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AGGLOMERATE BEHAVIOUR IN A RECIRCULATING FLUIDIZED BED WITH SHEDS: EFFECT OF AGGLOMERATE PROPERTIES

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ABSTRACT

The Radioactive Particle Tracking technique was used to study agglomerates of different sizes and densities inside a cold flow recirculating fluidized bed with sheds, to simulate Fluid Coker^{TM} sheds. The research found that both size and density of the agglomerates greatly affect their dynamics and interactions with bed internals.

INTRODUCTION

Fluid Coking^{TM} is a process that is used to upgrade heavy oils through thermal cracking. Oil is injected in a downward-flowing bed of hot coke particles, where it heats up and cracks into smaller vapour molecules. The down-flowing coke particles are sent to a burner where they are reheated. Valuable oil vapors trapped between the coke particles are recovered through steam stripping before the coke particles are sent to the burner. The stripper section of the Coker^{TM} consists of a system of baffles (sheds) that enhance the removal of hydrocarbon vapors from fluidized coke particles. When wet agglomerates of coke particles in presence of interstitial vapour hit the shed in poor fluidized areas, some of the hydrocarbons crack and form solids deposits that lead to stripper fouling. Extensive fouling decreases stripping efficiency and may cause premature shutdowns. Reducing fouling requires raising the Coker temperature, which reduces liquid yields. The density of the bitumen-coke agglomerates ranges from 940 to 1000 kg/m^3 and their diameter ranges from 1 to 20 mm (1)(5)(9). It is, therefore, essential to study the motion of agglomerates within the stripper zone, and to evaluate the probability of a collision between the agglomerate and the sheds.

The Radioactive Particle Tracking (RPT) technique allows the immediate determination of a radioactive tracer-particle location within a certain space or measurement zone inside a reactor. As showed by Sanchez and Granovskiy (8), the RPT technique can be used to measure the degree of fouling of a shed and can give important information about the hydrodynamics of the fluidized bed where the shed is immersed. In this study, it is used to track agglomerates inside the bed. Preliminary experiments have shown that the agglomerate motion is affected by agglomerate size and density, shed configuration, gas velocity and solids recirculation rate. In commercial Fluid Cokers^{TM}, it would be very difficult to change fluidization velocity, shed geometry and solid recirculation rate, since they have been optimized for the process. On the other hand agglomerate properties could be changed by modifying the spray nozzles. The objective of this study was to determine how agglomerate properties, such as size and density, affect the behavior of agglomerates in the stripper section of a cold flow recirculating fluidized bed.

EXPERIMENTAL APPARATUS AND PROCEDURE

Fluid coke provided by Syncrude Canada was used as the fluidized material. Its particle density was 1443 kg/m^3 and its Sauter-mean diameter was 140 µm. The bed mass was 19 kg.

An Epoxy/Gold tracer-particle prepared as suggested by Godfroy (4), was selected as the radioactive source. When gold is radiated in a nuclear reactor (for this research, the Material Test Reactor at McMaster University in Canada), some of it transforms into Au^{198} isotope with a half-life of 2.69 days (2). For this study, the tracer-particle radiation decreased gradually from 166 to 70 µCi. The simulated agglomerates were constructed using Epoxy Resin (West System, Inc. Bay City, MI), gold powder (Stream Chemicals, Inc. Newburyport, MA) and to lower their density, Glass Bubbles (Freeman Manufacturing and Supply Company, Avon, OH). For simulated agglomerates of lower densities, the tracer-particles and carriers were created using epoxy resin mixed with Glass Bubbles. For simulated agglomerates with larger diameters and densities, a Nylon Ball (McMaster-Carr, Aurora, OH) was selected as the carrier for the radioactive tracer, and epoxy putty (Polymeric Systems, Inc. Cheshire, WA) was used to close the orifice that was made to introduce the radioactive tracer, and adjust the agglomerate density. Table 1 presents the simulated agglomerates properties and construction materials that were used for this research.

Table 1. Simulated agglomerate properties and construction materials.

Tracer	**Density ρ (kg/m^3)**	**Diameter Ø (mm)**	**Materials**
1	1400	1.81	Epoxy Resin (1120 kg/m^3) and Gold Powder (19300 kg/m^3).
2	1390	12.65	Tracer 1, inside a Nylon Ball (1120 kg/m^3) seal with Epoxy Putty (1600 kg/m^3).
3	1060	1.94	Epoxy Resin (1120 kg/m^3), Gold Powder (19300 kg/m^3) and Glass Bubbles (150 kg/m^3).
4	1060	12.65	Tracer 3, inside an Epoxy Resin (1120 kg/m^3) mix with Glass Bubbles (150 kg/m^3) and seal with Epoxy Putty (1600 kg/m^3).
5	960	2.00	Epoxy Resin (1120 kg/m^3), Gold Powder (19300 kg/m^3) and Glass Bubbles (150 kg/m^3).
6	890	12.65	Tracer 5, inside an Epoxy Resin (1120 kg/m^3) mix with Glass Bubbles(150 kg/m^3) and seal with Epoxy Putty (1600 kg/m^3).

Experiments were carried out in a 0.19 m I.D. cold flow recirculating fluidized bed made of Plexiglas, which does not contain irregular surfaces were the tracer-particle could be trapped (Figure 1). A single tracer, simulating an agglomerate, was introduced into the fluidized bed that was operated at a superficial air velocity of 0.24 m/s to match the industrial Fluid Coker^{TM} hydrodynamics (3). The solid recirculation rate in the riser was set at 0.55 kg/s. The position rendition technique was the Computer Automated Radioactive Particle Tracking (CARPT) developed by Lin (6) and used by Sanchez and Granovskiy (8). The average fluidized bed density was 721 kg/m^3 while the emulsion phase density was 850 kg/m^3. This means that no tracer was buoyant in either the fluidized bed or the emulsion phase.

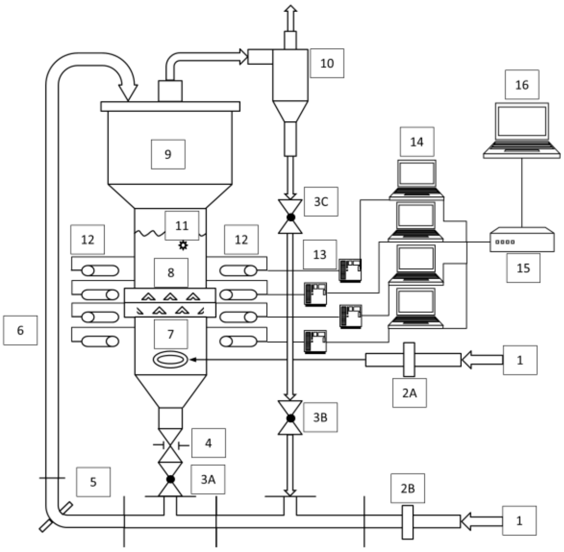

Figure 1. Fluidized bed apparatus components and instrumentations: (1) Compressed air inlet; (2) orifice plates for flow measurement; (3) ball valves; (4) pinch valve; (5) elbow pressure taps for solids flow measurement; (6) 6.35 cm I.D. riser; (7) loop sparger; (8) three up-row sheds and two complete down-row shed plus two half; (9) 29.21 cm I.D. disengagement zone; (10) cyclone; (11) γ-rays emitter; (12) twelve NaI Scintillation detectors in a four layer array; (13) USB hubs; (14) slave computers; (15) Ethernet computers and (16) server computer.

RESULTS AND DISCUSSION

The RPT technique is generally used with radioactive tracer-particles that are neutrally buoyant to study the bed hydrodynamics (2)(7). No research has been done using gamma emitters with different densities.

Interactions of the Agglomerates with the Sheds

It is important to characterize the type of interactions with the sheds of the agglomerate. Figure 2-a, shows that the motion of the agglomerates inside the bed is not straightforward. In this example, the agglomerate enters the measurement zone from above the shed zone, travels downward in the wall region, crosses the shed zone, moves back up through the shed zone in the central region and finally leaves the measurement zone. Although Figure 2-a only shows a short loop, in which the agglomerate only interacts twice with the shed, in some cases, the agglomerate may cross the shed zone over fifty times in a loop. For this research, a loop starts with the first appearance of the agglomerate above the shed zone and ends with its reappearance above the shed zone, after leaving the measurement region through the bottom of the measurement region.

Four types of shed/agglomerates interactions are proposed:

1) Above the bed: the agglomerate enters the shed zone from above, interacts with the sheds and later moves back up (Figure 2-b).
2) Below the shed: the agglomerate enters the shed zone from below, interacts with the sheds and later moves back down (Figure 2-c).

3) Upward shed zone passage: the agglomerate crosses through the shed zone from below and enters the zone above the shed (Figure 2-d).
4) Downward shed zone passage: the agglomerate crosses through the shed zone from above and enters the zone below the shed (Figure 2-e).

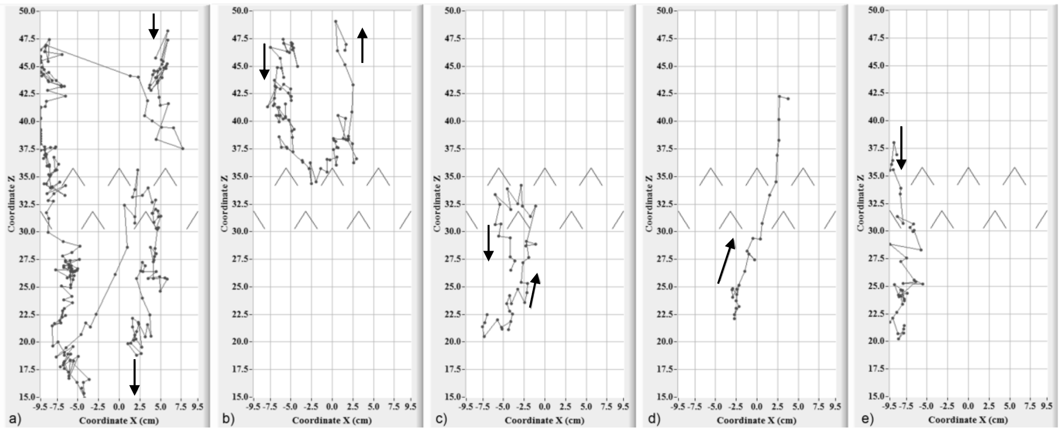

Figure 2. Type of Interactions of the agglomerates with the sheds. a) Small cycle of the tracer-particle in the measurement zone. b) Interaction from above the shed. c) Interaction from below the shed. d) Crossing the shed zone interaction starting from below the shed. And e) Crossing the shed zone interaction staring from above the shed.

Collisions of the wet agglomerates with the shed surfaces lead to their fouling. The RPT technique only gives the coordinates of the tracer particle and cannot detect an actual collision. The next three numbers are thus proposed, to characterize the interactions of agglomerate with the sheds:

1) The number of times the agglomerate enters each shed row per loop (First shed: between heights of 0.33 and 0.36 m above the gas distributor ring, shown in Figure 1. Second shed: between heights of 0.30 and 0.33 m.) A larger number is associated with a higher collision probability.
2) The residence time of the agglomerate in the complete shed zone (between the heights of 0.2930 and 0.3677 m). A higher time is associated with a higher collision probability.
3) The residence time of the agglomerate in the shed vicinity, as defined in Figure 5-a. A higher time is associated with a higher collision probability.

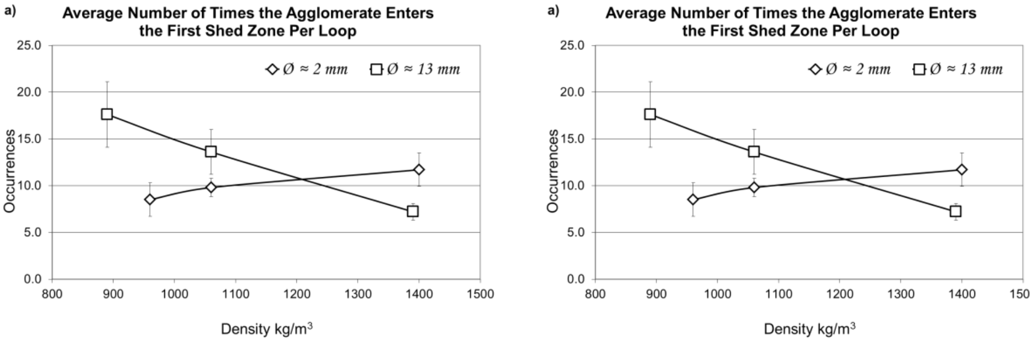

Figure 3. Average number of times the agglomerate enters a shed row a) upper shed row b) lower shed row (the error bars represent the standard deviation).

Figure 3 shows the average number of times per loop the agglomerate enters each shed row. Although it varies for each loop, there is not much deviation. Agglomerate size greatly affects agglomerate behavior. For the bigger agglomerate (Ø ≈ 13 mm), the average number of times it enters each sheds row more than doubles as the density of the agglomerate is reduced. In contrast, with the smaller agglomerate (Ø ≈ 2 mm), the average number of times it enters each shed row decreases as its density is reduced.

Figure 4 shows the average residence time of the agglomerate in the complete shed zone. In this instance, both sizes of agglomerates have a similar behavior, and the residence time in the shed zone area decreases with increasing agglomerate density. The same behavior can be seen with the residence time of the agglomerates in the vicinity of the shed. Figure 5-b presents the average residence time of the agglomerate in the shed vicinity. The larger agglomerate behavior is much more sensitive to its density.

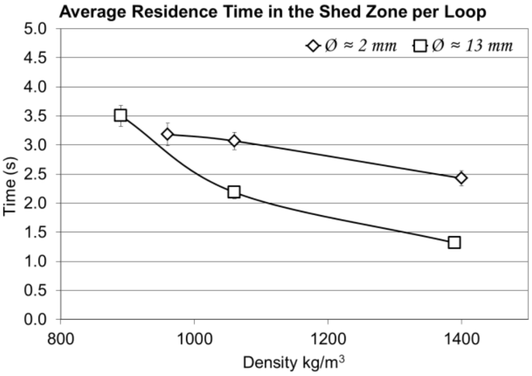

Figure 4. Average residence time of the agglomerate inside the complete shed zone area (error bars represent the standard deviation).

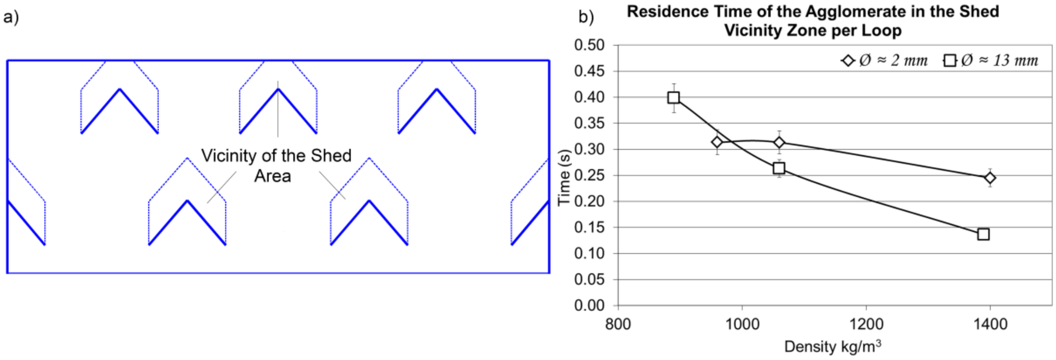

Figure 5. a) Vicinity of the shed area. b) Average residence time of the agglomerate inside the vicinity of the shed area (error bars represent the standard deviation).

Lagrangian Velocities

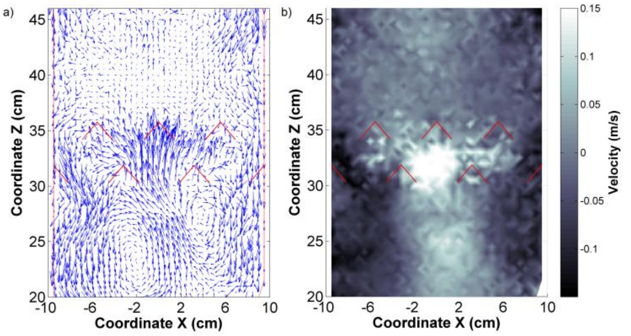

Figure 6. a) Typical mean Lagrangian velocity plot arrow for the X- and Z- coordinates. The X- coordinate is the coordinate that looks at the shed. b) Magnitude of the vertical component of the Lagrangian Velocity.

The RPT technique gives the average Lagrangian velocities around the measurement zone of the cold flow recirculating fluidized bed as shown in Figure 6-a. It is clear that the sheds reduce the velocity of the agglomerate when it is moving upward; above the shed, both horizontal and vertical velocity components are smaller. Although the recirculation configuration of the fluidized bed imposes a downward overall motion of solids, the fluidization gas that is introduced by the sparger and the bubbles it forms, generates the biggest magnitude in the vertical velocity below the shed. By isolating the vertical component of the velocity and plotting it in velocity zone map as in Figure 6-b, the effect of the shed on the fluidized bed can be enhanced. Below the shed, all the upward velocity of the agglomerate is concentrated in the center of the fluidized bed, while above the shed, this effect is heavily diminished and the velocity is more evenly distributed.

Using the coordinates of the tracer-particle inside the measurement zone, a frequency map of occurrence can be created by counting the number of times that the tracer was detected at each coordinate and dividing it by the total number of times the tracer was found inside the measurement zone. Figure 7 shows that, as with the velocity plot arrow, the influence of the sheds can easily be observed.

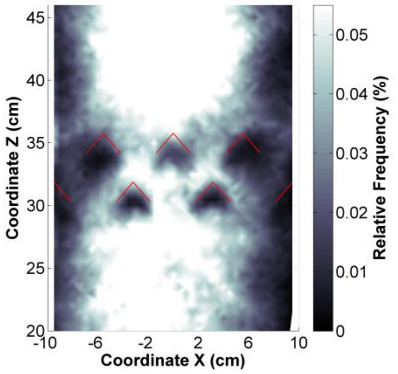

Figure 7. Typical frequency map of occurrences.

The velocity plot arrows for tracers 1, 3 and 5 in the shed zone are shown in Figure 8-I and in Figure 8-II for tracers 2, 4, and 6. For the small diameter agglomerate (Ø ≈ 2 mm), the mean Lagrangian velocities decrease with increasing agglomerate density; the reverse trend is observed with the larger agglomerate.

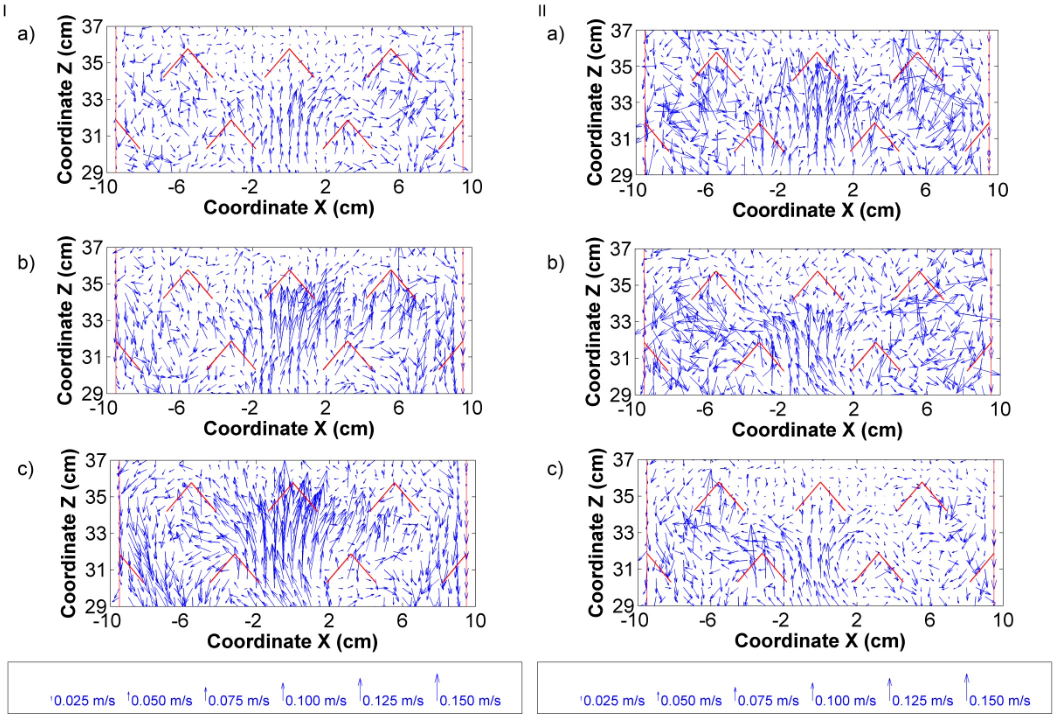

Figure 8. I) Velocity plot arrow for agglomerates: a) Tracer 1 ρ=1400 kg/m^3 Ø=1.81 mm. b) Tracer 3 ρ=1060 kg/m^3 Ø=1.94 mm. and c) Tracer 5 ρ=960 kg/m^3 Ø=2.00 mm. II) Velocity plot arrow for agglomerates: a) Tracer 2 ρ=1400 kg/m^3 Ø=12.65 mm. b) Tracer 4 ρ=1060 kg/m^3 Ø=12.65 mm. and c) Tracer 6 ρ=890 kg/m^3 Ø=12.65 mm.

Figure 9 shows the breakthrough velocity of the agglomerates in the shed zone, which is calculated by measuring the average time that the tracer-particle takes to cross the 0.0747 m of height of the shed zone in either the upward and downward directions. Both breakthrough velocities (upward and downward), increase with increasing agglomerate density. Smaller sizes (Ø ≈ 2 mm) move slightly faster than bigger sizes (Ø ≈ 13 mm), in the upward direction while the reverse phenomena is observed in the downward direction. Bigger agglomerates (Ø ≈ 13 mm) move slightly faster than smaller agglomerates (Ø ≈ 2 mm).

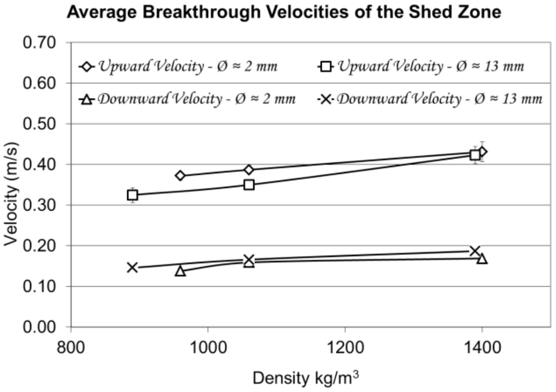

Figure 9. Breakthrough velocities (error bars represent the standard deviation).

By comparing, the data from the Lagrangian velocities plot (Figure 8) and the breakthrough velocity comparison graph (Figure 9) a better understanding of the hydrodynamic movement of the agglomerates can be attained. The lighter and bigger the agglomerates are, the slower they will move around and across the sheds. This phenomena increase the residence time of the agglomerate in the vicinity of the shed (as shown in Figure 5-b) and thus, the probability of fouling of the shed rises. Because none of the agglomerates are buoyant, they all sink through the bed, and larger and denser agglomerates sink faster; they only go up when they are picked up by gas bubbles and larger and denser agglomerates can only be picked by relatively large gas bubbles. This explains why larger and denser agglomerates have a higher downward breakthrough velocity. Because larger and denser agglomerates can only be picked by larger and, hence, faster bubbles, their upward breakthrough velocity is also higher.

The number of times an agglomerate will circulate through the shed zone mainly depends on how likely it is to exit the measurement zone and enter the recirculation loop and the riser. Denser agglomerates sink faster through the bed and have therefore less opportunity to be picked and sucked by the wake of the gas bubbles. Although solids move upward in the wake of the bubble, it seems that smaller and denser agglomerates enter and leave the wake of the bubble more easily, just to be entrained again by the bubble coming below. This would explain why the average velocity in the shed vicinity (Figure 8-I-a) is low, compared to less denser agglomerates (Figure 8-I-c).

CONCLUSION

In this research, the Radioactive Particle Tracking technique has been successfully applied to study the behavior of agglomerates with different sizes and densities inside a recirculating fluidized bed. The types of interactions that the agglomerates have with bed internals, for this case the sheds, have been characterized. While the number of times the agglomerates enter the sheds rows decreases with increasing density for bigger agglomerates, the contrary can be said for small size agglomerates. For agglomerates of all sizes, the average residence time that the agglomerate spends in the shed zone and in the vicinity of the shed greatly decreases with increasing agglomerate density. For small size agglomerates, it can then be concluded that, as their density is increased, they enter the shed zone more often but spend less time within this zone. Lastly, big and lighter agglomerates will move more slowly across and in the shed vicinity.

Therefore, the probability of an agglomerate colliding with a shed increases, as the agglomerates are bigger and lighter. The agglomerates contain considerable amounts of un-cracked liquid hydrocarbons, which can lead to fouling.

NOTATION

Ø	Diameter	ρ	Density

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