Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 45 (2014) 1337 – 1343

Energy Procedia

68th Conference of the Italian Thermal Machines Engineering Association, ATI2013

Thermodynamic analysis of ORC for energy production from geothermal resources

Giuliano Cammarata, Luigi Cammarata, Giuseppe Petrone*

Department of Industrial Engineering, University of Catania – Viale A. Doria, 6 – 95125 Catania, Italy

Abstract

This study concerns a thermodynamic analysis of Organic Rankine Cycles for energy conversion from geothermal resources. A numerical flow-chart tool based on a lumped parameters approach is adopted to compute values of thermodynamic variables during each transformation composing the cycle. The equation of state is expressed by the Peng-Robinson formulation. The different plant components are outlined by single blocks, linked each other by connections through balance equations. Analyses are carried-out considering two working fluids (isopentane and isobutane). Results are obtained for several sets of operating parameters, such as the evaporation and condensation pressure for the working fluid, the mass flow rate of the geothermal fluid and the cooling water temperature. From results, thermodynamic cycles are built-up in the T-s plan, allowing to quantify effectiveness and energy benefit related to the investigated functional scenarios.

"Keywords: ORC, geothermal, numerical"

1. Introduction

The organic Rankine cycle (ORC) is a promising process for conversion of low and medium temperature heat to electricity. Unlike the traditional steam Rankine cycle, the organic Rankine cycle (ORC) uses a high molecular mass organic fluid. It allows heat recovery from low temperature sources such as industrial waste heat, geothermal heat,

* Corresponding author. Tel.: +39 095 738 2452
E-mail address: gpetrone@dii.unict.it

doi:10.1016/j.egypro.2014.01.140

solar ponds, etc. The low temperature heat is converted into useful work, that can itself be converted into electricity. Organic Rankine Cycles seem to be a promising technology in the perspective of a decrease in plant size and investment costs. They can work at lower temperatures, and the total installed power can be reduced down to the kW scale. The market for ORC's is growing at a rapid pace. At the present, Organic Rankine Cycle (ORC) raises considerable interest as it makes it possible to produce electricity from cooler geothermal sources, typically within the 100–130 °C temperature range, exceptionally down to 90–95 °C, often available from below 1000 m deep production well increasing the number of geothermal reservoirs in the world that can potentially be used for generating electricity. Among the literature studies concerning this topic, Franco [1] presented an overview of current R&D in the field of small-scale ORC for the exploitation of geothermal sources with reduced temperature below 130 °C. He analyzed the performance of such those new cycles and to consider the potential improvements that will result in higher cycle performance or lower resource utilization and lower cost of electricity generation. He showed that the geothermal power plant with a regenerative Organic Rankine Cycle is an interesting and promising option, in particular the benefit gained by adding a regenerative heat exchanger which provides some of the preheating heat from the vapor exiting the turbine. Ghasemi et al. [2] provided numerical models for an existing commercial ORC operating by a regenerative cycle and using isobutane as working fluid. The condensation system was of air-cooled type. From their simulation results, validated by comparison with experimental data, it appears that at high ambient temperatures, the net power output of the ORC is limited by the capacity of condenser system. They also observed that at low ambient temperatures, the inlet of turbine should be in a saturated vapor state and the maximum feasible pressure as suggested by previous studies. However, as the ambient temperature increases, this conclusion does not hold anymore and a significant superheat is required to obtain the maximum in net power output of the ORC. This was considered a consequence of the off-maximum operation of the turbines and consequently variable isentropic efficiency. It means that at high ambient temperatures, the condenser system should be at full capacity for the optimal operation, but at low ambient temperatures, the cooling capacity of the condenser system need to be adjusted to obtain the optimal operation. A theoretical analyses of 12 natural and conventional working fluids-based transcritical Rankine power cycles driven by low-temperature geothermal sources have been carried out by Guo et al. [3] with the methodology of pinch point analysis using computer models. Their calculated results include the optimum turbine inlet pressure and the corresponding thermodynamic mean heating temperature, the net power output, thermal efficiency, heat transfer capacity as well as the real expansion rate in the turbine. From those parameters they were able to strike a balance about the more suitable working fluid depending functional conditions. Similar analyses were carried-out by Saleh et al. [4] and by Hung et al. [5]. In [4] the BACKONE equation of state is used for screening 31 pure component working fluids for ORC applications. A pinch point analysis for the external heat exchanger is also performed and results are discussed with relation to the optimization of the heat source. In [5] the suitability of several working fluids in terms of system efficiency is otherwise analyzed in relation to low-grade energy sources, such as solar pond and ocean thermal energy conversion systems. Quoilin et al. [6] developed a thermodynamic model of a waste heat recovery ORC in order to compare both the thermodynamic and the thermo-economic performance of several typical working fluids for low to medium temperature-range ORCs. Recently, a systematic comparison of ORC configurations by means of comprehensive performance indexes was proposed by Branchini et al. [7]. In the present framework, this paper reports a thermodynamic analysis of ORC applications for generating energy by exploiting geothermal resources. Results are carried-out for different working fluids and several operational and environmental conditions.

Nomenclature

p	Pressure
R	Ideal gas constant
Q	Mass flow rate
T	Temperature
V	Volume

Greek symbols

ω	Acentric factor

Subscripts
c Critical state

2. Modelling

Numerical models are built-up by a lumped parameters approach. Modelling workflow is based on the following steps. Firstly, a flow-sheet is created: in this step the working fluids and their physical properties are chosen and implemented. The following step concerns the mathematical model applied for computations. It lies on the formulation of the equation of state as proposed by Peng-Robinson [8], reading as follows:

$$p = \frac{RT}{\tilde{V} - b} - \frac{a \cdot \alpha(T)}{\tilde{V}^2 + 2b\tilde{V} - b^2} \quad (1)$$

where $\tilde{V}$ is the molar volume and coefficients are expressed as reported below:

$$a = \frac{0.45724 R^2 T_c^2}{P_c} \quad (2)$$

$$b = \frac{0.07780 R T_c}{P_c} \quad (3)$$

$$\alpha(T) = (1 + (0.37464 + 1.54226\omega - 0.26992\omega^2)(1 - T_r^{0.5}))^2 \quad (4)$$

$$T_r = \frac{T}{T_c} \quad (5)$$

A workspace can then be produced, where the plant elements are introduced. Links joining the different symbolic objects are then defined in respect of the mass and energy balances during the process. Boundary conditions and environmental parameters for the systems are set also. A schematic representation of the studied system in the workspace is illustrated in Fig. 1.

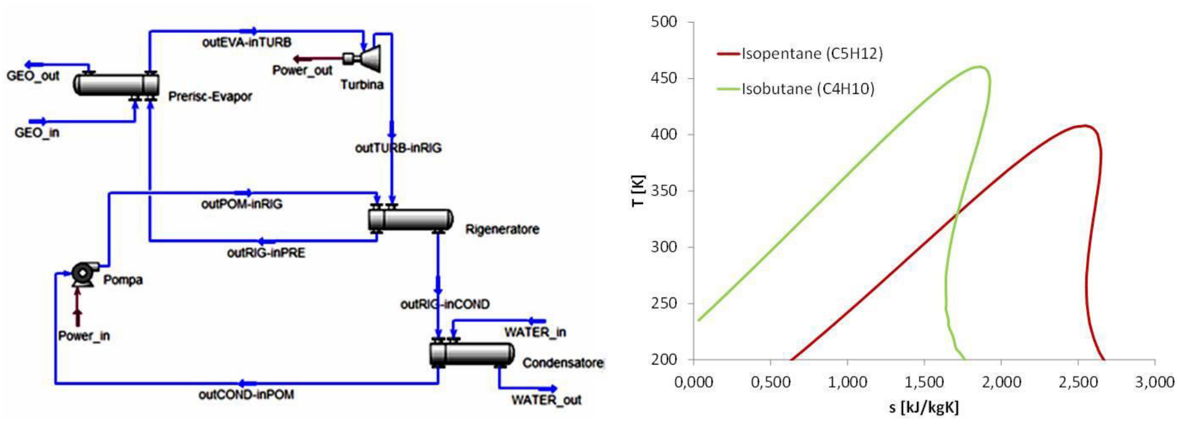

Fig. 1. Schematic outline of plant components / system flow-chart (left side) and saturation curves in the T-s diagram for the considered working fluids (right side).

The same figure shows the saturation curves in the T-s diagram for the considered working fluids (Isopentane and Isobutane). From a thermodynamic point of view, the functional principle of the organic Rankine cycle is the same as that of the Rankine cycle: the working fluid is pumped to a boiler where it is evaporated, passes through a turbine and is finally condensed. In the real cycle, the presence of irreversibilities lowers the cycle efficiency. These irreversibilities mainly occur during the expansion, in the heat exchangers and in the pump. The studied cycle is improved by using a regenerator: since the fluid has not reached the two-phase state at the end of the expansion, its temperature at this point is higher than the condensing temperature. The related enthalpy is exploited to preheat the liquid before it enters the evaporator, so that the power required from the heat source is therefore reduced and the efficiency is increased.

3. Results

In running simulations, the inlet temperature of geothermal fluid (GEO_in branch in Fig. 1) is fixed at value 120 °C. Therefore, the evaporation pressure corresponds to value 888 kPa (T=110.2 °C) for the isopentane and 2390 kPa (T=109.9 °C) for the isobutane. The cooling water temperature at the condenser (WATER_in branch in Fig. 1) is set at 18 °C for winter season and 27 °C for summer one. Mass flow rate considered in computations for geothermal fluid (Q GEO) is 110 kg/s for both working fluids. Mass flow rate of working fluid (Q WF) is otherwise 27 kg/s for the isobutane and 18 kg/s for the isopentane. Simulations are carried-out for working conditions listed in Table 1. Figures 2-3 report an extract of thermodynamic results (Simulation #3) obtained for both working fluids. Thermodynamic cycles are plotted in the T-s diagram also.

Table 1. Pressure and temperature values at the condenser (outRIG-inCOND) for both working fluids.

	Isopentane		Isobutane	
Simulation #	p [kPa]	T [°C]	p [kPa]	T [°C]
1	300	63.7	650	48.1
2	250	57.1	550	41.6
3	170	43.9	490	37.2

Simulation #3	T	T	Molar Entropy	Entropy
490kPa|1236 kW	[C]	[K]	[kJ/kgmoleK]	[kJ/kgK]
outPOMP-inRIG	39.00	312.15	90.79	1.56
outRIG-inPRE	51.85	325.00	96.81	1.67
	79.30	352.45	110.00	1.89
outPRE-inEVA	109.90	383.05	126.70	2.18
	109.90	383.05	130.00	2.24
	109.90	383.05	140.00	2.41
	109.90	383.05	145.00	2.49
outEVA-inTURB	109.90	383.05	153.90	2.65
outTURB-inRIG	56.83	329.98	156.70	2.70
outRIG-inCOND	39.00	312.15	150.70	2.59
	37.21	310.36	150.10	2.58
	37.21	310.36	145.00	2.49
	37.21	310.36	125.00	2.15
	37.21	310.36	105.00	1.81
	37.21	310.36	90.54	1.56
outCOND-inPOMP	37.21	310.36	90.53	1.56
WATER_in	27.00	300.15	54.22	3.01
WATER_out	37.31	310.46	56.85	3.16
GEO_in	120.00	393.15	75.34	4.18
GEO_out	99.87	373.02	71.15	3.95

		T	s
Condensator	in	312.15	2.59
		310.36	2.58
		310.36	2.49
		310.36	2.15
		310.36	1.81
		310.36	1.56
	out	310.36	1.56
Pump	in	310.36	1.56
	out	312.15	1.56
Rigenerator	in	312.15	1.56
	out	325.00	1.67
Preheater	in	325.00	1.67
		352.45	1.89
	out	383.05	2.18
Evaporator	in	383.05	2.18
		383.05	2.24
		383.05	2.41
		383.05	2.49
	out	383.05	2.65
Turbine	in	383.05	2.65
	out	329.98	2.70
|Rigenerator|	in	329.98	2.70
	out	312.15	2.59

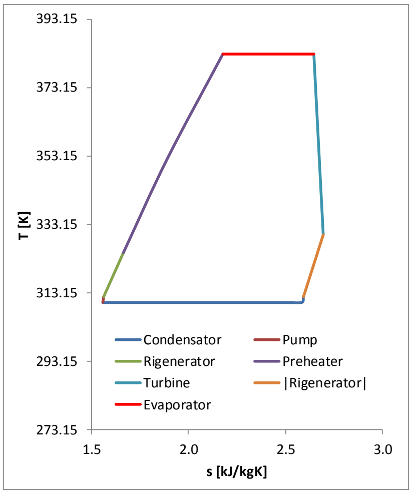

Fig. 2. Thermodynamic results carried-out by simulation #3 for isobutane.

Simulation #3	T	T	Molar Entropy	Entropy
170 kPa| 830.0 kW	[C]	[K]	[kJ/kgmoleK]	[kJ/kgK]
outPOMP-inRIG	44.37	317.52	47.11	0.65
outRIG-inPRE	68.65	341.80	59.99	0.83
	87.46	360.61	70.00	0.97
	106.00	379.15	80.00	1.11
outPRE-inEVA	110.30	383.45	82.35	1.14
	110.20	383.35	100.00	1.39
	110.20	383.35	125.00	1.73
outEVA-inTURB	110.20	383.35	131.80	1.83
outTURB-inRIG	76.25	349.40	135.00	1.87
outRIG-inCOND	44.38	317.53	122.30	1.70
	43.87	317.02	122.10	1.69
	43.86	317.01	100.00	1.39
	43.86	317.01	70.00	0.97
	43.86	317.01	60.00	0.83
	43.86	317.01	47.01	0.65
outCOND-inPOMP	43.86	317.01	47.01	0.65
WATER_in	27.00	300.15	54.22	3.01
WATER_out	43.83	316.98	58.46	3.25
GEO_in	120.00	393.15	75.34	4.18
GEO_out	106.10	379.25	72.47	4.02

		T	s
Condensator	in	317.53	1.70
		317.02	1.69
		317.01	1.39
		317.01	0.97
		317.01	0.83
		317.01	0.65
	out	317.01	0.65
Pump	in	317.01	0.65
	out	317.52	0.65
Rigenerator	in	317.52	0.65
	out	341.80	0.83
Preheater	in	341.80	0.83
		360.61	0.97
		379.15	1.11
	out	383.45	1.14
Evaporator	in	383.45	1.14
		383.35	1.39
		383.35	1.73
	out	383.35	1.83
Turbine	in	383.35	1.83
	out	349.40	1.87
|Rigenerator|	in	349.40	1.87
	out	317.53	1.70

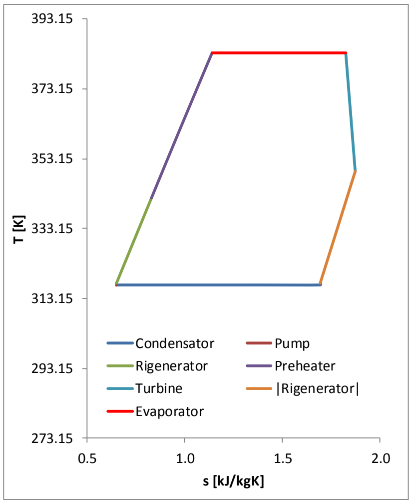

Fig. 3. Thermodynamic results carried-out by simulation #3 for isopentane.

For the previous listed simulations, Table 2 reports the obtained results in terms of supplied and generated power (Power_in and Power_out), thermal condition of the geothermal fluid at outlet (T GEO_out), mass flow rate of cooling water (Q WATER) needed at the condensation section and cycle efficiency (η).

Table 2. Results obtained for Simulation #1-3 for both considered working fluids.

	Isopentane				
Simulation #	Power_in [kW]	Power_out [kW]	T GEO_out [°C]	Q WATER [kg/s]	η
1	23.34	541.4	107.3	36	8.0%
2	24.98	634.2	106.9	45	8.3%
3	28.04	830.0	106.1	82	10.8%
	Isobutane				
Simulation #	Power_in [kW]	Power_out [kW]	T GEO_out [°C]	Q WATER [kg/s]	Cycle efficiency
1	117.3	1002	101.1	92	9.9%
2	123.2	1141	100.3	135	10.8%
3	126.3	1237	99.87	195	11.2%

Further analyses are then developed in order to investigate on influence of the vaporisation pressure (p_v) and the mass flow rate of the geothermal fluid (Q GEO). Main results are reported in Figures 4 and Table 3.

From results some items can be globally pointed-out. Decreasing in pressure level at the condensation section (simulations from #1 to #3) allows to improve the thermodynamic performance in terms of generated power (+53.3% for isopentane, +23.4% for isobutane) and efficiency (+2.8% for isopentane, +1.3% for isobutane). Temperature of the geothermal fluid at output does not change significantly (less than 2 °C in any case); on the other hand, a higher mass flow rate of cooling water is needed for the process (+127.7% for isopentane, +111.9% for isobutane).

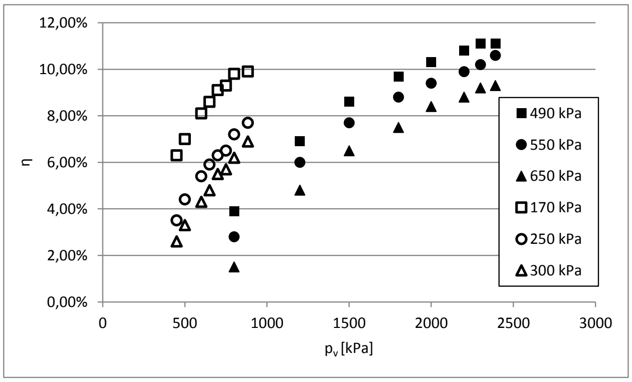

Fig. 4. Cycle efficiency as a function of the vaporization pressure for several values of pressure at the condenser section: filled and not-filled symbols corresponds to isobutane and isopentane results, respectively.

Table 3. Main system parameters variation with respect to the mass flow of the geothermal fluid.

Q GEO [kg/s]	Power_in [kW]		Power_out [kW]		T GEO_out [°C]		Q WATER [kg/s]		Q WF [kg/s]	
	Isobutane	Isopentane	Isobutane	Isopentane	Isobutane	Isopentane	Isobutane	Isopentane	Isobutane	Isopentane
110	127.9	28.92	1236.8	830.1	99.9	106.1	195	82	27	18
100	112.2	24.93	1100.2	744.2	100.2	106.3	177	74	24	16
90	102.9	21.81	1008.5	651.2	99.8	106.7	162	65	22	14
80	88.9	20.25	870.6	604.7	100.4	106.1	140	60	19	13
70	79.5	17.14	778.9	511.6	99.9	106.6	125	51	17	11
60	65.5	14.02	641.5	418.6	100.7	107.2	103	42	14	9
50	56.1	12.46	549.8	372.1	100.2	106.3	89	37	12	8
40	42.1	9.35	412.4	279.1	101.4	107.2	67	28	9	6
30	32.7	6.23	320.7	186.1	100.7	108.6	52	19	7	4

Increasing in vaporisation pressure level also determinates a sensible benefit on the cycle efficiency. In relation to the simulations carried-out, increasing in efficiency is in the range 7.2÷7.8 in percentage points for the isopentane; for the isobutane it is 3.6÷4.3 in percentage points. Focusing attention on the effect of the geothermal mass flow rate on the generated power, it is to notice that reduction of the first one determinates an almost proportional decreasing on the second one. The same quasi-proportional relationship can be deducted for the geothermal fluid mass flow rate with respect to both the cooling water and the working fluid mass flow rate.

4. Conclusions

A thermodynamic analysis of Rankine cycles of two organic fluids exploiting a geothermal primary source is performed by using a flow-chart numerical tool based on a lumped parameters approach. As result, we have been able to draw the several transformations composing the cycle in the T-s plan. From post-processing, cycle efficiency and energy benefit have been quantified in several operating conditions. Influence of vaporization and condensation pressures, cooling water temperature and mass flow rate of the geothermal fluid on thermodynamic performances has been then highlighted. The potential of the numerical tools in predicting the cycle performance in several operating conditions is highlighted.

References

[1] Franco A. Power production from a moderate temperature geothermal resource with regenerative Organic Rankine Cycles. Energy for Sustainable Development 2011; 15:411-419.

[2] Ghasemi H, Paci M, Tizzanini A, Mitsos A. Modeling and optimization of a binary geothermal power plant. Energy 2013; 50:412-428.

[3] Guo T, Wang H, Zhang S. Comparative analysis of natural and conventional working fluids for use in transcritical Rankine cycle using low-temperature geothermal source. Int. J. Energy Research 2011; 35:530-544.

[4] Saleh B, Koglbauer G, Wendland M, Fisher J. Working fluids for low-temperature organic Rankine cycles. Energy 2007; 32:1210-1221.

[5] Hung TC, Wang SK, Kuo CH, Pei BS, Tsai KF. A study of organic working fluids on system efficiency of an ORC using low-grade energy sources. Energy 2010; 35: 1403-1411.

[6] Quoilin S, Declaye S, Tchanche BF, Lemort V. Thermo-economic optimization of waste heat recovery Organic Rankine Cycles. Applied Thermal Engineering 2011; 31: 2885-2893

[7] Branchini L, De Pascale A, Peretto A. Systematic comparison of ORC configurations by means of comprehensive performance indexes. Applied Thermal Engineering 2013; 61: 129-140.

[8] Peng DY, Robinson DB. A New Two-Constant Equation-of-state, Industrial and Engineering Chemistry Fundamentals 1976; 15:59–64.