

Proposal for Development of a Novel 2kWp Solar Powered Rankine Cycle Power Generation System

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Abstract— Solar power generation is the most fast growing renewable technologies. Conventional heat engines and modern photovoltaics are basic methods for converting solar irradiation to power/electricity. Building-integrated photovoltaic systems have been becoming common for solar electricity generation. However, the cost is still very high most especially for rural economies. To overcome the drawback of high cost of PV systems, the conventional Rankine, Brayton or Stirling cycle heat engines have attracted wide investigations in the past decades. The design and description of a novel micro solar thermal power system based on Rankine cycle is presented. The conversion of low and medium temperature heat from solar thermal to electricity by using low cost, lightweight and low maintenance expander as well organic substances or hydrofluoroether, HFE 7000 is the subject of this research.

Keywords—Solar thermal; rankine cycle; hydrofluoroether

I. INTRODUCTION

A comprehensive review of solar-powered heat engines for power generation was made by Spencer [1] in 1989. Rankine cycles are most popular for solar power generation and they may operate at a low temperature. For example, Sawyer [2] described the Enreco organic Rankine cycle engine which was developed as part of solar pond technology to generate electricity from brine at 80°C. The overall power conversion efficiency of a solar-powered Rankine cycle may vary from less than 10% up to 20% depending on the operating temperature [3]. The solar collectors may the types of evacuated tube and parabolic concentrator. Zhang et al [4] studied a CO₂ Rankine cycle using an evacuated tube solar collector. The thermal efficiency of the collector was measured about 70% at a temperature of 80°C. The simulation by Rolim et al [5] show that parabolic solar concentrators may provide 100°C~400°C heat at an efficiency of 0.73~0.65 for a Rankine cycle system. Riffat and Zhao [6] investigated a hybrid solar/gas powered Rankine cycle system using HFE7100 as the working fluid while Nguyen et al [7] tested a low temperature Rankine cycle using n-pentane as the working fluid. Tchanche et al [8] have compared a number of potential working fluids and concluded that R134a appears as the most suitable for small scale solar applications. Various types of power convertors have been investigated for small scale low temperature Rankine cycle systems. Compared with the common turbines, multi-vane expanders [9] and scroll expanders [10] may be more suitable.

The aim of this research project is to develop a small scale medium temperature solar Rankine cycle power generation system. A prototype system with a power generation capacity of 1~2kWe will be constructed and tested. The solar heat at a temperature of 120°C~150°C will be provided by a purposely designed solar concentrating collector. The Rankine cycle system will employ “ozone-friendly” working fluid such as pentane, hydrofluoroethers (HFEs) or R134a.

II. INNOVATION

The proposed project is novel in the following ways:

- A. The system will be developed at a small scale with 1~2kWe power output, so suitable for residential applications.
- B. Market available multi-vane air expander will be modified as the power generation device for the proposed system. It is also intended to use market available automotive alternators as the electricity generator.
- C. The project will also include comparison of a multi-vane expander and a single screw expander.
- D. A novel trough solar concentrator with a mirror image co-focus line will be used in conjunction with evacuated tube solar collector. The new concentrator has forward focusing thus allows a convenient installation and insulation. The new concentrator also allows less accuracy tracking and thus use of less accuracy parabolic mirror.

III. DESCRIPTION OF THE PROPOSED SYSTEM

The proposed system is based on Rankine cycle power generation system as seen in Figure 1. The evacuated tube solar collector will be positioned in a purposely-designed parabolic concentrator to produce hot water at a temperature of 120°C ~ 150°C, which is the heat source to the Rankine cycle system. Hydrofluoroether HFE7000 which has the boiling point of 34°C may be used as the working fluid. Vaporation of HFE7000 at 120°C will produce a vapour at 5.0bar and the higher pressure vapour then drives the turbine or expander to produce mechanical energy and hence electricity at the alternator.

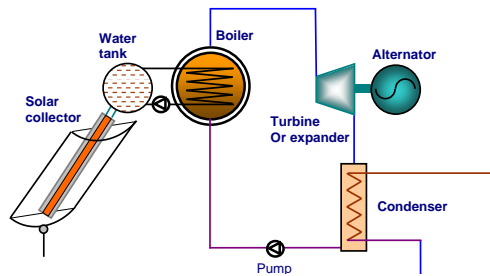


Figure 1: Rankine cycle power generation

The discharge vapour may condense at 60°C at the condenser and the condensed liquid is pumped back to the boiler to complete the Rankine cycle. The calculated power conversion efficiency for the above conditions is around 7%. This is close to the efficiency for the operating conditions with the boiling temperature of 100°C and the condensing temperature of 40°C . However, as the heat rejected at 60°C could be reused, the overall power generation and thermal efficiency of the Rankine cycle system is high and could be up to 37%.

A. Turbine System

It is intended to use a multi-vane expander as the power generator in the proposed system. Compared with the turbines, piston-type expanders and scroll expanders, the vane-type expanders are comparatively simple in design. Figure 4 show a commercial four-vane expander and its specification. The rotor of the expander is mounted eccentrically in the cylinder bore, and the vanes slide radially in the rotor slots as it turns. The vanes are thrown outwards by centrifugal force and pressed inwards by the cylinder. Expansion of high pressure vapour entering at the intake port pushes the vanes to sweep the cylinder and a torque is produced on the shaft. The exhaust vapour is discharged at the other side. The specification data for compressed air show a power out of 1kW at the inlet pressure of 7bar. The shaft work could be converted to electricity using an alternator. The authors have already carried out a preliminary test of the combination of a 4-vane expander and an automotive alternator at University of Nottingham. An electricity output of up to 200W has been measured on a small scale test rig.

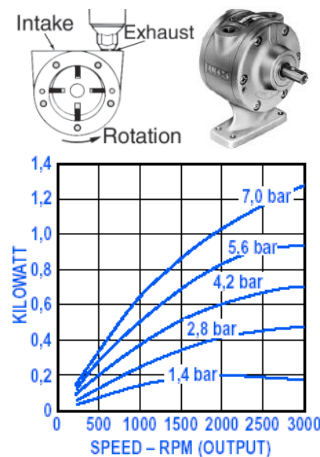


Figure 2: Structure and performance of a commercial 4-vane expander

It is also intended to compare the 4-vane expander with a single screw expander as the power generator in the proposed

system. In comparison, the screw expanders may be slightly more complicated, but more reliable and are suitable both small-scale and large-scale applications. The screw expanders are contrary to the conventional screw compressors which have been widely used in refrigeration, air conditioning and gas compression. A single screw expander is a rotary positive displacement expansion device including a main helical screw and two supporting rotors, as shown in Figure 3. The process in a single screw expander includes three stages, namely filling, expansion and discharge. Compared with the common two screw expanders, use of two supporting rotors make the single screw expander better balance in mechanical load, so it runs more quietly and reliably. The single screw expander would be also small size and light weight, therefore suitable for small scale applications.

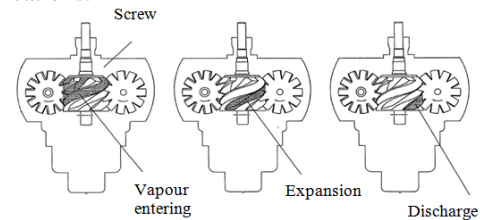


Figure 3: Working processes of a single screw expander

B. Solar Thermal System

The proposed system will use a novel new trough solar concentrator which has a mirror image co-focus. As shown in Figure 4, the new trough collector comprises two primary parabolic mirrors, two secondary flat mirrors, a third parabolic mirror at the bottom and a high temperature solar energy receiver. Its operating principle is described as follows. The light '4' at a direction parallel with the symmetry axis '5' enters the trough. The surface '1' of the primary parabolic mirror reflects the light '4' to the secondary flat mirror '2'. The light is then reflected by the secondary flat mirror '2' to concentrate at a mirror image focus line. The center line of the high-temperature solar receiver '8' just superposes with the mirror image focus line. A vacuum glass tube '7' is positioned outside the receiver '8' to reduce heat loss. The new trough solar concentrator also has a bottom parabolic mirror '3' connected with the secondary flat mirror '2' by the flange '9'. The focus line of the surface '3' also superposes with the center line of the high-temperature solar receiver '8'. The light striking onto the lower trough parabolic concentrator '3' is reflected to the receiver '8'. Therefore, the solar energy receiver '8' in the new trough can accept the reflected solar radiation from both upside and downside so that the receiving efficiency is enhanced. The reflected solar radiation is absorbed on the receiver to heat the working medium such as water inside.

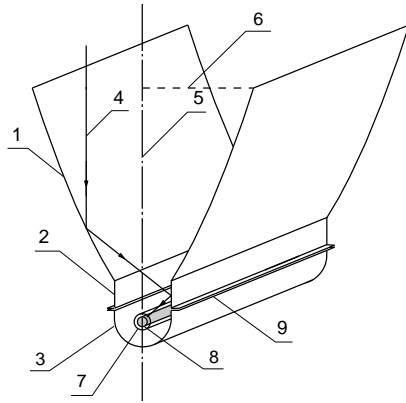


Figure 4: A novel v-trough solar concentrator

IV. RANKINE CYCLE DESIGN DETAIL

The Rankine cycle concept involves the use of organic fluids in a low temperature micro power generation system with an assembly of different but vital components articulated into a test rig. The schematic of the system prototype rig is shown in Figure 5. The major components are the expander (Turbine), the pump, the vapour generator (evaporator), a recuperator and the condenser. Other components include a receiver, which acts as reservoir for condensing working fluid and data acquisition components and other peripherals. These include various sensors such as thermocouples, pressure transducers, dc current transducer and the tachometer. The components that make up the test rig are further discussed in next sections. The challenge is to develop a means of exploiting solar thermal energy for power generation through a system that operates the Rankine cycle concept. The initial testing will be carried out using an electric boiler. The process emphasises the conversion of heat to work with the special devices already mentioned including the use of a novel working fluid known as hydrofluoroether (HFE), a working fluid that is not only environmentally friendly but with a low latent heat and high density to increase mass flow rate at the inlet of the prime mover.

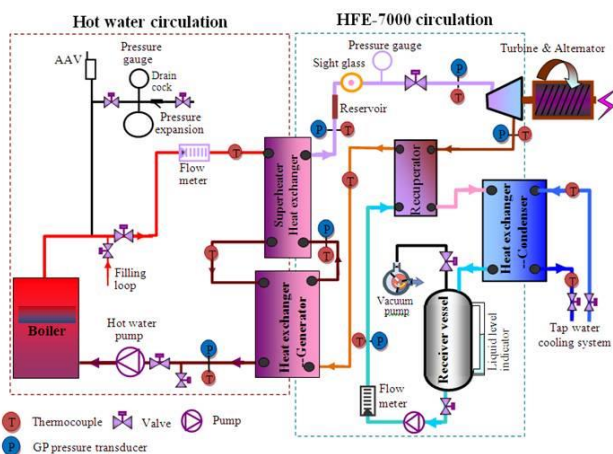


Figure 5: Detailed schematic of the Rankine cycle process

V. PROTOTYPE DEVELOPMENT

A prototype of micro power generation system based on Rankine cycle driven by solar thermal energy will be

developed and tested by the authors at SERC. The main system performance values to be investigated are turbine pressure ratio, turbine efficiency, alternator efficiency, Rankine cycle efficiency, boiler efficiency, electricity generation efficiency, thermal efficiency, complete system efficiency and so on. The vane-type expander is expected to be updated later in the project and the system will be further examined. It is intended initial testing will be carried out using electric boiler

These are just proposed components in order to have an idea cost estimate of the project. The research will include finding alternatives. It should be noted the cost does not include delivery charges. For now the cost of some other components such as heat exchangers cannot be estimated as they are produced based on application requirement and thus sole dependent on system design. It was so far estimated that a total cost of between \$13,450 – \$20,750 will be required for the project. The project will be carried out in three different stages within the solar thermal unit of SERC. Different researchers will form a working group whereby the project will be carried out concurrently.

Stage 1: Theoretical and experimental investigation of concentrated solar collector

Stage 2: Theoretical and experimental investigation of Rankine cycle turbine

Stage 3: Theoretical and experimental investigation of combined solar turbine power generation

A. Test Rig Components

The components that are required for the construction prototype system and also the test rig are shown in Table 1 below. The table also captures boiler and super heater as optional components to be utilized mainly for testing.

Table 1. Identified major components of the prototype system

Component	Type	Spec
Solar Collector	v-trough	2m ²
Working Fluid	HFE/7000	
Hot Water Pump	Grundfos Selectric UPS 15/50 Central heating Pump	
Turbine	Gast air motor	3kW
Alternator	Prestolite 140A alternator	140A
Other components	Pulley, Drive Belt, Piping, Drain Cock, Valves, etc	
Fabrication	Reservoir, Receiver Vessel, etc	
Pressure Expansion		
Sight Glass	Spirex Sarco	
Heat exchangers	Generator, Recuperator, Condenser	
Vacuum Pump		
Automatic Air Vent (AAV)		
Boiler (optional)	Chromalox-Model CES-12 480V	9kW
Superheater HX (optional)		

B. Instrumentation

The success of this project depends mainly on the measuring instruments used and their accuracy. Below is table detailing out instruments required and their specification.

Table 2. System instrumentation

Component	Type	Spec
Speed Control	Eurotherm 650 Series speed control	0.2-7.5kW
Data Logger	DT500 series data taker	
Computer		
Tachometer	Single memory optical tachometer	
Current Transducer	DK Current Transducer	100A, 4-20mA
Pressure Transducer	General purpose pressure Transducer	0-10 bar, 4-20mA
Thermocouple	Pipe Plug probe	
Pressure Gauge		
Flow Meter		

VI. CONCLUDING REMARK

This research describes the development of a novel 2kW solar powered Rankine cycle power generation system intended for remote off-grid locations, employing a multi-vane expander as the prime mover. The expander will harness power produced by high pressure vapour to generate torque and rotational motion on the shaft and the mechanical energy generated is converted to electricity by means of an automotive alternator. In order to assess and predict the performance of the system, a software simulation of a basic cycle will be carried out in order to compare the outcome with the actual cycle. A preliminary air test of the system will also be carried out to have a perspective on actual performance using compressed air. However, the organic substance, hydrofluoroether (HFE) to be used in further tests is selected because of its thermodynamic properties of having a lower specific volume and higher molecular weight than steam allowing for smaller, less complex, less costly energy applications like expanders and smaller diameter tubes to be employed for low temperature micro system. This is achieved through a phase change transformation in a Rankine cycle

process between specified temperature limits when compared to turbines which operate at higher temperature and pressure.

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