Gasification Based Waste Tire Integrated Energy Conversions Systems

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Abstract

The objective of this study was to evaluate the operating parameters impacts on the performance of a gasification-based waste tire integrated energy conversion system. In this system, the waste tires are put into a downdraft gasifier that is providing fuel for a solid oxide fuel cell (SOFC). The system is evaluated by the syngas production, power generation, and overall efficiency under various operating conditions. A hybrid 1-D model was adopted to perform a parametric study of the tire gasification and calculations were done to estimate the integrated system power generation and overall efficiency using MATLAB. Three parameters were studied: the moisture content of the waste tires, mixture ratio of wood and waste tire, and equivalence ratio (ER). Based on the efficiency of the system, an equivalence ratio of 0.25, 30% moisture content, and 40% mixture ratio were determined to be optimal. Applying these conditions simultaneously to the SOFC simulation resulted in an efficiency of 33% and power output of 1.06(10^8) W. The results show that tire is suitable to be used in a gasification based SOFC integrated system.

Keywords

Gasification, SOFC, Energy Systems

Introduction

Gasification is described as a technological process that converts feedstocks into synthesis gas; this process involves thermal conversion of biomass into a combustible gas mixture through incomplete combustion [1]. The biomass gasification integrated solid oxide fuel cell (SOFC) hybrid systems have been widely studied and research shows that the electrical efficiencies of such systems can reach a level of 40-42% [1]. Some common feedstocks that are converted into electrical energy are coal, biomass, and other waste streams. To reduce land-disposed pollution of tires, the technology of gasification has been proposed to convert tires for syngas production.

In 2017, the United States generated approximately 4 million tons of waste tires, and 18% of these tires were disposed of in landfills. This resulted in 60 million accumulated tire stockpiles in the United States [2]. The rubber component in tires is water and abrasion resistant and takes more than 100 years to be destroyed, this leads to heavy pollution of the environment.

Studies show that thermal conversions of tires are affordable and reduce environmental impact [2]. One promising technology is the integration of gasification and solid oxide fuel cell where waste reacts with agent gas such as air, steam, or oxygen in the gasification process to produce syngas for fuel cell utilization [3]. Waste tires would be an ideal calorific fuel biomass material because waste tires have an organic matter composition of more than 90% [4]. The hydrogen production to feedstock ratio was found to be 0.154 for tires, which was also competitive to one of the higher quality coals available for fuel usage which has a ratio of 0.158, making tires a good source to produce hydrogen [2].

Methodology

A parametric study was done to determine the impacts of syngas composition on the efficiency and power produced by the SOFC. This was done by comparing varying levels of moisture content, mixture ratio, and the equivalence ratio in the gasifier.

Based on the combustion theory, complete combustion occurs at an equivalence ratio of 1. As the amount of oxygen decreases the fuel-air mixture will become fuel rich, meaning that the equivalence ratio is greater than 1[5]. This results in a decrease in CO_2 and increase in CO. For the gasification process, CO_2 and CO are considered stoichiometric indicators [5]. When gasifying waste tires, the ER is thought to be between 0.2 and 0.5[3].

The moisture content of biomass is the quantity of water existing within the biomass, expressed as a percentage of the total material's mass [6]. Therefore, increasing the moisture content will result in more water reactants which reduces the gasification temperature and improves the water shift reaction [3].

The rubber structure of tires results in the CCR of the gasification process is lower than 82% [3]. To increase the CCR, researcher have used a mixture of wood and tire to replace the pour tire gasification [3]. In the gasification process, when the tire mixture ratio increases the percentage of N2 increases and the other components decrease [3]. A higher tire mixture ratio will result in more carbon reactions, which requires more air to keep the ER value constant and thus increases the syngas yield [3].

Syngas Output from Waste Tire Gasification

Changing the parameters in the gasifier also changes the parameters in the SOFC. Since the input to the SOFC is the output of the gasifier, a parametric study was performed on the gasifier to determine the effects of moisture content, equivalence ratio, and mixture ratio on the output component flow rates of the gasifier. When the mixture ratio varied, the equivalence ratio was held constant at 0.42 and the moisture content was held at 0.9%. When the moisture content was varied, the ER was held at 0.42, and there were no wood pellets added into the mixture. When the ER varied, the moisture content was held at 0.9% and there were no wood pellets added into the mixture. This held true for all the experiments run.

Increasing the moisture content led to an increase in power produced and efficiency of the SOFC. The flow rate of H_2, CO, CO_2, H_2O, and CH_4 out of the gasifier and into the SOFC increased as the moisture content increased. However, this caused a decrease in the flow rate of carbon and the flow rate of N_2 remained constant. When increasing the mixture ratio, the flow rate of H_2,CO, $CO_2$and CH_4increased coming out of the gasifier and into the SOFC while the flow rate of H_2O decreased. Increasing the equivalence ratio decreased the flow rate of CH_4 and C but increased the flow rate of H_2,CO, CO_2, N_2, and H_2O. The results are displayed in figure 1.

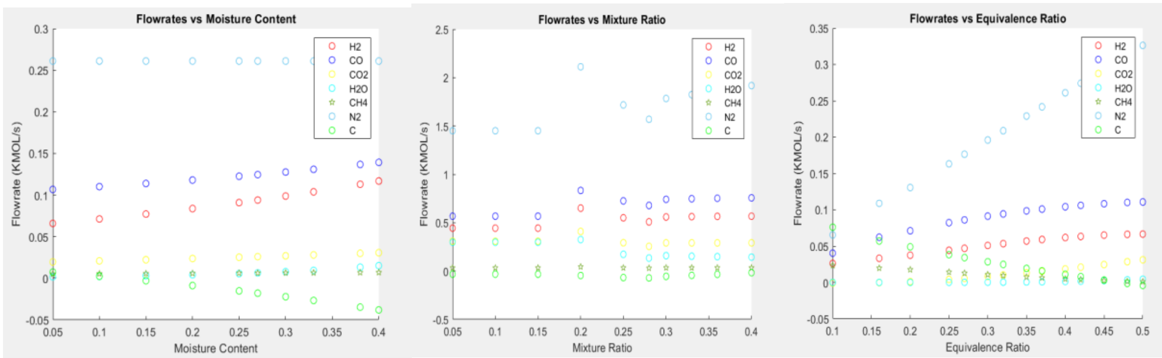

Figure 1: Flowrate Comparison

Performance of Waste Tire Integrated SOFC System

The parametric study compared the effects of moisture content, the mixture ratio, and the equivalence ratio of the waste tire on the output performance on the SOFC. As the moisture content of the waste tire increased, the power output of the SOFC increased. The maximum moisture content evaluated was 40%, and this produced a SOFC power output of 1.57(10^8) W. However, 40% moisture produced an efficiency of 28.22%; while the maximum efficiency produced was 22.28% at 35% moisture. This is shown in figure 2.

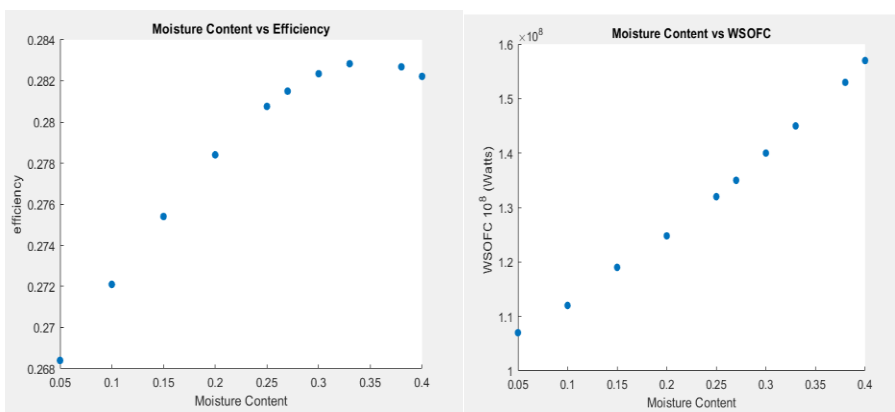

Figure 2: Moisture Content Study

Figure 3 shows the relationship between the equivalence ratio and power output of the system. As the equivalence ratio increases, the power produced increases. This is true up until an ER of 0.3 and power of 1.08(10^8) W, after this point the power output begins to decline. However, as the equivalence ratio increases the efficiency decreases. The maximum efficiency was 59.37% at an equivalence ratio of 0.1. When varying the equivalence ratio, there must be a design tradeoff between achieving maximum power and efficiency. Since the results show that increasing ER decreases efficiency, choosing a lower ER value that still achieves close to maximum power generated would be ideal. In this case, an ER of 0.25 could be considered optimal.

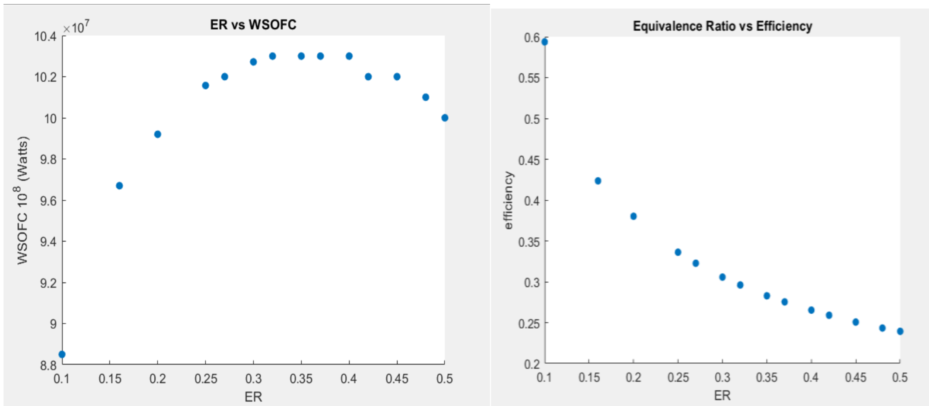

Figure 3: Equivalence Ratio Study

When varying the mixture ratio, the highest efficiency achieved was 25.2% at a mixture ratio of 0.22. As the mixture ratio increased, the efficiency increased up until 25.2%, this is demonstrated in figure 4. The power produced increased as the mixture ratio increased as well. The maximum power produced was 9.20(10^8) W at a mixture ratio of 0.2. This is shown in figure 4.

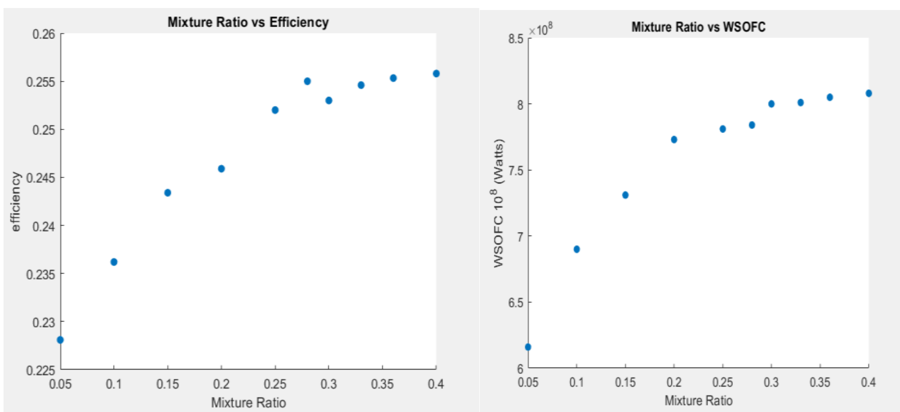

Figure 4: Mixture Ratio Study

From this study, optimal design parameters for the ER, mixture ratio, and moisture content were determined. These values are shown in the table 1. A simulation was done with these parameters as input, and the maximum efficiency achieved was 33% and the power generated was 1.06(10^9) W.

Table 1: Optimal Design Parameters

Optimal Design Parameters	
ER	0.25
Mixture Ratio	40%
Moisture Content	30%

Since the optimal equivalence ratio was determined to be 0.25, the SOFC power generated, and efficiency were determined at this optimal equivalence ratio. The mixture ratio and moisture content were varied while the optimal ER was held constant. Figure 5 shows the relationships for the mixture ratio. The power generated was between 8(10^8) W and 9.5(10^8) W. The maximum power generated was at a mixture ratio of 40%. The maximum efficiency reached was 32.5% at a mixture ratio of 40%.

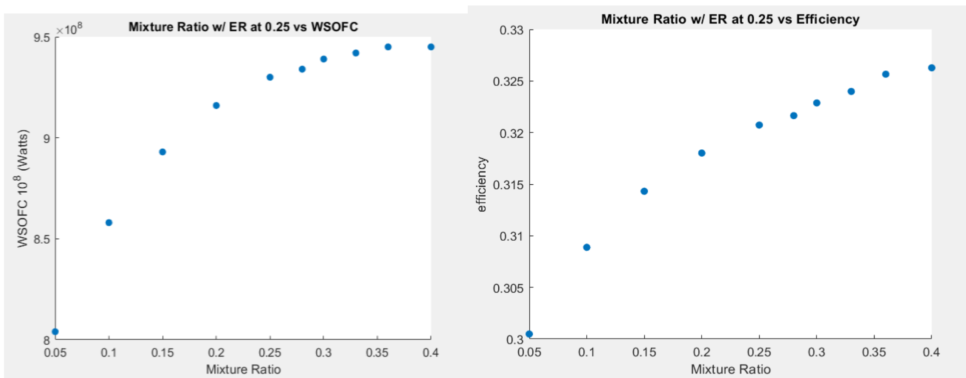

Figure 5: Mixture Ratio Variation with Optimal ER

The moisture content was also varied while holding the ER constant at 0.25. As the moisture content increased, both the power generated, and efficiency increased. The maximum power generated was at 1.7(10^8) W and a moisture content of 40%. The maximum efficiency was 35.8% at a moisture content of 40%. This relationship is shown in figure 6.

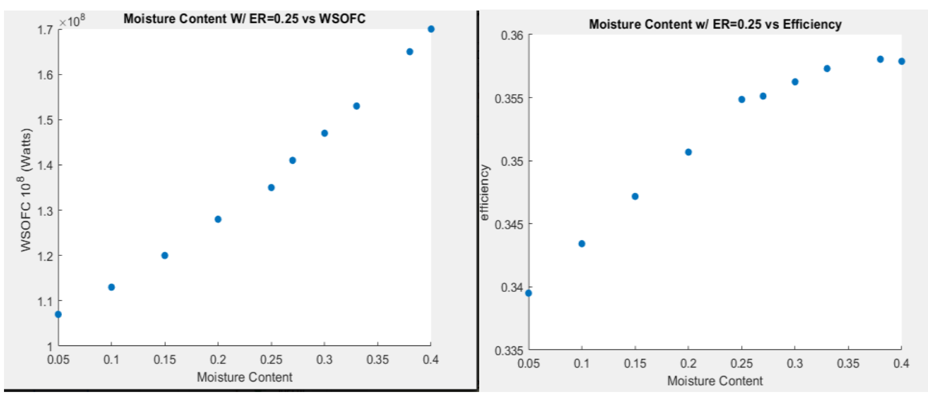

Figure 6: Moisture Content Variation with Optimal ER

The parametric study done on the SOFC was done by varying the equivalence ratio, mixture ratio, and moisture content of the waste tire input to the gasifier. This varied the efficiency and power generated by the SOFC. The initial variation of parameters determined that the optimal parameters for ER, mixture ratio, and moisture content were 0.25, 40%, and 30% respectively. Waste tire of this composition resulted in an SOFC efficiency of 33% and the power generated was 1.06(10^9) W. Table 2 displays these results. This newfound equivalence ratio was then held constant as the moisture content and mixture ratio were increased again. The results of this simulation are shown in table 2. Decreasing the initial ER from 0.4 to 0.25 resulted in nearly a 10% increase in efficiency in all cases. The power generated also increased. The overall highest power generated was with an ER of 0.25, moisture content of 0.90% and mixture ratio of 40%.

The efficiency at these conditions was 32.30%, but the highest efficiency achieved was 35.80%. This was done with an ER of 0.25 and moisture content of 40%.

Table 2: SOFC Parametric Study

SOFC Parametric Study				
ER	**Moisture Content**	**Mixture Ratio**	**W**	**EFF**
0.25	0.90%	-	1.0157(10^8)	33.62%
0.4	30%	-	1.40(10^8)	28.28%
0.25	40%	-	1.70(10^8)	35.80%
0.4	0.90%	40%	8.12(10^8)	25.28%
0.25	0.90%	40%	9.45(10^8)	32.60%

Solid oxide fuel cell electrical efficiencies are commonly between 28%-40% [5]. The maximum efficiency achieved in this study was 30%-60%. The overall maximum power generated was 9.45(10^8) W. This compares favorably to other studies done. SOFC can generate power at 181.5kW, and have an efficiency of 36% [1], 1395.61kW and 29.83% efficiency, 13.01MW and 39.09% efficiency [7]. These results were given for various biomass inputs studied; published results are given in table 3.

Table 3: Published Data

Published Data	
Efficiency	Power Generated
36%	181.5kW
29.83%	1395.61kW
39.09%	13.01MW
47%	50MW

Conclusions

Previous modeling was conducted in MATLAB to simulate the gasification of waste tires. The newly developed MATLAB model for the SOFC uses the output of the gasification model as the input. Therefore, varying the moisture content, equivalence ratio, and mixture ratio in the gasifier was necessary to obtain the output flow rates of the gasifier into the SOFC.

The parametric study conducted determined that the equivalence ratio had the greatest effect on the flow rates going into the fuel cell, the efficiency, and the power output. Throughout the study, efficiencies produced continuously ranged from 20%-50%, therefore proving that waste tires can provide a good source of fuel for an integrated gasification-SOFC system.

Future work to determine the overall performance and feasibility of the system should include an economic analysis and energy balance of the fuel cell. The energy balance would determine the output mass flow rates of the system, and the economic analysis would include the cost of waste tires for gasification and maintenance of the system.

Waste tires were initially proposed for fuel production due to their high organic matter composition of 90 % [1]. 60 million waste tires have accumulated in stockpiles in the United States, and these take up to 100 years to be destroyed by microorganisms [1]. Using waste tires as fuel could eliminate this problem. Current integrated gasification-SOFC systems that utilize coal as fuel can reach efficiencies of 30-40% [8]. The results of this study prove that waste tires as fuel is a possibility for integrated gasification-SOFC technologies in the future.

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