Performance of Thermosyphon Rankine Engine as Low Temperature Heat Engine

Samir M. Elshamy

Assistant professor at High Institute of Engineering, 6 October, Egypt

Abstract—Energy harvesting from the low-temperature heat source can be applied from thermosyphon rankine engine (TSR), this device depends on rankine cycle where evacuation the pressure from the device will decrease evaporation pressure according to applied pressure. This engine was developed in little experiments, so a new model was constructed depending on last models were investigated. Copper tube was the case of thermosyphon and impulse turbine was attached to harvest the steam then generate electrical power .the efficiency of this was little small but according to the cost of input power it considers to be the high efficiency of this system, especially there is no any emissions of this engine.

Index Terms—Thermosyphone, Rankine, Heat Engine, Low Temperature, Energy, Evaporator, Condenser

◆

1 INTRODUCTION

The Thermosyphon Rankine Engine (TSR) is a new concept for power generation using available low-grade heat sources. The concept of the engine is the modification of a heat pipe, with its excellent heat and mass transfer characteristics, to attach a turbine, thereby making the system into a Rankine Cycle Engine.
The TSR is directed towards power production from solar ponds, geothermal energy, and heat produced by solar collectors, as well as for waste heat utilization for electrical power generation. Thermosyphon Rankine engine (TSR) is an environmentally friendly system for direct extraction of electrical power using low enthalpy heat sources.
Thermosyphon heat transfer has certain operating and limiting mechanisms that need to be considered before further discussing thermosyphon technologies and applications. This consists of a metal pipe with a fixed amount of work-ing fluid sealed inside. During operation, heat is added through the bottom section (evaporator) and the working fluid becomes vapor. The vapor travels through the middle section (adiabatic section) to the top section (condenser) of the tube. In the condenser, the vapor releases the latent heat to the condenser wall and becomes liquid. In contrast to a heat pipe, which utilizes capillary forces for liquid return, the thermosyphon relies on gravitational or centrifugal force to return the condensed liquid to the evaporator.

Heat transfer performance of the thermosyphon is a function of many factors including the thermo-physical properties of the working fluid, geometry, and orientation of the thermosyphon, gravity field, and operating temperature or pressure. Fundamental heat transfer theory dictates that any mode of heat transfer is driven by a temperature difference and the larger the temperature difference, the higher the heat transfer rate. However, in many applications, it is desirable to transport a large amount of heat over a long distance but at a relatively small temperature difference. Inside an operating thermosyphon, the vapor carries a large amount of latent heat and vapor super heat from the evaporator to the condenser. Figure1 illustrate the schematic of TSR. It is a vertical wickless heat pipe. As shown in Fig. 1, an axial impulse vapor turbine has been installed between the adiabatic section and the condenser section and is capable of converting high kinetic energy of vapor in the pipe to electrical energy by us-ing a directly coupled electrical generator.
Ziapour [1] had developed a looped where vapor and liquid flow passage are separated by installing liquid feeding tube with showering nozzle. He enhanced the design of TSR system using impulse turbine. In his paper energy and exergy analysis of TRC was formulated in order to estimate its optimum operating conditions, his results showed that his present model can be able to increase the efficiency of the TSR system. Ziapour and et al. [2] in their work they improved the loop type TSR system by adding super heating process. The system drum (or pool) type evaporator had been selected instead of the showering nozzle type evaporator where this type of evaporator can be suitable for receiving the renewable energy need via the flow boiling process.

- *E-mail: smelshamy@csi.edu.eg*
- *Tel.:+2-01210609092*

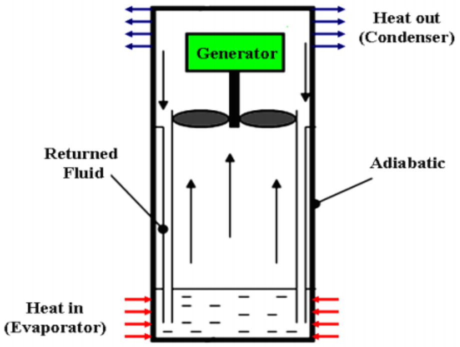

Fig.1. Schematic diagram of a simple TSR

So it found that the flow boiling process had beneficial heat transfer characteristics. In addition, in order to provide the supersonic vapor flow for blades of the impulse turbine they used a convergent-divergent nozzle after the super heating process. As result of this modification 0.78% increase in the turbine useful efficiency due to the superheating process was obtained.

There were multiple models of TSR were built at RMIT (Royal Melbourne Institute of Technology), where The initial rig was built at in approximately 1994 was housed in a vertically oriented, sealable copper tube measuring 2.9m tall with a 0.16m external diameter Nguyen et al.[3]. The combined length of the evaporator and adiabatic sections measured 2.0m (at rest, the working fluid level was 0.5m) while the condenser section measured 0.9m long. During testing, us-ing water as the working fluid, the first TSR ran with an evaporating temperature of 60^{o} and condensing temperature of 30^{o}C (operating under vacuum conditions). Producing a very modest electrical output, the turbine rotated at speeds between 600 and 800 rpm. A hydrostatic head of 1.7m (of the 2.0m possible) was recorded which displays that 85% of the maximum pressure difference for the unit was achieved.

The second TSR was redesigned to accommodate a higher mass flow rate (2000 times the previous setup) by increasing the nozzle size and improving the turbine blade profiles. It was observed from the experimental results that the second prototype had a relatively large temperature difference be-tween the heat source fluid and the working fluid in the evaporator (15°C) indicating a reasonably high thermal resistance there. Despite this handicap, the unit was able to achieve a 2kW heat transfer rate, with 9.0% of this being lost in transport across the heat pipe. The turbine generated power over a speed range of approximately 1750 to 3350 rpm and had a maximum electrical output of 0.35W at 2540 rpm. Although this represents an overall efficiency of 0.175%, it showed progress in the development of the TSR with the higher rotational speeds obtained and a measurable production of electricity.

The third TSR was designed to improve the overall efficiency of the heat pipe-turbine while also reducing production costs. The closed vertical cylinder (3.15m) had an external diameter of 0.16m and heights of 0.5m, 1.7m and 0.9m for the evaporator, adiabatic and condenser sections respectively. An increased heat transfer rate of 4.4 kW was calculated for the evaporator. The maximum turbine speed increased to approximately 5600 rpm and a peak electrical output of 4.5W was obtained at around 4800 rpm. It can be seen from the results that the design aims of the rotor in third TSR had been met in terms of increased heat input, simplicity, lack of expense and higher achievable rotational speeds. The overall conversion efficiency of the third TSR, however, was actually less than the second prototype at 0.125%.

The fourth prototype was again a revised design and this time it was made from transparent acrylic to allow visual inspection of all of the heat pipe operation. The evaporator section measured 0.5m, the adiabatic 1.7m and the condenser section measured 0.7m in length. It was decided to set the inside diameter at 0.5m in order to lower the rotational speed of the rotor whilst retaining the possibility of increasing the power output (due to increased torque). This model was tested and produced electricity at various evaporator temperatures from 44°C to 55°C. Tests were conducted to gather data that would allow for a range of heat source tem-peratures and varying heat exchanger effectiveness. Alt-hough the Carnot efficiencies start at 7.3%, (for 42°C evaporator temperature) and climb to 10.7% (for the 55°C run), the overall efficiencies achieved display a much greater spread. The overall conversion achieved was 0.2% for the 42°C run and up to 0.81% for the 55°C evaporator temperature, showing significantly higher overall conversion efficiencies in this region (efficiency quadrupled). It is impossible to con-sider separately the effect of the rotor and the generator in this setup. Using data from an earlier investigation into the operating characteristics of the Maxon DC generator, indica-tions are that the majority of the improvement in overall conversion efficiency can be contributed to the generator running in its preferred speed band. The minority of the overall efficiency increase would seem to be contributed from the increase in the turbine's isentropic efficiency during the higher temperature runs. Nonetheless, a more than 6 fold increase in the overall conversion efficiency gained by the fourth TSR over the third was the most significant im-provement achieved and showed further potential.

The fifth TSR was primarily designed by Akbarzadeh et al. [4] this prototype further simplified the design for ease of manufacturing and cost effectiveness. The turbine consists of a hub with two ‘S’ shaped pipes attached to it. The vapor flows vertically through the hub, and the direction of flow is changed to horizontal while entering the two pipes on the periphery. Then the vapor flows through the pipes and exits through the nozzle at the pipe outlets, causing the reaction which drives the turbine. The heat input for this turbine is 100 KW at 58 oC and it is expressed to deliver 3 KW of electrical output power

The aim of this project is to investigate experimentally the performance of TSR engine by designing a new model, where there are a very limited number of TSR models that have been investigated.

2 GOVERNING EQUATION FOR TSR ENGINE

The Rankine cycle is assumed for the different states of the working fluid in an idealized TSR engine. The Rankine cycle in its different steps is illustrated in Fig. 2 according to Nguyen et al. [3]

The steps are as follow:

1→2: Isentropic expansion of the vapor across the turbine, including partial condensation

2→3: Complete condensation in the condenser at constant temperature

3→4: Liquid return to the evaporator by gravity

4→5: Heat supplied from evaporator to change state 4 into saturated water at constant pressure

5→1: Evaporation at constant temperature

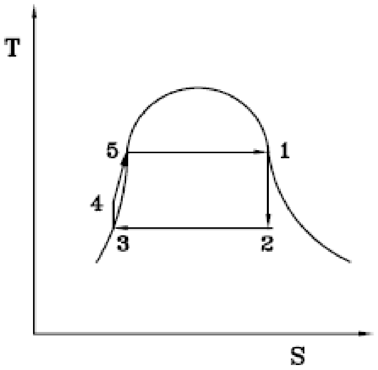

Fig.2 T-S Diagram of Rankine Cycle

In traditional power plants process 3-4 is done through pump, but here gravity does the pumping and therefore a pump is not used. So that the absence of a pump is one of the main advantages of TSR engines.

Let us assume that Q (W) is the rate of heat transfer in the evaporator section. This heat is provided from some external source, such as solar, geothermal or waste heat but here we will get heat from electric heater. The thermal relations are calculated from the experimental data as follows:

Electric power, Qelec (Heat added)

With measuring the voltage V and the current I of AC, the electric power applied to the evaporator section by the resistance heater is:

$Q_{elec} = V \times I \times cos\varphi$

Where φ is the phase angle between V and I

Work done, W

Measure output voltage (V) applied to load and electric current (I)

$$WorkDone = V \times I$$

Efficiency of the conversion of the thermal energy into electrical power can be written as

$$\eta = \frac{WorkDone}{Q(Heatadded)}$$

As mentioned before, it should be noted that no pump work is taken into account.

3 EXPERIMENTAL SETUP

This prototype as shown in Fig.3, was designed from the red copper tube measuring 1.4 m length with a 21 cm external diameter and the internal diameter 19.5 cm.

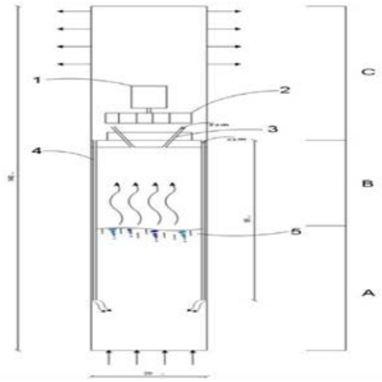

Fig.3 Schematic diagram of TSR Engine

The combined length of the evaporator and adiabatic sections (A+B) measured 0.8m while the condenser section (C) measured 0.6m. The turbine (2) was placed between the adiabatic and the condenser sections. Turbine blades are made of aluminum material and consist of 8 blades. Turbine set-up comprised two nozzles (3) with inner and outer diameter 3mm & 7mm respectively, to allow steam passes through. The two return pipe of condensed fluid (4) are made from copper with 5 mm diameter each, which was placed around the turbine blades to use for returning condensed water from condenser section to evaporator section. A 24VDC electrical generator (1) was coupled above the turbine, inside Thermosyphon Rankine Engine, to convert the mechanical ener-gy into electrical energy.

The operation of TSR is through the Electric power is applied to the electric heater with certain power after while water starts to evaporate at the certain temperature according to pressure applied. The vapor bass through the nozzles striking blades turbine causing to generate electricity where applied to load where measure current and volt generated, then steam rises up to the condenser section where condensed on walls of the tube then falls down according to gravity to the evaporation section passing through two side return pipes to complete the cycle. Figs. 4 and 5 illustrate photos of complete test rig and configuration of the turbine with the electric generator.

Fig.4 Photo of test rig

Fig.5 Photo of turbine and electric generator configuration

4 RESULTS AND DISCUSSIONS

The steady state reached after 60 min, where no change in temperature reading then data were recorded. As shown in Fig.5 the temperature of thermosyphon at applied input power is higher at evaporator section than condenser section where the temperature decreases as the steam moving away from evaporator section directed to condenser section, Also as seen the boiling temperature decrease according to evacuation pressure applied to the system where this option is good to decrease the power required to evaporate water. As the input power increase the all temperature gradient increase, also as seen the temperature gradient in the middle of the graph is almost horizontal this at the adiabatic section. Fig.6 illustrates as the input power increase the output power will increase. The efficiency of TSR decrease as the output power increase as shown in Fig.7 this as the input power increase so the output power is, but increase in output is not as much as the increase itself, where this is the reason of decreasing efficiency also mechanical losses is parameter can't ignore in this energy conversion.

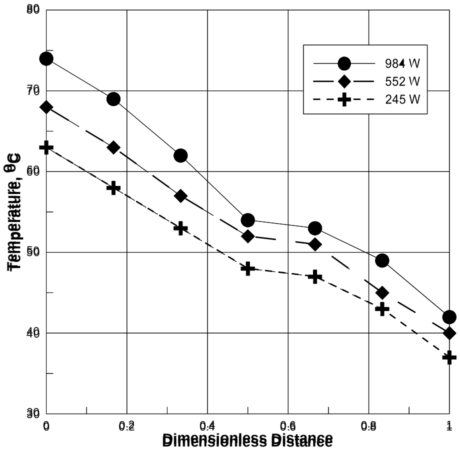

Fig. 5 variation of temperature with dimensionless distance for different input power

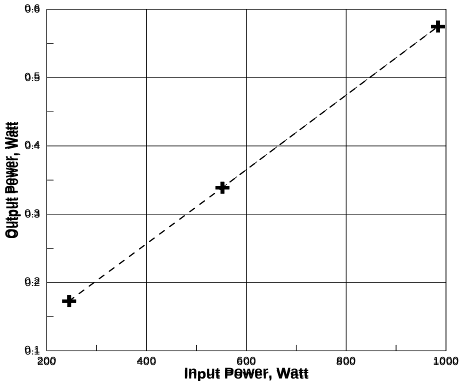

Fig. 6 variation of output power with input power

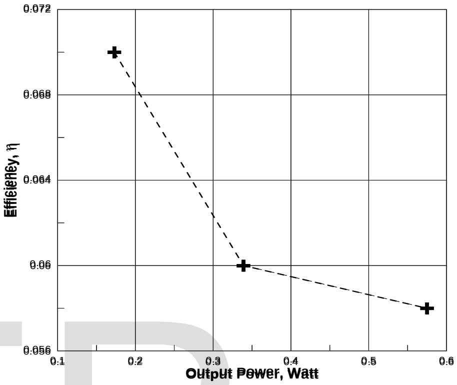

Fig.7 variation of efficiency with output power

5 CONCLUSION

TSR engine will be used as low-temperature heat engine where it don't need high temperature heat source as this source may be from solar, geothermal or waste heat , so the efficiency of this system will be acceptable.

REFERENCES

[1] B.M. Ziapour "Performance analysis of an enhanced thermosyphon Rankine cycle using impulse turbine", Energy 34 (2009) 1636–1641

[2] B.M. Ziapour, A. Mohammadnia, M. Baygan "More about Thermosyphone Rankine Cycle Performance Enhancement", International Journal of Engineering, 28, No. 4, (April 2015) 642-647.

[3] T.Nguyen, P. Johnson, A. Akbarzadeh, K. Gibson and M. Mochizuki " Design, Manufacture and Testing of a Closed Cycle Thermosyphon Rankine Engine" Heat Recovery Systems & CHP,15 , No.4, (1995) 333-346.

[4] A.Akbarzadeh , P.johnson , T.Nguyen , M.Mochizuki , M.Mashico , I.Sauciuc , S.Kusaba , H.Suzuki "Formulation and Analysis Of The Heat Pipe Turbine For Production Of Power From Renewable Sources",Applied Thermal Engineering 21(2001) 1551-1563.

[5] L.C.Spencer "A comprehensive review of small solar- powered heat engines: part 1", solar energy 43(4) (1989)191-196.

[6] L.C.Spencer "A comprehensive review of small solar- powered heat engines: part 2", solar energy 43(4) (1989)197-210.

[7] L.C.Spencer "A comprehensive review of small solar- powered heat

engines: part 3”, solar energy 43(4) (1989)211-225.

[8] S.L.Sawyer “Electricity Generation from low temperature heat sources using organic rankine cycle engines”,Electric energy conference, No.91,Darwin , Australia ,I.E.Aust.,(1991) 155-159

[9] R.J.Pryputniewicz,U.S.Haapala”An investigation of a heat pipe turbine generator system for production of energy”, proceeding of th17 Th intersociety energy conversion engineering conference (IECEC), (1982)1134-1139.

[10] S.Quoilin and et al., “Techno-economic survey of Organic Rankine Cycle (ORC) systems”, Renewable and Sustainable Energy Reviews, Vol. 22, (2013), 168-186.

[11] M.B.M.Tahir,N.Yamada, and T.Hoshino“Efficiency ofcompact organic Rankine cycle system with rotary-van typeexpander forlow-temperature waste heat recovery”, International Journal of Civil and Environmental Engineering, Vol. 2, (2010), 11-16.