A novel compressed air solar energy photo-thermal generating electricity system

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Abstract

On the basis of comparing the solar photovoltaic and photo-thermal generating electricity advantages and disadvantages, to overcome the phase-change losses caused by water evaporated into vapour, a compressed air solar energy photo-thermal generating electricity system was proposed in the present work. Air was compressed with compressor and heated with solar heater so as to get high temperature and pressure. High-temperature and high pressure air passes into turbine to generate electricity. The entire design is simple and compact, safe and reliability, energy saving and environmental protection. Thermodynamic cycle analysis was carried out. It comes to conclusion that practical efficiency depends on pressure ratio, the compressor and turbine efficiencies and solar photo-thermal conversion efficiency.

Keywords: Compressed air, solar energy, photo-thermal, generating electricity

1 Introduction

Solar energy is one of the most abundant renewable energy, which can be directly or indirectly used. Solar radiation features strong dispersion and low energy flux density. It is suitable to obtain low temperature thermal resources. At present, it has been widely used for various fields, including heating, solar drying, solar heat, solar air conditioning, solar thermal power generation in area [1].

Solar energy power generation mainly have two categories: photovoltaic and photo-thermal power generation. The three phase alternating current produced with the solar photo-thermal generating electricity can be directly connected to the power grid, and uses regenerative characteristics to achieve continuous power generation, which may be to replace the thermal power and nuclear power in the future. Compared to photovoltaic and wind power, the solar photo-thermal generating electricity belongs to the power source that is more easily accepted by power grid. The cumulative installed capacity of the global solar photo-thermal power generation in 2011 reached 1760 MW, representing an increase of 35% over last year, and new installed capacity of 450 MW [2-6]. Compared to 2010, although the new installed capacity of the solar photo-thermal power generation declined, but several large-scale projects are being under the construction. The global solar thermal power generation in 2012 continues to maintain the momentum of steady growth.

The solar photo-thermal generating electricity refers to the use of large-scale arrays of parabolic or dish-shaped mirror to collect the solar thermal energy to provide steam through a heat exchanger device, combined with the traditional process of turbine generator, so as to achieve the purpose of power generation. The use of the solar photo-thermal generating electricity technology avoids expensive silicon photoelectric conversion process, and can greatly reduce the cost of the solar power. Moreover, this form of solar energy using solar photo-thermal has great advantages, solar hot water can be stored in huge containers, a few hours after the sun goes down, will still be able to drive a steam turbine power generation, such as solar slotted disc and tower power generation devices. Zhang et al. [7] proposed a technical solution on the solar thermal power-heating. Optical plant has a scale of 10 condenser loops. Turbine generator has the installed capacity of 3 MW, which generates power in the non-heating period and uses the steam turbine cycle cooling water as a heating source in the heating period. It is equipped with the thermal storage system, which meets the need of 24 h heating. Zhang et al. [8] proposed another technical solution to couple the solar thermal power generation system with conventional thermal power plants by means of different ways so as to use solar optical thermal systems in place of some coal consumption, reducing the fired coal consumption. They adopted a trough solar thermal power system, geometric concentration ratio is in the range of 10 to 100, and the heat transfer medium temperature is up to 400℃. A four rank heat exchanger is used to collect heat from the heat collector field, and then heats the water by means of thermal oil carrier. The former two-stage heater heats some feed water to produce the superheated steam, which has the same parameters as the first and second extraction vapour. The superheated vapour enters the first and second extraction point to supply vapour to

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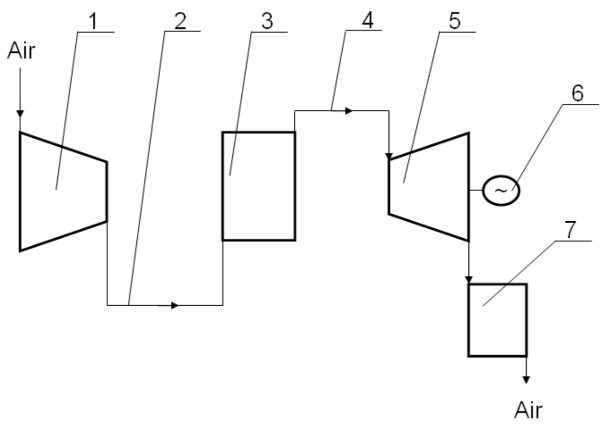
turbine. The latter two-stage heater is an alternative heater of the high-pressure heaters to feed water and low pressure heater to condensate. Based on their computational analysis, they concluded that it has a minimum coal consumption to adopt a complementary manner of the four-stage solar thermal with thermal power heat transfer. In order to overcome the lack of sunlight and night without illumination, the current solar thermal power systems use the thermal storage system , Wang [9] reviewed the prospects of the thermal storage system used for solar thermal power, including molten salt (sodium and potassium), concrete with high temperature thermal storage and phase-change alloy.

However, the existing solar photo-thermal power causes phase change loss because water transforms into vapour. To avoid phase change loss for improving the system efficiency of the solar photo-thermal power generation, this paper proposes a compressed air solar photo-thermal power generation system. The system uses the air as the working fluid, and the compressor and the solar heater were used to raise the temperature and pressure of the air, and then high-temperature and high-pressure air enters into to the turbine to generate electricity. The entire design is simple and compact, safe and reliable, energy saving and environmental protection.

2 System structure and work principle

Compressed air solar energy photo-thermal generating electricity system consists of the compressor, the turbine, and the generator, the cooler and the pipes, as shown in Figure 1. The outlet of the compressor is connected to the high-pressure air pipe, the other end of the high-pressure air pipe is connected to the solar heater, the other end of the solar heater is connected to high-temperature air pipe, and the other end of the high-temperature air pipe is connected to the turbine. The rotation shaft of the turbine is connected to the generator, and the outlet of the turbine is connected with the cooler.



1-compressor; 2-high-pressure air pipe; 3-solar heater; 4-high-temperature air pipe; 5-turbine; 6-generator; 7-cooler

FIGURE 1 Schematic diagram of compressed air solar photo-thermal generating electricity

When the air enters into the compressor, the pressure is lifted, and transforms into high-pressure air. High-pressure air flows through into the solar heater, heating by sunlight, transforming into high-temperature air. High-temperature and high-pressure air passes through into the turbine, promotes the expansion work and the impeller and drives generators. The exhaust gas discharged by the turbine is passed into the cooler; the waste heat of the exhaust gas is utilized.

3 Thermodynamic cycle analysis

3.1 IDEAL THERMODYNAMIC CYCLE ANALYSIS

The air is treated as an ideal gas. Ignoring friction and the area loss due to the flow in piping, valves, and the elbow, the ideal thermodynamic cycle is given in Figure 2.

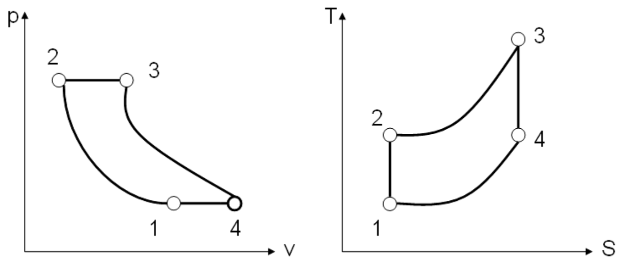


FIGURE 2 Ideal thermodynamics cycle schematics

The 1-2 is a process of the adiabatic compression of air. The compressor adiabatically compresses air from the ambient pressure to P_1 . According to the first law of thermodynamics, the compression work per kilogram air can be represented by the enthalpy difference of the initial and the end states.

$$W_{1-2} = h_2 - h_1 \tag{1}$$

The 2-3 is an air isobaric heating process. Under the solar radiation, the high-pressure air is heated to T_1 . In the process, the done work is zero; the heat absorbed by per kilogram air can be expressed as

$$Q_{2-3} = h_3 - h_2 \tag{2}$$

The 3-4 is a process of the adiabatic expansion of air. The high-pressure air expands in the turbine, and drives the generator to generate electricity. The done work per kilogram air in this process is given by the following formula:

$$W_{3-4} = h_4 - h_3 \tag{3}$$

The 4-1 is a process of the exhaust gas cooling. The exhaust gas discharged from the turbine is cooled to ambient temperature. The utilized waste heat can be expressed as

$$Q_{4-1} = h_4 - h_1 \tag{4}$$

According to the Carnot cycle, ideal cycle efficiency of compressed air solar photo-thermal generating electricity can be expressed as follows:

$$\eta = 1 - \frac{T_0}{T_1} \tag{5}$$

Given ambient temperature $T_0 = 273K$ and heating temperature $T_1 = 273 - 1000K$, figure 3 shows ideal cycle efficiency diagram. When T_1 ranges at 273-500K, ideal cycle efficiency obviously increases; when T_1 is larger than 500K, ideal cycle efficiency slightly increases. However, expensive exchanger materials and larger heat area need to use because of higher heating temperature, which causes an increase in the investment cost. Therefore, the heating temperature 500K is the optimal selection.

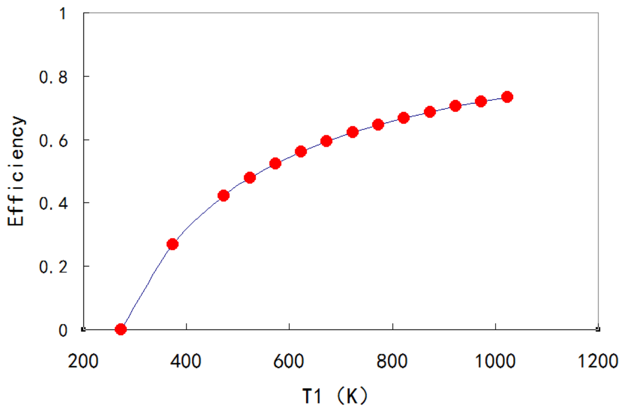


FIGURE 3 Ideal cycle efficiency diagram

3.2 PRACTICAL THERMODYNAMIC CYCLE ANALYSIS

The obtained electricity per kilogram air in unit time for compressed air solar photo-thermal generating electricity can be expressed as follows

$$P_p = Q_{2-3} + W_{1-2} - Q_{4-1} \tag{6}$$

Assumed that the solar photo-thermal conversion efficiency is expressed as η_h, efficiency of compressor is η_c, the ideal electricity per kilogram air in unit time for compressed air solar photo-thermal generating electricity system is

$$P_i = \frac{1}{\eta_T}\left(\frac{Q_{2-3}}{\eta_h} + \frac{W_{1-2}}{\eta_C}\right) - Q_{4-1} \tag{7}$$

Practical cycle efficiency of compressed air solar photo-thermal generating electricity, η_{TP}, is expressed as:

$$\eta_{TP} = \frac{P_p}{p_i} \tag{8}$$

According to thermodynamics, air adiabatic index is k, ambient temperature is T_0, ambient pressure is P_0, the net work of the compressor depends on pressure ratio, $\varepsilon = \frac{p_1}{p_0}$, and can be expressed as

$$W_{1-2} = \frac{k}{k-1} RT_0 \left(\varepsilon^{\frac{k-1}{k}} - 1\right) \tag{9}$$

Therefore, η_{TP} depends on η_h, η_c, η_T and ε.

Given ambient temperature =273K, the outlet air temperature of the solar heater $T_1 = 500K$, the compressor efficiency $\eta_c = 50\%$, $\eta_T = 80\%$ and pressure ratio $\varepsilon = 3$, Figure 4 shows effect of η_h on η_{TP}. As η_h increases, η_{TP} ascends. Given the solar photo-thermal conversion efficiency $\eta_h = 30\%$, other parameters is the same as the Figure 4.

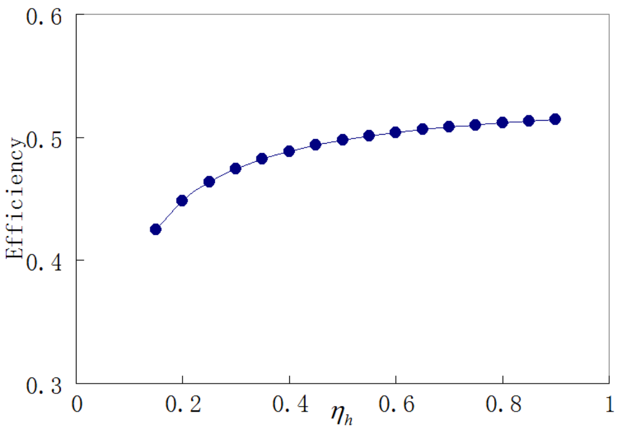


FIGURE 4 Effect of η_h on η_{TP}

Figure 5 shows effect of η_c on η_{TP}. η_{TP} Obviously increases with η_c.

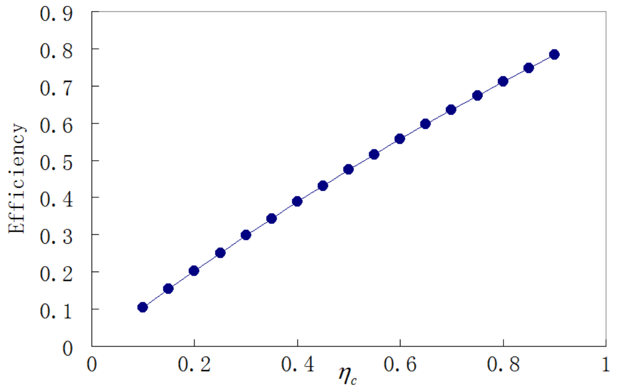


FIGURE 5 Effect of η_c on η_{TP}

Figure 6 shows effect of ε on η_{TP}. When $\varepsilon < 3$, η_{TP} obviously increases; when $\varepsilon > 3$, η_{TP} slightly increases. Therefore, $\varepsilon = 3$ can obtain the optimum η_{TP}.

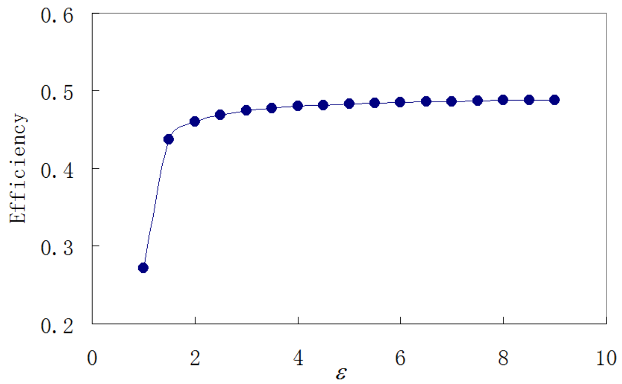


FIGURE 6 Effect of ε on η_{TP}

Figure 7 shows effect of η_T on η_{TP}. η_{TP} Obviously increases with η_c.

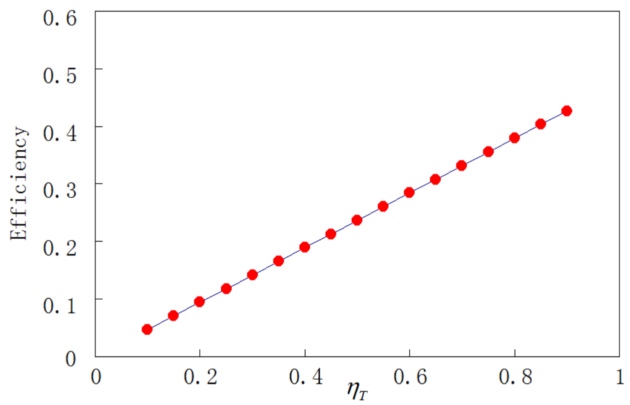


FIGURE 7 Effect of η_T on η_{TP}

3.3 THERMODYNAMIC CYCLE ANALYSIS

As for efficiency, the use period, the investment cost, as well as the environmental impact, the compressed air solar photo-thermal generating system may achieve better performance compared with existing solar photovoltaic and solar photo-thermal power generation system, and is a competitive technology. Solar photovoltaic battery will cause environmental pollution, solar pond and solar photo-thermal power generation system is constrained by the geographical conditions, the working fluid also pollutes the environment. Pollution-free compressed air solar power generation system always uses the air in the power generation process, which will not cause environmental problems. Compressed air solar photo-thermal power generation system takes advantage of existing the compressors, solar heaters and turbines, and not too many restrictions on the geographical conditions.

4 Conclusions

In this paper, the compressed air solar photo-thermal generating electricity was proposed. The system structure, working principle, efficiency and feasibility analysis were discussed. The compressed air solar photo-thermal generating electricity device utilizes existing compressor, solar heaters and turbine technology to produce electricity. This way to generating electricity is an environmentally friendly, without geographical restrictions, easy to implement device.

Thermodynamic knowledge is used to calculate efficiency of the compressed air solar photo-thermal generating electricity, respectively, discussing the effect of compressor and turbine efficiencies, the solar heater photo-thermal conversion efficiency and pressure ratio. Actual cycle efficiency will be increased as the efficiencies of the compressor and turbine, the heat conversion efficiency of the solar heater and the pressure ratio increases, the compressor efficiency has a more significant impact on the efficiency. Optimum air temperature of the solar heater outlet is 500 K, and optimum pressure ratio is 3.0.

5 Notation

h - the enthalpy;
k - the adiabatic index;
p - the pressure;
Q - the heat;
R - the gas constant;
T - the temperature;
W - the work;
η - the efficiency;
ε - the pressure ratio.

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