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FEASIBILITY STUDY OF ORC IMPLEMANTATION IN INDIAN POWER PLANTS

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ABSTRACT:

The aim of this work is to model the ORC using data obtained from Indian sources and to compare these two systems in terms of efficiency, power output, usability in Indian conditions and financial feasibility.

To determine what is the optimal working fluid for Organic Rankine Cycle is not easy process; there are many different criteria to deal with. These criteria mainly have to do with working fluids' thermodynamic and heat transfer properties from a side and safety and environmental aspects from other side. Today, when demand for energy is increasing with more developed technologies it is important to think about energy sources by themselves. Energy is considered a prime agent in the generation of wealth and a significant factor in economic development. Limited fossil resources and environmental problems associated with them have emphasized the need for new sustainable energy supply options that use renewable energies. Solar thermal power generation systems also known as Solar Thermal Electricity (STE) generating systems are emerging renewable energy technologies and can be developed as viable option for electricity generation in future. This paper discusses the technology options, their current status and opportunities and challenges in developing solar thermal power plants in the context of India.

INTRODUCTION

A solar thermal organic Rankine cycle (ORC) can provide affordable energy supplies in remote regions. The advent of low-cost medium temperature parabolic trough collectors and ORC technology taking advantage of mass produced fluid machinery from HVAC industries are enabling developments for the production of small scale autonomous power generation units. Construction and testing of this type of system is discussed, including benchmarking of scrolls expanders (up to 75% isentropic efficiency) and the field testing of solar collectors (50% thermal efficiency at 150°C operating temperatures) with a nominal cost.

Recent analysis suggests that small (i.e. kilowatt) scale Concentrating Solar Power (CSP) systems with organic Rankine cycle (ORC) power blocks may compete with photovoltaic's (PV) and diesel generators on a levelized cost of electricity (LCOE) basis for off-grid duty. Keys to successful and economically viable deployment of this technology lie in i) optimizing the parabolic trough solar collectors for medium temperature thermal output (<200°C), ii) use of an ORC embodying cost-effective expander-generator components (i.e. modifications of off-the-shelf equipment) and iii) use of autonomous to match system operation to fluctuating thermal input from the collector array. This paper discusses the design and testing of components for a 3kW Solar ORC both on test benches (MIT, U. Liege) and in the field (Lesotho, Africa).

Objectives

This study aims to determine the optimal working fluids for Organic Rankine Cycles. The focus of this study is on the thermodynamic, environmental and safety aspects, rather than the economics of the system.

In this study several simulation scenarios are created with different boundary conditions covering as much working fluids as possible. Organic Rankine Cycle converts thermal energy from low grade heat source to electricity. Heat source temperature and heat sink temperature are two important parameters needed to determine the optimal working fluids.

POSSIBLE APPLICATIONS OF ORC CYCLE

There are three types of Organic cycles depending on where the four thermodynamic processes (compression, heat addition, expansion and heat rejection) occur.

Subcritical Organic Rankine Cycle

In this cycle the four processes occur at pressures lower than the critical pressures for the working fluid.

Trans-critical Organic Rankine Cycle

In this cycle the process of heat addition occurs at a pressure higher than the critical pressure for the working fluid. The heat rejection process occurs at a pressure lower than the critical pressure for the working fluid. The compression and expansion processes occur between the two pressure levels.

Supercritical Organic Rankine Cycle

In this cycle the four processes occur at pressures higher than the critical pressures for the working fluid.

2. Small Solar ORC Concept

For decades solar ORC concepts for community power supplies have been extensively discussed but rarely implemented. Often the availability of lower-cost electricity from a power grid is cited as an impediment to adoption of solar ORC or other renewable sources of electric power. Rural regions of many countries lack centralized grid infrastructure, however, and in these circumstances distributed small scale CSP achieving economies of scope (many modular units with mass produced components) may be economically competitive with alternative off-grid power technologies, i.e. photovoltaic (PV) panels and diesel generators, which have a levelized cost of electricity (LCOE) in the $0.30-$0.50 kWh-1 range .Modern CSP technology that achieves 15-20 kWh-1 electricity exists in large-scale installations , suggesting that if it could be successfully scaled down, is could be cost effective for use in applications typically served by PV or diesel generators (e.g. clinics, schools, small enterprises). Several practical challenges must be addressed to meet this objective, including (1) the high initial and maintenance costs of solar collector receiver elements and mirror facets, (2) the unavailability of small thermal power blocks, and (3) the need for unattended operation. We propose a small-scale solar thermal ORC design that addresses these challenges by making use of simple, proven parabolic trough technology and a novel power block comprised of off-the shelf components and materials. These components include scroll compressors, heat exchangers, pumps and working fluids sourced from the HVAC and automotive industries; industrial motors and reflective aluminium sheeting; standard steel structural and pipe sections; and standard microcontroller and power electronics.

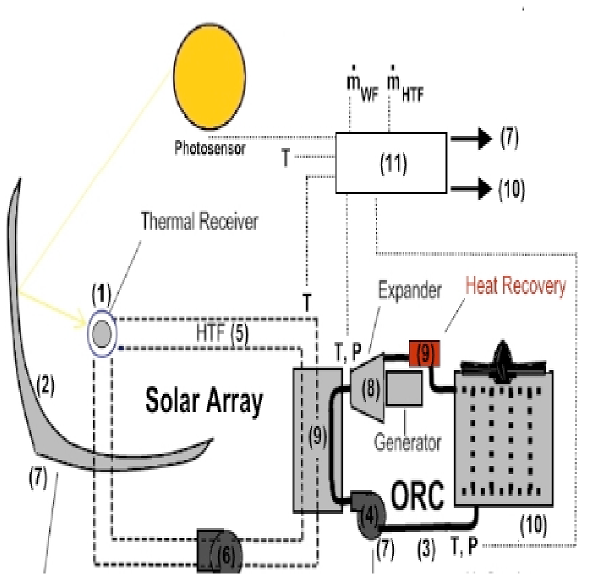


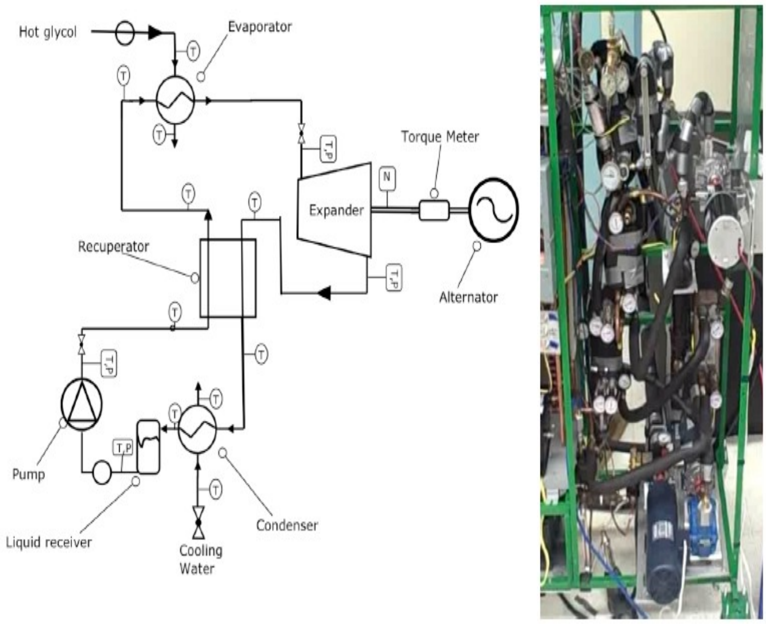
Figure 1: Schematic overview of the Solar ORC (numbers refer to Table 1).

Medium Temperature Low Cost Parabolic Troughs

Solar thermal power plants face tradeoffs between cost and thermal efficiency, particularly in light of countervailing trends in thermal efficiency between collector elements and heat engines. While the thermodynamic efficiency of heat engines increases with operating temperature, solar absorbers will have greater thermal losses due to convection and radiation Mitigating these losses under high temperature operation, e.g. by means of selective high absorbtivity and low emissivity coatings and evacuated glass glazing, entails higher costs in materials and manufacturing. These features may be economically justified in megawatt-scale installations, where large collector production volumes lead to lower specific costs and where the cost of land lease is an important consideration. Where the cost of space is not a constraint, however, and where small capacity units of deployment are preferred, optimization for the lowest LCOE may lead to medium temperature designs involving lower thermal efficiencies and increased footprint, e.g. from ~ 20 m2/k. We in a typical large scale CSP plant.

Low Cost, Robust ORC

Currently, ORC units suitable for solar power generation are commercially available only in capacities above a few hundred kilowatts (e.g. Ormat, UTC etc). For the application considered here, an easily manufactured, cost-effective ORC unit is required in the range of one to tens of kilowatts. We have proposed to adapt commercially available compressor machinery to this purposes. Given the many interlocking parameters to be optimized in ORC design, including but not limited to choice of working fluid, lubricant, pressure ratio etc.,



Schematic (above) and photo (right) of the MIT ORC test rig. The rig utilizes Type T thermocouples, pressure transducers, and 0.1% accurate turbine flow meters to establish the inter component thermodynamic states. Output is measured via a torque/RPM meter (open drive) or a power analyzing load bank (hermetic).

Control

Optimized control of the ORC involves a balance between fixed characteristics of the expander (i.e. optimal pressure ratio, torque vs. RPM characteristics) and the variable heat input delivered from the solar field. This is achieved through a combined analog/digital control architecture that maintains operating parameters within optimal zones via feedback based on input sensor levels.

The expander is an important component to optimize for effective small-scale solar ORC deployment. No purpose-built commercial expander exists for this application, however, one can be adapted from HVAC compressors. Automotive scrolls, though relatively inexpensive and widely available, generally use driveshaft and tip seals (excepting the Denso ES18) that are vulnerable to wear. They are also only available in limited displacements (typically <200cc rev-1) and output less than 1 kilowatt. Hermetic HVAC scrolls have the drawback that internal access entails opening the steel shell and welding flanges to the body and top cap, as well as the need for mechanical reinforcement (e.g. with springs) of the OEM floating seal mechanism for expander operation. In our experience however, the latter type of mass-produced scroll is ideal for small scale solar ORC duty due to (1) inherent axial and radial compliance, (2) a wide assortment of available displacements from a variety of manufacturers (Copeland, Danfoss, etc.), and (3) the built-in single or three phase induction motor which can be operated as a an efficient (>70% mechanical to electrical) generator when synchronized with an AC source or in standalone mode with appropriately sized run capacitors for maintaining field inductance.

Worldwide Organic Rankine Cycle Installation

Organic Rankine Systems have been successfully installed in many countries in the world. Figure (3) shows some countries which are already using ORC system for waste heat recovery. It is obvious that most of the units exist in USA, Canada, Italy and Germany while there is a single unit in each of Finland, Belgium, Swaziland, Austria, Russia, Romania, India and Morocco. Some of ORC equipment suppliers are Ormat, Turboden, ABB and Tas Energy. The units are used to recover wasted heat for some typical industries like oil and gas, biomass, energy, packaging, cement and glass industry. Opcon AB and Entrans are two active Swedish companies. Several Organic Rankine Cycles have been installed by Opcon AB in Sweden in recent years. The company Opcon AB has developed a technology called Opcon Power Box, this technology extract electrical power from waste heat.

Worldwide Organic Rankine Cycle Installation

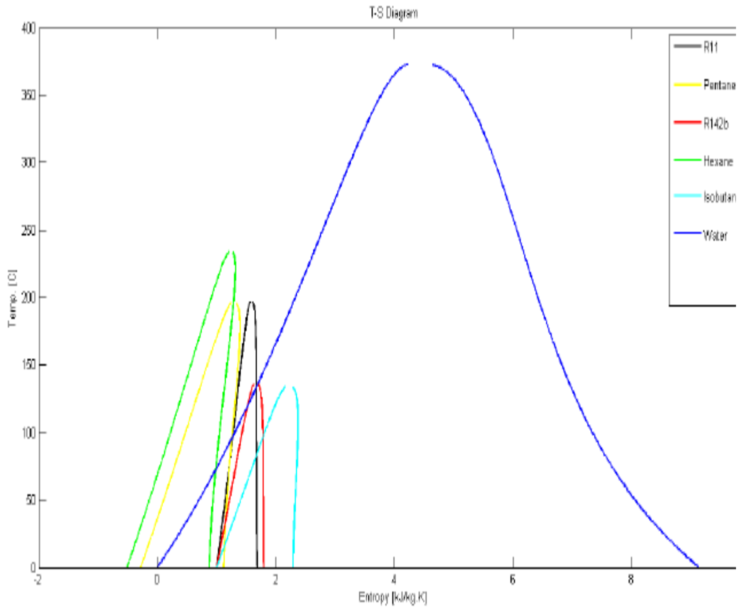
Working fluids

The main difference between the two cycles is the working fluid used in each cycle. Water is the only used working fluid in Steam Rankine Cycle while there are hundreds of different working fluids which can be used in Organic Rankine Cycles. The designing and discovering of new working fluids is a continuous process. The cycle architecture, components size and shape, and economics are highly dependent on the chosen working fluid´s thermo-physical properties. The thermo-physical, safety and environmental properties vary from one working fluid to another. The environmental and safety data are not available for many working fluids. The choice of the right working fluid is of key importance for the cycle efficiency, Net Work Out and etc.

Water properties and behaviours are well known under different cycle conditions. For Organic Rankine Cycle, especially if we deal with working fluid mixtures there are uncertainties in data bases and subsequently this leads to uncertainty in calculations and results. Under help files in NIST REFPROP 9 we can read following; "The NIST REFPROP program is designed to provide the most accurate thermophysical properties currently available for pure fluids and their mixtures. The present version is limited to vapour-liquid equilibrium (VLE) only and does not address liquid-liquid equilibrium (LLE), vapour-liquid-liquid equilibrium (VLLE) or other complex forms of phase equilibrium. The program does not know the location of the freezing line for mixtures. Certain mixtures can potentially enter into these areas without giving warnings to the user."

Normal Boiling Point and T-S diagram

Most of organic fluids have a lower normal boiling point NBP than water. This property make organic fluids need a lower heat source temperature than water to evaporate and recover thermal energy from low grade heat sources. Figure shows the T-S diagram for water and some other working fluids which can be used in Organic Rankine Cycles. The slope of saturation vapour line for organic fluids can be negative, positive or infinite while water has a negative slope. The positive and infinite slopes have enormous advantages for turbo machinery expanders. These working fluids leave the expander as superheated vapour and eliminate the corrosion risk in case of using turbo machinery expanders. Furthermore, there is no need for overheating the vapour before entering the expander, and a smaller and cheaper heat exchanger (evaporator) can be used.



The T-S diagram for water and some organic working fluids

A remarkable difference in figure is the entropy difference between the saturation liquid line and the saturation vapour line. Organic working fluids have a very low entropy change compared with water. Water as working fluid needs more thermal energy to change phase from saturated liquid to saturated vapour and can carry out more thermal energy per kg of water. The advantage of this property is that water needs a much lower mass flow rate than organic fluids to absorb the same amount of thermal power from a certain heat source. A higher mass flow rate leads to higher power consumption by pump and a higher piping system diameter should be used to overcome pressure losses related to high Reynolds number.

Many ORC cycles use dry or isentropic fluids and there is no need for superheat. The expansion process can start directly from the saturation vapour line and working fluids leave the expander as superheated vapour. No attention needs to be paid to vapour quality at the end of the expansion process. Sometimes the recuperate or Internal Heat Exchanger IHE is not needed, especially when the working fluid leaves the expander at temperature much lower than the temperature at pump outlet.

Condenser pressure

The condenser pressure in many ORC is higher than the atmospheric pressure. This is a desirable property because a condensing pressure lowers than the atmospheric pressure involves air infiltration problems in the cycle and reduces the cycle efficiency [14]. The water condensing pressure at 298 K is 3.15 kPa, at the same time it is 105.49 kPa for R11, 349.14 kPa for Isobutane, 586.67 for DME and 271.04 for R236fa.

Environmental and safety aspects

Water as working fluid is environmentally friendly, non-flammable, non-toxic, has no ozone depletion potential ODP and no global warming potential GWP. Many of the organic fluids have a high negative impact on the greenhouse effect and ozone depletion problems. At the same time these organic fluids can be flammable and toxic. Unknown safety and environmental data is another problem connected to some organic fluids.

Applications in Indian conditions

Waste heat recovery

Waste heat recovery is a process in which the energy is extracted from waste heat which comes from many processes, especially in industrial applications. In some applications waste heat boilers, recuperates and regenerators are used in order to directly recover and redirect heat to the process itself. In steam cycles the economics of waste heat recovery don´t justify when the temperature of the wasted heat is low. The Organic Rankine Cycle can be used to produce electricity from low grade heat sources.

Solar thermal power

The solar thermal power is a well-proven technology. The parabolic dish, the solar tower and the parabolic though are three different technologies used to extract power from solar thermal. The parabolic tower can work at a temperature range of 300 °C – 400 °C. For a long time this technology was linked to the traditional Steam Rankine Cycle for power generation. The Organic Rankine Cycle seems to be a more promising technology. However, the Steam Rankine Cycle needs higher temperature and a higher installed power in order to be profitable. The Organic Rankine Cycle can work at lower temperatures, offers a smaller component size and needs much lower investment cost compared to steam cycles. The installed power can be reduced to kW scale.

Geothermal power plants

The geothermal power has the potential to supply renewable electricity to a large number of communities. In 2007 was 1% of world´s electricity supplied by geothermal sources. This source of energy is clean and renewable and the production can be highly efficient. Dry steam power plants, flash steam power plants and binary cycle power plants are three different technologies used to extract power in geothermal power plants.

Biomass power plants

The traditional fossil fuels are expensive and have a huge impact on climate change and the greenhouse effect. Biomass is a cheap and environmentally friendly energy source and is experiencing a strong market growth. It can be used efficiently to produce both heat and power by fuelling a combined heat and power CHP system. Biomass fuels exist in many forms:

• Wood and wood wastes and combustible agriculture wastes
• Biogas from organic materials such as farm waste or wastewater sludge
• Black liquor which is a by product of the pulping process.

Trees, energy crops, agriculture residues, food waste and industrial waste and their co-products are some of the typical sources of biomass. Utilizing biomass fuels has many valuable benefits in regard to mitigating global warming, climate changes and economics associated with fuel prices. Biomass displaces purchased fossil fuel, decreasing tipping fees associated with waste disposal and freeing up landfill space. The most important difference between biomass and fossil fuels is that biomass takes carbon out of atmosphere while it is growing and returns it as it burns.

Conclusions

Concerning the capital cost for the power plants, more expensive and specific materials must be taken into account, which increases the capital cost. Also, the cost of maintenance is part of the investment that must be considered in a feasibility study. The modelled power plants are able to produce sufficient amounts of electric power for smaller towns by using the geothermal water for heating and possibly for cooling purposes. It is just a question for investors as to which of the modelled binary plants is more cost effective.

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