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Research article

Numerical study on entrained-flow gasification performance using combined slag model and experimental characterization of slag properties

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ABSTRACT

A steady-state model has been developed to describe the flow and heat transfer characteristics of the slag layer coating the reactor wall during dry-feed solid fuel gasification. The model is firstly tested as a stand-alone tool and secondly, coupled with a CFD-based reactor model. Comprehensive measurements of the slag properties substantiate the modeling results. In order to demonstrate the wide range of the model, two different slag types — a crystalline and a glassy one — were selected. Finally, the present model has been used to evaluate the effects of the gasifier operating conditions on the behavior of different slags. In particular, the slag model has been coupled with the CFD-based reactor model, which allows to analyze the interactions between the operating conditions, the slag layer thicknesses, and the main gasification parameters. A parametric study of operating conditions reveals that there is an optimum balance between the gasifier performance in terms of the cold gas efficiency and the syngas yield, the quality of the produced syngas, and the operational stability of the gasifier in terms of controlled slag formation on the walls.

1. Introduction

The entrained-flow gasifier has become the preferred coal gasifier principle for syngas production because of its advantages, such as almost complete carbon conversion, tar-free raw gas, high specific coal throughput, and low sensitivity to coal type [1,2]. Fig. 1a shows a single-stage downdraft entrained-flow gasifier. This is a top-fired reactor with a single centrally mounted water-cooled burner. The solid fuel enters the reactor as a dry-feed stream and is brought into contact with oxygen and steam in a downward co-current flow yielding slagging conditions at elevated pressures and temperatures above the ash melting point. The reaction chamber is equipped with a cooling screen. Raw gas and liquid slag leave the bottom of the reaction chamber at a common outlet. Most of the ash leaves the gasifier as molten slag and the remaining ash is entrained as fly ash by the syngas. Directly downstream of the reaction chamber, a partial or full water quench can be applied. The granulated slag is collected in a water bath at the bottom of the vessel and is discharged periodically.

The gas-tight membrane wall of the cooling screen essentially consists of spirally wound high-pressure tubes connected by flat steel bridges as shown in Fig. 1b. The tubes are provided with studs (fins) that act as anchors for a thin layer of castable refractory, usually silicon carbide. In the tubes of the cooling screen, water above the reactor pressure circulates, extracting heat equivalent to up to 4% of the fuel's lower heating value (LHV) input. During the operation the refractory is covered with a layer of solidified and liquid slag. The slag layer protects the wall from the syngas radiation and liquid slag erosion, and reduces the heat loss, increasing the cold gas efficiency. An increasing slag layer can cause the slag to clog at the reaction chamber outlet [2,3]. In larger units, the formation of a stable slag layer determines the maximum load gradient during start-ups [1,2].

The formation of the slag layer depends on the slag's physical properties, such as viscosity, density, and thermal conductivity, which are functions of the ash chemical composition, the gas atmosphere surrounding the char/ash particle, and the temperature. Predicting these physical properties is challenging due to the complex chemical composition of the ash/slag and the multiphase nature of

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Nomenclature

Latin

A	Surface area, m^2
a	Thermal diffusivity coefficient, $m^2\ s^{-1}$
c_p	Heat capacity, $J\ kg^{-1}\ K^{-1}$
D	Diameter, m
g	Standard acceleration due to gravity, $m\ s^{-2}$
H	Height, m
$\dot{m}$	Mass flux, $kg\ s^{-1}$
Nu	Nusselt number, –
Pr	Prandtl number, –
Re	Reynolds number, –
r	Radial coordinate, m
R	Radius, m
$\dot{Q}$	Heat flux, W
$\dot{Q}''$	Specific heat flux, $W\ m^{-2}$
t	Time, s
T	Temperature, K
$\dot{V}$	Volume flux, $m^3\ s^{-1}$
We	Weber number, –
y	Molar fraction, –
z	Axial coordinate, m

Greek

α	Heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
δ	Thickness, m
ε	Volume fraction, –
ϵ	Emissivity, –
η	Dynamic viscosity, Pa s
η_{CGE}	Cold gas efficiency, –
λ	Thermal conductivity coefficient, $W\ m^{-1}\ K^{-1}$
ν	Kinematic viscosity, $m^2\ s^{-1}$
ν	Stoichiometric coefficient, –
ρ	Density, $kg\ m^{-3}$
σ	Stefan-Boltzmann constant, $W\ m^{-2}\ K^{-4}$
υ	Flow velocity, $m\ s^{-1}$

Indices

cond	(superscript) conduction
conv	(superscript) convection
cr	critical
cv	critical viscosity
c	coolant
depos	slag deposition
devol	slag devolatilization
g	gas phase
in	inflow
l	liquid slag
max	maximal value
out	outflow
p	ash particles
rad	(superscript) radiation
(s)	solid specie
st	stoichiometric condition
s	solid slag
w	reactor wall

the slag flow [4–9]. The properties of both the solid and liquid slag as well as the corresponding layer thicknesses influence the gasification process, but are also influenced by the gasifier design and operating conditions (pressure, oxygen-to-fuel ratio, etc.) [10–15], so that the two process steps, the gasification and the slag formation, should be considered as strongly interrelated.

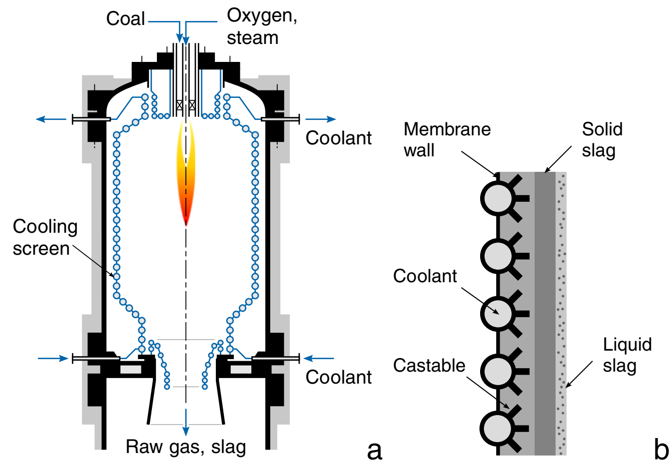

Fig. 1. Diagram of a dry-feed entrained-flow reactor for coal gasification with a cooling screen (a) and schematic representation of the membrane wall (b).

Computer-based simulation is one method to gain a better understanding of the underlying processes and optimize the gasification equipment. There are two modeling approaches. The preferred approach nowadays is to employ computational fluid dynamics (CFD) coupled with detailed sub-models for the various physical and chemical processes occurring inside the gasifier [10,12,13,16-25]. These models are capable of resolving all important process steps at a high level of detail, but are computationally demanding. For efficiency evaluation and operability tests, typically flowsheet simulations are used, which are based on less computationally expensive reduced-order models (ROMs) that capture the most important process steps including gasification, heat transfer, and slag deposition [26–37].

Several models have been proposed to predict slag formation and its influence on heat transfer in slagging coal gasifiers. The slag models can generally be categorized as analytical or discretization approaches. Analytical approaches derive algebraic functions from the conservation equations of mass, momentum, and enthalpy by assuming a specific temperature profile in the slag layer. The most well-known analytical model was proposed by Seggiani [16] to predict the slag layer thickness assuming a linear temperature profile in the total (liquid and solid) slag layer. Numerous variations of Seggiani's model have been adopted in many process modeling and CFD studies of various gasifiers [3,10,17,26,31,32,38]. In most of these models the slag properties except the viscosity were considered to be constant, or empirical correlations for one generic slag were taken from the literature. In contrast, numerical models solve the governing equations through spatial discretization, without making any assumptions regarding the temperature profile, by subdividing the slag layer in a radial direction into several control volumes [35,39,40] or using some multiphase approaches to capture the free surface of the slag [13,15,41,42]. A comparison of the two approaches shows that the discretization approach is more flexible, while analytical models achieve comparable results and are fast enough to be used in a comprehensive CFD-based reactor simulation or in combination with reduced-order models.

The objective of this work is to develop an improved analytical model for heat transfer through the membrane wall of an entrained-flow gasifier. Contrary to several widely used one-layer models, the new model considers a non-linear temperature distribution in two separate layers for solid and liquid slag. Several previous works focus on properties for a generic slag only. Since the quality of the results depends strongly on the reliability of the underlying material properties, comprehensive measurements of the different slag properties