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GASIFICATION OF BITUMINOUS COAL WITH OXYGEN IN A PILOT PLANT EQUIPPED FOR SLURRY FEEDING

by

L. F. Willmott,[1] K. D. Plants,[2] W. R. Huff,[2] and J. H. Holden[2]

ABSTRACT

Pulverized high-volatile A bituminous coal was gasified with oxygen and superheated steam in a pressure-gasification pilot plant equipped for slurry feeding. The minimum ratio of water to pulverized coal that could be pumped satisfactorily as a slurry was about 1 to 1. Heating this slurry produced a suspension of coal in superheated steam having a steam-to-coal ratio greater than the 0.3 to 1 proportion that is considered optimum for pressure gasification of pulverized coal. A steam separator removed enough steam to provide ratios down to about 0.5 to 1, but a 0.3 to 1 ratio was not achieved.

Gasification of Sewickley coal produced a synthesis gas containing about 36 percent H_2, 46 percent CO, and 13 percent CO_2. Gas output, gas composition, and coal and oxygen requirements were virtually the same as for a pilot plant equipped for fluidized-coal feeding. Typical results from the slurry-fed plant at 300 psig were carbon gasified, 95 percent; coal requirement, 34 lb/M (thousand) std cu ft CO + H_2 produced; oxygen requirement, 365 std cu ft/M std cu ft CO + H_2 produced.

The results showed that the two feeding methods are equally satisfactory from the standpoint of gasification. A choice between a fluidized-coal gasification process or a slurry gasification process depends on considerations relating to the coal-feeding phase itself, including capital and operating costs, manpower requirements, safety, and flexibility of operation.

INTRODUCTION

The Bureau of Mines has done extensive research and development at the Morgantown (W. Va.) Coal Research Center on the gasification of bituminous

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coal with oxygen and steam to produce synthesis gas. Methods of feeding coal to the gasifier have been an important part of this work.

In the first coal-feeding method developed--the fluidized or pneumatic-feeding method--coal entered the gasifier as finely divided particles suspended in air or inert gas. Details of the fluidized-coal feeding method and performance of pilot-scale gasifiers fed with fluidized coal were reported (1, 2, 4, 9-11).[3]

Another coal-feeding system, first introduced by the Texas Co., mixes pulverized coal with water to make a slurry; the water in the slurry is flashed into superheated steam, and the coal-steam mixture is fed to the gasifier. The Bureau of Mines issued publications on the development of pilot-size equipment to mix the pulverized coal with water, pump and meter the slurry, evaporate and superheat the water, and separate and meter the excess steam (5-7). Results were not published, however, on the performance of a gasifier equipped for slurry feeding. The purpose of this publication is to present performance results from a pressure gasifier and compare them with results from the same gasifier fed by a fluidized-coal feeder.

PRESSURE-GASIFICATION PILOT PLANT EQUIPPED FOR SLURRY FEEDING

Figure 1 is a flowsheet of the pressure-gasification pilot plant equipped for slurry feeding. Coal ground to about 70-percent-through-200-mesh is pneumatically conveyed by inert gas to a premix tank and mixed batchwise with water. Slurry from the premix tank flows by gravity to a scale-mounted mix tank in which the slurry is kept continuously agitated. The slurry then passes to a piston-type pump that delivers the slurry to a coil-type heater containing three sections of progressively larger pipe inside a refractory-lined shell. Hot gases from a combustion chamber heat the coils and transform the slurry into a suspension of coal in superheated steam.

The slurry from the mix tank contains 50 percent coal and 50 percent water. This was the maximum concentration of 70-percent-through-200-mesh coal that could be pumped satisfactorily, although others reportedly have pumped slurries containing as much as 70 to 75 percent coal but of different size consist. A concentration of 50 percent water, however, gives a higher steam-to-coal ratio than is suitable for gasification consistent with good thermal and slagging conditions. Therefore, the steam-coal mixture from the heater is passed through a separator to remove the excess steam. Steam extracted by the separator is metered.

The adjusted steam-coal mixture from the separator flows to the gasifier where oxygen is added and the coal is gasified by partial combustion into a gas consisting primarily of CO, H_2, and CO_2. The product gas is quenched with water inside the gasifier, cleaned in a water scrubber, metered, and flared. Slag settles into a vessel attached to the bottom of the gasifier.

[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

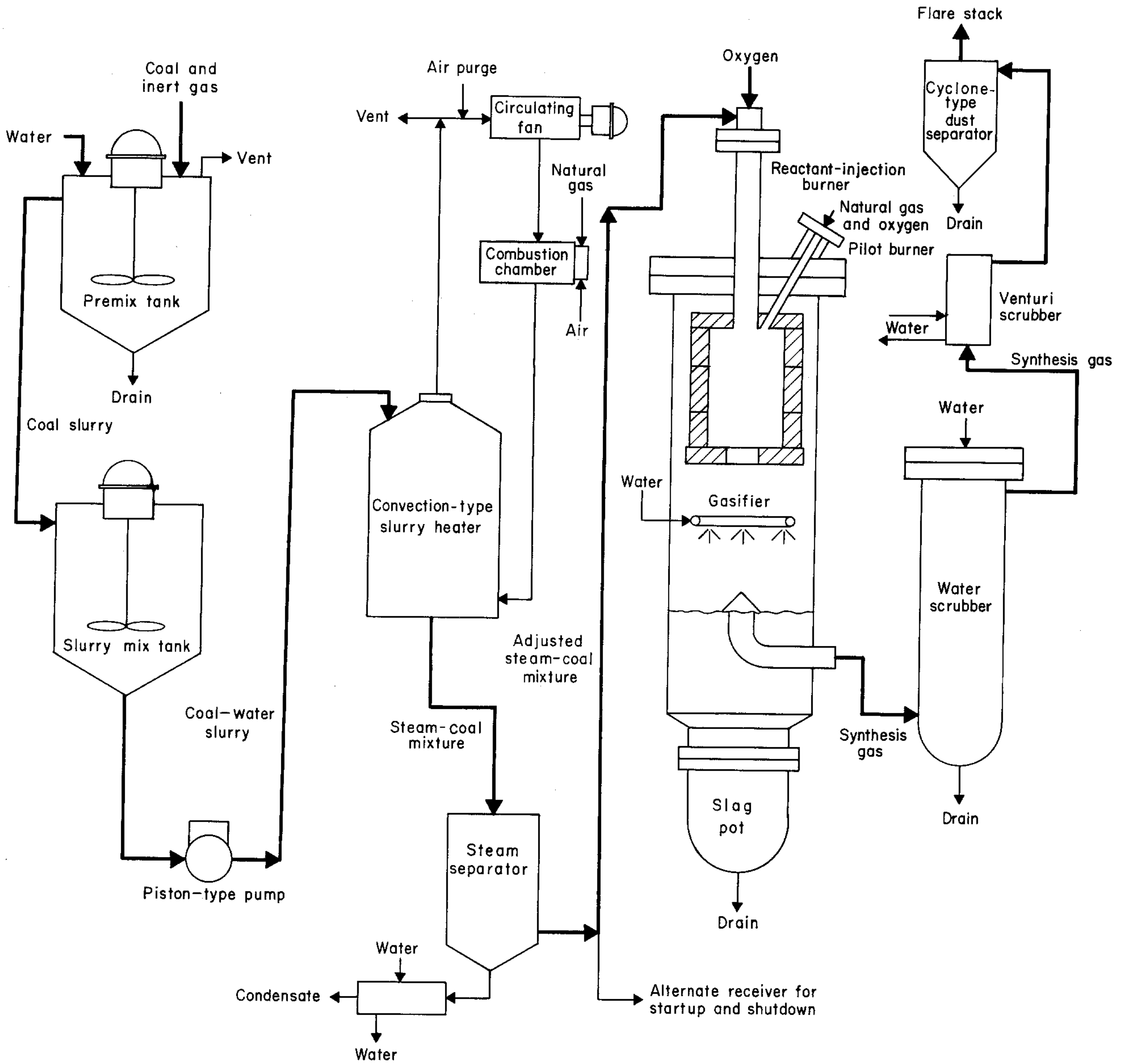

FIGURE 1. - Pressure-Gasification Pilot Plant Equipped for Slurry Feeding.

The integrated system is equipped with a safety system and with instruments that provide a complete and continuous record of process data, including flowrate, pressure, and concentrations of all reactants.

DESIGN CHANGES TO REACTANT-INJECTION BURNER

The reactant-injection burner through which the coal, oxygen, and steam are introduced to the gasifier had to be redesigned for use with the pilot plant equipped for slurry feeding. When coal was fed from a fluidized-coal feeder, the mixture of coal and inert gas passed through the central tube of the burner (fig. 2) and the oxygen and steam passed through an annular space

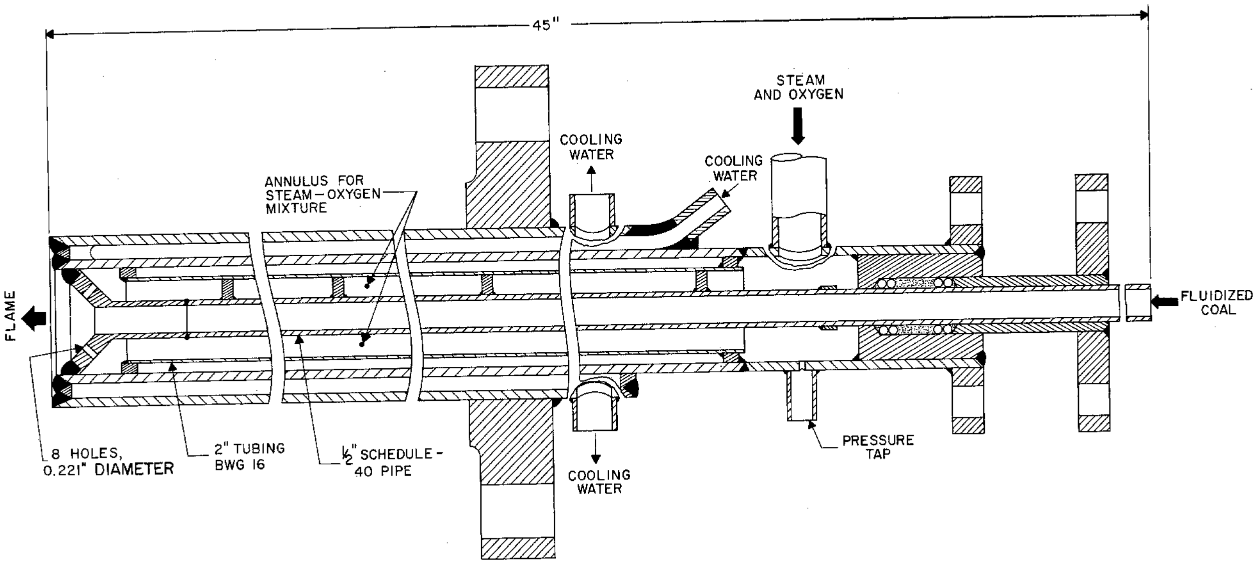

FIGURE 2. - Reactant-Injection Burner Used With Fluidized-Coal-Feeding System.

around this center tube and discharged at high velocity into the coal stream through ports in the burner nose. To obtain similar flame patterns with the slurry-feeding method, the central or coal tube was enlarged to accommodate the steam-coal mixture, and the discharge ports of the oxygen annulus were reduced in size (fig. 3). In other respects, the gasifier used in the slurry

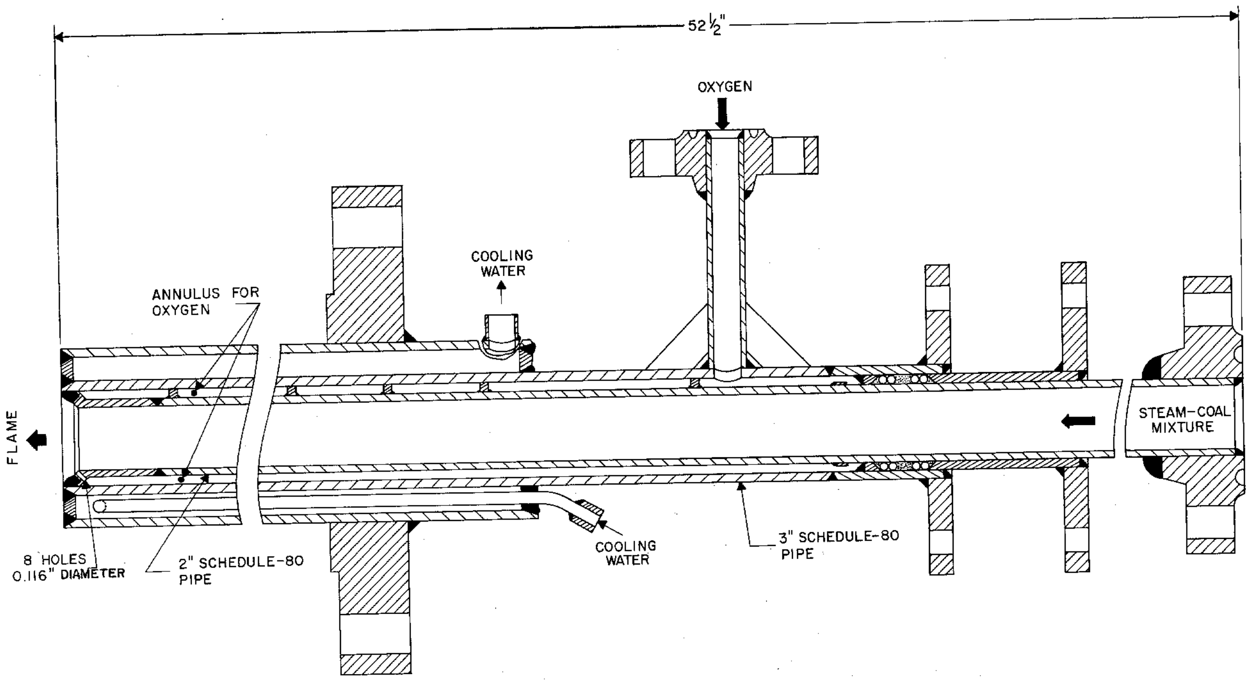

FIGURE 3. - Reactant-Injection Burner Used With Slurry-Feeding System.

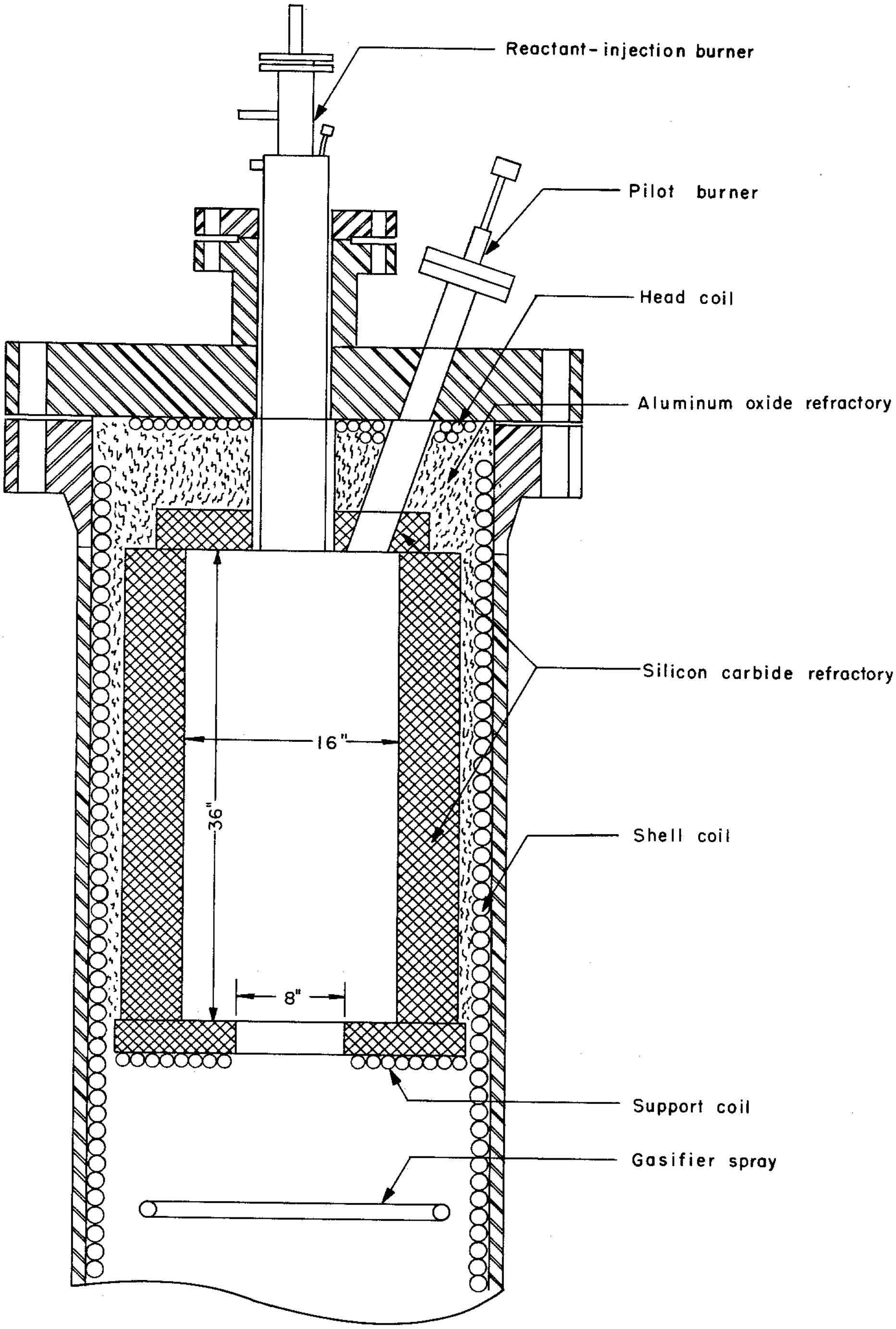

FIGURE 4. - Gasifier for Slurry Tests.

runs (fig. 4) was very similar to the gasifier used in previous gasification tests with a fluidized-coal-fed pilot plant (3).

EXPERIMENTAL PLAN

The primary purpose of operating the pilot plant equipped for slurry feed was to determine the operability of the gasifier with this feeding method and compare the results with those obtained when coal was fed with the fluidized-coal feeder. Therefore conditions of the fluidized-coal feeder runs were duplicated as nearly as possible. To this end, a factorial experiment was designed with the coal-feed rate at the only level possible with the slurry-feeding equipment, steam rate at two levels, oxygen rate at two levels, and operating pressure at two levels. All these variables could be duplicated except the steam-to-coal ratio. Steam-to-coal ratios in tests with the fluidized-coal feeder had been 0.3, 0.45 and 0.6 lb/lb, but in the initial tests with the slurry-fed plant the lowest ratios that could be achieved with the steam separator were 0.4 lb/lb. As a result, the factorial experiment was designed for steam-to-coal ratios of 0.45 and 0.7 lb/lb. Later, it was found that

0.45 steam-to-coal ratio also could not be consistently attained so the levels were again raised. Actual values ultimately were approximately 0.5 and 0.75 lb/lb. Runs at the lower level of oxygen-to-coal ratio also were not duplicated owing to slag deposition and other operating difficulties.

COAL GASIFIED

Coal gasified in these runs and in the previous gasification tests with the fluidized feeder was high-volatile A bituminous from the Sewickley bed, near Morgantown, W. Va. A typical analysis is moisture, 2 percent; ash, 13 percent; sulfur, 2 percent; H_2, 5 percent; C, 72 percent; O_2, 6 percent; and heating value, 13,000 Btu/lb of coal. More than 70 tons of this coal was gasified satisfactorily in the pilot plant equipped for slurry feeding. Lignite also has been gasified successfully with this pilot plant.

ACCURACY OF REACTANT AND PRODUCT GAS MEASUREMENT

The average estimated error in the measurement of the oxygen flowrate and the coal-feed rate was about 2 percent. Average error in the steam-feed rate was about 2 percent at the higher steam rates and 3 percent at the lower steam rates. These estimates are based on calculated results after the run, not on the planned values.

Because the product gas contained dust and moisture, its measurement was subject to somewhat larger errors. The standard deviation of the difference in flow as measured by orifice-type and positive-displacement-type meters was 2.7 percent.

Oxygen requirement, coal requirement, and percent of carbon gasified were subject to errors caused by inaccuracies in product-gas and coal-rate measurement.

DISCUSSION

Major dependent variables in the pressure-gasification process include (1) the fraction of carbon converted into gas; (2) the amount of oxygen required to produce 1,000 (M) standard cubic feet of carbon monoxide and hydrogen ($CO + H_2$); and (3) the amount of coal required to produce 1,000 std cu ft of $CO + H_2$. These variables influence both equipment design and process economy and serve as a basis of comparison of results from the two feeding methods. Results from the gasification of coal fed as a slurry are from actual operating data at specified conditions. Results from the pilot plant equipped for fluidized-coal feeding were calculated values for the same operating conditions and were determined from mathematical correlation of experimental data (3).

Comparison of Results

Table 1 shows gasification results for the two feeding methods, at 150 psig and 300 psig. The standard deviation of the tests in which the fluidized feeder was used is compared with the standard deviation of the differences between the two feeding methods.

TABLE 1. - Results from gasification of coal with the two feeding methods

Operating conditions			Performance data[1]								
			Carbon gasified, pct.			Coal requirement, lb/M std cu ft $CO + H_2$			Oxygen requirement, std cu ft/M std cu ft $CO + H_2$		
Coal rate, lb/hr[2]	Oxygen to coal ratio, std cu ft/lb	Steam to coal ratio, lb/lb	Slurry feeder[3]	Fluidized feeder	Diff.	Slurry feeder	Fluidized feeder	Diff.	Slurry feeder	Fluidized feeder	Diff.
Operating pressure, 150 psig											
771	10.97	0.754	88.0	91.4	-3.4	38.5	35.3	3.2	422	388	34
785	10.75	.729	92.2	90.3	1.9	34.8	35.5	-.7	373	382	-9
788	10.70	.452	92.8	91.5	1.3	35.5	36.4	-.9	379	390	-11
810	10.49	.527	86.5	92.2	-5.7	38.4	36.0	2.4	403	379	24
781	8.58	.740	74.9	78.4	-3.5	42.7	39.3	3.4	366	337	29
774	8.80	.487	78.8	80.7	-1.9	39.7	39.7	0	349	349	0
Average........................			85.5	87.4	-1.9	38.3	37.0	1.3	382	371	11
Operating pressure, 300 psig											
788	10.70	.712	94.3	91.6	2.7	33.6	35.2	-1.6	359	378	-19
775	10.85	.766	96.1	91.8	4.3	33.6	34.4	-.8	364	375	-11
789	10.74	.504	94.2	92.0	2.2	33.4	36.6	-3.2	358	391	-33
780	10.77	.491	94.8	91.4	3.4	34.9	36.5	-1.6	376	392	-16
794	8.53	.705	79.7	80.3	-.6	38.5	38.8	-.3	328	334	-6
778	8.75	.496	81.0	81.4	-.4	37.5	39.4	-1.9	328	346	-18
Average........................			90.0	88.1	1.9	35.3	36.8	-1.5	352	369	-17
Average of both pressures.......			87.8	87.8	0	36.8	36.9	-.1	367	370	-3.0
Standard deviation of differences....			-	-	3.0	-	-	2.0	-	-	20.3
Standard deviation of fluidized-coal feeder correlation................			-	-	3.3	-	-	1.5	-	-	14.5

[1]Values for slurry feeding are observed; values for fluidized-coal feeding are calculated. Reactants to gasifier in slurry runs carried about 75-150 more Btu/lb of coal as sensible heat than would have been the case in fluidized-coal feeder tests, introducing slight bias in favor of slurry method.
[2]Planned coal rate 800 lb/hr.
[3]Slurry contained 50 wt pct coal.

The differences in results are of the same magnitude as the standard deviations for the fluidized-coal feeder operations, indicating that the two feeding methods give similar results. When averaged over both pressures, there is little or no difference in the performance figures. At each of the two pressures, however, the difference may be significant; more favorable results are indicated at 150 psig with fluidized-coal feeder, whereas at 300 psig performance data are best for the slurry operations. These results may have been caused by difference in reactant injection and reactor geometry. Variations in oxygen-to-coal and steam-to-coal ratios had little effect.

Table 2 shows typical analyses of the gases produced during slurry-feeding and fluidized-coal feeding operations. Differences in composition of gas produced by the two feeding methods are probably due to the difference in steam-to-coal ratios. Gas composition correlations were not made for the fluidized-coal feeder runs; consequently, actual results and conditions are given instead of results computed at the conditions of the slurry experiments.

TABLE 2. - Typical analyses of gases produced in pilot plant equipped with the different coal-feeding methods

Coal-feeding method	Oxygen-to-coal ratio, std cu ft/lb	Steam-to-coal ratio, lb/lb	Composition of gas, vol pct		
			CO_2	H_2	CO
Operating pressure, 150 psig					
Fluidized-coal........	8.54	0.300	10.0	34.5	50.3
Do................	8.42	.600	14.0	37.0	44.4
Slurry................	8.80	.487	13.7	38.4	45.3
Do................	8.58	.740	17.0	39.6	39.9
Fluidized-coal........	10.55	.300	11.6	32.6	52.0
Do................	10.74	.600	14.9	35.4	46.5
Slurry................	10.60	.490	14.2	35.2	47.5
Do................	10.86	.742	15.4	35.7	43.6
Operating pressure, 300 psig					
Fluidized-coal........	8.48	0.300	9.2	35.0	49.9
Do................	8.55	.600	13.9	37.5	42.7
Slurry................	8.75	.496	11.5	38.4	46.8
Do................	8.53	.705	14.7	40.5	42.5
Fluidized-coal........	10.51	.300	11.3	32.0	51.5
Do................	10.77	.600	14.0	35.2	46.3
Slurry................	10.76	.498	12.6	36.0	48.6
Do................	10.78	.739	15.2	37.8	43.5

Similarity in results at the two pressures indicates that gasification of coal fed as a slurry produces virtually the same volume of synthesis gas per unit weight of carbon fed (table 1), and that the gas is of about the same composition as when the coal is fed in a fluidized state. Thus, assuming adequate reactant injection and reactor geometry, either feeding method can be based on the correlations available from gasification tests with the fluidized-coal feeder. (3, 4)

Heat Transfer in the Slurry Heater

Heat transfer to a coal-water or coal-steam mixture probably is not significantly different from heat transfer to water and steam except for the effects of coal particles on the wall of the coil in the slurry heater; the coal particles can have opposing effects on heat-transfer rate. One effect is that the solids may scour the inside of the coil, giving a higher heat-transfer rate. The opposite effect is that part of the coal ash may dissolve in the water and deposit downstream on the inside wall of the steaming section, or the particles may adhere to the wall of the superheating section, decreasing the heat-transfer rate. Adherence of the particles to the wall of the coil is possibly self-perpetuating because once they adhere, the particles insulate the metal wall from the heat-removing stream, causing hot spots that coke the coal and cause further build up of solids inside the pipe.

The slurry heater was designed primarily for operability and for use in the development of auxiliary equipment, and precise heat-transfer data were not obtained. Calculations based on certain approximations, however, showed that the heat-transfer coefficients for the process stream in the superheating section were lower than for pure steam. This suggests fouling of the inside wall of the tube in this section. Such fouling may have taken place during normal operation or on certain occasions when the coal flow was interrupted by plugging or other inadvertent shutdown.

Because the main resistance to heat transfer was in the gas film, the effect of the solids on the heat-transfer coefficients for the liquid and boiling sections could not be determined. The overall heat-transfer coefficients for these sections was about 15 Btu $hr^{-1} ft^2$ $°F^{-1}$ whereas the gas film coefficient, calculated (8), was 21 Btu $hr^{-1} ft^2$ $°F^{-1}$. Heat flux, Btu/hr-ft^2, for the individual sections was as follows: Preheat zone, 3,400 to 3,600; boiling zone, 2,500 to 2,800; and superheating zone, 1,500 to 1,900.

CONCLUSIONS

The slurry system offers a satisfactory means of feeding pulverized coal to a pressure gasifier. Performance data were identical to those obtained with fluidized-coal feeding. The chief problem with the slurry-feeding method is that only relatively low heat-transfer rates are practicable with forced-convection heaters. Heat-transfer rates are further reduced by fouling and scaling of the heater coil. With respect to coal-feed rates, the operable range of the slurry-feeding system was rather narrow owing to erosion of the heater coil at high velocities and settling of coal particles at low velocities. Also, the lower end of the desired steam-to-coal range could not be obtained. Thus, to develop an economical process, considerable additional work is required to obtain higher heat-transfer rates, pump slurries with higher concentrations of coal, and improve the separation of excess steam.

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