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EFFECTS OF BED DIAMETER, BAFFLES, FINES CONTENT AND OPERATING CONDITIONS ON PRESSURE FLUCTUATIONS IN FLUIDIZED BEDS OF FCC CATALYST PARTICLES

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ABSTRACT

Differential pressure fluctuations are routinely measured in fluidized beds to delineate fluidization regimes, provide hydrodynamics data and/or assess fluidization quality. Tests were conducted in 0.3-, 0.6-, and 0.9-m-diameter cylindrical and 1.52-m-diameter semicircular units, all about 6 m tall using FCC catalyst particles. At some of the operating conditions gas bypassing, a form of intense gas mal-distribution, was detected in the bed. The objective of this study was to determine if overall differential pressure fluctuations are affected by bed diameter and the various methods used to mitigate gas bypassing in fluidized beds of Group A materials. Results showed that bed diameter did not have a significant effect on the pressure fluctuations. However, bed height, superficial gas velocity, fines content, system pressure and installation of baffles significantly affected the pressure fluctuations.

INTRODUCTION

Differential pressure (ΔP) fluctuations have regularly been used to study fluidized bed regime transitions, hydrodynamics as well as to give a measure or index of fluidization quality (Bi et al. (1), Galluci et al. (2) and Briens et al. (3)). Fluctuations in the differential pressure in fluidized beds are largely caused by the interactions of the solids with the rising bubbles or voids as well as by the collapse of the bubbles or voids when they emerge from the bed surface. ΔP fluctuations measured across the entire bed can capture the global flow dynamics, whereas ΔP fluctuations measured across short sections of the bed give an understanding of the local flow behavior. Fluidized beds of Group A materials have been found for some operating conditions to suffer from a significant gas maldistribution called gas bypassing, also called streaming (Knowlton (4), Wells (5), Karri et al. (6) and Karimipour and Pugsley (7)). In such instances, the fluidizing gas preferentially flows up the side of the bed in a jet of fast moving bubbles leaving the remainder of the bed in either a defluidized or poorly fluidized state. Karri et al. (6) conducted tests with grids that gave a pressure drop of about 30 to 300% that of the bed pressure drop and showed that gas bypassing was not due to poor gas distribution from the distributor. Issangya et al. (8) diagnosed gas bypassing in a 0.9-m-dia. fluidized bed from differential pressure fluctuations measured across four 61 cm sections around the column. The quadrant(s) containing the gas bypass stream had significantly higher standard deviations of pressure fluctuations than the other quadrants that did not have the gas bypass stream. This paper discusses differential pressure fluctuation data measured over the entire bed height in four units over a wide range of operating conditions encompassing both uniform and gas bypassing conditions.

EXPERIMENTAL

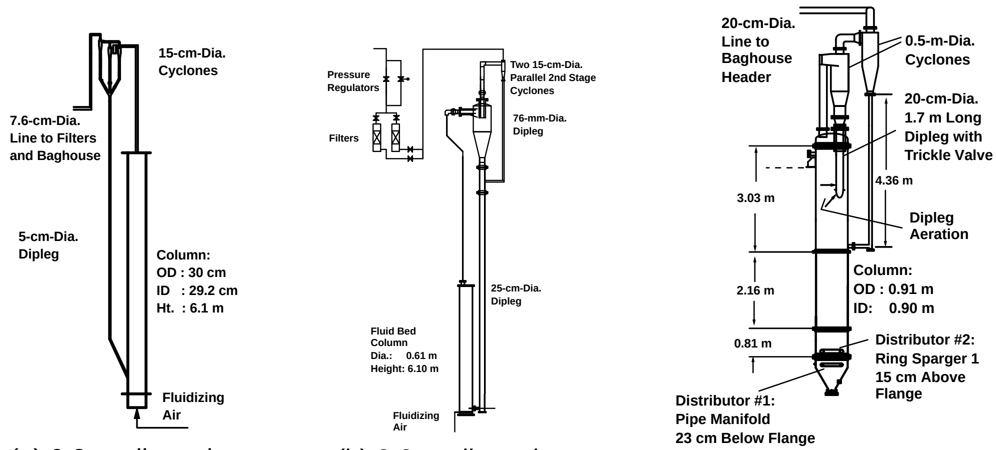
Tests were conducted in 0.3-, 0.6- and 0.9-m-dia. units, all 6.1 m tall, and in a 1.52-m- dia. semicircular, 5.7 m tall unit shown in Figure 1 (a to d). The 0.3-m-dia. unit was made of transparent acrylic pipe. The 0.6-m-dia. unit, used for testing the effect of system pressure, was constructed from steel. Air exiting the primary cyclone passed through two, parallel second-stage cyclones and then into a pipe that branched into a 102-mm-dia. line with a butterfly valve and a 25-mm-dia. line with a pressure control needle valve. The operating pressure was roughly set manually with the butterfly valve and then fine-tuned by the needle valve. The 0.9-m-dia. unit had an interchangeable 2.1 m Plexiglas section that enabled visual observations and video recording for low gas velocity tests. The Plexiglas section was replaced with a steel section for tests at gas velocities exceeding 0.5 m/s. The 1.52-m-diameter semicircular unit had a Plexiglas faceplate to enable visual observation and had three primary cyclones whose diplegs discharged solids into the bed.

Fluidization behavior was characterized by a combination of (i) visual observation (ii) ΔP fluctuations measured across 61 cm long axial sections around the columns and across the entire bed, and (iii) radial bubble void fraction profiles from optical fiber probes. ΔP fluctuations were measured using 6.3-mm-OD x 0.9 mm wall thickness purged steel tubes connected to high frequency *Validyne*© *DP15* transmitters by 6.3-mm-dia. plastic tubing. Bubble and ΔP fluctuations signals were simultaneously sampled at 1000 Hz for 3 minutes durations. In some cases, when sampled alone, ΔP fluctuations were acquired at 200 Hz. The test materials were light and heavy FCC catalyst particles of various fines contents between 3 and 12% < 44 μm and particle densities of 1200 and 1490 kg/m^3, respectively. Their particle sizes (dp_{50}) ranged between 68 and 81 μm. The particle size distributions are shown in Figure 2.

RESULTS AND DISCUSSION

Effects of bed height and fines content

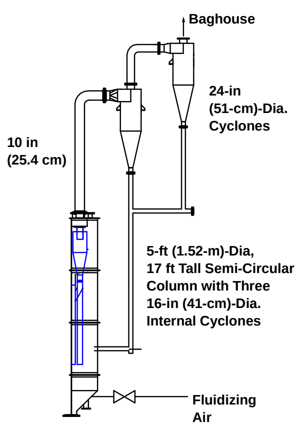
Figure 3 shows the standard deviation of the ΔP fluctuations in the 0.3-m-dia. unit for 12% fines light FCC catalyst particles versus superficial gas velocity for various static bed heights. The standard deviation of the ΔP fluctuations (σ_{sp}) increased with increasing bed height. It increased with increasing gas velocity reaching a peak value and then decreased sharply. The peak standard deviation is traditionally used to indicate the transition from bubbling to turbulent fluidization regime. It was, however, found that for the 12% fines FCC catalyst, only static bed heights below 1.52 m had uniform fluidization at all superficial air velocities. Beds taller than 1.52 m



(a) 0.3-m-dia. unit

(b) 0.6-m-dia. unit

(c) 0.9-m-dia. unit



(d) 1.52-m-dia. semicircular unit

Figure 1. Schematic drawings of the test units.

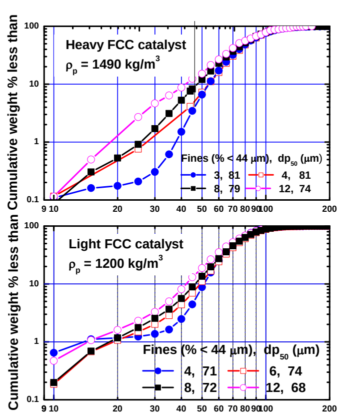


Figure 2. Particle size distribution of test material.

had uniform fluidization at all superficial air velocities. Beds taller than 1.52 m had gas bypassing, and they only transitioned to uniform fluidization when the gas velocity approximately exceeded the gas velocity that corresponds to the peak σ_{sp}.

Figure 4 is a plot of the σ_{sp} in the 0.3-m-dia. unit for 4% fines light FCC catalyst particles. Gas bypassing and slugging were observed for the 3.05 m static bed height tests. For all the other bed heights, no slugging was observed and the σ_{sp} initially increased with increasing superficial air velocity, reached a peak and, depending on bed height, leveled off or started to decrease. The 0.76 m static bed height fluidization was uniform at all gas velocities and the peak σ_{sp} occurred at Ug ≈ 0.5 m/s. This is about equal to the value of Uc for FCC catalyst particles. Gas bypassing was present for the 1.22 m static height at all superficial gas velocities up to about Ug = 1.13 m/s when the bed started to fluidize uniformly. Gas bypassing persisted in the other taller beds of 4% fines FCC catalyst particles. Increasing Ug alone could not eliminate it. Figure 4 also shows that Ug at peak σ_{sp} changed with bed height, increasing from about 0.5 m/s to about 1.1 m/s as the static bed height was raised from 0.76 m to 1.98 m.

The influence of fines content is shown in Figure 5 where σ_{sp} for a 2.44 m static bed height is plotted against Ug for light FCC particles of 4, 6, 8 and 12% fines content. Increasing the fines content lowered the σ_{sp}. Depending on gas velocity, gas bypassing was detected for all the four fines contents. It remained present at all gas velocities for the 4 and 6% fines content but it disappeared for the 12 and 8% fines content when Ug was increased to about 0.27 and 0.6 m/s, respectively. So high fines materials had a lesser tendency to cause gas bypassing than the low fines materials and as a result low fines materials gave higher ΔP fluctuations.

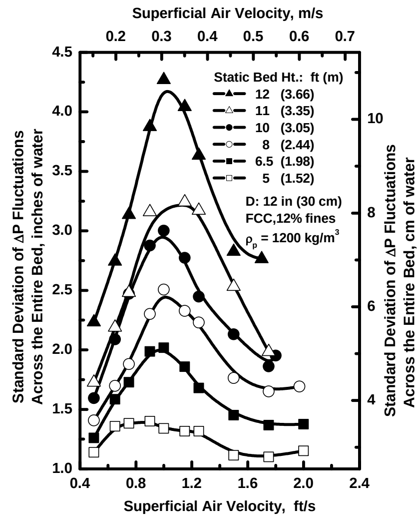


Figure 3. σ_{sp} versus gas velocity for 12% fines light FCC catalyst particles in the 0.3-m-dia. unit with various static bed heights.

Increasing the fines content in uniformly fluidized bubbling beds leads to smaller bubbles, which tend to lower the ΔP fluctuations. However, in beds with gas bypassing, ΔP fluctuations are also affected by the significant improvement in fluidization quality as the gas bypassing intensity diminishes and eventually disappears when sufficiently high amount of fines are added to the bed. In describing the effect of fines on gas bypassing, Wells (5) and Karri et al. (6) suggested that the emulsion phase density at/or near a fluidized bed surface is equal to the minimum bubbling density of the solid particles at the prevailing conditions, and that it increases with bed depth due to the compression of the emulsion gas by the added pressure head. The emulsion phase density, therefore, can reach at some depth a value high enough such that defluidization occurs in the bed. This critical value of the emulsion phase density is likely equal or very close to the minimum fluidization density of the solids at the given operating pressure and temperature. Because adding fines to a Geldart Group A material decreases the minimum bubbling density relative to the minimum fluidization density (Abrahamsen and Geldart (9)), the emulsion phase in high fines beds can undergo more gas compression before defluidization occurs, which enables significantly deeper beds to fluidize uniformly without gas bypassing when compared to fluidized beds of low fines materials.

Figures 6 and 7 show gas bypassing-to-uniform fluidization transition points determined in 0.3- and 0.9-m-dia. units for light and heavy FCC catalyst particles, respectively. The transition height is plotted in Figure 6 as a function of gas velocity for 4, 6, 8 and 12% fines contents, and in Figure 7 against fines content for various superficial gas velocities. The transition points were established from visual observation, local ΔP fluctuations and radial bubble profiles. With gas bypassing, radial bubble void fraction profiles were time-dependent because the gas bypass stream moved around the column, but they were generally skewed towards the bypassing location. When gas bypassing was eliminated radial bubble voidage fraction profiles were symmetrical (Figure 8).

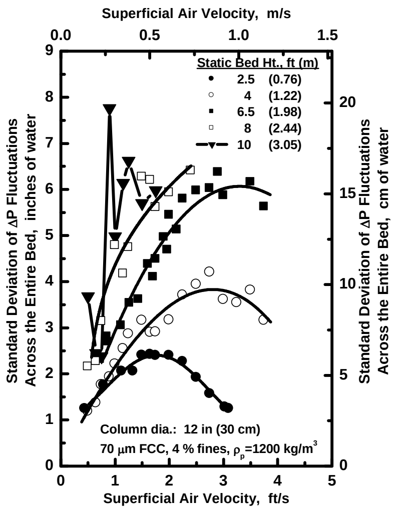


Figure 4. σ_{sp} versus gas velocity for 4% fines light FCC catalyst particles in the 0.3-m-dia. unit with various static bed heights.

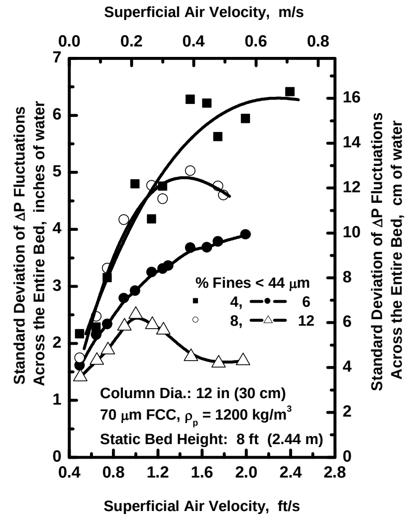


Figure 5. σ_{sp} versus gas velocity in the 0.3-m-dia. unit for a static bed height of 2.44 m using light FCC catalyst particles of various fines content.

Effect of Baffles

Tests were conducted in the 0.9-m-dia. unit with a static bed height of 3.05 m using 3% fines heavy FCC catalyst particles. Four horizontal baffles made from standard steel subway grating with 25.4 mm x 102 mm openings and an 80% open area were installed 0.76 m apart. The 0.76 m baffles separation distance was based on tests for 3% fines FCC particles that showed that gas bypassing could be eliminated in an un-baffled bed if the static bed height was equal or less than 0.76 m. Visual observations of the fluidization column showed that with no baffles there was severe gas bypassing, but with the baffles installed, gas bypassing was eliminated and fluidization was quite uniform. Local radial bubble void fraction profiles (Figure 8) were symmetrical. The improvement in the fluidization quality caused by the baffles

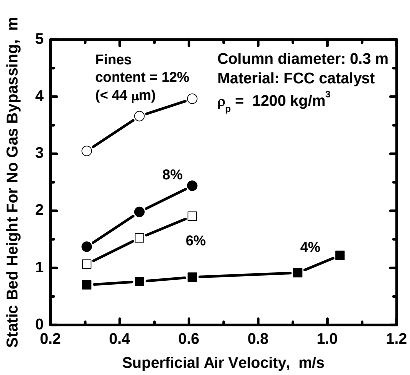


Figure 6. Static bed heights for no gas bypassing in the 0.3-m-dia. unit versus gas velocity for 4, 6, 8 and 12% fines light FCC catalyst.

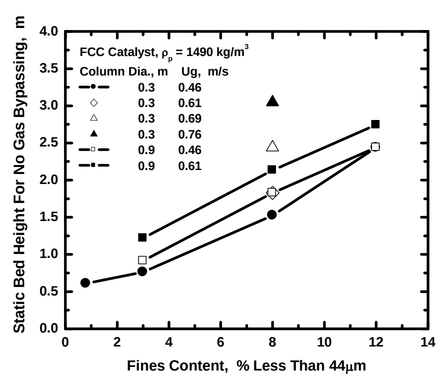


Figure 7. Static bed heights for no gas bypassing in the 0.3-m and 0.9-m-dia. units as a function of fines content for heavy FCC catalyst.

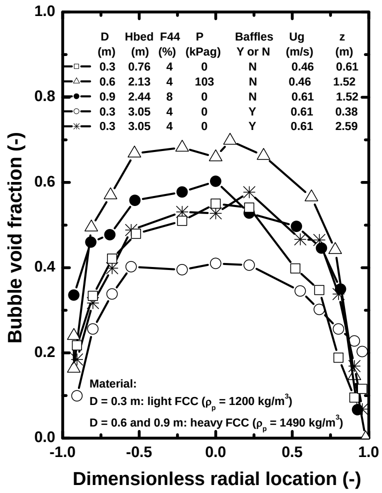


Figure 8. Radial bubble void fraction profiles for FCC catalyst particles in the 0.3-, 0.6- and 0.9-m-dia. columns at various operating conditions.

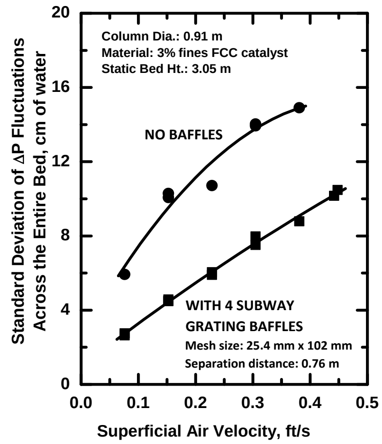


Figure 9. σ_{sp} versus gas velocity in a 0.6-m-dia unit with 4 subway grating baffles spaced 0.76 m for a 3.05 m static bed height using 3% fines heavy FCC particles.

is due to the defluidized solids being broken up when flowing around the grating bars. This allowed air to permeate into the emulsion phase and flow more uniformly through the solids, which led to lower pressure fluctuations when compared to an un-baffled bed (Figure 9).

Effect of Pressure

Figure 10 shows the σ_{sp} as a function of freeboard pressure in the 0.6-m-dia. unit for 3% fines heavy FCC catalyst particles. The gas velocity was 0.46 m/s and the static bed height was 3.66 m. The σ_{sp} decreased with increasing pressure, initially rather sharply from about 15 cm to 10 cm of water as the pressure was increased from 25 to 103 kPag and thereafter to about 7 cm of water as the pressure was raised to about 200 kPag. At atmospheric pressure the 3.66 m static bed height had severe gas bypassing. The initial decrease in ΔP fluctuations intensity was a result of the elimination of gas bypassing by the imposed pressure. The latter change in the σ_{sp} over the 100 to 200 kPag range was presumably due to the effect of pressure on hydrodynamics variables, e.g. bubble size, bubble frequency, etc. The mitigating ability comes from the fact that when the system pressure is increased the emulsion gas compression ratio between the top and bottom of the bed decreases lessening the likelihood of gas bypassing.

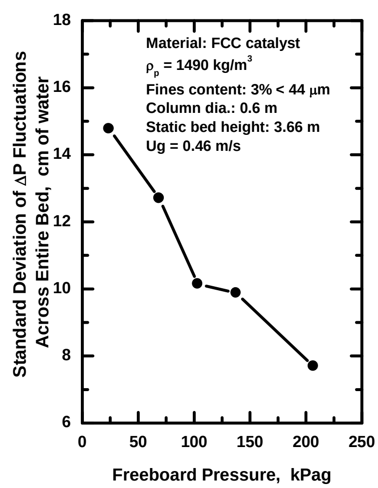


Figure 10. σ_{sp} versus pressure in a 0.6-m-dia. fluidized bed of 3% fines heavy FCC catalyst. (Ug = 0.46 m/s, H = 3.66m).

Effect of Bed Diameter

The σ_{sp} versus gas velocity for the 0.3-, 0.6- and 0.9-m-dia. units for 3% fines heavy FCC catalyst particles are compared in Figure 11. The 3.05 and 3.66 m static bed heights gave significantly higher σ_{sp} deviations in the 0.3-m-dia. column because both slugging and gas bypassing were present. No slugging was detected for the lower bed heights or in the larger diameter units. There was no significant column diameter effect on the ΔP fluctuations data. Figure 12 compares σ_{sp} in the 0.9-m and 1.52-m-dia. units for heavy FCC catalyst. The static bed heights were 1.22 and 1.52 m in the 0.9 and 1.52 m units, respectively. Again, the effect of column diameter is not significant. Figures 11 and 12 include data from both well fluidized and gas-bypassing beds. Apparently, diameter in itself is only a factor if the bed height-to-column diameter ratio is too large to lead to slugging and, as noted elsewhere (Issangya et al. (8)), larger units can have multiple gas bypass streams.

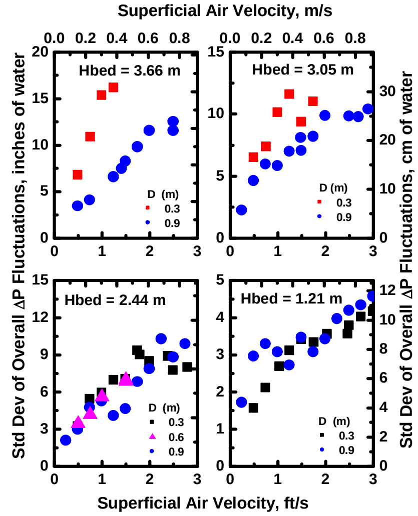


Figure 11. Effect bed diameter on σ_{sp} for various static bed heights using 3% fines heavy FCC catalyst particles.

Figure 13 shows σ_{sp} versus gas velocity in the 0.3-, 0.6- and 0.9-m-dia. units for heavy FCC catalyst at various operating conditions. These data are only for beds with no gas bypassing; which was achieved by the use of horizontal baffles, increasing gas velocity, system pressure and bed material fines content. The ΔP fluctuations intensities were not very different under these different operating

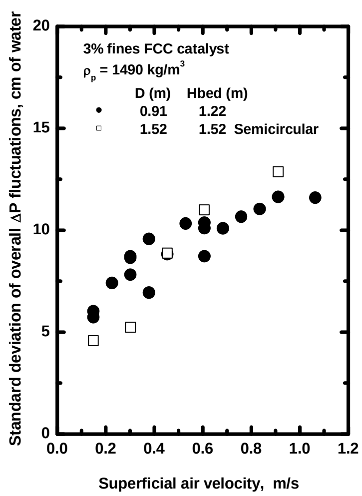


Figure 12. σ_{sp} versus gas velocity for 3% fines heavy FCC catalyst particles in the 0.9-m-dia. cylindrical and the 1.52-m-dia. semicircular unit.

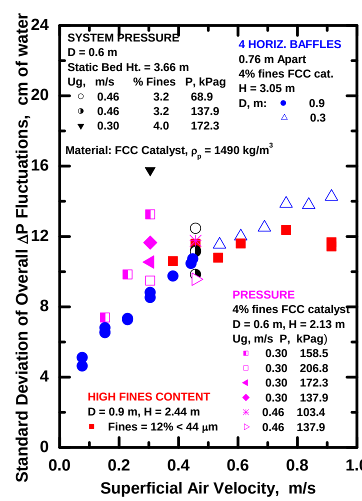


Figure 13. σ_{sp} for fluidized with no gas bypassing versus gas velocity in the 0.3-, 0.6- and 0.9-m-dia. units for heavy FCC catalyst particles at various operating conditions.

conditions, which suggests that the fluidization behavior was probably very similar. Since pressure fluctuations in well fluidized beds are largely caused by the interaction of bubbles/voids with the solids phase, it is likely that the bubble/void sizes were nearly the same under the given operating conditions. This requires further investigation.

CONCLUSIONS

The σ_{sp} increased with increasing bed height and decreased with increasing system pressure, with increasing fines content in the bed and by installing horizontal baffles. The high ΔP fluctuations were mostly a result of gas bypassing in the beds. Column diameter did not have a significant influence on gas bypassing, and there were no significant differences in the differential pressure fluctuations in the 0.3-, 0.6-, 0.9- and 1.52-m-diameter test units. The gas velocity at the peak σ_{sp} varied significantly with bed height for low fines FCC catalyst particles and it's likely not equal to the bubbling-turbulent regime transition velocity, Uc. It might be helpful in regime transition studies that utilize ΔP fluctuations to also assess the bed fluidization quality, for the presence of gas bypassing. Gas bypassing can be eliminated by lowering the bed level, installing horizontal baffles, increasing system gas velocity and pressure or by adding more fines to the bed.

NOTATION

D	Column diameter	F44	Percent fines content < 44 μm	H	Static bed height
P	Pressure	Ug	Superficial gas velocity	ΔP	Differential pressure
ρ_p	Particle density	z	Height above gas distributor		
Uc	Bubbling to turbulent regime transition superficial gas velocity				

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