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Effect of interaction between spray and attrition jets in a high temperature fluidized bed

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ABSTRACT

A high temperature fluidized bed unit was used with simultaneous liquid injection and jet attrition, using separate nozzles that were located to allow for interactions between the jet cavities they created in the fluidized bed. The effect of jet interactions on liquid–solid contact and particle attrition was studied. When the attrition nozzle was located and inclined so that its jet would interact with the spray jet, there was a large reduction in the formation of large liquid–solid agglomerates, but particle attrition was reduced and the formation of fines was increased. The best results were obtained when the attrition jet hits the spray jet at its base, just downstream of its nozzle tip.

1. Introduction

Fluid Coking™ is used commercially to thermally crack bituminous feed in a fluidized bed of hot coke particles. Bitumen feed is atomized with steam and injected in reactors at around 350 °C. The cracking reaction takes place on the surface of coke particles at temperatures of 510–550 °C [1] and produces gas, liquid oil and solid coke. The gas and liquid oil leave the reactor in gaseous form while solid coke deposits over existing bed particles. Coke particles are continuously removed from the bottom of the coker and conveyed to a burner, where they are partially combusted to raise their temperature; the hot coke particles are then conveyed back to the top of the coker and provide heat for the endothermic thermal cracking reactions. As the coke particles flow down the coker, they first encounter bitumen spray nozzles, attrition nozzles and stripper sheds. To maintain good, continuous operation of a Fluid Coker™ and maximize the yield of valuable liquid, the size of the coke particles in the bed must be controlled, and the formation of wet agglomerates in the spray region must be minimized.

The size of the coke particles in the bed must be controlled as they would otherwise become gradually larger due to the deposition of product coke layers and the agglomeration of smaller particles. If the particles were too large, the fluidized bed would not be properly fluidized and slugging would occur; moreover, the coke transfer lines to and from the burner would not operate properly. High velocity steam jets are, therefore, introduced into the coker fluidized bed with attrition nozzles to control the size of the particles. The steam jets entrain bed particles, accelerate them and slam them onto dense bed particles, resulting in attrition and breakage. Reducing the attrition steam would have two benefits: first, the production of waste water from the coker products separation train would be reduced, and, second, the bitumen feedrate could be increased, as the capacity of commercial cokers is currently limited by the superficial velocity in their freeboard.

A study by Dunlop et al. [2] found that the presence of large quantities of fines, smaller than 50 μm in diameter, has a negative impact on the fluidization quality of the bed and increases undesirable dust emissions. Fine particles also tend to adhere to each other to form larger agglomerates. It is thus desirable to maintain a uniform particle size distribution in the Fluid Coker while minimizing steam consumption and the quantity of generated fines.

The formation of wet agglomerates in the spray region must be minimized. Previous studies have shown that agglomeration result in lower yields of valuable liquid product, as well as fouling of the stripper sheds [1]. Ariyapadi et al. [3] and Bruhns and Werther [4] detected the formation of wet agglomerates from spray jets. The former used X-ray imaging to show that with the conventional nozzle configuration, agglomerates are formed at the jet bed interface due to the coalescence of wet particles and droplets near the tip of the spray jet cavity. Weber et al. [5] showed that drier agglomerates break up more quickly, mitigating the problems caused by agglomeration. It is therefore essential to improve solid–liquid mixing in or near the spray jets to minimize the liquid content of the wet agglomerates. Iveson et al. [6] suggested that solid–liquid mixing would be improved by maximizing the solid flux at the interface between the dense bed and the spray jet cavity.

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McMillan et al. [7] showed that placing a co-axial tube downstream of the spray nozzle tip enhances solid–liquid mixing within the jet cavity. This new feed nozzle configuration is known as ESE (Enhanced Solid Entrainment) nozzle and is quite effective in reducing the formation of liquid–solid agglomerates. However, the application of ESE in Fluid Cokers has been limited by concerns about the erosion of the ESE internals by high velocity coke particles.

The type of attrition nozzles used in the Fluid Coker™ is a converging–diverging type. This type of nozzle configuration is characterized by sonic gas velocities at the nozzle throat which is a desired characteristic to achieve a high grinding efficiency of the bed particles. The grinding efficiency η is defined as the ratio of the new particle surface created by attrition to the mass of required attrition gas such that:

$$\text{Grinding efficiency}, \eta = \frac{\text{New particle surface created by attrition}}{\text{Mass of required attrition gas}} = \frac{\text{m}^2/\text{s}}{\text{kg}/\text{s}} = \frac{\text{m}^2}{\text{kg}}.$$

Further improvement to the nozzle geometry, such as the angle of the divergent section, can further maximize the grinding efficiency as shown in Cruz et al. [8]. Furthermore, Li [9] studied the effect of bed temperature on attrition performance and reported higher grinding efficiencies at higher bed temperatures. Finally, Tuunila and Nystorm [10] studied the effect of varying the attrition nozzle inclination with respect to the horizontal direction on the grinding efficiency. They obtained the highest attrition efficiency with the largest angle above the horizontal plane that they tested: 43°.

In current Fluid Cokers™, jet cavities from spray and attrition nozzles do not interact. Consequently, the objective of this study is to determine whether an interaction between the jet cavities from both nozzles could minimize agglomerate formation.

2. Experimental setup and methodology

Experiments were performed in a hot fluidized bed column, 1.23 m high, with a 0.51 m × 0.11 m rectangular cross-section as shown in Fig. 1. The fluidized bed height was 0.45 m. Bed particles were petroleum coke with a Sauter mean diameter of 110 μm and a particle density of 1450 kg/m^3. The coke particles were fluidized with nitrogen gas introduced through a sparger distributor and heated to 250 °C with an electric heater immersed in the upper region of the bed, well above the spray and attrition nozzles.

A cold binding solution of 30 wt.% sugar in water was atomized with nitrogen gas and injected inside the hot bed at a height of 0.25 m above the sparger. This combination of an aqueous solution of sucrose can be easily adjusted by selecting the proper sucrose concentration that can render similar viscosity value (3 cP) as that encountered in the bitumen system at the injection temperature of 350 °C [11]. In addition, this system can mimic the coke formation by caramelizing the sucrose content and can generate stable agglomerates. As the sugar solution heats up upon contact with hot coke particles, the sugar converts to caramel that coats the particles, while water evaporates: this simulates what occurs in Fluid Cokers™, when bitumen contacts hot coke particles, vapors are emitted and coke deposits on the particles. In Fluid Cokers™, the solid coke represents about 20 to 25 wt.% of the injected bitumen while with the sugar solution, about 25 wt.% of the solution forms caramel (sugar is first deposited and there is a subsequent mass loss as the sugar undergoes caramelization).

Cold nitrogen gas was injected into the hot fluidized bed through an attrition nozzle at a height of 0.13 m above the gas distributor and 0.12 m below the spray nozzle. Two sampling ports, which were located 0.13 m and 0.25 m above the gas distributor, used a screw system to collect bed samples. The bed was equipped with three cyclones; an internal primary cyclone that recycled the bed material through a dipleg, and two external cyclones (secondary and tertiary) placed in series.

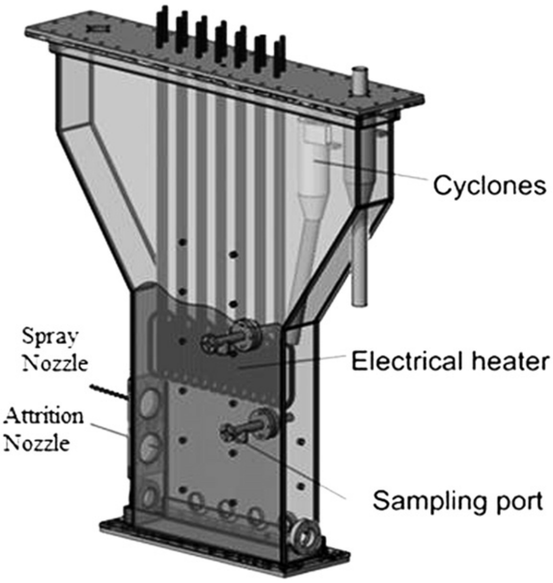

Fig. 1. Schematic of the hot fluidized bed with spray and attrition nozzle. Modified from Li [9].

A TEB nozzle [12] with a throat diameter of 2.7 mm was used as spray nozzle (Fig. 2). Pressurized sugar solution was mixed with atomization gas through a venturi pre-mixer (Figs. 3 and 4). Pressure regulators were used to control the pressures at P_1 and P_2 (Fig. 4) to achieve the required mass flow rates of injected liquid and atomization gas. The ratio of these flow rates is expressed as gas-to-liquid ratio (GLR). The liquid flow rate was obtained by mass balance of the liquid in the tank and the mass flow rate of atomization gas was obtained by measuring the pressure P_2 upstream of a calibrated sonic orifice.

A convergent–divergent attrition nozzle with a 1.7 mm throat diameter (Fig. 5) was used with a gas mass flow rate of 320 g/min and an upstream pressure of 2.17 MPa (300 psig). In such a convergent–divergent nozzle, sonic velocity is reached at the throat followed by supersonic velocity in the divergent channel [8]. A total of three different orientations of the attrition nozzle with respect to the horizontal plane were tested in this work: 0° (conventional orientation), 14° and 45° (Fig. 6). Preliminary measurements (Fig. 6) showed that:

- There was no interaction between the spray and attrition jets at a nozzle inclination of 0°.
- At 14°, both jet cavities met near the spray jet tip.
- At 45°, both jet cavities met near the spray jet base, just ahead of the spray nozzle tip.

These results were confirmed by estimating the lengths of both the spray and attrition jet cavities with well established correlations for the nozzle types used in this study. The length of the gas–liquid jet L_{jet} was calculated with an empirical correlation from Ariyapadi et al. [13]:

$$L_{jet} = \frac{5.52}{g^{0.27}} \frac{1}{\left(\rho_P - \rho_g\right)^{0.27}} \left(\frac{G_L^2 (1 + ALR\ [S])}{\rho_L (1 - \varepsilon')} \right)^{0.27} d^{0.73} C_g.$$

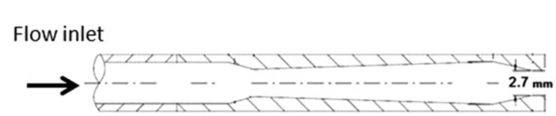

Fig. 2. TEB spray nozzle (throat diameter 2.7 mm).