SPINNING STRAW INTO GOLD: TURNING ACADEMIC PAPERS INTO COMMERCIAL FLUIDIZED BED REACTOR SOLUTIONS

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ABSTRACT

This paper presents an example of academic work that has been applied in industry. A case is presented of a solution to a serious operational problem involving fluidization phenomena threatening to cause structural damage to an operating chemical reactor. The process used to analyze the problem and arrive at a probable cause and design solutions are presented.

INTRODUCTION

With the large volume of academic work published in the field of fluidization phenomena, the authors have frequently found it laborious and time-consuming to locate appropriate published work to apply to the problems that they have faced and to judge the applicability of that work. This paper presents a case in which academic work was extracted from the literature and used in an industrial setting. The authors aim to provide insight as to how academic work is commonly applied in an industrial setting and thus to give examples of work that they have found useful.

The case presented describes the solution of a serious operating problem in a pyridine reactor. The problem was particularly serious and urgent and the cause appeared to be some unexpected fluidization phenomenon. This paper presents the reasoning and the scientific work that was used to arrive at a solution.

PYRIDINE REACTOR VIBRATION

Several years ago a certain pyridine fluidized bed reactor was started up for the first time. Upon startup, the reactor vibrated so violently that the integrity of the piping and support structure was put at risk. The vibrations produced by this reactor were of very large amplitude. The horizontal deflection of the reactor vessel itself was measured at up to 10 mm with a period of 2 to 4 seconds. The deflections were measured at the vessel supports which were located near or slightly above the center of gravity of the vessel when loaded with catalyst. The vibrations were irregular and the system was damped by supports and attached piping. The frequency was therefore probably that of the initiating force. The reactor vessel was about 1.7 meters in diameter and about 13 m high. Vibrations of any discernable magnitude had never been observed by the authors even in the largest reactors operating at superficial velocities up to 0.6 m/s. The following presents the results of the investigation to determine the cause of the vibrations.

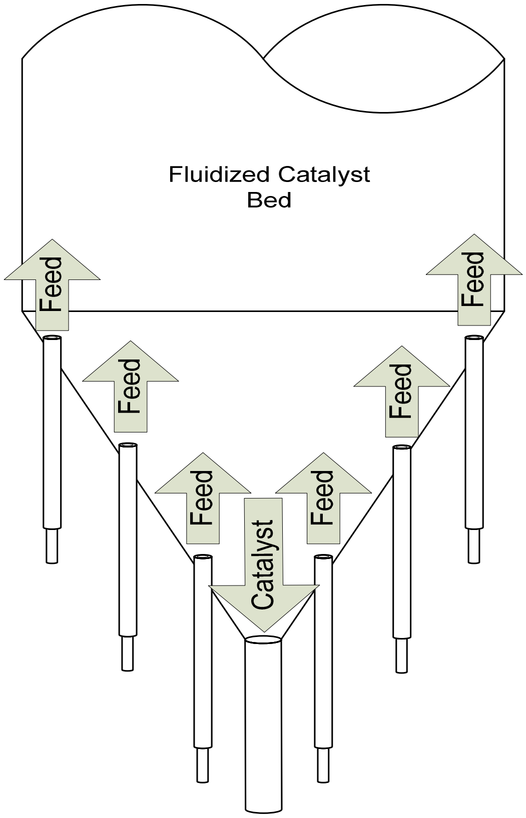

Figure 1: Cone Design Grid

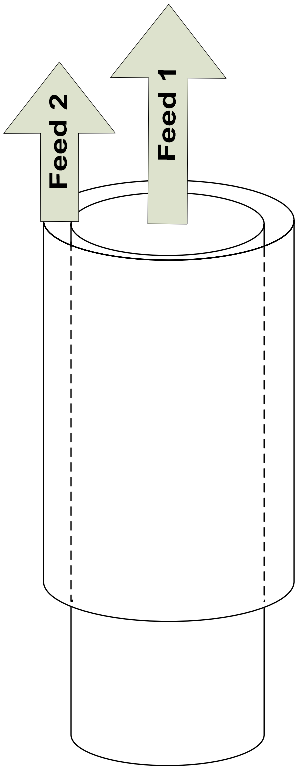

Figure 2: Coaxial Tuyere

First the salient features of this reactor were reviewed:

The catalyst was very similar in density and particle size to FCC catalyst.: d_{p50} =80 mm; particle density = 1320 kg/m3; Geldart Group A.

A. The operating pressure was close to atmospheric: 1.31 bara in the freeboard.
B. The bed depth was 5.4m with a pressure at the grid of 1.54 bara
C. The superficial velocity at the grid was 0.7 m/s.

D. During startup there was a loss of fines from this reactor. The measured fines content, however, was found to be as high as 15% while the vibrations were being observed.

E. Catalyst was circulated through the bottom of the vessel cone head to a regenerator (see Figure 1) and regenerated catalyst was returned through a nozzle in the side of the reactor.

F. Feed gases were introduced through multiple coaxial tuyeres (see Figure 2).

G. Feed 1 entrance velocity at feed temperature was 15 m/s; Feed 2 entrance velocity was 9 m/s. This was considerably higher than the original design. Moreover, the catalyst bed was at a significantly higher temperature than the entering feed.

H. Entrained catalyst was collected in cyclones and returned to the bed.

I. Besides the cyclone diplegs, fitted with trickle valves, there were no reactor internals

J. Similar reactors and the regenerator all of which used the same or similar material and operated at the same or similar pressures did not experience these vibrations, These non-vibrating vessels all shared a similar plenum grid design as depicted in Figure 3.

K. Vibrations began immediately upon startup

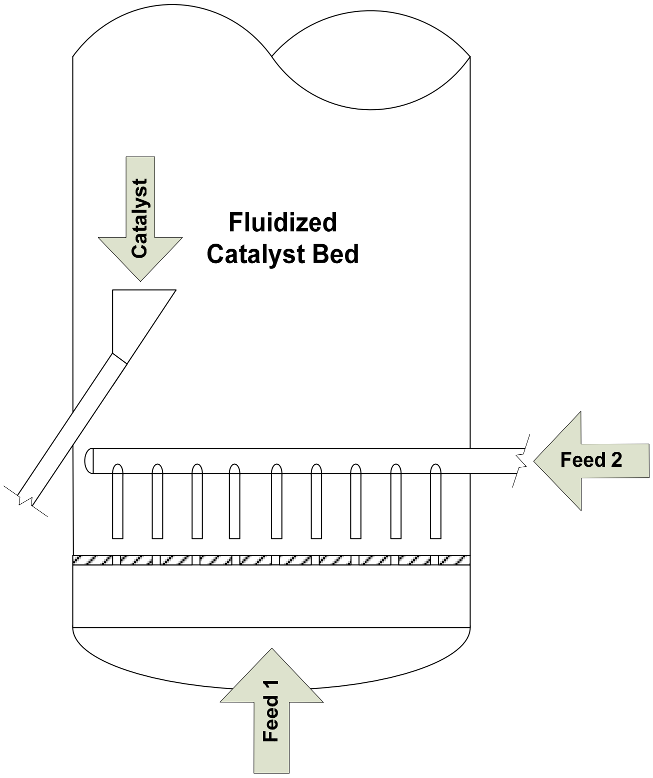

Figure 3: Plenum Design Grid

Next several theories of the cause of the vibrations were developed:

1) Feed gas entrained down into the standpipe by the solids mass flux in the cone was causing hammering in the catalyst circulation line.
2) Solids traffic in the cyclone dipleg had a lateral force vector for an unexplained reason.
3) Rapid vaporization of liquid in the feed was causing expanding bubbles which were then collapsing.
4) Unbalanced flow distribution in the cone grid was causing a preferential flow of feed gas along one side of the reactor causing turbulence
5) Lack of fines leading to or a Geldart group B bed material with unlimited bubble size was causing violent movement of the catalyst in the bed.
6) Massive gas by-passing and the periodic shifting of the by-passing stream was causing shifting of the catalyst mass in the bed.

The forces necessary to cause the vibrations observed were then estimated:

The catalyst mass was about 7200 kg and the reactor mass was about 5000 kg. The total mass was therefore about 12200 kg. As a first approximation, we can assume that for each displacement, the reactor mass started at rest and the maximum velocity was reached at half of the displacement, with the structure and piping resistance decelerating the reactor mass during the second half of the displacement. The time from start to the peak velocity is therefore 0.75 s. The acceleration would therefore be about 0.010m / $(0.75s)^2$ = 0.0178 m/s^2 and the force required to produce these vibrations would then be approximately 217 N. Since this estimate neglects the resistance due to the structure and piping during the acceleration of the vessel, it is the minimum force that would be required to achieve this deflection in that time.

Next each of the possible causes was examined in detail to gather evidence to verify or falsify each.

1) Catalyst circulation was stopped by shutting the slide valve and the vibrations continued. Indeed, the qualitative observation was that the vibrations increased in intensity when the circulation was stopped. The mass flux at the entrance to the standpipe was estimated to be 290 $kg/m^2 \cdot s$ based on the measured solids circulation rate. The bed density measurements indicated a density close to the bulk density of the catalyst and were therefore judged not to be reliable, the bed density was estimated using the King (1989) correlation. (1) The maximum downward velocity at the standpipe entrance was estimated to be about 0.6 m/s. The initial bubble size estimated by the Chiba, et al. (1972) correlation (2) was found to be already larger than the maximum stable bubble size (diameter = 0.146m) for Geldart Group A material using the Geldart (1977) correlation. (3) The bubble rise velocity estimated using the Werther (1977) correlation (4) was found to be 3.3 m/s, much higher than the standpipe entrance velocity. There was, therefore, no massive gas entrainment down the standpipe. The maximum possible force that could be exerted by the catalyst inventory in the circulating line was estimated to be about 40 N in the upward direction based on the transport velocity and 70 N downward based on

gravity with the impulse being exerted in 0.75s. Neither force would have a significant horizontal component.

2) Entrainment from the bed was estimated using the PSRI correlation. (5) Solids traffic down the first stage dipleg approximates the entrainment rate for the purposes of this study and was estimated to be approximately 32 kg/s. If the solids collected in the dipleg for three seconds and then discharged over the 0.75s impulse time over which the force was required to cause the reactor displacement, the solids would have to have a horizontal velocity component of about 1.7 m/s. The trickle valve would have had to remain shut while maintaining a differential pressure of about 10 kPa before suddenly dumping the retained solids.

3) Rapid vaporization of liquid in the feed vapor entrained from the feed vaporizer could cause sufficient acceleration of the bed solids that would provide a force of the required magnitude. This theory accounts for the difference in behavior of the two grid designs: the plenum grid provides liquid knockout capacity that the cone design does not. On the other hand, rapid vaporization would cause an equal expansion in all directions and would not explain the periodic and directional behavior of the vibrations. In addition, when air was substituted for the feed vapor, the vibrations did not cease.

4) Unbalanced flow distribution, especially at the very high feed distributor velocities would also account for the forces required to cause the vibrations. This could account for the energy input, but, if the estimated maximum stable bubble size were correct, the impulses remain unexplained. Impulses generated by the collapse of these bubbles would generate forces no greater than about 60 N calculated using the bubble volume, loose bulk density of the catalyst, bubble rise velocity, and the 0.75s impulse time. Unbalanced flow distribution or high feed distributor velocity could be a contributing factor, but it could not supply a complete explanation for the reactor's behavior.

5) It is well-known that the original Geldart powder classification was developed for fluidized beds operating with air as a fluidizing gas at atmospheric pressure. Since the original work in 1973 (6), several investigators including Molerus (1982), (7) Grace (1986) (8), Goossen (1998), (9) and Yang (2007).(10) have re-interpreted and expanded this classification system to include operations at varying temperatures, pressures and fluidizing gases. Most have sought to correlate the class boundaries based on Archimedes number. The Group A/B boundary used in the original troubleshooting analysis used the Grace work, but regardless of the correlation used, this fluidized bed is well within Group A. This remains true not only of the powder samples taken from the bed, but also of the same samples when all material less than 45 μm is removed. The maximum stable bubble size would not have exceeded 0.2 m diameter even if all the fines had been lost. Transition to Group B fluidization must be rejected as a possible cause for the vessel vibrations.

6) A Particulate Solids Research, Inc. (PSRI) video (11) showing the large Plexiglas fluidized bed during gas by-passing experiments shows large-scale shifting of masses of solids in the bed that, at the scale of the commercial vessel in question, could reasonably cause the forces that would explain the observed deflections and low frequency vibrations. Gas bypassing and defluidization of certain zones in deep fluidized beds of Geldart Group A material has been reported in the open literature only rarely prior to the present case. Wells (2001) reported this phenomenon and attributed it to the compression of the gas in the emulsion phase due to the pressure

head developed in deep beds.(12) This same compression has been identified as the cause of bridging and by-passing in catalyst strippers (13) and of irregular flow in standpipes. (14) PSRI has investigated this phenomenon and verified that massive gas by-passing can occur in deep fluidized beds of Geldart Group A material.(15, 16) This phenomenon occurs if the pressure drop through the bed is a significant fraction of the absolute operating pressure and there are no internals present to promote gas and solids mixing. Fines content is also an important factor with higher fines content inhibiting the onset of by-passing to a higher bed height and consequently a higher gas compression ratio. Nevertheless, by-passing occurred in beds with fines content as high as 12%. The defluidized zone that accompanies the streaming flow in this phenomenon would also explain the observation that the bed density measurements appeared to be unreasonably high and that the cyclones did not operate at the expected efficiency.

Recent work by Karimipour and Pugsley (2010) (17) reproduced this streaming flow in fluidized Geldart Group A beds. They found no effect of grid design or fines content. They analyzed their pressure fluctuation data using autocorrelation, cross correlation, and power spectral density and coherency techniques. They found that dominant frequencies of 40 cm and 80 cm deep beds were 4 Hz and 2.7 Hz respectively and that increasing the bed depth shifts the dominant frequency towards very low frequencies. This is consistent with the observations of the reactor in the field.

One observation that remains unexplained is why similar fluidized beds operating with the same material but with a different grid design did not exhibit these vibrations. This reactor operated with a bed depth that was significantly higher than the investigations cited. Moreover, the entrance velocity of the gas in the initial case was probably also much higher than those used in the laboratory. The findings suggest that further investigation of the effects of grid design and entrance velocity are indicated.

CONCLUSIONS

This analysis did not unequivocally identify a unique cause for the reactor vibrations, although most possibilities were eliminated and one possible cause appears more likely than others. More often in investigations of plant operating problems several possible causes are identified and none stands out as a leading possibility. As a result of this analysis the reactor was subsequently modified by both replacing the cone with a plenum grid and adding “subway grating” baffles as described in the literature as preventing massive gas bypassing. In addition the cyclone diplegs were shortened and the first stage dipleg trickle valve was replaced with a target plate. Upon startup after these modifications, the vibrations were virtually eliminated. Thus several of the most probable causes were addressed simultaneously and the threat to the integrity of the vessel was eliminated. This unfortunately does not advance the state of knowledge of fluidization, but the practical result was that the problem was solved with only one shutdown and one series of vessel modifications. Experiences such as this lead several industrial practitioners to draw varying conclusions from the same set of data and observations. Unfortunately, industrial equipment is typically made of steel rather than Plexiglas and most phenomena occurring in equipment must be inferred rather than observed. Academic work, and especially that which can be directly observed, will frequently shed light on an industrial design or operational problem. It can be very useful, but it is seldom decisive.

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