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The Research of Solar-heated Generation System Using CPC Collector

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***Abstract*—In this paper, a new solar-heated generation system with capacity of 10kW is designed. The system is based on solar-heated Rankine cycle. The CPC solar energy collector array is used as the main heat source, and the gas boiler as the assistant heat source. The heat storage facility provides heat for put-off 24 hours generating without sun's radiation. The paper is focused on the analysis of four typical working processes under the different climatic conditions. The shape of the CPC solar collector is designed, and the thermal efficiency is analyzed, and the collector array is ranged suitably. Finally, the economical benefit of the system is discussed.**

***Index Terms*—solar energy, CPC collector, generation**

I. INTRODUCTION

Compared with primary energy sources, solar electricity energy generation system has some merits such as energy-regeneration, cleanness, no-pollution and safety etc.. At the present time, there are two major techniques for solar electricity energy generation, one is solar photovoltaic generation, and the other is solar-heated generation. There are some merits of the solar photovoltaic technology such as no noise, on mechanical frictions and rotatable parts, but there are high generating cost and low generating efficient. The solar-heated generation technology is basically samed as the traditional thermal power generation. The generating cost of it is low, and the technology of it is perfect, so it's a better way for solar electricity generation.

The basic process of solar-heated generation is firstly to transfer the solar radiation energy to the heat energy with the collector, then to heat the working medium from water to steam. As the steam enters turbine, it drives the turbomachine to generating, then it is condensed into water. Then, the water is pumped into heater, and circulated just like above again.

A solar-heated generation system with capacity of 10kW is designed in this paper. The system uses the CPC solar collector array as the main heat source, in conjunction with the gas boiler for the assistant heat source; The system is applicable to four working processes under the different weather conditions; The system has a heat storage facility, which can satisfy the request that it continues providing heat and generating electricity steady for 24 hours without sun's radiation. The system adopts the compound parabolic concentrator (CPC) solar collector with higher concentration ratio, which can supply high temperature steam for turbine generator unit. In this paper, four kinds of typical working processes in generation system are analyzed in detail under the different weather conditions; the moulding surface of the CPC solar energy collector unit is designed and its thermal efficiency is analyzed, and the collector array is ranged reasonably; the economical benefit of the generation system is discussed finally.

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II. PROCESS DESIGN

This design is based on the Rankine cycle, and it uses the CPC solar energy collector array for the main heat source in conjunction with the gas boiler for the assistant heat source; the system has a heat storage facility and uses the CPC solar energy collector with higher concentration ratio. The main equipments include: CPC collector array, heat storage facility, gas boiler, turbine generator unit, and condenser, water circulating pump, valves and pipelines. The detailed processes as Fig.1

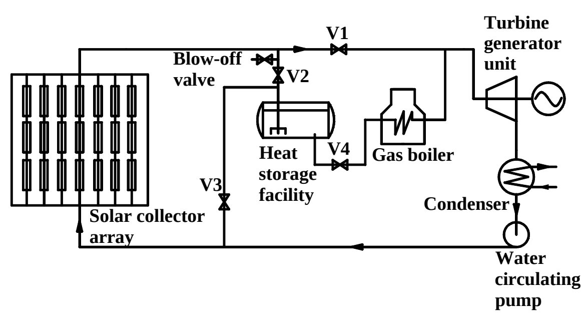

Fig. 1 Process diagram of solar-heated generation system

This paper designs a solar-heated generation system with 10kW of electricity generation. The steam temperature at the inlet of turbomachine is 250℃ with the inlet pressure is 2MPa.

The analysis of four typical working processes under the different weather conditions is as follows:

(1) When the weather is fine, the steam at the outlet of collector with high temperature can satisfy the request of steam admission. Then open the valve V1, V2, and parts of steam required enter the turbomachine for generating, while the other steam enter the heat storage facility and deposited.

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The boiler is out of work, and the valves V3, V4 are both closed.

(2) When the weather is not good enough, the steam or water at the outlet of collector can not satisfy the request of steam admission of turbomachine. Now open the valve V2 and V4, and close the valve V1 and V3. The fluid at the collector outlet enters the heat storage facility directly, mixed with the original water in the container. The preheated water enters the gas boiler, for heating to the required steam of turbomachine for generating.

(3) When the weather is bad or it's at night, the CPC collector arrays are out of work nearly. Now close the valve V1, V2, and open the valve V3, V4. The circled water is delivered to the heat storage facility directly and is mixed with the original hot water, and then enters the gas boiler. This method can reduce the resistance loss when the water flows through the CPC collector array.

(4) When the volume of saturated water in the heat storage facility reaches to the 90% of the designed and the temperature reaches to the saturation temperature, close the valve V2 and open the blow-off valve, emptying the redundant steam for protecting the heat storage facility. This kind of state is rare, it appears only in several hottest weeks every year.

The electricity generation flow processes of this paper can ensure the system keeps generating steady under four typical work conditions above in conjunction with the switch of automatic valves and the control of the temperature, pressure and flux.

III. CPC SOLAR COLLECOTOR ARRAY

A. CPC collector structure

The shape of CPC collector unit as Fig. 2, it is maked up of two symmetric paraboloid reflectors (AC) in side, two involute reflectors (GC) in bottom and the round heat sink. The round heat sink is produced by the stainless steel tube drilling through the glass tube coaxially and then creating a vacuum between them.

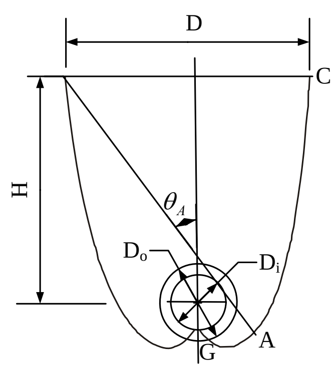

Fig. 2 Molded lines of the collector reflecting surface

The CPC is a sort of non-imaging optical collector designed by the principle of marginal ray. Compared with the conventional collector, it has many merits, such as large acceptance angle, simple structure, cost-effective, without autotracker in operation, effective work by adjusting rake angle several times when seasons changes every year etc.. The CPC collector can absorb perpendicular incidence and scattered radiation in the received range, and making the work temperature reach 250℃ or even higher.

For the CPC concentration ratio C:

$$C = 1/\sin\theta_A \tag{1}$$

For the width of CPC collector cover D:

$$D = D_i C \tag{2}$$

For the relation between the widths of collector cover D and height of the collector H:

$$H = \frac{D}{2\tan\theta_A} \tag{3}$$

In the above formulas: θ_A is the half reception angle of CPC collector, and D_i is the outside diameter of the stainless steel tube in the absorber. Compared with the other collectors, the surface area of CPC is larger, but the light gathering efficiency of the upside surface of the collector is bad, so the increment of concentration ratio is little when the height of collector increases, especially in the CPC with higher concentration ratio. Cutting out the low efficiency part properly on the top of the CPC can reduce the material and cost, and increase the cost performance. In the design, the truncation ratio is chosen to 2/3, and the actual height of the collector H' *is* equaled to 2/3H.

In this design, the concentration ratio C of the CPC selects to 5, and the outside diameter D_i of the stainless steel tube selects to 45mm, so the half acceptance angle θ_A is 11.5°, and the cover width D of collector is 707mm, and the actual height H' is 1159mm.

The stainless steel tube as the heat receiver in absorber, with the wall thickness of 3mm is covered with the selective absorption coat--the black nickel selective absorbability surface outside the surface with absorptance α equal to 0.93, and emissivity ε equal to 0.09. The design uses the vacuum tube technology in order to reduce the heat convection between the absorbability surface and the circumstance. The length of stainless steel tube is 2.1m; the diameter D_o of glass tube is 65mm, and the length of it is 2m. The vacuum interlayer between the stainless steel tube and the glass tube is 10mm. After capsulation, 50mm is protruded in each ends of the stainless steel tubes for soldering the same collector units.

B. The heat loss coefficient of the absorber U_L

$$U_L = \left[\frac{A_r}{\left(h_w + h_{r,c-a}\right) A_C} + \frac{1}{h_{r,r-c}} \right]^{-1} \tag{5}$$

For all of above: A_r is the area of heat-pipe surface, h_w is the heat convection coefficient between the glass tube and the circumstance, $h_{r,c-a}$ is the radiation heat exchange coefficient between the glass tube and the circumstance, $h_{r,r-c}$ is the radiation heat exchange coefficient between the glass tube and the stainless steel tube.

After calculation, in this CPC solar energy collector, h_w is 47W/(m^2·℃); $h_{r,c-a}$ is 5.83 W/(m^2·℃); $h_{r,r-c}$ is 1.62 W/(m^2·℃). The total heat loss coefficient U_L is 1.59 W/(m^2·℃).

C. The valid heat energy gathered by the CPC collector unit

The outside diameter D_i of the stainless steel tube is 45mm. The outside diameter D_o of the glass tube is 65mm.

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The design flow of water in one collector is 0.015 kg/s.

Considering the heat convection of liquid in the tubes, the heat loss coefficient of the absorber should be corrected. The corrected heat loss coefficient is:

$$U_o = \left(\frac{1}{U_L} + \frac{D_o}{h_{f,i}} + \frac{D_o \ln D_o / D_i}{2k}\right)^{-1} \quad (6)$$

In the formula above: $h_{f,i}$ is the mean heat convection coefficient of the liquid in tubes, and k is the heat transfer coefficient of the stainless steel.

For the efficiency factor of collector:

$$F' = \frac{U_o}{U_L} \quad (7)$$

For the factor of flow:

$$F'' = \frac{\dot{m}C_p}{A_r U_L F'}(1 - e^{-A_r U_L F' / \dot{m}C_p}) \quad (8)$$

For the factor of thermal migration:

$$F_R = F' F'' \quad (9)$$

The valid energy for use:

$$Q_u = A_r F_R \left[I_p \rho \tau \alpha - \frac{A_r}{A_c} U_L (T_{f,i} - T_a) \right] \quad (10)$$

In the formula above: A_r is the area of the collector tube; A_a is the cover area deducting the area of the collector tube; I_p is the total amount of the solar radiation in inclined plane; ρ is the reflectivity of the reflector; τ is the permeation rate of the cover plate; α is the absorption rate of the absorber.

The CPC gathers the valid heat energy in each unit equal to 762W.

D. Arrangement layout and floor area of CPC collector array

The assumed average work time a day is 5 hours. The flux of liquid in each collector unit is 0.015kg/s, and the system can assure enough the solar energy for one day, so 60 collector units are connected in series for one group according to the working request of the system, and 4.5 group are connected in parallel for one division. There are 10 collector divisions, namely 45 groups of collector tubes in series, and 2700 pieces of tubes in all.

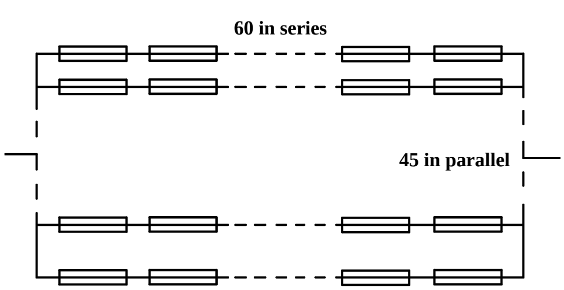

Fig.3. series & parallel chart of the collector array

The designed space according to the collector array:

$$d_{CPC} = H \tan \theta_A \quad (11)$$

d_{CPC} is the axial line distance of the absorber between two groups of collector units. After calculation, d_{CPC} is 236 mm, floor areas is 5346m^2.

IV. HEAT STORAGE FACILITY

Because of the intermittence and instability of the acquisition of the solar energy, besides using gas boiler as the assistant heat source in the generating process, the heat storage facility is installed in order to ensure the system works smoothly. The unit deposits the redundant solar energy absorbed in the daytime which is used at night or in cloudy days. Take water as its heat storage medium because of large specific thermal capacitance and safety and inexpensive. It can supply heat steady for 24 hours without sun's radiation. The shape of the heat storage unit is a horizontal column and the maximum of the water storage is 90% of the total volume. Outside the unit covers the rock wool insulating layer. After calculation, the diameter of the bottom surface of the unit is 4.23m, and the length is 5m, and the total volume is 70m^3, and the thickness of the thermal retardation material is 70mm.

V. ECONOMIC ANALYSIS OF THE ELECTRICITY GENERATION SYSTEM

Assumed half time of one year is fine days, taking the valid energy received by the absorber in average weather conditions a year as the standard, we can calculate the energy-saving efficiency of every year.

We can know from the calculation above, the average valid energy in each collector unit Q_u is 762W, and the collector array are composed by 2700 pieces of collector units, so the total valid energy are 2.06MW, and the total valid energy in one year are 6.96×10^{6}MJ. According to the average heat value of the natural gas equal to 31.4MJ/m^3 and the price equal to RMB 2Yuan/m^3, the valid energy received by the CPC collector array one year is the same as combustion heat value of 2×10^{5}m^3 natural gas, and the saving cost of the natural gas one year reaches to RMB 400,000 Yuan.

VI. CONCLUSION

This paper designs a set of new solar-heated generation system with 10kW of electricity generation based on the Rankine cycle. It uses the CPC collector array for the main heat source in conjunction with the gas boiler for the assistant heat source; The system has a heat storage facility with the water for the heat storage medium in order to ensure the system works smoothly. In this paper, four kinds of typical working processes in generating system are analyzed in detail under different weather conditions and the switchover is discussed between different valves; According to the request, the vacuum tube CPC collector is designed with the concentration ratio equal to 5, and the height of the CPC collector is truncated rationally. The influence factors of the collector's efficiency are analyzed. According to the design request, the collector units are arranged reasonably and the CPC collector array is designed and its floor area is 5346m^2, 60 collector units are connected in series for one group and 45 groups are connected in parallel for an array. It is estimated that the system can save more than 2×10^{5}m^3 natural gas one year. So the solar-heated generating system has good economic and environmental benefits, and has a good development foreground.

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