimensional two-fluid gas–solids models are highly dependent on the numerical formulation and the capability of the numerical method of choice to capture and fully resolve discontinuities in the solution of the model equations.

2. Background

Most process optimization scenarios involve minimizing power requirements while maintaining adequate gas flow for particulate transport. This typically translates to minimizing pressure drop in the system while maintaining a particular flow condition or regime suitable for the specific operation. Gas–solid models developed for process automation frameworks need to be accurate under the broad spectrum of flow regimes expected under dilute and dense phase flow conditions but simple enough to minimize computational costs. For a vertical pneumatic transport system, Fig. 1 shows the typical curves of pressure drop as a function of superficial gas velocity at fixed solid mass feed rates (W_{s_1}, W_{s_2}, W_{s_3}) also known as the flow characteristics curve (FCC) or Zenz state diagram [28].