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Dynamic modeling of the circulating fluidized bed riser

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ABSTRACT

Dynamic modeling is required to understand hydrodynamics of a circulating fluidized bed (CFB) riser as a function of time. The paper develops a dynamic model of the riser from the conservation of solid mass. Solid mass that flows out of the riser requires particle residence time to close the mass balance equation. The mean residence time of solids was derived as the riser length divided by the superficial riser gas velocity normalized by a ratio of solid concentration in the riser outlet to that in the riser itself. For bed materials including high-density polyethylene beads, glass beads, and cork, the percentage of solid concentration in the horizontal crossover pipe connecting the riser exit and the cyclone inlet was found to be 22% of the average concentration of solids in the riser. Upon finding the particle residence time, we calculated the solid flow rate out of the riser and along with the knowledge of solids flowing into the riser column we determined the riser inventory as a function of time. We used the estimated solid inventory to model overall pressure drop across the riser from the conservation of momentum. The momentum equation included the balance of pressure force by the hydrostatic head of solids, and the wall frictions due to gas and solids in a fully developed zone. The prediction of overall riser pressure drop compared well with its measured values at many dynamic conditions. Therefore, our dynamic model is useful for developing advanced control strategy or for improving existing control systems of the CFB plant. The residence time approach is also useful for the design of a transport reactor. The technique also comes handy when setting up the boundary condition for the overall pressure drop in the CFD modeling that can simulate incremental pressures along the riser height.

1. Introduction

Circulating fluidized beds have many industrial applications including coal gasification, oil refining, Fischer–Tropsch synthesis, and several other chemical processes that use solid circulation system and employ one or more fluidized beds. A circulating bed can transport large quantities of material thereby transferring a significant amount of heat required for different applications. A circulating fluidized bed (CFB) consists of a riser and a standpipe in a closed loop. The two components are arranged vertically beside one another (Fig. 1). At the bottom of the loop, the solid flow from the standpipe, also called a downcomer, into the riser. In Fig. 1, the solid transfer is motivated by means of aerating the non-mechanical L-valve. In other installations, a mechanical valve such as a slide valve is used. The gas supplied at the riser bottom transports the solid to its top. After exiting the top, these solids are directed horizontally by a crossover pipe and injected tangentially into a cyclone. The cyclone separates the solid from the gas that exits through its top, and the solid fall back into the downcomer. The cycle repeats thus creating a continuous circulation of solid around the CFB loop.

In the past, many researchers have attempted to characterize the hydrodynamics of the circulating fluidized bed (CFB) risers. Even the competitions involving hydrodynamic modeling of the CFB riser were arranged in the form of challenge problems for the last 20 years [1–3]. Researchers working in the multiphase flow area participated in these challenges. The strengths and weaknesses of their models were investigated against the experimental data collected during steady states. However, there have not been many developments of dynamic models describing the riser hydrodynamics compared to its steady state counterparts. Dynamic models help understand the riser hydrodynamics as a function of time that eventually helps in developing better control strategy and CFB optimizations.

In circulating fluidized bed systems, reactions are normally conducted in the riser and for catalytic processes, the catalyst regeneration is performed in the vessel fed by the downcomer and recycled back to the riser. In this respect, the solid circulation rate, the superficial riser gas velocity and the system inventory are the key operating variables. They determine the pressure drop across the riser as well as across other components of the circulating system. For calculating mass inventory in the riser, void fraction or voidage is needed. The fraction of column cross-sectional area available for flow of gas is determined by the volume fraction occupied by gas, ε_r. As a result, the fraction of pipe area available for the flow of solids is $(1-\varepsilon_r)$. Experimentally,

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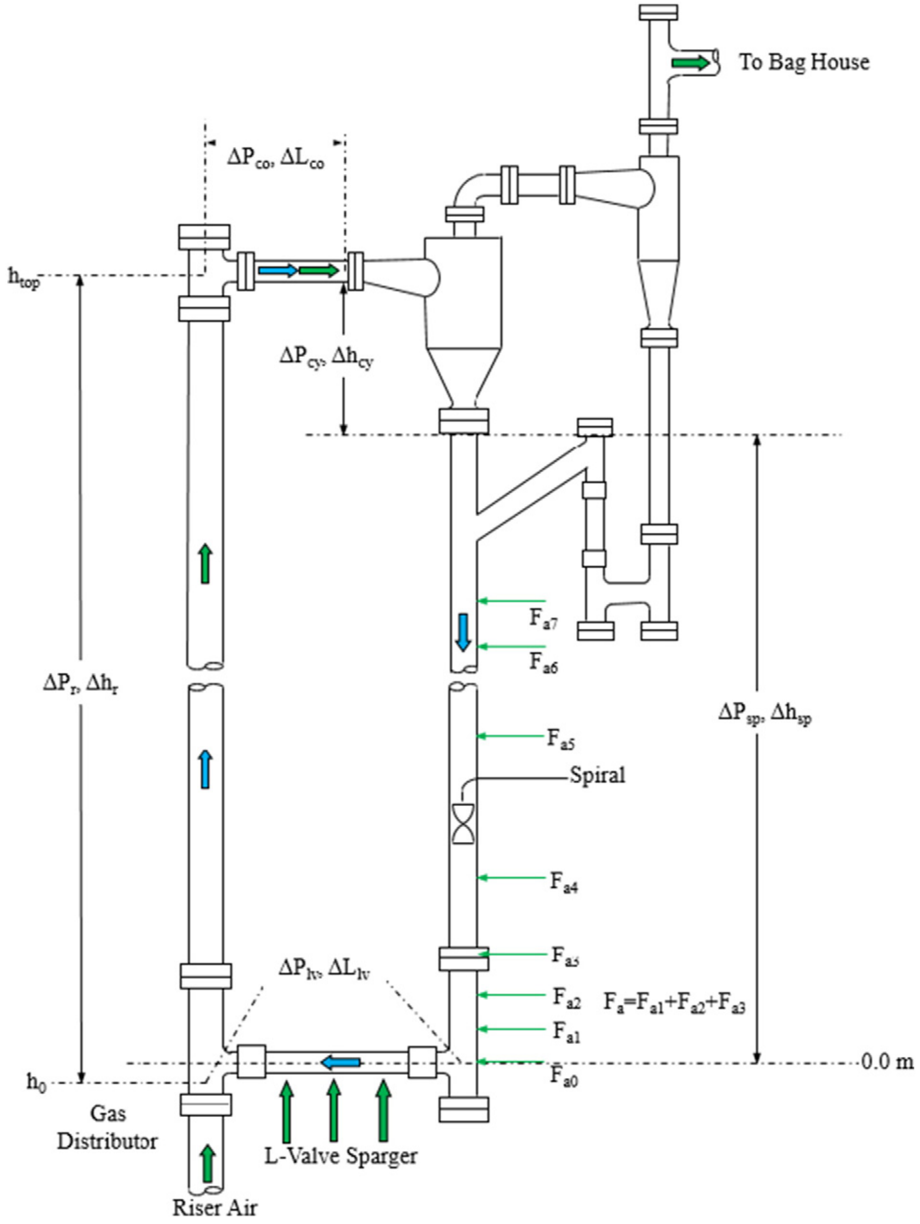

Fig. 1. Schematic of the NETL circulating fluidized bed unit. Green arrows represent gas flow and the light blue arrows indicate the solid flow. The aeration F_{a0} is referred to as an eductor that is occasionally used in high solid circulation rate experiments. The secondary cyclone separates the residual solids leaving the primary cyclone above the standpipe. The separated solids are fed back to the standpipe by opening the valve (not shown) or are sent directly to the bag house.

the total solid inventory in the riser can be determined in several ways. In one way, the CFB unit is brought to a steady state at a given operating condition. Then, the solid inventory is obtained by shutting off the gas and solid feed into the riser, and draining and weighing the accumulated solid in the riser. In another way, the solid feed to the riser is cut off by shutting off the standpipe and L-valve aeration flows. The riser column is allowed to empty by continuously feeding the gas at its bottom. The amount of solid leaving the riser top accumulates in the standpipe. The difference between the bed heights in the standpipe before and after solid cutoff provides the mass of solid initially present in the riser. Both of these techniques require shutting down either the solid flow in the CFB or the gas flow in the riser. As a result, the solid circulation ceases around the loop. Therefore, these techniques are impractical in critical applications such as establishing riser inventories in the utility power distribution. Coal fired power plants burn coal in the CFB boiler for transferring heat to the water boiler drum, which turns the steam turbine coupled to the electrical generator. The amount of coal to be burnt in the CFB is determined by the customer demand. During a high demand period, more coal is needed and hence, it is impractical to shut down the CFB boiler to meet the customer demand.

There are studies that have attempted to continuously monitor riser inventory [4–8] during the operation of CFB units. The common technique involves determining solid inventory from pressure drop measurements. The solid inventory is calculated by assuming that the weight of solid balances the riser pressure drop. The shear stress at the wall is usually neglected even though it may contribute significantly to the total pressure drop [9]. Most of these analyses focused only on the steady state conditions in which, by definition, the rate of change of riser inventory is zero. As a result, the mass flowing into the riser equals the mass flowing out.

During transients, the mass balance equation is described by a partial differential equation rather than an algebraic expression. In the