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Syngas Production From Refuse-Derived Fuel Through Gasification Simulation for a Fuel Cell System

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Abstract

The global desire for alternative energy and energy sustainability continues to dominate the quest for energy resource research. The path of waste-to-energy technology is a viable alternative approach to address the demand and reduce the burden of solid wastes. This study investigated the viability of production of hydrogen-rich syngas from domestic waste-municipal solid waste (MSW) gasification for a fuel cell system. The pretreatment of MSW was performed to produce Refuse-derived Fuel (RDF) to improve energy density and high heating value (HHV). The simulation was carried out with Aspen plus model for RDF gasification to predict the RDF gasification behavior under various operating parameters-equivalent ratio (ER), temperature, and steam flowrate (SFR), in an air-blown downdraft gasifier. The HHV of RDFs was between 18.17 MJ/kg and 28.91 MJ/kg, with energy density increasing from 4142.07 MJ/m^3 to 10735.80 MJ/m^3. Optimum SFR values for various RDFs were determined to be within these values 2.80, 2.50 and 3.50 and optimum ER values for RDFs were also determined to be within these values 0.15, 0.04, and 0.08. These conditions produced the desired high molar ratio of H_2/CO yield in the syngas mixture in the product stream. The molar ratios of H_2/CO yield in the syngas mixture in the product stream for all the RDFs were between 18.81 and 20.16. The values of H_2/CO satisfy the requirement for fuel cell application.

Categories: Combustion and Alternative Fuels, Quality and Process Improvement, Environmental Engineering
Keywords: municipal solid wastes, syngas, hydrogen, gasification, aspen plus modelling

Introduction

Daily domestic contribution of household municipal solid waste (MSW) to overall MSW composition is significant. MSWs are different from other solid waste (such as heavy industrial waste, nuclear waste, heavy sludge, hazardous waste, e-waste, construction debris, and other industrial wastes) because they are regularly produced [1-7]. The physical characterizations of MSW are heterogeneous but its chemical composition is fairly uniform [4]. The solid fuel resource-based potentials found in MSW are useful because of substantial parts of MSW are combustible with minimal adverse environmental footprint if waste-to-energy/chemical technology is considered [8]. Landfills, open dumping, and incineration have been traditional methods of disposing of solid waste for centuries and the methods are still available in most developing countries. The contemporary challenges have changed the focus toward a better awareness of the environmental implications of traditional MSW management methods (such as various emissions from open dumping, landfills, and incinerators) of disposal methods [1,9-13]. However, there are still ongoing arguments about incineration technologies and landfill treatment. Both incineration technologies and landfill treatments without pre-treatment of the MSW are associated with emissions of pollutants that are harmful to land, water, atmosphere, with no value-added chemicals produced [14-17]. The introduction of pre-treatment procedures (drying, sorting, shredding (size reduction), screening (uniform size of MSW), and pelletization (size enlargement)) are essential for optimal energy and material recovery. The contemporary waste-to-energy/chemical technologies are matured technologies but still lack exploitation in most developing countries [17,18]. Largely, in most towns and cities, there is an absence of both regular and standard waste collection methods and disposal services. The standard procedure (MSW generation, sorting at the source, storage, collection, transfer and transport, pre-treatment/processing and disposal) [19,20] is not common. The standard waste collection and disposal services are instrumental to optimum energy and material recovery [18]. In Cape Town, South Africa, over 2 million tonnes of MSW are disposed at MSW facilities annually with six landfill sites (only three landfill sites are still active), and several private landfill sites (with or without regulation) responsible for landfilling of the MSW. A number of initiatives (composting and material recovery facilities, awareness programmes on recycling, and sorting procedures at source) to diversify the MSW management in Cape Town have been employed [4,21]. The success rate of these initiatives was not encouraging and landfilling remains the predominant method of municipal solid waste management [22,23]. However, there is no existing thermochemical conversion technology utilized for MSW management for energy recovery in the City of Cape Town, South Africa. Gasification technologies have advantages of cleaner technology,

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reduction of emissions, and production of value-added chemicals like syngas but economic evaluation of the thermochemical conversion is essential for its sustainability [24,25]. Considering suitable gasification technology, air-blown downdraft fixed-bed gasifier was selected because of low tar formation and removal, MSW fuel compatibility, moisture content tolerance, low gasification temperature, and a suitable power range as described in the previous study [26]. Hence, there is a need for robust modeling through simulation methods to address potential integration and production of rich hydrogen from MSW for fuel cell application. The objective of the study was to use the Aspen plus model to simulate RDF gasification; to predict the hydrogen-rich syngas (H_2 and CO) production from various operating parameters in an air-blown downdraft gasifier condition. The hydrogen-rich syngas is a renewable alternative for fuel cell application.

Materials And Methods

The MSW samples were collected from selected municipal solid waste disposal facilities spread around the settlements in Cape Town. Thirteen solid waste disposal facilities (drop-off sites, transfer stations, and landfill sites) were considered. The combustible materials (including the plastics) were shredded and pulverized to form a fluffy material after the separation (Figure *1*). The organic fraction of the MSW samples were first dried at 105°C for 2 h, then shredded into particles in sizes of approximately less than 5 mm [27]. The physicochemical characterization was carried out on the pre-treated MSW samples. Air-blown downdraft fixed-bed gasifier was selected with the following reaction schemes: drying (dehydration and decarboxylation), thermal decompositions, char combustion/tar reforming, and gasification and char gasification reactions [28-30]. The Aspen plus model process tool was employed to investigate the reactions (exothermic and endothermic) in the downdraft gasification. Figure *2* showed a process flowsheet diagram in the Aspen plus model interface [26].

FIGURE 1: Production of refuse-derived fuel (RDF) from raw MSW

MSW, municipal solid waste

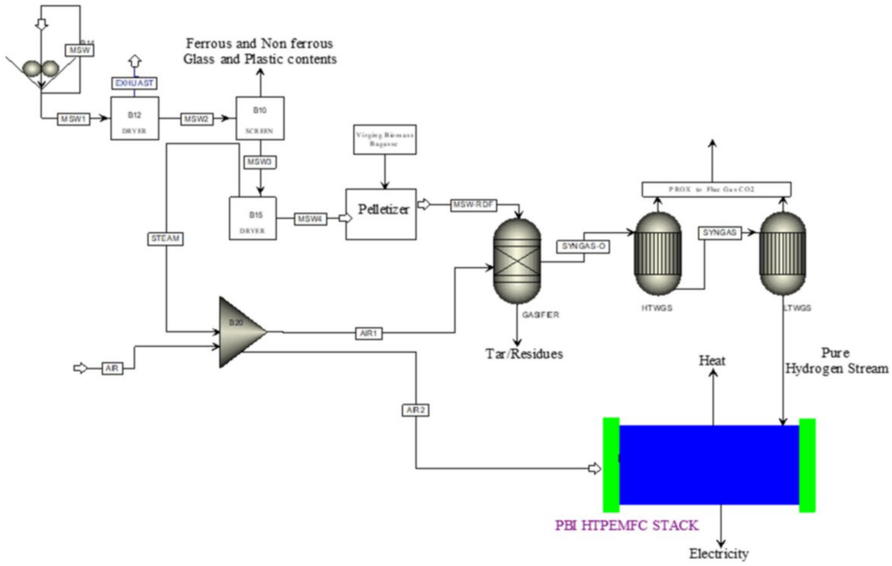

FIGURE 2: The process flow diagram of RDF gasification in Aspen model interface

RDF, refuse-derived fuel; MSW, municipal solid waste

Results

The results of physicochemical characterization are summarized in Table *1*. These quantities of MSW come from residential, commercial, and industrial activities in these fractions: 2:1:1. More than 40% of the MSW is from organic matters while combustible contents are approximately 70% of all MSW generated in the city of Cape Town. The derived molecular formula ($CH_{1.45}O_{1.85}$) was selected for gasification simulation.

Proximate Analysis	RDF1	RDF2 (KL)	RDF3 (LM)	Average
Moisture Content (wt. %)	-	10.7008	9.0906	8.2947
Volatile Matter (wt. %)	79.70	74.1680	40.8804	54.4543
Fixed Carbon (wt. %)	6.80	11.1194	28.2188	23.1067
Ash (wt. %)	13.50	4.0012	21.8101	14.2612
Heating Values (MJ/kg)	19.88	20.8463	24.6553	19.4433
Bulk Density (kg/m^3)	270	515.0	425.6	367.7
Ultimate Analysis				
Carbon (wt. %)	48.80	32.049	33.891	30.3950
Hydrogen (wt. %)	7.80	4.048	4.239	3.8285
Oxygen (wt. %)	29.20	-	38.877	-
Nitrogen (wt. %)	0.70	-	1.183	0.9761
Sulphur (wt. %)	0.00	2.908	3.04	2.8721

TABLE 1: Summary of physicochemical characterization of pre-treated MSW samples

MSW, municipal solid waste

The simulation in this study evaluated the effects of equivalence ratios (ERs) on RDFs and the effects of steam solid fuel ratios.

Effects of equivalence ratios

The ERs used in the Aspen plus modeling for gasification of various types of RDF were in the range of 0.02 and 0.60 (corresponding to the airflow rate of 1.00 to 30 kg/h). RDF1 (from literature) [31], RDF2, and RDF3 (produced in this study) were used as feed for the gasification process. Selected simulation results are presented in Figures *3*-*11*. Between the ER values of 0.10 and 0.35, at the constant, high temperature in the gasifier, the syngas (H_2 and CO) content increases steadily but the hydrogen molar concentration is higher compared to others. The molar concentration of CO_2 was relatively stable and higher than that of other products just after the ER value of 0.45 for all cases of steam flowrate (SFR), although a slight decline was noticed toward the end of the simulation (Figures *3* and 4). The H_2 and CO molar ratios obtained could avoid the CO-poisoning of the fuel cell by reducing the efficiency of the fuel cell. These values are higher than similar experimental products of char H_2/CO molar ratios (6.80 and 14.80) by [32]. However, RDF1 gasification produced H_2/CO molar ratio of 18.81 for the ER value of 0.15 and the SFR value of 2.80. The corresponding value of hydrogen in the mixture of the molar ratio was less than that obtained at the ER value of 0.35, but a corresponding H_2/CO molar ratio for the ER value of 0.35 was less, and hence the molar ratio of 18.81 is the optimum value for this RDF1.

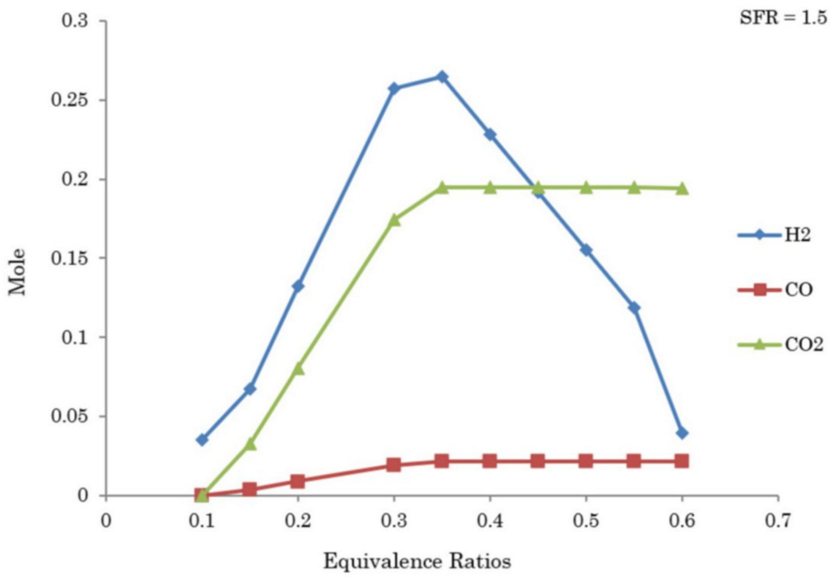

FIGURE 3: Molar distribution of desired products at SFR 1.50 (RDF1)

SFR, steam flowrate; RDF, refuse-derived fuel

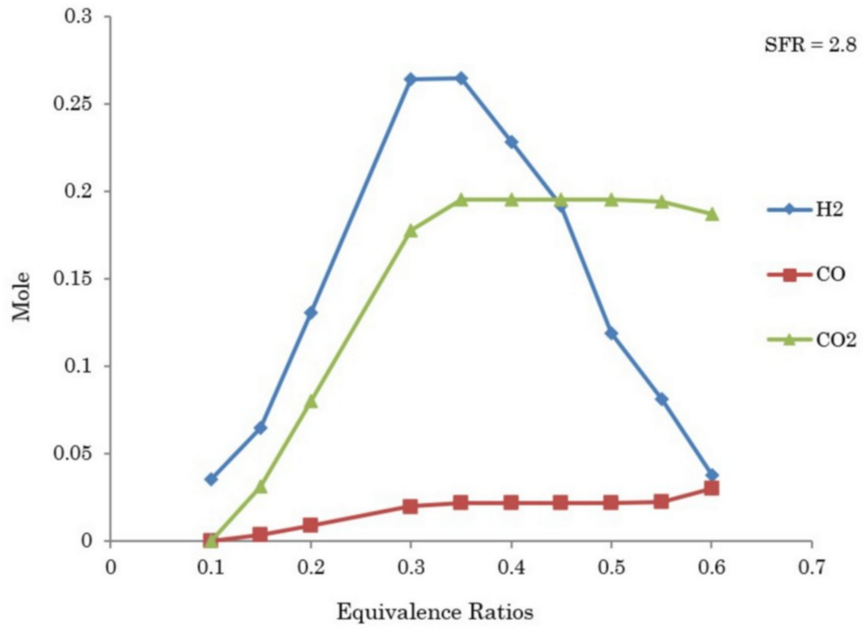

FIGURE 4: Molar distribution of desired products at SFR 2.80 (RDF1)

SFR, steam flowrate; RDF, refuse-derived fuel

The results obtained from RDF2 were different from RDF1 gasification. Although the molar hydrogen concentrations were higher than that of RDF1, the H_2/CO molar ratio was lower. This is because of the effect of high SFR being effective at low ER values. The molar quantities of hydrogen, produced from RDF2 gasification for values of ER values (0.10, 0.20, and 0.30), as shown in Figures *5* and 6, were higher when compared to the other co-products at a constant, high temperature in the gasifier. These concentrations reduced as the ER values increased for all SFR values. This trend shown by co-products, CO and CO_2, was not similar to that of the hydrogen concentration, particularly evident in Figures *6* and 7, where the increase for CO_2 and decrease for CO were observed, respectively. The hydrogen molar concentration trend was also similar to the studies of Chen et al. [33], Yunus et al. [34], and Dalai et al. [35]. However, the RDF2 gasification Aspen model produced 18.12 of H_2/CO molar ratio for the ER value of 0.04 and the SFR value of 5.20.

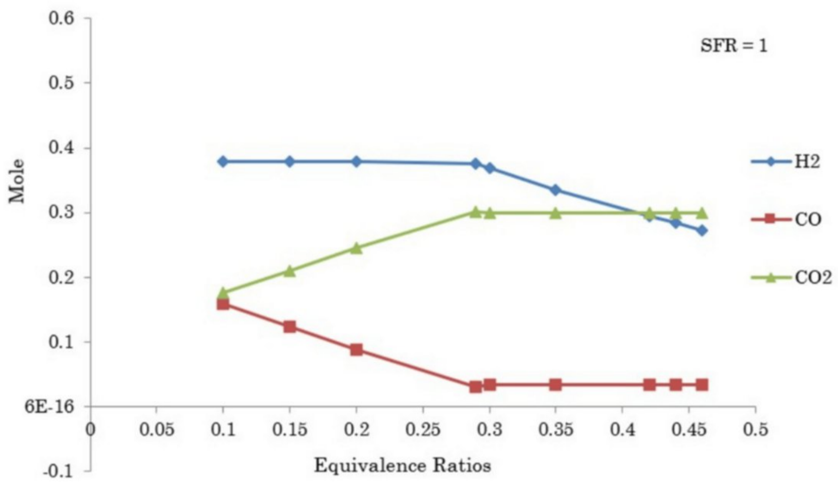

FIGURE 5: Molar distribution of desired products at SFR 1.00 (RDF2)

SFR, steam flowrate; RDF, refuse-derived fuel

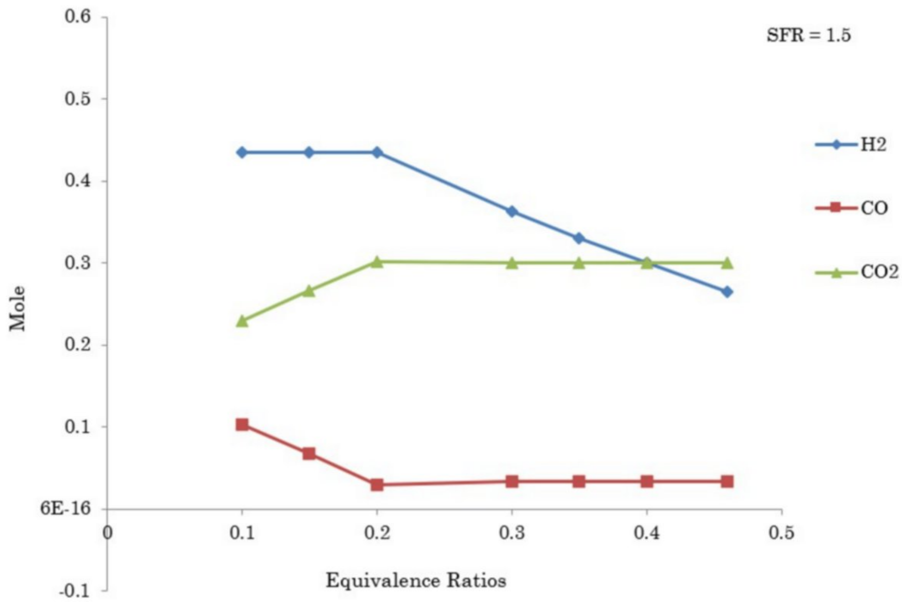

FIGURE 6: Molar distribution of desired products at SFR 1.50 (RDF2)

SFR, steam flowrate; RDF, refuse-derived fuel

The results obtained for RDF3 were similar to RDF2 gasification, though the molar hydrogen concentrations were slightly higher than that of the RDF2, and the H_2/CO molar ratios were also higher. These molar concentrations of hydrogen were relatively stable and began to reduce as the ER values increased to a maximum of 0.50 for all values of SFR.

However, there were increases in the molar quantities of hydrogen produced as SFR values increased to the required maximum. Also, the trend shown by the co-products (CO and CO_2) was not like that of the hydrogen molar concentrations, particularly in where Figures 6 to Figure 7, where an initial increase for CO_2 and a decrease for CO were observed respectively, as can be seen in Figures 6 and 7. These hydrogen molar concentrations were like the RDF2 trend produced in the previous section. The molar concentrations of CO and CO_2 were relatively stable for the SFR values of 3.00 and 3.50. The molar concentrations of CO and CO_2 were relatively stable and showed kind of relationship, which might be attributed to the Boudouard reaction at a later stage of ER values, while the initial relationship might be the influence of the complete combustion of the RDF3 gasification as mentioned earlier in the discussion.

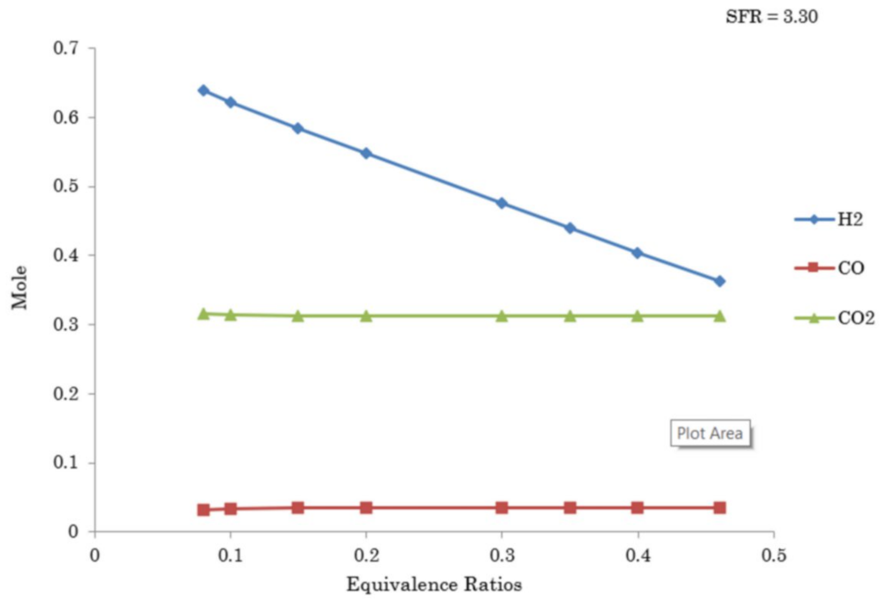

FIGURE 7: Molar distribution of desired products at SFR 3.00 (RDF3)

SFR, steam flowrate; RDF, refuse-derived fuel

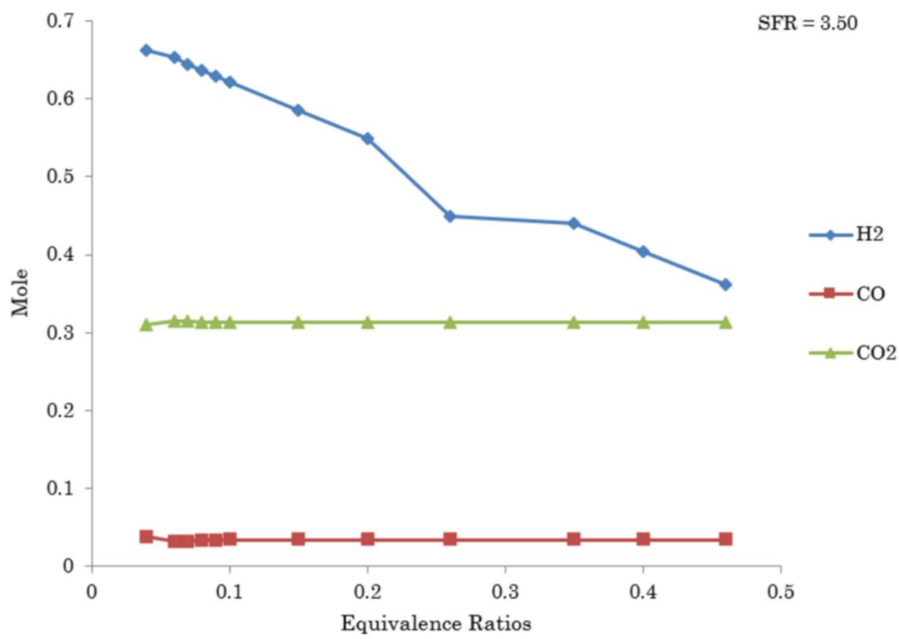

FIGURE 8: Molar distribution of desired products at SFR 3.50 (RDF3)

SFR, steam flowrate; RDF, refuse-derived fuel

It was observed at a low ER and high SFR that the model could produce the same molar concentration, H_2/CO ~ 1.00, which was not desirable for application in a fuel cell but could be used for energy and chemical productions. However, RDF3 gasification simulation produced the highest molar quantities of hydrogen in the syngas mixture compared to RDF1 and RDF2. The RDF3 gasification model produced a molar ratio of 20.16 for H_2/CO for the ER value of 0.08 and an SFR value of 3.30.

Discussion

Effects of steam solid fuel ratios

The effect of a steam solid fuel ratio on the RDFs gasification process was also studied in the range of 1.00 to 3.90 (corresponding to steam flow rates of 2.10 to 8.20) with 5 kg/h for RDF1 and 10 kg/h for RDF2 and RDF3 feed rates, respectively. Usually, during gasification reactions, steam can contribute to oxidation reactions.

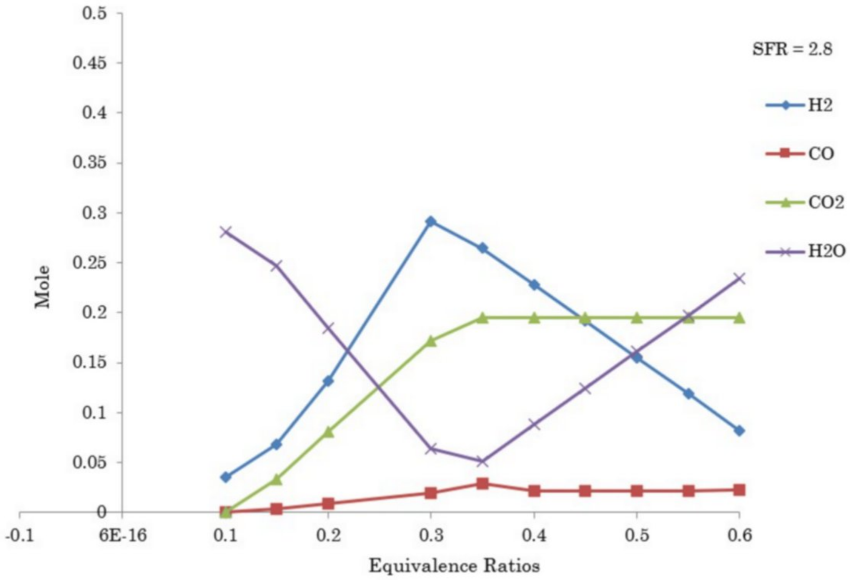

FIGURE 9: Molar distribution of desired products and steam (RDF1)

RDF, refuse-derived fuel

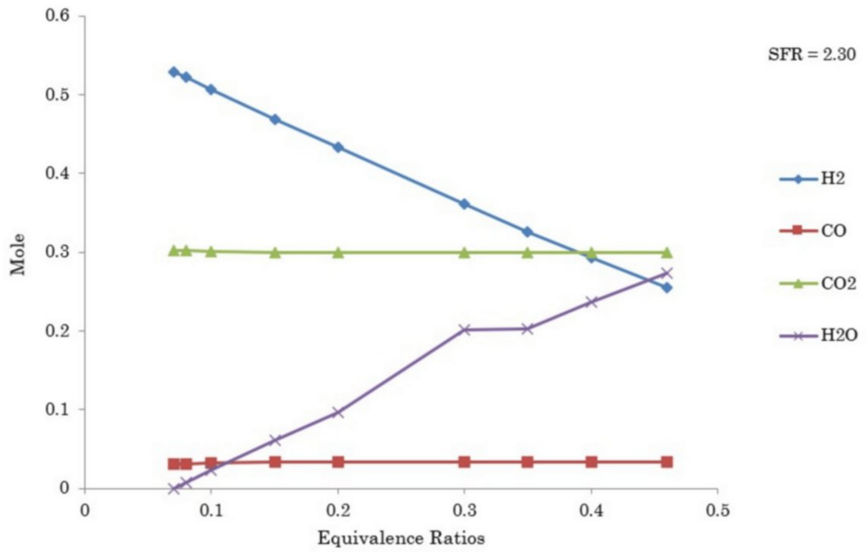

FIGURE 10: Molar distribution of desired products and steam (RDF2)

RDF, refuse-derived fuel

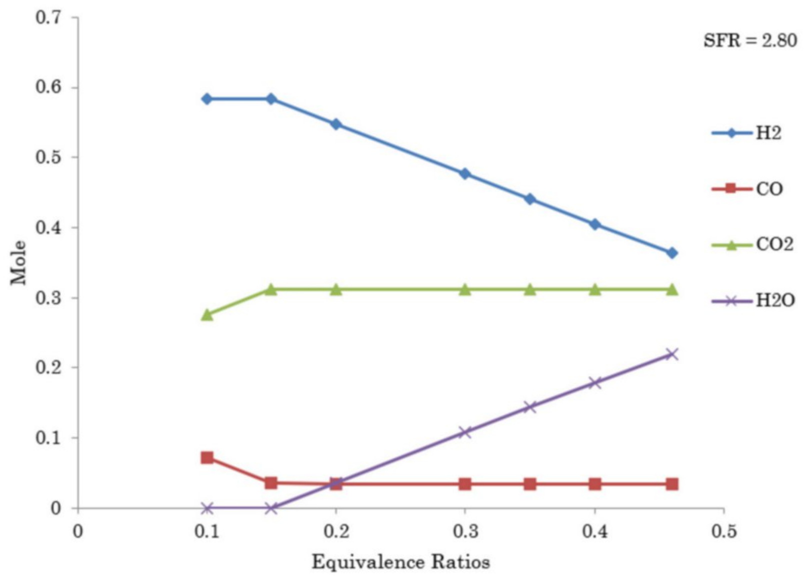

FIGURE 11: Molar distribution of desired products and steam (RDF3)

RDF, refuse-derived fuel

The following Figures (9-11) above demonstrate the variation of the product stream molar composition as it varied and influenced the production of hydrogen in the syngas mixture. Similar characteristics were reported by the studies [32,36,37]. The SFR contributed immensely to the generation of the high hydrogen concentration in the syngas mixture, as discussed earlier in the previous section. The effects of the ERs and the SFRs on gasification were relevant in the modeling. The simulation results obtained were for RDF1, RDF2, and RDF3, and they were H2/CO molar ratios of 18.81, 18.12, and 20.16, respectively. The gasification of RDFs revealed that SFR values of 2.85, 2.80, and 3.30 produced good H_2/CO molar ratio for ERs of 0.04 and 0.15 (Table *1*), while the SFR values more or less do not yield the required H_2/CO molar ratio.

Conclusions

Gasification enhances the hydrogen content of the products and reduces the carbon content of MSW to produce useful gases with a higher hydrogen-to-carbon (H/C) ratio. Gasification technology offers better gaseous products over other thermochemical conversions to produce syngas because MSW-derived RDF gasification technology demonstrates more efficient and cleaner products, specified oxidant flowrate, less volume, but high-density gaseous products, and control of hazardous emissions to the environment.

The results of the simulation enabled one to predict the feasibility of the behavior of the gasification of RDFs under various operating parameters in an air-blown downdraft gasifier. Temperature contributed a vital role in controlling the conversion and product composition, while other parameters were varied to achieve the desired syngas mixture. The effects of the ERs and the SFRs on gasification were relevant in the modeling. The simulation results obtained were for RDF1, RDF2, and RDF3, and they were H2/CO molar ratios of 18.81, 18.12, and 20.16, respectively.

The results provide a basis for the optimum performance of RDF gasification for the air-blown downdraft gasifier. The RDFs gasification Aspen model produced values for an ER of 0.08 and an SFR of 3.30. These values can satisfy the requirements of rich-hydrogen syngas fuel cell applications. The trend of results shows the complementary influence and dependence of ER values and SFR values on the desired product and co-products.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Ismail B. Adefeso

Acquisition, analysis, or interpretation of data: Ismail B. Adefeso

Drafting of the manuscript: Ismail B. Adefeso

Critical review of the manuscript for important intellectual content: Ismail B. Adefeso

Supervision: Ismail B. Adefeso

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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