Fuel 164 (2016) 172–179

Contents lists available at ScienceDirect

Fuel

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

Comparative study of coal plasma gasification: Simulation and experiment

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HIGHLIGHTS

- Plasma steam and air gasification of high ash bituminous coal is fulfilled.
- Availability of the high ash power coal use for high-calorific syngas production is shown.
- High integral indexes of the gasification processes were achieved.
- Syngas from the coal at steam gasification is higher quality.
- The numerical and experimental results comparison showed their satisfied agreement.

ARTICLE INFO

Article history:
Received 18 August 2014
Received in revised form 29 September 2015
Accepted 30 September 2015
Available online 11 October 2015

Keywords:
Coal
Plasma
Arc-plasma reactor
Gasification
Syngas

ABSTRACT

Results of complex experimental and numerical investigation of coal plasma gasification in steam and air are presented. To analyse numerically the universal thermodynamic calculation code TERRA was used. The data base of it contains thermodynamic properties for 3500 individual components in temperature interval from 300 to 6000 K. Experiments were fulfilled at an original installation for coal plasma gasification. Nominal electric power of the plasma gasifier is 100 kW and sum consumption of the reagents is up to 20 kg/h. High integral indexes of the gasification processes were achieved. The numerical and experimental results comparison showed their satisfied agreement.

1. Introduction

The increasing interest in environmental problems has recently led to the development of clean coal technologies, designed to enhance both the efficiency and environmental acceptability of coal extraction, preparation and use, in particular for power generation [1–3]. Among clean coal technologies, gasification [4], and especially plasma gasification [1,2] is particularly interesting since it allows both power generation (in Integrated Gasification Combined Cycles power plants, IGCC) and environmental friendly fuel production, with a particular reference to hydrogen [3,5].

This paper describes numerical and experimental investigation of coal air and water steam gasification in arc-plasma reactor. First air–coal and steam–coal mixture gasification was investigated numerically with the aid of a thermodynamic program TERRA [6]. Then these mixtures were investigated experimentally and the numerical results were validated against operational data got in the experiments. Kazakhstan 'Kuuchekinski' bituminous coal 40% of ash content was used for the investigation. Special plasma reactor for coal gasification allows performing processes thermo impact on coal for getting syngas ($CO + H_2$) from organic part of a low-rank coal free from nitrogen and sulfur oxides. The experimental installation is intended for work in range of electric power 30–100 kW, mass averaged temperature 1800–4000 K, coal dust consumption 2–10 kg/h and gas-oxidant flow 0.5–10 kg/h. High calorific clean syngas was produced from the coal.

2. Numerical simulation

Software package TERRA [6] was used for thermodynamic analysis of the coal plasma gasification process. It was created for high-temperature processes computations and in contrast to traditional thermochemical methods of equilibrium computation

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http://dx.doi.org/10.1016/j.fuel.2015.09.095
0016-2361/

that use the Gibbs energy, equilibrium constants and Guldberg and Vaage law of acting mass, TERRA is based on the principle of maximizing entropy for isolated thermodynamic systems in equilibrium. TERRA has its own database of thermochemical properties for more than 3500 chemical agents over a temperature range of 300–6000 K.

The process of Kuuchekinski (Kazakhstan) high-ash bituminous coal (Table 1) gasification was calculated in temperature interval from 400 to 4000 K at pressure 0.1 MPa. The temperature is suggested to be kept at the expense of external heat source, which is an arc in a plasma-chemical reactor. Note despite of the fact that plasma reactor is not isolated system and there is an exchange of energy and substance with external medium, thermodynamic modeling of coal gasification inside the plasma-chemical reactors is possible. First, at preparation of heat and material balances of the plasma gasifier actual heat losses are taken into account, and in this case mean temperature in the plasma reactor corresponds to the temperature of thermodynamically isolated system. Second, residence time in plasma reactor (0.5–0.7 s) is enough for thermodynamic equilibration in the system at high temperature of the process [6]. Third, the plasma-chemical reactor is flow-type and quasi-stationary process of gasification is provided.

The first variant of calculations was performed for the system of 100 kg of coal +127.5 kg of air and the second one −100 kg of coal +62.75 kg of water steam.

The aim was to determine integral indexes of the coal gasification, which are carbon gasification degree, specific power consumptions, equilibrium compound of the products of coal gasification.

Figs. 1 and 2 present temperature dependence of the products composition in a temperature interval of 400–4000 K. The gas phase mainly consists of synthesis gas ($CO + H_2$) thermodynamically steady to co-products of coal gasification process (Fig. 1a). Its concentration reaches the maximum 54.79% at $T = 1800$ K. Concentration of oxidants (H_2O and CO_2) decreases to zero at temperature increase to 1400 K. Nitrogenated substances are presented mainly in form of molecular nitrogen (N_2). Nitrogen concentration decreases with temperature increase because of syngas appearance in gas phase and increase its concentration as well as due to the coal mineral mass destruction and mineral components from coal appearance in gas phase at temperatures over 1600 K (Fig. 1b). Carbon monoxide (CO) concentration reaches the maximal value (35.74%) at temperature 1800 K. Concentration of molecular hydrogen (H_2) in temperature interval from 400 to 1600 K increases promptly and reaches the maximum of 20.3% at $T = 1600$ K. At the temperature over 1600 K H_2 concentration decreases because of its dissociation, and in gas phase atomic hydrogen (H) is appeared. Concentration of H increases with the temperature and reaches 23.34% at 4000 K. At the temperature over 1600 K in gas phase there is hydrogen cyanide (HCN) and cyanide (CN), total concentration of which reaches 2% at temperature 2800 K.

Mineral components of the coal sublimate into gas phase (Fig. 1b) with the process temperature increase. They are mainly aluminum (Al) and silicon (Si). In gas phase they appear at the temperature over 2200 K. Their sum concentration reaches 5.5% at 4000 K. Total concentration of all the other species of mineral mass in gas phase reaches 1%. Due to ballast nitrogen concentrations of highly volatile potassium (K) and natrium (Na) are out of the scale.

Table 1
The bituminous coal proximate and ultimate analyses, weight%.

Proximate analysis		Ultimate analysis			
Moisture (total)	5.8	Hydrogen	3.05	SiO_2	23.09
Volatile matter	26.0	Carbon	48.86	Al_2O_3	13.8
Fixed carbon (by difference)	28.2	Sulfur	0.73	Fe_2O_3	2.15
Ash	40	Nitrogen	0.8	CaO	0.34
Total	100.0	Oxygen	6.56	MgO	0.31
Higher heating value (kJ/kg)	16632.0	Ash	40.0	K_2O	0.16
		Total	100.0	Na_2O	0.15

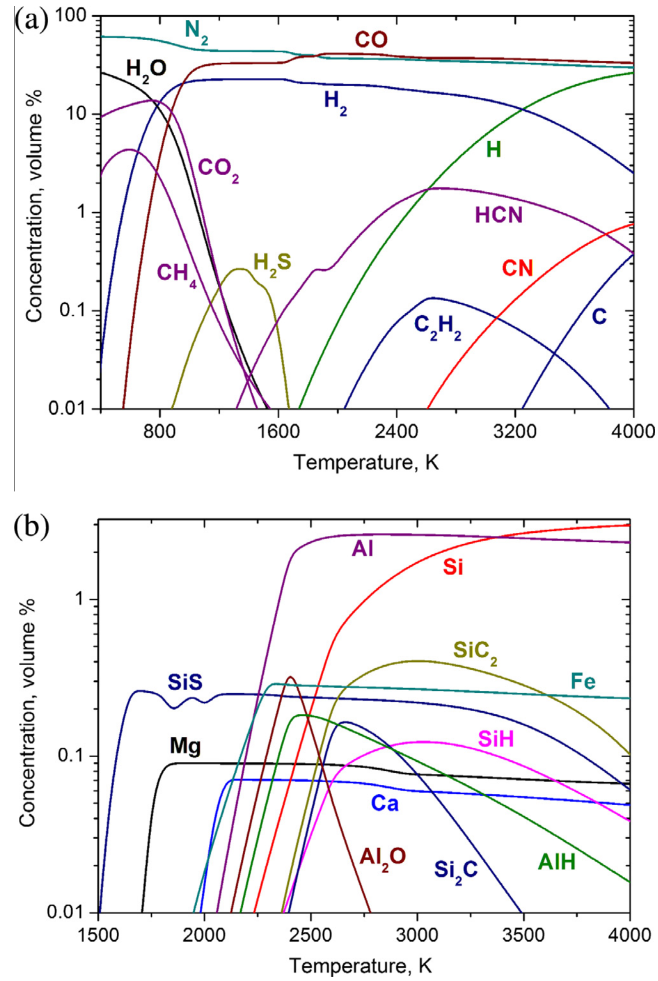

Fig. 1. Composition of organic (a) and mineral (b) components in gas phase versus temperature (air gasification).

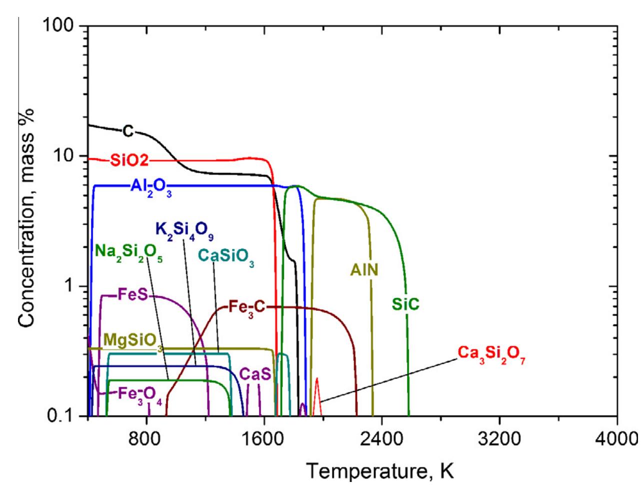

Fig. 2. Composition of condensed phase components versus temperature (air gasification).