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**Cold Slumping Characteristics
of a Fluidized Bed**

M. E. Lackey

Fossil
Energy
Program

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CONTENTS

	<u>Page</u>
ABSTRACT	1
1. INTRODUCTION	1
2. SYSTEM DESCRIPTION	3
3. TEST DESCRIPTION AND RESULTS	9
3.1 Minimum Fluidizing Velocity Test	10
3.2 Slumping Test	11
4. GENERAL RESULTS AND CONCLUSIONS	22
4.1 Leakage	22
4.2 Inventory Displacement	27
5. RECOMMENDATIONS	28

COLD SLUMPING CHARACTERISTICS OF A FLUIDIZED BED

M. E. Lackey

ABSTRACT

Cold slumping tests were performed on a 4 × 4 Plexiglas model of the TVA 20-MW atmospheric fluidized bed combustion pilot plant. The tests were conducted to determine mixing between the active and slumped sections, fluidizing air bypass through the slumped section, elutriation from the fluidized section, and maximum buildup in the slumped section. With an 18-in. bed depth and a mean particle size of 370 μm , the average superficial velocity in the slumped section was approximately one-half of the minimum fluidizing velocity. The maximum buildup in the slumped section was ~35% of the bed static depth. The elutriation from the active bed resulted in a decrease of ~20% in the static bed height.

1. INTRODUCTION

The Tennessee Valley Authority (TVA) has assumed a lead role in the demonstration of atmospheric fluidized bed combustion (AFBC) technology for application in large utility boilers. The first phase of this demonstration involves the operation of a 20-MW AFBC pilot plant. The TVA Energy Demonstration and Technology Division enlisted the assistance of Oak Ridge National Laboratory (ORNL) in providing technical support and services for the pilot plant.*

The pilot plant will be operated in such a manner as to allow the determination of the operating characteristics of a large bed for utility application. One area that will be investigated is load-following capability. One method of reducing the thermal output of a fluidized bed is bed slumping, which involves defluidization of a section of the bed and continued operation of the remaining sections. Several areas of uncertainty are associated with this method of operation: mixing between the active and slumped sections, fluidizing air bypass through the slumped

*Interagency agreement between TVA, DOE, and ORNL — Agreement TV48296A, Subagreement 5.

section, elutriation from the fluidized section, and maximum buildup in the slumped section.

The approach taken in the scale-down test was to run with a bed height of about one-fourth the depth of the full-scale bed so that the cold model in effect represents a bed about 4 times as wide or 16 times as large in area. The reduced bed height will make it possible to obtain a fluidized zone, transition zone, and slumped zone in the present width of the cold model. In scaling down, totally accurate characteristics cannot be obtained with respect to elutriation. The best approach is believed to be reduction of fluidizing velocity in proportion to bed height. The mean particle size was then reduced to give good fluidization over the lower velocity range. The tube diameter was also scaled down for the reduced bed height.

Two dimensionless groups, the Archimedes number (Ar) and the Reynolds number (Re), are used in defining the operating characteristics of the bed. The Archimedes number is used to characterize the degree of buoyancy of the particles, and the Reynolds number is used to characterize the drag of the fluidizing medium on the particles.

The Archimedes number and Reynolds number are defined as

$$Ar = \frac{g \rho_f (\rho_s - \rho_f) D^3}{\mu^2}$$

and

$$Re = \frac{DV \rho_f}{\mu},$$

where

ρ_f = fluid density,

ρ_s = particle density,

D = particle diameter,

V = fluid superficial velocity,

μ = fluid viscosity,

g = gravitational constant.

To properly scale the fluid dynamics of the fluidized bed, approximately the same Archimedes number and Reynolds number should be maintained. The parameters for the full-scale bed and the subscale model are compared in Table 1.

As Table 1 indicates, both the Archimedes and Reynolds numbers for the subscale unit are in the midrange of those for the full-scale unit, which results in a good representation of the fluid dynamics of the full-scale unit.

Table 1. Parameters for subscale model bed slumping test.

	Full-scale unit	Subscale cold model
Bed size, ft	16 × 16	4 × 4
Bed height, ft	4-6	1.5
Fluidizing velocity, fps	4-8	2
Particle mean size, μm	1,000-2,000	446
Tube OD, in.	2	0.5
Archimedes number	3,400-27,000	8,200
Reynolds number	8.6-34.3	17.6

2. SYSTEM DESCRIPTION

An existing 4 × 4 cold flow Plexiglas model was modified by installing a divider in the windbox to allow one-half of the bed to be slumped while the other half was being fluidized. A tube bundle was designed to simulate a typical boiler tube arrangement for a fluidized bed combustor (FBC). The bundle was based on a one-fourth-scale factor — that is, the tube diameter, bed depth, and fluidizing velocity are approximately one-fourth that of the full-scale TVA pilot plant FBC boiler (Fig. 1).

The tube bundle (Fig. 2) consists of nine rows of triangular-spaced 1/2-in.-OD rods with a horizontal spacing of 1.5 in. and a vertical spacing of 3/4 in. The air distributor plate is shown in Fig. 3. The air nozzles are 3/4-in. nominal pipe stubs with 0.105-in.-diam holes to vent the air. The nozzles are spaced on a 3-in. square pitch. The piping that supplies the air to the two sections of the windbox is shown in Fig. 4. The complete test module is shown in Fig. 5.

Fig. 1. Slumping test module for TVA 20-MW pilot plant.

Fig. 2. Simulated fluidized bed combustor tube bundle.

The slumping test to determine the operating characteristics of a slumped bed consisted of two main parts. One concerned the fluidizing air bypass through the slumped section, which could lead to areas having a reducing zone at the interface of the slumped and active beds during coal-burning operation. The second concerned the elutriation of bed material from the active bed and subsequent deposit in the slumped portion of the

Fig. 3. Air distributor plate for slumping test module.

bed. This second effect could result in uncovering of the heat transfer surface during coal-burning operation.

The flow distribution in the bed was inferred from the bed pressure distribution determined for flows below and above the minimum fluidizing velocity. The effects of elutriation were determined by operating the bed in the slumped condition until an equilibrium bed height in the slumped section was reached.

Fig. 4. Windbox supply piping for slumping test module.

Fig. 5. Slumping test module installation.

3. TEST DESCRIPTION AND RESULTS

The windbox of the 4 × 4 cold flow model was divided into equal sections by a stainless steel plate that was sealed at the edges with both a gasket and a synthetic rubber sealant. Before installation of the air supply piping, the divider was tested for leaks. No detectable leakage was found when a pressure difference of 2 psi was imposed across the plate.

A simulated tube bundle was constructed of 266 1/2-in. aluminum rods. The bundle tubes were placed in nine rows with a triangular spacing of 1.5 in. horizontally and 3/4 in. vertically. The bundle was positioned in the model with a clearance of 6.25 in. between the air nozzles and the first row of tubes. The top row of tubes in the bundle was located 12.75 in. above the air nozzles.

The pressure distribution in the bed was measured with eight wall taps located 3 in. above the air nozzles. The fluidizing air was supplied by an air blower that has a capacity of ~20,000 lb/h at a discharge pressure of 100 in. of H₂O. The air flow rate to the bed was measured with an orifice located in the blower discharge line.

In preparation for testing, the system was loaded with ~1700 lb of limestone purchased from the Calcium Carbonate Company of Quincy, Illinois, designated as Quincy limestone Q20-60. The sieve analysis of this limestone at the conclusion of the test series is given in Table 2. The harmonic mean diameter for the distribution shown in Table 2 is 368 μm , the median diameter is 448 μm , and the weight mean diameter is 446 μm .

Table 2. Sieve analysis
of Quincy limestone

Particle size (μm)	Percent in grade by weight
+850	1.76
+600-850	17.23
+425-600	35.76
+300-425	22.92
+212-300	11.83
+150-212	8.46
+106-150	2.03
-150	0.01

3.1 Minimum Fluidizing Velocity Test

In preparation for running the slumping tests, the minimum fluidizing velocity for the limestone was determined. The static bed height above the tube bundle was ~1 in., or 13.83 in. above the air inlet nozzles at the beginning of the test series. The fluidizing characteristics of the 20 x 60 Quincy limestone are shown in Fig. 6. The data for Fig. 6 were

Fig. 6. Fluidizing characteristics of Quincy limestone, size 20 x 60.

obtained by taking the bed pressure drop starting at a flow rate of ~ 2 ft/s and then progressively reducing the flow to give the curve shown. The minimum fluidizing velocity, obtained from the intersection of the vertical and horizontal tangents shown in Fig. 6, was ~ 0.5 ft/s. The data of Fig. 6 show that the system is not fully fluidized until the superficial velocity approaches a value of ~ 1 ft/s, or twice the minimum fluidizing velocity.

3.2 Slumping Test

Because the pressure gradient in the slumped section between the distributor plate and the freeboard is different from the gradient in the fluidized section, the fluidizing air leaks from the fluidized bed into the slumped section. After the flow reaches the minimum fluidizing velocity, the pressure gradient in the fluidized section is constant and independent of the superficial velocity. Using the determined minimum fluidized velocity of 0.5 ft/s as the velocity required to establish a constant pressure gradient in the fluidized section of the bed, a series of runs was made with a constant flow of ~ 0.48 ft/s (96% of minimum fluidizing velocity) in active portions of the bed and with various average velocities in the slumped portion of the bed. The measured pressure gradient is shown in Fig. 7. The 0.252-ft/s flow through the slumped side was caused entirely by leakage from the active bed into the slumped section. A fraction of this flow leaked into the windbox of the slumped section through air nozzles located near the interface of the slumped and fluidized sections. This leakage air flows across the slumped-side windbox and back into the slumped bed through air nozzles located further from the interface of the slumped and fluidized sections of the bed. The flows of 0.35 and 0.46 ft/s shown in Fig. 7 were obtained by supplying air to the windbox of the slumped section.

An estimate of the bed superficial velocity distribution with various slumped-bed flows was obtained by assuming that the vertical flow component of the average flow was proportional to the vertical pressure drop. The velocity distribution obtained from this approach is shown in Fig. 8.

Fig. 7. Bed pressure distribution at 3 in. above air inlet nozzles with various slumped bed flows.

Fig. 8. Estimated bed superficial velocity distribution with various slumped bed flows.

An elutriation test was performed with a nominal superficial velocity of 2 ft/s supplied to the windbox of the bed's fluidized section. No air was supplied to the windbox of the bed's slumped section. Coal with a top size of 1/16 in. was used to spike the bed to a concentration of ~1% by weight to allow an observation to be made of the behavior of the coal that would be present in a burning bed when operating in a slumped mode. Figures 9 and 10 show the bed operating in the slumped mode and indicate the variations in surface activity; the solid throw in Fig. 9 is rather concentrated and has a height of ~8 in., while the solid throw in Fig. 10 is more diffuse and has a height of ~5 in. These variations are typical deviations in the surface conditions of fluidized beds and do not represent abnormal conditions.

A solids downflow region was detected at the junction of the fluidized and slumped sections of the bed. Close-ups of this region are shown in Fig. 11(a through d) — (a) and (b) indicate the general solids downflow that occurs at the interface and (c) and (d) show the return of the coal to the active portion of the bed. This coal was elutriated preferentially from the fluidized side and deposited on the upper surface of the slumped section.

The bed was operated in the slumped mode until an equilibrium was obtained between the fluidized and slumped sections. Shown in Fig. 12 is the progressive change in the static bed solids distribution after the bed had been operated for 2 and 4 h. Figure 13 shows the static bed solids distribution after the bed had been operated for 6 h in the slumped mode. Height measurements were made of the static bed solids distribution as a function of operating time. These values are shown in Fig. 14. As Fig. 14 shows, the solids distribution had reached a state of quasi equilibrium after an operating period of ~4 h.

The magnitude of the downflow zone shown in Fig. 11(a through d) is indicated in Fig. 15. Figure 15 shows a region of the fluidized section located near the interface and extending ~7 in. above the air inlet nozzle datum and ~3 in. into the fluidized zone in which the solids are static. This region is probably defluidized as a result of air loss through the slumped region bed and distributor plate.

Fig. 9. Cold flow model with right half fluidized at nominal velocity of 2 ft/s and no flow supplied to left-side windbox. Dense throw ~ 8 in.

Fig. 10. Cold flow model with right half fluidized at nominal velocity of 2 ft/s and no flow supplied to left-side windbox. Dense throw ~ 5 in.

Fig. 11. Downflow zone at intersection of slumped and fluidized beds. Nominal superficial velocity of 2 ft/s in fluidized section and no flow supplied to slumped section.

Fig. 12. Solids distribution after 2 and 4 h of operation. Nominal fluidizing velocity of 2 ft/s and no flow to slumped section windbox.

Fig. 13. Solids distribution after 5 h of operation. Nominal fluidizing velocity of 2 ft/s and no flow to slumped section windbox.

Fig. 14. Solids distribution after operation for 2, 4, and 6 h at nominal superficial velocity of 2 ft/s and no flow to slumped section windbox.

Fig. 15. Solids downflow zone after operation for 6 h at nominal superficial velocity of 2 ft/s and no flow to slumped section windbox.

Two additional elutriation tests were performed to determine the effects of flow to the slumped section of the bed on the distribution. These tests were with a nominal superficial velocity of 2 ft/s in the fluidized section of the bed and nominal velocities of 0.46 and 0.55 ft/s (~90 and 110% of the minimum fluidizing velocity) in the slumped section of the bed. Under these conditions, approximately one-fourth as much time was required to obtain an equilibrium static solids distribution as in the previous no-flow test. The operating and static bed contours for the 0.55-ft/s test are shown in Figs. 16 and 17.

The static contour of the bed after an operating time of 2 h is shown in Figs. 18 and 19. As inspection of the bed contours indicates, a slip plane zone exists in the slumped bed in addition to the downflow zone noted for the case in which no air is supplied to the slumped section of the bed. Comparison of the contours shown in Figs. 18 and 19 with that of Fig. 15 indicates that the size and location of the solids peak height in the slumped zone are a function of the air supplied to the slumped section of the bed.

4. GENERAL RESULTS AND CONCLUSIONS

4.1 Leakage

The air leakage from the fluidized section of the bed into the slumped section of the bed could result in alternating oxidation and reduction conditions at the interface of the two sections. The air leakage is indicated by the slope of the superficial velocity curve shown in Fig. 8. The coal that is preferentially elutriated from the fluidized section of the bed is returned to the active bed by way of the solids downflow zone as Fig. 11(a through d) shows. Since the coal does not return as a uniform mixture, the conditions required for alternating oxidizing and reducing atmospheres exist at the interface. These conditions probably will not be serious in the region of the boiler tube penetration of the interface since these tubes have a surface temperature that does not exceed ~600°F. However, in the regions where superheater tubes pass through the interface, relatively rapid corrosion could take place since these tubes have a surface temperature in the range of 1000 to 1100°F.

Fig. 16. Cold flow model with right half fluidized at nominal velocity of 2 ft/s and nominal flow of 0.55 ft/s supplied to left side of wind-box.

Fig. 17. Solids distribution after 2 h of operation. Nominal fluidizing velocity of 2 ft/s in right half and 0.55 ft/s in left half.

Fig. 18. Solids distribution after operation for 2 h with superficial velocity of 2 ft/s in fluidized side and 0.46 ft/s in slumped side.

Fig. 19. Solids distribution after operation for 2 h with superficial velocity of 2 ft/s in fluidized side and 0.55 ft/s in slumped side.

The potential reducing conditions can be partially alleviated by supplying air to the slumped area of the bed adjacent to the fluidized section. The effects of this action on the bed contour are shown in Figs. 8, 15, 18, and 19. The decrease in the slope of the superficial velocity curve shown in Fig. 8 with an increase in the flow supplied to the slumped section of the bed indicates a decrease in the leak flow from the fluidized section to the slumped section. The increase in the size of the down-flow area shown in Figs. 15, 18, and 19, in addition to the formation of slip planes and a general reduction in the height of elutriation buildup in the slumped region, indicates a decrease in the retention time of the preferentially elutriated coal in the slumped region. The shorter retention time indicates a decrease in the coal concentration which, when coupled with the increase in air flow, should give a constant oxidizing condition in the slumped zone.

In addition to the oxidation-reduction problem resulting from operation with no air supplied to the slumped section of the bed, the elutriated coal could form a crust which in turn may prevent a restart of the slumped section of the bed. Supplying air to the slumped section may prevent this condition by increasing interchange between the fluidized and slumped areas and thus decreasing the surface concentration of the coal in the slumped zone. Another effect of the increased air flow to the slumped zone that could decrease chance of crusting is the increase in surface activity of the slumped region when it is operating in the range of 90 to 110% of minimum fluidizing velocity.

4.2 Inventory Displacement

The solids inventory of the fluidized section of the bed is removed by elutriation and deposited on the surface of the slumped section of the bed. This effect as a function of the air supplied to the slumped section is shown in Figs. 15, 18, and 19. As inspection of these distributions shows, they are valid only for the case of equal division of the bed area between the slumped and fluidized sections. These contours further indicate that the cases of 1:3 or 3:1 slumped bed-to-fluidized bed area ratios would present different contours because of the location of the bed wall

relative to the interface between bed zones. Some of the possible operating modes may allow the removal of sufficient inventory from the fluidized zone to uncover the heat transfer surfaces and require, as a result, the addition of inventory which subsequently would have to be removed for other modes of operation.

A possible method of preventing the inventory displacement would be the installation of baffles in the freeboard above the tube bundles. These baffles, which can be either cooled or uncooled, should extend into the splash zone of the bed at the bottom and far enough into the freeboard to block horizontal particle movement. Such baffles should prevent inventory displacement resulting from elutriation and at the same time allow a free interchange of material between bed sections when they are both fluidized.

5. RECOMMENDATIONS

The potential oxidizing-reducing condition at the interface of the slumped and fluidized bed sections as well as the chance of crusting the slumped section may be prevented by supplying air to the windboxes of the slumped sections. It is recommended that this approach be allowed for in the design of the pilot plant by the installation of the equipment required to meter the air flow to the windbox of each bed section that can be slumped. The approximate air-metering range should be from 25 to 110% of air required for minimum fluidization of the section.

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