Csaba I. Farkas, István Rabi

ISSN 0350-350X
GOMABN 53, 4, 354-363
Stručni rad / Professional paper

UTILIZATION OF CASCADE STRUCTURE ORGANIC RANKINE CYCLE IN PETROLEUM INDUSTRY

Abstract
In the last few years in petroleum industry the focus of innovation has turned to the increase of energy efficiency and the reduction of carbon dioxide emission. One of the most difficult engineering challenges is the utilization of low temperature process streams (<180 °C) although the largest part of waste heat has been generated in this segment. Installation of Organic Rankine Cycle (ORC) system to the waste heat source unit is providing an adequate solution for handling of loss energy and yielding "green" electricity for the facility. This system involves the same devices as in the usual steam power plant (a boiler, a work-producing expansion device, a generator, a condenser and a pump). However, for such a system, the working fluid is an organic compound having a lower ebullition temperature than water and allowing reduced evaporating temperatures. The success of this technology is coming from its box module application: a similar ORC system can be used, with little modifications for handling various heat sources. Moreover, unlike the conventional Rankine cycle, local and small scale power generation is made possible by this technology. Today, Organic Rankine Cycles are commercially available even in the MW power range.The object of our examination in this paper is a unit having three technical points for future ORC utilization: i) a small quantity of liquid naphtha side draw at 165 °C; ii) a higher amount of vapor column overhead at 140 °C; iii) a furnace flue gas at 250 °C. We investigated the utilization of these streams in a cascade structure using isopentane as working fluid. Cascade structure has two working fluid cycles: a relatively high pressure (12.5 bar) for the utilization of higher temperature streams and a relatively low pressure (5.5 bar) for the utilization of lower temperature level streams. Analysis of the potential of energy saving has been made by supporting the steady-state process flowsheeting and simulation. As the result of this investigation promising results were brought for the industrial scale utilization of cascade ORC system. One can see the dimensions of this system including needed area of heat exchangers, calculated expander performances, efficiency of the system etc.

Keywords: organic Rankine cycle; waste energy utilization; flue gas; cascade cycles

Introduction

Nowadays highly increasing energy prices and the effort of carbon dioxide emission reduction - via European Union so called “20-20-20” policy - compels petroleum industry to squeeze more from the actual technology, to make it more energy efficient. Currently cooling of the low temperature level (<180 °C) of the process streams leads to an enormous energy waste through the air and water coolers [1]. Organic Rankine Cycle (ORC) provides a good solution to utilize this heat for generating electric power from the actual unutilized streams. Several papers were dealin with the topic. Ayachi et al. [2] made the exergy study in case of simple and cascade systems. Liu et al. [3], and Saleh et al. [4] examined the effect of the working fluid, regarding its properties and operating conditions. Other papers, performed by Madhawa et al. [5] and Kanoglu et al. [6] are based on the energy analysis approaches to properly determine and analyze ORCs for geothermal applications.

This paper contains the analysis of real industrial technology waste heat utilization in the following three sections. In the section Characterization of resources three technological points are identified where the application of ORC technology can be a proper solution for energy recovery. The main viewpoints of selection were the quantity and temperature of the stream to be cooled. In addition the cooling and working media of the examined cycle are listed. In section Analysis the results of simulation are discussed. In order to establish the working potential of the examined technology a detailed simulation model was made to determine the main data, such as recovered energy, heat exchanger area, etc.

1. Characterization of resources

In this section three technological points are identified where the application of ORC technology can be a proper solution for energy recovery. It is very important to clarify the viewpoints of the selection procedure. First of all the location of these points have a significant relevance, as they have to be on the same site and as near to each other as it is possible in order to minimize heat loss, and extra investment costs for a bigger pipe system.

As the intention was to examine a cascade structure ORC technology it is obvious why streams on different temperature levels were selectrd. A huge amount of heat is wasted on air coolers and cooling water heat exchangers especially if the stream wanted to be cooled down is condensing, so a condensing vapor stream was selected too.

Here is the list of the selected technology point (Table 1):

a. Heat source 1 (signed COV): a fractionation column overhead vapor and mixed liquid, has to be totally condensed.
b. Heat source 2 (signed CSP): a fractionation column side product has to be cooled down.
c. Heat source 3 (signed FFG): a furnace flue gas, there is possiblility to cooled down.

Table 1: Main parameters of heat sources

Stream Name	UOM	CSP	COV	FFG
Temperature	°C	165	115	250
Pressure	BARG	18,0	0,59	4,0
Total Mass Rate	kg/h	45000	81214	68684
Total Enthalpy	MWATT	4,64	7,32	9,76
Total Sp. Enthalpy	kJ/kg	371,44	324,48	511,53
Phase		Liquid	Mixed	Vapor

As a working fluid we used i-pentane for the calculations because of its relatively low boiling point (27.7 °C at 0 barg). During the ideal Rankine cycle the working media has the following phase changes:

1. Pressure increase of working media (Figure 1, line 1-2).
2. Heating and evaporation of the working media at constant pressure (Figure 1, line 2-3-4-5).
3. Isentropic or adiabatic expansion of working media through a turbine from the phase of superheated vapor to the pressure of the condenser (Figure 1, line 5-6-7).
4. Condensation of the working media at constant pressure, it becomes a saturated liquid (Figure 1, line 7-1).

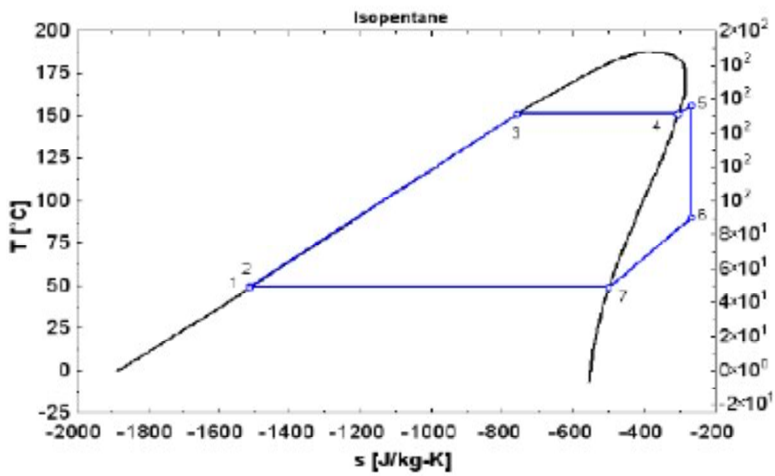

Figure 1: *T*-*s* chart of isopentane

As it Figure 1 shows, in case of a positive slope of T-s curve (i-pentane) the vapor is not condensing during the expansion, so there cannot be liquid drops in the expander and it can be applied safely. However the vapor coming from the expander has to be subcooled before it is in two phase state as it is seen on Figure 1, 6-7 line of work. Other significant properties for the good working fluid are low freezing point, high stability temperature, high heat of vaporization and density, low environmental impact, safe usage, good availability and low cost and acceptable pressure. Cooling water can be the bottleneck of the process as its amount for utilization is finite and ORC needs a huge quantity of cooling potential. So it is really important to treat cooling water as one of the most significant utilities of the cascade cycle. Therefore two cases were examined: a winter mode when the temperature of the cooling water is 20 °C and summer mode when the temperature of the cooling water is 25 °C.

At last the design of the cascade ORC is presented (see on Figure 2). As one can see in the picture, two cycles are placed in series, one at a high pressure and one at a low pressure. In the high pressure cycle the heat of FFG, which has a higher temperature is utilized in an evaporator. On the turbine of the high pressure cycle its pressure is decreased to the level of the low pressure cycle for further utilization. In low pressure cycle remained heat of FFG and a heat of COV and CSP is utilized on CSP and COV evaporators, where working media of the low pressure cycle is evaporating-on the low pressure cycle turbine. After depressuring of the working media in the low pressure cycle turbine it is condensed in a condenser, using the available cooling water.

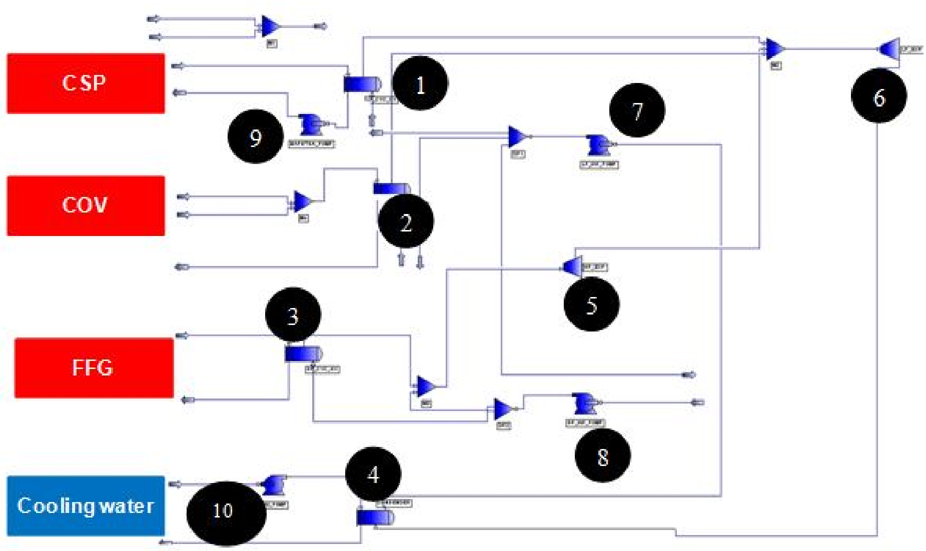

Figure 2: Schematic drawing of the examined cascade ORC

The elements of drawing (Figure 2):

1. CSP evaporator: in this equipment working fluid is evaporating, gaining heat from CSP.
2. COV evaporator: in this equipment working fluid is evaporating, gaining heat from COV.
3. FFG evaporator: in this equipment working fluid is evaporating, gaining heat from FFG.
4. Condenser: condensing the working media with cooling water.
5. High pressure turbine: turbine of the high pressure cycle, depressuring working media from the high pressure cycle to the pressure of the low pressure cycle.
6. Low pressure turbine: turbine of the low pressure cycle, depressuring working media of the low pressure cycle to the pressure of the condensation.
7. Low pressure working media pump: pump increasing the pressure of low pressure cycle's working media to the working pressure of the low pressure cycle.
8. High pressure working media pump: pump increasing the pressure of high pressure cycle's working media to the working pressure of the high pressure cycle.
9. Cooling water pump: increasing the pressure of cooling water.
10. CSP pump: increasing the pressure of CSP to its transport value.

2. Analysis

In most ORC applications, despite the conventional power plants, the off-design application can be actually the normal mode of operation. For instance, when recovering industrial waste heat, the temperature, composition or even the pressure of the waste heat source can vary. However, the goal of the application is to utilize waste heat, it is very difficult to define the exact performance of the system. A commercial simulation software steady state model was made to examine cascade ORC cycle presented in Figure 2.

In this section the results of simulation are discussed. In order to establish the working potential of the examined technology a detailed simulation model was made to determine needed data, such as recovered energy, heat exchanger area, etc. During the simulation the shell and tube heat exchangers were built in and detailed heat exchanger calculations were done to determine the evaporating potential of heat sources. The anticipated efficiency for calculations for the pumps was 65 % and for turbines 85 %.

In Table 2 the operational parameters of the cycles are presented. As it is seen low pressure cycle is using a magnitude higher amount of working media. These values are correlating the expectations coming from the heat content estimations of the examined heat sources.

Table 2: Operational parameters of the examined cascade ORC

Operational parameters	Low pressure cycle	High pressure cycle
Pressure, barg	5.5	12.5
Temp. before expander, °C	89.6	126.5
Temp. after condenser, °C	38.9	
Working fluid	i-pentane	i-pentane
Working fluid flow rate, t/h	70.3	18.0

In Table 3 the main parameters of the heat exchangers used in cycles are presented. COND identifies the condenser of the cascade while FFG, COV and CSP identify the evaporators. As it is seen COV evaporator which is evaporating i-pentane and COND which is condensing i-pentane after the low pressure cycle turbine. The area of heat exchangers is adumbrating a huge CAPEX need.

Table 3: Main parameters of evaporators and condenser

	UOM	COND.	FFG	CSP	COV
Duty	MWATT	7.52	2.38	2.81	3.26
Area	m^2	2000	250	750	1200
LMTD	^oC	11.4	78.6	29.7	15.9

In Table 4 the gained energy on turbines (expanders) are presented. Due to the higher amount of working fluid in the low pressure cycle the the actual work of the expander is higher (LP_EXP in Table 4). The remained energy of working fluid after the high pressure cycle expander (HP_EXP in Table 4) is still utilized in the low pressure cycle on a lower temperature and pressure level. The working media of the high pressure cycle is going to the low pressure cycle as a superheated vapor.

In Table 5 the operational parameters of the defined pumps are presented.

Table 4: Gained energy on expanders

Expander Name		LP_EXP	HP_EXP
Inlet Pressure	BARG	4.5	11.5
Outlet Pressure	BARG	0.4	4.5
Outlet Temperature	^oC	63.2	103.5
Actual Work	KW	819.5	128.4

Table 5: Operational parameters of pumps when using 20 °C CW

Pump Name		LP_WF_PUMP	NAPHTHA_PUMP	CW_PUMP	HP_WF_PUMP
Pressure Gain	BAR	4.1	1.0	3.0	7.0
Head	M	68.84	15.01	30.68	118.66
Work	kW	35.1	2.8	113.6	8.9

After the calculations of the cascade ORC cycle using 20 °C cooling water the efficiency of the cycle has to be defined according to the Equation 1.

$$\eta = \frac{\left(W_{LP\_EXP} + W_{HP\_EXP}\right) - \left(P_{LP\_WF} + P_{HP\_WF} + P_{CW} + P_{Naphtha}\right)}{D_{FFG} + D_{CSP} + D_{COV}} \times 100 \qquad \text{[Eq. 1.]}$$

Where η is the efficiency [%], W is the work of low pressure (LP_EXP) and high pressure (HP_EXP) expander [kW], P is the performance of pumps [kW], D is the duty of FFG, CSP and COV evaporators [kW]. Using the defined equation the calculated efficiency is 10.2 %.

Afterwards, the calculation when the temperature of the inlet CW is 25 °C was performed. There were no changes in the duty of the evaporators and condenser as expected and no difference is experienced in the work of the turbines (expanders). To maintain the same cooling capacity the amount of CW increased compared to the 20 °C CW case. In Table 6 the difference is presented. This means that the performance of CW pump is changed too (Table 7).

Table 6: Needed cooling water quantity

Cooling water temperature, °C	20	25
Flow rate, m³/h	459	809

Table 7: Operational parameters of pumps when using 25 °C CW

Pump Name		LP_WF_PUMP	NAPHTHA_PUMP	CW_PUMP	HP_WF_PUMP
Pressure Gain	BAR	4.1	1.0	3.0	7.0
Head	M	80.13	15.01	30.71	118.65
Work	kW	23.6	2.8	104.09	8.9

Now the efficiency of the cascade ORC system using 25 °C CW can be determined by using Eq. 1.: the calculated efficiency is 8.0 % which is more than 20 % lower than it was in case of 20 °C CW, so it can be supposed that the temperature of CW has a key impact on the Cycle's performance.

Table 8: Simplified payback time calculation in case of S&T HXs

Shell & tube HX	UOM	CW - 20 °C	CW - 25 °C
CAPEX	th $	6056	6056
OPEX	th $	349	615
Working hours	h	8400	8400
Income	th $	725	684
Gross Margin	th $	376	69
Payback time	year	16	87

The simplified payback time calculations are presented in Table 8. The CAPEX (rude estimation) of the calculated cycle is rather huge, because of the extremely high area of evaporators and condensers, so the solution with the shell and tube heat exchangers will never justify its application in energy sector of oil industry. However income can be better if we take into account the savings on an air cooler or the savings due to the CO_2 decreasing.

In order to improve the solution the shell and tube heat exchangers are replaced with plate heat exchangers to reduce the drive force and needed HX area. The area and CAPEX changes are summarized in Table 9.

Table 9: Comparison of CAPEX need in case of different types of HX

HX	Area, m^2		Shells/unit		Sum area, m^2		Cost/shell, k$		Sum cost, k$	
Type	S&T	Plate	S&T	Plate	S&T	Plate	S&T	Plate	S&T	Plate
COV	300	63	4	7	1200	441	555	151	2220	1057
CSP	250	53	3	4	750	212	481	140	1443	560
FFG	250	0	1	0	250	0	481	0	481	0
COND.	200	60	10	11	2000	660	308	148	3080	1628
								Sum	7224	3245

The simplified payback time recalculations are presented in Table 10, the payback time is lower than in case of the shell and tube heat exchangers but it is still not acceptable, not for the period under five years. It is rather interesting that the difference between cases almost vanished which is the effect of the more impressive heat exchanging solution.

An analysis was done to investigate the effect of electricity price on the payback time of cascade ORC with plate heat exchangers. As it is seen in Figure 3 the higher the electricity price is the lower the payback time is (red curve indicates payback times if 25 °C CW was used and blue curve indicates payback times if 20 °C CW was used).

Table 10: Simplified payback time calculation in case of plate HXs

Plate HX	UOM	CW - 20 °C	CW - 25 °C
CAPEX	th $	3403	3403
OPEX	th $	304	342
Working hours	h	8400	8400
Income	th $	728	723
Gross Margin	th $	424	381
Payback time	year	8	9

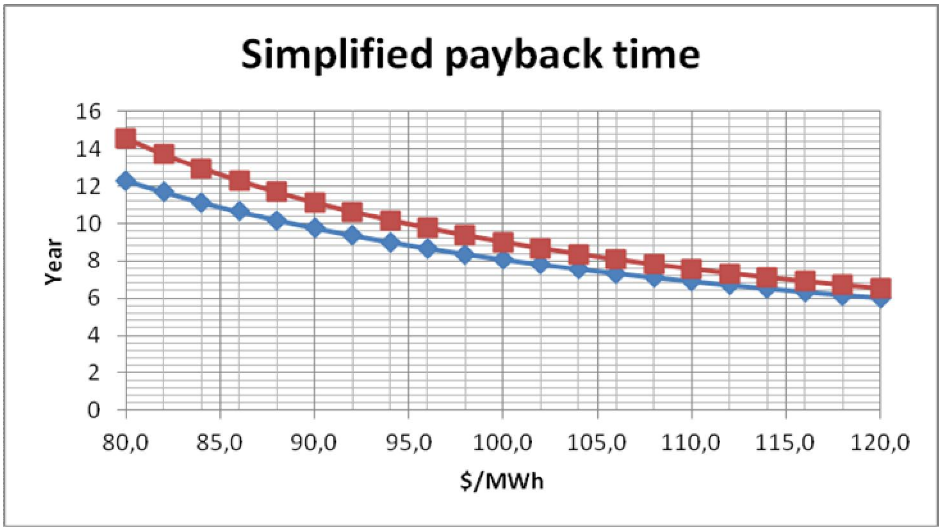

Figure 3: Analysis of the influence of electricity price on payback time

3. Conclusion

After calculations of a cascade ORC presenting a real technological situation we can state that with the current equipment prices this solution will never be recovered economically. In the future with increasing electricity price and more effective and cheaper heat exchanging devices the technology can be a solution for the waste heat utilization in a modern refinery.

Nomenclature:

CAPEX	capital expenditures
COV	column overhead vapor
CSP	column side product
CW	cooling water
D	duty of evaporators, condensers, kW
FFG	furnace flue gas
HX	heat exchanger
OPEX	operational expenditures
ORC	organic Rankine cycle
P	performance of pump, kW
s	entropy, kJ / kg K
T	temperature, °C
UOM	units of measures
W	work of turbines (expanders), kW
Greek letters:	
η	efficiency, %

References

[1] Panchal, C.B.: Waste Heat to Power, Selecting a Technology. Argonne National Laboratory 2007, Houston, TX, September 25, 2007.
[2] Ayachi, F. et al. Exergy Assessment of Recovery Solutions from Dry and Moist Gas Available at Medium Temperature. Energies 2012, 5, 718-730.
[3] Liu, B.T.; Chien, K.H.; Wang, C.C. Effect of working fluids on organic Rankine cycle for waste heat recovery. Energy 2004, 29, 1207-1217.
[4] Saleh, B.; Koglbauer, G.; Wendland, M.; Fischer, J. Working fluids for low-temperature organic rankine cycles. Energy 2007, 32, 1210-1221.
[5] Madhawa, H.D. et al.Optimum design criteria for an organic rankine cycle using low-temperature geothermal heat sources. Energy 2007, 32, 1698-1706.
[6] Kanoglu, M.; Bolatturk, A. Performance and parametric investigation of a binary geothermal power plant by exergy. Renew. Energy 2008, 33, 2366-2374.

Acknowledgements

Authors would like to thank to the experts of University of Pannonia for cooperation, especially to Dr. Zoltán Varga for his tireless work to make the technology clear and accessible for us.

Authors

Csaba I. Farkas, István Rabi; e-mail: ICsFarkas@mol.hu
MOL Plc.; H-2440 Százhalombatta, Olajmunkás str. 2.

Received

2.10.2012.

Accepted

10.11.2014.