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Numerical investigation on performance of coal gasification under various injection patterns in an entrained flow gasifier

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HIGHLIGHTS

▶ A numerical method is developed to predict coal gasification phenomena.
▶ Particular emphasis is placed on the influence of injection pattern upon syngas production.
▶ The parameter of steam/coal ratio is also taken into account.
▶ The appropriate injection for the performance of coal gasification is suggested.
▶ The obtained results have provided a useful insight into the operation of coal gasification.

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ABSTRACT

Gasification plays an important role in the development of clean coal technology. To seek appropriate operations for synthesis gas (syngas) formation, the present study develops a numerical method to predict coal gasification phenomena in an entrained-flow gasifier. Particular emphasis is placed on the influence of injection pattern upon syngas production. The parameter of steam/coal ratio is also taken into account to evaluate its impact on hydrogen generation. The simulations suggest that the developed numerical method is able to provide an accurate prediction on syngas formation. With oxygen injected from the center inlet and coal from the middle ring inlet of the reactor, the operating pattern gives the best performance of coal gasification where the carbon conversion (CC) and coal gas efficiency (CGE) are 89% and 72%, respectively. Increasing steam into the reactor reduces CC and less CO is generated. Nevertheless, more H_2 is produced stemming from water gas shift reaction. This results in slight variation in CGE with altering steam/coal ratio. The obtained results have provided a useful insight into the operation of fuel and oxidant injection for coal gasification.

1. Introduction

On account of the impact of atmospheric environmental pollution, greenhouse effect and rapid shortage of oil upon human life, many researchers have devoted themselves to the development of clean coal technology. According to the report of International Energy Agency (IEA) [1], the demand of coal will grow to a great extent in the next two decades because of its relatively abundant reserve and lower price. In clean coal technology, the thermal conversion processes, such as combustion and gasification, are the most commonly employed techniques. The prime difference between combustion and gasification is the amount of oxygen for chemical reactions. Specifically, the reaction process of combustion is under the condition of sufficient oxygen, whereas gasification is an incomplete combustion process with the condition of deficient oxygen. From the viewpoint of reducing greenhouse gas emissions, gasification where coals are converted into synthetic gas (syngas) and other gas components, is a better choice than combustion [2]. Syngas is a gaseous mixture of hydrogen (H_2) and carbon-monoxide (CO) [2] and it can be employed as a fuel in gas turbines, even in Integrated Gasification Combined Cycle (IGCC), for power generation [3–6].

As far as coal gasification is concerned, the reactors can be catalogued into fixed-bed, fluidized-bed and entrained-flow gasifiers. By virtue of higher syngas yield and tar-free product gas, entrained-flow gasifiers have been widely utilized in power plants [2]. The flow pattern in an entrained-flow gasifier pertains to co-current flow in nature, that is, pulverized coal, oxygen and/or steam are transported into the gasifier from the top of the reactor.

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Nomenclature

A	pre-exponential factor
B	temperature exponent
C	molecular concentration or turbulence constant
c_p	specific heat (J kg K^{-1})
D	diffusion coefficient (m^2 s^{-1})
E_a	activation energy (J $kmol^{-1}$)
G_k	generation of turbulence kinetic energy
ΔH^0	heat of reaction (at 298 K and 1 atm)
K_{eq}	equilibrium reaction rate
k	reaction rate constant or turbulence kinetic energy (m^2 s^{-2})
M	molecular weight
N	reaction apparent order
Pr	Prandtl number
p	pressure (atm)
r	radial coordinate
R	universal gas constant (J kmol K^{-1})
S	source term
Sc	Schmidt number
T	temperature (K)
T_P	coal particle temperature (K)
t	time (s)
u	gas velocity component (m s^{-1})
V	mass fraction of volatiles
v_r	stoichiometric coefficient of reaction r
w	reaction rate (kg m^{-3} s^{-1})
x	coordinate (m)
Y	stoichiometric coefficient or species
z	axial coordinate

Greek letters

α	molecular fraction
ε	turbulence dissipation rate (m^2 s^{-3})
λ	thermal conductivity (W mK^{-1})
μ	viscosity (kg ms^{-1})
ρ	density (kg m^{-3})
τ_{ij}	symmetric stress tensor
η	rate exponent for species

Subscripts

f	forward
h	high temperature or energy
i	species i or spatial coordinate
j	momentum or spatial coordinate or species j
l	low temperature
m	mass (kg)
P	coal particle
r	reaction
t	turbulence
k	kinetic energy
μ	viscosity
ε	dissipation

Furthermore, according to the types of feedstock, entrained-flow gasifiers can be classified into a coal-water-slurry (CWS) feed gasifier and a dry coal feed one. The former has been extensively employed in GE/Texaco processes, whereas the latter has been fulfilled by Shell and Krupp-Koppers (Prenflo) [7].

In view of potential applications of gasification, there have existed a number of experimental studies to figure out gasification phenomena and enhance gasification performance in the last decade. For example, Na et al. [8] reported that the compositions of H_2 and CO depended upon the oxygen/fuel rate in an oxygen-blown gasification process. Chen et al. [9] outlined that transient coal gasification was characterized by a two-stage reaction, which included a devolatilization and a pyrolysis reaction processes. Alternatively, based on syngas combustion, Chen et al. [10] observed that the entire gasification process could be decomposed into an initiated, a growing, a rapidly decaying, a progressively decaying and a frozen periods. Umeki et al. [11] practiced a high-temperature steam-only gasification experiment; their results indicated that the steam/carbon ratio had a significant effect on the gas compositions through the water–gas shift reaction. In the study of Shen et al. [12] concerning co-gasification of coal and petroleum coke in an entrained-flow gasifier, they found that the slagging problem was highly related to the ash content of coal and blending ratio between the two fuels; their study also suggested that the appropriate O_2/C ratio for co-gasification was between 0.6 and 0.65 Nm^3 kg^{-1}.

In addition to experimental research, a number of numerical studies have also been reported and several operating conditions and indices have been conducted to evaluate the gasification performance. Chen et al. [13] addressed that the air/coal rate had pronounced influence on the heating value of the product gas in a two-stage air-blow entrained-flow gasifier. Choi et al. [14] observed that increasing O/C ratio caused an increase in the syngas yield of the coal gasification process. Watanabe and Otaka [15] elucidated the high dependence of carbon conversion from the air/coal ratio in an entrained-flow gasifier where the atmosphere in the gasifier became more oxidative as the air ratio increased and the calorific value of the product gas was decreased. Umeki et al. [16] modeled a gasification process with high temperature steam; they noted that the H_2 mole fraction was higher and the CO mole fraction was lower at higher steam temperatures and steam/carbon ratios.

In reviewing past studies, a number of studies have been performed on gasification phenomena in entrained-flow coal gasifiers; however, the research concerning the effect of feeding pattern or design on gasification performance remains absent. For this reason, the purpose of this study is to develop a numerical method to investigate the gasification performance in an entrained-flow coal gasifier. Particular emphases are placed on the design of inlet flow pattern and influence of steam/coal ratio on coal gasification so as to find feasible operating conditions for the gasifier.

2. Numerical method

2.1. Configuration of the gasifier

The schematic of the investigated entrained-flow coal gasifier is shown in Fig. 1. It is a dry feed, pressurized entrained-flow gasifier with the capacity of two metric ton per day [12]. As shown in Fig. 1a, the height of the gasifier is 5151.2 mm and the width is 270.3 mm. The inlet configuration consists of a center inlet and three concentric ring inlets. The three inlets are referred to as the inner ring inlet, the middle ring inlet and the outer ring inlet and their distances to the gasifier centerline are 15 mm, 45 mm and 90 mm, respectively. Fig. 1b shows the top view of the gasifier where the diameter of the center inlet is 20 mm and the width of each ring inlet is 5 mm.