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Full Length Article

Dynamic reduced order modeling of an entrained-flow slagging gasifier using a new recirculation ratio correlation

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HIGHLIGHTS

- A dynamic model is presented for CanmetENERGY's gasifier.
- A new empirical correlation is proposed for recirculation ratio.
- Transient experimental data was used to validate the model.

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ABSTRACT

This study presents a dynamic reduced order model (ROM) that describes the transient behaviour of an entrained-flow slagging gasifier. A new correlation for estimation of the recirculation ratio in the ROM's reactor network is presented in this work by using the ROM and experimental data. The proposed correlation improves the well-known method of Thring and Newby for jet-flow recirculation by adding a term that takes into account the changes in the feed streams (multi-phase jet and secondary flows) on the recirculation. This feature enhances the prediction capabilities of the reactor network, especially in dynamic simulations where the inlet flowrates may change over time, e.g., for load-following power plants. The proposed dynamic ROM has been validated using steady-state and transient experimental data. Furthermore, the dynamic responses of dry syngas composition, temperature distribution, cold gas efficiency, slag thickness and flowrate were studied under load-following and co-firing (petroleum coke/coal) scenarios.

1. Introduction

The complexity and high integration of unit operations in Integrated Gasification Combined Cycle (IGCC) power plants render it challenging and expensive to make IGCC plants flexible [1]. The responses of an IGCC's unit operations to disturbances and the interactions between the units can lead to undesired fluctuations which may drastically affect the operability, availability and efficiency. It is therefore essential to study the dynamic performance of IGCCs as it provides insights that can lead to improvements in start-ups, set-point tracking and handling of disturbances, e.g., feed composition variability and load changes. While multiple studies on air separation and CO_2 capture units have been performed to evaluate the dynamic behaviour of these systems in IGCC power plants [2], studies providing insight on the dynamic performance of an IGCC's gasification unit are limited. The multi-phase transport phenomena and the reactions associated with a gasification process are often simulated with complex steady-state computational fluid dynamic (CFD) models which are not sufficiently computationally efficient to be extended into the dynamic (i.e., unsteady-state) mode. In addition, some process simulators, such as Aspen®, are not capable of handling solid particles in dynamic mode [3].

Previous works that have studied the dynamics of IGCC's gasification units have employed models that are relatively simple and that only account for limited aspects of the gasification process. Aggarwal et al. [4] proposed an equilibrium-based gasifier model using Gibbs free energy minimization. In that study, only a limited number of reactions were considered which may lead to significant deviations with respect to the actual operation of the unit. Tan et al. [5] presented a gasifier model where only a few outputs such as gas calorific value, mass, gas pressure and gas temperature were reported. Robinson and Luyben [6] presented an alternative approach to simulate solid particles in Aspen® that lead to the

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Nomenclature

Symbols

A	area (m^2)
C	concentration ($mole/m^3$)
c_p	heat capacity (J/kg/K)
d	diameter (m)
D	diffusivity (m^2/s)
F'	volumetric force (N/m^3)
g	gravitational acceleration (m/s^2)
h	convection coefficient ($W/m^2/K$)
H	enthalpy (J/kg)
k	thermal conductivity (W/m/K)
m	mass (kg)
m'	mass flux ($kg/m^2/s$)
M	mass flow (kg/s)
N	number density (m^{-3})
P	pressure (Pa)
Q'	heat flux (W/m^2)
r	radius (m)
R	reactions
S	silica ratio
t	time (s)
T	temperature (K)
u	velocity (m/s)
w	weight fraction
x	molar fraction
z	axial domain (m)

Greek symbols

α	model parameter
β	model parameter
ε	volume fraction
δ	slag thickness (m)
ρ	density (kg/m^3)
μ	viscosity (Pa s)
τ	time constant (s)
γ	recirculation ratio

Subscripts

conv	convection
cs	cross section
eff	effective
g	gas
het	heterogeneous reactions
horn	homogeneous reactions
i	ith gas phase specie
p	particle

development of a gasifier model in Aspen Dynamics®. That study assumed a high molecular weight hydrocarbon (available in the Aspen® library) as a pseudo fuel to represent coal. Although this model captures the macro-scale thermal, pressure, flow, and composition dynamics of the gasifier's outlet, it does not account for solid particles and other key features of the system, e.g., temperature and composition distribution inside the gasifier.

Recent studies have shown that the development of one-dimensional reduced order models (ROMs) describing the essential features of the gasification process is a suitable and computationally attractive approach to study the transient performance of these systems [7–10]. Some of the ROMs have used a single reactor to model the full gasification system [9,10]. Although computationally attractive, these models may not provide accurate predictions since they may not precisely capture the multi-phase flow structure behaviour of the system. In more comprehensive ROMs, the gasifier's behaviour is approximated by specific zones based on the flow characteristics (mixing or laminar flows) and one-dimensional governing equations are solved for each zone to provide a distribution of different properties, i.e., mass, energy and momentum [7,8]. Monaghan and Ghoniem presented a dynamic ROM for a GE gasifier to study transient response of the system during start-up, fluxant removal, load following and feed change [8]. Yang et al. used a dynamic ROM to compare the transient response of a refractory wall gasifier against membrane wall gasifier [11]. The same authors presented a dynamic ROM for a two-stage entrained-flow gasifier to study its performance in controlling slag thickness with changes in feedstock [12]. The current authors previously presented a steady-state ROM for CanmetENERGY's entrained-flow gasifier [13]. The ROM was developed based on CFD simulation of a short-residence time (<1 s) gasifier and the results were in agreement with CFD simulations [14]. The ROM was further validated with a set of experimental tests performed for petroleum coke gasification [15]. Model validation indicated that identification of the streamlines inside the gasifier to develop a fixed geometry ROM could predict petroleum coke gasification carbon conversions in the range of 48–90% with less than 5 percentage point deviation from experimental values.

The aim of this article is to extend the prediction capabilities of the ROM to consider the transient behaviour of the gasifier, assess its prediction capabilities with respect to experimental data, and study the dynamic performance of the gasifier under different scenarios. Despite efforts in this field, most of the ROMs have been validated using stationary experimental data or simulated data extracted from CFD simulations for a single operating condition. To the authors' knowledge, this is the first time that transient experimental data is being used to validate the transient response of a gasifier model. A ROM that explicitly accounts for the gasifier's dynamic behaviour is key to gain insight on the dynamic operability and availability of these systems under different scenarios. Therefore, having a dynamically validate ROM is important to accurately predict the gasifier's transient response and potential operational difficulties in transient conditions. Additionally, a new correlation that updates the recirculation ratio based on the inlet flowrates is introduced. One key concern with a dynamic ROM based on a reactor network is the ability of the model to update its parameters during changes in the operating conditions, e.g., inlet flowrates. The recirculation ratio of a reactor network is one of the most sensitive parameters affecting the model's output and has a significant impact on carbon conversion and temperature predictions [14,16]. This study proposes a new semi-empirical correlation which estimate the recirculation ratio as function of inlet flowrates. This correlation increases the accuracy of the ROM in predicting the results of experiments. To further improve the modeling capabilities of the dynamic ROM in predicting the slag thickness on gasifier's wall, a single-phase slag sub-model is incorporated into the reactor network model. Furthermore, the present contribution aims to explore the transient response of the gasifier during changes in feed and load. Therefore, case studies involving sinusoidal changes in the fuel's flowrate (where transient experimental data was used for dynamic validation), load-following and co-firing of petroleum coke/coal have been considered in this study.