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Research Paper

Effect of working fluids on the performance of a novel direct vapor generation solar organic Rankine cycle system

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HIGHLIGHTS

- A novel, flexible direct vapor generation solar ORC is proposed.
- Technical feasibility of the system is discussed.
- Fluid effect on collector efficiency is explored.
- The system is more efficient than solar ORC with HTF.

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ABSTRACT

A novel solar organic Rankine cycle (ORC) system with direct vapor generation (DVG) is proposed. A heat storage unit is embedded in the ORC to guarantee the stability of power generation. Compared with conventional solar ORCs, the proposed system avoids the secondary heat transfer intermediate and shows good reaction to the fluctuation of solar radiation. The technical feasibility of the system is discussed. Performance is analyzed by using 17 dry and isentropic working fluids. Fluid effects on the efficiencies of ORC, collectors and the whole system are studied. The results indicate that the collector efficiency generally decreases while the ORC and system efficiencies increase with the increment in fluid critical temperature. At evaporation temperature of 120 °C and solar radiation of 800 Wm^{-2}, the ORC, collector and overall thermal efficiencies of R236fa are 10.59, 56.14 and 5.08% while their values for Benzene are 12.5, 52.58 and 6.57% respectively. The difference between collector efficiencies using R236fa and Benzene gets larger at lower solar radiation. The heat collection is strongly correlated with latent and sensible heat of the working fluid. Among the fluids, R123 exhibits the highest overall performance and seems to be suitable for the proposed system in the short term.

1. Introduction

Solar energy is one of the potential heat source for organic Rankine cycle (ORC). Solar radiation has the maximum capacity and the minimum replenishment time among all of available sustainable energies [1]. By using the ORC, low-medium temperature solar thermal power system can be an attractive option. A temperature of about 100 °C or slightly higher is sufficient to drive the ORC and evacuated/double glazing flat plate collectors (FPC), evacuated tube collectors (ETC), compound parabolic concentrators (CPC), and parabolic trough collectors (PTC) with small concentration ratio can be competent in solar energy collection for the ORC. Such solar ORC systems are capable of efficiently harnessing solar energy in temperature ranges from 100 to 200 °C. They have advantages including the ability to scale down to small unit sizes, cogeneration near the point of usage, relatively low technical requirement in heat storage and good applicability in regions without rich direct solar radiation resource.

At present, most of the solar ORCs under investigation use heat transfer fluid (HTF) to carry away energy in the collectors and then release it to the organic fluid [2–11]. The heat transfer irreversibility in the evaporator is very large as shown in Fig. 1. The vertical axis is the temperature and the horizontal axis is the heat transferred from HTF to the organic fluid. Adverse current heat exchanger is exemplified. The inlet temperature of the organic fluid is close to the environment temperature. Given the pinch point temperature (ΔT_{pp}) and the ORC operating condition, a low mass flow rate of HTF results in a high HTF inlet temperature while a high one is accompanied with a high HTF outlet temperature. Therefore, it is difficult to lower the HTF average temperature. This is disadvantageous because solar energy collection is less efficient at high operating temperature. Moreover, the use of HTF increases the investment. Additional power is needed for the pumping of HTF, which can significantly reduce the system net power output especially for small-scale solar ORCs.

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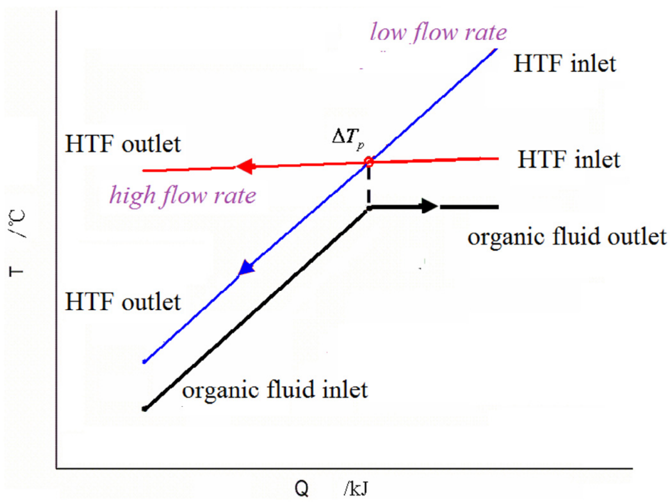

Fig. 1. The temperature–heat (*T*–*Q*) curve for the evaporator [12].

The above mentioned problems can be solved by using direct vapor generation (DVG) technology. The DVG technology with water as the working fluid (known as direct steam generation, DSG) has been widely investigated [13–17]. In a DSG system, steam is directly generated in the solar field, hence eliminating the boiler in the power section. The power consumption by the solar field recirculating pump is also reduced. The collectors benefit from the constant temperature and high coefficient of heat transfer in the evaporation region of water. The feasibility of the DSG technology has been demonstrated within the DISS (Direct Solar Steam) project [18,19]. During the 1500 hour operation, no problem in the solar specific components like the absorber tubes or the ball joints has occurred. A demonstration plant of 8 MWht has also been built by Abengoa Solar [20]. The plant has been operated and evaluated for one year. In this period, an innovative control strategy system that guarantees the stability of the plant even under transient conditions has been validated. The first commercial solar thermal parabolic trough power plant with DSG technology in the world has been producing electricity since 2011 [21]. The 5 MWe solar thermal power plant uses a new generation of parabolic trough made of composite material combined with an efficient thin-glass mirror that reflects more than 95% of the sun's radiation. After two years of successful operation, the power plant has shown practical applicability of the DSG technology.

Though the DVG technology using the organic fluid for the purpose of power conversion has not yet attracted much attention, it seems to be a perfect match to the ORC. The reasons given are as follows.

Firstly, it can react to the fluctuation in solar radiation in a simple way. In the conventional DSG power generation system, in order to prevent the droplets from hitting the blades and causing damage, the water (a typical wet fluid) entering the expander must be superheated. This leads to great difficulty in controlling the system under variable solar radiation. The superheated steam is also accompanied by low coefficient of heat transfer in the receiver, and thus the collector efficiency is decreased. Through the replacement of water by a dry or isentropic organic fluid, these problems can be overcome. There is no need to guarantee the superheat state when the fluid leaves the solar field. The fluid from the collectors can be even at liquid or binary phase states with a specially designed heat storage unit. The power generation is steady over a wide range of solar radiation, which is certainly a big advantage of this kind of system.

Secondly, the technical issues associated with the pressure are less critical. In the conventional DSG system, the maximum operation pressure is generally above 10 MPa, and the technical requirement on the receiver is high. While in a DVG-ORC system, the pressure can be significantly reduced by choosing appropriate fluids. For example, the saturation pressure of R245fa at 100 °C is 1.3 MPa, and it is 1.3 MPa for R123 at 125 °C, 1.1 MPa for acetone at 150 °C, 1.6 MPa for PF5056 (perfluorohexane) at 175 °C, 1.3 MPa for cyclohexane at 200 °C. These fluids can be considered for different operating temperatures. The technical requirement in the DVG system gets much lower than that in the DSG system. Moreover, the operating pressure in the DVG system may be even lower than that of HTF in a commercial solar thermal power plant. The mixture of two aromatic hydrocarbons (diphenyl and diphenyl ether, THERMINOL® VP-1) is a suitable fluid to transport heat in the solar field [12,22]. The saturation pressure of this HTF at 400 °C is about 1.2 MPa. The design pressure at the solar field inlet has been set at 2.5 MPa to avoid evaporation at the outlet of the solar field. The technical issues associated with the HTF pressure in the receiver, storage tank, etc. are similar with those in the DVG system. Since the HTF technology has been well proven, the DVG technology is expected to be feasible.

Thirdly, there have been many successful applications of DVG technology using refrigerant. One application is the solar assisted heat pump (SAHP) systems [23–26]. CPC, FPC and evacuated heat pipe collectors can be employed. The solar collectors and the heat pump evaporator are integrated into a single unit to transfer solar heat to the refrigerant. The direct expansion SAHP systems are widely used for domestic heating and bathing. Long-term performance (>5 years) has been investigated and demonstrated [27]. There are products available in the market [28,29]. R134a is a commonly used fluid in SAHP systems, in which the operating pressure may range from 0.4 to 1.6 MPa (the saturation pressure at 10 and 60 °C respectively). The DVG technology with low boiling point refrigerant has reached a considerable degree of maturity.

The solar ORC system with DVG is promising. However, study on this kind of system is limited. A close view to its performance is required. In particular, as vapor is generated directly in the collectors, the working fluid influences not only the heat to power conversion but also the solar energy collection. Among the properties of the working fluid, the critical temperature seems to be most relevant to the thermodynamic performance. The effects of fluid critical temperature on the efficiencies of isolated ORC [30–32], geothermal power generation [33], waste heat recovery [31,34,35] and solar power system [3] have been estimated by lots of researchers. A general conclusion has been made: higher system efficiency can be achieved by using fluid of higher critical temperature.

Notably, the influence of working fluids on the solar energy collection is rarely investigated. In the proposed solar ORC system, an inner-type heat storage unit is employed, which enables the system to work steadily. Seventeen fluids have been selected as listed in Table 1. These working fluids have also been examined in many previous studies [3,7,31,32,36]. The working fluids are vaporized directly in the collectors. Due this innovative design the effect of working fluids is different from that on a solo ORC or conventional solar ORC system with HTF. In this paper, influence of working fluids on the collectors, ORC, and the whole system is investigated with respect to their critical temperatures. Suitable fluids are suggested with comprehensive consideration of the thermodynamic efficiency, technical and environmental aspects.

2. System configuration

The configuration of the proposed system is shown in Fig. 2. The system consists of solar collectors, pumps (P) and a fluid storage tank with phase change material (PCM), expander, generator (G) and