Refereed Proceedings

The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering

Engineering Conferences International *Year* 2007

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D. Rusnell[*] John R. Grace[†] Xiaotao T. Bi[‡]
C. Jim Lim[**] P. Ronan[††] C. A. McKnight[‡‡]

[*]Syncrude Canada Limited
[†]University of British Columbia, jgrace@chml.ubc.ca
[‡]University of British Columbia, xbi@chml.ubc.ca
[**]The University of British Columbia, cjlim@chml.ubc.ca
[††]Syncrude Canada Limited
[‡‡]Syncrude Research Centre

IMPROVED STANDPIPE ENTRANCE FOR STABLE HIGH-FLUX SOLIDS FLOW

D. Rusnell[1], J.R. Grace[2], H.T. Bi[2], C.J. Lim[2], P. Ronan[1] and C.A. McKnight[3]

1. Syncrude Canada Limited, Fort McMurray, Alberta, Canada T9H 3L1.
2. Dept. of Chemical and Biological Engineering, University of British Columbia, 2360 East Mall, Vancouver, Canada, V6T 1Z3.
3. Syncrude Research Centre, 9421 – 17th Avenue, Edmonton, Alberta Canada T6N 1H4.

ABSTRACT

Cold model tests were used to show the causes of instabilities in the operation of the standpipe entrance ("sore thumb") in industrial scale fluid cokers. New geometries were tested which might provide higher flows and prevent operating problems such as flow reversals and flooding, while also minimizing the adverse effects of fouling. The tests were conducted using FCC particles in a geometrically and dynamically scaled half-column of approximately 1/9th scale which had previously been used to show the effects of baffles on fluid coker strippers. The addition of sloping surfaces to increase the surface area for ingress of particles was helpful to an extent, but excessive overhang resulted in bubbles being drawn in. A perforated top surface was found to be instrumental in the degassing of the solids, whereas porous side area was essential for solids entry. Aeration of the standpipe reduced stick-slip flow, but excessive aeration made degassing more difficult and therefore promoted flow reversal. Loss of area at the top, and to a lesser extent, at the sides was found to be detrimental to the performance of the standpipe entrance. Several new geometries were tested, leading to one that provided better flow stability, improved flow control, excellent pressure build-up in the standpipe, more tolerance to fouling, and enhanced circulation capacity.

INTRODUCTION

One of the most advantageous features of fluidized beds is their ability to transfer solid particles between separate vessels (1). This can be important, for example, in reactor/ regenerator systems where catalyst particles must be continuously sent to, and retrieved from, a separate vessel in which deactivated catalyst is regenerated. It is also an integral feature of circulating fluidized bed systems, where particles entrained from the riser must be returned continuously to the bottom of the riser, with the return system available for other purposes such as heat recovery or secondary reactions.

In fluid coking, much like fluid catalytic cracking, particles are continuously withdrawn through a stripper section at the base of a fluidized bed reactor and sent to a secondary reactor (burner) where coke is reheated (2). Hot coke is then returned to the main reactor (fluid coker), with the heat which is generated in this manner vital in providing for the endothermic heat of reaction of the coking process. Smooth problem-free circulation of fluid coke particles between the coker and the burner is essential to maintain excellent overall operation of the coking process. In addition, achieving high fluxes of particles back and forth between the vessels is one of the principal constraints limiting the upper limit of throughput in the process. The work described in this paper was undertaken to improve the understanding of flow into the vertical standpipe operated as the first part of the transfer line to send "cold coke" to the burner. Once the operation was better understood, attempts were made to improve the geometry of the standpipe entrance to give higher fluxes, improved flow stability, greater tolerance to fouling and trouble-free operation. The work was carried out in a cold-model facility constructed and previously used in testing of the hydrodynamics, flooding and baffle design improvements in Syncrude's original fluid cokers.

EXPERIMENTAL

Apparatus

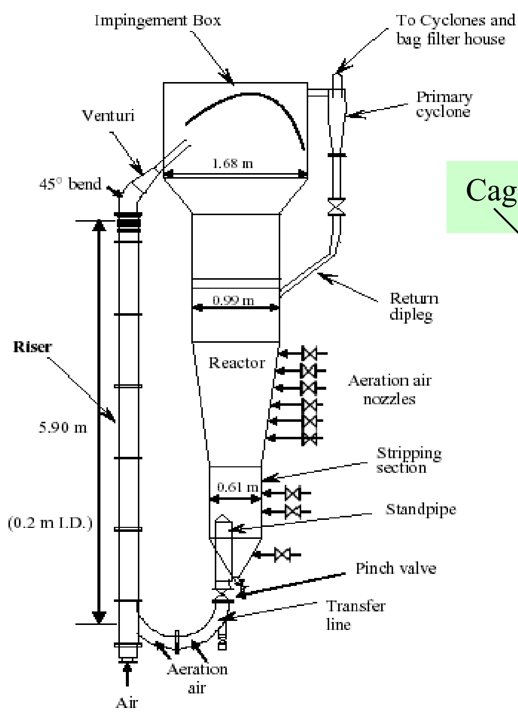

Figure 1: Schematic of fluid coker cold model plexiglas facility.

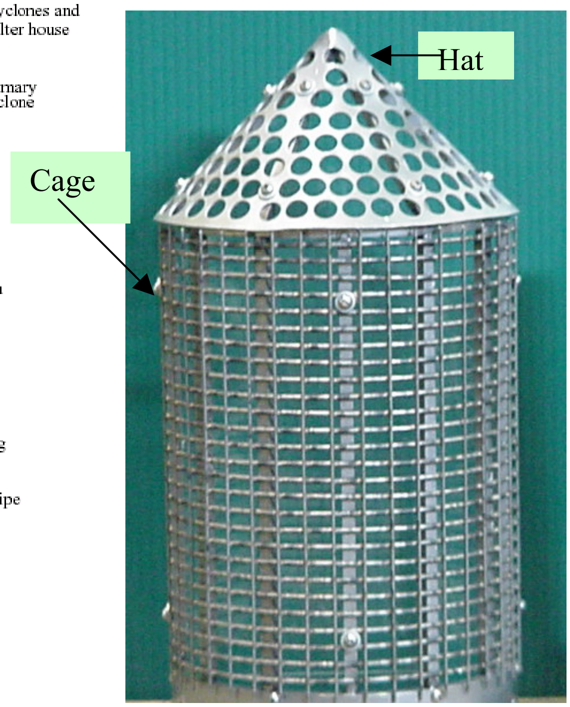

Figure 2: Geometry of original sore thumb standpipe entrance.

The experiments were carried out in a plexiglas cold model shown schematically in Figure 1. This equipment was constructed to allow testing of the stripper section of two large industrial fluid cokers operated by Syncrude Canada Limited for the upgrading of bitumen derived from oil sands in Western Canada. The column was approximately 1/9th scale relative to the industrial units, and also constructed as a "half-column", i.e. semi-circular in cross-section. The inner diameter of the half-column stripper section was 0.61 m. All dimensions were geometrically scaled, and dynamic scaling was assured by matching key dimensionless groups such as the particle/gas density ratio, Archimedes number and particle/gas flux ratio. Further details of the experimental system are given elsewhere (3, 4).

As in the industrial units based on Exxon technology, the sore thumb and vertical standpipe were not located axi-symmetrically, but were instead offset from the axis of the column. The inner diameter of the standpipe was 100 mm. In the first stage of the experimental work, solids were continuously removed from the bottom of the stripper section of the reactor through a semi-circular "sore-thumb" device, whose geometry, shown in Figure 2, is scaled from the industrial units. The device had a perforated conical top or "hat", and grid perforations in the vertical section below the cone (the "cage"). In the industrial units, the perforations at the top help to exclude large agglomerates from entering and blocking the standpipe. In commercial practice, the top and side perforations become fouled by coke deposits during the extended runs (lasting two years and more), blocking significant fractions of the open area. Fouling of the standpipe entrance was simulated by pasting cardboard over part of the hat and/or outer side (cage) area of the sore thumb.

The net solids circulation flux (G_s) through the riser was measured by monitoring the pressure drop across the venturi constriction at the top of the riser while simultaneously measuring the solids mass flux in the standpipe using a fibre optical velocimeter probe to determine the solids void fraction and velocity. The air flowrate in the riser was determined by an orifice-meter. Instantaneous pressure drops were measured via pressure transducers across various ports, the key ones for this paper being ports 418, 419 and 420, located as shown in Figure 3 below.

The solid particles used in this study were fluid cracking catalyst (FCC) particles of mean diameter 70 microns and density 1700 kg/m^3. Air at 28 $\pm$ 3^{o}C and a pressure of 1.1 bar was the fluidizing agent in all cases. Additional air could also be injected via aeration ports in the standpipe, below the sheds (baffles), through attrition nozzles above the top row of sheds and through spargers at other locations. The superficial velocity through the stripper was maintained at 0.3 m/s for all of the tests described in this paper.

Since the column, including the flat front face of the semi-cylindrical standpipe, was transparent, the solids flow could be viewed at all times. The solids flowrate was controlled by a pinch valve at the bottom of the standpipe, simulating a slide valve in the industrial units.

RESULTS AND DISCUSSION

1. Original Geometry:

Observations of flow through the original sore thumb (Figure 2) indicated that most of the solids entered through the vertical sides of the sore thumb, whereas the perforated conical "hat" chiefly served to allow degassing, i.e. escape of small bubbles which entered with the particles. At relatively low solids fluxes (e.g. < 1000 kg/m^{2}s, based on a horizontal cross-section of the standpipe), the dense solids flow throughout the standpipe, including the entrance region, was remarkably constant and spatially uniform. However, with increasing solids flux, gas bubbles coalesced to form a void space in the top part of the sore thumb, with the interface between this void and the dense-phase solids flow below fluctuating over time. When the solids flux reached about 2200 kg/m^{2}s, the gas void filled the top region of the standpipe and the device was unable to maintain a stable flow. This "flooding" of the entrance region occurred at lower fluxes when cardboard was taped over the top or sides of the sore thumb, simulating fouling. Loss of surface area was more serious for the top (hat) area than for the sides, and for the side near the axis of the column than for the side nearest the outer wall, indicating that fouling of the hat is likely to have the most serious consequences, and that fouling in the near-wall region is less serious than an equal amount of fouling on the open side. Removing the cage hat altogether led to a poor performance (maximum circulation flux about 800 kg/m^{2}s), showing the benefit of the perforated sides and hat relative to simple vertical pipe open at the top.

Pressure drops between ports 418 and 420 shown in Figure 3 give a good indication of the efficacy of the standpipe entrance. Port 418 is outside the standpipe (in the surrounding fluidized bed), whereas port 420 is inside, just below the cage area. When the flow remains stable and a configuration is able to achieve a high flow without flooding, (P_{420} – P_{418}) remains nearly constant with increasing solids flow, whereas this pressure difference falls precipitously when the capacity is limited. The pressure drop between these two levels can be written as

$$\Delta P_{420-418} = \Delta P_{hydrostatic} - \Delta P_{wall\ friction} - \Delta P_{acceleration} - \Delta P_{cage} - \Delta P_{standpipe\ entry}$$

The various terms can be modelled in a conventional manner:

$\Delta P_{hydrostatic} = \lfloor \rho_p (1-\varepsilon) + \rho_g \varepsilon \rfloor gh$; $\Delta P_{wall\ friction}$ from Konno and Saito (5);

$$\Delta P_{acceleration} = 0.5 G_s v_s \; ; \quad \Delta P_{cage} = \frac{0.5}{\rho_p (1-\varepsilon) + \rho_g \varepsilon} \left(\frac{W_s}{A_{cage} C_{Dcage}} \right)^2 \; ;$$

$$\Delta P_{standpipe\ entry} = \frac{0.5}{\rho_p (1-\varepsilon) + \rho_g \varepsilon} \left(\frac{W_s}{A_{standpipe} C_{Dstandpipe}} \right)^2$$

The experimental results for different fractional coverage (0, 21 and 42% hole blockage) of the original standpipe led to fitted values of the drag coefficients of $C_{Dcage} = 0.48$ and $C_{Dstandpipe} = 1.87$. As shown in Figure 4, these values, with fitted values also of the voidage, ε, gave good agreement with the experimental data.

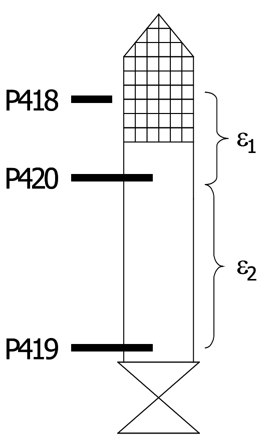

Figure 3: Schematic drawing showing positions of three pressure taps in standpipe entrance region. The two average voidages are derived from the corresponding time-mean pressure drops.

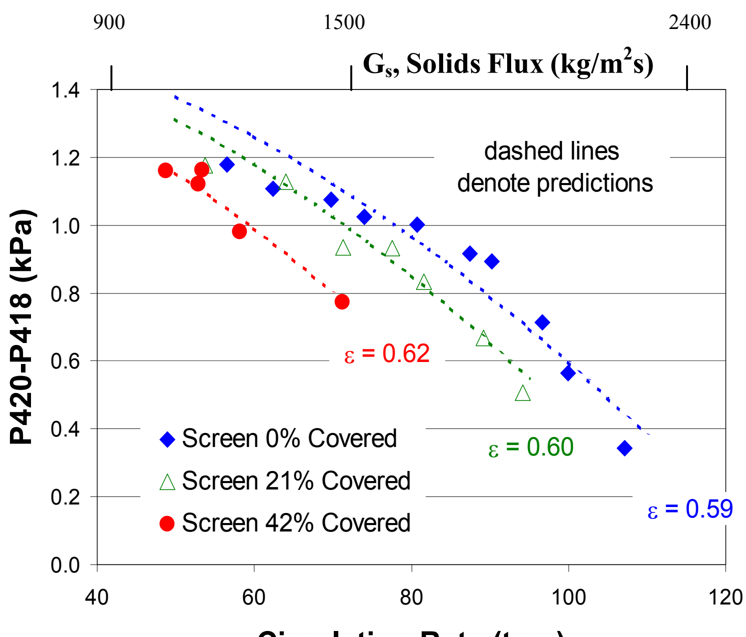

Figure 4: Pressure drop between ports 418 and 420 in Figure 3 as a function of solids flux and equivalent industrial circulation rate, in comparison with predictions of the simple model.

2. First Three Modified Configurations:

In an effort to find a configuration able to extend the range of operation of the commercial units to higher fluxes, while also improving the flow stability and tolerance to fouling, three alternative geometries, shown in Figure 5, were first tested in the facility. Each of these modified geometries increased the area of both top hat and the sides, in order to provide more area for degassing and solids entry, and to increase the tolerance to blockage of open area by fouling. All three were asymmetric. In case A, nicknamed the “fist”, the expansion was entirely towards the axis of the column, with the base maintained the same as for the original sore thumb. Geometries B and C (“gabled roof” and “ski slope”) both extended to the near wall, and both necessitated changes in the basal geometry to be connected to the standpipe on the outside of the column.

Geometry A provided additional area for degassing and extended the upper limit of operating flux range. However, it was found that bubbles could enter the sloped overhanging (downward-facing) outer portion of the side area. When part of this was covered, as shown by the white diagonal cardboard in Figure 5(A), so that the total areas for the original configuration (Figure 2) and modification A were the same, but A had twice the hat open area and 20% less side area, the maximum circulation flux in the standpipe was increased to 2500 kg/m^{2}s. This implies that the top or “hat” (degassing) open area is more important than the side (solids entry) area, at least for the range of conditions studied.

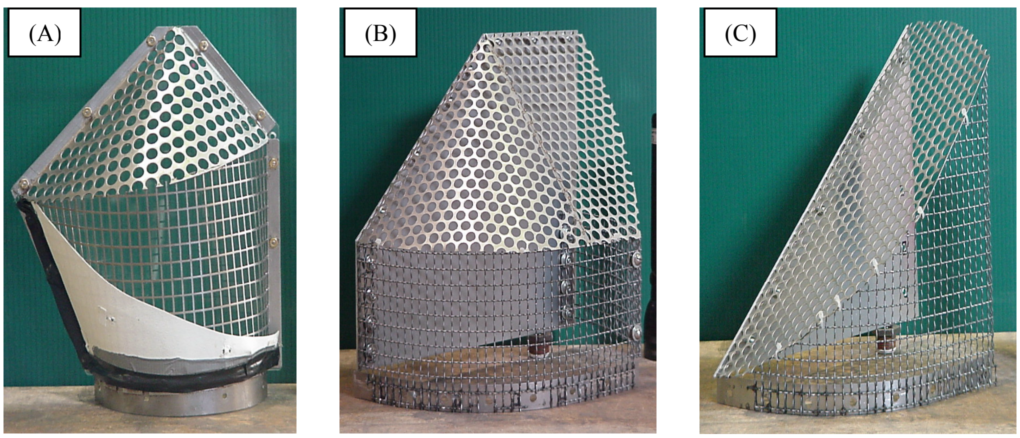

Figure 5: Photographs of first three modified sore thumb configurations tested in cold model facility: A. “Fist”; B. “Gabled roof”; C. “Ski slope”.

Configurations B and C permitted a maximum flux of at least 2700 kg/m^{2}s (at which point the pinch valve became the limiting resistance, so that it was impossible to test higher fluxes). While the flow was clearly more stable and the maximum flux greatly increased, stick-slip flow was evident inside the sore thumb, a mode of flow that was undesirable for sticky material like fluid coke where traces of liquid hydrocarbon can adhere to the outer surface of particles. For these geometries, the standpipe was flared at 15^o to the vertical resulting in a 500% increase in the cross-sectional area of the entrance. The outer surface (side area) was no longer a limiting factor for particle entry for both of these geometries.

3. Two More Modified Geometries:

Configurations A, B and C gave encouraging results, but fine-tuning was needed to avoid excessive degassing in the sore thumb leading to stick-slip flow. (This would likely be more serious for commercial units where gas compression due to the hydrostatic head would be significantly larger.) The angle of 15^o to the vertical had been too large to avoid stick-slip flow, so a maximum angle of 8^o was adopted, while also providing for some aeration inside the sore thumb.

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Two new sore thumbs were designed and fabricated, both based on 8° cones (total included angle of 16°). Both were constrained to have their peaks at the same level as the original sore thumb, and both had to connect to the vertical standpipe entering the reactor through the conical base of the reactor shell. Modification D, shown in Figure 6, was axi-symmetric in all aspects, i.e. hat, cage and cone connecting the standpipe to standpipe where it penetrated through the conical base of the reactor. Hence its peak was at exactly the same point (radially as well as axially) as the apex of the original sore thumb. Its cage open area was 55% greater than the original, while its hat area was 90% greater. This sore thumb achieved a maximum circulation flux of 2700 kg/m^{2}s.

Modification E was the best of the geometries tested. Whereas its hat and cage were axisymmetric, the cone connecting it to the vertical standpipe was flared inwards towards the axis of the reactor, with the result that its peak was no longer directly above the axis of the standpipe, but displaced slightly inwards towards the centre of the column. A schematic drawing, with dimensions and angles, is shown in Figure 7. The cage area was increased by 70% relative to the original sore thumb, whereas the hat area was 170% greater than the original. As in all the other cases, the hat was perforated, and the cage was a grid containing coarse rectangular openings. For this standpipe entrance, the maximum circulation flux (again expressed in terms of the horizontal area of the standpipe), was more than 2800 kg/m^{2}s. Without aeration, there was some stick-slip flow tendency, but this was successfully eliminated by minimal aeration within the standpipe at two levels. With the aeration in place, the flow in this sore thumb, observed through the front face, was remarkably stable, and pressure fluctuations were also of very small amplitude.

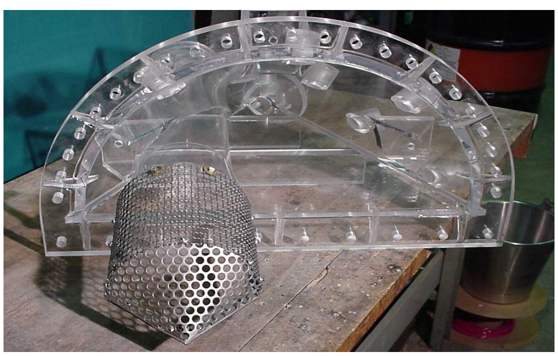

Figure 6: Modification D shown installed in plexiglas conical base section of cold model of stripper.

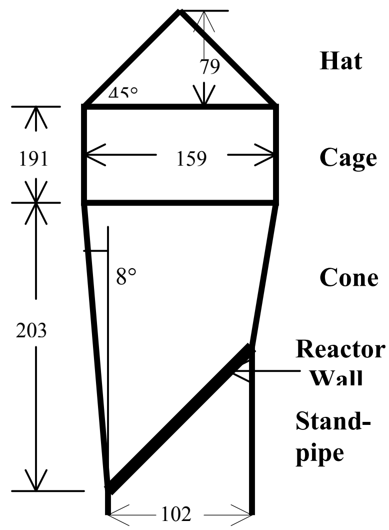

Figure 7: Schematic of modification E. Cage and hat were perforated as in the other cases. All dimensions in mm. (Not to scale.)

4. Other Applications:

Since completing the tests in the cold-model fluid coker, standpipe entrances based on the geometry of modification E (Figure 7) have operated very successfully in tests at Particulate Solid Research Inc. (PSRI), in thesis work on UBC's high-density circulating fluidized bed flow loop (6), and in high-flux downer tests (7). In each of these three cases, the sore thumb tested was axisymmetric. This geometry is ideally suited for downers since the major hurdle limiting the adoption of downers for practical applications appears to be the limitation in achievable solids flux and hold-up within downer reactors. A feeder that provides uniform continuous high-flux solids flow addresses this restraint directly.

CONCLUSIONS

Standpipe entrances employed in fluid cokers have a perforated inverted conical “hat” on top of a vertical section (“cage”) made up of a coarse mesh grid. The perforations prevent ingress of oversized agglomerates. Both the hat and the cage play a role in assuring uniform and steady solids flow into the standpipe, with the former primarily serving for degassing of the entering solids, whereas the latter provide passages where the solid particles enter the top of the standpipe. Blocking either the hat or the cage, e.g. due to fouling, can reduce the flow capacity of the standpipe, lead to fluctuations in flow and eventually cause flooding. The hat area is especially important for the original geometry introduced by Exxon.

Augmenting the hat and cage area can lead to increased capacity, greater tolerance to fouling and more stable and steady operation. However, overhang is undesirable as bubbles can be drawn into the device. An angle of 15° to the vertical is too large, as it leads to stick-slip flow. An angle of 8° to the vertical, however, gives much less stick-slip flow, and, combined with judicious aeration, can lead to a considerable improvement. When the standpipe is located asymmetrically, an asymmetric design which displaces the axis towards the centre of the upstream chamber is possible. The best geometry tested (modification E in Figure 7) gave at least a 30% increase in overall capacity, much more stable operation and a great increase in fouling tolerance relative to the original “sore thumb” standpipe entrance.

ACKNOWLEDGEMENT

The authors are grateful to Syncrude Canada Limited for sponsoring this work and for permission to publish these results. Assistance with the experimental work from Andrew Donald and advice from Ted Knowlton and his colleagues at PSRI are also acknowledged with gratitude.

NOTATION

A	Cross-sectional area, m^2
C_D	Discharge coefficient, -
g	Acceleration of gravity, m/s^2
G_s	Solids flux through the standpipe, kg/m^{2}s
h	Vertical distance between pressure taps, m
P	Pressure, Pa
W_s	Solids flow rate, kg/s
ΔP	Pressure drop, Pa
ε	Time-mean void fraction of dense suspension in standpipe entrance, -
ρ_g	Gas density, kg/m^3
ρ_p	Particle density, kg/m^3

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