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CSFB applied to fluidized-bed gasification of special fuels

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ABSTRACT

The new version of a comprehensive simulation program of moving and fluidized-beds (CSFB or CSFMB) has been tested against data generated from a gasification unit at the University of California at Davis (UCD), Department of Biological and Agricultural Engineering. The pilot operated at atmospheric pressure under bubbling fluidized-bed and consumed various biomasses as well residues. Air was used as gasifying agent and electrical resistances around the reactor helped heating the reactor during start-up and were kept under low energy discharge during experiments. CSFMB was adapted to allow simulation of such cases as well to several other possibilities of additional heating systems to reactors. The present paper presents the results from cases of almond shells and walnut pruning gasification. Good to reasonable agreement between simulation and operational data have been obtained.

1. Introduction

Since its first version [1,2] the mathematical model and respective simulation program of a comprehensive simulator for moving and fluidized-bed equipment (CSFB or CSFMB) has been improved and applied to various classes of equipment consuming a wide range of fuels [3–24]. Among the simulated units, there were: boilers, gasifiers, shale retorting reactors, dryers and pyrolysers consuming various coal ranks, biomasses, and residues. Recently [25], a new version CSFMB was developed to simulate cases of units with special heating devices, such as:

(a) Electrical resistances around the reactor or in its interior.
(b) Steam or hot gas passing through jackets around the reactor.
(c) Steam or hot gas injected into tube banks inserted into the reactor.

All those methods can be applied to any case of bubbling, circulating or even updraft and downdraft moving bed equipment.

The simulation program has been successfully tested against many operations of boilers, gasifiers, and oil shale retorting [1–6,13–15,18–25]. However, none of those included electrically heated units. Of course, application of electrical power might be difficult to justify for most of industrial-scale processes. Despite that, the tests were a good source for testing CSFMB in such situation and this paper is devoted to the two first cases reported by UCD team [26]. Other comparisons should follow soon.

2. Adaptation to simulate equipment with additional heating

The fundamental aspects of the mathematical model and simulation strategy are summarized at the Appendix. Detailed description of the model basic equations and correlations in which the last version is based upon can be found in recent publications [24,25]. That version already includes the possibilities of using jackets around the bed and freeboard regions. Hot or cold gases or liquids can be injected into the jacket or jackets to exchange heat with various regions of the equipment. Since the model takes into account terms related to the heat transfer between the equipment interior and jackets, any other energy source terms can also be added to the energy balances (represented by Eqs. A.5 and A.11 at Ref. [25]). Consequently, the adaptation to simulate the effect of electrical heating is a straightforward because the rate of energy delivered by resistances could be imposed as evenly distributed throughout the section coated by them.

3. Experimental results

Several tests were carried at a pilot gasification unit at the UCD Department of Biological and Agricultural Engineering consuming almond shells, walnut pruning, rice straw, whole tree wood chips, sludge and non-recyclable waste paper [26].

The basic characteristics of the reactor are described in Table 1.

As mentioned above, the present paper concentrates in the cases of almond shells and walnut pruning with properties shown in Table 2. Table 3 lists the main operational conditions for each test.

Alumina-Silicate (43.5% Al_2O_3 and 53.5% SiO_2) was employed as inert material for the bed. Its apparent particle density was around

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Table 1
Main design data of UCD gasifier.

Basic characteristic	Value
Bed internal diameter	0.073 m
Freeboard internal diameter	0.127 m
Average bed dynamic height	1.0 m
Total internal height[a]	1.4 m
Average operational pressure	101 kPa
Average temperature of injected air	293 K
Position of fuel feeding[a]	0.025 m
Thickness of reactor insulation	0.1 m
Insulation average thermal conductivity	0.6 W m^{-1} K^{-1}
Thickness of distributor porous plate	0.1 m
Distributor average thermal conductivity	0.3 W m^{-1} K^{-1}

[a] From the distributor internal surface.

Table 2
Characteristics of the solid fuels fed into the gasifier.

Properities	Biomass	
	Almond shell	Walnut pruning
Proximate analysis (w.b. %)		
Moisture	9.00	14.3
Volatiles	53.51	69.25
Fixed carbon	13.47	13.54
Ultimate analysis (% d.b.)[a]		
C	36.27	48.20
H	3.94	4.41
N	0.79	0.59
O	32.38	44.34
S	0.05	0.03
Ash	26.57	2.43
HHV (d.b.) (MJ/kg)	15.1	19.0
Particle app. density (kg/m^3)	1070	1010
Particle true density (kg/m^3)	1500	1490
Particle size distribution		
Sieve opening (mm)	% Mass retained	
2.000	0.6	0.0
1.410	3.3	0.1
0.851	6.5	3.0
0.420	27.5	65.2[b]
0.149	32.2	22.5
<0.149	29.7	9.2

[a] According to private communication with UCD team, few values are a bit different from the published in the original report [26].
[b] Corrected value from original report [26] to allow consistency.

Table 3
Main operational conditions during two tests of UCD gasification experiments.

Operational condition	Test	
	Almond shell first test (AS1)	Walnut prunings first test (WP1)
Fuel feeding (kg/s)	2.120×10^{-3}	1.482×10^{-3}
Injected air flow (kg/s)	4.80×10^{-4}	6.05×10^{-4}
Oxygen ratio (%)	5.97	9.20
Injected air temperature (K)	293	576
Mass of inert initially in the bed (kg)	0.866	0.433

2700 kg/m^3 and almost all particles passed through the 0.5 mm and were retained at 0.21 mm sieve apertures.

Tables 4 and 5 illustrate the comparisons between real operations and simulation results.

4. Discussion

Tables 4 and 5 demonstrate that CSFMB is able to reproduce relatively well the experimental tests carried by UCD. Not only the concentration of species in the produced gases, but also tempera-

Table 4
Composition of gas produced during real operations of UCD gasifier and respective simulation results.

Composition of produced gas (mol%, dry and tar free)	Test			
	AS1		WP1	
	Real	Simulation	Real	Simulation
H_2	13	13.6500	10	10.5315
H_2S	n.d.	0.0022	n.d.	0.0005
NH_3	0.503	0.9028	0.199	0.0000
NO	n.d.	0.0000	n.d.	0.0000
NO_2	n.d.	0.0000	n.d.	0.0000
N_2	39	40.0834	42	39.5875
N_2O	n.d.	0.0000	n.d.	0.0000
O_2	1	0.0000	3	0.0000
SO_2	n.d.	0.0073	n.d.	0.0025
CO	20	18.7722	22	22.3692
CO_2	20	17.7035	16	17.6226
HCN	0	0.0014	0	0.0000
CH_4	7	7.7099	7	9.3476
C_2H_4	n.d.	0.4307	n.d.	0.0446
C_2H_6	n.d.	0.1046	n.d.	0.0000
C_3H_6	n.d.	0.0000	n.d.	0.0000
C_3H_8	n.d.	0.0000	n.d.	0.0000
C_6H_6	n.d.	0.1575	n.d.	0.0244
Ar	n.d.	0.4745	n.d.	0.4697

n.d.: not determined or reported.

tures and even rates of elutriated particles were simulated within acceptable deviations.

Utilizing the features of CSFMB, few graphs showing the profiles of main process variables are presented at Figs. 1–7.

Fig. 1 reveals that, for most of the bed, all temperatures are very close to the average, while Fig. 2 the same however with steady decreases of temperatures in the freeboard. In contrast, many bubbling fluidization processes lead to surges of temperature in the bed and not so linear profiles in the freeboard [1–25]. For instance, in many cases temperature of bubbles depart significantly from the average at intermediary regions of the bed. This is so due the following sequence of events:

(1) At the distributor, part of the injected oxidant gas (air or mixtures with oxygen) forms bubbles and the remaining flows to the emulsion phase.
(2) As the emulsion retains almost all solid fuel particles, little or no oxygen remains in that phase at positions not too far from the distributor. That reducing condition allows the increases in concentrations of fuel gases produced by gasification reactions.
(3) On the other hand, bubbles are relatively free of fuel particles and remain relatively cold, even at regions well above the distributor.
(4) In their progress toward the top, bubbles receive fuel gases migrating from the emulsion phase. While the bubbles remain relatively cold, the oxygen does not significantly react with those gases. However, once their temperature rise due to heat exchange with the emulsion, ignition of the combustible gases occur, leading to the temperature surge.
(5) After that, the temperature of bubbles tends to follow the average in the bed.

If the rate of oxygen (or air) injection into the bed is relatively low, the surge of temperature is not too pronounced, as illustrated by Fig. 1.

As described above as well at the Appendix, the different concentrations of gases found in the emulsion and bubbles drive the intense mass transfers between these phases. Such process greatly influences combustion and gasification in bubbling fluidized-beds [1–25]. CSFMB provides the concentration profiles of 18 gaseous