Numerical Modeling of the Entrained Flow Gasification (EFG) of Kentucky Coal and Biomass

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Abstract

The entrained flow gasification of two feedstocks (Kentucky coal and wood waste) had been conducted in this study with numerical modelling. The main objective of this work is to determine the gasification behaviour of Kentucky coal and wood waste along the gasifier, and to evaluate the effect of gasification parameters such as equivalence ratio, pressure and temperature on the gasification metrics. The experimental study was conducted in the air-blown atmospheric drop tube experimental facility at the Waste-2-Energy Laboratory at Masdar Institute. The numerical model, which was based on the Lagrangian-Eulerian scheme, predicted the experimental results reasonably. The effect of the fuel type on the gas composition along the centreline of the gasifier indicated that Kentucky coal produced a higher efficiency when compared to that of wood waste. Moreover, the gasification efficiency was most sensitive to the equivalence ratio.

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Keywords: Entrained Flow Gasification, Kentucky Coal, Wood Waste, Numerical Modeling

1. Introduction

The potentiality of entrained flow gasification to be employed in carbon capture through the utilization of integrated gasification combined cycle (IGCC), the possibility of gasifiers to operate with multiple feedstocks and their ability to be used for cogeneration are some of the chief reasons why entrained flow gasifiers (EFG) has been popular today [1]. For instance, the capability of EFGs to employ multiple feedstocks can be used to tackle millions of tons of solid wastes which are generated annually and continue to pose serious environmental and ecological threats to our planet. In 2009, the total amount of

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solid waste generated in Abu Dhabi, United Arab Emirates was 5,756 thousand tons according to the estimates of the Centre of Waste Management, with the construction sector contributing 61% of the total waste due to the construction boom taking place in the Emirate [2], and with continuous population growth, development and industrialization, this trend would tend to intensify. These solid wastes, which often end up in landfills that generate a lot of havoc, can be gasified for energy production due to the ability of EFGs to operate with multiple feedstocks. However, there is need for the development of predictive models for gasification systems in order to resolve the problems of fuel flexibility, poor space usage, feed injector failure and high initial cost associated with EFGs. High fidelity models, which have excellent predictability of centerline experimental data, can be used to conduct sensitivity studies in order to optimize EFGs design and operation.

Because there are few centerline experimental diagnostics of EFGs, there are only some numerical models which had been rigorously validated with axial values. Watanabe and Otaka [4] developed a three-dimensional model based on Lagrangian-Eulerian scheme for a 2-ton per day research scale coal entrained flow gasifier. The model predicted results were in reasonable agreement with centerline experimental data. Chen et al. [5] investigated the performance of a two-stage, entrained-flow gasifier upon scale up and their numerical model was validated with centerline measurements. Abani and Ghoniem [6] investigated coal gasification in an entrained flow gasifier using Large Eddy Simulation (LES) for the gas phase turbulence and Lagrangian-Eulerian approach to study the gasifier. Their numerical model provides close prediction of the centerline experimental data of Brown et al. [3].

The entrained flow gasification of two feedstocks (Kentucky coal and wood waste) had been conducted in this study with numerical modeling in order to gain insightful knowledge of their gasification characteristics. Hence, a better understanding of the gasification behavior of these feedstocks can lead to the optimization of their gasification process. This study investigates the effect of gasification parameters like equivalence ratio, pressure and temperature on the entrained flow gasification of Kentucky coal and wood waste.

2. Material Characterization

Material characterization is the next step after a potential feedstock for gasification has been identified. A profound knowledge of the composition of a feedstock will help in estimating the suitability of the fuel for gasification conversion processes, and support in the simulation of the gasifier. Three pathways have been considered in this work to characterize Kentucky RTC coal and construction waste wood: The proximate analysis with DSC/TGA Q600 thermal analyzer, ultimate analysis with FLASH 2000 CHNOS analyzer and the heating value determination with a Parr 6100 bomb calorimeter (Table 1). The Kentucky coal is a bituminous coal type obtained from the River Trading Company and the wood waste is plywood collected from the Al Dhafra landfill in Abu Dhabi. Both feedstocks can be considered as good candidates for gasification as the cumulative of the moisture and ash content is less than 10% altogether.

<table>
<thead>
<tr>
<th>Material Characterization of Kentucky Coal and Waste Wood</th>
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<tbody>
<tr>
<td>Proximate Analysis (wt. %)</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Moisture</td>
</tr>
<tr>
<td>Volatile</td>
</tr>
<tr>
<td>Fixed Carbon</td>
</tr>
<tr>
<td>Ash</td>
</tr>
<tr>
<td>HHV (MJ/kg) Value</td>
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3. Experimental Study

The atmospheric drop tube reactor (DTR) - designed at the Waste-2-Energy Laboratory at Masdar Institute- is composed basically of a stainless steel rectangular shaped furnace fitted with insulation and heating modules which can attain up to a wall temperature of 1,400K, a drop tube where the gasification process actually occurs, a gas supply system for feeding the oxidant and nitrogen for entrainment of the particles into the drop tube, a particle injection system for supplying the feedstocks into the drop tube, and diagnostics tools for determining the centreline and exit temperature and gas concentrations. The experimental set-up and its schematic representation are depicted in Fig. 1.

4. Model Development

The assumption of instantaneous equilibrium and equal diffusivity may be too generic for numerical solid feedstock conversion under gasification conditions. Hence, the numerical investigation for this gasification study is based on global reaction kinetics in order to more accurately describe the multi-physics, multi-scale, multi-phase model. The gasification process, which is based on the Langrangian-Eulerian approach due to the low volume loading in EFGs, is modeled with the consideration of four events. As the particle is injected into the gasifier, residual moisture content in the feedstock is evaporated during passive heating. The volatile content is then released in a process known as devolatilization or pyrolysis. The volatiles and other gaseous species then undergo homogeneous reactions, but the char is consumed through heterogeneous reactions. While the particle was monitored over space, the continuum approach was used for the gas phase. The multi-physics, multi-scale model was developed to describe the details of the different physical and chemical processes occurring in the DTR through key sub-models and their coupling. The summary of the sub-models and their interactions is as shown in Fig. 2.
The fuel-air equivalence ratio used is defined as:

$$\phi = \frac{\text{Actual Fuel - Air Ratio}}{\text{Stoichiometric Fuel - Air Ratio}}$$

For gasification condition, the fuel-air equivalence ratio must be greater than unity.

5. Results and Discussion

Model Validation: The validity of the results of every point on the contour depends mainly on the rigor of the constraint for the validation of the experimental data. The more the model results agree with the experimental values, the more the fidelity in the model. Hence, the numerical model has been validated with experimental data obtained in this work. The model results predict the experimental values reasonably well as depicted in Fig. 3 a-c.

Effect of Temperature: Increase in the temperature of the gasification system enhances the char gasification process with H₂O and CO₂ which are highly endothermic. Hence, a rise in the temperature of gasification leads to the formation of more CO and H₂ for both feedstocks as the endothermic char reactions produces more of these gases at higher temperature. In addition, the CO₂ and H₂O levels were lowered at higher temperatures as these gases undergo endothermic reaction with the char. One interesting point to consider is the effect of gas composition on the utilization of the same gasifier with full length heating at 1,373K. Heating the whole length of the gasifier promotes the formation of more CO and H₂ at an amount which was almost double the amount produced even at higher temperature at the middle heating section (Fig. 4).
Effect of Equivalence Ratio: The effect of equivalence ratio on gasification is very crucial because a value lower than the optimum condition will lead to combustion and a value higher than the optimum condition will result in the production of lower amount of syngas. Both cases are undesirable and should be avoided. Hence, the effect of equivalence ratio on the gasification of Kentucky RTC coal and waste wood has been studied. Generally, higher equivalence ratio yields more CO and H$_2$ and less CO$_2$ and H$_2$O. Therefore, the mole fraction of the syngas at the exit rose with a change in the equivalence value between 1.2 and 2.4. However, the mole fraction of CO was lower than CO$_2$ for waste wood for all equivalence ratio studied. This behaviour can be linked with the higher volatile content in the wood which is dominated by a particularly fast volatile combustion. Furthermore, the mole fraction of H$_2$ generated by waste wood at the outlet of the reactor is usually lower than 1% of the total gas composition at the exit which is due to the lower fraction of H$_2$ in the waste wood (Fig. 5).

Fig. 3. Model validation with (a) Non-reactive central length temperature data (b) Reactive central length temperature data (c) Exit gas composition measurements ($\Phi$ is the equivalence ratio)
Effect of Pressure: The effect of pressure on the gasification of Kentucky RTC coal and waste wood has been analyzed. The behaviour of the two feedstocks under an increasing pressure was significantly different. While the fraction of CO at the exit during the gasification of coal rose sharply with an increase in pressure, the fraction of CO at the exit during the gasification of wood increased albeit gradually with the same rise in pressure. This is due to the difference in the structural network and char reactivity of both feedstocks. Basically, the char reactivity of Kentucky RTC coal improves greatly with additional pressure of the reactor, but that of waste wood increases by a small amount. In the same vein, the amount of CO\(_2\) reduction during gasification at a higher pressure was sharper with Kentucky RTC coal as compared with waste wood. One striking occurrence is the reduction of the H\(_2\) content during the gasification of waste wood as opposed to the improvement in the quantity of H\(_2\) produced from coal under the same conditions of pressure (Fig. 6).

Fig. 4. Effect of temperature on the gasification of Kentucky coal and wood waste

Fig. 5. Effect of equivalence ratio on the gasification of Kentucky coal and wood waste
6. Conclusion

The entrained flow gasification of Kentucky coal and wood waste had been conducted in this study with numerical modelling and centreline experimental diagnostics to gain insightful knowledge of their gasification characteristics. Model results agreed reasonably well with the centreline experimental data. Both feedstocks can be considered as good candidates for gasification as the aggregate of the moisture and ash content is less than 10% altogether. The heating value of the Kentucky RTC coal (30.42MJ/kg) was almost twice that of the waste wood (18.7MJ/kg) due to the presence of higher fixed carbon content in the coal. However, the wood contained high oxygen (43.62%) and volatile (68.89%) contents which imply that the volatile has a high oxygen content as the ash, fixed carbon and moisture have small oxygen content altogether. Wood waste has more volatile, moisture content and oxygen than Kentucky coal, and this has influenced the behaviour of wood during its gasification in the reactor. Although the axial temperature for both feedstocks spiked between 0.7-0.9m along the gasifier, the overall temperature attained by the wood waste was more. In addition, wood waste has more volatile which allows for a quick exothermic reaction that generates a lot of heat. The effect of the fuel type on the gas composition along the centreline of the gasifier indicated that Kentucky coal produced a higher efficiency when compared to that of wood waste. Moreover, increasing the temperature, equivalence ratio and pressure led to the production of more CO and H₂ for both feedstocks, and hence an increase in gasification efficiency. However, the gasification efficiency was most sensitive to the equivalence ratio.

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References


Biography

Dr. Janajreh is Virginia Tech Ph.D and MS holder, work for 10 years at Michelin American & France, GE, and Pratt and Whitney. Served in 2007 visiting MIT professor and currently is an associate Mechanical Engineering Professor At Masdar Institute. His research encompasses Renewable Energy Conversion System, Fundamentals of Combustion, Reactive Fluid Dynamics, and Computational Fluid Dynamics. A key contributor to three Michelin patents (Catamran, Primacy, X-one) and three books (traction, rolling resistance, noise). He is a chief editor (http://www.erpublications.com/), associate editor (http://www.iasks.org/journals/ijtee), (http://www.solid-waste.org) and regular reviewer for many international journals, member of ASME, TS&T, Rubber Division, ASCE, and advisor to several international scientific committees and conferences.