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A review on solar Rankine cycles: Working fluids, applications, and cycle modifications

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ABSTRACT

The Rankine cycle is considered the most common and competitive power generation cycle to produce electricity from solar thermal energy. This paper reviews the work done on the solar Rankine cycle systems for power generation and focuses on the working fluids investigated in the literature and the application of these systems in water pumping and water desalination.

1. Introduction

The worldwide energy demands are increasing gradually as a result of advances in science and technology, rise of new industrial countries such as China and India, and increase of the world population. Most of the world energy in the past century was provided by fossil fuels, such as coal, oil and natural gas. These fuels are cheaper and more convenient to use than other alternative energy sources due to established technology developed over the years in their exploration, production and utilization. The energy obtained from fossil fuels by combustion leads to emission of carbon dioxide, nitrogen oxides, and sulfur dioxides. These gases are environmental pollutants that have negative effects on the environment such as global warming and acid rains. Furthermore, fossil fuels are limited and their use is not sustainable.

Nuclear power production is another source of energy, but nuclear-fission products are radioactive causing disposal problems because of radiation hazards [1,2].

Renewable energy, produced by converting naturally-occurring renewable sources of energy into useful forms of energy, has attracted more attention in the past four decades. The oil crisis in the 1970s, energy shortage, environmental aspects, geopolitical considerations and other issues contribute to the increasing interest in renewable energy. In 2015, about 23% of the overall electricity generation was generated by means of renewable sources, including hydropower, and it is expected to grow to 30% in 2020 reaching 7300 terawatt hours (TWh) [3]. Despite this impressive progress, there are 1.6 billion people in remote areas, desert, and developing countries still living without electricity [4].

The sun is the major source of renewable energy on our planet. Of the $1.75*10^5$ TW, which is the total energy of the sun striking the earth's atmosphere, about $1*10^5$ TW reaches the earth's surface continuously [5]. However, this energy is not consumed sufficiently at its full extent. There are regions on the earth that have enough irradiation intensity while others do not, resulting in unbalances in the receipt of solar irradiation amounts [2]. Solar energy has several advantages; It is available in many regions round the world and it is a clean energy that does not cause environmental pollution [6]. It represents the most promising and viable option for power generation nowadays and in the future [7]. At the end of 2015, the global capacity of the installed solar-powered electricity reached 227 GW_e which accounts for about 1% of all the electricity used globally [8].

There are two commercial methods for the generation of power from solar energy: (1) solar photovoltaic (PV) systems in which solar irradiance is directly converted to electricity and (2) solar thermal

Abbreviations: CAMD, Computer Aided Molecular Design; CFCs, Chloroflourocarbons; CPC, Compound Parabolic Collector; CSP, Concentrated solar power; DVG, Direct Vapor Generation; ED, Electrodialysis; ETC, Evacuated Tube Collector; FPC, Flat Plate Collector; GWP, Global Warming Potential; HTF, Heat Transfer Fluid; HCs, Hydrocarbons; HCFCs, Hydrochloroflurocarbons; HFCs, Hydroflurocarbons; HFOs, Hydrofluoroolefins; ISCCS, Integrated Solar Combined Cycle System; LFR, Linear Fresnel Reflector; MED, Multi Effect Distillation; MSF, Multi-Stage Flash Evaporation; ODP, Ozone Depletion Potential; PFCs, Perfluorocarbons; PTC, Parabolic Trough Collector; TIT, Turbine Inlet Temperature; TIP, Turbine Inlet Pressure; TPP, Pinch-Point Temperature; RO, Reverse Osmosis; SRC-RO, Solar Rankine Cycle Systems for Reverse Osmosis Desalination; SRWP, Solar Rankine Water Pumping Systems

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systems in which solar energy is captured and directly used in heating applications or heat is converted to mechanical work via one of the common power cycles [9].

Within the last two decades, the PV market has been growing exponentially driven by the European and Asian Installations such that the global installed capacity increased by at least 40% year-on-year [10]. Many PV installations are now connected to the electric grid [11]. As long as the sun is shining, the electricity is generated steadily in PV systems. However, the clouds in the sky can greatly affect the power output [11]. Typical efficiencies of PV systems range between 12% to 20% [9].

On the other hand, solar thermal systems are competitive and attractive, especially for large scale, as the storage of thermal energy is relatively easy and efficient, while storing electricity generated from PV systems is not particularly efficient [12]. The efficiency of solar thermal systems could reach 60% in case of direct heating applications, while it is lower in case of power generation applications unless a high degree of concentration is used [9].

The main disadvantages of solar energy technologies are the high capital cost and the low power density as large areas are needed for the generation of hundreds of kWs [13]. High concentration solar collectors have been used to overcome the low-intensity limitation by achieving high temperatures [14]. The intermittent nature of solar energy can be overcome via the storage of thermal energy, which is a common option in these systems [15]. Energy is stored by the accumulation of certain amount of energy in daytime to be used at night or during unfavorable meteorological conditions [16]. It is reported that the addition of six hours of thermal storage can double capacity factors but results in significant increase in capital costs [17].

Solar thermal systems for power generation has the greatest potential of any single renewable energy area. However, the development of these systems has been delayed, since the 1980s, due to poor political and financial support from incentive programs in addition to resistance of the market to large plant sizes [18]. Fortunately, there has been a rapid development recently that by 2050, about 11% of the total electricity generation worldwide could be obtained using solar thermal energy according to an optimistic high-renewable outlook [19]. Advances related to these systems was reviewed by Mills [18].

Solar thermal energy is converted to mechanical power by means of power cycles such as Rankine cycle, Brayton cycle or the Stirling engine. The Rankine cycle is considered the most common and competitive power generation cycle used to produce electricity from solar thermal energy [20]. Solar Rankine cycles are reviewed in the literature. Some studies explained the Rankine cycles as they reviewed the status of low- and medium-temperature technologies of solar thermal power plants with more focusing on the solar collectors efficiency [7]. Other works reviewed various applications of Rankine cycles in the conversion of low-grade heat into power including solar thermal power systems with more focusing on the applications such as solar ponds power systems, solar-reverse osmosis desalination systems, and duplex-Rankine cooling systems [21]. Quoilin et al. [22] and Li [23] discussed the use of organic Rankine cycle (ORC) in solar power plants as a section of the wider topic. Giovannelli mentioned the use of Rankine cycle in his work [19] in which suitable technologies for electricity or cogenerated production using small scale (< 1 MW) concentrated solar power plants were described.

Desai and Bandyopadhyay [24] reviewed solar power plants with line-focusing solar and discussed the use of Rankine cycles in these systems. Markides [10] also reviewed low-concentration solar power systems (at temperatures < 400 °C) based on ORCs for distributed scale applications (1 kW–1 MW). They focused only on subcritical ORC without regeneration or reheat. Kim and Han [25] gave a brief review of the solar Rankine and its application.

However, according to the authors' knowledge, there is no recent published study that comprehensively reviews the solar Rankine cycle, the used working fluids and its application briefly. The aim of this study is to provide a comprehensive background and review of solar Rankine cycle systems for power generation. The main components of a typical solar Rankine cycle are introduced in Section 2. Section 3 deals with types of solar collectors used in solar Rankine cycles. Being the most important factor in the cycle efficiency, the selection of working fluids is discussed in Section 4. This section also includes a summary of the used working fluids and the corresponding solar collector. The most two common applications of solar Rankine cycle for power generation, which are water pumping and reverse osmosis desalination systems, are reviewed in Section 5. Finally, in Section 6, the minor and major modifications made on the Rankine cycle and solar collectors whether in the configuration of the system or by combination with other power systems are presented.

2. Solar Rankine cycle

The Rankine cycle is considered the most common and competitive power generation cycle that is used to produce electricity from solar thermal energy [20]. The main components of a solar thermal Rankine system are (1) the solar collector, which is discussed in Sections 20, (2) the thermal energy storage, [26], and (3) the Rankine cycle.

As shown in Fig. 1, the four main components of a Rankine cycle are (1) a boiler, which evaporates the working fluid; (2) a turbine, in which the working fluid expands and generates power; (3) a condenser, in which the fluid condenses at lower pressure; and (4) a pump, which pressurizes the condensed fluid.

Based on the working fluid used, the Rankine cycle will be either steam Rankine cycle or organic Rankine cycle (ORC). The conventional Rankine cycle employs water as a working fluid and is of great importance as it takes part in the generation of 85% of all the used electric power throughout the world in the form of steam engines [23]. Generally, water is the most suitable working fluid when the utilized heat sources are high temperatures (> 370 °C). At lower temperatures the steam Rankine cycle is less efficient and more costly [27,28].

On the other hand, ORCs employ organic fluids, such as hydrocarbons, refrigerants and siloxanes and are considered to be a better solution to utilize heat from low and medium temperature sources due to the low boiling points of organic fluids [22]. The use of ORCs for power generation, ranging from few watts to several megawatts, has found increasingly wider application. ORCs utilize energy from different energy sources such as geothermal, ocean thermal, biomass, waste heat recovery and solar thermal [4]. By the end of 2013, the installed capacity of the ORC power plants reached approximately 1700 MW [23].

Both steam and organic Rankine cycles have been used early to utilize solar energy. The Application of the steam Rankine cycle utilizing solar energy for water pumping in the 19th century has been

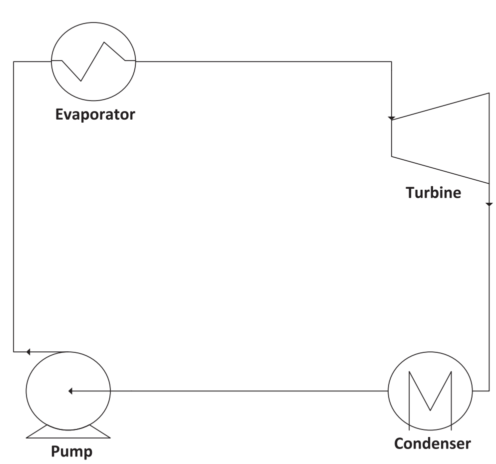

Fig. 1. Typical Rankine cycle.