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Application of multiple swirl burners in pilot-scale entrained bed gasifier for short residence time

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HIGHLIGHTS

- A new concept of entrained bed coal gasifier with a short residence time was verified at 3 t/d-scale.
- Cold gas efficiency above 72% was achieved with CO and H_2 of 71.8% in the syngas.
- Overall carbon conversion for all tests was higher than 98% with 2 s of residence time.

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ABSTRACT

The design concept of an entrained bed gasifier is presented. A 3 t/d-scale gasification system was constructed based on this concept. Syngas residence time in the gasifier was set to 2 s, relatively shorter than that of commercial gasifiers, to verify the possibility of complete gasification reaction within a short residence time. A series of gasification tests were conducted under high pressures and high temperatures. Performance data of the gasification experiment using multiple swirl burners showed that the carbon conversion and cold gas efficiency were higher than 98% and 72%, respectively. This high performance seemed to be attributable to the effects of rigorous mixing of oxygen and pulverized coal by the strong swirl flow and the relatively uniform oxygen concentration by the swirling plug flow. Syngas composition of the experimental result well agreed with that of the equilibrium state. This project demonstrated the feasibility of complete gasification reaction within a short residence time for low-rank coal of high reactivity.

1. Introduction

Recently, the reduction of fossil fuel utilization and the acquisition of new and economical renewable energy sources have been considered effective in reducing the green house gas, especially carbon dioxide emission. The increase in the consumption of alternative energy sources, such as natural gas, will lead to the reduction in the consumption of coal, a major source of CO_2 emission; however, coal consumption will still remain considerable for several decades, because of coal abundance and the wide distribution of coal reserves in the world. Therefore, the effective and clean use of coal is crucial, and one of the enabling technologies is coal gasification. Coal gasification is considered to be the next-generation clean coal technology because of its high efficiency, high cleanness and easy CO_2 capture capability. So, many coal gasification technologies have been developed and are still being developed by companies such as Shell, GE Energy, Uhde, Phillips 66 and so onto apply the IGCC (Integrated Gasification Combined Cycle), CTL (Coal to Liquid), SNG (Substitute Natural Gas) and to produce various chemicals such as methanol and DME (Di-Methyl Ether) [1–4].

In general, coal gasification is a fairly expensive technology, but the cost issue can be overcome by considering CCS (Carbon Capture and Storage), whose capital and operating costs in the coal gasification system are fairly lower than those in other coal utilization systems. Furthermore, one of the very expensive equipment in a coal gasification system is the coal gasifier. So, the simultaneous reduction of the capital cost and the increase of the efficiency of the coal gasifier are essential to realize an economical coal gasification system. These requirements may be met by the compact gasifier of PWR (Pratt Whitney Rocketdyne). They have been trying to achieve complete gasification reaction within 0.5 s at high efficiency to reduce the capital cost of the gasification system. They adopted an ultra dense coal transport and rapid mixing multi-nozzles, which had been used in rocket engine applications [5,6]. The volume of PWR's 18 t/d-scale pilot gasifier has been reported to be

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1/10 of that used in commercial technologies [6]. The residence time of syngas and coal particles in the entrained flow gasifier is on the order of seconds to tens of seconds [7–10]. The design point of residence time for complete reaction of commercial gasifiers have never been revealed officially but can be presumed to be about 5–6 s from PWR's data [6] or reverse engineering calculations based on the approximate dimensions of commercial gasifiers (private communications).

Motivated by PWR's technology, we investigate gasification characteristics under very short gas residence time to ultimately develop a low cost gasifier. On the other hand, recent interests are focused on the utilization of low rank coal such as subbituminous coal and lignite due to the high coal price, which is closely associated with the high oil price. So, the study of the gasification characteristics of low rank coal of higher reactivity is very interesting and valuable, scientifically, technologically and economically.

Therefore, numerical [11–13] and kinetic studies [14–16] have been carried out on coal gasification; however, only a few gasification experiments of considerable scale have been reported [17] because of the difficulty in carrying out gasification experiments under high temperatures and high pressures. So, in this study, a series of gasification tests with Inner-Mongolia lignite was performed by using a dry feeding, 3 t/d-scale entrained bed gasifier under a pressurized condition at a high temperature. Syngas residence time was set to $\sim$2 s as a first step to check the possibility of complete gasification reaction within a short residence time. The design concept of the entrained bed gasifier is presented. The gasification performance such as carbon conversion and cold gas efficiency were examined.

2. Conceptual design of entrained bed gasifier

2.1. Calculation of syngas composition

Gasification reaction is fairly complex and the major components of syngas products are CO, H_2, CO_2, H_2O and inert N_2 for entrained bed gasification and some CH_4 when gasification temperature is relatively low such as in fluidized or fixed bed gasification. Chemical equilibrium assumption is considered valid for the calculation of the gas composition of entrained bed gasification operated under a high temperature, e.g., 1300–1600 °C, so it is widely applied to obtain or predict the design concept of commercial gasifiers [18–20]. First, we developed a gas composition calculation program based on the elemental mass balance of C, H, O, N and S, and the chemical equilibrium constant of the water gas shift reaction under the chemical equilibrium assumption. Minor but non-negligible components such as H_2S and COS were assumed to be produced at a prescribed ratio from the given sulfur, e.g., 90%:10% in this study. Production of tiny amount of gases such as NH_3, HCl and so on was neglected to simplify the calculation. Such relations are well represented in Eq. (1) for the mass balance of each chemical element and in the Eq. (2) for the chemical equilibrium of the water gas shift reaction, consequently constituting a closed set of chemical components of entrained-bed gasification.

$$n_{C_{i,in}} = n_{C_{i,out}} \text{ for } C_i = \mathrm{C, H, O, N, S} \tag{1}$$

$$\frac{[n_{CO_2}]\cdot[n_{H_2}]}{[n_{CO}]\cdot[n_{H_2O}]} = f(T) \tag{2}$$

The summation of the atomic mole numbers of all elements of the product gases is shown on the right hand side of Eq. (1) and that of the input material which originated from the coal and oxidant is shown on the left hand side. The equilibrium constant of the water gas shift reaction is assumed to be a function of only temperature, which is reasonable for high temperature entrained bed gasification and supported by the reference [21] as Eq. (3), with Kelvin temperature, or this constant can be obtained from a set of Gibb's energy minimization calculations. The equilibrium constant formula of methanation reaction as a function of temperature and pressure should be added when CH_4 formation is considerable.

$$f(T) = \exp\left(-3.689 + \frac{4019}{T}\right) \tag{3}$$

Table 1 shows the comparison between calculation results of this study and those of well known commercial softwares, ASPEN Plus and HSC Chemistry.

2.2. Residence time calculation and reactor sizing

One of the reasons for obtaining gas composition is to calculate the reactor volume, which is a crucial parameter of gasifier design. Reactor volume can be determined by a very simple relation, Eq. (4), based on calculated actual volume flow rate and given residence time, 2 s in this study, where $\dot{Q}_a$ is the actual volume flow rate at a given operating temperature and pressure. Finally, our gasifier was designed such that the diameter and height of the gasifier reaction zone were 200 mm and 1500 mm, respectively, in which the residence time of the syngas was about 2 s for 3 t/d capacity under 2.0 MPa and 1400 °C with our design coal.

$$\tau = V_{\text{gasifier}}/\dot{Q}_a \tag{4}$$

2.3. Operating condition by energy balance

Calculation of gas composition by the above mentioned procedure is merely a mass balance calculation based on assumed oxidants (O_2 and H_2O) to coal ratios at a given operating temperature. Whether the given oxidants to coal ratios are reasonable or not should be checked based on the energy balance of the gasifier, including the sensible heat of syngas and various heat losses. Energy balance can be checked by the following equation, Eq. (5). If the given oxidants (oxygen and steam), to coal ratios satisfy Eq. (5), they can be considered valid design conditions of the entrained bed gasifier [18]. Otherwise, iterative calculations with new values of oxidants to coal ratios should be done until the result satisfies Eq. (5) and the reactor volume should be re-calculated based on new gas composition and volume flow rate. In Eq. (5), $Q_{\text{aux.fuel}}$ is the energy supplied by the auxiliary fuel, CH_4 via the slag tap burner in this study, and $Q_{\text{uncountable heat loss}}$ denotes the various heat losses, which are difficult to know or calculate, one of which is the radiation heat transfer from hot syngas to quench water. In this study, various uncountable heat losses were set to 2% in our iterative calculations to obtain the operating condition.

According to our series of energy balance calculations using various O_2/coal and H_2O/coal ratios, only the O_2 supply without steam gave a better operating condition than that with steam for most low rank coals, including our test coal, Inner-Mongolia lignite.

$$Q_{\text{coal}} + Q_{\text{aux.fuel}} = Q_{\text{CO+H}_2} + Q_{\text{syngas sensible heat}} + Q_{\text{wall loss}} + Q_{\text{unburned-carbon loss}} + Q_{\text{ash and slag loss}} + Q_{\text{uncountable heat loss}} \tag{5}$$

2.4. Top feeding compact gasifier with multiple swirl burners

The main purpose of this study was to verify the possibility of complete gasification under short residence time. In general, turbulent mixing is predominant rather than Arrhenius type chemical kinetics because a heterogeneous particle reaction is mainly controlled by the diffusion of an oxidant to the particle surface under a high temperature environment [22]. So, the design concept of the