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Emergent Behavior in a Low-Order Fluidized-Bed Bubble Model

John S. Halow
National Energy Technology Laboratory
Morgantown WV 26507-0880

C. Stuart Daw
Oak Ridge National Laboratory
Oak Ridge TN 37831-8088

C.E.A. Finney
University of Tennessee at Knoxville
Knoxville TN 37996-2210

ABSTRACT
Low-order models are becoming increasingly useful for simulating the complex collective behavior arising in large dynamical systems. Modeling of traffic flow and the behavior of biological systems such as ant colonies and bird flocks are commonly referenced examples of this new approach. We have explored the application of this type of model to describe the dynamics of voids in bubbling fluidized beds. The model considers vertical interactions between neighboring bubbles in fluidized beds. Emergent collective behavior is shown to arise in a manner consistent with observed experimental behaviors of fluidized beds. One important example is the tendency for larger beds to form a central channel of high void fraction. This effect is shown to occur without invoking the usual assumption that lateral bubble motion is induced by solids convection. Another behavior captured by this model is the tendency to form multiple preferred bubble migration paths (channels) much like the "rat-holing" observed in cohesive powder beds. Visualizations of example emergent behavior in the bubble patterns of both 2-D and 3-D fluidized beds are presented.

Background
Since the publication of Davidson and Harrison's classic book(1) on fluidization in 1963, the two-phase model has been the most widely used concepts to describe the behavior of bubbling fluidized beds. The model is simple and elegant and has an intuitive appeal that is extremely helpful in understanding the basic physics of fluidized beds.

Since the introduction of the two-phase model, there have been numerous studies and publications to explain practical aspects of bed performance. Chemical conversion, heat transfer, solids mixing, flow around internals, particle entrainment, and jet behavior have all been explained on the basis of the two-phase assumption. An obvious limitation of many applications is that they assume a single "average" bubble size, while it is known, in fact, that there is a wide range of sizes present at the same time. Various authors(2-5) have recognized the importance of bubble interactions, coalescence, and distribution of bubble sizes in the past, but the available computational power limited their models to simple cases.

Recently we(6) developed a low-order bubble model that simulates many dynamic features of bubbling beds at near real-time speed using a desktop computer. Such simulation capability is highly desirable because it allows rapid investigations of bed design and operating changes and may eventually lead to interactive model-based controls. Our low-order model is based on classical two-phase bubbles that behave according to a simple set of deterministic rules defining how each bubble moves and interacts with its neighbors. In their implementation, these rules are similar to those used in cellular automata (CA), except that the bubbles are allowed to move freely and there is no fixed spatial grid. Thus, in effect, the dynamics are tracked in a local Lagrangian frame of reference. The bottom boundary condition of the bed specifies how bubbles are initially injected into the bed, and the rising bubbles are then free to rise, interact, and coalesce according to the rules. Bubbles reaching the top of the bed exit and disappear according to the upper boundary condition. Global patterns of emergent behavior appear as the net effect of iterating all of the multiple interactions over time.

In studying the simulated bubble patterns from this model, we have observed unexpectedly rich behavior that is reminiscent of emergent behavior in biological and societal systems. Such behavior suggests that results from these other research areas might also be used to improve our understanding of fluidized beds.

Low-Order Models and Emergent Behavior

Emergent behavior refers to collective patterns exhibited by a large group of agents following simple rules for interactions(7-11). Oft-cited examples are the flow of traffic (where the rules govern the behavior of each driver) and the flocking of birds (where the rules define each birds flight path relative to its neighbors). Some general characteristics of low-order models for emergent systems are:

- The model consists of multiple interacting copies of a limited number of agents.
- The configuration of the agents and components change as time evolves (the model is dynamic).
- Interactions are constrained to a succinct set of deterministic rules.
- Because the interactions are nonlinear and subject to sensitivity to initial conditions, the collective behavior of many agents cannot be predicted from the behavior of an “average” individual agent.

Emergent systems will generally exhibit a variety of “states” in which some set of interactions have set up a pattern (or non-pattern) of behavior. And usually some set or sets of external perturbations will lead to the transition into or out of one state to another.

An important advantage of using low-order models to study emergent behavior is that such models can reveal the essential underlying physics (that is, they help to identify which aspect of the component interactions is really controlling the major features). Likewise, such models are very amenable to fast computation and, when appropriate, parallelization.

The Low-Order Bubble Model

We begin our bubble model with the assumption that our component “agents” are the individual bubbles. The only options open to each bubble are to rise according to the local conditions or to coalesce when they come in direct contact with a neighboring bubble. All of the observed dynamics result from the collective effects of each bubble acting individually according to the rules that define these two actions.

The rule for bubble rise velocity is that each individual bubble will rise according to an empirical rise velocity correlation derived from capacitance imaging experiments (12). This correlation accounts for pair-wise bubble interactions and wall effects and simplifies to classical single-bubble expressions for rise velocity in the limit as neighboring bubbles and walls are removed.

Each bubble’s spatial trajectory is described by integrating a first-order, nonlinear ordinary differential equation through time. Thus, if there are "n" bubbles in the bed, then we use "n" equations to describe their motion. Bubbles are dynamically coupled through the dependence of each rise velocity on the distance to its closest leading neighbor (i.e., the nearest bubble above). This system of equations for “n” bubbles can be written as:

$$\frac{dZ_i}{dt} = U_i = \left[\sqrt{\frac{gL_i}{2+\left(\frac{A^*}{1-A^*}\right)^2}}\right]\left[\left(1+3\left(\frac{D_{Li}}{S_{Li}}\right)^3\right]\right. \qquad \text{for } i = 1,2,3...n$$

Referring to a bubble "I" in the bed, U_I is its rise velocity, L_i is its length, A* is the ratio of its cross-sectional area to that of the bed, D_{li} is the diameter of the bubble leading it, and S_{li} is the vertical distance between bubble I and the bubble leading it. The direction Z_i is taken to be along a line connecting the center of bubble "i" with the center of the bubble, Li, that is leading it. If there is no leading bubble, the term D_{Li}/S_{Li} is zero.

The second key rule we employ is that bubbles which touch vertically must coalesce to form a single bubble of equal total volume. Because of coalescence, the number of bubbles (and thus the number of equations) vary with time. While this constant shifting in the number of equations creates an unusual mathematical system, it is easy to implement numerically.

Other key model assumptions are:

- Gas in excess of that required for minimum fluidization passes through the bed in the form of bubbles (i.e., the basic two-phase assumption).

- Bubbles are assumed to be spherical if their diameters are less than or equal to 85% of the bed diameter. Larger bubbles are assumed to be cylindrical slugs with hemispherical end caps with diameters equal to 85% of the bed diameter.

- A bubble is said to be leading a bubble behind it if their projected area on the horizontal plane overlap. The following bubble is said to trail the leading bubble. If more than one bubble can qualify as a leading bubble, the closest leading bubble is chosen.

- Bubbles are formed at the distributor by accumulating the excess gas above minimum fluidization velocity until sufficient gas volume exists to form a bubble. The initial diameter is calculated from an appropriate correlation for the type of distributor (orifice or porous plate) using the correlations Mori and Wen (18), or it can be independently specified. Currently, with Pentium computers, the simulation runs reasonably fast with up to 1000 bubbles formed per second. The simulation limits the initial size to keep the initial bubble formation rate within that limit. To simulate beds with porous plate grids, the bubbles are placed at a random location on the grid. For grids with defined orifices, bubbles may be released randomly from these orifices or in specified sequences.

- Bubbles are removed from the simulation when their upper surface reaches the bed surface.

- The bed volume, and therefore the bed height, increases and decreases depending on the volume of bubbles in the bed.

- Net solids down flow (or upflow) can be specified for standpipes and moving beds. The bubble rise velocity is relative to the solids flow.

Results

Formation of a Central Channel: Under conditions where bubble population is high and there are many significant bubble-to-bubble interactions, there is a tendency for the bubbles to collect into a persistent central channel. This channeling toward the middle has been experimentally observed for a long time and has been attributed to downward solids convection near the wall. In carefully considering our model, however, we find that such solids-induced lateral motion is not necessary to explain the observations. Rather, it appears that the underlying cause of bubble stream contraction is the fact that bubble interactions are more likely near the bed center, creating a self-propagating cascade of bubble coalescence. Thus it is the basic nature of bubble interactions that is driving the emergence of the channel pattern. In this context, we would also argue that the observed solids circulation pattern is really just a result of the central bubble channeling and not the cause of it.

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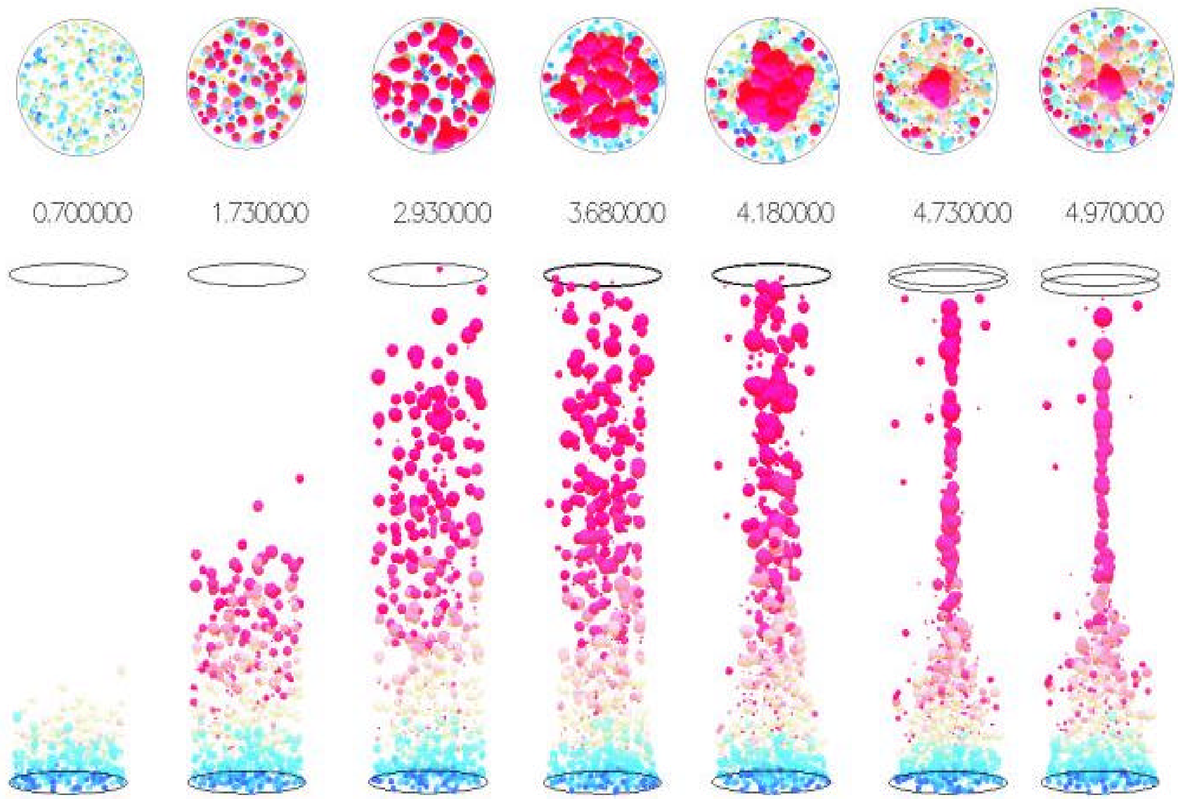
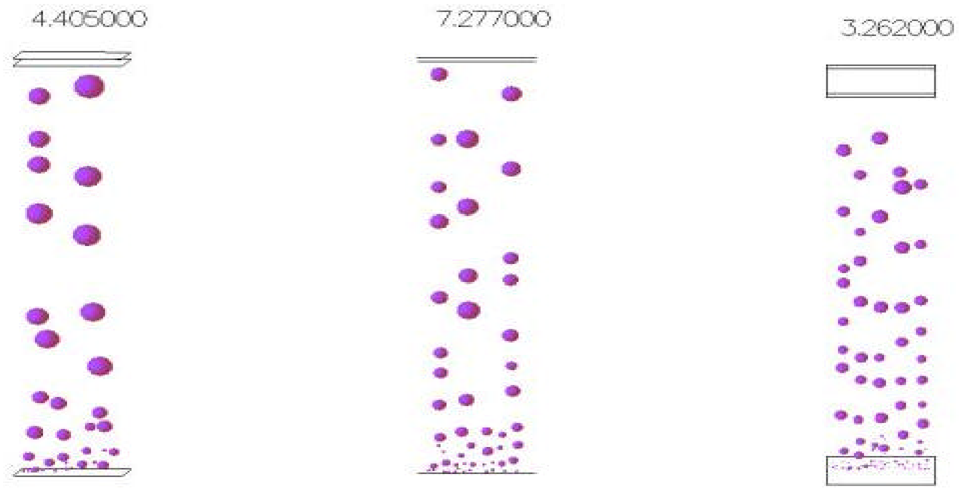
The figure below illustrates a simulation that resulted in the formation of a central bubble channel in a 3-D bed. Starting with a bed without bubbles, 5-cm-diameter bubbles are released at random locations on the grid of a 100 cm diameter bed. After about 2.9 seconds, bubbles released at startup have begun to reach the surface of the bed. It is apparent that there has been some lining up of the bubbles at this point. At 3.7 seconds, some compression of bubbles towards the center is becoming apparent and after 4 seconds compression proceeds rapidly into a collapse of the bubble swarm into a central channel. This channel will persist indefinitely, with some fluctuations in its general shape and in the location where it forms.



Multiple bubble channels in 2-D beds

A 2-D version of the model was constructed to allow comparison of the model with 2-D bed data. It has the advantage of having simpler dynamics and is easier to visualize the motion of the bubbles. The 2-D model predicts that bubbles will tend to form an integral number of more or less evenly spaced channels. The number of channels formed depends mainly on the excess gas velocity and the width and depth of the bed, although initial bubble size and other parameters may effect it as well. The following figure illustrates the channels formed under several conditions:



In the first panel, two bubble chains form while in the second, lower velocity case, the persistent pattern seems to involve three channels. In the third panel, a wider bed leads to the formation of 5 channels. Even though the bubbles are initially formed at random locations on the grid, they tend to develop into the more or less evenly spaced chains because unevenly spaced chains would lead to coalesce of the chains and therefore would not be stable.

Summary

We find that a simple model of bubble rise along with simple rules for formation and coalescence can give rise to channel formation in beds. This result is caused by the vertical interaction of bubbles leading to the formation of bubble chains and the collapse of small chains into larger chains. In 2-D beds, these channels are equally spaced because this condition is the where coalescence of the chains can be stable. In a 3-D bed, it appears that the probability of finding a leading bubble available for coalescence is higher toward the center of the bed, thus causing preferential chain formation near the bed axis.

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