Fuel 181 (2016) 587–599

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

A process model for underground coal gasification – Part-II growth of outflow channel

Ganesh Samdani [a], Preeti Aghalayam [b], Anuradda Ganesh [c], R.K. Sapru [d], B.L. Lohar [d], Sanjay Mahajani [a,*]

[a] *Department of Chemical Engineering, Indian Institute of Technology Bombay, Mumbai, India*
[b] *Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai, India*
[c] *Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Mumbai, India*
[d] *Institute of Reservoir Studies (IRS), ONGC, Ahmedabad, India*

HIGHLIGHTS

- Proposed a compartment model for phase-II of UCG using actual on-field RTD studies.
- Integrated non-ideal flow patterns with spalling and detailed kinetics of the given coal.
- Good agreement with exit gas quality and coal consumed in laboratory experiments.
- Provided justification for the approach of modeling two phases of UCG, separately.

ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form 31 March 2016
Accepted 5 May 2016
Available online 14 May 2016

Keywords:
Underground coal gasification
Outflow channel
Compartment model
Spalling

ABSTRACT

Underground Coal Gasification (UCG) is a process of gasifying coal *in-situ* to produce syn-gas. The gas thus produced, passes through the outflow channel that leads to the production well. As explained in part-I of this paper (Samdani et al., 2015), UCG can be divided in two distinct phases. The phase-I corresponds to initial vertical growth of the cavity and the output from phase-I model provides input to the phase-II model. This paper presents an unsteady state model for phase-II of UCG, wherein, the growth occurs in the horizontal direction towards the production well through the outflow channel. A compartment model, based on tracer studies performed on actual UCG cavity, is developed for phase-II of UCG. Here, the outflow channel is divided in small sections along the length, each consisting of rubble zone, void zone and roof at the top. This reduces the complexity caused by non-ideal flow patterns and changing sizes of different subzones inside the outflow channel. The subzones and the sections are linked appropriately, for mass and energy flow, to give overall performance of UCG. The proposed approach combines chemical reactions, heat and mass transfer effects, spalling characteristic and complex flow patterns to achieve meaningful results. In all, seven gas species, three solid species and eleven reactions are included. The simulation results such as variation in solid density, dynamics of different zones, exit gas quality are presented. The model is validated by comparing the predicted exit gas quality and that observed during similar laboratory scale experiments. Finally the results are also compared with pilot scale field-trials. This model along with the phase-I model provides a complete modeling solution for UCG process.

1. Introduction

Underground coal gasification (UCG) is a process of producing syn-gas by gasifying coal *in-situ* that is otherwise technically or economically unminable [1]. The process involves a sequence of steps starting from drilling of injection and production wells to the syngas generation by injecting gasifying agents. Fig. 1 shows the typical stages involved in UCG process and different phases of UCG as are explained in first part of this paper [2].

The injection and production wells are typically around 50–60 m apart from each other [3]. This distance is decided based on the permeability and thickness of coal seam and the amount of available reserves. The same are connected at the bottom of the coal seam by a permeable channel. This permeable channel can be created by in-seam directional horizontal drilling. The cavity near the injection well starts growing initially and it reaches the overburden much earlier than reaching the production well. This is because of the longer distance between injection and production

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* Corresponding author.
E-mail address: sanjaym@iitb.ac.in (S. Mahajani).

http://dx.doi.org/10.1016/j.fuel.2016.05.017

Nomenclature

Acronyms

CRIP	Controlled Retracting Ignition Point
CSTR	Continuous Stirred Tank Reactor
DAE	Differential-Algebraic Equation
LVW	Linked Vertical Wells
RTD	Residence Time Distribution
UCG	Underground Coal Gasification
WGS	Water Gas Shift

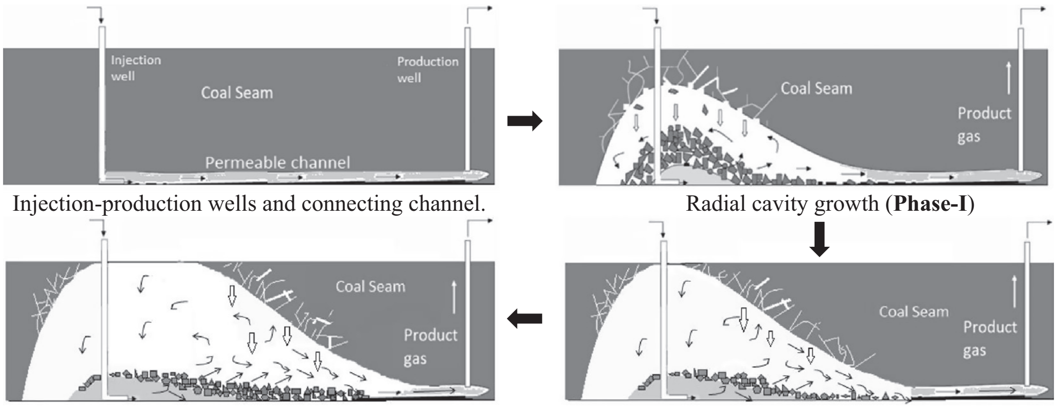
Symbols

A_C	area of cross-section (m^2)
A_{roof}	area of roof surface (m^2) changes with time
C_g	gas concentration (kmol/m^3)
C_p	specific heat (kJ/kmol/K for gas and kJ/kg/K for solids)
D_{eff}	effective diffusivity (m^2/s)
ΔH	heat of reaction (kJ/kmol)
F_w	rate of water influx (kmol/s)
H	enthalpy (kJ/kmol)
M	molecular weight (kg/kmol)
V	volume (m^3)
R_j	jth reaction (kmol/m^3/s)
T	temperature (K)
a_{ij}	stoichiometric coeff of ith gas species in jth reaction
$a_{s,ij}$	stoichiometric coeff of ith solid species in jth reaction
h_T	heat transfer coefficient in between gas and bed of particles (kW/m^3/K)
h_{Tcav}	heat transfer coefficient from void to wall transfer (kW/m^2/K)
k_{eff}	effective conductivity (kW/m/K)
$k_{y,cav}$	mass transfer coefficient from void to wall transfer (m/s)
t	time (s)
v_{df}	velocity of drying front (m/s)
ε_r	radiation emissivity
ρ	solid density (kg/m^3)
σ	Stefan Boltzman constant (kW/m^2/K^4)
τ	residence time in a zone (s)
Φ	porosity
v	gas flow rate (m^3/s)

Subscripts

g	gas phase
s	solid phase
c	cross-section
w	water influx or water
d	drying
i	species index
j	reaction index
in	inlet of a zone
$void$	void zone in channel
$roof$	cavity roof
vap	vaporization
df	drying front
$spall$	conditions inside spalled rubble
T	volume of total coal seam (at the end of wet zone)
l	liquid phase

wells compared to the coal seam thickness. After the cavity hits the overburden, growth starts occurring mostly in lateral direction towards the production well. This phase of lateral growth is termed as phase-II, which is essentially the gasification in outflow channel. The outflow channel, in the absence of spalling, can be modeled like a channel gasifier with reactive porous walls. However, in case of coal with a tendency to spall, underground gasifier geometry becomes complex due to the presence of rubble on the floor of outflow channel as well. There are several studies reported in literature to model channel gasifiers [4–10]. However, these studies either do not consider complex flow patterns and spalling or oversimplify their presence. A notable effort by Chang [5] is on developing a process model for channel gasifier, which is partially filled by spalled rubble. In their model, the definition of spalling requires estimation of three empirical constants for every coal. The empirical constants relate the width of the cavity (W) and char surface temperature (T) with rate of spalling using a power law equation of the type $aW^b(T - T_{ref})^c$. In addition, kinetics of reactions is also simplified, e.g. assumption of reaction equilibrium for the water–gas-shift reaction. Later few other researchers [11,12] also attempted to model spalling which was limited by dimensionality of model or approximate spalling definitions. To the best of our knowledge, there is no work in open literature which considers two distinct phases of UCG and models the complex reaction chemistry, actual non-ideal flow dynamics and spalling all at a time. In the most general case, the output from phase-I model serves as the input to the phase-II model to give overall performance of the UCG process. However, if the spalling tendency of



Injection-production wells and connecting channel.

Radial cavity growth (**Phase-I**)

Forward growth towards production well (**phase-II**)

Cavity hits the overburden (**end of phase-I**)

Fig. 1. Schematic of UCG showing different phases of UCG cavity growth [2].