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Evaluation of the energy efficiency of the shell coal gasification process by coal type

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ABSTRACT

The energy efficiency of the coal gasification process for five different coals (Pittsburgh #8, Illinois #6, Drayton coal, a coal from Montana Rosebud, and Wyoming coal) was evaluated using a rigorous dynamic model. The model considered a Shell entrained-flow gasifier with a membrane wall and a quenching system for a 300 MW-class integrated gasification combined cycle (IGCC) power plant. Parametric studies on gasifying agents (oxygen and steam) were conducted to identify the optimal ratios of oxygen and steam to each coal for maximum cold gas efficiency (CGE). The gasifier performance was evaluated in terms of the product gas flow rate, CGE, gas temperature, slag generation, and steam consumption. The optimal ratio of oxygen to coal flow for the maximum CGE varied from 0.704 to 0.871 depending on the coal type. Then, the maximum CGE of the coals was achieved in the range of 79.8–80.4% without the addition of steam. The CGEs of bituminous coals were improved by the addition of steam, resulting in 80.8–81.3% of CGEs. By contrast, sub-bituminous coals did not have any benefit to the CGE from the addition of steam, showing 79.8–80.3% of CGEs. Therefore, the optimal amount of both oxygen and steam for each coal was determined to maximize energy production in the gasification process. Based on the same lower heating value of syngas from the gasifier (739.5 MJ/s), the total recovered energy in the gasifier was 175.2–188.6 MJ/s for bituminous coals and 146.7–155.2 MJ/s for sub-bituminous coals at optimal gasifying agents. The energy demand of the gasification system and related units (air separating unit, coal treatment, and steam consumption) was in the range of 39.4–40.2 MW, which showed a small difference among coal types. Consequently, the energy efficiency of the gasifier strongly depended on the HHV of coal. However, considering the significantly lower energy density of sub-bituminous coals compared to bituminous coals, the performance of their gasification was considerably high in the Shell gasifier.

1. Introduction

The integrated gasification combined cycle (IGCC) process is a promising power generation technology for utilizing solid fuels as an alternative to conventional pulverized coal plants. The IGCC process also has the highest potential for carbon capture and storage with the lowest penalty on the process cost and efficiency [1]. Due to the importance of the environmental aspects, many studies have considered the prospects of the overall IGCC process and the coal-based process [1–3]. Many studies using various coal types have been conducted on the overall IGCC process. The studies examined different rank coals ranging from lignites to low-volatile bituminous coals to investigate the sensitivity of the thermal efficiency of the overall IGCC process with slurry feed gasifiers [4–7]. A natural gas combined cycle (NGCC) plant and an IGCC plant with petroleum coke and high and low-rank coals were also recently discussed in terms of their cost and process performance [8,9]. The researchers frequently highlighted the potential of the gasification process with low-rank coals in a dry-fed gasifier using a simulation study of the overall IGCC process.

In an efficiency evaluation of IGCC plants, the gasifier is the key unit because the composition and amount of syngas strongly depends on the coal type and the operating conditions. The overall efficiency of an IGCC plant is strongly influenced by the gasifier performance. Therefore, understanding the coal gasification process is important for optimizing the gasifier operation. Among gasifiers, an entrained-flow type gasifier allows for the use of flexible feedstock and provides a clean and tar-free product gas [7]. A dry-fed entrained-flow gasifier is appropriate for the gasification of a variety of coals because the coal moisture level is controlled before gasification [10]. The Shell gasification process, which utilizes a dry-fed, oxygen-blown, entrained-flow gasifier, is operated at high temperatures of over 1400 °C and at high pressures

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Nomenclature

Capital letters

A	area (m^2) or area per control volume (m^2/m^3)
C	mole concentration ($mole/m^3$) or mass concentration (kg/m^3)
D	diffusivity (m^2/s)
F	friction ($kg/m^2/s^2$) or muliflier (–)
HS	heat sources ($J/m^3/s$)
$(HS)'$	heat sources per axial length (kg/m/s)
HT	heat transfer rate ($J/m^3/s$)
MS	mass sources ($mole/m^3/s$) or ($kg/m^3/s$)
MT	mass transfer rate ($kg/m^3/s$)
Nu	Nusselt number
OF	oxygen to coal feed rate
P	pressure (Pa) or perimeters (m)
Q	heat transfer rate ($J/m^3/s$)
Re	Reynolds number
SF	steam to coal feed rate
T	temperature (K)
BFW	boiling feed water

Lowercase

c_p	heat capacity (J/mole/K)
d	diameter (m)
f	friction factor
f_c	correlating factor
g_z	gravitational acceleration (m/s^2)
h	heat transfer coefficient ($W/m^2/K$) or enthalpy (J/kg)
k	thermal conductivity (W/m/K)
m	mass per char particle (kg/#)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
q	heat flow rate (J/s)
q_{flux}	heat flux ($J/m^2/s$)
q'	linear heat flowrate (J/m/s)
r	radius (m)
t	time (s)
u	velocity (m/s)
x	vapor fraction in water zone (-)
x_l	thickness of slag layer (m)
x_m	thickness of membrane
Δx	wall layer thickness
y_m	width of membrane
Δy	width of control volume
z	axial position (m)

Greek letters

Δ	arbitrarily small number
Ω	wall roughness (m)
β	angle of the wall from the vertical direction
ε	volume fraction (m^3/m^3), porosity (m^3/m^3) or emissivity (-)
μ	viscosity of slag (Pa·s)
ρ	density (kg/m^3) or number density ($\#/m^3$)
σ	Stefan-Boltzmann constant (5.67×10^{-11} $kW/m^2/K^4$)
υ	stoichiometric coefficient for reactions
ψ	particle structural parameter
ϕ	mechanism factor based on the stoichiometric relation of CO and CO_2

Subscripts & superscripts

0	initial conditions
cb	convective boiling
conv	convective
cs	cross section
daf	dry ash free
dev	devolatilization
g	gas
gw	gas to wall
Hetero	heterogeneous reactions
Homo	homogeneous reactions
i	gas phase component or inner
L	liquid
m	membrane
N	number
nb	nucleate boiling
o	outer
p	char particle
pf	pressure correction factor
pg	particle to gas
pw	particle to wall
r	reduced
rad	radiative
RXN	reactions
sat	saturation
Sur	surface
Tot	total phase (gas + solid) or total gas phase component
tp	two phase
Vap	vapor
VM	volatile matter
w	wall

of 20–70 bar [11]. The gasifier is surrounded by a membrane wall structure with boiling feed water (BFW) to withstand the severe conditions. In addition, the gasifier contains a slagging system where the melted slag flows down and comes out at the bottom of the gasifier. The dynamic behavior of the Shell gasifier was previously analyzed under the severe operating conditions [12,13].

Approximately 45% of global coal reserves are bituminous coals while another 45% are sub-bituminous coals [14,15]. Depending on the coal mine, coal has a wide range of carbon, moisture content, and heating value. Since gasifier operation is affected by the coal quality, the effects of the coal type on the gasifier need to be investigated to efficiently operate the gasification process. In addition to coal type, several other parameters that affect the gasifier performance must be studied simultaneously, including operating conditions and gasifying agents. Gasifying agents are generally supplied to the coal gasifier to improve the quality of the syngas. As an oxidant, a supply of high purity oxygen produces syngas with a high heating value, but it requires an air separation unit (ASU) in most gasification plants [16]. Likewise, steam is recommended as a gasifying agent because it can improve hydrogen production and carbon conversion [17,18].

As shown in Fig. 1, a variety of coals with different carbon contents and heating values were previously studied in gasification processes. Several studies referred in Fig. 1 reported an effect of gasifying agents for a specific coal on the gasifier performance. The effect of oxygen and coal slurry water on the E-gas gasifier using a high-ash coal was analyzed by means of kinetic and equilibrium study [17]. The gasification of a coal with oxygen and steam in a bubbling fluidized-bed gasifier was studied by using Aspen Plus [18]. In many studies, the performance of gasification processes was generally evaluated by means of the cold gas efficiency (CGE) [5,17–20]. Others conducted simulations of the