1.3.1.3

Hydrogen-Fueled Power Systems

Wen-Ching Yang

Department of Chemical &
Petroleum Engineering
University of Pittsburgh
Pittsburgh, PA 15261

(724) 327-3011
wcyang@pitt.edu

1.3.1.3-1 Introduction

The concept of a hydrogen economy was introduced in the 1960s as a vision for future energy requirements to replace the inevitable exhaustion of fossil fuels. In the hydrogen economy, the storable and transportable hydrogen is envisioned to be a dominant energy carrier. The hydrogen can also be exploited as a clean, renewable, and nonpolluting fuel. The use of hydrogen as a fuel is attractive for a number of reasons:

- Hydrogen burns with 15-22% higher thermal efficiency than that of gasoline;
- From an environmental standpoint, hydrogen combustion with pure oxygen results in no emissions of the greenhouse gases, CO, CO_2, SO_x, and NO_x; and
- It generates only steam and water.

Serious hydrogen-fueled turbine development program primarily comes from the initiatives of the Japanese government in 1992, through its New Energy and Industrial Technology Development (NEDO). It created the World Energy Network (WE-NET) Program, a 28-year effort from 1993 to 2020, directed at research and development of the technologies needed to develop a hydrogen-based energy conversion system[1]. Part of this effort is directed toward research and development of a hydrogen-fueled combustion turbine system[2] which can efficiently convert the chemical energy stored in hydrogen to electricity via a heat engine in which the hydrogen is combusted with pure oxygen. Turbine manufacturers developing hydrogen-fueled power generation cycles under the WE-NET program include Westinghouse, Toshiba and Mitsubishi Heavy Industries[3]. The hydrogen-fuel power systems resulting from the WE-NET program and others reported in the literature are summarized below.

1.3.1.3-2 The High Temperature Steam Cycle (HTSC) Power System

The High Temperature Steam Cycle (HTSC) power system, shown in figure 1 and reported by Kizuka et al.,, was based on that suggested by Jericha, et al.[4]. It has two closed cycles: the topping and the bottoming cycles. The topping cycle consists of a compressor, combustor, intermediate pressure (IP) turbine, steam cooler 1, and steam cooler 2. The bottoming cycle includes a low pressure (LP) turbine, condenser, preheater, high pressure (HP) turbine, combustor, and IP turbine. The key design considerations are to increase the outlet temperature of the IP turbine to generate more steam in the bottoming cycle and to increase the inlet temperature of the LP turbine to obtain more power.

The HTSC power system makes use of the closed-loop cooling systems. Closed-loop cooling techniques will be favored in advanced combustion turbines because they (1) eliminate the disruption of the turbine flowfield caused by coolant ejection, (2) eliminate mixing losses caused by coolant ejection, (3) reduce the decrease in gas path temperature caused by turbine cooling, and (4) return the turbine coolant to the primary cycle[5].

The conceptual designs of the cooling systems were studied by Kizuka et al.,[6]. The three systems studied are (1) closed-circuit water cooling system for nozzle blades and steam cooling system for rotor blade; (2) closed-circuit steam cooling system for nozzle and rotor blades; and (3) open-circuit steam cooling system for nozzle and rotor blades.

The main component parameters employed to evaluate the cycle performance is summarized in table 1. The reported performance of three different types of cooling systems for a 1700°C-class, hydrogen-fueled combustion gas turbine varies from 54.9 % to 61.3 % efficiency based on HHV.

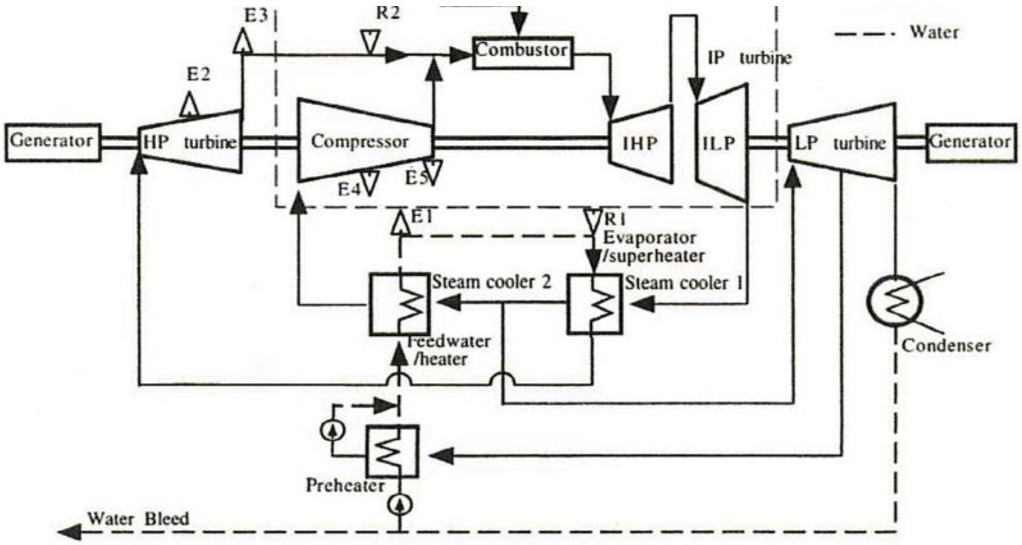

Fig. 1. Process Diagram for the HTSC Power System

Table 1 Main Component Parameters for HTSC Plant

IP Turbine (Topping Cycle Gas Turbine)	
Compressor	
Inlet Pressure (MPa)	0.14
Inlet Temperature (°C)	114
Outlet Pressure (MPa)	4.90
Rotational Speed (rpm)	6,500
Combustor	
Fuel	$H_2 + O_2$
Outlet Temperature (°C)	1,700
Turbine	
Stage	2(IHP) + 6(ILP)
Rotational Speed (rpm)	6,500(IHP), 3,000(ILP)
Inlet Gas Flow (kg/s)	222.3
Outlet Pressure (MPa)	0.16
Bottoming Cycle	
HP Turbine	
Inlet Pressure (MPa)	19.00
Outlet Pressure (MPa)	5.00
LP Turbine	
Inlet Pressure (MPa)	0.15
Outlet Pressure (MPa)	0.05

1.3.1.3-3 The New Rankine Cycle

Figure 2 depicts the so-called new Rankine cycle configuration involving direct steam expansion proposed and investigated by Funatsu et al.[7]. The combustion gas in the cycle consists of only pure steam by combusting hydrogen and oxygen stoichiometrically in the high pressure combustor (HPCOMB) and low pressure combustor (LPCOMB).

The feed water from the condenser (COND) is pressurized by the boiler feed water pump (BFP) to the super critical pressure, and then heated in the heat recovery boiler (HRBL). The steam generated in the HRBL is first expanded in the high pressure turbine (HT). The exhaust from HT is then reheated in the high pressure combustor (HPCOMB) and expanded in the intermediate pressure gas turbine (IHT) again. Finally, the reheat and expansion is repeated in the low pressure combustor (LPCOMB) and the low pressure gas turbine (ILT). The steam from ILT exchanges heat with the feed water in HRBL, expands through the low pressure steam turbine (LT), and condenses in the condenser (COND). The operating parameters at different stations shown in figure 2 are reported in table 2. The reported thermal efficiency is over 60 percent HHV or 71.89 percent LHV.

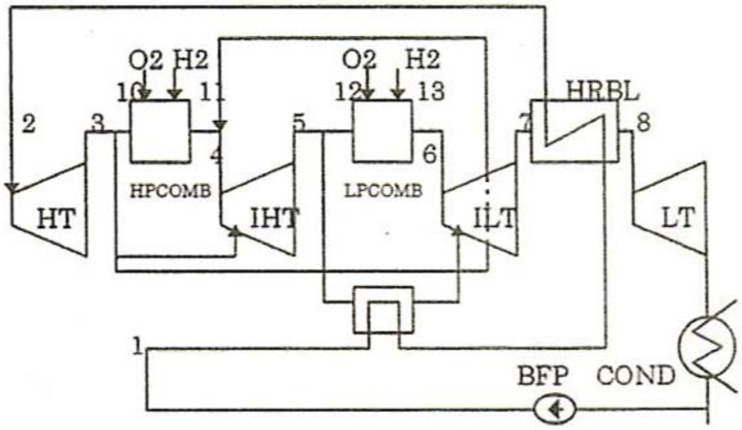

Fig. 2. Process Diagram for the New Rankine Cycle Power System

1.3.1.3-4 The Rankine Cycle With Reheat And Recuperation

In the studies by the Westinghouse team on an optimum hydrogen-fueled combustion turbine system, alternative turbine systems were evaluated[8]. (The Power Generation Division of Westinghouse Electric Corporation was acquired by Siemens AG in 1998 and became Siemens Westinghouse Power Corporation, a fully-own subsidiary of Siemens). The Rankine cycle with regeneration and reheat was identified as the best system with potential to reach the highest efficiency. A Rankine cycle with reheat and recuperation was thus selected as the general reference system for the study of hydrogen-fueled power systems. Westinghouse has assessed both a near-term reference plant and a long-term reference plant. The near-term plant requires moderate development based on extrapolation of current steam turbine technology for the HP turbine (650°C inlet temperature), and extrapolation of current combustion turbine technology for the IP turbine (1700°C inlet temperature). In contrast, the long-term plant requires more extensive development for an additional intermediate high pressure (IHP) reheat turbine (1700°C inlet temperature), and is more complex than the near-term plant¸ with closed-loop steam cooling[9] of the IHP and IP turbines, and extractive feedwater heating. A single reheat stage is used in the near-term plant and two reheats are used in the long-term plant. The HRSG operates at atmospheric pressure, producing supercritical steam.

The Westinghouse studies identified the trade-offs between the efficiency benefits and the developmental challenges of the near-term and long-term reference plants. The near-term plant achieves 65.2 percent net plant efficiency, and the long-term plants achieve 71.4 percent net plant efficiency. Even though the near-term plant does not achieve the goal of 70.9 percent net plant efficiency, its relative simplicity and low cost make it attractive as a next step.

Process flow diagrams for the near-term and long-term plants are shown in figures 3 and 4. Representative temperatures and pressures are listed at various locations on the flow diagrams. Table 3 provides a summary of the essential technical assumptions for the component performance factors, and the reference plant requirements and boundary conditions.

Table 2 The New Rankine Cycle Performance Parameters

Location	**Pressure**	**Flow**	**Temperature**	**Enthalpy**
	MPa	kg/s	°C	kJ/kg
1	38.0	104.2	100	447.9
2	34.3	104.2	750	3851.1
3	7.35	104.2	464	3315.9
4	6.99	115.8	1700	6506.3
5	0.98	133.1	1146	4798.1
6	0.93	148.0	1700	6510.5
7	0.14	156.1	1129	4965.5
8	0.13	156.1	148	2771.7
9	0.005	145.1	33	2315.3
10	-	25.7	-	-
11	-	3.2	-	-
12	-	20.4	-	-
13	-	2.6	-	-
Generating Power 500MW				
Thermal Efficiency 60.57 % (HHV) 71.89 % (LHV)				

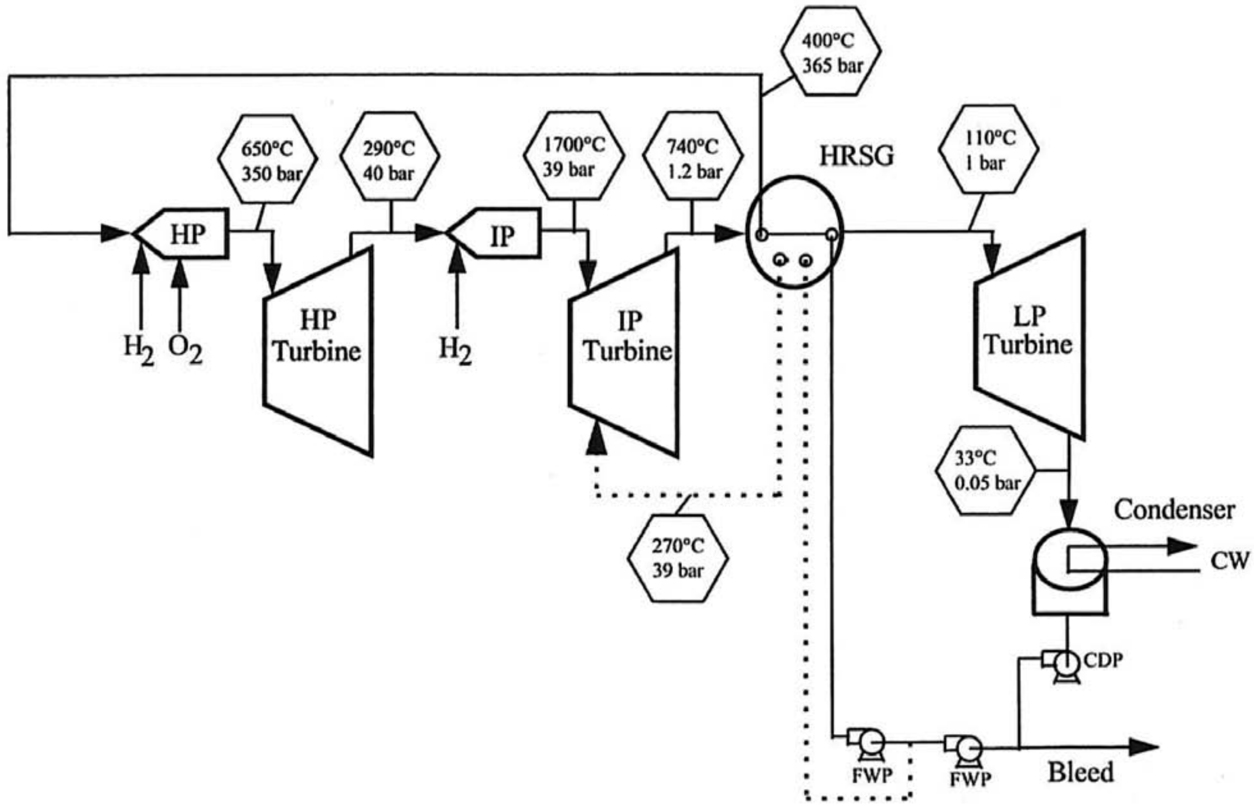

Fig. 3. Process Diagram for the Near-Term Rankine Cycle with Reheat and Recuperation

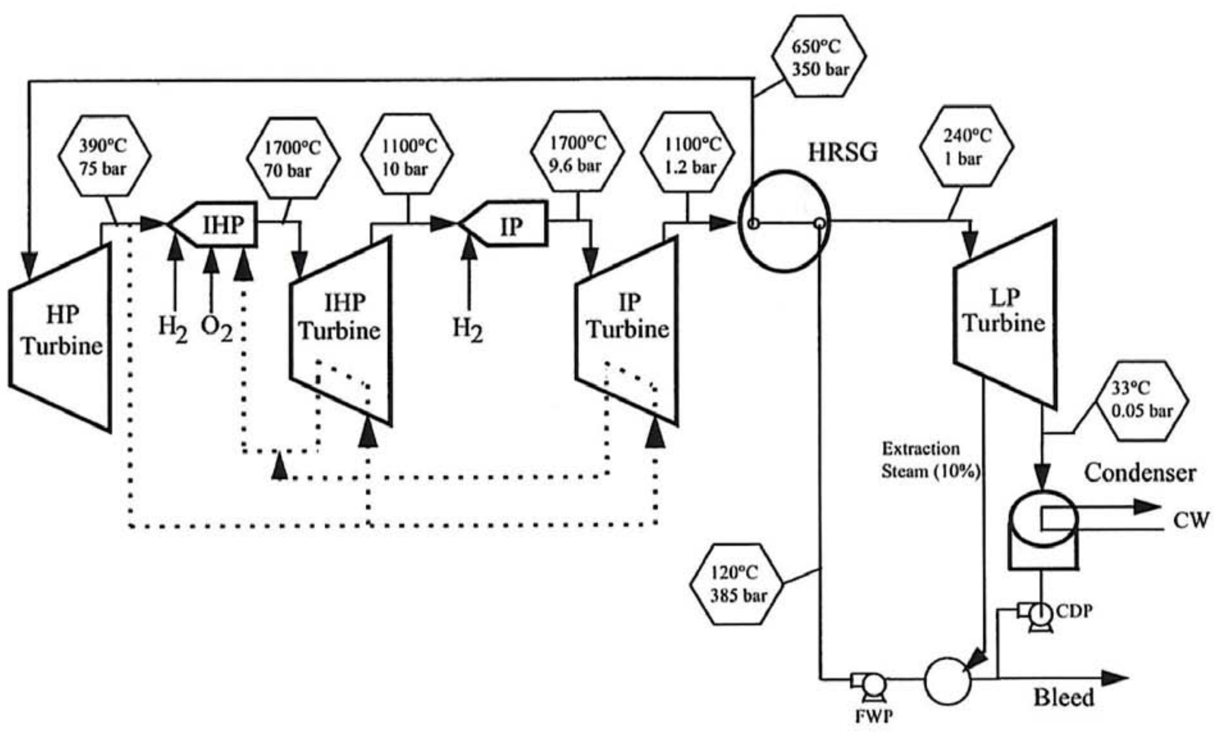

Fig. 4. Process Diagram for the Long-Term Rankine Cycle with Reheat and Recuperation

Table 3 Estimated Component Performance Factors and Reference Plant Conditions

PLANT	
Capacity (MWe)	500
Site Type	Greenfield, Sea-Side
Ambient Air Temperature (°C)	15
Ambient Pressure (bar)	1.01325
Relative Humidity (%)	60
Cooling Sea Water Temperature (°C)	21
Hydrogen and Oxygen Supply Temperature (°C)	15
Hydrogen and Oxygen Supply Pressure	As Required
Hydrogen Purity (%)	100
Oxygen Purity (%)	100
Hydrogen HHV (kJ/kg)	141742
CONDENSER	
Type	Vacuum
Shell Pressure (bar)	0.0508
PUMPS	
Adiabatic Efficiency (%)	85
Motor Efficiency (%)	98
Mechanical Efficiency (%)	98
HRSG	
Tube-Side Pressure Drop (%)	3
Shell-Side Pressure Drop (%)	3
Heat Loss (% of heat transferred)	0.2
COMBUSTORS	
Pressure Drop (%)	3
Combustion Efficiency (%)	99.9
Heat Loss (% of heat input)	0.1
TURBINES	
Rotation Speed (rpm)	3,600
Bearing Losses (% of shaft power)	0.6
Adiabatic Efficiency (%; HP, IHP, IP, LP)	93, 93, 93, 93
Exhaust Losses	Neglect for HP Turbine
Steam Leaks (% of inlet flow)	2
Shaft Leakages	Neglect
Windage and Pumping for Steam Leaks	Neglect
Steam Cooling (% of inlet flow for IHP, IP)	15, 15
Coolant Pressure Drop (%)	10
LP Turbine Maximum Moisture Content (%)	15
LP Turbine Minimum Inlet Temperature (°C)	110
OTHERS	
Steam Piping Pressure Drop (%)	3
Generator Efficiency (%)	99.2
House Load (% of plant shaft power)	1.5 (near-term); 1.0 (long-term)

In the near-term plant, figure 3, hydrogen and excess oxygen are combined in the HP combustor and are mixed with recycle steam to produce a 650°C combustion product at a nominal pressure of 350 bar. This is then expanded through the uncooled HP turbine, producing an exhaust stream having nominal conditions of 290°C and 40 bar. This exhaust stream, containing excess oxygen, is combined with stoichiometric hydrogen to generate the IP combustion products at a temperature of 1700°C. The IP turbine expands this combustion stream to exhaust conditions of about 740°C and 1.15 bar. The IP turbine exhaust stream is cooled in the HRSG down to about 110°C before being expanded through the LP turbine to about 33°C and the condenser pressure. A bleed stream of water is taken from the water condensate. Feedwater pumps provide high-pressure water for the HRSG to produce high-pressure steam for recycle, and intermediate-pressure water for the HRSG to produce intermediate pressure steam for open-loop cooling of the IP turbine. The conceptual design characteristics for HP turbine and IP turbine for the near-term plant are tabulated in tables 4 and 5. Table 6 shows the conceptual design characteristics of the HRSG.

Table 4 Near-Term HP Turbine Design Characteristics

Cooling Needs	None
Inlet Temperature (°C)	650
Exhaust Temperature (°C)	288
Inlet Pressure (bar)	350
Expansion Ratio	8.75
Gas Flow (kg/s)	150
Number of Stages	15
Number of Cooled Stages	0
Blade Heights (first stage/last stage) (cm)	2.3/6.4
Turbine Casing Diameter (m)	1.7
Length of Flow Passage (cm)	270
Total Turbine Length (m)	4.9

Table 5 Near-Term IP Turbine Conceptual Characteristics

Cooling Needs	Open-Loop Steam
Inlet Temperature (°C)	1700
Exhaust Temperature (°C)	740
Inlet Pressure (bar)	38.8
Expansion Ratio	33.7
Gas Flow (kg/s)	154
Number of Stages	6
Number of Cooled Rows	11
Blade Heights (first stage/last stage) (cm)	7.4/36.4
Turbine Casing Diameter (inlet/exhaust) (m)	2.3/3.7
Length of Flow Passage (cm)	200
Total Turbine Length (m)	5.6

Table 6 HRSG Conceptual Characteristics

FLUE SIDE	
Inlet Gas	Steam with trace oxygen and noncondensibles
Inlet Gas Flow (kg/s)	177
Inlet Gas Temperature (°C)	740
Inlet Gas Pressure (bar)	1.15
Outlet Temperature (°C)	110
Pressure Drop (bar)	0.09
TUBE SIDE	
Inlet Fluid	0.15 µS cation conductivity water
Inlet Temperature (°C)	33
IP Inlet Pressure (bar)	40
Inlet Flow (kg/s)	121
HP Inlet Pressure (bar)	385
HP Outlet Flow (kg/s)	98
IP Outlet Temperature (°C)	269
HP Outlet Temperature (°C)	397
HRSG DIMENSIONS	
HRSG Length (m)	24
HRSG Width (m)	12
HRSG Height (m)	14

Figure 4 depicts the long-term reference plant process diagram. The differences between the long-term plant and the near-term plant diagrams are primarily related to the insertion of an additional turbine stage, the IHP turbine, and the use of extractive feedwater heating. The long-term plant HP turbine expands recycle steam at 650°C and 350 bar. The HP turbine exhaust stream has nominal conditions of 387°C and 75 bar. A portion of the HP exhaust stream is used for closed-loop cooling of the IHP turbine and the IP turbine. The remainder of the HP exhaust stream is combined with hydrogen fuel, excess oxygen, and the exiting IHP and IP turbine closed-loop cooling streams. The IHP combustion produces a 1700°C, 70 bar stream to be expanded in the IHP turbine. The IHP turbine exhaust stream is at about 1100°C and 10 bar pressure. The IHP exhaust stream is combined with a stoichiometric amount of hydrogen to generate IP combustion products at 1700°C and 9.6 bar for expansion in the IP turbine. The IP turbine exhaust is about 1100°C and 1.2 bar pressure. Both the IHP turbine and the IP turbine produce very high temperature exhaust stream requiring high temperature piping designs. The IP expansion stream is cooled in the HRSG to about 240°C before expansion in the LP turbine. Steam is extracted from the IP turbine for feedwater heating. In contrast to the near-term plant, the long-term plant HRSG produces recycle steam at a single pressure level to be expanded in the HP turbine.

The HP turbine in both the near-term and long-term plants is close to, or within the range of current steam turbine technology[10]. In contrast, the long-term plant IHP turbine is a large technology step above both current steam turbine practices and advanced combustion turbine developments. The IP turbine has conditions close to the conditions of advanced combustion turbines being developed for natural gas fuels [11].

The conceptual design of the reference plant was developed by using several design tools and sources of engineering experience. A commercial process simulator (ASPEN PLUS™) was applied to develop the reference plant process flow diagrams and thermal performance estimates. Westinghouse proprietary design codes were used to design and size turbines, combustors, and the HRSG. Advanced combustion turbine engineering experience resulting from development programs in the United States[12] and advance steam turbine engineering experience resulting from past studies and testing at Westinghouse[13] were used to extrapolate current technology to the demands of the reference plant.

Plant heat and materials balances and cycle calculations were generated for the reference plant at its rated load of 500 MWe using the component performance assumptions described. No hydrogen or oxygen preheat is used in the plants, and extractive feedwater heating is used in the long-term plant only, providing a simple, compact plant configurations. Table 7 lists the reference plant performance and power generation breakdown for the long-term and the near-term plants. The plant net efficiency for the near-term plant is estimated to be 65.2 % (LHV) and that for the long-term plant, 71.4% (LHV).

Table 7 Reference Plant Thermal Performance

	Long-Term Plant	**Near-Term Plant**
HP Turbine (MWe)	42.3	81.6
IHP Turbine (MWe)	189.9	-
IP Turbine (MWe)	215.4	362.5
LP Turbine (MWe)	67.9	74.1
Gross Power (MWe)	515.5	518.2
Gross Efficiency (%)	73.5	67.6
Generator Losses (MWe)	4.1	4.1
Pumping Power (MWe)	6.2	6.5
BOP Losses (MWe)	5.2	7.8
Net Power (MWe)	500.0	500.0
Net Efficiency (%)	71.4	65.2

The reference plant environmental performance is expected to be superior to that of other power generation concepts using other fuels, by having very low nitrogen oxides, sulfur oxide, particulate, toxic species, and green-house gas emissions. The generation of solid waste and liquid/sludge wastes would also be negligible. The only significant emissions could result from fuel or oxygen contaminants, or from noise.

1.3.1.3-5 Developmental Requirements

In a final report[14] published in 1999, Westinghouse discussed the developmental requirements for realization of hydrogen-fueled power systems to be developed in the general areas of 1) Materials, 2) Closed-loop turbine cooling, and 3) Hydrogen combustion for the major equipment components: combustors, compressors, expanders, and heat exchangers. The nature of these developmental requirements depend on the specific component operating conditions. The feasibility of manufacturing the equipment components with current technology must also be considered.

The near-term plant HP turbine development should center on combustion phenomena and design features of the combustor and materials selection. The near-term HP turbine design needs to be an adaptation of conventional HP steam turbine designs. The IP turbine development needs should center on the component cooling needs- airfoils, cylinder, blade rings, and rotor bearings. The cooling design should follow from closed-loop steam cooling features currently under development for advanced combustion turbines operating under similar temperature and pressure conditions.

HP and IP combustion development should focus on the nature of the hydrogen combustion products and the control of its chemistry, as well as the combustor operability: flame stability, ignition, flame detection, and combustion-induced oscillations. Combustor liner and transition cooling should also be part of the combustor development testing.

Materials testing should focus on the durability of candidate materials during exposure to the hydrogen combustion products at simulated commercial operating duty conditions. This includes hydrogen embrittlement, oxidation, stress corrosion cracking, corrosion deposits, and creep rupture. The development of appropriate corrosion coatings and TBCs, and their associated bond coating, should be a major part of the materials program. These may include advanced combustion turbine Ni-based super-alloys (single crystal and directionally-solidified), and advanced combustion turbine TBCs (e.g., yttia-stabilized zirconia, alumina, TiN). The materials testing associated with the IP turbine should also consider the limited use of ceramic components in ring segments, combustor liners and transitions, and, vane and blade leading edges.

The stability of candidate ceramic materials and alternative ceramic forms in simulated combustion-steam environments (e.g. zirconia in composite forms, tile forms, and fibrous insulating forms) should also be considered.

1.3.1.3-6 Conclusions

The development of a hydrogen-fueled power plant with an efficiency higher than 70 percent (LHV) can be accomplished. Four conceptual reference cycle power systems, the high-temperature steam cycle, the new Rankine cycle and the near-term and long-term Rankine cycle with reheat and recuperation, were reviewed and reported. The reference plants environmental performance is expected to be superior to that of other power generation concepts using other fuels, by having very low nitrogen oxide, sulfur oxide, particulate, toxic species, and green-house gas emissions. The generation of solid waste and liquid/sludge wastes would also be negligible. The only significant emissions could result from fuel or oxygen contaminants, or from noise.

To reach the ultimate reality, the hydrogen-combustion turbine cycles described require development in the general areas of materials, closed-loop turbine cooling, and hydrogen combustion for the major equipment components: combustors, compressors, expanders, and heat exchangers.

1.3.1.3-7 Notes

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BIOGRAPHY

1.3.1.3 Hydrogen-Fueled Power Systems

Wen-Ching Yang

Department of Chemical &
Petroleum Engineering
University of Pittsburgh
Pittsburgh, PA 15261

phone: (724) 327-3011
email: wcyang@pitt.edu

Dr. Yang worked for Westinghouse Electric Corporation and Siemens Westinghouse Power Corporation for more than 36 years primarily in the area of advanced fossil fuel power generation systems for IGCC applications. In the past 6 years, he concentrated on the detailed design of commercial gas turbines through cold flow simulation testing, experimentation at commercial sites, theoretical modeling, and development of advance sensors to monitor performance of gas turbines. He was elected a Fellow of American Institute of Chemical Engineers in 1992 and awarded a honorary Guest Professorship at the Thermal Engineering Department of Tsinghua University in Beijing, China, in 1996. He holds several patents relating to turbine applications in the area of partial oxidation, thermal chemical recuperation, and hydrogen-fueled power plants. He retired at the end of July 2004 and is now an adjunct Professor at the Department of Chemical and Petroleum Engineering, Univeristy of Pittsburgh.