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FCC riser hydrodynamics: Effect of some operating variables

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Fluidized bed catalytic cracking is an important secondary process in a modern refinery. Unlike in western countries Indian refineries are often operated in distillate mode requiring design modifications and changes in operating conditions. Riser hydrodynamics together with cracking kinetics are often very useful to simulate the performance of FCC riser reactor and accurately predict conversion of the process. The present paper reports the experimental data on hydrodynamics of a FCC riser including its pressure and voidage profiles along the riser length in a cold model of the FCC unit assembly. Effects of some operating variables on the riser hydrodynamics have been reported.

Keywords: FCC riser, Hydrodynamics, Pressure and voidage profiles, Conversion

IPC Code(s): C10G32/00

Fluidized-bed catalytic cracking (FCC) is a major secondary conversion process in refinery industry. Presently, there are 300 or more units all over the world with a total capacity exceeding 1 MT per day. The consumption of FCC catalyst is the highest in any process industry, being 1000 T/day. Since its inception, about six decades back, major developments have taken place both in its hardware modification and operational characteristics. Owing to its vital role in the functioning of a modern refinery, various oil companies have taken keen interest in its design but very little is available in the literature.

A modern FCC unit consists of three basic sub-systems, namely, the riser reactor, the stripper and the regenerator. The feed is introduced at the bottom of the riser after preheating. Hot regenerated catalyst, air and feed get well mixed in this zone and travel upwards at a very high velocity through the tall riser. At the end of the riser the solid catalyst gets disengaged from the catalyst-oil vapour, enters the stripper and falls downwards. Steam is used in the stripper to strip off hydrocarbon vapour both from the interspaces and within the pores of the catalyst particles. The stripped catalyst descends downwards to the regenerator wherein air is introduced to burn off the coke deposited on the catalyst. The regenerated catalyst is then fed back to the riser for its reuse.

The primary objective for development of this secondary process is to upgrade the heavy petroleum fraction to lighter products, particularly gasoline. On one hand, the FCC unit is quite flexible with respect to feed quality and product pattern and on the other hand, the interdependence of the major operating parameters makes the process very complex. To satisfy the variation in yield structure in different countries (for example in US and other western countries, the main product is gasoline whereas, in India, the major products are diesel and kerosene) FCC units are operated in two different modes: Gasoline mode and middle-distillate mode. Kinetically, maximum middle distillate yield is possible if the per pass conversion (here conversion is defined as the percentage product boiling below 216°C) is restricted up to 45-50%. This is accomplished by controlling the reaction and regeneration severities to a moderate level. Annexure A summarizes the major operating conditions and yield structures of FCC units operating according to these two modes[1]. Since the unit conversion is kept low, there exits a large amount of uncracked material (20-40% of fresh feed), which is recycled back to the riser. Again, the performance of stripper is also different in distillate mode as compared to gasoline mode operation. Ghosh and Das[2] reported that the efficiency of stripping, as indicated by hydrogen in coke, is much higher at low severity operation (10-13%) than in gasoline mode FCC units (5-6%). Annexure B provides in details the recent developments in FCC hardware modification.

Although the economical importance of FCC is well known, their simulation is rather empirical because of complex interactions among operating variables. FCC reactions in the riser reactor operate usually in the pneumatic/transport bed mode requiring residence times between two and four seconds. In order to obtain better predictions of conversions and product yield, it is desirable that the transport process within the riser reactor including variation in its pressure and voidage along its length are known before hand. Leon-Becerril *et al.*[3] suggested that voidage and pressure profile along the riser height together with cracking kinetics can be used successfully to predict the performance of FCC units. Of late, several models[4,5] on FCC riser reactor have appeared in the literature with varying degrees of simplifications and assumptions. Gupta and Subba Rao[5] summarized these findings while presenting their models.

A fairly large cold FCC riser reactor assembly fabricated by using perspex sheets and column simulating broad features of FCC units in Indian Refinery were made and experiments at cold conditions simulating the operational features of Indian FCC units were conducted. The present paper reports hydrodynamic data of the unit showing the effects of different operating variables like solids circulation rate, stripper air velocity, change in the type of stripper internals, etc. on the hydrodynamic behaviour of riser. For these purpose static pressure data have been obtained. Using static pressure data voidage profile along the riser height also has been determined. Axial voidage profile is an important criterion related to the solids loading, catalyst-oil vapour mixing and chemical reaction in the riser-reactor. Although hydrodynamic data, specially its pressure and voidage profiles in cold model of FCC riser reactor are hard to obtain in the open literature, several investigators[6-8] have studied axial voidage profiles in the riser column of CFB and suggested that pressure and voidage profiles in the riser are dependent on the (i) particle size distribution, (ii) solid inventory, (iii) superficial gas velocity, and (iv) solids circulation rate (which, in the present case, is dependent on the type of internal, spent catalyst valve position and stripper air velocity).

Experimental Procedure

The set-up (Fig. 1), discussed in detail[9], essentially consists of a riser-reactor (fast bed G), a stripper (H) equipped with internals (I), a cyclone separator (L), a solids return leg (N), a slow bed (regenerator R), two transfer lines (Q_1 and Q_2, one from the stripper to slow bed and the other from slow bed to fast bed) with butterfly valves (P_1 and P_2), a deflector (K) and two root blowers (A_1 and A_2). Other accessories include a bag filter attached to the exit end of the cyclone separator, valves to control the air flow rate, orifice meter, and panel boards on which the manometers are mounted (particulars are given in Table 1).

Table 1—Dimensions of FCC unit

Riser	
diameter, m	0.1016
height, m	5.7000
Stripper	
diameter, m	0.4572
height, m	4.0350
Cyclone	
diameter, m	0.3048
height, m	1.2200
Solids return leg	
diameter, m	0.1016
height, m	2.1300
Slow bed column	
diameter, m	0.2032
height, m	1.7800
Spent catalyst standpipe	
diameter, m	0.0762
height, m	0.8900
Regenerated catalyst standpipe	
diameter, m	0.0762
height, m	0.9700
Solids circulation device	Butterfly valve
Pressure taps number	
Riser	6
Stripper (including all angular points)	32 (13 for first internal)
Bend	1
Solids Return Leg	2
Spent catalyst standpipe	3
Slow bed	2
Regenerated catalyst standpipe	2
Sampling probes for measuring CO_2 concentration	
Length, m	0.2000
Diameter, m	0.0032

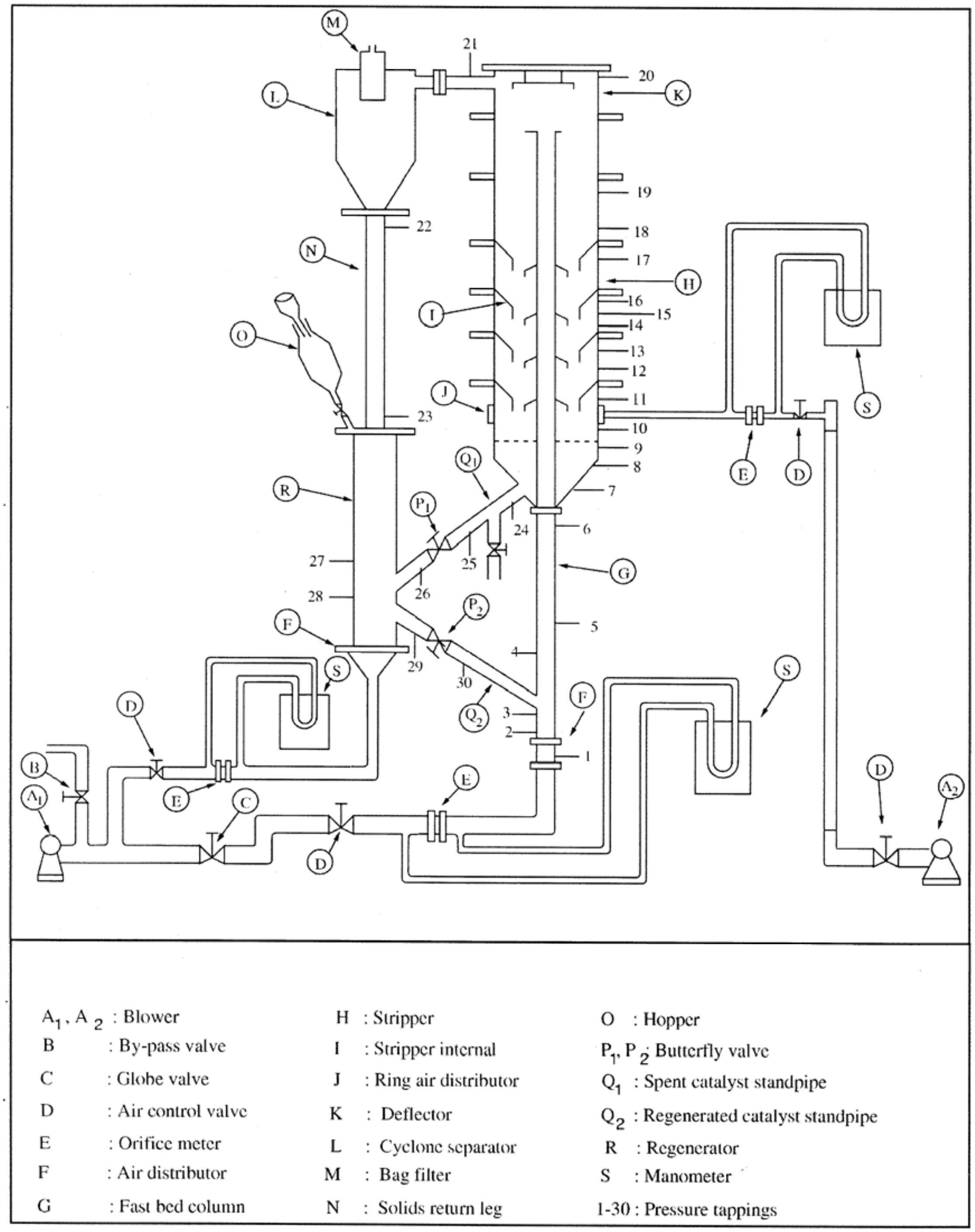

Fig. 1—Schematic diagram of experimental set-up (fitted with the second internal)

The riser is 0.1016 m in diameter and 5.7 m in height. It passes centrally through the stripper. Six pressure taps are fitted to the column wall axially by means of polythene tubing. To prevent entry of solids into the polythene tubes, fine wire mesh (400 micron S.S. sieves) is fixed at the mouth of each tube. The stripper is annular in configuration with a conical bottom. It is equipped with four pairs of internals and these are located at different stripper heights. Four different types of internals, as practiced in Indian oil refineries, have been used throughout the experiment. A ring-shaped air distributor fluidizes the descending catalyst bed within the stripper. The air distributor having four injection points at 90° apart encircles the stripper like a piezometer ring. 400 mesh (SS) wire gauges are embedded over each injection port to prevent entry of solids into the line. The regenerator is connected with riser-reactor as well as stripper via two solids transfer line. One solid transfer line, called the spent catalyst standpipe, connects it with the stripper while the other one, i.e. regenerated catalyst standpipe, serves as the link between the riser and regenerator. For smooth flow of solids, the angle of inclination in both cases has been kept at 30° with the vertical axis of the regenerator. The air distributors are attached at the bottom of riser and regenerator is covered with 400 mesh (SS) wire netting. The whole set-up (FCC unit assembly) is made of transparent acrylic tube and plate so as to permit visual observation of the mixing pattern and contacting process of the air-solid system.

The experiments have been carried out with one type of bed material (equilibrium silica-alumina catalyst) supplied by Indian Oil Corporation Limited, R/D Center, Faridabad. The physical properties of the solids have been determined in the laboratory and are presented in Table 2.

To start with, the unit is run empty to check for air leakage. Then, the charge (FCC catalyst) is fully transferred to the upper supply hopper. The upper (P_1) and lower (P_2) valves are closed to isolate and prevent the flow of solids to the slow and fast bed. After stabilization, both the valves are opened simultaneously. The solids from the stripper descend down the transfer line to the slow bed and then to the fast bed by means of gravity. A static bed height of 0.4-0.5 m is maintained in the riser. At first, valve P_2 and then P_1 are closed to prevent flow of solids into the riser. After the charging, the rotary blower (A_1) is started to supply air to the riser and slow bed. The airflow rate is maintained such that fluidization commences in the riser. Both the valves, P_1 and then P_2 are opened and so adjusted that the airflow rate is sufficient enough to carry the solids upwards to the top. Then the rotary blower (A_2) is operated to supply air to the stripper at a controlled rate. Within 3-4 min of the start-up, the whole system becomes steady. Part of the solids (the finer particles) is carried over, which gets separated in the cyclone and is fed back into the slow bed via the down comer. The dust gets collected in the bag filter fitted to the cyclone. The solids are recirculated via the slow bed and transfer lines. At steady state, the solids circulation rates are measured for a given system condition and the manometer readings (which also help in checking whether steady state has been reached) are noted. The entire operation lasts for about 40-45 min.

Table 2—Characteristics of bed material

Bed material	FCC Catalyst
Particle size distribution	- 72 + 100 = 8 % -100 + 150 = 24 % -150 + 200 = 62 % -200 + 240 = 6 %
Mean particle size, $\bar{dp} = \frac{1}{\sum \frac{X_i}{dp_i}}$	99.6 μm
X_i = weight fraction for particles with size dp_i	
Bulk density, ρ_B	1008 kg/m^3
Particle density, ρ_s	1670 kg/m^3
Minimum fluidisation voidage, ε_{mf}	0.38
Minimum fluidisation velocity, U_{mf}	0.0054 m/s
Terminal velocity, U_t	0.25 m/s

For the measurement of solids circulation rate, a three-way valve is installed downstream of P_2 (Fig. 1). By momentarily closing the flow of solids to the riser, the solids are taken to the cyclone, later taken out and continuously weighed with the help of a spring balance.

Experiments were conducted in the cold FCC assembly unit using equilibrium FCC catalyst as the bed material. The hydrodynamics (specially its pressure and voidage profiles along its height) in the FCC riser unit is expected to be influenced by (i) inventory of solids in the unit, (ii) superficial riser gas velocity, (iii) solids circulation rate. While the air flow rate to the riser can be independently made to vary by controlling air inlet valve, the solids circulation rate depend on a number of interacting parameters, like the flow of solids from the stripper to the slow bed (the spent catalyst valve or the valve between slow bed and rise), the type of stripper internals and stripper air velocity. For the present series of run reported, the riser air velocity was kept constant, but the solids circulation rate varied by (i) changing the spent catalyst valve position, (ii) types of internals, and (iii) stripper air velocity. Experimental data for each type of internal have been taken by varying stripper air velocity and solids circulation rate. Data for pressure profile are obtained from manometer readings. Usually, 3 - 4 observations are taken at periodic intervals for a given system

Table 3—Details of experimental conditions

Item	Design of Internals			
	First Internal (INT1)	Second Internal (INT2)	Third Internal (INT3)	Fourth Internal (INT4)
Superficial air velocity in riser, $(U_g)_R$, m/s ⟷	6.40 to 7.75		6.40	
Superficial air velocity in stripper $(U_g)_{str}$, m/s ⟷	(i) 0.027 (ii) 0.046 (iii) 0.066		(i) 0.026 (ii) 0.036 (iii) 0.051	
Solids inventory, kg	300		210 - 225 ⟷	
*Valve position to control solids circulation rate	4-8, 5-8, 6-7		4-8, 5-8, 6-8 ⟷	
Solids circulation rate, (on the basis of riser cross-sectional area) G_s kg/m^2-s	54.8 - 78.5	28.7 - 62.0	30.1- 49.2	31.9 - 56.9

*The first number indicates the valve position between stripper and slow bed, while the second between slow bed and riser. For fixed valve position, with changes in stripper air velocity, the solids circulation rate also varies.

condition. These data are utilized to determine the voidage profile along the riser. The details of experimental conditions used for the study are reported in Table 3.

Results and Discussion

Figure 2(a-d) shows the static pressure profiles along the length of the riser at different operating conditions. The last two points in these figures are actually located at the top of the stripper. These curves indicate the existence of three different sections:

(i) the acceleration section at the bottom of the riser column,

(ii) a section of constant pressure gradient which is the characteristics of a fully developed flow, and

(iii) a section at the riser and stripper top with decelerating pressure drop.

When the flow is being developed, there is a sharp decay in pressure as against the developed flow condition. In the developing flow region, the up flowing core particles experience a relatively large upward drag force and vigorous interaction with other particles. The sharp decline in the pressure profile with height is possibly due to the combined effects of particle acceleration and net radial movement of solids from the up flowing core suspensions to the down flowing wall regions. In the developed flow region the decay in pressure profile is small as the solids concentration as well as the variation in the particle velocity with height is rather low. This trend of pressure variation in the riser is true for all types of internals fitted into the stripper.

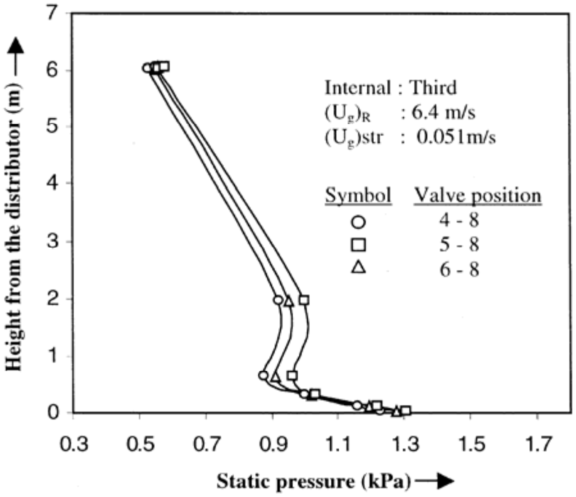

Fig. 2(a)—Pressure profile along the riser – effect of spent catalyst valve position

Pressure profiles

Figure 2(a-b) shows the effect of spent catalyst valve position on the static pressure profile at a constant riser air velocity of 6.4 m/s. It is observed that irrespective of the type of internal (Third / Fourth), for a fixed stripper air injection rate, the solids circulation rate increases with an increase in the spent catalyst valve opening. This is evident from the higher level of static pressure along the length of the riser. With an increase in the riser height, the pressure drops, but the drop is very sharp at the initial stage. As the solids are recirculated from the slow bed into the riser, at about 0.6-2 m from the riser distributor plate, there is some accumulation of solids, which increases the pressure level in the riser. Thereafter, once again, there is a drop in pressure along the riser height.

Figure 2(c) shows the effect of the type of internal (fitted within the stripper) on the static pressure profile in the riser. At constant spent catalyst valve opening (valve position 6-8), riser air rate and stripper air rate, it is observed that the static pressure along the riser height is more in the second internal as compared to the third and fourth internals. This can be explained by the fact that the solids circulation rates are higher in the case of second internal than those in the third and fourth internals. Again, the fourth internal has a higher solids circulation rate than the third. Further, with change in type of internal, the magnitude of the static pressure at the bottom of the riser changes sharply. However, as the height increases, the change in pressure becomes relatively low.

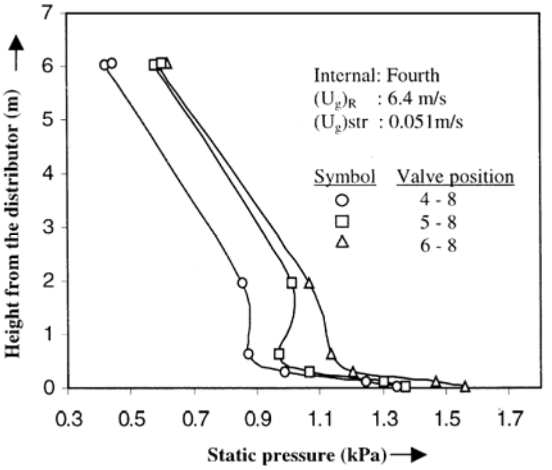

Fig. 2(b)—Pressure profile along the riser – effect of spent catalyst valve position

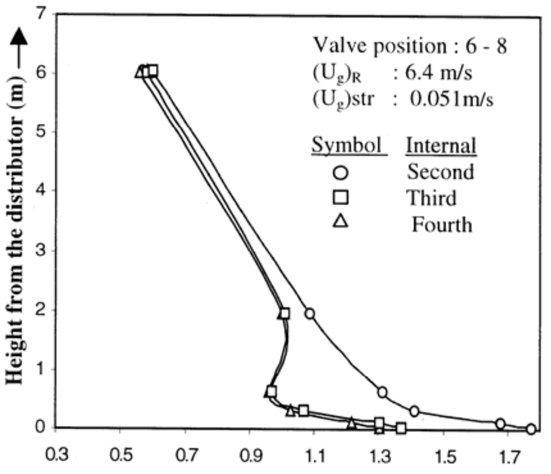

Fig. 2(c)—Pressure profile along the riser – effect of type of stripper internal

Figure 2(d) shows the effect of stripper air velocity on the extent of solids circulation and riser static pressure profile. For these studies, other independent variables like the spent catalyst valve position and riser air velocity have been kept constant. It is observed that with an increase in the stripper air velocity, the solids circulation rate as well as the pressure level in the riser increases. In an industrial stripper, where steam is injected, it acts as a valve. With more steam flow rate, it impedes the flow of solid downwards and so, the solids circulation rate decreases. It could be that a substantial part of the stripper air moves downwards, thereby aiding in the downward flow of solids. Logically, therefore, the higher the stripper air rate, the more should be the flow of solids towards the riser. This trend is, however, found to be absent while using the fourth internal for valve position (4-8).

Voidage profiles

Figure 3(a-c) shows typical voidage profiles for air-FCC catalyst systems in 10.16 cm diameter riser column. These curves have resemblance with the findings of Wong *et al.*[8], characterized distinctly by

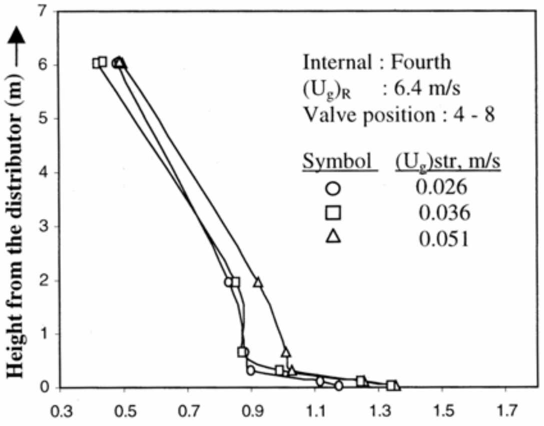

Fig. 2(d)—Pressure profile along the riser – effect of stripper air velocity

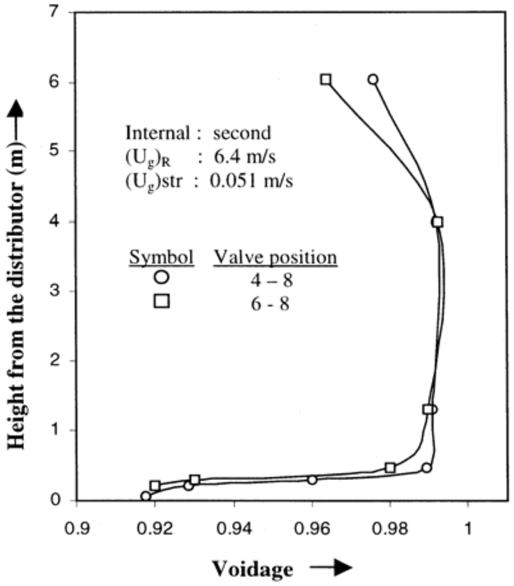

Fig. 3(a)—Voidage profile along the riser – effect of spent catalyst valve position

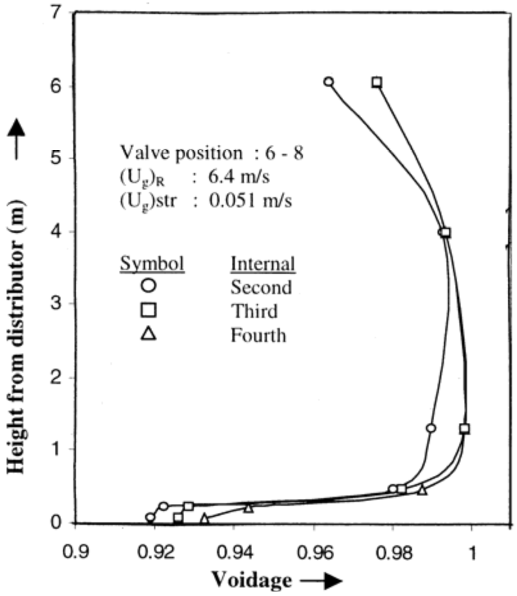

Fig. 3(b)—Voidage profile along the riser – effect of type of stripper internal

three zones; an acceleration zone, a developed flow zone and a deceleration zone (for risers equipped with an abrupt exit configuration). The voidages in these cases have been calculated from the measured pressure gradient, assuming negligible acceleration effect and shear stress at the wall, according to following formula

$$\Delta P/\Delta z = \rho_s (1-\varepsilon) g \quad \text{... (1)}$$

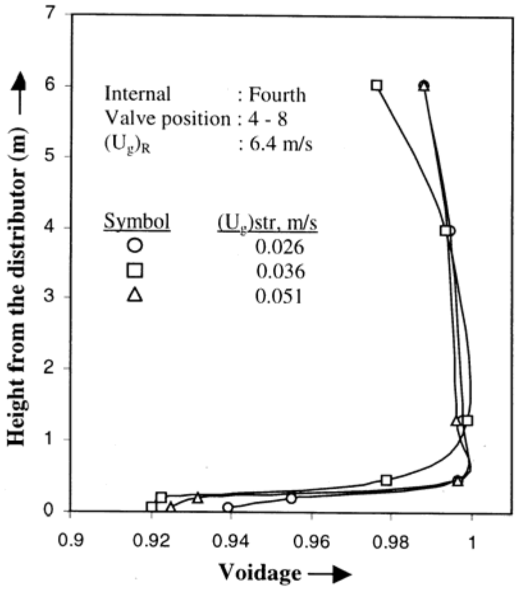

Fig 3(c)—Voidage profile along the riser – effect of stripper air velocity

where P is static pressure in column, Pa; z is vertical position coordinate measured upwards from the distributor, m; ρ_s is Solid density, kg/m^3; and ε is voidage.

Figure 3 (a) shows the effect of spent catalyst valve position on the riser voidage profile. Three distinct zones are visible as stated above. With the increase in the opening of valve position, solids circulation rate increases while the voidage decreases and this is reflected in the acceleration (riser bottom) zone. The gradual decrease of solids hold-up is due to the acceleration of the solids as they enter the riser from the slow bed. With further increase in the riser height, the solids stop accumulating. The flow gradually transforms into dilute zone and the curves tend to merge. The flow of gas and solids is considered to be hydrodynamically developed, once the voidage becomes constant with height. At the top of the riser, due to abrupt exit configuration as used in this work (the gas-solids mixture coming out of the riser strikes at the impactor fitted near the stripper top), there is a densification of solids. In general, the figure shows that the higher the solids mass flux, the greater is the length of acceleration zone and the greater is the tendency towards densification at the top of the riser.

Figure 3(b) presents typical voidage profiles wherein the effect of the type of stripper internal can be seen. As in earlier cases, the voidage profile is characterized by three distinct zones. With the second internal, the solids circulation rate is more, so is the solids loading in the acceleration zone, developed zone and deceleration zone at the top. The voidage profiles for the third and fourth internals tend to merge in some zones, indicating probably that there was not much change in the solids circulation rate.

Figure 3(c) shows a typical plot depicting the effect of stripper air velocity on the riser voidage profiles for the fourth internal. With increase in stripper air velocity, the solids circulation rate increases and there is a corresponding decrease in the voidage all along the length of the riser. Similar trend was noted for other types of internal as well.

Conclusion

Experimental data on the hydrodynamics (pressure and voidage profiles) in the riser reactor of a cold FCC unit model have been reported. It has been generally found that with the increase in riser height and gas velocity, the voidage increases but at the end of the riser length, densification of solids occurs and the voidage tends to decrease. An opposite trend, i.e a decrease in voidage all along the riser height, is noticeable with the rise in solids circulation rate.

Nomenclature

d_p : Particle diameter, μm
G_s : Solids mass flux, kg/m^{2}s
g : Acceleration due to gravity, m/s^2
ΔP : Pressure drop, Pa
$(U_g)_R$: Superficial gas velocity in riser, m/s
$(U_g)_{str}$: Superficial gas velocity in stripper, m/s
U_{mf} : Minimum fluidization velocity, m/s
U_t : Terminal velocity, m/s
Δz : Axial length variation in the column ,m

Greek letters
ε : Voidage
ε_{mf} : Minimum fluidization voidage
ρ_g : Gas density , kg/m^3
ρ_s : Solid density, kg/m^3
ρ_B : Bulk density, kg/m^3

References

1 Das A K, Murthy V L N & Ghosh S, *Proc Grace Singapour FCC Semina*, Singapour, June 16-17, 1992.
2 Ghosh S & Das A K, *Chemical Industry Digest*, June (1994).
3 Leon-Becerril E, Maya-Yescas R & Salazar-Sotelo D, *Chem Eng J*, 100 (2004) 181.
4 Fligner M, Schipper P H, Sapre A V & Krambeck F J, *Chem Eng Sc*i, 49 (1994) 5813.
5 Gupta A & Subba Rao D, *Chem Eng Sci*, 56 (2001) 4489.
6 Bai D R, Jin Y, Yu Z Q & Zhu J X, *Powder Technol*, 71 (1992) 51.
7 Mastellone M L & Arena U, *Chem Eng Sci*, 54 (1999) 5383.
8 Wong R, Pugsley T & Berruti F, *Chem Eng Sci*, 47 (1992) 2301.
9 Das S, *Some Investigations into the Hydrodynamic Behaviour of FCC Unit*, Ph.D. Thesis, Indian Institute of Technology, Kharagpur, 1998.

Annexure A—Comparison of gasoline and distillate mode FCC operation

Item	Distillate mode	Gasoline mode
Products (wt% of total feed)		
Dry Gas	1.50	4.00
LPG	7.00	18.00
Gasoline (C_5 – 150°C)	22.00	41.00
Heavy Naphtha (150 - 216°C)	11.50	13.00
LCO (216 – 370°C)	26.00	15.00
TCO (150 – 370°C)	37.50	28.00
Bottom (370 +°C)	30.00	4.00
Coke	2.00	5.00
216 Conversion	44.00	81.00
370 Conversion	70.00	96.00
Operating condition		
CFR	1.37	1.04
Riser top temperature, °C	492.00	527.00
Riser contact time, s	2.00	4.00
Catalyst mat activity	60.00	75.00
Cat/Oil ratio	4.51	7.00
Regenerator		
Dense temperature, °C	642.00	728.00
Dilute temperature, °C	663.00	740.00
CRC (carbon on regenerated catalyst), wt%	0.50	0.05

Annexure B—Recent developments of FCC hardware

Reactor section	
• Multiple nozzle feed distributor	Better atomization; Improved feed mixing
• Short contact time riser	Arresting undesired secondary reactions
• Closed-coupled cyclones	Reduction of particulate emission
Stripper section	
(iv) Improved catalyst and feed distributor	Increases stripping efficiency
(v) Multiple point steam injection	Do
(vi) Improved internals	Do
Regenerator section	
(vii) Improved air distributor	Higher efficiency
(viii) Catalyst cooler	Debottlenecking heat balance constraints
(ix) Two-stage regeneration	Cleaner regenerated catalyst; Reduction of catalyst damage
Other sections	
(x) Turbo expanders	Energy recovery
(xi) Continuous catalyst addition and withdrawal systems	Steady operation