A Clean-Coal Control Technology Application Study: Modelling and Control Issues for a Coal Gasifier

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Abstract: The dynamic behaviour of a coal slurry gasifier in an Integrated Gasification Combined Cycle is modelled by means of mass, energy and momentum conservation equations as well as reaction kinetics descriptions. The main phenomena taken into consideration are (i) slurry drying and devolatilisation, (ii) char and volatile gas combustion, char gasification and water-gas shift reaction, and (iii) syngas cooling. The proposed 0-dimensional description is sufficient to capture process dynamics and it is a useful starting point for control design and verification. In particular, basic control strategies are discussed. Both model and control implementation is carried out in the Matlab-Simulink environment. Simulation results are shown to support model reliability and control effectiveness.

Keywords: Process modelling, Process automation, Process control, Process simulators, Power generation, Coal gasification.

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1. INTRODUCTION

As it is well known, nowadays the scenario in electric energy production is characterised by a constant increase in demand, a decrease in fossil fuel reserves, more and more demanding restrictions on pollutant levels. Feasible solutions can be increasing efficiency and reducing pollutant emissions in thermoelectric power plants, and contributing to the development of the so called "green energy". Coal can play a major role, especially because of the important amount of its proven reserves worldwide; a main challenge for research is then to develop high-efficiency coal-based energy production systems with near zero emissions. In this paper, reference is made to a 70 MWe coal-fed Integrated Gasification Combined Cycle (IGCC) pilot plant (Fantini et al., 2007), allowing flexible production of electric energy and hydrogen. For the design, work is in progress to build up a simulator of the whole process, in order to obtain reliable predictions of its dynamic behaviour in different operating conditions and to study the operating manoeuvres. Dynamical models of the shift reactor and of the Pressure Swing Adsorption (PSA) unit have already been studied ((Bittanti et al., 2008), (Canevese et al., 2007)). Here, we focus on the gasifier, working out a first-principle model useful for control design.

In Section 2 of this paper, the gasification process is analysed, and its main phases are represented by a dynamical model, based on a thermo-fluid-dynamical and a kinetic-chemical description; such model has been developed in full detail starting from the basic conservation equations and the constitutive equations (including the kinetic equation of char gasification); here, of course, we will present only a partial outline of this model. Section 3 deals with control problems. Section 4 reports some simulation results highlighting control effectiveness. Finally, Section 5 reports some conclusions and hints to future work.

2. PROCESS ANALYSIS

The gasifier under study is an entrained-flow gasifier working at about 65 bar and 1650-1700 K. It is formed essentially by two coaxial cylinders: in the inner one, the gasification process occurs, while the outer one is employed for a first syngas cooling. As illustrated in Fig. 1, the reactor is fed with slurry (pulverized coal mixed with water which can be handled like a liquid fuel) and highly pure oxygen and it produces a gaseous mixture whose main components are CO, CO_2, H_2, N_2, H_2O, and pollutants (COS, H_2S, and dusts). We sketch the overall process of gasification and cooling as composed of the following phases (Smoot and Smith, 1985):

- *drying and devolatilisation*:

slurry can be described as coal powder where each particle is coated with a water film; when it is pumped into the inner cylinder, the high temperature that it meets makes water evaporate, thus yielding dry char, and then makes volatile gases (such as N_2, H_2S, H_2O and several kinds of hydrocarbons, among which CH_4) leave char;

- *oxidation and gasification*:

oxygen burns both the volatile gases and the char, according to the reactions

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (volatile\ combustion)\,, \tag{1}$$

$$\begin{gathered} C + \left(1/\phi\right)O_2 \rightarrow 2\left(1 - 1/\phi\right)CO + \left(2/\phi - 1\right)CO_2, \\ 1 \le \phi \le 2 \quad (char\ combustion) \end{gathered} \tag{2}$$

(the mechanism factor ϕ indicating whether CO or CO_2 is transported from the particle surface is calculated according to (Wen and Dutta, 1979), (van der Looij, 1988)). The related temperature increase sustains the drying and volatile emission process and the endothermic reactions

$$C + H_2O \rightarrow CO + H_2 \quad (gasification)\,, \tag{3}$$

$$C + CO_2 \rightarrow 2CO \quad (char - CO_2\ reduction)\,, \tag{4}$$

$$CO + H_2O \rightleftarrows CO_2 + H_2 \quad (water - gas\ shift)\,; \tag{5}$$

- *cooling*:

the thus obtained hot syngas (its temperature is around 1760 K) is sent to the bottom of the reactor, where contact with relatively cold liquid water causes a thermal shock which decreases the gas temperature abruptly and stops all reactions still going on; besides, unburned char residuals and char ashes solidify, fall down and are extracted as slag. After bubbling into water, the syngas is pushed by pressure difference (65 bar Vs 62 bar in the considered case) to the outer cylinder, where it is further cooled by a counter-current water spray. Spray temperature and flow rate can be used to control the outlet fluid mixture temperature and humidity. ■

Actually, the first two phases occur in the same region (gasification region). A detailed 3-D description of the phenomena taking place here is suggested, e.g., in (Chen, et al., 2000). Simpler models can be worked out by assuming that both temperature and pressure are uniform in the whole region (0-D assumption). This assumption, motivated by the intense recirculation of gases and adopted also in (Schoen, 1993) for a different type of gasifier, is adopted herein. The proposed model is able to capture the process fundamental dynamics with a low complexity degree, thus ensuring both clear physical insight and short simulation times, in view of the study of control strategies.

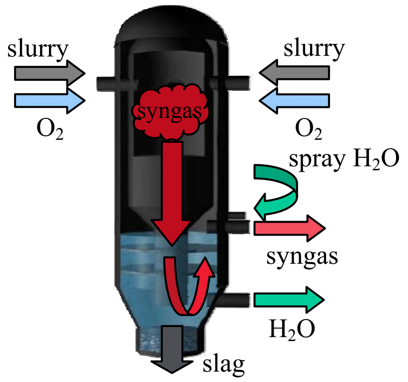

Fig. 1. The GE-Texaco gasifier: schematic view.

The following subsections report the conservation equations employed to model each phase and a reaction kinetic description for the second phase. Table 1 collects the main symbols employed.

Table 1. Nomenclature

Symbol	Description	Unit
c	Specific heat	kJ/(kg·K)
e	Relative energy	kJ/kg
f	Mass fraction	-
h	Relative enthalpy	kJ/kg
$j_k^{(r)}$	Component *k* stoichiometric coefficient in reaction *r*=1,..,5	-
p	Pressure	bar
w	Mass flow rate	kg/s
$\tilde{w}$	Molar flow rate	kmol/s
x	Molar fraction	-
A	Area	m^2
L	Length	m
M	Mass	kg
PM_k	Component *k* molecular weight	kg/kmol
Q	Thermal power	W
S_{ch}	Char active surface	m^2
T	Temperature	K
V	Volume	m^3
β	Mass exchange coefficient	kg/(N·s)
γ	Convective energy exchange coefficient	W/(K·m^2)
ρ	Density	kg/m^3
Ω	Equivalent perimeter	m
	Subscripts	
c	Cooling region	
ch	Char	
d/u	Volume under/above the cooling liquid surface	
ev/vol	Resulting from evaporation/devolatilisation	
g/l	Gas/liquid phase	
g-l	Exchange between gas and liquid phases	
in/out	At the inlet/outlet of the region under study	
int/ext	Internal/external chamber	
sat	Saturation	
sh	Shift reaction	
sl	Slurry	
surf	Char surface	

2.1 Drying and Devolatilisation

The coal slurry injected into the gasifier forms a jet of length L_{ev} where the water evaporates heated by the hot gases. Then, after water evaporation, the volatile release takes place, due to further heating of the mass of dried coal.

The mass conservation equations for the liquid water and the dry char are respectively

$$\rho_{H_2O}\bar{A}_{H_2O}\dot{L}_{ev} = w_{sl} f_{H_2O,in} - w_{ev}\,, \tag{6}$$

$$\begin{aligned} \dot{M}_{dry} \equiv \frac{d(\rho_{dry}\bar{A}_{dry}L_{ev})}{dt} &= w_{sl}(1 - f_{H_2O,in}) + \\ &- M_{dry}u_j \big/ L_{ev} + \rho_{dry}\bar{A}_{dry}\dot{L}_{ev}, \end{aligned} \tag{7}$$

where $\bar{A}_{H_2O}$ is the evaporation average equivalent area for water and $\bar{A}_{dry}$ is the equivalent area for char,