Operating Performance of an Energy-Saving Boiler System Using Solar-Thermal Collector Pipe

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Abstract. A compact industrial boiler system that is combined with solar-thermal collector pipe has lower fuel consumption and CO$_2$ emissions than conventional systems, and has been subjected to basic testing. High-pressure steam generated by the compact boiler drives a steam ejector to decrease the pressure inside the tank, causing the generation of low-pressure steam within them using solar thermal energy. Steam from both sources is mixed in the ejector and is supplied on demand at low to medium pressure to where its use is required. Evaluation results of the operating performance of the boiler system using evacuated dual glass tube confirmed that the internal pressure of the tank was maintained at close to predicted levels, and that there was a stable supply of low-pressure steam.

Introduction

Among renewable energy sources, solar-thermal utilization has potential on a par with wind power and sunlight (photovoltaics). Figure 1 shows fields where solar energy is used. Photovoltaics convert sunlight directly into electricity and are coming into widespread use particularly inside Japan. Globally, household solar-thermal collector panels for producing hot water are increasingly popular, and solar-thermal power plants employing large-scale thermal-collector plants are being constructed. As shown in Figure 1, it is possible, by converting energy from sunlight into thermal energy, to greatly expand its scope of application beyond electric power.

Figure 2 shows a diagram of solar-thermal utilization technology. Temperature is indicated on the horizontal axis, with output scale of the equipment/plant on the vertical axis. A major feature of solar-thermal utilization is that the utilization temperature can be controlled and selected by concentrating light with optical equipment such as mirrors and lenses. Optimal temperatures vary according to the application, and generally speaking, as utilization temperatures increase, plant sizes increase as well. Large-scale solar-thermal electrical power generation using concentrating-type solar
systems holds promise for regions in so-called “sunbelts” (Mediterranean coast, Middle East, Australia, Southwestern United States) due to their abundant direct sunlight. However, in places such as Japan with a higher percentage of diffuse light (where sunlight arrives after being reflected and scattered by fine particles in the air as well as by surrounding objects) non-concentrating solar systems are more effective. Thus, in terms of heat utilization, it is expected that solar-thermal collector panels will be utilized at a high level.

![Figure 2. Solar thermal utilization technology map.](image)

Solar-thermal collector panels have been in widespread use as household water heaters since around the 1970’s. Their solar energy utilization efficiency is between 40 and 60%—far surpassing that of photovoltaics—but their use has been limited to producing hot water (up to 70°C) and there has been almost no new development to expand their fields of application. However, various thermal collector and insulation structure innovations have made it possible to efficiently use these systems for low-pressure steam production at temperatures around 100°C. This study proposes a system combining solar-thermal energy with a small once-through boiler to achieve reduced fuel consumption and carbon dioxide emissions. The operating characteristics of the system are also examined.

**Experimental Method**

**Solar-Thermal Assisted Boiler System**

Figure 3 shows an overview of the boiler system using solar-thermal. Figure 3(a) is the solar-thermal collector pipe used in this experiment. It has an effective thermal collection area of 2.27 m². Figure 3(b) gives the characteristics of the system. Ordinary once-through boiler systems generate steam at a high pressure of 0.6–0.9 MPa, and then a pressure-reduction valve adjusts to the specified pressure, and steam is supplied to the process where it is used. In the proposed system, this pressure reduction valve is replaced with a steam ejector. The inside of the tank on top of the solar-thermal collector pipe is suctioned out by the energy when pressure is reduced, thereby reducing pressure in the tank and producing low-pressure steam. If, for example, pressure in the tank is reduced to 0.05 MPa (abs.), the boiling point of water becomes 81.3°C, making it possible to produce steam at temperatures that under normal circumstances (atmospheric pressure) would produce only hot water. Low-pressure steam generated by this process is mixed with high-pressure drive steam and supplied as low/medium-pressure steam to a steam-utilization process.

The following are advantages of this system:

Even if sunlight conditions degrade due to weather, output of the once-through boiler system as a whole can be maintained at or above a certain level.

None of the equipment (boiler or thermal-collector pipe) has elements requiring new development.
Due to the reduced pressure, temperature in the tank is kept lower than that of the supplied steam. Therefore, thermal collection efficiency comparable to hot water production can be expected.

(a) Comparison of the proposed system and the conventional system

(b) Equipment in the system

Figure 3. Overview of the boiler system using solar-thermal.

**Experimental Equipment**

Specifications of the basic test system are indicated in Table 1.

| Item                          | Unit     | Specification |
|-------------------------------|----------|---------------|
| Small once-through boiler     |          |               |
| Conversion evaporation amount | kg/h     | 200           |
| Working pressure              | MPa      | 0.5-0.9       |
| Boiler efficiency             | %        | 90            |
| Fuel                          | kg/h     | Kerosene      |
| Steam ejector                 |          |               |
| Drive flow rate               | kg/h     | 100           |
| Drive pressure                | MPa (G)  | 0.9           |
| Suction flow rate             | kg/h     | 4.5           |
| Suction pressure              | MPa(abs.)| -             |
| Discharge pressure            | MPa(G)   | 0.1           |
| Solar-thermal collector pipe  |          |               |
| Tank capacity                 | L        | 195           |
| Glass tube number             | number   | 24            |
| Glass tube size               | mm       | φ 47 × 1500   |
| Effective heat collection area| m²       | 2.27          |
| Product dry weight            | kg       | 110           |
Figure 4 shows the structure of the evacuated dual glass tube used as the solar-thermal collector pipe. The outer glass is transparent and the inner glass is black with a selective absorption coating. A vacuum between the outer and inner glass prevents heat conduction and does not let heat to escape once it is absorbed, making thermal collection possible up to high temperatures.

**Experiment Results**

**Performance of Evacuated Dual Glass Tube**

In order to evaluate the performance of evacuated dual glass tubes, two identical types of dual glass tubes were used. One tube was an evacuated dual glass tube (with a vacuum between the layers of glass), whereas the other had atmospheric pressure between the two layers of glass. An experiment was carried out in which water was placed directly in the glass tubes, and the temperature was increased. The results are shown in Figure 5. As shown in the figure, heat dissipation loss increased in the tube with atmospheric pressure, and the upper limit temperature was approximately 50°C. Also, in time slots when sunlight was weaker, temperature gradually decreased. With the evacuated glass tube, on the other hand, the temperature continued to rise, reaching 100°C even at times when sunlight was weaker. Since the experiment was conducted with water, 100°C was the maximum temperature, but if oil were heated, or if the tube were empty, temperatures would reach 200°C.

![Figure 5. Temperature rising comparison with a vacuum tube and an atmospheric pressure pipe.](image-url)
Next, thermal collection performance of the solar-thermal collector pipe was examined. Figure 6 shows the typical instantaneous thermal collection efficiency using as standards solar irradiance of 600 W/m$^2$ when sunny and 100 W/m$^2$ when rainy. The graph is the approximate curve obtained using the least squares method from measurement data. When solar irradiance of 600 W/m$^2$ is used as the standard, it is evident that an almost constant thermal collection efficiency is maintained with little effect due to the difference with the ambient temperature. Compared to when solar irradiance is 600 W/m$^2$, there is a major drop in thermal collection efficiency when solar irradiance is 100 W/m$^2$, particularly at an ambient temperature of 60°C, for which the reduction is approximately 44%. On the other hand, when considering thermal collection in the winter, evacuated tubes are known to be superior to flat panels.

![Figure 6. Heat collection efficiency of flat plate and vacuum tub.](image)

**Operating performance of a solar-thermal assisted boiler system**

Figure 7 shows the system operating situation on a clear day in November. As shown in the figure, the sun is at the highest point at around 11:30 a.m. and this is the point at which solar irradiance is highest. Suction operation by the ejector was started approximately one hour prior to this time. As suction started, internal temperature of the tank dropped quickly. This indicates that water started boiling in the tank. The temperature inside the tank remained stable at almost the boiling point of water with respect to the internal pressure of the tank (0.05–0.06MPa (abs.)). Drive pressure indicates the pressure of the drive steam flowing into the ejector from the once-through boiler, and although there is some variation due to the timing of the water supply in the boiler, stable operation was confirmed.
Conclusion
This study proposed a solar-thermal assisted boiler system using a solar-thermal collector pipe and reported a basic test of an evacuated dual glass tube used as a solar-thermal collector pipe. It also examined the operating principle and basic performance of the boiler system.
1. Compared to atmospheric pressure tube, evacuated dual glass tube maintained a higher thermal collection temperature even with weaker solar irradiance.
2. Under conditions with high solar irradiance, the thermal collection efficiency of the evacuated dual glass tubing was not affected by the ambient temperature.
3. Evaluation results of the operating performance of the boiler system using evacuated dual glass tube confirmed that the internal pressure of the tank was maintained at close to predicted levels, and that there was a stable supply of low-pressure steam.

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