

The Highly Efficient Integrated Plasma Fuel Cell (IPFC) Energy Cycle for Conversion of Fossil and Biomass Fuels to Electric Power Generation and Hydrogen and Liquid Transportation Fuel Production with Reduced or Zero CO₂ Emission

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Abstract

The IPFC is a high efficiency energy cycle, which converts fossil and biomass fuel to electricity and co-product hydrogen and liquid transportation fuels (gasoline and diesel). The cycle consists of two basic units, a hydrogen plasma black reactor (HPBR) which converts the carbonaceous fuel feedstock to elemental carbon and hydrogen and CO gas. The carbon is used as fuel in a direct carbon fuel cell (DCFC), which generates electricity, a small part of which is used to power the plasma reactor. The gases are cleaned and water gas shifted for either hydrogen or syngas formation. The hydrogen is separated for production or the syngas is catalytically converted in a Fischer-Tropsch (F-T) reactor to gasoline and/or diesel fuel. Based on the demonstrated efficiencies of each of the component reactors, the overall IPFC thermal efficiency for electricity and hydrogen or transportation fuel is estimated to vary from 70% to 90% depending on the feedstock and the co-product gas or liquid fuel produced. The CO₂ emissions are proportionately reduced and are in concentrated streams directly ready for sequestration. Preliminary cost estimates indicate that IPFC is highly competitive with respect to conventional integrated combined cycle plants (NGCC and IGCC) for production of electricity and hydrogen and transportation fuels.

Keywords: combined cycle, hydrogen plasma, direct carbon fuel cell, hydrogen, CO₂

1. Introduction

Process Description

In an earlier paper [1] the IPFC is principally applied to electrical power production. In this paper the IPFC is applied as a co-producer of electricity and hydrogen and/or transportation fuel (i.e., gasoline and diesel). Figure 1 shows the basic concept of integrating the Hydrogen Plasma Black Reactor (HPBR) [2-3] with the Direct Carbon Fuel Cell (DCFC).[4-6]

The HPBR decomposes any dry carbonaceous fuel to elemental carbon and gaseous H₂ and CO. Since no oxygen or steam is used in this gasification reactor, CO gas is only formed when oxygen is present in the feedstock, as in coal and biomass fuel. Since the temperature in the thermal hydrogen arc is very high (~1500°C) the conversion to elemental carbon and gaseous products is near 100%. Because the thermodynamic energy of decomposition of the feedstock fuel is small compared to the heating value of the feedstock, the thermal efficiency is found to be over 90%.[2-3] This means that the electrical energy requirement for the HPBR is very small. Based on the thermodynamic energy (enthalpy) of decomposition of natural gas and petroleum, the electrical energy efficiency (process energy efficiency) was determined to be 60% for an industrial unit.[3] Although, the specific energy requirement for decomposition of solid fuel (coal and biomass) is yet to be determined, this process efficiency was applied to the thermodynamics of decomposition of these feedstocks. It should also be noted that the thermodynamic energy (enthalpy) of decomposition is less for petroleum than for natural gas and coal is less than for petroleum. Other plasma reactors have been operated for steam gasification of solid fuels, however, these required higher power inputs because the steam gasification reactions are highly endothermic, requiring higher electrical energy inputs.[10] Due to the much lower endothermicity of the thermal decomposition reaction and operation in a dry hydrogen atmosphere the HPBR requires much less energy than the plasma steam gasifier.

The elemental particulate carbon is separated from the gas stream cyclonically or by asbestos bag filters or by absorption directly into a molten carbonate salt stream. The latter is preferred since the Direct Carbon Fuel Cell (DCFC) operates with a molten carbonate electrolyte. Any sulfur in the

feedstock is gasified to H_2S , which is removed, by reactants (ZnO) or adsorbents. The ash should form molten agglomerates, which can be separated from the carbon particulates cyclonically or gravimetrically in a fluidized bed. Experimental work is required to determine the optimum carbon separation technique. The carbon is added to the molten carbonate salt to form a concentrated slurry for use in the DCFC.

The carbon/molten salt slurry is sent to the anode compartment of the Direct Carbon Fuel Cell and air is fed to the cathode. The mixed molten carbonate salt (Na, K salts) acts as the electrolyte operating at $700-800^\circ C$. The carbonate ion carries the electrons from the cathode to the anode compartment through a membrane, which then reacts with the carbon at the anode releasing undiluted CO_2 gas thus completing the electrical fuel cell circuit. Voltage efficiencies of 80 to 90% have been obtained with amorphous carbon at reasonable current densities ($0.2-0.8 \text{ Kw/M}^2$). [4-6] The overall reaction in the DCFC is the oxidation of carbon to CO_2 , the theoretical thermodynamic efficiency of which is 100% since the entropy change for the reaction is zero.

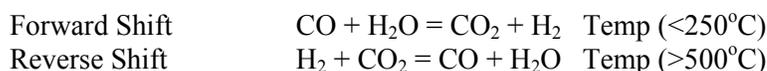


The combination of HPBR with DCFC is unique in that no outside source of electricity is necessary to drive the process. The DCFC supplies the HPBR with electrical power and the HPBR supplies the carbon for operation of the DCFC. The high efficiency of the DCFC and the relatively low power requirements for the HPBR produces a highly efficient integrated system for electrical power generation. The gases from the HPBR after cleaning can be used to produce either H_2 or syngas depending on the type of feedstock used.

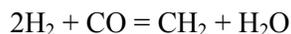
In Figure 2, the flowsheet for hydrogen production is completed by adding a water gas shift (WGS) reactor to convert the CO to hydrogen and CO_2 with the addition of steam (water). The CO_2 is separated by membrane or absorption/stripping and a clean pure H_2 stream is produced for sale.

Alternatively the syngas can be water gas shifted either forward or reverse (depending on the feedstock) to produce a stream in which the ratio of H_2/CO is 2.0 for feed to a Fischer-Tropsch catalytic converter to produce either gasoline (C_8-C_{11} average C_8H_{18}) or diesel ($C_{11}-C_{21}$ average $C_{16}H_{34}$) [7,8,9] transportation fuel. Figure 3 shows the IPFC-FT flowsheet.

The reactions in the WGS are as follows:



For reverse shift the CO_2 can be obtained from the DCFC. Note that using the higher heating value, the water gas shift reactions are essentially energy neutral ($\Delta H \cong 0$). The exothermic reactions in the Fischer-Tropsch catalytic reactor are represented by the following typical reaction with the unit CH_2 representing the unit alkane fuel molecule.



Typically, the enthalpy of reaction is $\Delta H = -49.5 \text{ Kcal/gmol}$ of unit CH_2 , exothermic

It should be noted in the simple flowsheets presented, the heat exchangers, recycling streams and multiple stage reactors are not shown but which must be included in the design of the process to maintain heat balance and take into account equilibrium and kinetic rate processes in each reactor. This brief analysis indicates there is sufficient high temperature waste heat to preserve the heat balance and resulting thermal efficiency.

Energy Efficiency of IPFC

Using thermodynamic data for each of the feedstocks, the thermal efficiency of the IPFC is defined as follows:

$$\% \text{ Thermal Efficiency} = \frac{\text{Output Electrical Energy} + \text{Heating Value of H}_2 \text{ or Transportation Fuel (CH}_2\text{)}}{\text{Input Heating Value of Feedstock}} \times 100$$

In Table 1 the mass and energy balance is presented for 5 fuel feedstocks together with the assumed reactor efficiencies, the calculated thermal efficiencies for electricity and hydrogen production and the total efficiency. It is noted that the efficiencies range around the 90% value. It should be noted that the reason the efficiencies are high is that the DCFC electrical efficiency is assumed to be 90%, the energy for decomposition of the feedstocks are relatively very low and when calculating the thermal efficiency for hydrogen production, the entire higher heating value is taken for H₂. Wherever the hydrogen is used downstream, the efficiency or loss of energy is assumed by that end-use system, for example in hydrogen fuel cells or for synthetic fuel production.

Table 2 gives the mass and energy balances and the thermal efficiencies for electricity and transportation fuel production using the IPFC-FT cycle. The efficiencies range from 70% to 83% for the 5 feedstocks studied in this paper. The liquid hydrocarbon transportation fuel can be used in current internal combustion engine vehicles and in the recent gas-electric hybrids as well as in other automotive vehicles that will be developed in the future to increase miles/gal (mpg) efficiency. The benefit of liquid fuels is that the current infrastructure for distribution, storage and engines are in place, which is not the case for hydrogen as an automotive fuel in fuel cell vehicles.

Table 3 indicates the CO₂ emissions from the IPFC in terms of lbsCO₂/Kwh of energy output in the form of electricity and hydrogen. The CO₂ emissions are compared to that of an equivalent IGCC plant providing the same quantity and ratio of product electricity and hydrogen output. Figure 4 shows a flowsheet for the IGCC plant with the addition of Fischer-Tropsch reactor. For hydrogen production, the flowsheet stops after the water gas shift.[11] The differences between the IGCC and IPFC is that an air liquefaction unit, a steam-gasifier and a combined cycle power generator are needed for the IGCC while only the hydrogen plasma black reactor and the direct carbon fuel cell makeup the IPFC. Estimates of the efficiency of the IGCC varies from 54 to 72% while the IPFC efficiencies range from 87 to 92%. As a result, the CO₂ emission reduction for IPFC is from 20 to 40% less per unit energy in the products than the IGCC. There is yet another advantage of IPFC over the IGCC. All the CO₂ emitted from the IPFC is undiluted. For sequestration of the CO₂ no further separation or capture energy expenditure is needed before sequestration. However, for IGCC, the gas fraction from the gasifier used for electricity production is combusted with air in the combined cycle plant and thus the CO₂ is diluted with nitrogen. The CO₂ must be captured and separated before sequestration. Cost estimates indicate a savings of several mills/Kwh(e) accruing to IPFC.[12]

Table 4 estimates the CO₂ emission reduction for IPFC compared to IGCC when electricity and transportation fuel (gasoline or diesel) are produced in the same relative amounts when using a lignite coal. The IPFC efficiency is 82% compared to the IGCC efficiency of 60%. As a result the total emissions for IPFC is 26% lower than for IGCC. Compared to a coal burning steam plant generating power at 38% efficiency, the IPFC plant shows a 76.4% reduction in emission of CO₂ per unit of electricity. Table 4 also shows a 36.4% reduction in CO₂ for IPFC producing gasoline compared to a gasification synfuel plant producing gasoline alone.

Preliminary economic estimates[12] indicate that IPFC plants can produce electricity and hydrogen or transportation fuels at a significantly lower cost than conventional steam and combined cycle plants (NGCC and IGCC). Furthermore, production of two co-products permits adjusting the sale price of electricity upwards to meet current market price, which allows adjusting the price downward of the co-product IPFC synthetic transportation fuel to allow direct competition with current oil refinery production prices.

Conclusion

It is shown that the integration of a hydrogen plasma black reactor (HPBR) with the direct carbon fuel cell (DCFC) for co-producing electricity and hydrogen or syngas from fossil fuel and biomass is a

highly efficient system. The thermal efficiency of producing electricity and hydrogen varies from 87 to 92% depending on the type of fuel and biomass feedstock used. For producing electricity and transportation fuels (gasoline and diesel) with the use of a Fischer-Tropsch catalytic converter, the thermal efficiencies ranged from 70% to 83% depending on the feedstocks fuel. The CO₂ emissions savings indicated a 20% to 40% reduction for the Integrated Plasma Fuel Cell Plant (IPFC) compared to the nearest competitor, the Integrated Gasification Combined Cycle Plant (IGCC) when co-producing electricity and hydrogen. Similar CO₂ emission reduction is found when co-producing electricity and transportation fuel. The bulk of the CO₂ emitted from the IPFC is undiluted compared to CO₂ dilution with atmospheric nitrogen in the IGCC plant, which results in a further cost savings when considering sequestration. These results underline the importance of increasing efficiency of converting fossil fuels and biomass to useful power and transportation fuels not only for fuel cost savings but also for gaining significant CO₂ emission reduction benefits.

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Table 1
Integrated Plasma Fuel Cell (IPFC) Cycle
Electrical Power and Hydrogen Production
Mass and Energy Balance and Thermal Efficiency
Basis – 1 gmol of Fuel

Fuel Feedstock	Natural Gas	Crude Oil	N. Dakota Lignite Coal	Kentucky Bit. Coal	Biomass (wood)	
Molar Composition	CH ₄	CH _{1.7}	CH _{0.77} O _{0.24}	CH _{0.81} O _{0.08}	CH _{1.38} O _{0.81}	
<u>Plasma Decomp. Products</u>						
Mole/Mole Fuel						
C	1.0	1.0	0.76	0.92	0.41	
CO	-	-	0.24	0.08	0.59	
H ₂	2.0	0.85	0.39	0.41	1.1	
Ash, S, N	-	~1.0	9.8	12.6	1.1	
Enthalpy of Decomp.	+18.0	+3.0	+3.6	+4.8	+12.7	
<u>Reactor Energy Balance, Energy Values, Kcal/gmol Fuel</u>						
<u>Unit</u>	<u>Eff%</u>					
DCFC	90	84.6	84.6	64.3	77.8	34.7
WGS	100	0	0	0	0	0
HPBR	60	-30.0	-5.0	-6.0	-8.0	-21.2
(consumed)						
<u>Product Output, Energy Values, Kcal/gmol Fuel</u>						
Net Electrical Energy	54.6	79.6	58.3	69.8	13.5	
HHV of H ₂ produced*	<u>136.0</u>	<u>57.8</u>	<u>42.8</u>	<u>33.3</u>	<u>87.0</u>	
Total Energy Output	190.6	137.4	101.1	103.1	100.5	
HHV of Feed Input	212.0	149.0	110.3	119.3	112.8	
Thermal Efficiency						
Electricity %	25.8	53.4	52.8	58.6	12.0	
Hydrogen %	<u>64.2</u>	<u>38.8</u>	<u>38.8</u>	<u>28.0</u>	<u>77.1</u>	
Overall Efficiency%	90.0	92.2	91.6	86.6	89.1	

*HHV of hydrogen = 68 Kcal/mol. Full value taken for Thermal Efficiency

Table 2
Integrated Plasma Fuel Cell (IPFC) Cycle
Electrical Power and Transportation Fuel Production
Mass and Energy Balances and Thermal Efficiency
Basis – 1 gmol of Feedstock Fuel

Fuel Feedstock	Natural Gas	Petroleum	N. Dakota Lignite Coal	Kentucky Bit. Coal	Biomass (wood)
Molar Composition (MAF) (MW)	CH ₄ 16.00	CH _{1.7} 13.70	CH _{0.77} O _{0.24} 16.61	CH _{0.81} O _{0.08} 14.09	CH _{1.38} O _{0.81} 22.82
<u>Plasma Decomp. Products</u>					
Mole/Mole Fuel					
C	1.0	1.0	0.76	0.92	0.41
CO	0	0	0.24	0.08	0.59
H ₂	2.0	0.85	0.385	0.41	0.69
Ash, S, N (wt%)	-	~1.0	9.8	12.6	1.1
Enthalpy of Decomp. Kcal/gmol feestock	18.0	3.0	3.6	4.8	12.7
Water gas shift, (WGS) gmol CO, and H ₂ per mol feed to obtain H ₂ /CO = 2.0	0.667	0.283	0.032	0.083	0.163
Transportation Fuel Production Gasoline or Diesel gmol CH ₂ /mol feed	0.667	0.283	0.208	0.163	0.427

Electric Power and Transportation Fuel Production Enthalpy Energy Values in Kcal/gmol Fuel

<u>Unit</u>	<u>Eff%</u>					
DCFC	90	84.6	84.6	64.3	77.8	34.7
WGS	100	-	-	-	-	-
HPBR	60	-30.0	-5.0	-6.0	-8.0	-21.2
consumed						
Net Electricity Prod.		54.6	79.6	58.3	69.8	13.5
F-T Gas. Diesel Fuel*		103.5	43.7	32.1	25.2	66.0
Total Energy Output		<u>158.1</u>	<u>123.3</u>	<u>90.4</u>	<u>95.0</u>	<u>79.5</u>
HHV of Fuel Feedstock		212.0	149.0	110.3	119.0	112.8
Thermal Efficiency %		74.5	82.8	82.0	79.8	70.4

*HHV of gasoline and diesel fuel = 154.5 Kcal/gmol

Table 3
Efficiency and CO₂ Emissions from Conventional and Integrated Plasma Fuel Cell (IPFC)
Combined Cycle Plants for Production of Electricity and Hydrogen

Fuel	Cycle	Product Ratio <u>Electricity</u> Hydrogen	Thermal Efficiency %	CO ₂ Emission Lbs/KWh(e&t)	% Reduction of CO ₂ Emission from IGCC
<u>Advanced Integrated Plasma IPFC⁽¹⁾</u>					
Natural Gas		0.40	90.0	0.437	19.5
Crude Oil		1.37	92.2	0.607	29.8
N. Dakota Lignite		1.38	91.2	0.829	39.8
Kentucky Bit. Coal		2.09	86.8	0.807	37.5
Biomass (wood)		0.16	89.1	(0.830)**	100.0
<u>Conventional Combined Cycle IGCC⁽²⁾</u>					
Natural Gas		0.40	72.4	0.543	-
Petroleum		1.37	64.7	0.865	-
N. Dakota Lignite		1.38	54.9	1.378	-
Kentucky Bit. Coal		2.09	54.3	1.291	-
Biomass (wood)		0.16	58.5	(1.264)**	100.0

- 1) IPFC is the advanced Integrated Plasma Fuel Cell Plant.
2) IGCC is the Integrated Gasification Combined Cycle Plant.

** For biomass, this is the amount of CO₂ emitted from power cycle, however, because of the photosynthesis of biomass formation from CO₂ there is no net emission of CO₂.

Table 4
Comparing Efficiency and CO₂ Emission from Conventional IGCC with Advanced IPFC
Combined Cycle Plants for Electricity and Transportation Fuel Production
Feedstock – North Dakota Lignite

Plant Cycle	IPFC	IGCC
Product Energy Ratio Output	1.82	1.82
% Electricity/ % Gasoline	64.5/35.5	64.5/34.5
Thermal Efficiency - %		
Electricity	52.9	38.7
<u>Gasoline</u>	<u>29.1</u>	<u>21.3</u>
Total	82.0%	60.0%
CO ₂ Emissions – LbsCO ₂ /Kwh		
Electricity	0.471	0.640
<u>Gasoline</u>	<u>0.259</u>	<u>0.352</u>
Total	0.730	0.992
% Reduction of CO ₂ Emissions		
<u>From IGCC Total</u>	26.5	-
<u>Electricity from Steam Plant</u> @38% Efficiency	76.4	67.9
<u>Gasoline from Gasification</u> Synfuel Plant @ 65% Efficiency*	36.4	13.4

* This gasification synfuel plant only produces transportation fuel.