Research Article
Volume 10:4, 2021

Journal of Material Sciences & Engineering

ISSN: 2169-0022

Open Access

Thermodynamic Modeling of oxyhydrogen fueled combined cycle power plant

Joshua Partheepan and **Emily M. Hunt***

College of Engineering, West Texas A&M University, USA

Abstract

Renewable power generation can reduce the dependence on fossil fuels while minimizing greenhouse gas emissions from electric power generation. However, most renewable energy sources are naturally occurring which makes them seasonal and generally unpredictable over time. With more countries trending toward renewable power by 2050, it is imperative that technologies are developed which can utilize and optimize the storage and distribution of this type of power. Hydrogen energy storage is becoming increasingly popular due to its versatility. It is considered an energy carrier like electricity and can be generated and stored in large quantities and for long periods of time. Hydrogen can be derived from water, biomass, and other technologies and can generate electric power using fuel cells and through combustion. This study investigates a novel combined cycle configuration which is thermodynamically analyzed to identify its potential to adapt steam from a hydrogen oxygen steam generator. A thermodynamic analysis on the system is performed using Engineering Equation Solver from F Chart Software. Results show that the oxygen hydrogen fueled combined cycle excels in the specific power ratio, as this cycle was able to achieve the lowest pressure values at the highest points for both thermal loading and pressure loading. This is a major advantage since the thermal loading on some of the power cycles are much higher that what is currently in use, thus reducing it even by a smaller percentage is significant. The oxygen hydrogen fueled combine cycle reduced the specific power by 78%, pressure at the most thermal loaded point by 157%, and pressure at the most pressure loaded element by 10% when compared to other common cycles.

Keywords: Oxy hydrogen • Combustion • Thermodynamic cycle

Introduction

In the 21st century, thirst for alternative energy, concerns over carbon induced global warming, government regulations; public perception and energy security have led to the development of renewable power generation alternatives and a renewable energy growth by almost 7% in 2020 for generating electricity [1]. Renewable power generation can reduce the dependence on fossil fuels and minimizing greenhouse gas emissions from electric power generation. However, most renewable energy sources are seasonal, variable, and uncertain making most form of renewable energy non-dispatchable in nature. Research literature has pointed out that higher presence of renewable power generators needs backup generation and energy storage to maintain the reliability of the grid [2,3].

Several countries around the world and several utilities around in the United States (US) are pledging to achieve 100% generation from carbon neutral power generation by 2050 [4,5]. Energy storage will play a major role in the future electric grid to support carbon neutral power generators to meet all of the electric demand. Different energy storage technologies are out there which can help the grid in different ways such as to regulate frequencies, peak shaving, uninterrupted power supply, load leveling, etc. [6]. Hydrogen energy storage is one of the promising low cost energy storage technique. Hydrogen is considered an energy carrier like electricity [7]. The strongest argument for the use of hydrogen is its versatility. Hydrogen can be generated and stored in large quantity and for long periods using mature technology. It can directly fuel cars; it can produce electricity (through combustion or fuel cells). It can be used as a primary chemical for many products. It can be used for hydro cracking in refineries. It can be injected into the gas grid (up to 5 to 10%) [7]. All of these potential uses have attracted interest for research into hydrogen energy storage in the resent years.

Hydrogen is a secondary source of energy [7]. Hydrogen can be obtained from multiple sources like water, natural gas molecules, or biomass and the technology to obtain hydrogen from such sources is mature and several new techniques are in research and development phase [8,9]. Hydrogen storage under high pressure in tanks is currently investigated by automobile industries, however large scale underground storage of hydrogen and liquid hydrogen storage is a mature technology used in oil and gas and space exploration industry [10,11].

Hydrogen can be used to generate electric power using fuel cells, or as a combustible fuel for internal combustion engines and gas turbines or for generating steam in a aphodid burner which can power a steam turbine [12]. There is increased interest in the use of hydrogen as a fuel source for traditional or catalytic combustion because hydrogen creates none of the pollutants associated with fossil fuels carbon monoxide, carbon dioxide, sulfur dioxide, particulates and photochemical oxidants. Hydrogen combustion with air results in water and smaller concentrations of oxides of nitrogen as byproduct. Hydrogen has been proven to increase the efficiency of engines and gas turbines [13]. Power generation based on hydrogen is currently dominated by fuel cells [14], but the idea of using hydrogen combustion in power plan is not new. Hydrogen combusted with pure oxygen results in high temperature pure steam, which needs to be cooled by diluting it with water or low temperature steam to achieve the desired temperature that a turbine can tolerate. Few studies related to the use of H2/O2 combustion for direct steam generation have been reported in literature.

***Address for Correspondence:** Emily M. Hunt, Department of Engineering, West Texas A&M University, USA, Email: ehunt@wtamu.edu*

Received date: 23 March, 2021; **Accepted date:** 06 April, 2021; **Published date:** 13 April, 2021

The principle of burning hydrogen and oxygen at stoichiometry was used in rocket engines initially. Due to the tremendous amount of energy released in the form of steam, some researchers were attracted to a design model based on the concept of producing steam in an aphodid burner and using it in steam turbines to generate electric power. This was patented in 1967 by Oklahoma State University [15]. The German Aerospace Center (DLR) and the Institute of Combustion Aerothermics Reactivity and Environment (ICARE) in France collaborated to study several configurations of hydrogen oxygen combustion based steam generators for power generation with several configurations of water injection into the steam generators [16]. The Institute for High Temperature of Russian Academy of Science (IVTAN) designed and developed a hydrogen oxygen steam generator for powering a steam cycle power plant [17]. West Texas A & M University (WTAMU) is actively involved in design and developing a proof of concept for hydrogen oxygen steam generator [18].

Materials and Methods

The hydrogen oxygen steam generator has a combustion efficiency of 99% [16-18], ranking power plant cycle in practice are not optimized for hydrogen oxygen steam generator to generate power efficiently. Several patents and published work discuss about specific thermodynamic cycle for hydrogen oxygen steam generator. A thermodynamic analysis on several proposed steam turbine cycle configurations (GRAZ, TOSHIBA, WESTINGHOUSE and MNRC) were discussed in literature, which shows that the cycle can obtain efficiency as high as 66.4% Higher Heating Value (HHV) of hydrogen for power generation which is much higher than traditional fossil fuel fired power plant or a combine cycle power plant [19]. The studied literature reveals that most of the patent and thermodynamic model for hydrogen oxygen steam generator uses Rankine cycle or some form of modified Rankine cycle, which uses steam turbine. One of the primary challenges discussed in all the literature is the presence of residual gases in the product steam stream from hydrogen oxygen steam generator, which pose a significant threat to steam turbine since steam turbine is not designed to handle impurities in turbine inlet steam [16,18]. In this paper a novel combined cycle configuration is thermodynamically analyzed to identify its potential to adapt steam from hydrogen oxygen steam generator.

The analyzed novel combined cycle configuration is based on the US patent “Combined Brayton/Rankine Cycle Gas and Steam Turbine Generating System Operated in Two Closed Loops”. The uniqueness of the patent is, the steam generated by hydrogen oxygen combustion is injected into gas turbine rather than a steam turbine, which has a greater advantage in terms of handling impurities in the steam stream form the hydrogen oxygen combustor [20]. A simple flow diagram of the Combined Brayton/Rankine Cycle Gas and Steam Turbine Generating System Operated in Two Closed Loops, for now on will be referred as oxyhydrogen fueled combined cycle

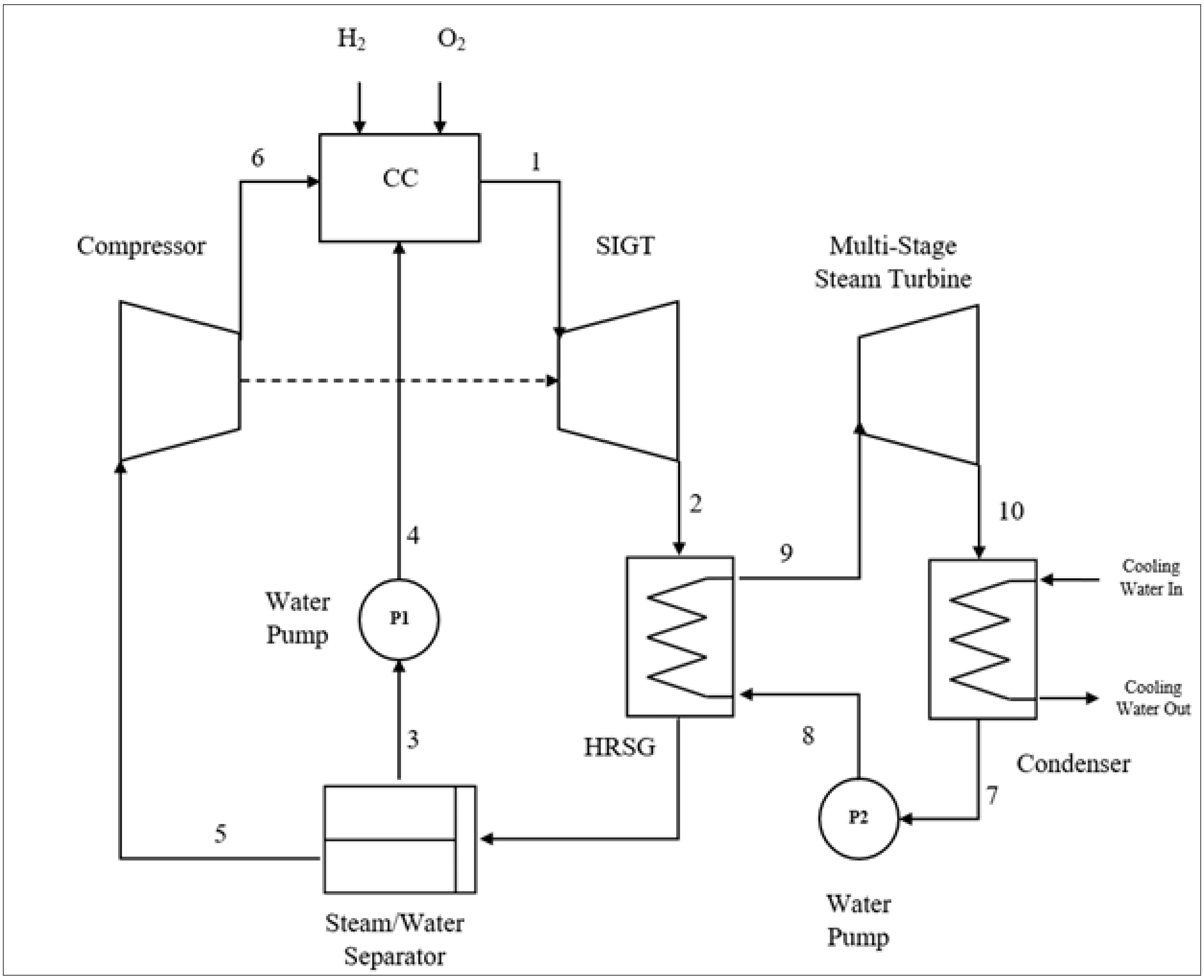

Figure 1. A simple flow diagram of oxyhydrogen fueled combined cycle power plant.

power plant (OHFCC) is show in Figure 1.

The oxyhydrogen fueled combined cycle power plant consists of Brayton (gas turbine) as topping cycle and Rankine (steam turbine) as bottoming cycle. The toping cycle consist of a steam compressor, oxy-hydrogen steam generator; steam injected gas turbine (SIGT), heat recovery steam generator (HRSG), steam/water separator and water pump. The bottoming cycle consist of multi stage steam turbine, condenser and a water pump. The hydrogen and oxygen which in the future can be generated by an electrolyzer which uses surplus renewable power generation will be stored in cylinders or underground storage is used as a source for the power plant.

The oxy-hydrogen steam generator takes pressurized oxygen and hydrogen and burns it at stoichiometric condition to generate maximum energy, which is then used to generate high temperature high pressure (HTHP) steam at desired temperature by mixing combustion product with cooling steam and/or cooling water. Oxy-hydrogen steam generator can generate steam at wide range of temperature, pressure, and quantity in a short amount of time at high combustion efficiency of 99% [15-18].

The HTHP steam is feed into SIGT and allowed to expand, while converting the energy in HTHP steam to rotational energy, which can be used to drive an alternator/generator or other mechanical load depending on the end use. Steam exiting SIGT is usually low in pressure but has significant temperature; hence the high temperature low pressure (HTLP) steam is feed in heat recovery steam generator (HRSG).

HRSG, recovers the residue heat available in the SIGT out HTLP steam and uses that heat to convert high pressure water into medium temperature high pressure steam (MTHP), which will be injected into steam turbine. The HRSG might be a little different that traditional HRSG used in fossil fuel fired combined cycle power plant, since the operating fluid is water in both the loop, and the temperature in Brayton cycle at HRSG outlet can reach low temperature resulting in partial condensation of water, there by leading to phase change in the working fluid of both the loops.

The low temperature low pressure (LTLP) steam water mixture from HRSG will be feed to steam water separator which separates the LTLP steam from water and feeds the LTLP steam to steam compressor to raise the pressure which then can be feed to oxy-hydrogen steam generator as cooling steam. The separated water is pressurized using water pump P1 and then feed into oxy-hydrogen steam generator as cooling water. The cooling steam and water can also be used in turbine cooling, when modern SIGT are used which operates at much higher temperature when compared to traditional gas turbines.

On the Rankine cycle side, the heat extracted from the HRSG is transferred to the pressurized water from water pump P2, which is converted into to MTHP steam which is feed into a multistage steam turbine to extract maximum energy from it before feeding the steam into condenser. The condenser cools the steam from steam turbine and feeds it into the water pump P2 to continue operating the loop in closed cycle.

Results and Discussion

A thermodynamic analysis on the system is performed using Engineering Equation Solver (EES) from F Chart Software. The parameters used in the calculation are listed in Table 1. Most of the parameters are adapted from previously published studies on oxy-hydrogen steam generator based power cycles [19] to make the calculations more generalized and some specific parameters unique to this cycle are adopted in accordance with industrial standard.

Parameter	Unit	Value
Compressor stages group internal efficiency	%	90
Turbine stages group internal efficiency	%	90
Combustor efficiency	%	99
Heat exchanger pressure loss	%	4.3
Combustor pressure loss	%	5
Pump efficiency	%	90
Electric generator efficiency	%	99
Cycle overall mechanical efficiency	%	99
Overall power output	MW	500
Temperature after a combustor	°C	1,700
Condenser pressure	MPa	0.005
Condensate temperature	°C	33
Pressure at steam turbine inlet in steam cycle	MPa	25
Compressor ratio of compressor in gas turbine cycle	-	30

Table 1. Nominal conditions used for analysis of the cycle

For simplicity, the compressor ratio of compressor in the gas turbine cycle is assumed to 3 MPa which are common in modern stationary gas turbine units [21]. The pressure of steam at steam turbine in the steam cycle is limited to 25 MPa, which is an industrial average for steam turbine. The cooling steam and cooling water exiting the steam water separator is assumed to exit at atmospheric pressure and finally, the mass flow rate of cooling water and cooling steam is assumed to be equal. The results from the calculation are presented in Table 2, along with the results from similar

Cycle Parameter	GRAZ	TOSHIBA	WESTINGHOUSE	MNRC	OHFCC
Pmax, MPa	35	38	25	25	25
Tmax, °C	1,700	1,700	1,700	1,700	1,700
Gross power, MW	513	513	513	513	513
ηLHV, %	70.8	71.2	74	79	71.32
ηHHV, %	59.5	59.8	62.2	66.4	60.36
Specific power, kJ/kg	2,202	3,331	3,489	4,706	2,066
Net (electric) power, MW	500	500	500	500	500
η_{el},LHV, %	69	69.4	72.2	77	70.61
η_{el},HHV, %	58	58.3	60.6	64.7	59.76
Temperature at the most thermal loaded point, °C	1,700	1,700	1,700	1,700	1,700
Pressure at the most thermal loaded point, MPa	5	7.3	25	25	3
Pressure at the most pressure loaded element, MPa	35	34.3	27.7	27.7	25
Temperature at the most pressure loaded element, °C	650	876	517	463	868.7
Quantity of heat exchanged (HRSG heat load), MW	315	329	256	165	520

Table 2. Nominal conditions used for analysis of the cycle

calculation done in the literature [19].

OHFCC cycle is often compared to GRAZ, TOSHIBA, WESTINGHOUSE and MNRC cycle in terms of efficiency. Where OHFCC excels is in the specific power ration, pressure at the most thermal loaded point, and pressure at the most pressure loaded element since it was able to achieve the lowest value when compared to all the other cycles. This is a major advantage since the thermal loading on some of the power cycles are much higher that what is currently in use, thus reducing it even by a smaller percentage is significant. The most efficient cycle in theory is MNRC, and comparatively OHFCC is 10% less efficient, however OHFCC manages to reduce specific power by 78%, pressure at the most thermal loaded point by 157% and pressure at the most pressure loaded element by 10%. On the other hand, the temperature at the most pressure loaded element is 61% higher, but well within the industrial operational range.

Conclusion

There are several parameters involved in the OHFCC cycle which play a vital role in determining the efficiency of operation of the cycle. Those parameters are steam compressor pressure ratio, cooling steam to cooling water mass flow rate ratio, SIGT inlet steam temperature, HRSG exit steam temperature in Brayton cycle, HRSG exit steam temperature in Rankine cycle, and steam turbine inlet steam temperature. These parameters can be further optimized to enhance the efficiency.

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How to cite this article: Joshua Partheepan and Emily M. Hunt." Thermodynamic Modeling of oxyhydrogen fueled combined cycle power plant". J Material Sci Eng 10 (2021)..01-04