DEVELOPMENT OF AN ADVANCED FLUIDIZED BED COAL GASIFICATION PROCESS

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Introduction

Westinghouse Electric Corporation, under contract with the U.S. Department of Energy, is developing a coal gasification process. The process utilizes a variety of caking or non-caking coals to produce a clean combustible gas. The process was designed to supply a clean, low-Btu gas for electric power generation through a gas and steam turbine combined-cycle plant; however, the process can be used to produce a low-Btu or medium-Btu gas for either industrial fuel gas or synthesis gas. The Westinghouse coal gasification process can also be used for the cogeneration of steam, gas, and power.

The Westinghouse coal gasification system includes two fluidized bed reactors (see Figure 1). The first reactor, the devolatilizer, is used to devolatilize and decake coals as required. Coal is fed from lockhoppers to this reactor through a draft tube into a fluidized bed which operates at 1690 kPa (230 psig) and 870°C (1600°F). Devolatilized char circulates around the draft tube and dilutes the incoming coal, thus preventing the agglutination of coal particles as they pass through the plastic stage during heating. The two product streams from the devolatilizer are a combustible gas and char.

The second reactor, the gasifier, is used to gasify a wide range of feed materials which include coals as well as coal-derived chars. In the gasifier, the feed materials react with steam and air. The carbon-air combustion reaction provides the heat for the entire process and also causes the ash present in the char to agglomerate at about 1095°C (2000°F). These heavier, larger ash particles defluidize and are withdrawn from the bed. The steam-carbon gasification reaction is used to consume the remainder of the carbon not combusted by air. The gasification reaction moderates the reactor temperature and provides the combustible gas which is introduced into the devolatilizer as the fluidizing medium.

Since August 1972, a three-phased effort has been in progress at Westinghouse: bench scale and analytical work; pilot scale development on a 545 kg/hr (1200 lb/hr) Process Development Unit (PDU); and scale-up studies for a commercial scale plant. This paper considers only the work related to the PDU.

Mechanical completion of the PDU was achieved in September 1974. Precommissioning of utilities and process systems was completed by January 1975. The synthesis gas generators were commissioned in early 1975. Shakedown of the generators resulted in their redesign, which was followed by their successful commissioning in September 1975. Testing of the devolatilizer reactor began in October 1975. The tests, which were completed in August 1976, demonstrated the feasibility of the draft tube concept for this portion of the process. The results of these tests are reported elsewhere[1-6].

Testing of the gasifier reactor started in November 1976 and ended in December 1977. During this series of tests, successful operation of the gasifier was demonstrated with a wide variety of feedstocks which included chars produced early in the devolatilizer test series. Controlled tests of 100 to 150 hours were readily achieved during the gasifier tests. Also, the concept of agglomerating the ash in the feed material and the subsequent separation of the agglomerated ash from the fluidized char bed was demonstrated. This paper will discuss the conceptual design of the gasifier and operating results from some of the tests.

Westinghouse Gasifier Description

The gasifier includes two distinct sections (see Figure 1). During gasifier operation, the upper section contains a fluidized bed of coal-derived char particles. In this fluidized bed, the combustion and gasification reactions consume the carbon in the char particles. The agglomeration of the ash remaining in the particles also occurs within the upper section. The physical separation of the char and ash takes place in the lower section of the gasifier which is called the ash annulus.

The upper fluidized bed section of the gasifier is conceptually subdivided into a combustion/agglomeration region and a gasification region. The combustion/agglomeration region is located just above the air tube. The solid feed material (char or coal) which is pneumatically conveyed to the gasifier is injected directly into this region. In this region, char combusts with air, producing the heat necessary to: 1) promote agglomeration of ash rich particles, and 2) drive the carbon-steam gasification reaction. The gasification region of the fluidized bed is the reducing atmosphere region of fluidized bed where the carbon-steam gasification reaction occurs.

The gas flow rates into the upper section of the reactor control the fluid dynamics in this section. Circulation of solids within the fluidized bed is a function of the air tube volumetric flow which can be controlled by adjusting either air mass flow and/or air preheat temperature. The other control on solids circulation in the upper section is at the transition between the ash annulus and the larger diameter fluidized bed section of the gasifier. Gas flow (either steam or recycle gas) is injected into a grid at this transition to insure movement of material in this region.

Gas flow rates to the upper section of the gasifier also control the temperature of the fluidized bed. Air, steam, and to a lesser extent, cold recycle product gas, are used to control temperature. Fluidized bed temperatures can be easily controlled anywhere from 760°C (1400°F) to 1095°C (2000°F).

The lower section of the gasifier, or ash annulus, is where the separation of char and ash particles occur. Both a slugging bed and a fixed bed exist in the ash annulus. The slugging region contains a mixture of char and ash particles. As the char and ash are separated, the larger and heavier ash particles defluidize. The defluidized ash particles make up a moving fixed bed region which is withdrawn from the bottom of the ash annulus. The molar gas flow rate through the ash annulus controls the char/ash separation. Separation of char and ash occurs at relatively low velocities, typically less than 0.75 m/s (2.5 ft/s). The main advantage of the ash annulus is that it divorces the char/ash separation zone from the well-mixed fluid bed.

Test Results for the Westinghouse Gasifier

In 1977, the Westinghouse gasifier was operated on a wide variety of feed materials which included both chars and coals. The chars processed were from the following sources: 1) coke breeze from metallurgical coke production; 2) FMC char from the COED plant in Princeton, New Jersey; and 3) char produced in the earlier tests of the Westinghouse devolatilizer. In addition to the char processed, three types of coals were processed in the gasifier for short time periods. The coals included a non-caking, a mildly caking, and a highly caking coal.

Most of the tests run in 1977 were conducted using char materials which were derived from various coals. The predominate feedstock used in the early design evaluation and operability tests was coke breeze. The origin of the coke breeze is a Pittsburgh seam coal. The FMC chars processed in the gasifier were derived from two coal sources: a Kentucky coal and a Utah coal. Finally, the devolatilizer chars were derived from three coal sources: 1) an Indiana #7 seam; 2) a Pittsburgh seam; and 3) an Upper Freeport seam. Typical feed properties of the chars are given in Table I.

In addition to the chars processed, three coals were fed directly without pretreatment to the gasifier. The coals include a Wyoming sub-bituminous C coal, a mildly caking bituminous coal (Indiana #7), and a highly caking bituminous coal (Pittsburgh seam). Typical properties of the coals processed are given in Table I.

Successful operation of the gasifier was achieved on both chars and coals. The two different configurations used for char or coal feed are shown in Figure 2. Typical operating conditions, feed rates, and product gas and solids compositions for the various runs are given in Table II. Run times in excess of 6 days were achieved on char materials. The important concept of agglomerating the ash in the feed material and the subsequent separation of the agglomerated ash particles from the char bed was successfully demonstrated in the gasifier tests.

Typical particle size distributions for feed material, ash agglomerates, and fines which are carried over in the gasifier off-gas to the cyclone separator are shown in Figure 3. It can be seen that significant particle growth occurs due to ash agglomeration. Table II also shows that the bulk density of the ash product is greater than the feed or the fluidized bed char. Both the increase in particle size and density allows the agglomerated ash to be separated from char material. As for the fines carried over from the reactor, comparing their size distribution with that of the feed material has shown that most fines are simply entrained feed material. The fines are recycled to extinction by reinjection directly into the combustion zone.

During the gasifier tests, it was shown that the agglomerated ash particle size, shape, and physical appearance depends both on gasifier temperature and ash holdup or residence time in the reactor. Figure 5 shows the effect of gasifier temperature on the ash agglomerates. Agglomerates produced at higher reactor temperatures tend to be denser and more spherical. The effect of ash residence time is shown in Figure 6. By forcing the ash particles to remain in the reactor and pass repeatedly through the high temperature zone, the ash particles coalesce and grow in size.

In addition to studying ash agglomeration, the carbon-steam gasification reaction kinetics were analyzed for the PDU gasifier. Based on more detailed carbon-steam reaction kinetics studies being conducted on a bench scale unit at the Westinghouse Research Laboratories, the following equation was used to analyze the PDU data:

$$r_c = C \exp(-E/RT) \, (P_{H_2O})^n \qquad 1)$$

where r_c is the mass rate of carbon consumed per mass of carbon in the bed (min)-1,

C is an empirically determined constant,

E is the activation energy (218,200 j/g mole or 93,800 Btu/lb mole)[7],

P_{H_2O} is the inlet stream partial pressure, psia.

A plot of specific reaction rate ($r_c \exp(E/RT)$) as a function of steam partial pressure for various PDU test points is given in Figure 4. The regressed data for coke breeze gave a steam partial pressure exponent, n, of 0.72. This compares favorably with values of 0.66[7] and 0.63[8] reported elsewhere.

It is worth noting in Figure 4 that the relative reactivity of coke breeze is much less than other chars or coals processed in the gasifier. This apparently low reactivity is probably a result of the severe processing which occurs during coking. Coke is produced at temperatures of 1035-1095°C (1900-2000°F) and has a residence time at these temperatures of between 16-30 hours. The other char materials used during the gasifier tests were typically produced at temperatures between 705-870°C (1300-1600°F) with a residence time at these temperatures of between 1 to 2 hours.

In conclusion, the gasifier test series has been very successful. A wide variety of feed material which includes coal and coal-derived chars have been processed in the Westinghouse gasifier. Controlled operation of the gasifier has been achieved for continuous runs in excess of 6 days. Insights into ash agglomeration and subsequent separation from the char bed has been gained and laboratory scale experiments have proved helpful in analyzing the gasification kinetics for the PDU gasifier.

Acknowledgments

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Figure 1. Westinghouse Coal Gasification System

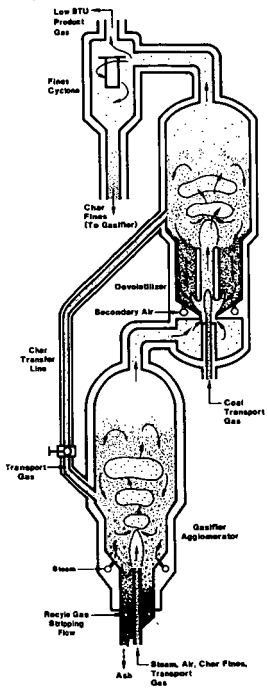

Figure 2. Westinghouse Gasifier Feed Configurations

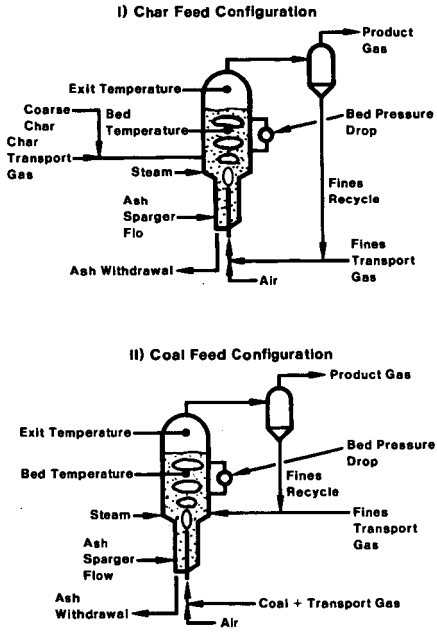

Table 1. Gasifier Feedstocks Properties

	Pittsburgh Coke Breeze (-8 mesh)	PDU Pittsburgh Char	PDU Indiana 7 Char	FMC-COED W. Ky. & Utah Chars	Pittsburgh Coal	Indiana 7 Coal	Wyoming Sub-C Coal
Proximate Analysis, %							
Carbon	83	76	78	75	47	46	36
Volatiles	5	3	3	10	45	40	47
Moisture	1	1	1	2	2	6	13
Ash	11	18	18	13	6	8	2
Size, Microns							
Coarse Feed	800	1,270	1,100	200	820	1,000	1,100
Fines Feed	200	230	210	200	200	200	200
Bulk Density							
kg/m^3	610	370	385	480	736	914	690
lb/ft^3	38	23	24	30	46	57	43
Caking Properties							
Free Swell Index	0	0	0	0	8	2	0
Gaiseler Plasticity	0	0	0	0	28,000	–	–
Heating Value J/g (Btu/lb)	–	–	–	–	32,300 (13,927)	27,900 (12,024)	24,400 (10,505)
Relative Reactivity*	1.0	2.5	9.9	11.8	–	–	12.0
Acid Insoluble Iron, % of Total	34	24	17	8	–	–	–

*Based on lab data for initial rate.

Table 2. Typical Gasifier Results

			Pittsburgh Coke Breeze		PDU Indiana Char		PDU Upper Freeport Char		FMC-COED Char (Utah)		Pittsburgh Coal		Indiana 7 Coal		Wyoming Sub-C Char	
System Pressure	kPa	(psia)	1690	(245)	1690	(245)	1690	(245)	1690	(245)	1690	(245)	1690	(245)	1690	(245)
Exit Gas Temperature	°C	(°F)	960	(1800)	950	(1740)	955	(1750)	955	(1750)	965	(1770)	935	(1720)	935	(1720)
Bed Temperature	°C	(°F)	1020	(1865)	985	(1805)	1000	(1830)	1000	(1835)	1000	(1835)	965	(1770)	960	(1760)
Coal or Char Feed Rate	kg/hr	(lb/hr)	200	(440)	225	(500)	325	(720)	370	(820)	385	(850)	410	(900)	455	(1000)
Char Fines Recycle Rate	kg/hr	(lb/hr)	200	(440)	110	(240)	160	(350)	205	(873)*	130	(285)	245	(540)	315	(700)
Air Rate	kg/hr	(lb/hr)	635	(1400)	575	(1265)	1020	(2250)	960	(2120)	1495	(3300)	1615	(3560)	1290	(2840)
Steam Rate	kg/hr	(lb/hr)	70	(155)	35	(80)	90	(200)	135	(300)	110	(245)	75	(170)	0	(0)
Recycled Product Gas	kg/hr	(lb/hr)	475	(1050)	500	(1105)	610	(1340)	410	(900)	655	(1440)	560	(1230)	460	(1060)
Coal or Char Transport Gas Rate	kg/hr	(lb/hr)	290	(645)	345	(765)	320	(700)	340	(750)	265	(590)	345	(765)	190	(415)
Char Fines Transport Gas Rate	kg/hr	(lb/hr)	375	(830)**	375	(825)**	370	(820)**	350	(775)**	175	(385)	210	(465)	315	(690)**
Ash Withdrawal Rate	kg/hr	(lb/hr)	75	(160)	45	(95)	55	(120)	45	(100)	25	(55)	35	(90)	10	(25)
Average Bed Pressure Drop	Pa/m	(psi/ft)	420	(0.20)	210	(0.10)	210	(0.10)	315	(0.15)	210	(0.10)	210	(0.10)	315	(0.15)
Average Bed Height	m	(ft)	7.6	(25)	7.0	(23)	7.6	(25)	7.0	(23)	8.0	(26)	7.6	(25)	7.6	(25)
Feedboard Velocity	cm/sec	(ft/sec)	60	(1.9)	5.0	(1.7)	8.0	(2.7)	7.5	(2.5)	9.0	(3.0)	9.5	(3.1)	7.6	(2.4)
Ash Annulus Gas Velocity	cm/sec	(ft/sec)	3.5	(1.2)	3.0	(1.0)	4.5	(1.4)	3.0	(1.0)	5.0	(1.6)	4.0	(1.3)	3.5	(1.2)
Bed Ash Content	wt %		20-25		30-35		30-35		30-45		15-25		15-25		15-25	
Ash Withdrawal Ash Content	wt %		45-65		60-70		50-65		40-60		30-45		30-45		30-55	
Bed Bulk Density	kg/m^3	(lb/ft^3)	560	(35)	400	(25)	320	(20)	480	(30)	400	(25)	320	(20)	320	(20)
Ash Withdrawal Bulk Density	kg/m^3	(lb/ft^3)	640	(40)	480	(30)	560	(35)	640	(40)	560	(35)	560	(35)	640	(40)
Product Gas Composition																
CH_4	mol %		0		0		0		0		2.0		0.6		1.1	
CO	mol %		9.8		15.0		13.7		18.4		14.2		10.3		10.9	
H_2	mol %		2.6		2.9		3.3		7.2		10.3		6.0		10.3	
CO_2	mol %		22.1		18.9		21.2		19.3		12.6		21.2		10.9	
N_2	mol %		63.3		62.4		56.6		53.2		55.2		53.4		52.1	
H_2O	mol %		2.3		0.9		5.3		1.9		5.7		8.2		3.9	

*No recycled fines. This feed is FMC char.
**Transport gas for this case is air.

Figure 3. Typical Size Distributions of Gasifier Feeds and Products

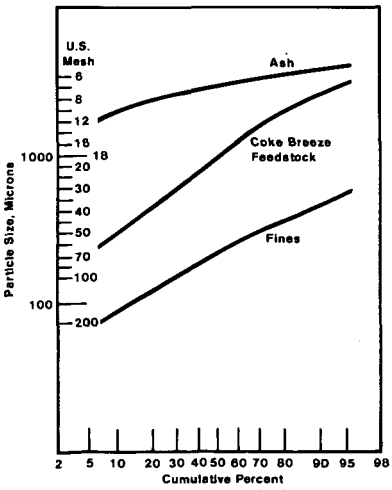

Figure 4. Specific Reaction Rate as a Function of Steam Partial Pressures for Various Gasifier Feed Material

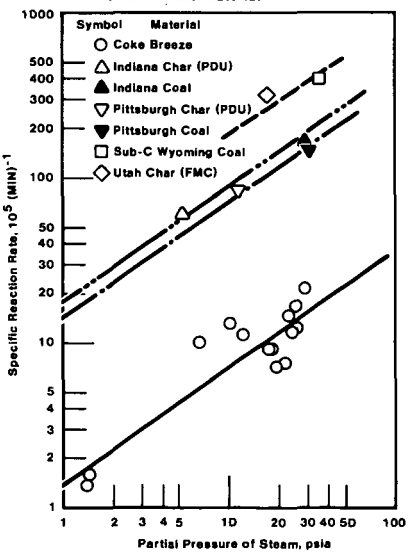

Figure 5. The Effect of Temperature on Ash Agglomerates

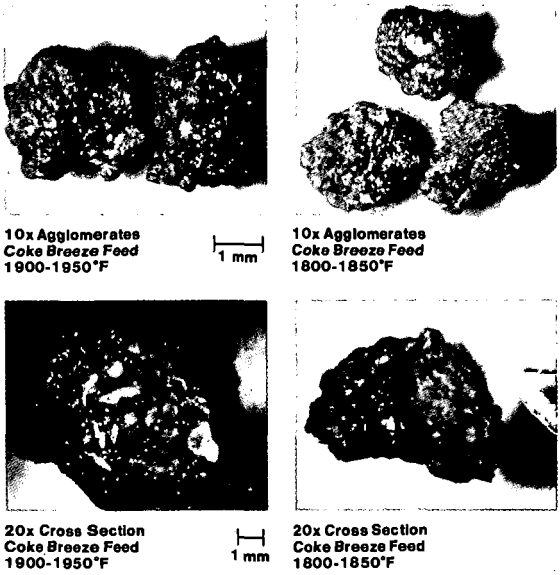
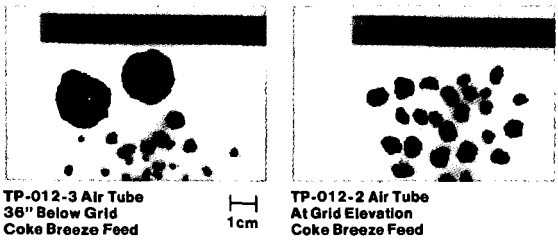
Figure 6. The Effect of Increased Holdup in the Reactor on Ash Agglomerates