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 CO_2 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 CO_2 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, direction carbon fuel cell, hydrogen, CO_2

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 H_2 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^{o}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^{o}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 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.

$$C + O_2 = CO_2 \text{ through the } CO_3^{=} \text{ (carbonate ion) electrolyte}$$

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:

Forward Shift	$CO + H_2O = CO_2 + H_2$	Temp (<250°C)
Reverse Shift	$H_2 + CO_2 = CO + H_2O$	Temp (>500°C)

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 ($\Delta H \cong O$). 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.

$$2H_2 + CO = CH_2 + H_2O$$

Typically, the enthalpy of reaction is, ΔH = -49.5 Kcal/gmol of unit CH2, 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:

$$\%\,Thermal\ Efficiency = \frac{Output\ Electrical\ Energy + Heating\ Value\ of\ H_2\ or\ Transportation\ Fuel\ (CH_2)}{Input\ Heating\ Value\ of\ Feedstock}\ x100$$

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 H_2. Whereever 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 CO_2 emissions from the IPFC in terms of lbsCO_2/kWh of energy output in the form of electricity and hydrogen. The CO_2 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 vary from 54 to 72% while the IPFC efficiencies range from 87 to 92%. As a result, the CO_2 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 CO_2 emitted from the IPFC is undiluted. For sequestration of the CO_2 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 CO_2 is diluted with nitrogen. The CO_2 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 CO_2 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 are 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 CO_2 per unit of electricity. Table 4 also shows a 36.4% reduction in CO_2 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 CO_2 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 CO_2 emission reduction is found when co-producing electricity and transportation fuel. The bulk of the CO_2 emitted from the IPFC is undiluted compared to CO_2 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 CO_2 emission reduction benefits.

References

[1] Steinberg, M. "An Innovative Highly Efficient Combined Cycle Fossil and Biomass Fuel Power Generation and Hydrogen Production with Zero CO_2 Emission", Second International Conference on Carbon Sequestration, Alexandria, VA (May 6-8, 2003).

[2] Gaudernack, B. and Lynum, S. 11th World Hydrogen Energy Conference, Cocoa Beach, Florida, pp. 511-23 (June 1996).

[3] Seguin, L. "The Karbomont Production Plant, Montreal Canada", Private Communication (2002).

[4] Cooper, J.F., et al. "Turning Carbon Directly into Electricity, Science and Technology Review" pp. 4-12, Lawrence Livermore National Laboratory, Livermore, CA (June 2001).

[5] Cooper, J.F., et al. "Direct Electrochemical Conversion of Carbon" Report UCRL-JC-138900 DOERD-059, Lawrence Livermore National Laboratory, Livermore, CA (2000).

[6] Cooper, J.F. "Direct Conversion of Coal and Coal Derived Carbon in Fuel Cells", 2nd International Conference on Fuel Cell Science, Engineering and Technology ASME, Rochester, NY (June 14-19, 2004).

[7] Probstein, R.F. and Hicks, R.E. Synthetic Fuels, pp. 271-6, pH Press, Cambridge, MA (1990).

[8] Xu, L. et al. "Don't Rule Out Iron Catalysts for Fischer-Tropsch Synthesis", Chemtec, pp. 47-53 (January 1998).

[9] Sasol Synfuels International "Fischer-Tropsch Conversion", Johannesburg, South Africa (1997).

[10] Do, R.T. "An Integrated Plasma Gasification Combined Cycle (IPGCC) System for Many Domestic Fuels" Solena Group, Inc., Washington, DC (2002).

[11] Johnson, J. "Getting to Clean Coal", Chem. & Eng. News, pp. 20-2, 24-5, 44 (February 23, 2004).

[12] To be presented in a subsequent HCE LLC report (2004).

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	$CH_{1.7}$	$CH_{0.77}O_{0.24}$	$CH_{0.81}O_{0.08}$	$CH_{1.38}O_{0.81}$
Plasma Decomp. Products						
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
Reactor Energy Balance, Energy Values, Kcal/gmol Fuel						
Unit	Eff%					
DCFC	90	84.6	84.6	64.3	77.8	34.7
WGS	100	0	0	0	0	0
HPBR	60 (consumed)	-30.0	-5.0	-6.0	-8.0	-21.2
Product Output, Energy Values, Kcal/gmol Fuel						
Net Electrical Energy		54.6	79.6	58.3	69.8	13.5
HHV of H_2 produced*		136.0	57.8	42.8	33.3	87.0
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 %		64.2	38.8	38.8	28.0	77.1
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 Transporation 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)	CH_4	$CH_{1.7}$	$CH_{0.77}O_{0.24}$	$CH_{0.81}O_{0.08}$	$CH_{1.38}O_{0.81}$
(MW)	16.00	13.70	16.61	14.09	22.82
Plasma Decomp. Products					
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 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

Unit	Eff%	Natural Gas	Petroleum	N. Dakota Lignite Coal	Kentucky Bit. Coal	Biomass (wood)
DCFC	90 .	84.6	84.6	64.3	77.8	34.7
WGS	100	-	-	-	-	-
HPBR	60 consumed	-30.0	-5.0	-6.0	-8.0	-21.2
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		158.1	123.3	90.4	95.0	79.5
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
Effciency and CO_2 Emissions from Conventional and Integrated Plasma Fuel Cell (IPFC) Combined Cycle Plants for Production of Electricity and Hydrogen

Fuel	Cycle	Product Ratio Electricity / Hydrogen	Thermal Efficiency %	CO_2 Emission Lbs/kWh(e&t)	% Reduction of CO_2 Emission from IGCC
Advanced Integrated Plasma IPFC(1)					
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
Conventional Combined Cycle IGCC(2)					
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 CO_2 emitted from power cycle, however, because of the photosynthesis of biomass formation from CO_2 there is no net emission of CO_2.

Table 4
Comparing Efficiency and CO_2 Emission from Conventional IGCC with Advanced IPFC Combined Cycle Plants for Electricity and Transporation 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
Gasoline	29.1	21.3
Total	82.0%	60.0%
CO_2 Emissions – LbsCO_2/kWh		
Electricity	0.471	0.640
Gasoline	0.259	0.352
Total	0.730	0.992
% Reduction of CO_2 Emissions		
From IGCC Total	26.0	-
Electricity from Steam Plant @38% Efficiency	76.4	67.9
Gasoline from Gasification Synfuel Plant @ 65% Efficiency*	36.4	13.4

* This gasification synfuel plant only produces transporation fuel.

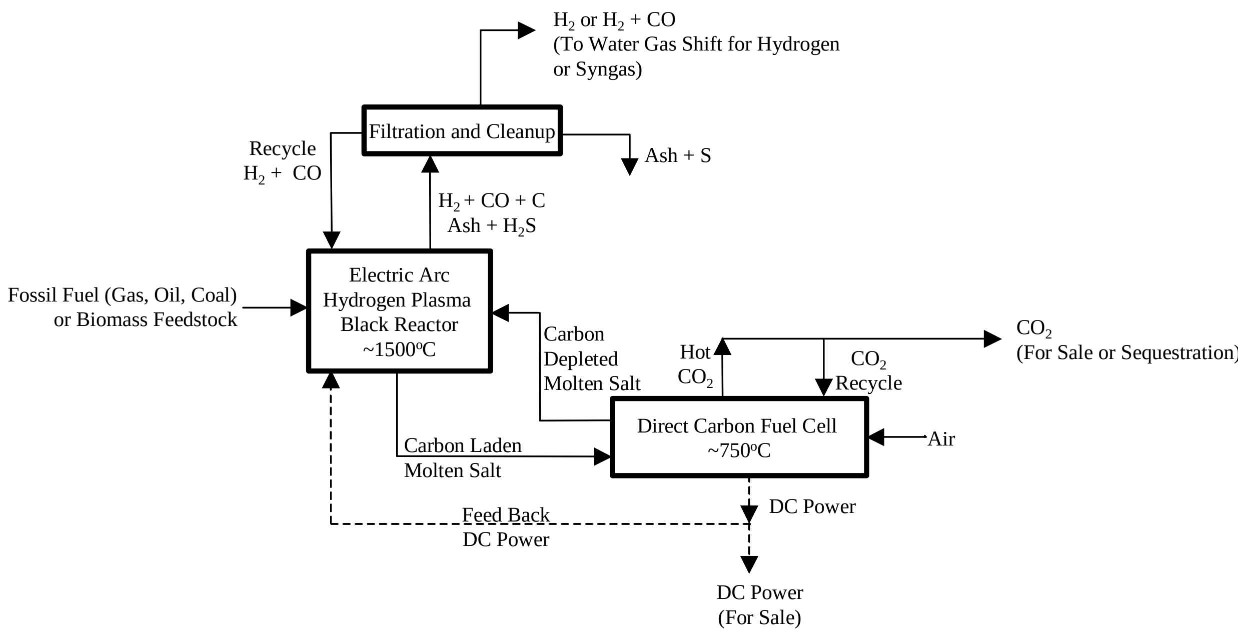

FIG. 1 -- Hydrogen Plasma Black Reactor Integrated with Direct Carbon Fuel Cell for Conversion of Fossil Fuels or Biomass to Electric Power and Hydrogen or Syngas. (IPFC)

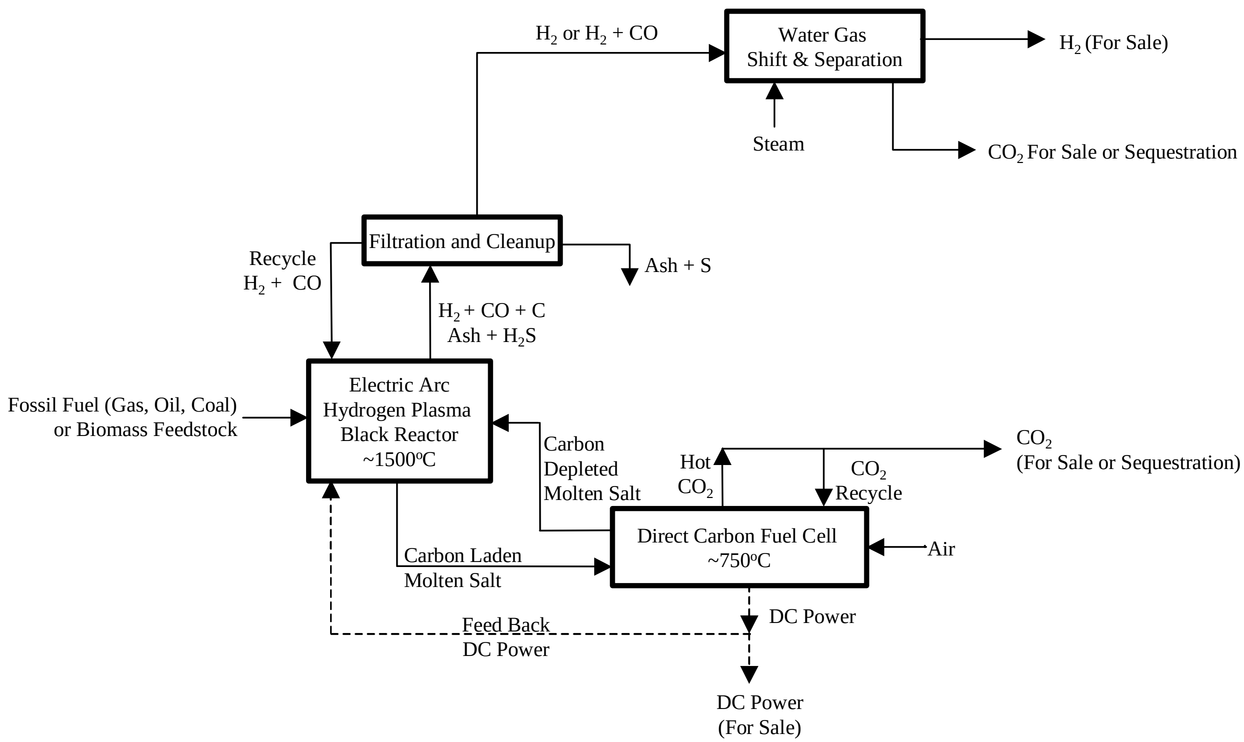

FIG. 2 -- Hydrogen Plasma Black Reactor Integrated with Direct Carbon Fuel Cell for Conversion of Fossil Fuels or Biomass to Electric Power and Hydrogen . (IPFC)

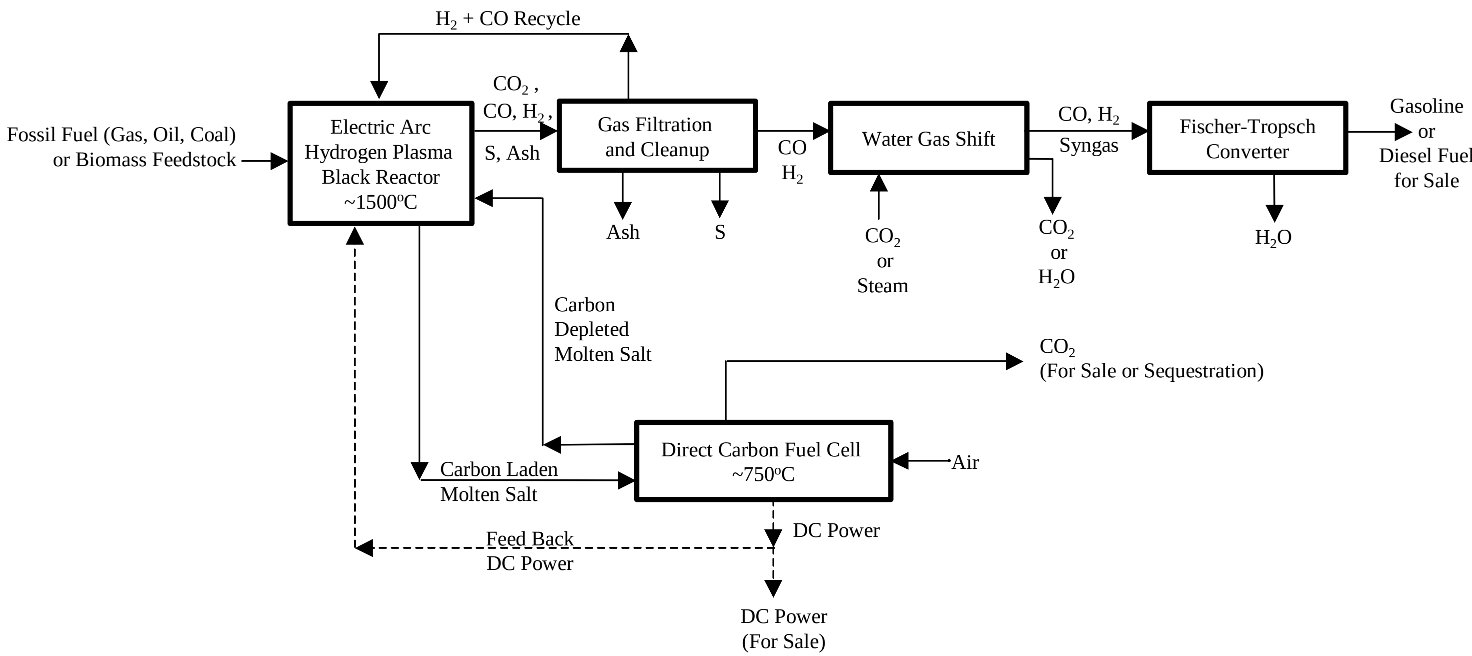

FIG. 3 -- Integrated Plasma Fuel Cell Plant for Producing Power and Transportation Fuels (IPFC – FT).

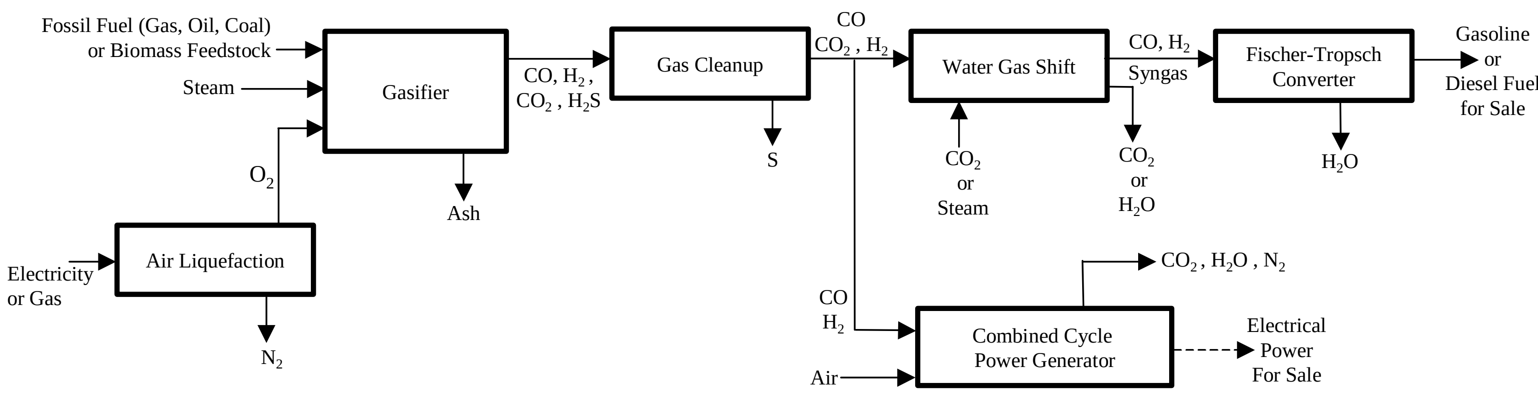

FIG. 4 -- Integrated Gasification Combined Cycle Plant for Producing Power and Transportation Fuels (IGCC – FT)