Reciprocating Biomass Conversion Reactor (RBCR)

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Abstract—**The reciprocating biomass conversion reactor (RBCR) is a novel means to produce bio-oil by fast-pyrolysis whose core is a re-purposed 4-cycle internal combustion engine. An inert gas and a small volume-fraction of pulverized biomass are input into the RBCR intake, and the crankshaft is cycled by an external energy source to supply the process heat. The biomass is converted during the compression stroke, and then the bio-products are exhausted. The cycle is: intake, compression/heating, expansion/cooling, and exhaust. This strategy is unique in its reciprocating approach and the potential benefits of the RBCR relative to the state of the art are increased efficiency, throughput, and bio-oil quality.**

I. Introduction

Thermo-chemical biomass conversion by fast pyrolysis to bio-oil, bio-char, and bio-gas is a part of an attractive path to an alternative energy source because of the upgrade in heating value and density [1] so that it may be easily transported as part of a new distribution network [2]. Biomass is pulverized, pyrolyzed, and the bio-products are recovered. Bio-oil can be used directly in boilers (i.e., for heating or electricity), or upgraded for use as a "drop-in" fuel [3]. There are a number of reactor types for fast pyrolysis: entrained flow reactor, wire mesh reactor, vacuum furnace reactor, vortex reactor, rotating reactor, microwave reactor, fluidized-bed reactor, and the circulating fluidized-bed reactor [4]. Some of these reactors are complicated and require a large external energy source for operation. The fluidized-bed reactor (FBR) is representative of
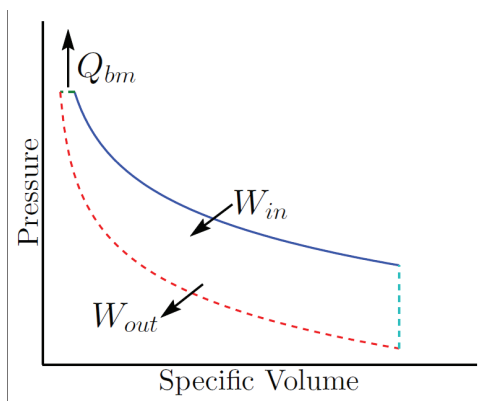

Fig. 1. Idealization of RBCR cycle; cycle proceeds counter-clockwise. Isentropic compression of dusty-gas/fluidizing-gas mixture W_{in}, isobaric heat transfer from the fluidizing gas to the biomass Q_{bm}, and then isentropic expansion of bio-products for energy recovery W_{out}.

the current state of the art; the FBR requires a condenser to cool the bio-products and quench the undesirable secondary pyrolysis reactions [4].

The reciprocating biomass conversion reactor (RBCR) is a novel scheme for thermo-chemical conversion of biomass to bio-products. At its essence, the conversion scheme is a high compression-ratio motor being cycled by an external power source to efficiently provide process heat to biomass. The typical Diesel cycle is intake, compression, power, and exhaust; in the RBCR, this is replaced with: intake, compression/heating, expansion/cooling, and exhaust. The idealized cycle for the proposed biomass conversion scheme, as in Fig. 1, proceeds as follows: A two-phase mixture of a non-oxidizing fluidizing gas (Ar, N_2, or a CO/CO_2 mixture) and a small volume-fraction of pulverized biomass are input into the cylinder of a high compression-ratio engine. An external power source turns the crankshaft which drives the piston to compress and heat the biomass/fluidizing-gas mixture within the cylinder (W_{in} in Fig. 1). Process heat is transferred from the fluidizing gas to the biomass (Q_{bm} in Fig. 1); this process heat is sufficient to heat and thermo-chemically convert the biomass to bio-products by fast pyrolysis. The expansion stroke rapidly decreases the temperature and pressure of the fluidizing-gas/bio-products mixture within the cylinder, and a fraction of the energy required to compress the system is recovered (W_{out} in Fig. 1). The recovered energy may be used on the compression stroke of another cylinder on the same crankshaft. The exhaust stroke forces the fluidizing-gas/bio-products mixture from the cylinder.

In this paper, an overview and results of a model are presented for the decomposition of multi-component biomass in a reciprocating biomass conversion reactor (RBCR).

II. Model Formulation

Here, we analyze the compression and expansion strokes of the RBCR cycle with a closed, transient control volume. In this control volume are a well-mixed and evenly distributed fluidizing gas and biomass/bio-products mixture. Q is the energy that is transferred into a control volume by heat transfer, W is is the energy that is transferred out of a control volume by work, and H_P is the energy required to pyrolyze the biomass. The subscripts b, g, and s represent the biomass, fluidizing gas, and surroundings, respectively. Two subscripts in succession indicate "from a to b," e.g., Q_{bg} is the energy

TABLE I
BIOMASS COMPOSITION FRACTION [11]

Feedstock	Cellulose	Hemicellulose	Lignin
Pure Cellulose	1.00	0.00	0.00
Bagasse	0.36	0.47	0.17
Oak	0.35	0.40	0.25
Olive Husk	0.22	0.33	0.45

Fig. 2. Mechanism for pyrolysis adapted from [11], [16]–[27]. j may be cellulose C, hemicellulose H, or lignin, L.

transferred from the biomass to the fluidizing gas by heat transfer.

Following [5], differential equations are formulated from the application of the first law to the fluidizing gas and the biomass/bio-products in the reactor. The time-rate form of the first law applied to the fluidizing gas is

$$c_{vg} n_g \frac{dT_g}{dt} = \dot{Q}_{sg} + \dot{Q}_{bg} - P\frac{dV_g}{dt}. \tag{1}$$

The biomass is assumed to be a collection of independent spheres that act as a lumped mass. We write the time-rate form of the first law applied to the biomass to predict the biomass temperature (T_b) change as

$$m_b c_b \frac{dT_b}{dt} = -\dot{Q}_{bg} + \dot{Q}_{sb} + \dot{Q}_{\Delta h}. \tag{2}$$

Radiation and combined natural/forced convection are included in both heat-transfer terms in Eqs. 1 and 2. The combined natural/forced heat transfer coefficients are found from correlations [6]. The convection to the walls [7] and to the biomass [8] are assumed to be steady by non-dimensional analysis. Mass transfer will alter the heat transfer coefficient to the biomass, so the high mass-transfer rate film theory correction is used to modify the heat transfer coefficient [9], [10].

The emerging nature of the biomass pyrolysis modeling field (reviews in [12]–[15]) presents a number of options to model the production rates of bio-products. We choose a model which "super poses" cellulose, hemicellulose, and lignin as

$$m_b = m_c + m_h + m_l \tag{3}$$

where m_c, m_h, and m_l are the individual masses of cellulose, hemicellulose, and lignin, respectively. Examples of different compositions are given in Table I.

The mechanism to predict the decomposition of biomass closely follows the development in references [11], [16]–[27]. In particular, the works by Xue et al. [26], [27] have resulted in a model which will be used for this work. The mechanism appears as Fig. 2, and pictorially depicts how the cellulose, hemicellulose, and lignin decompose. The indicies for each component can be found in Table II.
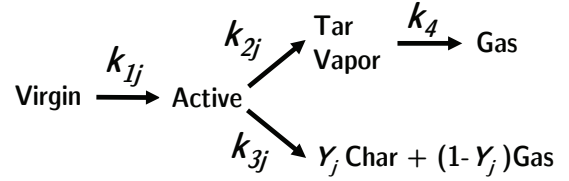
TABLE II
INDICIES OF EACH COMPONENT

Component	Index
Virgin Cellulose	1
Virgin Hemicellulose	2
Virgin Lignin	3
Active Cellulose	4
Active Hemicellulose	5
Active Lignin	6
Tar Vapor	7
Gas	8
Char	9

The equations for each component in Fig. 2 are written as

$$\dot{m}_1 = -k_{1C}m_1 \tag{4a}$$
$$\dot{m}_2 = -k_{1H}m_2 \tag{4b}$$
$$\dot{m}_3 = -k_{1L}m_3 \tag{4c}$$
$$\dot{m}_4 = k_{1C}m_1 - k_{2C}m_4 - k_{3C}m_4 \tag{4d}$$
$$\dot{m}_5 = k_{1H}m_2 - k_{2H}m_5 - k_{3H}m_5 \tag{4e}$$
$$\dot{m}_6 = k_{1L}m_3 - k_{2L}m_6 - k_{3L}m_6 \tag{4f}$$
$$\dot{m}_7 = k_{2C}m_4 + k_{2H}m_5 + k_{2L}m_6 - k_4 m_7 \tag{4g}$$
$$\dot{m}_8 = (1-Y_C)k_{3C}m_4 + (1-Y_H)k_{3H}m_H+ \tag{4h}$$
$$(1-Y_L)k_{3L}m_6 - \Gamma \tag{4i}$$
$$\dot{m}_9 = Y_C k_{3C}m_4 + Y_H k_{3H}m_H + Y_L k_{3L}m_6 + \Gamma \tag{4j}$$

where gamma is the rate at which char is formed in the pores in the biomass, per Xue et al. [26], [27],

$$\Gamma = \frac{\rho_g}{\rho_b}(\dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 + \dot{m}_5 + \dot{m}_6) - \frac{\rho_g}{\rho_c}\dot{m}_9 \tag{5}$$

The first-order kinetic rates of Arrhenius form, $k_i = A_i \exp(E_i/(R_u T_b))$, are tabulated in Xue et al. [26], [27]. The char formations ratios are $Y_C = 0.35$, $Y_H = 0.60$, and $Y_L = 0.75$, for cellulose, hemicellulose, and lignin, respectively [11], [16], [20], [26].

The heat required for the steps in Fig. 2 is accounted for as $\dot{Q}_{\Delta h}$ in Eq.2. The energies required for each step are given in [21], [23].

Thermo-physical properties for the fluidizing gas are calculated using Cantera [28] with the appropriate thermodynamic data [29] fitted to polynomials of temperature. The biomass true density is assumed to be that of cellulose:

$\rho_b = 1580$ kg/m³ [30]. The specific heat of the biomass (c_b) is assumed to be that of cellulose given in [31].

The system of implicit ordinary differential equations, Eqs. 1, 2, and 4, are integrated in time to calculate the evolution of pressure, biomass temperature, fluidizing-gas temperature, and conversion fractions for the compression and expansion strokes of the RBCR. The initial conditions are:

- The biomass begins as virgin material (Fig. 2).
- The initial biomass and fluidizing-gas temperatures are $T_b = T_g = 22°C$.
- The mass of the biomass m_b and the biomass radius r_b are specified for one cycle.

MATLAB [32] is used to perform the integration for the implicit equations for prescribed cycle period, which is determined by the engine speed. The results for the integrations presented herein are not sensitive to the ODE solver tolerance, bringing confidence in the calculation result.

III. CONVERSION OF BAGASSE IN A RBCR

In this section, we apply the model described in Section II to the decomposition of Bagasse in a RBCR. The core of the reactor is a 4-stroke 7.3 L Diesel motor with a compression ratio of 21.5. A mixture of argon and spherical biomass particles 50 μm in diameter is injected into the intake of the engine. The composition of the biomass is split between cellulose, hemicellulose, and lignin to simulate bagasse decomposition (Table I).

Parameters and results for the decomposition of Bagasse are given in Table III. Tabulated are: number of cylinders, bore, stroke, engine speed, mass flow of fluidizing gas $\dot{m}_{FG}$, volume-fraction of biomass V_F, the input energy per unit mass of biomass required to thermo-chemically convert the biomass e_{in}, and the feed rate of biomass $\dot{m}_b$. The ratio of power

TABLE III
COMPARISON OF CALCULATED RBCR RESULTS WITH EXPERIMENTAL LAB-SCALE FLUIDIZED-BED REACTOR RESULTS.

Parameter	RBCR	Lab FBR [34]
Cylindersrs	8	-
Bore	104 mm	-
Stroke	106 mm	-
RPM	400	-
$\dot{m}_{FG/CG}$	18.9 kg/hr (Ar)	4.8 kg/hr (N_2)
V_F	52 ppm	0.46 (wt/wt)
$\dot{m}_b$	7.58 kg/hr	2.2 kg/hr
Feedstock	Bagasse	Switchgrass
e_{in}	1.52 MJ/kg	3.5 MJ/kg
η	9.4	3.5
Input particle diameter	50 μm	<500 μm

available from bio-oil out to the power required to operate the reactor, η is also tabulated.

$$\eta = \frac{\dot{m}_b Q_{hv} X_{tv/bo}}{\dot{Q}_{in}} \quad (6)$$

where $Q_{hv} \approx 20$ MJ/kg is the heating value of bio-oil [33], $Y_{tv/bo}$ is the mass fraction of tar vapor or bio-oil for the calculations and the experimental results, respectively. The power supplied to the reactor is $\dot{Q}_{in}$. Experimental results from a lab-scale fluidized bed reactor (Lab FBR) are taken from the literature [34] for the purposes of comparison.

A time-history of reactor pressure P, fluidizing-gas temperature T_g, and biomass temperature T_b for the reactor is presented as Fig. 3 for the compression and expansion strokes of the RBCR cycle. The temperatures and heating rates are consistent with those found in the literature [4] for fast pyrolysis. In Fig. 4, the biomass weight fraction evolution
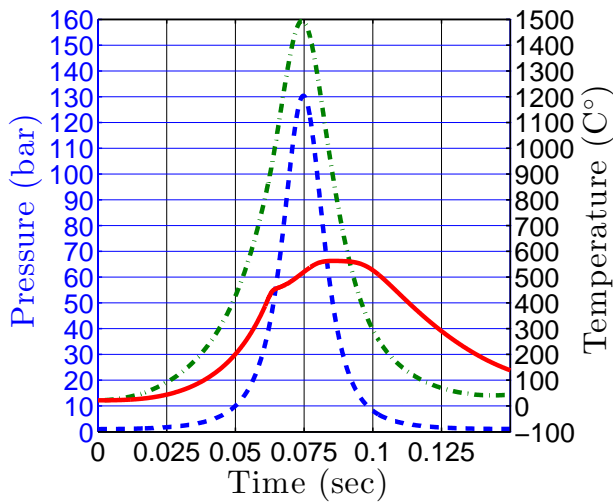

Fig. 3. Compression (0-0.075 s) and expansion (0.075-0.130 s) strokes for the pilot-scale experiment. Calculation of reactor pressure P (blue, dashed), fluidizing-gas temperature T_g in (green, dashed-dot), and biomass temperature T_b (red, solid) for a reciprocating engine used for thermo-chemical biomass conversion.
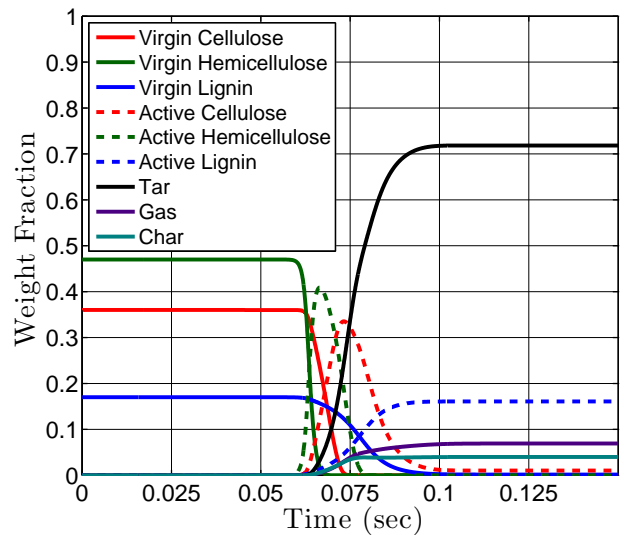

Fig. 4. Compression (0-0.075 s) and expansion (0.075-0.130 s) strokes for the pilot-scale experiment. Calculated weight fractions vs. time per the model formulated in Section II.

is presented per the model formulated in Section II. The virgin/active cellulose and hemicellulose is degraded primarily between 0.06-0.10 s.

IV. Summary and Conclusion

In this paper, a model is formulated for the decomposition of multi-component biomass in a reciprocating biomass conversion reactor (RBCR). The RBCR decomposition of Bagasse calculations compare favorably to the experimental data for a lab scale fluidized bed reaction. Calculations indicate that the efficiency is increased by greater than 50%. The throughput also compares favorably to the FBR, as the RBCR is able to process significantly more biomass (3x). Such efficiency and throughput increases would result in a decrease in the operational costs of biomass conversion. The RBCR permits control over the residence time within the reactor so that unwanted reactions will not take place; this quenching occurs during the rapid expansion stroke in the RBCR. This process is in direct contrast to the FBR where the pyrolysis products must be processed by condensers to quench the unwanted secondary reactions.

Acknowledgment

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