Thermodynamic Performance Analysis of a Novel Hydrogen-Oxygen/Coal-Fired Combined Cycle System Postprint

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Abstract

This paper proposes a novel hydrogen-oxygen-coal combined cycle system based on traditional coal-fired power generation units and hydrogen-oxygen combined cycles. This system couples ultra-supercritical coal-fired units with hydrogen-oxygen combined cycles, achieving efficient utilization of hydrogen energy and coal, and enriching the utilization modes of the two fuels. This paper uses EBSILON to conduct preliminary simulation of this system. The research results show that this system achieves a power generation efficiency of 49.74% at an initial steam pressure of 25.6 MPa and a maximum temperature of 1300°C, and that higher efficiency can be achieved by increasing the cycle maximum temperature and gas turbine expansion ratio.

Full Text

Thermodynamic Performance Analysis of a Novel H2/O2-Coal Fired Combined Cycle System

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Abstract

This paper proposes a novel H2/O2-coal fired combined cycle system based on traditional coal-fired power plants and hydrogen-oxygen combined cycles. This system couples an ultra-supercritical coal-fired unit with an H2/O2 combined cycle, enabling efficient utilization of both hydrogen and coal while diversifying fuel utilization approaches. Preliminary simulations using EBSILON Professional software demonstrate that the system can achieve a power generation efficiency of 49.74% under initial steam pressure of 25.6 MPa and maximum temperature of 1300°C, with potential for even higher efficiency through increased cycle maximum temperature and gas turbine expansion ratio.

Keywords: H2/O2 combined cycle; coal-fired power plant; thermodynamic analysis; key parameters

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0 Introduction

China' s 12th Five-Year Plan established clear requirements for the energy sector: by 2020, non-fossil energy should account for approximately 15% of primary energy consumption, and CO2 emissions per unit of GDP should decrease by 40-45% compared to 2005 levels [1]. To fulfill these commitments regarding energy structure adjustment and greenhouse gas emission control, China' s power industry must accelerate its development transformation by optimizing coal power distribution and vigorously developing clean energy [2].

Among various new energy sources, hydrogen represents the cleanest carbon-free secondary energy, characterized by high calorific value and diverse sources. From a long-term perspective, hydrogen energy with zero pollution emissions holds broad development prospects [3]. As early as the early 1990s, researchers in China, Japan, and the United States almost simultaneously proposed the concept of hydrogen-oxygen combined cycles utilizing hydrogen energy [4-7]. Both the United States and Japan now have research programs to implement this technology practically. In H2/O2 combined cycles, hydrogen serves as fuel and the turbine back pressure corresponds to steam condensation pressure rather than atmospheric pressure typical of conventional gas turbines, resulting in significantly greater power output. Additionally, while most combined cycles require a waste heat boiler coupling the topping and bottoming cycles with exhaust temperatures around 150°C, causing substantial energy losses, H2/O2 combined cycles eliminate this loss source and can therefore achieve higher efficiencies [8-9]. Recent research by scholars including Fang Gang [4], M. Gambini [10], S.P. Cicconardi [11], and Xu Hong [9,12] has focused on design, analysis, and improvement of H2/O2 combined cycles, confirming their status as efficient and clean power generation systems. Considering that hydrogen-oxygen combustion produces only water vapor—the same working fluid as conventional coal-fired units—hydrogen energy can potentially be utilized in traditional coal-fired plants through appropriate integration approaches.

Accordingly, this paper proposes a novel H2/O2-coal fired combined cycle that details key system components to achieve efficient utilization of both hydrogen and coal, thereby enriching fuel utilization options.

1 System Description

1.1 Conventional Ultra-Supercritical Coal-Fired Unit (Reference Case)

This study selects a typical 1000 MW single-reheat ultra-supercritical unit as the reference case, with a simplified system flow diagram shown in [Figure 1: see original paper]. The reference system employs an ultra-supercritical variable-pressure once-through boiler and an N1000-26.25/600/600 ultra-supercritical, single intermediate reheat condensing steam turbine with eight stages of non-adjustable regenerative extraction. presents the main operating parameters of the reference unit.

1.2 Proposal of the H2/O2-Coal Fired Combined Cycle

Based on conventional coal-fired units and integrated with H2/O2 combined cycles, this paper proposes an H2/O2-coal fired combined cycle system, with the process flow diagram illustrated in [Figure 2: see original paper]. After leaving the boiler, main steam expands through the high-pressure steam turbine. The exhaust steam is then heated in a reheat preheater before entering the combustion chamber. The combustion chamber uses pure hydrogen as fuel and pure oxygen as oxidizer, generating high-temperature water vapor that mixes with high-pressure turbine exhaust before entering the gas turbine for expansion work. Due to the high exhaust temperature from the gas turbine, the exhaust first preheats reheat steam in the reheat preheater and subsequently heats boiler feedwater in the feedwater preheater before entering the low-pressure steam turbine. After expansion in the low-pressure turbine, steam condenses into water. Following separation of the water produced by hydrogen-oxygen combustion, the water is pressurized by feedwater pumps, heated in the feedwater preheater, and returned to the boiler, completing the cycle.

Key design features of the new system include: (1) elimination of the coal-fired boiler' s reheat system, with steam reheating accomplished by the H2/O2 combustion chamber; (2) removal of the extraction regenerative system due to excessively high steam temperatures in the gas turbine for safety and heat transfer considerations; and (3) addition of reheat and feedwater preheaters to recover waste heat from the high-temperature gas turbine exhaust, following the principle of "temperature matching and cascade utilization" to improve system heat utilization efficiency. [Figure 3: see original paper] shows the temperature-entropy diagram of this system.

As shown in [Figure 3: see original paper], compared with conventional ultra-supercritical coal-fired units, the steam temperature is significantly increased, raising the system' s average heat absorption temperature. Meanwhile, the high-temperature gas turbine exhaust (process 7-8) preheats high-pressure turbine exhaust (process 4-5), and process 8-9 heats boiler feedwater (process 1-2), enabling effective recovery of exhaust heat through the regenerative system.

2 Thermodynamic Analysis

2.1 Thermodynamic Analysis Model

The mass balance relationship for the H_2/O_2-coal fired combined cycle system is:

$$HPSTm + Hm = GTm = LPSTm$$

where GTm, LPSTm, and HPSTm represent the mass flow rates through the gas turbine, low-pressure steam turbine, and high-pressure steam turbine respectively (kg/s), and Hm is the hydrogen flow rate into the combustion chamber (kg/s).

The total work output from the cycle is:

$$W_{total} = WHPST + WGT + WLPST = HPSTm(h3 - h4) + GTm(h6 - h7) + LPSTm(h9 - h10)$$

where h represents specific enthalpy at different points (kJ/kg), and WHPST, WGT, and WLPST are the work outputs from the high-pressure steam turbine, gas turbine, and low-pressure steam turbine respectively (kW).

Considering end-use system efficiency for hydrogen, compression work for hydrogen and oxygen is not included, so the net power output is:

$$W_{net} = W_{total} - WFWP$$

where WFWP is the feedwater pump power consumption (kW).

Heat input to the system is:

$$Q_{in} = QC + QH = (HPSTm - Hm)(h3 - h2) + Hm \times LHV_{H2}$$

where QLHV is the lower heating value of hydrogen (kJ/kg).

System power generation efficiency is:

$${}_e = (W_{net} \times {}_m \times {}_g) / Q_{in}$$

where ${}_m$ is mechanical efficiency (%) and ${}_g$ is generator efficiency (%). The cycle maximum temperature Tmax is defined as the gas turbine inlet temperature, and the gas turbine expansion ratio β is the ratio of inlet pressure to outlet pressure.

This study uses EBSILON Professional software to simulate the H_2/O_2-coal fired combined cycle system. EBSILON is a professional integrated power plant simulation software widely used for design, evaluation, and optimization of power plants and other thermal systems. Simulation results are presented in .

2.2 Analysis of Calculation Results

The system adopts the main steam parameters and high-pressure cylinder exhaust parameters from the reference unit, with a gas turbine exhaust pressure of 0.1 MPa. Key system parameters were assumed as shown in .

** Main Parameters and Assumptions of the Cycle System**

Parameter	Value
Maximum steam pressure	25.6 MPa
Superheat/reheat temperature	600°C
Boiler efficiency	94%
Steam turbine efficiency	90%
Gas turbine inlet temperature	1300°C
Gas turbine efficiency	92%
Gas turbine inlet pressure	5.5 MPa
Gas turbine expansion ratio	55
Mechanical efficiency	98.5%
Generator efficiency	98.5%
Combustion chamber efficiency	99%
Reheater preheater upper terminal difference	50°C
Feedwater preheater lower terminal difference	30°C
Combustion chamber pressure loss	3%
Heat exchanger pressure loss	3%
Low-pressure steam turbine exhaust pressure	0.005 MPa

** Thermodynamic Performance Analysis of the H2/O2-Coal Fired Combined Cycle**

Parameter	Unit	H2/O2-Coal Combined Cycle
Heat input	MW	2010.3
Coal heat input QC	MW	861.2 (42.84%)
Hydrogen heat input QH	MW	1149.0 (57.16%)
High-pressure steam turbine output	MW	127.0 (12.45%)
Gas turbine output	MW	737.3 (72.32%)
Low-pressure steam turbine output	MW	282.3 (27.68%)
Feedwater pump power	MW	5.3 (0.52%)
Net power output	MW	1000.0
Power generation efficiency _e	%	49.74%

As shown in , under the selected operating conditions, the H2/O2-coal fired combined cycle system achieves improved power generation efficiency. At a maximum cycle temperature of 1300°C and maximum pressure of 26.25 MPa, the system attains 49.74% efficiency—4.96 percentage points higher than the reference unit.

Define Φ as the ratio of gas turbine work output to steam turbine work output, and as the ratio of hydrogen heat input to coal heat input. The results indicate that the gas turbine dominates power generation, producing 737.3 MW (72.32% of total output), while steam turbines contribute 282.3 MW (27.68%), yielding $\Phi = 2.61$. Hydrogen also dominates heat input at 57.16% compared to coal' s 42.84%, giving = 1.33.

Furthermore, using the H2/O2 combustion chamber for reheating reduces coal consumption to 38.6% of the original system, with corresponding reductions in pollutant and greenhouse gas emissions and significantly lower energy consumption for emission control.

3 Influence of Key Parameters

3.1 Impact of Key Parameters on System Efficiency

Literature [13-14] indicates that in hydrogen-fueled combined cycles, temperature, pressure, and expansion ratio substantially affect system efficiency. With other parameters held constant, this study analyzed system performance by varying gas turbine inlet temperature Tmax and inlet pressure. Efficiency variations are shown in [Figure 4: see original paper].

As illustrated in [Figure 4: see original paper], increasing both the cycle expansion ratio β and maximum temperature Tmax improves power generation efficiency, with temperature exhibiting a more pronounced effect. At $\beta = 70$ and Tmax = 1700°C, the system efficiency reaches 54.1%. The maximum cycle temperature is constrained by gas turbine material strength, thermal barrier coatings, and cooling technology [15]; as these technologies advance, Tmax will gradually increase, further improving system efficiency.

3.2 Influence of Maximum Temperature on Work and Heat Ratios

Since the H2/O2-coal combined cycle employs dual fuels and two turbine types, this study analyzed the turbine work ratio Φ and hydrogen-to-coal heat ratio under different maximum cycle temperatures. Simulation results are presented in [Figure 5: see original paper].

[Figure 5: see original paper] demonstrates that both Φ and remain greater than 1, indicating gas turbine dominance in power output and hydrogen dominance in heat input. As Tmax increases, both Φ and gradually rise. At Tmax = 1700°C, gas turbine output becomes 3.5 times steam turbine output, and hydrogen heat input reaches 2.2 times coal heat input. Therefore, improving the hydrogen combustion environment and optimizing gas turbine structure will significantly enhance system performance.

4 Conclusions

This paper proposes a novel H2/O2-coal fired combined cycle system based on conventional ultra-supercritical coal-fired units integrated with hydrogen-oxygen combined cycles. The system couples traditional coal-fired power plants with H2/O2 combined cycles, diversifying hydrogen and coal utilization forms. Simulation analysis demonstrates that the system can achieve high efficiency while substantially reducing pollutant and greenhouse gas emissions. Further efficiency improvements are possible through optimization of expansion ratio β and maximum cycle temperature Tmax.

1. Compared with conventional ultra-supercritical units, the H2/O2-coal combined cycle system achieves higher power generation efficiency. At Tmax = 1300°C and gas turbine expansion ratio of 55, the cycle efficiency reaches 49.74%—a 4.96 percentage point improvement over the reference unit.

2. The maximum cycle temperature and gas turbine expansion ratio significantly affect system efficiency. Increasing both parameters improves efficiency. At $\beta = 70$ and Tmax = 1700°C, the cycle efficiency reaches 54.1%.

3. Power output is dominated by the gas turbine, while heat input is dominated by hydrogen. As Tmax increases, both the work ratio Φ and heat ratio rise. At Tmax = 1700°C, gas turbine output is 3.5 times steam turbine output, and hydrogen heat input is 2.2 times coal heat input.

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Note: Figure translations are in progress. See original paper for figures.