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Study of the Hydrogen-Steam Turbine Composite Cycle

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Abstract

It is proposed a new type of the thermodynamic cycle in this article. The cycle is mainly composed by Hydrogen Generator (HG), Hydrogen Turbine (HT), Hydrogen-Oxygen Combustor (HOC) and Steam Turbine (ST). The pure hydrogen is generated in HG at high pressure and is heated up. The hydrogen with high pressure and high temperature develops power by flowing through HT. The hydrogen passed through HT is burned with pure oxygen in HOC, and the generated steam provides power by expansion in ST sequentially. Different from the conventional Combined Cycle (CC), this thermodynamic cycle is series-wound by hydrogen turbine and steam turbine. Based on these features this cycle is called as the Hydrogen-Steam Turbine Composite Cycle (HSTCC) in this article. It is indicated that HSTCC has a higher efficiency. It should be a competitive power generating system using the sophisticated turbine technique for hydrogen energy in future.

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Keywords: Thermodynamic Cycle, Hydrogen Energy, Hydrogen Turbine, Steam Turbine.

Nomenclature

η	thermal cycle efficiency
W_{HT}	power generated by HT
W_{ST}	power generated by ST
Q_{H2}	combustion heat of hydrogen in HOC

1. Introduction

World energy consumption is greatly growing with the progress of civilization and society. Energy supply has become the fundament of existence and development of society. The large scale consumption of fossil fuels causes the serious environmental pollution and social problems. It is urgent to find a new types of energy and consuming technologies that free human from the environmental pollution. As energy carrier, hydrogen has outstanding advantages in this aspect and is given more expectations [1].

For the mobile and distributed energy system, the pollution can be considerably reduced by utilization of hydrogen [2]. The hydrogen belongs to secondary energy, the mass production of hydrogen and power generation by hydrogen can control the pollution emission in a small area. How efficiently to generate power by hydrogen becomes a key technology accordingly. Many researchers have investigated the novel strategy for consuming the hydrogen, for example the fuel cell technique [3]. Technologies of traditional power generation, such as turbine and internal-combustion engine, are sophisticated and have been accumulated the rich experience in practical engineering. In order to minimize the researching and producing cost many researchers have carried out the investigation for efficiently transforming the chemical energy of hydrogen using these traditional technologies[4][5].

Due to the peculiarity of turbine engine, researchers have studied the application of gas turbine fueled by hydrogen in ship [6]. Or using the gas turbine as key component, a variety of advanced power cycle can be built up [7][8]. And these cycle can be efficiently operated in a clean power generation through CO2 capture and/or NOx elimination [9].

As the potential energy carrier for future, the hydrogen can be produced by various methods [10][11]. Some of the methods can be used to produce the pure hydrogen, for example the water photolysis pool or the thermal decomposition furnace. Such unit is called as the hydrogen generator (HG) in this article.

It is proposed a new type of thermal cycle using turbine technology based on the concept of HG in this article. In this proposed cycle the water photolysis pool (PP) is used as HG. There are a gas turbine (hydrogen turbine, HT) and a steam

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turbine (ST) in the cycle, but different from CC, the HT is connected with steam turbine in series. In the HT and ST the solar energy collected by process in HG will be transformed into thermal and mechanical energy in combustor and turbines efficiently. It is showed that the cycle has high efficiency without pollution. It provides an optional cycle technique for hydrogen power generation in future.

2. Layout of the proposal thermal system

It is shown the layout of the proposed cycle in Figure 1.

The cycle consists of Feed Pump (FP), Hydrogen Generator (HG), Hydrogen Heat Exchanger (HHE), Hydrogen Turbine(HT), Hydrogen-Oxygen Combustor (HOC), Steam Turbine (ST), Condenser (Cd), Condenser Pump (CP) and Feed pump (FP). During the cycle operating, water is firstly pressurized by the FP. The pressurized water is decomposed into hydrogen and oxygen by sunlight in HG. Then the hydrogen enters in the HHE and be heated, and the energy for heating the hydrogen is come from the HOC. After that the hydrogen will firstly expand and generate power in the HT. The in HT expanded hydrogen will then enter into the HOC and combust with pure oxygen from the PP. Part of the energy produced in combustion will be used to heat the hydrogen in the HHE. Because the temperature of steam, the product of the combustion product of pure hydrogen-oxygen, is very high, the steam must be cooled by using the liquid water so that the material of the turbine can suffer the high temperature. Thereafter the steam will expand sequentially and generate power in the ST. The steam exhaust will finally condense into water in the Cd. And the condensed water will be pumped by the pump in the CP and HOC proportionally. After these processes the cycle is completed.

In the above mentioned cycle, the components before the HT constitute the top cycle and that after the HOC constitute the bottom cycle. It can be concluded that the proposed cycle uses sunlight as the energy and combined with sophisticated technologies of gas (hydrogen) and steam turbines. The high grad energy can be utilized in HT and that of the low grad will be utilized in ST contrarily. So the cycle accords with the cascade utilization principle of thermal energy and should have higher efficiency. Because the HT and ST are serially connected in the proposed cycle, it is named as Hydrogen-Steam Turbine Composite Cycle (HSTCC) especially.

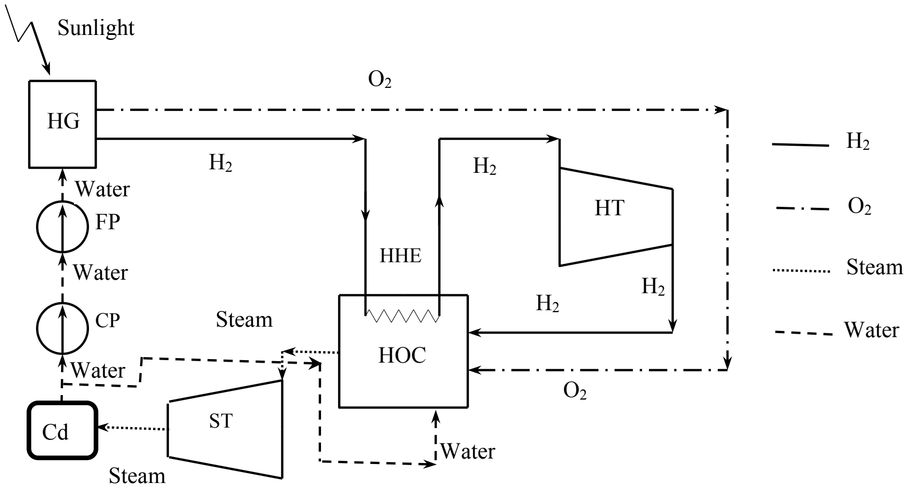

Figure 1 Layout of the HSTCC system

3. Evaluation Result and Discussion

3.1. Evaluation Result of HSTCC

There is no evaluation method for the proposed cycle efficiency at present. To analyze performance of this it is treated as below:

Taking 1kg water entered in HG for example, the enthalpy of the substance from this 1kg water at different period in the HSTCC is calculated. Because there are two units outputting power in the HSTCC, so the cycle efficiency is defined by:

$$\eta = \frac{W_{HT} + W_{ST}}{Q_{H2}} \quad (1)$$

W_{HT} , W_{ST} and Q_{H2} can be calculated according to the relevant theory.

The maximal temperature in a thermal cycle is the most important parameter for efficiency. The combustion heat of pure hydrogen and oxygen is so tremendous that no materials can be suffered the temperature of the combustion product without cooling. So the generated steam in the HOC must be firstly cooled with coolant. Considering the feature of the cycle it is suitable to use water as the coolant. According to the present technology and possible progress in future, it is assumed that the highest temperatures in the cycle equals to 1673.15K in evaluation. The temperature in other components is shown as follows:

The water is decomposed to pure hydrogen and oxygen by photolysis in the HG and the temperature of the decomposed pure hydrogen and oxygen equals to 293.15K. The hydrogen entered in HHE will be heated to a certain temperature, and the highest temperature is assumed to 873.15K in this article. In HOC the water at 293.15K is used to cool the combustion product and the highest temperature of stream at the HOC outlet equals to 1673.15K. The pressure at ST outlet is set to 8.5kPa according to the steam turbine power plant specification. This pressure corresponds to the temperature of 315.84K in condenser.

Other parameters for efficiency evaluation of the HSTCC are summarized in Table 1.

Table 1. Parameters for Evaluation of HSTCC

Component	Symbol	Data
FP	WM	Water
	η_{FP}	0.9
	P_{FP}	50~150
	T_{FP}	293.15
HG	WM	Water/Hydrogen
	η_{HG}	0.02
	T_{HG}	293.15
HHE	WM	Hydrogen
	η_{PHHE}	0.03
	T_{HHE}	293.15~873.15
HT	WM	Hydrogen
	η_{HT}	0.88
	P_{HTO}	10~30
HOC	WM	Hydrogen/Oxygen
	η_{PHOC}	0.02
	η_C	0.995
	T_{HOC}	473.15~1673.15
	T_{HOCW}	293.15
ST	WM	Steam
	η_{ST}	0.88
	P_{ST}	0.0085
Condenser	WM	Steam/Water
	P_C	0.0085
	T_C	315.83
CP	WM	Water
	η_{FP}	0.9
	T_{CP}	293.15

- WM: working medium
- TC: The temperature is corresponding to P_c.

For evaluating the efficiency the hydrogen is treated as ideal gas and the steam property is referred to [12]. Recurring to simulation, the influence of different parameters to cycle efficiency is also investigated, such as the hydrogen recuperative temperature in HHE, and the temperature at HOC outlet.

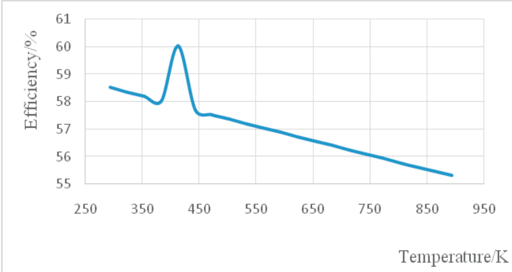

Figure 2. The cycle efficiency versus the recuperative temperature at HHE inlet

It is presented the curve of the cycle efficiency to the recuperative temperature of hydrogen at the HHE outlet in Figure 2. This curve is corresponding to following condition: water pressure of 100MPa at the FP outlet, hydrogen pressure of 10MPa at the HT outlet and steam temperature of 1673.15K at the HOC outlet. It is indicated that the highest cycle efficiency is 60.18% when the recuperative temperature of hydrogen equals to 392K. And the higher cycle efficiency can be achieved at the lower recuperative temperature of the HHE. It means that the comparative cycle efficiency can be obtained using the simple layout without the HHE. With another word, the HHE is be moved away from the HSTCC in order to simplify the system and decrease the building cost.

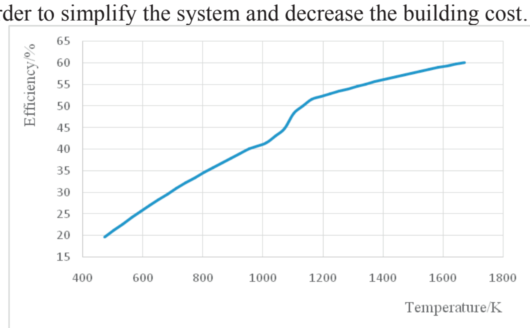

Figure 3. Cycle efficiency versus temperature at HOC outlet

It is shown the relation curve between the cycle efficiency and the steam temperature at HOC outlet in Figure 3. Other conditions are presented as following: water pressure of 100MPa at the FP outlet, hydrogen pressure of 10MPa at the HT outlet and hydrogen recuperative temperature of 392K at the HHE. It is indicated that the cycle efficiency will increase with the steam temperature at the HOC outlet (i.e. ST inlet). The result is consistent with conventional understanding.

3.2. Discussion

At same temperature of 1673.15K the efficiency of the HSTCC is higher about 1% than that of the Humid Air Turbine (HAT). And compared with other power cycle with gas turbine, such as Combined Cycle (CC), HAT and Steam Injected Gas Turbine (SIGT), HSTCC can not only achieve the high efficient, but also has many other advantages: First, feed pump is used as the stating part of HSTCC so that there is no loss caused by compressing air in gas turbine. Second, pure oxygen is used for combustion, then the hydrogen turbine and the stream turbine can be connected in series, the exhaust loss of the gas turbine in other kind of cycle will be vanished. These all can increase the efficiency of the HSTCC.

Both of the HT and ST generate power in HSTCC. The power generated by the HT will be affected by its pressure drop. Because the HT and ST are connected in series, the total pressure drop of the cycle equals the product of the pressure drop in HT and ST. Therefore the FP in HSTCC should have a strong boosting ability comparing to the compressor in the above mentioned cycles. The liquid water, which is easy to be boosted, is applied as the working medium in the FP, it is feasible to boost the water at high pressure ratio in practical engineering. The total generated power of the cycle is interconnected with the recuperative temperature of hydrogen in HHE. With poor recuperation at the HHE, the hydrogen temperature at HT outlet becomes lower, thus the generated power by the HT will have the decreasing trend. On the contrary, the energy which is transferred by H2 into the HOC will be increased with strong recuperation, the power output by the ST should have the increased tendency. Under the effect of these contradictory factors the cycle has an efficiency curve like Figure 2.

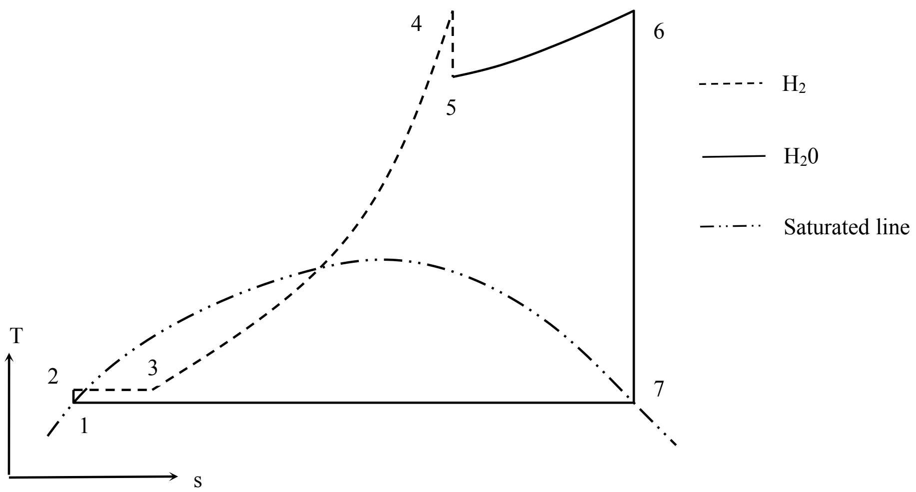

Figure 4 T-s curve of HSTCC

With increasing the temperature at the HOC inlet, the water for cooling the steam formed by combusting in HOC will be decreased. Because the specific enthalpy of the water in the condenser is constant, the efficiency will be risen with the temperature at HOC outlet as shown in Figure 3.

Because the water at 293.15K is directly used for cooling the steam with high temperature in HOC, so it will exist a large amount of the entropy loss. If the water as the coolant is recuperated at the appropriate location in the system, the cycle efficiency should be furthermore increased.

The working mediums in the HSTCC change constantly in its substance, amount and state. It is different from the traditional cycles for performance evaluation, in which the substance composition, amount is invariable, or barely unchangeable. To evaluate the cycle efficiency the unit mass (1 kg) of working medium in the starting component will be used to analysis this composite cycle in T-s concept. If the working medium is reacted with another substance, the enthalpy of all reaction resultants will be used for evaluating the cycle performance.

Based on this analytic method, the hydrogen of an amount of 0.111kg produced from 1 kg water by photolysis will be investigated in HG. When a substance is added to the process of energy transformation from outside, such as oxygen and cooling water is added to HOC, the enthalpy of the total amount of the vapor will be simulated. So the amount of the working medium at different stage should be considered for evaluating the HSTCC. It is schematically shown the T-s curve of HSTCC according to the above mentioned method in Figure 4.

As shown in Figure 4, “1” means the liquid water of 1 kg in CP/FP. It is boosted by FP and translated to “2” and the temperature is raised. Because of the incompressibility of water this temperature rise is ignored in this article. The photolysis process in HG is presented as “2” to “3”, it is considered as an isothermal process. “3” to “4” means the isobaric heating process of hydrogen in HHE, which has an amount of 0.111kg. “4” to “5” presented the isentropic expansion of hydrogen of 0.111kg. “5” to “6” means the isobaric heating process in HOC, in which pure hydrogen and oxygen is combusted and injected water is evaporated for cooling the steam. In this stage the amount of working medium is greatly increased. “6” to “7” presents the isentropic expansion process of steam in ST. ‘7’ to “1” presents the exothermic process at constant pressure of vapor in condenser. Thus it can be concluded that there is no exhaust loss in HSTCC compared to CC. It is beneficial to improve the efficiency of the cycle.

When the hydrogen turbine is introduced into the cycle, thermal process of HSTCC is much more close to isothermal expansion. Therefore the increase of efficiency becomes a merited course.

Based on the same reason, other strategies, such as the heat recuperation, are introduced in the HSTCC, the efficiency should be father improved.

4. Conclusion

It is proposed a new type of thermal cycle called as HSTCC in this paper. According to evaluation it can be concluded below:

- In comparison with CC, there is no exhaust-heat boiler and compression work in HSTCC. So this cycle has the advantages of the simple layout and higher efficiency.
- Except for HG, other components in HSTCC are sophisticated in technology. So the developing cost for the new thermal cycle is low.
- The HSTCC can use sunlight as sources of energy. And there are pure hydrogen and pure oxygen in combustor only, so no NOx can be formed during combustion. So it is an environment-friendly power generation technique.
- The thermal process of HSTCC is much more close to isothermal expansion, so it has an expectant potential for increasing the efficiency.

Based on the above advantage, the HSTCC should be a competitive power generating system using the sophisticated turbine technique for hydrogen energy in future.

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