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NOVEL THERMO-CHEMICAL BIOMASS CONVERSION WITH THE RECIPROCATING BIOMASS CONVERSION REACTOR (RBCR)

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Introduction

The reciprocating biomass conversion reactor (RBCR) is a novel means of converting biomass to bio-oil. The RBCR is a repurposed high-compression 4-stroke internal combustion engine into which a fluidizing gas and a small volume fraction of pulverized biomass are introduced, and the crankshaft is cycled by an external energy source to supply the process heat for thermo-chemical conversion (Fig. 1). The RBCR uses a four-stroke process: 1) intake biomass/fluidizing gas, 2) compression for heating/conversion, 3) expansion for cooling/quenching, and 4) exhaust. Relative to the state of the art (which we consider to be the fluidized bed reactor), calculations predict that, for a comparable footprint, the RBCR can increase the biomass throughput by greater than 100% and decrease the mass-specific energy requirement by more than 50% to thermo-chemically convert biomass to bio-oil, bio-char, and bio-gas by fast-pyrolysis.

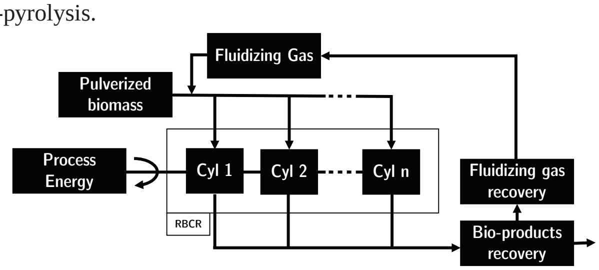

Figure 1. Reciprocating biomass conversion reactor (RBCR) process.

The increase in efficiency relative to the state of the art is derived from the expansion stroke. The instant following desired biomass conversion, the bio-products and fluidizing gas reside within the cylinder at an elevated temperature and pressure. This is surplus process heat, and in contrast to the state of the art, the surplus process heat is easily reused by mechanical transfer through the crankshaft to another piston/cylinder during the expansion stroke. Moreover, the expansion stroke rapidly quenches the undesirable secondary pyrolysis reactions an order of magnitude more quickly than the state of the art, which will improve the bio-oil quality because the residence time can be accurately controlled.

Control Volume Analysis of RBCR

Here, we analyze a closed, transient control volume, presented as Fig. 2 which surrounds one cylinder of the RBCR shown in Fig. 1. More details can be found in Parziale.[1] There is a well-mixed and evenly distributed fluidizing gas and biomass/bio-products mixture in this control volume. In Fig. 2, Q is the energy that is transferred into a control volume by heat transfer and is quantified with correlations from Bird,[2] W is is the energy that is transferred out of a control volume by work, and ΔH_P is the change in enthalpy required to pyrolyze the biomass. The subscripts b, g, and w represent the biomass, fluidizing gas, and wall, respectively.

The change in internal energy for the fluidizing gas is $\Delta U_g = c_{vg} n_g \Delta T_g$ and the work term is $W_{gw} = P\Delta V_g$. Here, c_{vg}, n_g, ΔT_g, and V_g

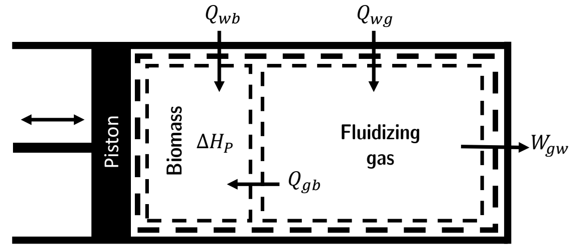

Figure 2. Transient closed control volume for analysis of the compression and expansion strokes of the RBCR. We assume a well-mixed and evenly distributed fluidizing gas and biomass/bio-products mixture in this control volume; they are separated only to clearly show the direction of energy flow.

are the constant-volume molar specific heat, number of moles, change in temperature, and volume of the fluidizing gas, respectively. The first law for the control volume of the fluidzing gas can be rewritten as written as

$$\frac{dT_g}{dt} = \left(-\dot{Q}_{gb} + \dot{Q}_{wg} - P\frac{dV_g}{dt}\right)/(c_{vg}n_g). \tag{1}$$

The change in enthalpy of the biomass, ΔH_b, includes the change in sensible enthalpy, ΔH_S, and enthalpy of pyrolysis reactions, ΔH_P, as $\Delta H_b = \Delta H_S + \Delta H_P = \Delta U_b + \Delta(PV_b)$. We assume that there is no volumetric change of the biomass. The change in enthalpy due to pyrolysis is $\Delta H_P = m_P \Delta h_P$, and the change in sensible enthalpy is $\Delta H_S = m_b c_b \Delta T_b$. Here m_p, Δh_P, m_b, c_b, and ΔT_b are the pyrolyzed mass, mass-specific enthalpy of pyrolysis, biomass mass, biomass specific heat, and change in biomass temperature, respectively. The first law for the control volume for the biomass can be rewritten as

$$\frac{dT_b}{dt} = \left(\dot{Q}_{gb} + \dot{Q}_{wb} - \Delta\dot{H}_P + V_b\frac{dP}{dt}\right)/(m_b c_b). \tag{2}$$

The rate of heat loss from the pyrolysis reactions requires the calculation of the rate at which the biomass is decomposed. This is modeled with a kinetics mechanism found in the literature.[3]

$$\dot{m}_{VC} = -k_{CA}m_{VC} - k_{CC}m_{VC}, \tag{3a}$$
$$\dot{m}_{CW} = k_{CC}m_{VC} + k_{AC}m_{AC}, \tag{3b}$$
$$\dot{m}_{AC} = k_{CA}m_{VC} - k_{AC}m_{AC} - k_{AG}m_{AC} - k_{AV}m_{AC}, \tag{3c}$$
$$\dot{m}_{PV} = k_{AV}m_{AC} - k_{VG}m_{PV} - k_{VT}m_{PV}, \tag{3d}$$
$$\dot{m}_{SG} = k_{AG}m_{AC} + k_{VG}m_{PV}, \tag{3e}$$
$$\dot{m}_{ST} = k_{VT}m_{PV}. \tag{3f}$$

Here, VC is virgin cellulose, CW is Char and H_2O, AC is active cellulose, PV is pyrolysis vapor, SG is secondary gas, and ST is secondary tar. Equations 1, 2, and 3 form a series of eight coupled ODEs which may be integrated in time through the compression and expansion strokes of the RBCR to predict performance and conversion fraction.

Preliminary Heat-Transfer Model Results

A single-cylinder diesel engine (Fig. 3) was used to assess the accuracy of the heat transfer model described earlier. The engine was manufactured by Carroll Stream, and relevant specs are 418 cc, 86 mm bore, 72 mm stroke, 19:1 geometric compression ratio, and 13:1 effective compression ratio. Room air is used as the fluidizing gas, and no biomass is injected. The engine is cycled with the electric starter motor at 450 RPM. Pressure within the cylinder is measured with a fast-response pressure transducer (PCB 113b22/482b05) that is placed in the direct injection port. The experimental results are shown in Fig. 4 with circular markers. These are compared to results from the model presented in the previous section with the effective compression ratio equal to 13:1; the lower effective compression ratio is a result of valve timing, and valve and piston ring blow-by.

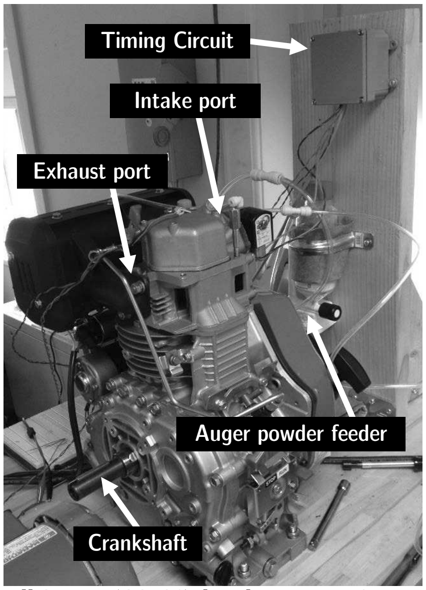

Figure 3. Carroll Stream (CS186) diesel engine. 418 cc, 4 Stroke, Single Cylinder.

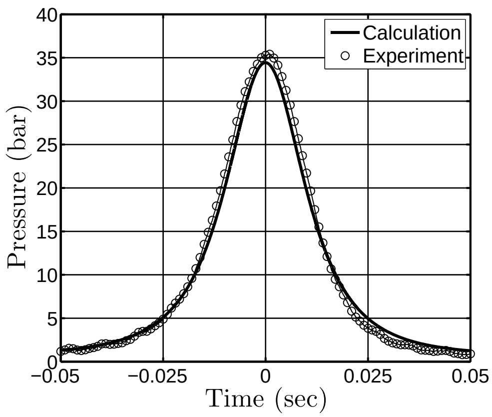

Figure 4. Pressure vs. time within the CS186 engine for air without biomass.

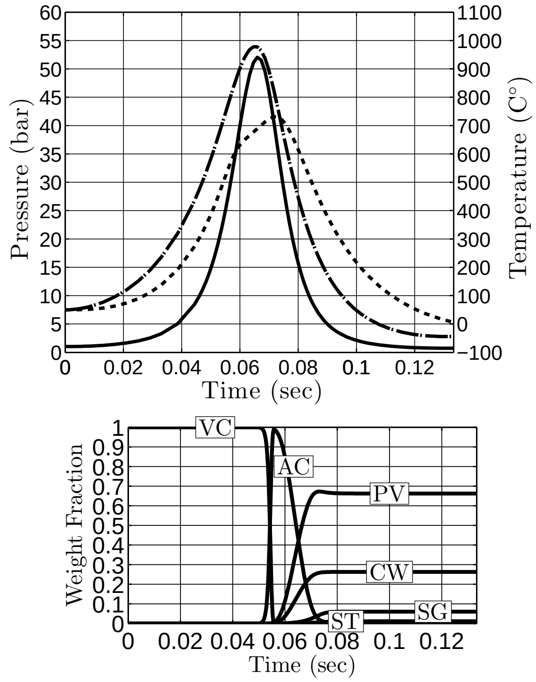

Figure 5. Compression (0-0.06 s) and expansion (0.06-0.12 s) strokes for the pilot-scale experiment. *Top:* Calculation of reactor pressure P (solid), fluidizing-gas temperature T_g (dashed-dot), and biomass temperature T_b (dashed). *Bottom:* Weight fraction evloution. VC: Virgin Cellulose, CW: Char and H_2O, AC: Active Cellulose, PV: Pyrolysis Vapor, SG: Secondary Gas, ST: Secondary Tar.

Extrapolation to Lab Scale and Comparison to the State of the Art

Qualitatively similar calculation results can be obtained for a larger scale 7.3 L, 8-cylinder RBCR. This is of similar footprint to a fluidized bed reactor (FBR) at the lab scale reported in Boateng et al.[4] In the 7.3 L engine, we assume that argon is used as the fluidizing gas and the engine has an effective compression ratio of 13:1. The evolution of temperature, pressure, and weight fraction (Fig. 5) within the RBCR is calculated using the model for heat transfer and chemical kinetics discussed previously. The biomass is assumed to have the thermo-physical properties of cornstover.[5] The heating and cooling rate of the biomass and bio-products are in excess of 5000°C/s which results in precise control over the distribution of bio-products because the secondary pyrolysis reactions may be quenched. We assume that because the footprint of the FBR and RBCR reactors are similar, that the capital costs are also similar; so, comparison at this scale is appropriate. Calculations in Parziale[1] indicate the input energy per unit mass of biomass required for conversion (e_{in}), is reduced from 3.5 MJ/kg in a FBR to 1.8 MJ/kg in a RBCR. The biomass feedrate ($\dot{m}_b$) is increased from 2.2 kg/hr in a FBR to 4.3 kg/hr in a RBCR. And the ratio of power available from bio-oil out to the power required to operate the reactor (η) is increased from 3.5 in a FBR to 7.6 in a RBCR.

Conclusions and Future Work

A model to predict the temperature, pressure, and weight fractions of bio-products in a novel biomass conversion scheme is outlined. This model predicts that, at comparable scale, the reciprocating biomass conversion reactor (RBCR) improves performance relative to the state of the art; in this case: a fluidized bed reactor (FBR).

Testing of a small-scale RBCR comprised of a single-cylinder diesel engine has begun. The heat-transfer model is tested by cycling the engine with the starter motor and running room air with no biomass into the intake. Pressure data indicate excellent agreement if the effective compression ratio is adjusted to 13:1 (down from the geometric compression ratio of 19:1). The reduction in effective compression ratio is expected.

In the future, an appropriate external electric motor will be installed so that the RBCR may be cycled with argon as the fluidizing gas; this is not currently possible because the starter motor does not have the requisite torque to do so. Additionally, an auger-style powder feeder will dispense biomass into a stream of argon that is pulsed with a timing circuit; this will be triggered by the opening and closing of the RBCR intake valve.

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