Chemical Engineering and Processing 74 (2013) 131–141

Contents lists available at ScienceDirect

Chemical Engineering and Processing: Process Intensification

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

Modeling of an oxygen-staged membrane wall gasifier: effects of secondary oxygen

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ARTICLE INFO

Article history:
Received 24 July 2013
Received in revised form 2 September 2013
Accepted 19 September 2013
Available online 26 September 2013

Keywords:
Gasification
Dynamic model
Oxygen-staged gasifier
Membrane wall
Reduced order model

ABSTRACT

A new type of entrained flow gasifier with membrane wall and two-stage oxygen supply is being developed in China. The fraction of the secondary oxygen in total oxygen (FSO) is an important parameter for this kind of gasifier. A dynamic reduced order model (ROM) based on a reactor network model (RNM) is developed for this gasifier, which is used to investigate the effects of FSO on the slag layer thickness profile on the wall and explore the potential of FSO in dynamic slag control. The ROM adopts a flexible RNM blocking method, which varies with FSO to account for the influence of FSO on the flow pattern in the gasifier. Available industrial data was used to validate the model and a detailed sensitivity analysis for the calculation of slag layer thickness was performed. Static analyses show that FSO has a marked effect on the slag thickness distribution and higher FSO leads to lower heat loss through the wall. Finally, a slag control system, which introduced FSO as an auxiliary regulator, is proposed. Dynamic simulation shows that the new control system offers an improved performance in slag control and can broaden the regulating range of operating temperature.

1. Introduction

Coal gasification is an important clean coal technology in which coal is broken down into its chemical constituents via thermo-chemical processes. The resulting syngas, which primarily consists of carbon monoxide and hydrogen, can be used for electricity production or as inputs of chemical industry. Driven by rising energy prices and environmental concerns, the development of coal gasification technology has accelerated over the past few decades in China. One of the most important breakthroughs of coal gasification is replacing traditional refractory wall with membrane wall for slurry-feed entrained flow gasifiers. The first slurry-feed membrane wall entrained flow gasifier was coming into operation in 2012 [1–4]. Operational experience indicates that it has higher availability and improved feedstock flexibility compared with slurry-feed gasifiers with refractory wall. Moreover, the heat loss through the membrane wall only accounts for 0.5% of the calorific value of input coal, which is almost the same level as that in a refractory wall gasifier. Recently, Tsinghua University is trying to apply the two-stage oxygen supply technology, which is an existing technology in gasification [5,6] that can achieve enhanced carbon conversion and prolonged nozzle lifetime [7,8], to this new type of gasifier. By combining the membrane wall and two-stage oxygen supply, the performance of slurry-feed entrained flow gasifier can be greatly improved.

For this new type of gasifier, the fraction of the second-stage oxygen in total oxygen supply (FSO) is an important operating parameter. On one hand, it influences the internal flow and mixing processes; on the other hand, it affects the temperature distribution and heat flux to the wall and the formation of slag layer on the surface of the wall. In the gasifier, the second-stage oxygen (hereinafter referred to as secondary oxygen) acts as horizontal jets in a cross-flow. There have been numerous studies [9–13] on the effects of horizontal jets on flow characteristics in boilers and gasifiers, yet few of them involve the effects on heat transfer and the formation of slag layer. Because controlling slag plays an important role in the safe and economic operation of a membrane wall gasifier, in-depth research of how FSO affects the slag layer is desired for optimal operation of the new type of gasifier.

In industrial-scale gasifiers, the extreme operation conditions, e.g., high temperature, high pressure and reducing atmosphere, pose great challenges to online measurement of the formation and evolution of slag. Therefore, a dynamic gasifier model including slag simulation is of great importance. Among all available

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http://dx.doi.org/10.1016/j.cep.2013.09.009

Nomenclature

A	Flow area inside reactors in the network, m^2
CC	Carbon conversion
f	Friction factors
F_{ash}	mass flow rate of total ash in incoming coal
$F_{g,i}$	mole flow rate of the ith gas species, mol/s
f_Q	The portion absorbed by particles in the energy produced by gas-particle reactions
h_g	gas phase specific enthalpy, kJ/kmol
h_p	solid phase specific enthalpy, kJ/kg
HHV	high heating value of the coal, MJ/kg
L_{WSR}	length of a well-stirred reactor
$\dot{m}_{slagging}$	slag impinging rate on unit-length wall, kg/m/s
Nu	Nusselt number for convection inside water tubes
Pr	Prandtl number for convection inside water tubes
$\dot{Q}_{conv,p\rightarrow g}$	heat transfer term for convection between particles and gas, kW/m
$\dot{Q}_{conv,g\rightarrow w}$	heat transfer term for convection between gas and wall, kW/m
$\dot{Q}_{rad,p\rightarrow w}$	heat transfer term for radiation between particles and wall kW/m
$\dot{Q}_{rad,p\rightarrow p}$	heat transfer term for radiation between particles in adjacent zones, kW/m
$\ddot{Q}_{homo}$	heat source of gas-gas reactions, kW/m^3
$\ddot{Q}_{hete}$	heat source of gas-particle reactions, kW/m^3
Re	Reynolds number
s	time, h
S_C	chemical reaction source of carbon in particles, $kg/m^3/s$
$S_{g,i}$	chemical reaction source of ith gas species, $kmol/m^3/s$
S_p	chemical reaction source of particles, $kg/m^3/s$
T_{cv}	temperature of critical viscosity of slag, °C
X_C	mass fraction of carbon in particles
z	distance from gasifier top, m
z^*	normalized distance from gasifier top

Subscripts

i	Index of gas species
g	gas phase
m	the mth heterogeneous reaction
n	the nth homogeneous reaction
p	particle phase

dynamic modeling approaches for entrained flow gasifiers [14–24], the reduced order modeling is regarded as one of the most powerful modeling techniques. This method adopts a reactor network model (RNM) [25,26] to depict the flow structure in gasifiers, making it not only be able to predict the temperature and composition of syngas at the gasifier outlet, but can offer reasonable internal temperature distribution as well. The internal temperature distribution is crucial for estimation of the slag layer thickness. Currently, all of the reduced order models (ROMs) for gasifiers adopted fixed blocking schemes for RNM organization [20–22,27,28]; this kind of blocking, though convenient, cannot reflect the flow structure change caused by variations of operation parameters such as FSO.

In this study, we established a dynamic ROM for the oxygen-staged membrane wall gasifier based on a flexible RNM blocking that varies with FSO. With this model, we investigated the effects of FSO on the slag thickness distribution along the wall and explored the potential ability of FSO in the dynamic control of slag.

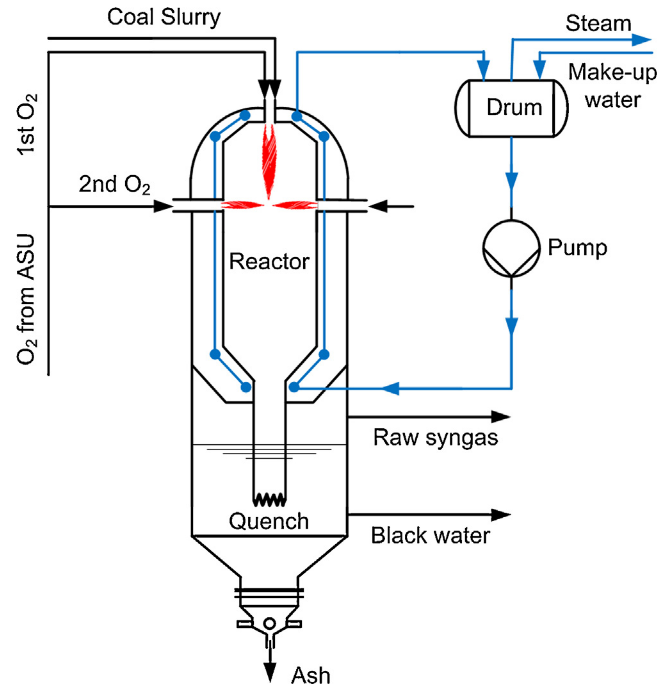

Fig. 1. A schematic of the structure of the oxygen-staged membrane wall gasifier.

2. Oxygen-staged membrane wall gasifier

Fig. 1 shows the configuration of an oxygen-staged membrane wall gasifier. It contains a nozzle on the top and three horizontal injectors on the side wall. Part of the oxygen is fed into the gasifier chamber together with coal slurry through the top nozzle while secondary oxygen is introduced through the horizontal injectors. The membrane wall is comprised of a series of tubes. Saturated water in the drum, where water and steam are separated, flows through these tubes from bottom to top and then returns to the drum.

Due to the low temperature on the membrane wall surface, when molten ash hits the wall it will re-solidify and form a solid slag layer, which can isolate the membrane wall from the high temperature syngas and corrosive molten slag. The thickness of the slag layer is important: if it is too thin, the membrane wall might be damaged; if it is too thick, the slag trap at the bottom may be blocked, which may requires to shut down the gasifier for cleaning.

As this new type of gasifier is in the design phase, in this study, the primary design and operation parameters are determined according to the single-stage slurry-feed membrane wall gasifier [1–4]. Table 1 provides the geometric parameters of the gasifier chamber. The operating pressure is 4.0 MPa, the coal slurry flow rate is 700 t/d, the mass content of coal in the slurry is 59.1%, and the ratio of mass flow rate of oxygen to coal (Oxy/Coal) is 0.94. The purity of the oxygen stream is 95%. Proximate and ultimate analyses of the gasified coal are summarized in Table 2. The van

Table 1
Geometry parameters of the gasifier chamber.

Parameter	Value
Height of the top expansion zone (m)	0.25
Height of the bottom shrinking zone (m)	0.58
Height of the outlet zone (m)	0.6
Total height of the chamber (m)	6.7
Maximum internal diameter (m)	1.676
Diameter of the outlet zone (m)	0.51
Distance between the horizontal injectors to the top (m)	1.86