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Design and Fabrication of Solar Organic Rankine Cycle Test Rig with Helical Coil Heat Exchangers and working fluid selection strategy

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Abstract

Organic Rankine Cycle (ORC) is a modified Rankine cycle which uses organic working fluid to convert heat into useful energy. ORC has proven its potential in the field of exploiting waste heat generated by process industries. Due to environmental concerns and power demand, researchers now started exploiting renewable energy sources like solar and geothermal energies as heat source for ORC. The research in the field of ORC has revealed that, the energy conversion efficiency of ORC is very low and depends on working fluids used in it. Although variety of organic working fluids are available in market, the Zeotropic working fluids have revealed the better performance in ORC systems due to their temperature glide characteristics in evaporator and condenser but the unknown thermophysical characteristics of these working fluids restricts their use in ORC. This motivates a researcher to explore new possibilities to use these working fluids and improve ORC efficiency. In this regard a systematic test setup is designed and developed to test the potential of Zeotropic working fluids with solar energy as heat source. This paper presents the development of ORC test setup and the working fluid selection strategies for ORC

Keywords: *Organic Rankine Cycle, Scroll Expander, Thermal efficiency, Solar parabolic collector, Zeotropic working fluid.*

1. Introduction

Energy crisis and environmental protection are the global challenges of 21st century. It is estimated that global energy demand will increase by 33% in near future as a result of, increasing population and industrialization. Ever increasing energy demand warrants for burning of more fossil fuels to produce electricity, which contributes for serious environmental problems such as global warming and ozone depletion by reducing deposits of fossil fuels in earth crust. Thus, in the current day a lot of efforts are taking place in the sector of power generation to improve the efficiency of electricity generation techniques and also to exploit the renewable energy sources as well as the waste heat produced by industries and IC engines. One such technique of exploiting waste heat and renewable energy sources like solar, geothermal heat is to include Organic Rankine Cycle (ORC) due to its simplicity and adaptability.

The working principle of an ORC plant is based on the same process as traditional water-steam cycles used in conventional power plants for 150 years. Using water as a working fluid is state of the art in nuclear and coal-fired power plants. However, exchanging the working fluid with an organic medium with a lower evaporation point enables application of the technological concept also in small to medium scale applications with relatively low-temperature ranges.

Unlike zero-emission technologies such as wind turbines and solar panels, ORC plants can deliver base load and flexible response power as long as the heat source is working. Therefore, these plants are optimally plannable and there is no need for complex grid stability studies. Applying an ORC plant to a newly built or existing system either increases the total output with the same amount of fuel or generates the same output with less fuel. In both cases, the efficiency of the system increases significantly.

2. Background

2.1 Solar ORC

During the past two decades research on ORC has become a field of interest and most of the studies reported were on thermodynamic behavior of ORC and several significant conclusions were drawn based on the research [1].

From many years the research on ORC was confined only to waste heat recovery but, as the importance of renewable energy sources was understood, scientists and engineers throughout the globe started exploiting solar, geothermal and biomass heat as the primary heat source for ORC. In this context regenerative ORC utilizing geothermal heat, working with R123 was presented by Li et al. [2], Besides Qiu et al. [3] investigated the ORC system with 50kWt biomass-fired boiler and the results showed that the developed CHP system is capable of producing 860.7 W of electricity and 47.26 kW of heat, with electricity generation efficiency and CHP efficiency of 1.14% and 78.69% respectively. Also expander efficiency of 53.92%, alternator efficiency of 50.94%, boiler efficiency of 3.78% are observed and concluded that implementation of internal heat exchanger will improve the efficiency and hot water temperature may reach 180^{o}C

Further progress in the research was oriented towards solar ORC as geothermal sources are not available in all the geographical locations and rigorous experimentation and investigations were conducted to understand the feasibility of using solar energy in ORC for power generation. Villarini et al. [4] reviewed the research articles on small scale solar powered ORC and summarized the cycles and working fluids that can be applied in a small scale solar ORC and suggested that using the nearly isentropic fluid in the cycle will be the best choice for ORC with CHP system. Similarly, Desai et al. [5] showed the thermo-economic comparisons of ORC and SRC integrated with line focusing concentrating solar collectors, furthermore Quoilin et al. [6] reviewed different applications of ORC and revealed that ORC cycles are appropriate for moderate power ranges or low temperature application when compared with steam Rankine Cycle. Also, Jing et al. [7] optimized solar thermal electricity generation system with ORC operating at low temperatures in Bombay, Lhasa, Singapore, Canberra, Berlin and Sacramento. The system worked with solar CPC connected with ORC having R123 and the performance was investigated, which showed two stage heat exchange will improve efficiency by 8.1 to 20.9%. Another author Antonelli et al. [8] presented an analysis on solar plant having a rotary expander and compound solar collector. The results showed the role played by working fluid at saturation temperature. This particular parameter effected the efficiency of the cycle and solar plant, further it was possible to determine the optimal operating conditions for ORC proposed and it was also concluded that the temperatures above 110-120^{o} C will give more efficiency if the expansion takes place in single stage device. Using these understandings Higgo et al. [9] characterized an ORC prototype for low grade solar energy

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

conversion to understand its behavior and concluded that, by the further research in this field it is expected that these systems may become commercially viable for electrifying rural areas.

2.2 Expanders

Expander can be called as heart of any ORC system as it is an important component which decides the efficiency of the cycle. In order to have improved cycle efficiency, selection of proper expander plays an important role in ORC. Selection of ORC typically depend on desired power output and operating conditions of the cycle [10].

Quoilin et al. [6] reviewed different applications of ORC. In the study, the conclusion was that ORC cycles are appropriate for sensible power ranges and better for low-temperature application when compared with the steam Rankine Cycle. Two main aspects in ORC were found to be working fluids and the expanders. For small scale applications, positive displacement machines are found to be the best choice whereas turbomachines are mainly designed for high power ranges. A further study from the authors showed that scroll and screw type expanders are widely used for small scale applications. Song et al. [11] also reviewed various scroll expanders for ORC systems. The work carried by authors throws light on technical features, technical limitations, and performances in the application. It is found that generally the modified scroll expanders will have relatively low efficiency due to some of the factors like losses in suction or discharge, mechanical losses, and leakages. For overcoming these losses and leakages various features were incorporated to improve the efficiency of the expander.

Even after conducting many experimental and theoretical studies in order to address the selection of expander for ORC, based on the magnitude of power generation it is seen from the literature that the volumetric type expanders are gaining importance as they are best suited for small scale power applications and are available at low costs in the market. Even if the expanders are not commercially available in the market of some countries, with some modifications scroll compressors can be the best choice to work as an expander for power requirements of less than 5 kW. Gao et al. [12] tested a modified scroll expander from an automotive air condition compressor. The experiment was conducted using compressed air as a working fluid. The isentropic efficiency varied from 0.6 to 0.7 for the expander. ORC system showed an energy efficiency of 3.2% and maximum efficiency obtained was 16.9% at an inlet pressure of 0.61 MPa and expander efficiency was 0.553.

Mendoza et al. [13] experimentally characterized and modeled a scroll expander which was modified from a scroll compressor. Authors used air and ammonia as working fluids for testing. The study undertaken confirmed that the scroll expanders can be successfully used in absorption power cycles. Morini et al. [14] analyzed the adaption of scroll compressor as scroll expander by using reverse engineering and CFD methodologies. Initially, a commercial scroll compressor was reverse engineered for getting the scroll geometry in digital data and that model was imported in CFD. The scroll was initially studied as compressor and then as an expander. The scroll was analyzed for performance characters, pressure, mass flow rate, volumetric efficiency. In continuation, Clemente et al. [15] analyzed cogeneration ORC system with scroll expanders. From the work undertaken, it was concluded by the authors that the scroll expanders converted from scroll compressors are the best choice for small scale ORC applications like waste heat recovery and solar system. The maximum conversion efficiency of the system was found to be 5% to 6% which is in line with solar panels, but it has to be noted that from ORC not only electricity is extracted but also it produces hot

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

water for further applications. Wherein it is estimated that with 20 m^2 solar collector area ORC can develop 1kW electricity and 10kW of heat. The working fluid considered in this study was R245fa but compared with isopentane. Also, Twomey et al. [16] tried to harness solar energy using cogeneration ORC a scroll expander model and analyzed for application in solar cogeneration with ORC. When the expander was simulated with the area of 50 m2, it showed maximum isentropic efficiency of 59%, 1st law efficiency 3.47% and 2nd law efficiency of 15.7% to 23.2%. The total energy produced was 1710 kWh and total hot water available was 2540 L/day. Maximum power developed was 676 W. from the data obtained from the study it is clear that the scroll expander efficiency and power generation capacity is low, but when proper mechanical modifications are made expander efficiency can be improved. Another experimental work presented by Lu et al. [17], the relationship between the inlet pressure and discharge has been experimentally calculated for a scroll expander and 2.80 of a volume ratio was achieved under the tested conditions. Minimum start state to generate power from scroll was found to be 145kPa whereas isentropic efficiency was found to be 0.6 for the expander. The electrical efficiency of the system was achieved at 0.35 to 0.40 under the pressure of 238 kPa and 333.5 kPa respectively.

Lemort et al. [18] investigated expander performance expressed in terms of overall isentropic efficiency and filling factor. The prototype showed maximum isentropic efficiency of 68%.

Wu et al. [19] presented the performance of a scroll expander with numerous loads and flow rates and also the process was simulated using the geometry and thermodynamic equations. In the work, authors used a modified scroll expander from a scroll compressor which was operated stably on ORC test facility. Maximum isentropic efficiency, power and, speed observed were 0.86, 1540 W and 2165 r/min respectively. Chang et al. [20] focused their work on the experimental studies on ORC with scroll type expander. The expander used in this work was modified from a scroll type air compressor. The experiment was conducted by fixing superheating at the inlet of the expander and by fixed pressure difference while rotational speeds were varying with superheating. The conclusion was that the superheating and pressure at the inlet of expander have a positive effect on ORC.

2.3 Working fluids

Working fluids play an important role in ORC as it acts as the thermal carrier in the cycle. Working fluid selection is a crucial part while designing any ORC, the reason being that conventional Rankine cycle works only with water as working fluid, whereas for ORC there is a numerous number of working fluids available for selection and to match dynamically varying operating conditions of ORC lot of efforts are required while selecting a working fluid for ORC. This warrants developing advanced methodologies and investigations both numerically and experimentally to facilitate the data for choosing appropriate working fluid which can give better heat carrying capacity and improved thermal efficiency in the cycle. Furthermore, there has been no literature which can give adequate data for working fluid selection criteria, but some of the common properties that a working fluid has to satisfy are, global warming potential and ozone depletion potential.

Tchanche et al. [21] studied 20 working fluids with cycle operating with low-temperature solar heat source. In the study, pressure, mass and volume flow rates, efficiencies, cycle heat input, safety and environmental data (ODP, GWP) were considered and concluded that R134a, R152a, R600, R600a and R290 are most suitable fluids for low temperature applications having 90^{o} C as heat source temperature, in continuation Brown et

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

al. [22] investigated five ORC applications corresponding to five renewable heat source temperatures namely, Geothermal application, Low-temperature solar application, Low-temperature WHR application, High-temperature WHR application, High-temperature solar/biomass application. Authors varied thermodynamic critical temperature and critical ideal gas heat capacity parametrically and observed that simple hydrocarbons like propane, butane, pentane, and cyclopropane provide good thermodynamic performance for low-temperature ORC and complex hydrocarbons like cyclohexane, toluene is appropriate for high-temperature ORC applications. As it was difficult to select working fluids Saloux et al. [23] suggested a methodology for selecting more suitable working fluid in ORC application. A reconstruction procedure is adopted for a thermodynamic cycle, which is necessary to calculate the primary variables like pressure, temperature and mass flow rate of working fluid. Soon after calculating these data, choice of most suitable working fluid will be done based on environmental, safety and practical engineering restrictions. Then the methodology will be applied for any situations of low-temperature ORC. Another work conducted on domestic scale CHP system coupled with solar energy comprising ORC for electricity generation in UK [24] presented that, among 11 working fluids considered in the study R245fa can give highest electrical output for single stage Solar – Combined Heat and Power application. Similarly, Mavrou et al. [25] addressed the selection of working fluid mixtures considering operating variability in solar ORC. Sensitivity analysis was adopted in order to select the working fluids and it helped in identification of the mixtures with minimum sensitivity on Organic Rankine Cycle efficiency.

Furthermore, it was necessary to understand the thermal efficiency of ORC for selecting better working fluid, so Quoilin et al. [26] developed thermo economic model having a thermodynamic model of WHR-ORC and evaluated typical working fluids n-butane, n-pentane, R245fa, R123, R1234yf, and Solkatherm. The study revealed the existence optimum evaporation temperature which increases power and proposed that the thermo-economic evaluation and optimization leads to higher evaporating temperatures as it increases the pressure and vapor density which cuts the cost of expander and evaporator.

Mavrou et al. [27] investigated the performance of working fluid mixtures for ORC with flat plate collectors. The working fluid mixtures considered include both novel mixtures designed by CAMD method and conventional fluids often chosen in ORC's. Another analysis was conducted to identify the operating conditions at which solar ORC generates more power. Considering these conditions 91 combinations of working fluids were reduced to 15 and out of these 15, neopentane-2-fluoromethoxy-2-methylpropane mixture at 70% neopentane qualifies as most efficient maximum power generating fluid, which also improved thermal efficiency but

Most of the previous literature available, deal with binary or single working fluids and it was observed to have higher values of irreversibilities in the ORC components as there was a huge difference between the source and cycle temperatures. As it was observed that the working fluid having lower critical temperature can lead to higher exergy efficiency, the problem can be overcome by the use of Zeotropic working fluids because of their temperature gliding characteristics which made the pinch point temperature to reach heat source and sink temperature. Many investigations and experimentations were conducted to improve the cycle efficiency and to reduce irreversibility in ORC.

Liu et al. [28] parametrically optimized and analyzed the performance of geothermal Rankine

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

cycle working with R600a/R601a mixtures and Lu et al. [29] analyzed ORC using R601a/R600 and R245fa/R600a Zeotropic Fluids as working fluids in various restrictive conditions and found increment in power with pure fluids while condenser bubble temperature is kept constant due to increase in temperature glide but when cooling water temperature or cooling water flow rate is fixed the Zeotropic mixtures will lead to higher power output compared to pure working fluid. To understand the dynamic behavior of ORC Collings et al. [30] used Zeotropic Mixture of R245fa and R134a. The reason for using Zeotropic Mixture was being that these mixtures can improve cycle efficiency and power production of ORC systems. In the case study they revealed that the annual thermal efficiency can be improved by 23% when compared with the conventional ORC of heat source 100^{o} C. Composition shift affects were addressed by Zhou et al. [31] using Zeotropic mixtures of working fluids. The binary mixture of working fluid considered for the study was R227ea/R245fa as R245fa is extensively used in the ORC system. All the property values of the pure substances were obtained from REFPROP 9.0 for the analysis. In the analysis, it is found that the mass fraction of the low boiling point component, the magnitudes of temperature glide and shift in composition show decent undeviating relation. Similarly, Satanphol et al. [32] investigated the potential of Zeotropic working fluids in ORC. The composition of the working fluids was optimized by Aspen Plus v.8.4 simulation software and the type of fluids, composition and the operating conditions were decided by flow sheet modeling. The working fluids considered here are 400 series refrigerants from REFPROP database. Zhao et al. [33] investigated the influence of composition shift on ORC with Zeotropic working fluids. It is concluded that the composition change has a notable effect on the performance of ORC with Zeotropic fluids as they account lower work output of expander and higher power consumption at pump resulting to lower work output and thermal efficiency. Another analysis conducted by Yue et al. [34] showed the thermal matching performance of an ORC system having Zeotropic working fluids operating with the geothermal heat source. Zeotropic mixtures of isobutene and isopentane were used as the working fluids in order to improve the thermal matching between evaporator and condenser. Zeotropic working fluids improved the thermodynamic first law and second law efficiencies and optimal overall thermal performance is achieved at some certain Zeotropic mixtures compositions.

Dong et al. [35] examined the performance of low-temperature ORC with pure and Zeotropic working fluids. In the study R245fa, R123, R365mfc, R113 were used as pure working fluids and their mixtures were used as Zeotropic fluids and first law efficiency, cost-effective performances were taken as the criteria for the comparison to analyze the potential of Zeotropic fluids for ORC. With the use of mixtures, 17.96% of efficiency was increased when compared with the pure fluids and the use of Zeotropic mixtures can lead to next-generation ORC. When compared with the performance of pure working fluids, Zeotropic blends shown the best results due to better thermodynamic efficiency in the condenser. When the potential of Zeotropic mixtures as working fluids in ORC with heat source temperatures of 150^{o} C and 250^{o} C was studied, it presented that the use of suitable Zeotropic mixtures as working fluids has a cooperative effect on ORC and 16% of improvement in ORC performance was observed and 20% of electricity production improved for low temperature heat source [36]. Zhou et al. [37] analyzed the performance of the partial evaporating ORC (PEORC) using R245fa/R227ea mixtures as Zeotropic fluids. 1st and 2nd law efficiencies were considered and observed reduction in exergy at condenser because of temperature glide and primarily PEORC reduces exergy loss in the

TEST Engineering & Management

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

evaporator by improving temperature match between the heat source and the working fluid.

Abadi et al. [38] discussed the usefulness and issues of using Zeotropic mixtures as working fluids in ORC. Use of the Zeotropic fluids increase the 1st and 2nd law efficiency as the temperature of working fluid can be made nearly equal to that of heat source and sink but four issues of using Zeotropic fluids were found to be unidentified thermodynamic properties, heat transfer coefficient values, cost-effectiveness and composition shift and fractionating but in spite of these issues these fluids can be used in the ORC as they show increased exergy efficiency and reduced irreversibilities in the evaporator. Lecompte et al. [39] investigated 8 Zeotropic working fluids namely R245fa-pentane, R245fa-R365mfc, isopentane-isohexane, isopentane-cyclohexane, isopentane-isohexane, isobutene-isopentane and pentane-hexane for second law efficiency and Exergy. The results obtained show that there is the highest exergy loss in the evaporator but still the best performance is observed when the condenser heat profiles are matched. The second law efficiency has improved for about 7.1% and 14.2% when compared with pure working fluids. Dong et al. [40] investigated the thermodynamic and economic performance of the low-grade Zeotropic ORC with pinch analysis method. In the investigation, the authors chose R245fa, R245ca, R123, R365mfc, R113 and their mixtures. When compared with the pure fluids Zeotropic ORC has produced more power and the net power increment is larger when the heat source outlet temperature was lower. It is also observed that for the higher temperatures of the heat exchanger Zeotropic fluids will have higher net power output than pure fluids but the only drawback is for Zeotropic fluids heat exchanger area has to be more. Heberle et al. [41] studied the ORC with Zeotropic working fluids coupled with low enthalpy geothermal resources. The working fluids considered were mixtures of isobutene/isopentane and R227ea/R245fa. It is found from the study that efficiency of the cycle improved as a result of glide match of temperature profiles in the condenser and the evaporator. 15% of increase in efficiency was also observed for Zeotropic working fluids and as a result irreversibilities of the system reduced, especially in the condenser. Deethayat et al. [42] analyzed the performance of 50kW ORC having an internal heat exchanger with Zeotropic working fluid. In this work, various compositions of R245fa/R152a were considered as the working fluids and were investigated for the cycle efficiency and irreversibilities. The results obtained, showed reduced irreversibilities in the cycle because of temperature gliding during the phase change of mixture and higher temperature, higher internal heat exchanger effectiveness also improve the cycle efficiency. The suitable composition was found to be 80% mass fraction of R245fa with 20% R152a.

Zeotropic mixture active design method for ORC was proposed by Zhai et al. [43]. The work mainly focusses on providing preliminary design guidelines for mixture selection without massive calculation or blind trial instead of recommending mixtures or compositions for a specified heat source. The Zeotropic mixtures designed from this method have better performance when compared with the pure working fluids and it is observed that they have better temperature glide matching with the cooling source.

The literature review conducted, showed that the research on ORC is mainly based on the aspects like selection of expander, types of working fluids, thermodynamic and economic performances or equipment and hardware. Further, the literature presented that the performance of an ORC can be affected by several factors like heat source temperature, type of working fluids, ambient conditions, expanders but, it was noted that the choice of working fluid is one of the key factors among others.

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

Numerous works on working fluid selection for an ORC have been studied to choose the right working fluid in various aspects. Several screening criteria for choosing a suitable working fluid such as cost, cycle performance, environmental impact, thermal stability, flammability or toxicity were applied. Basically, the cycle performance is the main objective used to identify an appropriate working fluid. Some literature revealed that the temperature glide of working fluids in condenser and evaporators improve the efficiency of the cycle. This temperature gliding characteristic is observed for mixtures of pure working fluids, specially the Zeotropic working fluids.

It was also found from the literature that, very few Zeotropic working fluids are tested in ORC for fixed evaporator and condenser temperatures i.e., at steady state conditions and the dynamic behavior of ORC at varying heat source and sink temperatures is not properly known.

3. Motivation

With reference to the literature review made on several research areas of ORC in section 2, it is clearly understood that the efficiency of the cycle depends on various parameters but, mainly on working fluids. Recent researches have exposed that the Zeotropic working fluids can be good choice for ORC over pure working fluid in order to improve the cycle efficiency but, there are only limited number of Zeotropic working fluids tested in ORC so far as the,

1. Performance of Zeotropic working fluids are not properly known when used in solar energy as heat source.

2. Behavior of Zeotropic working fluids are not known for varying condenser and evaporator temperatures.

3. Unknown thermophysical properties of various blends of Zeotropic fluids leads to the limitation of their usage in ORC.

4. Optimized blends of Zeotropic working fluids are not proposed to have higher ORC efficiency.

In order to address the above identified gaps and problems, it is proposed to develop a systematic ORC test setup to test the behavior of Zeotropic fluids for various operating parameters and to optimize the blend of the Zeotropic fluids for enhanced ORC efficiency.

4. Experimental setup

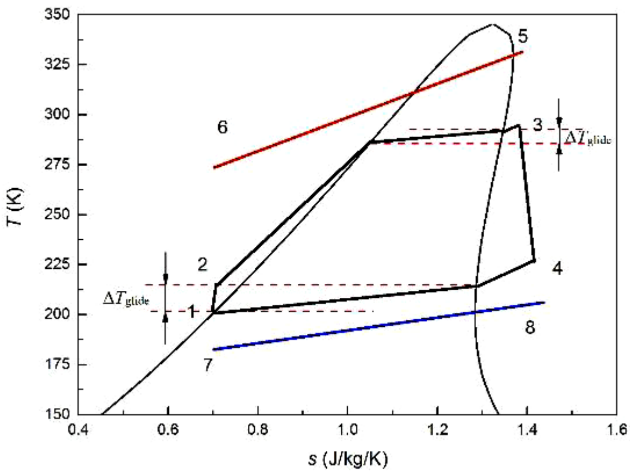

Figure 1: T-s diagram of general ORC

Figure 1 represents the T-s diagram of the proposed Organic Rankine Cycle 1-2-3-4-1. 1-2 represents pump work, 2-3 is heating of working fluid, 3-4 is expansion of working fluid in the expander and 4-1 represent heat rejection in condenser. 5-6 is heat transfer through thermal oil and 7-8 is heat rejection to heat sink.

4.1 Design and Overview of experimental setup

The design process for ORC starts with considerations of heat source and the sink temperatures. The thermodynamic parameters like pressure, temperature at heat sources and sinks affect the efficiency of the ORC. Figure 2

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

represent the planned test setup.

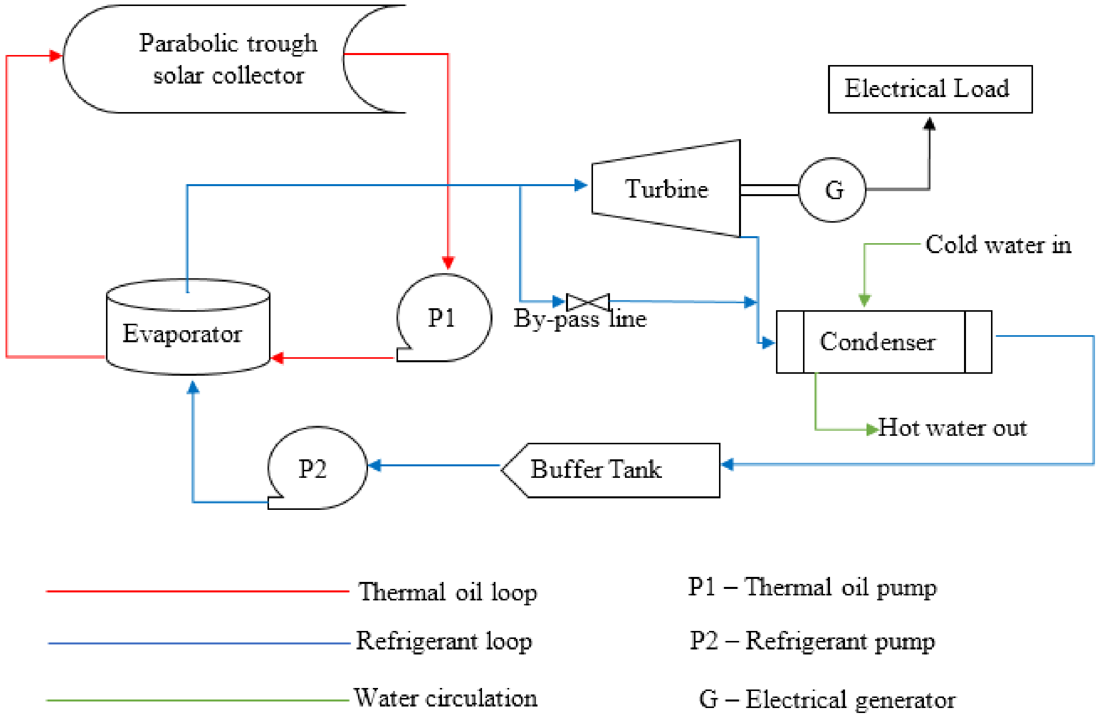

Figure 2: Outline of the ORC test setup

Economical point of view it was not preferable to manufacture an expander for using it in the test setup, so a suitable scroll compressor was selected from the available market and the non-return valve was removed from it, to operate it reverse as expander. The expansion ratio was calculated for the converted scroll expander and according to that, the heat exchangers were designed.

The following thermodynamic equations can be used for the analysis of the test setup,

Carnot efficiency:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} \quad \text{(i)}$$

First law efficiency:

$$\eta_I = \frac{W_{exp} - W_p}{Q_{in}} \quad \text{(ii)}$$

Expander work:

$$W_{exp} = m_R(h_{exp,i} - h_{exp,o}) \quad \text{(iii)}$$

Pump work:

$$W_p = m_R(h_{p,o} - h_{p,i}) \quad \text{(iv)}$$

Heat input at evaporator:

$$Q_{in} = m_R(h_{evp,o} - h_{evp,i}) \quad \text{(v)}$$

Heat lost in condenser:

$$Q_{out} = m_R(h_{con,i} - h_{con,o}) \quad \text{(vi)}$$

Heat carried away by cooling water:

$$Q_{cw} = m_{cw} * c_{p,cw}(T_{cw,out} - T_{cw,in}) \quad \text{(vii)}$$

Second law efficiency:

$$\eta_{II} = \frac{\eta_I}{\eta_{Carnot}} \quad \text{(viii)}$$

Isentropic efficiency of expander:

$$\eta_{expander} = \frac{h_3 - h_4}{h_3 - h_{4s}} \quad \text{(ix)}$$

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

Isentropic efficiency of pump:

$$\eta_{pump} = \frac{h_{2s} - h_1}{h_2 - h_1} \quad \text{(x)}$$

Exergy loss during evaporation:

$$I_{eva} = T_0[m_{wf}(s_3 - s_2) + m_{hf}(s_5 - s_6) \quad \text{(xi)}$$

Exergy loss during expansion:

$$I_{exp} = T_0 m_{wf}(s_4 - s_3) \quad \text{(xii)}$$

Exergy loss during condensation:

$$I_{cd} = m_{wf}[(h_4 - h_1) - T_0(s_4 - s_1)] \quad \text{(xiii)}$$

Exergy loss in pump:

$$I_{pp} = T_0 m_{wf}(s_2 - s_1) \quad \text{(xiv)}$$

Exergy balance:

$$E_{hs\_tra} = \sum I + W_{net} \quad \text{(xv)}$$

Exergy of heat source:

$$E_{hs} = m_{hs}[(h_5 - h_0) - T_0(s_5 - s_0)] \quad \text{(xvi)}$$

Exergy transfer to heating fluid:

$$E_{hs\_tra} = m_{hs}[(h_5 - h_6) - T_0(s_5 - s_6)] \quad \text{(xvii)}$$

Exergy supplied to working fluid:

$$E_{wf\_eva} = m_{wf}[(h_3 - h_2) - T_0(s_3 - s_2)] \quad \text{(xviii)}$$

Note: Subscripts mentioned in equations are the states of working fluids as mentioned in figure 1.

4.2 Details of the experimental setup

The expander selected here is modified from scroll compressor. The scroll machine is initially tested with compressed air to check power production capacity and found that it is capable of producing about 500 W at air pressures of 8 to 10 bar. The scroll machine used in building the test bed is coupled to AC generator of capacity 1 kW using a belt drive.

Helical coil heat exchangers were manufactured by G4 Tech Lab. As the test setup was to be used for varying conditions of heat source and sink, the heat exchangers were fabricated in accordance with worst case performance and also to meet pinch point temperatures for better performance. Evaporator shell is made of mild steel and painted with high temperature withstanding paint to prevent rust and corrosion at high temperature. Helical coil inside the evaporator is concentric type helical coil and is made of copper consisting of 10/10 turns with diameters of 0.1375 m/0.075m giving up total heat transfer area of 0.5 m^2. 620W/m^2 °C is the overall heat transfer coefficient of evaporator. Maximum pressure drop across evaporator was 20kPa on working fluid side. Condenser also is helical coil type heat exchanger using water as the cooling medium and having the heat transfer area of 0.38m^2. Pressure drop in condenser side was estimated to be 15kPa.

Organic working fluid pump is a critical component in ORC as it circulates the fluid throughout the cycle. For small scale systems, it is generally difficult to select a proper pump due to varying operating conditions. In the present scenario of building the test bed of ORC, use of centrifugal pump is not possible as it is not suitable for low mass flow rates and high differential pressures. Diaphragm pump is not suggested as the diaphragm may get corroded while working with organic fluid and also pulsation phenomenon of these pumps is unwanted in the operation. Vane type positive displacement pump was found to be a great choice, as it can handle low viscosity fluids easily for wide range of flow rates and pressures. The vane pump was supplied by a company named Malhar. Pump selected has a capacity of handling a flow of 0.1-0.5 kg/s and produce 13 bar pressure when operated at 3000 RPM. This pump was coupled with a AC motor of 3000 rpm with a help of a belt and the motor was connected with Variable Frequency Drive to control the mass flow rate through condenser. As the test setup is designed for low power output, 5 electric bulbs of total capacity of 700 W were used. These bulbs were connected to generator at expander side.

A solar parabolic trough collector (PTC) having 1.6 m^2 aperture area and 120 mm focal length is used to collect heat from sun and transfer it to thermal oil circulated through PTC. Thermal oil is circulated through PTC with the help of gear pump attached with VFD to control the flow rate of thermal oil. As solar energy is not available all the time, 12 halogen lamps each of 500 W capacity were used to simulate solar energy and heat the oil flowing though PTC.

Turbine type flow meters were used to measure the flow rates of water in condenser side and the organic working fluid in heat recovery loop. PT100 type thermocouples having range of 0^oC to 250^oC were used for temperature measurements. Pressure gauges used were diaphragm type having a range of 0 to 25 bar with ±0.5% tolerance. Watt meters were used to measure the generated power and pump power. All the measuring instruments were provided by Microsense instrumentation systems. RS485 input output module was used to measure Thermocouples, watt meters and pressure transducers. Labview software was used to implement the control logic and data acquisition for the test bed.

4.3 Fabrication

The system has a footprint of 0.6 m x 2m x 1.5m (Width x Length x Height). Figure 3 present the ORC test rig after its fabrication in accordance with piping diagram mentioned in figure 2 and they present the major components of the test rig. During the fabrication of system, it was ensured that no other material apart from Copper, Brass and Stainless steel were used for piping and thin layers of Teflon was used as gaskets for sealing purpose. Parabolic solar collector was fabricated using mild steel and glass mirrors were used as reflecting surfaces.

The fabricated test setup consists of two loops namely, closed thermal oil loop and closed refrigerant loop. In the thermal oil loop, thermic fluid is heated by solar parabolic trough collector provided at the top of test setup and is received in the evaporator chamber. In the evaporator chamber the helical coil heat exchanger is provided in which the refrigerant absorbs the heat and gets evaporated by increasing its temperature and pressure. The pressurized refrigerant flows into expander and expands itself by giving out heat to expander and it produces electricity as it is coupled with a generator. A suitable electrical loading is provided to measure the power developed by the expander and the hot refrigerant after expansion flows into the water cooled condenser. The liquid refrigerant after condensation is received by the positive displacement pump and the refrigerant pumped reaches evaporator again and the cycle continues. Here sufficient care is taken for the pump that it only receives liquid refrigerant as a buffer tank is provided before the pump. To measure the temperature, pressure and temperature of the working fluid at various critical points sensors are used which can withstand the high temperatures up to 200^oC. The fabricated test setup is equipped with data acquisition system and is integrated with REFPROP10a software to analyse the state of the working fluids in ORC.

After the fabrication of the test rig, system was pressurized with nitrogen gas to check for the leakages. It was observed that most of the minor leakages occurred at instrumentation joints with the pipes and were sealed by torque adjustment in threads and using thread lock sealants. Epoxy resin was also used over the joints to prevent leakage at high pressures of 20 Bar and above.

TEST Engineering & Management

March - April 2020
ISSN: 0193-4120 Page No. 2379 - 2393

Figure 3: Fabricated Test bed

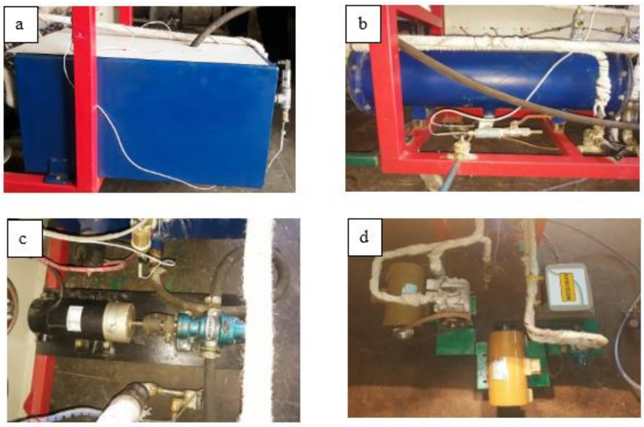

Figure 4: (a) Evaporator, (b) Condenser, (c) Thermic oil pump, (d) Expander with generator

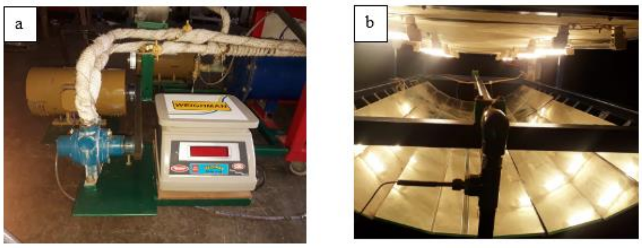

Figure 5: (a) Pump and weighing scale, (b) Parabolic trough collector

5. Working fluids selection strategy

The detailed literature in section 2, showed that the selection of the working fluids for mainly depends on the working parameters of the cycle and the environmental concerns. Further it was also found that, the use of Zeotropic working fluids have an added advantage when used in ORC because of their temperature glide characteristic.

The Zeotropic working fluids selection strategy based on the literature can be summarized as follows,

Step 1: Define the cycle temperature and heat source
Step 2: Select a working fluid group on a common criterion (Example: Critical pressure and Critical temperature etc.,)
Step 3: Prepare the combination of the working fluids
Step 4: Calculate the physical properties
Step 5: Categorize the types of fluids based on saturation vapor curve
Step 6: Screen the fluids based on

- High vapor density
- Low viscosity
- High thermal conductivity
- Acceptable evaporating temperature
- Positive condensing gauge pressure
- Flammability
- Toxicity

Step 7: Screen the fluids based on environmental concerns

- Low global warming potential
- Low ozone depletion potential

Step 8: Evaluate thermodynamic performance

6. Summary

In the present work, a systematic ORC test setup was designed and fabricated by selecting and fabricating the required components and is ready for charging and testing. Also in this paper, working fluid selection strategies for solar ORC were discussed.

7. Future work

The instant future work is charging the developed system with R134a refrigerant. The system will be thoroughly tested for varying operating conditions and the performance of ORC will be analysed and any necessary changes will be implemented. Once all the system controls are optimized, the performance and behaviour of various Zeotropic working fluids will be tested in the developed setup in small and manageable level.

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Nomenclature

T_L	– Heat sink temperature
T_H	– Heat source temperature
W_{exp}	– Expander work
W_p	– Pump work
Q_{in}	– Heat input
m_R	– Mass flow rate of working fluid
$h_{exp,i}$	– Enthalpy of working fluid at inlet of expander
$h_{exp,o}$	– Enthalpy of working fluid at outlet of expander
$h_{p,o}$	– Enthalpy of working fluid at the outlet of the pump
$h_{p,i}$	– Enthalpy of working fluid at the inlet of the pump
$h_{evp,o}$	– Enthalpy of working fluid at outlet of the evaporator
$h_{evp,i}$	– Enthalpy of working fluid at inlet of the evaporator
$h_{con,o}$	– Enthalpy of working fluid at outlet of the condenser
$h_{con,i}$	– Enthalpy of working fluid at inlet of the condenser
m_{cw}	– Mass flow rate of cooling water
$C_{p,cw}$	– Specific heat of cooling water
$T_{cw,out}$	– Temperature of cooling water at outlet of condenser
$T_{cw,in}$	– Temperature of cooling water at inlet of condenser
h	– Enthalpy
I	– Irreversibility
S	– Entropy of the working fluid
T_0	– Ambient temperature

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March - April 2020
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