Journal of Analytical and Applied Pyrolysis 120 (2016) 474–483

Contents lists available at ScienceDirect

Journal of Analytical and Applied Pyrolysis

journal homepage: www.elsevier.com/locate/jaap

Coal particle chemical transformational behaviour after thermochemical conversion in a fixed bed

Frederik H. Conradie*, John R. Bunt, Frans B. Waanders

Coal Research Group, Unit for Energy and Technology Systems, School of Chemical and Minerals Engineering, North-West University, Potchefstroom, 2520, South Africa

ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 20 June 2016
Accepted 25 June 2016
Available online 27 June 2016

Keywords:
Coal
Thermochemical conversion
Fixed bed
Combustion
Gasification

ABSTRACT

This paper examines the chemical transformational behaviour that coal particles undergo during conversion in deep packed beds, typically found in industrial combustion and gasification operations. Experiments were performed in a transient overfeed packed bed laboratory scale reactor fed with 4, 6 and 8 mm coal particles. The reactor was operated at atmospheric pressure and is 1.2 m in length and has an inner diameter of 104 mm. The coal loading was 3.3 kg and resulted in a bed height of 520 mm. A typical inertinite-rich South African seam four coal from the Highveld region was used as fuel in the reactor. The transient temperature profile in the descending bed as well as the exit gas composition is presented here. A post experiment dissection of the bed contents along with full chemical characterisation was undertaken. Care was taken to ensure that the dissection method, specifically designed for minimal disturbance to the fixed bed structure, could provide an accurate representation of the characteristic reaction zones. The residual volatile matter and the overlap in the reduction and pyrolysis zones were insensitive to particle size variation and mainly determined by the maximum temperature in each zone. Where it was found useful, these reaction zone profiles are compared to industrial and pilot operations. The reaction front velocity and heating rates that particles experience in the different reaction zones was obtained and showed significant variation during the transient start-up stage, but are remarkably comparable once the stable reaction front is formed. This current mode of operation represents fixed bed combustion and gasification operations particularly during the transient start-up stages.

1. Introduction

Fixed bed combustion and gasification of coal is used extensively for synthesis gas generation in the coal to liquids process in South Africa. Little research has been carried out on discrete coal particles as it undergoes chemical and physical change inside packed bed combustion and gasification operations. Normative research relating to the characterisation of the operational behaviour during solid fuels combustion and gasification have widespread significance in fossil as well as bio-fuels thermochemical applications. However, sampling solids from online operational coal gasifiers has considerable technical difficulties and economic implications and to date no reported studies are published. There is however, much that could be learned from quenching an entire gasifier and subsequently characterising the bed contents as was shown in recent studies [1–11]. This paper presents a bed dissection method, on laboratory scale, with minimal disturbance to the bed structure and the subsequent chemical characterisation of coal, char and ash particles from the bed length. The aim was to partially convert the bed contents, and in so doing it is possible to study the transformational behaviour of particles along the bed length as the reaction front propagates through the stagnant bed of particles. Industrial and pilot scale representativeness of this reactor and the bed characterisation technique was recently established [12].

Much of the recent and older literature account for laboratory packed bed coal combustion and gasification in either overfeed (continuous feed of solid fuel at the top) or a transient mode (where solid fuel is loaded batch wise) [13–25]. In general, fundamental mass transfer theories were developed and tested, based on temperature profile and gas composition from sampling probes inserted into the fuel bed. It is commonly considered that the validation of modern numerical modelling of reacting fuel beds like these rely on detailed measurements of bed temperature, concentration profiles, reacting rates, and fuel properties: particle size, sphericity, density, bed void fraction, and ultimate analysis [25]. However, detailed and comprehensive experimental data sets are

* Corresponding author.
E-mail address: frikkie.conradie@nwu.ac.za (F.H. Conradie).

http://dx.doi.org/10.1016/j.jaap.2016.06.020
0165-2370/

Table 1
Key reactor operational data.

	Unit	SM4_8mm_1	SM4_8mm_2	SM4_8mm_3	SM4_6mm_1	SM4_4mm_1
Particle Size	(mm)	+6.7−9.5	+6.7−9.6	+6.7−9.7	+4.75−6.7	+3.35−4.75
Sauter Mean Diameter	(mm)	8.1	8.1	8.1	5.7	4.1
Bed height to diameter ratio	(−)	64	64	64	91	128
Diameter to particle ratio	(−)	13	13	13	18	26
Bulk Density	(kg/m^3)	742	748	745	772	764
Apparent Particle Density	(kg/m^3)	1699	1699	1699	1826	1709
Particle Density	(kg/m^3)	1445	1445	1445	1393	1305
Bed Void	(−)	0.49	0.48	0.48	0.45	0.42
Particle Porosity	(−)	0.15	0.15	0.15	0.24	0.24
Sphericity	(−)	0.71	0.71	0.71	0.73	0.68
Air flux	(kg/m^2 h)	217	217	217	217	217
Height Bed Start	(mm)	520	520	520	520	520
Height Bed End	(mm)	315	313	320	314	312
Bed Velocity	(mm/min)	0.98	0.99	0.95	0.98	0.99
CO Molar Selectivity	(−)	0.72	0.70	0.70	0.73	0.73
H2/CO Molar Ratio	(−)	0.85	0.85	0.87	0.89	0.92
Mass Total In	(g)	3280	3305	3290	3412	3373
Mass Total Out	(g)	1702	1793	1634	1708	1705
Sectional Mass Out T_1 Top	(g)	88	79	96	85	78
Sectional Mass Out T2	(g)	284	269	265	280	301
Sectional Mass Out T3	(g)	374	391	384	384	386
Sectional Mass Out T4	(g)	350	385	363	368	374
Sectional Mass Out T5	(g)	286	318	264	285	273
Sectional Mass Out T6 Bottom	(g)	175	219	119	171	172
Consumption:						
Coal	(kg/h)	0.45	0.43	0.47	0.49	0.48
Oxygen	(Nm^3/kg Coal)	0.671	0.701	0.640	0.622	0.635
Crude Gas Yield	(Nm^3/kg Coal)	4.7	4.9	4.4	4.5	4.2
Specific throughput						
Coal	(kg Coal/m^2 h)	53.1	50.8	55.7	57.3	56.1
Oxygen	(Nm^3 O2/m^2 h)	35.6	35.6	35.6	35.6	35.6
Crude Gas	(Nm^3 Gas/m^2 h)	117	114	113	123	102
Gas Composition (dry basis)						
H2	(mol%)	16.7	16.4	16.6	18.4	16.6
CO	(mol%)	22.0	21.1	20.7	21.8	19.4
CO2	(mol%)	7.98	8.59	8.47	7.79	7.33
CH4	(mol%)	0.0031	0.0033	0.0034	0.0034	0.0032
O2	(mol%)	0.019	0.023	0.023	0.020	0.039
N2	(mol%)	53.3	53.9	54.2	52.0	56.6

not readily available [26]. In overfeed operations, where the reaction front moves up in the reactor, a great deal of research was conducted on uniform fuel particle sizes and recently, Hallett et al. [27] validated the use of the Sauter mean diameter when modelling reacting fuel beds where the particle size distribution is wide. Hobbs et al. [26], however noted a lack in experimental data in the form of bed dissection results especially in the millimetre size range, also citing that most modelling efforts attempting to explain the complex gasification phenomena is validated based on exit gas composition and temperature profiles measured on laboratory scale reactors.

To simulate fixed bed combustion and gasification as in the case of Sasol's coal gasification, the transient overfeed configuration with a reacting front that moves upward through the packed bed operating on coal has proven useful [28,29]. Fundamental to previous work in the transient mode of operation was the differentiation between the diffusional controlled combustion zone and the reaction controlled gasification zone [19]. The most important properties that will adversely affect the reaction process are ash content, volatile matter, moisture, swelling, grading, grit carryover, temperature and quality of feed gas as well as rank of coal [30]. Hydrodynamic instabilities could be brought about by channelling effects, in turn brought about by wide particle size distributions and high gas loads [31]. It becomes clear when the current available literature is examined that the chemical transformational behaviour of coal particles characterised after thermal conversion in a fixed bed was not a particular focus. The most distinctive feature of previous researched reactors were also not the capability of carefully removing bed contents without disturbing the bed structure especially when investigating deep packed beds.

The objective of this paper is to determine through transient overfeed combustion and gasification experiments, and with post bed dissection chemical analysis the degree of reaction zone development of different particle size packings under constant gas flow conditions. To accomplish these objectives the measurement of the transient exit gas composition and temperature profile is used to establish the start-up behaviour and stable combustion front formation during coal combustion. The detailed axial sampling methodology and subsequent proximate and ultimate analysis of the bed contents are expected to deliver the characteristic reaction zone data. The laboratory scale reactor offers an advantage during sampling; especially since sampling industrial scale gasifiers requires processing of 100 t [1] of sample. The current transient mode of operation, where no additional solids are fed to the reactor, represents combustors and gasifiers particularly during start-up procedures.

2. Experimental

The reactor used in this study was a laboratory scale fixed bed reactor and has been described in detail elsewhere [12]. Briefly, the inner diameter is 104 mm and the length is 1.2 m, thermocouples are inserted from the top and bottom of the reactor and fixed in position to record the transient temperature profile axially