Efficient Organic Rankine Cycle (ORC) Power Generation with low grade energy as heat source: preliminary design of Effi low res ORC unit

M.GR. VRACHOPOULOS, N.S. TACHOS, M.K. KOUKOU, G.K. KARANASIOU
Energy and Environmental Research Laboratory, Mechanical Engineering Department
Central Greece University of Applied Sciences (TEI STEREAS ELLADAS)
344 00 Psachna, Evia Greece
e-mail: mvrachop@gmail.com https://renewablelab.wordpress.com/english
and
C. KARYTSAS
Center for Renewable Energy Sources and Saving (CRES)
19o Km Marathonos Ave, 19009, Pikermi Attiki Greece
e-mail: kkari@cres.gr https://www.cres.gr

Abstract: - The Effi low res project intends to develop an ORC power generation unit working at low temperatures with improved overall efficiency and to improve cost-effectiveness, competitiveness and penetration of the ORC systems in the Greek market. The major goal is the performance optimization of an ORC unit by exploiting low temperature sources so as to make it cost effective. For that purpose a combined cycle has been designed which exploits the properties of the selected working fluid (refrigerant) that vaporize at low temperatures. Computational simulation techniques were used to investigate the performance of refrigerants selected for the specific application so as to substantiate the choice of the most suitable refrigerant for process optimization. Results show that R134a as a working fluid is an optimal solution to balancing three factors studied: required amount of heat, mass flow rate and cost.

Key-Words: ORC, geothermal energy, solar energy, refrigerant

1 Introduction

Renewable energy sources, such as solar thermal and geothermal energy are potentially energy sources that are capable to meet electricity demand. However, the moderate temperature heat from these sources cannot be converted efficiently to electrical power when using conventional power generation methods. For that reason and for the conversion of low-grade heat sources into electricity various cycles have been proposed [1-3] as the organic Rankine Cycle (ORC), supercritical Rankine cycle, Kalina cycle, etc. The literature shows extensive analyses and comparisons among different thermodynamic cycles and working fluids [1-12]. However, most of the comparisons were conducted under certain predefined temperature conditions and used only a few working fluids [4–12]. As ORC is much less complex and need less maintenance it is a promising process for conversion of low and medium temperature heat to electricity.

In Greece, there are areas with water sources with temperature higher than 80^{o}C [13]. Also, classic solar thermal systems with flat solar collectors may produce temperature around or more than 80^{o}C. Both cases have been exploited for various uses mainly for space heating, greenhouse heating etc or other thermal uses [14]. The exploitation period of such systems is limited in periods with thermal needs, namely periods where these systems (especially the solar thermal systems) show decreased performance and present increased losses. However, the period that the above heats are available is during the whole year while they are maximized during summer where thermal needs are limited. For the improvement of the performance and exploitability of those applications during the whole year various technologies have been developed, the main one among them is cooling production technology or/and power generation with a relatively low efficiency especially at temperatures around or up to 80^{o}C.

The Effi Low Res project intends to develop an ORC power generation unit working at low temperatures with improved overall efficiency by exploiting low temperature sources so as to make it cost effective. The ORC applies the principle of Rankine cycle steam but uses an organic fluid with a low boiling point to recover the heat from low temperature heat sources. The choice of refrigerant for a given application is a key to its successful

implementation [1-12] as it plays a major role in the cycle. A working fluid must not only have the necessary thermo-physical properties that match the application but also possess adequate chemical stability in the desired temperature range.
The current study refers to the preliminary design of the ORC apparatus giving technical specifications that comprises working fluid selection, sizing of solar plant, heat exchangers and expanders and other auxiliary equipment.

2 The Effi Low Res project

The current work focuses on the design and modeling of an experimental apparatus of a low-temperature geothermal and solar ORC system for electrical power generation. The apparatus will be manufactured and installed at two pilot sites in Greece. The one ORC will be powered by low enthalpy geothermal well and the second one by solar collectors.

2.1 Geothermal

The electrical power generation plant proposed in the current work from low enthalpy geothermal well, will be installed at Lesvos island, Greece, in the Polichnitos area [15], utilizing the heat of an existing geothermal field as shown in Fig. 1.

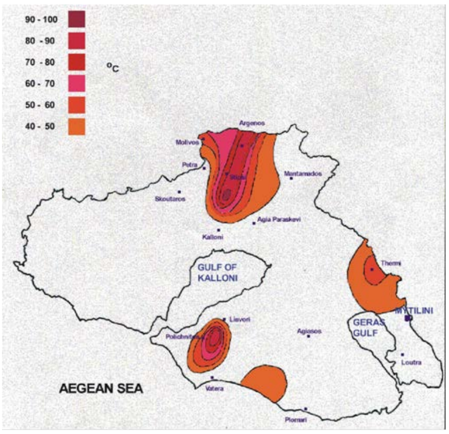

Fig.1 Isocontours of geothermal field in Lesvos island, Greece.

Polichnitos has been recognized as an area with high temperature geothermal field that is used for district heating [15]. The thermal energy to be used for the present application of electrical generation from an ORC plant is derived from the geothermal well at Polychnitos. Table 1 shows the technical specifications of the selected geothermal well.

area [km^2]	Reservoir depth [m]	flow rate [t/h]	Tmax [°C]	TDS [g/kg]	Fluid type	(maturity indice
10	50-200	400	92	12	Cl	<2

Table 1 Technical specifications of Polichnitos geothermal production well.

The geothermal fluid yields thermal energy by the geothermal well in a temperature of approximately 85°C, through an intermediate Plate Heat Exchanger to the evaporator of the ORC that operates with refrigerant R134a.

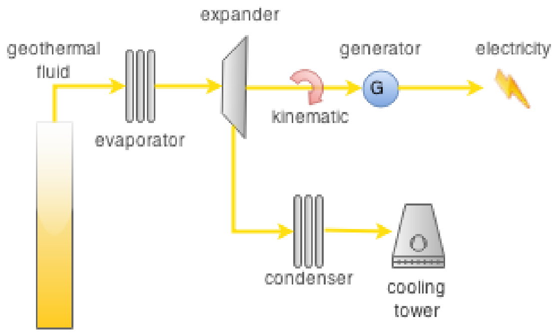

Fig.2 Energy flow diagram for geothermal ORC system.

From the existing drilling, the geothermal fluid will be pumped in a temperature of approximately ~85°C, with a productivity of 35m^3/h at a depth of 150m.

2.2 Solar

The solar apparatus will be installed at Central Greece University of Applied Sciences Campus at Psachna Evias, in building D of Mechanical Engineering Department (Fig.3).

Fig.3 Ground plan of the building at Psachna Evias Source: Google Earth

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The working fluid in the close loop of solar system will be a mixture of water and glycol. The solar system consists of two subsystems with different collector technology. The first subsystem consists of flat solar panels with selective coating and the second one of vacuum tube solar collectors.

The two subsystems of solar collector are independent from each other and both feature independent buffer tanks.

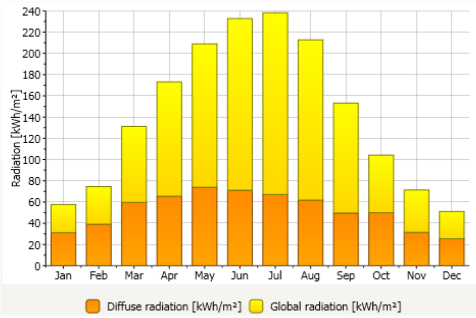

Fig.4 Solar Radiation, Psachna Evias, Source: Meteonorm

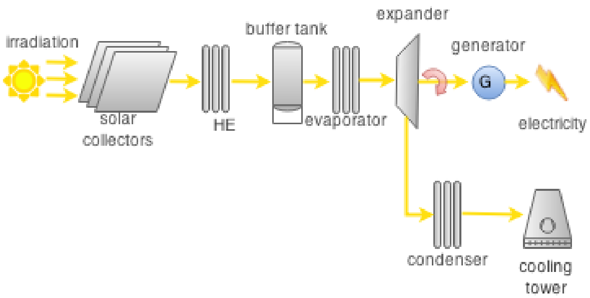

Fig.5 Energy flow diagram for solar ORC system.

The technical specifications of the proposed system are shown in the following table.

	Area [m^2]	a_o	a_1 [W/m^2K]	a_2 [W/m^2K]
Vacuum collectors	323	>0.51	<1.31	<0.008
Flat collectors	100	>0.67	<3.24	<0.017

Table 2 Technical specifications of solar collectors.

The working fluid of the solar system will transfer its heat to the evaporator heat exchanger at temperature of approximately ~85°C.

2.3 Selection of working fluid

The fluid selection affects system efficiency, operating conditions, environmental impact and economic viability. The working fluid must meet criteria such as: stability, non-fouling, non-corrosiveness, no toxicity, non-flammability, etc. Indicatively the characteristics of the cooling fluid being investigated include [3]:

1. Thermodynamic performance: efficiency and power output should be the maximum for given temperature conditions.
2. Positive or isentropic vapor saturation curve. In case of positive pressure saturation curve (dry fluid) recovery exchanger may be used (recuperator) to increase the efficiency of the cycle. Negative curve leads to the formation of drops at the end of expansion [4]. The steam must be overheated at the inlet of the turbine in order to avoid destruction of the turbine, which reduces the efficiency of the cycle [5].
3. High vapor density: this parameter is important especially for fluids which show a low condensation pressure. Low density leads to large equipment at the levels of expansion and condensation.
4. Accepted pressures: high pressures usually lead to higher investment costs and increased complexity.
5. High stability temperature: in contrast to water, organic fluids usually suffer of chemical wear and decays at high temperatures. Therefore the maximum temperature is limited by the chemical stability of the fluid.
6. Low boiling point under the requirements of the project Effi Low Res.
7. Low environmental impact and high level of security: the main parameters taken into account are the Ozone Depleting Potential (ODP), the Greenhouse Warming Potential (GWP), toxicity and flammability.
8. Good commercial availability and low cost.

Refrigerant that were investigated have minimal toxicity and maintain good material compatibility and stability limits. In selecting the refrigerant for ORC with an inlet temperature of ~ 75°C to the expander different refrigerants were studied namely R410A, R404A, HFC125, but as the critical point of their curve at p-h diagram was near the temperature

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of 75°C, were discarded. Also, for refrigerants such as R407c, R32, significant overheating is required to prevent droplets in the expander, leading to a significant reduction of yield, therefore they were also discarded. Considering therefore the basic criteria of the expander inlet temperature and performance of the refrigerant cycle as well as the aforementioned environmental criteria and the availability in the market three refrigerants were selected for further investigation R134a, R245fa and HFE7000. In order to select the optimum refrigerant several simulations were conducted.

3 Design and simulation of Effi Low Res ORC cycle

3.1 ORC calculations

The ORC was calculated using the software Cycle Tempo [16] and fluid properties were based on REFPROP 9.1 [17]. The ORC modeled in Cycle-Tempo was based on the theoretical calculation of an ORC using all three selected refrigerants and was designed to produce about 10 kW of electricity. Fig. 6 shows the model of the ORC in Cycle Tempo.

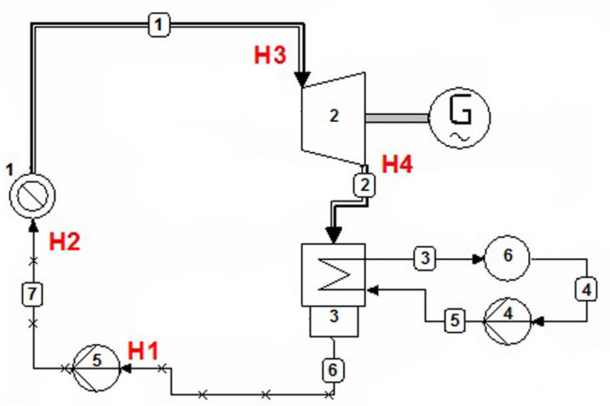

Fig.6 ORC model

For the simulation of the refrigeration cycle the following assumptions were made:

- The pressure and temperature of the heat source [1], derived from the list of RefProp for the fluid and according to the desired temperature (75°C).
- It was considered that expander [2] has isentropic efficiency (0.70) and mechanical efficiency (0.8).
- It was considered that the electrical power of the generator is 10kWe with efficiency (0.97).
- The inlet pressure in the tube [2] was derived from the list of RefProp for the fluid. As concerns the output temperature of the organic liquid at the condenser [3] it was the desired (40°C).
- In the pipe [6] as inlet condition was given that the organic fluid is 100% liquid, namely, condenser converts all organic fluid from the gaseous to the liquid state.
- Pump [5] was considered to have isentropic efficiency (1) and that it brings the organic liquid at a pressure equal to the desired. The value derived from the list of RefProp for the fluid.
- For the condenser (heat exchange equipment) the thermal power that was transferred for the cooling of the organic fluid is estimated.

The results of the simulations for a specific temperature range are presented in the following tables.

R134a									
expander's temperature			enthalpy after expander	enthalpy before expander	enthalpy before heat source	enthlpy before refrig. Pump	enthalpy difference		efficiency
T3	T4	ΔT	H4	H3	H2	H1	H3-H4	H3-H1	[-]
R134a									
75	40	35	419,43	429,03	257,97	256,41	9,6	172,62	**5,56%**
HFE7000									
75	40	35	397,76	408,75	249,05	248,81	10,99	159,94	**6,87%**
R245fa									
75	40	35	443,51	458,4	253,03	252,57	14,89	205,83	**7,23%**

Table 3 Simulated results for the refrigerant candidates for the Effi Low Res ORC cycle.

- Under the temperature range the R245fa has the best efficiency. Specifically introduces better performance by ~1.5% than the performance of R134a and by ~0.5% better performance than the HFE7000. However, R245fa requires larger amounts for its condensation. On average for the three fluids it is required:
  R134a: 177kJ/kg HFE7000: 162kJ/kg R245fa: 208kJ/kg

Based on the above data from the simulations it is proved that the organic R245fa is discarded due to the high required amount of heat, HFE7000 is discarded due to higher required mass flow, and R134a is selected as an optimal solution to balancing these three factors studied.

3.2 Design of experimental apparatus

In order to conduct a parametric experimental investigation of a small scale ORC, Effi Low Res participants will build and instrument a unit by adapting market parts.

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A 3d drawing of the experimental unit that will be assembled is shown in Fig. 7. The experimental rig will include a range of pressure and temperature probes and it is part of a closed loop automated system that ensures that the required test parameters are controlled to within the testing tolerance specification.

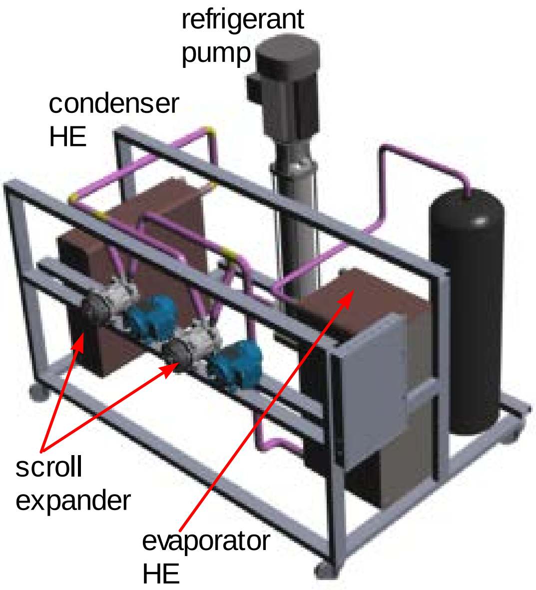

Fig.7 3d representation of ORC test rig

The evaporator and condenser are market heat exchangers (Alfa Laval). The single component that has the greatest bearing on the viability of a low temperature ORC cycle is the expander. Most commercially available turbines developed for power production purposes were designed for service with steam power plants. These units are not, however, suitable for use with many low boiling point working fluids such as hydrocarbons. Scroll type compressors lend themselves well to operating in reverse as ORC expanders [18,19]. They are mass produced leading to their cost effective application to low temperature ORC units. The Effi Low Res apparatus is designed to incorporate two (2) scroll expanders combined with electrical power generators of 5kWe each.

4 Conclusion

There is limited literature available on the cost effective mass production of ORC systems combined with low temperature heat sources. The key element for the achievement of such goal is the selection of the working fluid expander due to the trade-off between efficiency and capital cost. Also, the selection of a working fluid that achieves a favourable ideal cycle efficiency is also of great impact upon the viability of these systems.

In the current work, a preliminary design study was conducted for an Efficient ORC Power Generation system with low grade energy as heat source. The results from the cycle tempo simulations showed that R134a working fluid is an optimal solution to balancing three factors studied: required amount of heat, mass flow rate and cost. Finally, scroll expander is the one selected technology because of its mass market production, cost and robustness.

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