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A NOVEL BECCS POWER CYCLE USING CO_2 EXHAUST GAS RECYCLING TO ENHANCE BIOMASS GASIFICATION

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ABSTRACT

Although not yet a mature technology, biomass energy with carbon capture and storage (BECCS) is expected to be the leading negative emissions technology deployed over the 21st century to reduce greenhouse gas (GHG) emissions. In this paper, a novel BECCS cycle using exhaust gas recycling (EGR)-enhanced biomass gasification is described and analysed. This cycle combines an atmospheric gasifier and an Otto cycle engine operating under an oxy-gasification/combustion CCS scheme. Exhaust gasses from the Otto cycle, rich in CO_2 and at high temperature, are recycled to the gasifier to enhance syngas production. Analysis of a representative numerical model illustrates how EGR creates higher system efficiency and lower specific CO_2 emissions while allowing for lower gasifier O_2 equivalence ratios (E/R). Compared to a similar power cycle without EGR, the proposed cycle improved system efficiency from 21.7% to 28.8% while reducing specific CO_2 emissions from the cycle by 25%.

Keywords: Biomass gasification, BECCS, CO_2 gasification, Integrated gasification power cycle, Negative emissions

NONMENCLATURE

Symbols	
$\Delta\hat{h}^0$	Molar standard enthalpy of reaction (kJ/mol)
e_{O_2}	Specific energy of O_2 separation (kJ/kg)
$\dot{m}$	Mass flow (kg/s)
$\dot{n}$	Mole flow (kmol/s)
$\dot{W}$	Power (kW)
η_{sys}	Total system efficiency

1. INTRODUCTION

Negative GHG emissions technologies will likely be needed if 2°C climate warming is to be avoided. BECCS will feature prominently in this role, possibly removing 100-1000 Gt-CO_2 from the atmosphere by the year 2100 according to IPCC modelling [1]. Gasification schemes adopted to the BECCS concept present benefits particularly when considering power generation as the desired system output. Pollutant emissions from gasification plants are lower and material streams are easier to clean. Gasification plants also provide easier and less costly CCS schemes to be implemented for GHG control. Additionally, gasification allows for a wider range of energy conversion technologies and simpler generating systems to be employed by virtue of changing the solid feedstock into a gaseous fuel stream [2]. Recent research has focused on using CO_2 as a medium for gasifying solid biomass fuels [3, 4] to provide a pathway for simultaneously utilising CO_2 produced during power generation while augmenting the output of syngas from the feedstock [5]. Specifically, using CO_2 as a gasifying agent will enhance the Boudouard reaction (eq(1)) by directly providing additional reactant to be converted into CO syngas.

$$C_{(s)} + CO_2 \rightarrow 2CO \; ; \quad \Delta\hat{h}^0 = 172\ kJ/mol \qquad (1)$$

Applications that recycle CO_2 from combustion to enhance gasification within an integrated gasification combined cycle (IGCC) have been investigated for coal-fed systems with Brayton cycle gas turbines and Rankine

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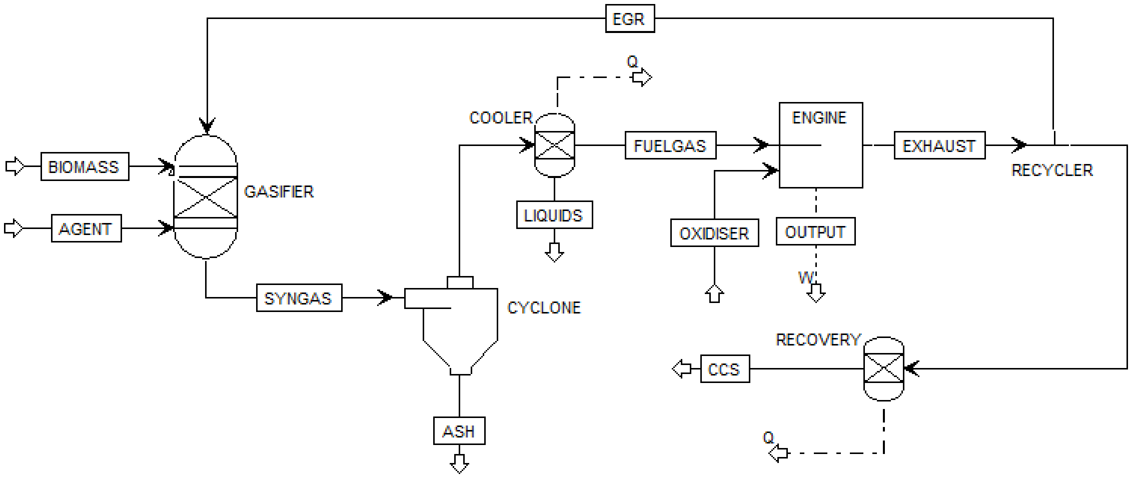

Fig 1: Schematic of proposed Integrated Gasification and Exhaust Recycling System

cycle steam turbines [6, 7] and biomass-fed systems with regenerative gas turbine Brayton cycles [8]. Using exhaust gas recycling (EGR) in these systems not only provides an additional gasifying agent but also uses waste heat to improve gasification processes. These referenced studies use oxy-combustion/gasification methodologies, allowing for direct capture of CO_2 emissions from the power cycles at the expense of separating O_2 from ambient air using an air separation unit (ASU).

In this work, a novel BECCS power cycle will be described along with a numerical model used to analyse system performance. The impact of EGR on this model will also be discussed in the context of overall system efficiency and specific CO_2 emissions from the cycle.

2. SYSTEM DESCRIPTION

The proposed system, shown in Fig 1, is based on an integrated oxy-combustion/gasification cycle using CO_2 EGR to enhance syngas production (ref. [8]). Syngas produced in the gasifier is cooled and dried before being burned in a power generation cycle. A portion of the power cycle exhaust gasses, rich in CO_2 and at high temperature, are returned to the gasifier as gasifying agents. Residual exhaust is cooled and sent to CCS.

A novel feature of this system is the use of an Otto cycle spark ignition engine (SIE) in place of the Brayton cycle turbines or combined gas/steam cycles commonly used in other EGR gasification systems [8, 6]. Internal combustion engines (ICE) are currently the most prevalent energy conversion technology. ICEs are highly scalable between the kW to MW output range, with larger sized engines usually boasting higher conversion efficiencies. These engines also demonstrate a consistent conversion efficiency across a variety of off-design operating points making them ideal for meeting any variability in output requirements [9]. Coupled with low capital costs and good reliability, ICEs are identified as having great potential for use with syngas applications [10]. Despite these advantages and having been shown as a viable option for integration with gasification cycles [11, 12], no efforts to investigate the effects of CO_2 gasification from EGR on such a combined system have been made to date.

2.1 Input Feed Streams

Biomass (48.9% C, 5.8% H, 45.1% O, 0.2%N by mass) and O_2 feeds are introduced to the system at ambient conditions (298 K, 1atm). Biomass feed rate is fixed at 100 kg/h while gasifying agent flow is varied to produce a range of equivalence ratios. Engine O_2 intake is controlled, providing stoichiometric combustion conditions thus ensuring no excess O_2 is returned to the gasifier in the EGR stream. The energy required to generate the O_2 streams in an ASU is assumed to be 576 kJ/kg-O_2 based on AirLiquide ASU technology [13].

2.2 Modelling approach

Aspen Plus commercial simulation software was used to execute numerical modelling of the proposed novel system. The model applies a non-stoichiometric, equilibrium approach to the gasification process following the methods used by others [14]. Energy conversion modelling uses an ideal Otto cycle to represent the power generation process. A custom user model was implemented in Aspen Plus to simulate each Otto cycle process with the relevant thermodynamic calculations for temperature, pressure, and work [15]. A volumetric compression ratio of 10 is assumed for the Otto cycle.

3. RESULTS AND DISCUSSION

3.1 Gasifier model validation

The Aspen gasification equilibrium model was validated against a published numerical simulation with good agreement. Fig 2 compares model gasifier results for an integrated biomass gasifier model with EGR employed [8].

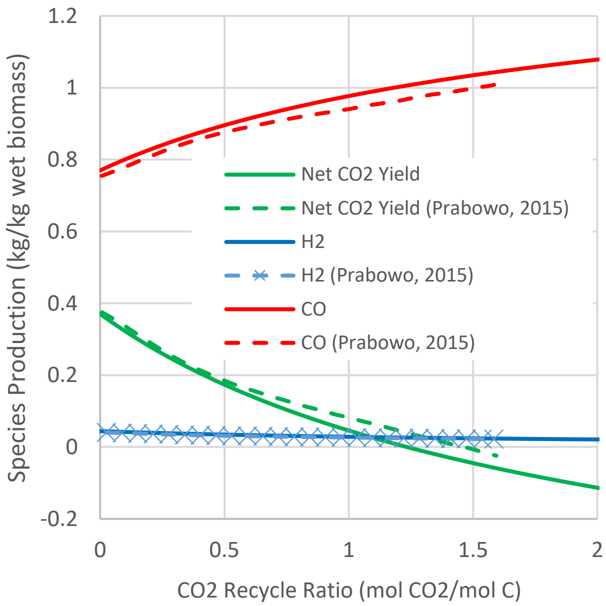

Fig 2: Comparison of syngas composition from a biomass gasifier integrated with CO_2 recycling from gas turbine exhaust. Solid lines represent current model while dashed lines and markers represent published results *[8]*

3.2 Effect of EGR and E/R

Recycling different mass percentages of engine exhaust gasses to the gasifier (Fig 3) shifts the observed efficiency peaks to lower gasifier equivalence ratios (E/R). Gasifier cold gas efficiency (CGE) (eq(2)) improvements from higher exhaust recycling are due to an increase in syngas CO content which in turn is due to the enhancement of the Boudouard reaction through increased CO_2 input to the gasifier. Overall system efficiency (eq(3)) changes only with the gasifier CGE as the Otto cycle thermal efficiency remains relatively insensitive to EGR under these conditions. The fundamental impact of recycling exhaust gasses rich in CO_2 and at high temperature to the gasifier is to increase the gasifier CGE, particularly at lower E/R.

$$CGE = \frac{\dot{n}_{syn}\cdot\overline{LHV}_{syn}}{\dot{m}_{bio}\cdot LHV_{bio} + \left(\dot{m}_{O_2}\cdot e_{O_2}\right)_{gasifier}} \quad (2)$$

$$\eta_{sys} = \frac{\dot{W}_{net,Otto}}{\dot{m}_{bio}\cdot LHV_{bio} + \left(\dot{m}_{O_2}\cdot e_{O_2}\right)_{gasif} + \left(\dot{m}_{O_2}\cdot e_{O_2}\right)_{Otto}} \quad (3)$$

Exploration of overall system efficiency at different E/R across a range of recycling ratios is shown in Fig 4. Peak system efficiencies now occur at lower E/Rs but require higher exhaust recycling. Although individual efficiency peaks are present for each E/R investigated, system performance remains fairly constant beyond the carbon boundary with efficiency variations of less than 0.01 observed. Best system efficiency of 28.80% was observed for E/R of 0.1 and recycling ratio 2.12 mol-CO_2/mol-C_{bio}. Without EGR, peak system efficiency was only 21.73% and required an E/R of 0.3. Efficiency at E/R of 0.3 also increased to 22.62% at a recycling ratio of 2.12 mol-CO_2/mol-C_{bio}.

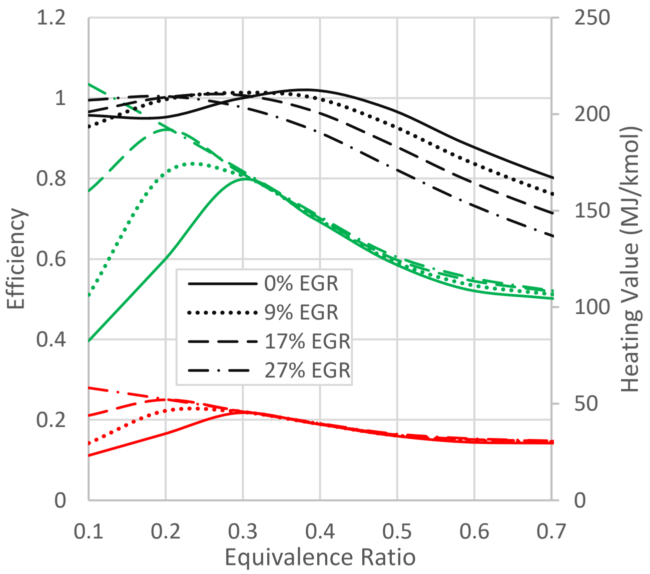

Fig 3: Changes in system efficiency (red), cold gas efficiency (green), and syngas LHV (black) as EGR is increased.

At peak conversion efficiency (η_{sys}=28.8%), the system generated 1.14 kg-CO_2/kWh of net-work. For the baseline case without EGR, the peak efficiency condition corresponded to specific emissions of 1.52 kg-CO_2/kWh. If CCS of these emissions requires pipelining, pressurising the dried exhaust to 150 atm reduces the net-work and thus system efficiencies are reduced by 4.8 percentage points for both the EGR and non-EGR cases.

Gasifier equilibrium temperature peaks just after the carbon boundary before gradually declining as EGR increases. This behaviour suggests that exhaust temperature has an important role in determining gasification temperature since the decreasing trend beyond the CBP can be attributed to the diluting effect of CO_2 decreasing the adiabatic flame temperatures in the Otto cycle. Further temperature reduction is due to the enhancement of the endothermic Boudouard reaction. Despite the decreasing temperature trends beyond the CBP, the peak efficiency point at E/R of 0.1 and recycling ratio 2.12 mol-CO_2/mol-C_{bio} generates an equilibrium gasifier temperature of 1796 K.

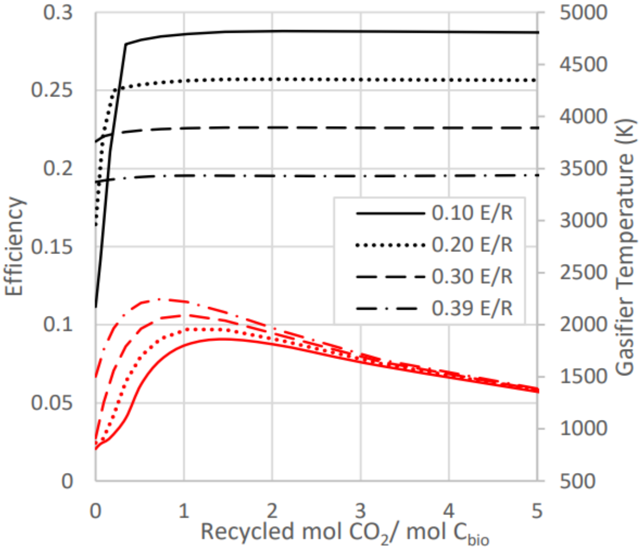

Fig 4: System efficiency (black) and gasifier temperature (red) at selected E/R over a range of CO2 recycling ratios

4. CONCLUSIONS

A novel oxy-gasification/combustion BECCS cycle combining a biomass gasifier and an Otto cycle ICE using EGR-enhanced gasification has been described along with a representative numerical model of the ideal cycle. Results show recycling 2.11 mol-CO_2/mol-C_{bio} to the gasifier from the exhaust stream improves the overall system efficiency from 21.7% at an E/R of 0.3 to 28.8% at an E/R of 0.1. This EGR case also produces the lowest specific CO_2 emissions of 1.14 kg-CO_2/kWh compared to 1.53 kg-CO_2/kWh without EGR. This demonstrates that EGR will improve cycle efficiency, specific CO_2 emissions, and reduce O_2 gasifying agent demand.

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REFERENCES

[1] IPCC, "IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways," IPCC, Incheon, Republic of Korea, 2018.

[2] P. Basu, Biomass gasification and pyrolysis: Practical design and theory, 2nd ed., Boston: Academic Press, 2013.

[3] C. Guizani, O. Louisnard, F. J. Escudero Sanz and S. Salvador, "Gasification of woody biomass under high heating rate conditions in pure CO2: Experiments and modelling," *Biomass and Bioenergy,* vol. 83, pp. 169-182, 2015.

[4] H.-H. Bui, L. Wang, K.-Q. Tran and O. Skreiberg, "CO2 gasification of charcoals produced at various pressures," *Fuel Processing Technology,* vol. 152, pp. 207-214, 2016.

[5] H. C. Butterman and M. J. Castaldi, "CO2 as a Carbon Neutral Fuel Source via Enhanced Biomass Gasification," *Environmental science & technology,* vol. 43, no. 23, pp. 9030-9037, December 2009.

[6] Y. Oki, H. Hamada, M. Kobayashi, I. Yuri and S. Hara, "Development of high-efficiency oxy-fuel IGCC system," in *Energy Procedia*, Lausanne, Switzerland, 2017.

[7] M. E. Walker, J. Abbasian, D. J. Chmielewski and M. J. Castaldi, "Dry Gasification Oxy-combustion Power Cycle," *Energy & Fuels,* vol. 25, pp. 2258-2266, 2011.

[8] B. Prabowo, M. Aziz, K. Umeki, H. Susanto, M. Yan and K. Yoshikawa, "CO2-recycling biomass gasification system for highly efficient and carbon-negative power generation," *Applied Energy,* vol. 158, pp. 97-106, 2015.

[9] P. A. Breeze, Combined Heat and Power, London: Elsevier, 2018.

[10] F. Y. Hagos, A. R. Aziz and S. A. Sulaiman, "Trends of Syngas as a Fuel in Internal Combustion Engines," *Advances in Mechanical Engineering,* pp. 1-10, 2014.

[11] N. P. Perez, E. B. Machin, D. T. Pedroso, J. J. Roberts, J. S. Antunes and J. L. Silveira, "Biomass gasification for combined heat and power generation in the Cuban context: Energetic and economic analysis," *Applied Thermal Engineering,* vol. 90, pp. 1-12, 2015.

[12] M. Baratieri, P. Baggio, B. Bosio and G. A. Longo, "The use of biomass syngas in IC engines and CCGT plants: A comparative analysis," *Applied Thermal Engineering,* vol. 29, pp. 3309-3318, 2009.

[13] J.-P. Tranier, R. Dubettier, A. Darde and N. Perrin, "Air Separation, flue gas compression and purification units for oxy-coal combustion systems," *Energy Procedia,* vol. 4, pp. 966-971, 2011.

[14] A. Ravikiran, T. Renganathan, S. Pushpavanam, R. K. Voolapalli and Y. S. Cho, "Generalized Analysis of Gasifier Performance using Equilibrium Modeling," *Industrial and Engineering Chemistry Research,* vol. 51, pp. 1601-1611, 2012.

[15] J. B. Heywood, Internal Combustion Engine Fundamentals, New York: McGraw-Hill, 1988.