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Waste Heat Recovery with Organic Rankine Cycle in the Petroleum Industry

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This paper summarizes the results of an engineering study of partial substitution of an air cooler, which cools a process stream from 140 °C to 45 °C meantime dissipates heat of 32 MW into the environment, with an organic Rankine cycle (ORC). Aims were to investigate the application of different working fluids, and ranking them based on the following criteria maximum achievable power output, efficiency of the cycle, amount of the heat recovered, required heat exchanger area, attainable CO_2 emission reduction, and payback time of the investment. Results showed that in case of the applied working fluids and design parameters the efficiency of the system obtained at the highest power generated (W_T) varied between 9.8 % and 10.2 %. The maximum calculated power output was in the range of 1.63 – 2.11 MW. Additionally, it was determined that the maximum turbine power and cycle efficiency not coincided for n-pentane, isopenatane and n-butane working fluids. The waste heat (Q_H) recovered in the evaporator varied between 16.10 MW and 18.70 MW. Results also displayed that the maximum power generated by the turbine and the maximum waste heat recovery did not coincide for every working fluid applied in the design boundaries. The attainable reduction in the CO_2 emission was in the range of 2600-3400 t/y based on production of electricity by natural gas. The preliminary economic calculation showed that the payback time is between 6.3-7.0 y. Based on the techno-economic evaluation of the ORC system most appropriate working fluid could not be selected at the given process conditions. But the butanes gave higher turbine power, efficiency and CO_2 emission reduction at same heat recovery level.

1. Introduction

Nowadays, the energy efficiency improvement becomes to one of most important key factors in the hydrocarbon processing industry, because more and more stricter green house gas emission regulations have been implemented all over the World (Thernesz et al, 2010). Additionally, the increase in the energy efficiency contributes to decreasing the fuel cost and increasing the profitability (Varga et al, 2010). Huge amount of heat is wasted through air coolers and water coolers to cool streams of temperature lower than 150 °C in crude oil refineries. For example, more than 20 % of the heat added in the furnace is wasted to the environment in a typical crude oil distillation unit. Utilization of part of this heat is possible with various technologies (Papadopoulos et al, 2010, Quoilin et al, 2011, Schuster et al, 2009, Véleza et al, 2012, Walsh, 2011) e.g. boiler feed water preheating, organic Rankine cycle (ORC), Kalina cycle, thermo electric generator, heat pump etc.

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This paper summarizes the results of an engineering study of partial substitution of an air cooler with ORC system to use low-grade energy to generate power. Aims were to investigate the application of different working fluids, and ranking them based on the following criteria maximum achievable power output, efficiency of the cycle, amount of the heat recovered, required heat exchanger area, attainable CO_2 emission reduction, and payback time of the investment.

2. Methodology

The first step of the study was the selection of heat source for the ORC system. Many air coolers and water coolers were examined based on the criteria the inlet temperature of process stream to be in the range of 100-150 °C. The selected air cooler is situated in one of the main process units of the refinery and it cools the process stream from 140 °C to 45 °C meantime dissipates heat of 32 MW into the environment. Preliminary selection of working fluid of ORC was performed based on physicochemical (e.g. boiling point, vapour pressure, vapour density etc.) and application properties (halogen free, available in the refinery, cheap etc.), and n-butane, isobutane, n-pentane and isopentane were selected. In the next step models of ORC system were prepared for the study of the utilization of waste heat of the air cooler applying standard process engineering software tools (Invensys ProII v8.3), using all of the selected working fluids. The applied design constrains were the following: temperature of condenser set to 40 °C, minimal temperature approach was 5 °C for both the evaporator and condenser, inlet temperature of cooling water entering into the condenser was 25 °C and the allowable temperature rise was 10 °C, expander outlet pressure set to be equal to the condensation pressure of working fluid at the condenser temperature and the adiabatic efficiency of the expander was 85 %. Maximum allowable system pressure was set to 20 bar. The efficiency of the ORC system was described with Eq. 1:

$$\eta = \frac{W_T - W_P}{Q_H} \tag{1}$$

where W_T: turbine power, MW
W_P: power for pumping working fluid, MW
Q_H: heat recovered in the evaporator, MW

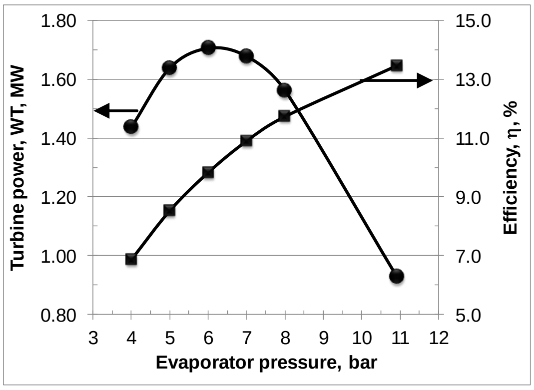
The objectives for selecting the advantageous process parameters were the following: maximum turbine power, maximum heat recovery and minimum payback time.

3. Results and discussion

To determine the advantageous process parameters including the most appropriate working fluid within design boundaries the effect of the pressure of the evaporator (e.g. turbine inlet pressure) on turbine power, system efficiency (see Eq. 1), outlet temperature of the process stream at leaving the evaporator and the heat recovered in the evaporator was investigated for all working fluids. Results are displayed on Figure 1a – Figure 3b.

Pressure of evaporator was varied between 4 - 11 bar for pentanes, and 10 – 18 bar for butanes. Figure 1a, 2a and 3a clearly show that the system efficiency was continuously increased by raising the pressure in case of all working fluids applied. In contrary, the power generated by the turbine showed a maximum in function of the pressure for pentanes and n-butane in the design boundaries. However, the isobutene as working fluid displayed different picture, because both the efficiency and turbine power were increased by raising the pressure of the evaporator (Figure 3a).

Additionally, the highest efficiency of 13.5 % was obtained applying isopentane at 11 bar where the power generated by the turbine was 0.93 MW, by contrast the highest power of 2.11 MW was achieved using isobutane at 18 bar where the efficiency was "only" 10.2 %. These results clearly showed that the efficiency not to be the sole selection criteria for working fluids.



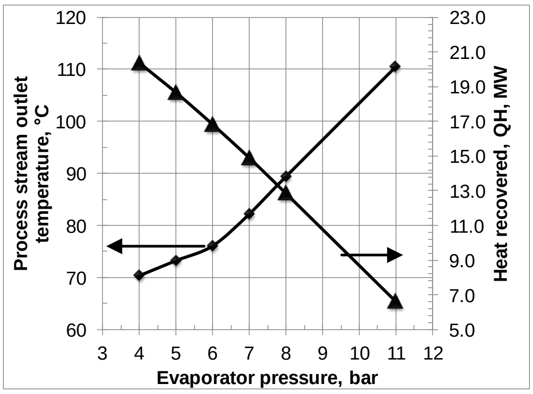


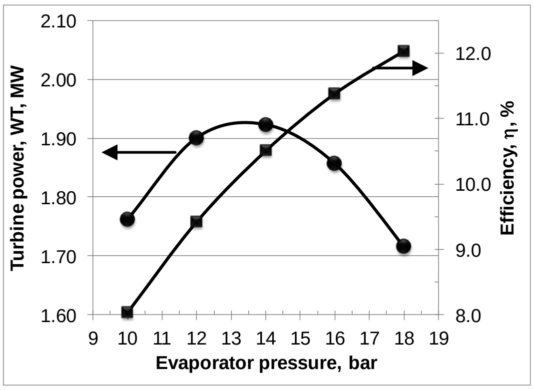
Figure 1a: Change of the turbine power and efficiency in function of evaporator pressure for isopentane

Figure 1b: Change of the process outlet temperature and heat recovery in function of evaporator pressure for isopentane

Variation of outlet temperature of the process stream with the pressure was investigated, too (see Figure 1b, 2b and 3b). Because the lower the outlet temperature of process stream is less cooling power is required to cool down it to the target temperature. From this aspect the most advantageous working fluid is the isobutane because outlet temperature of 57 °C can be obtained at evaporator pressure of 10 bar. However, this pressure is unfavourable in respect of both the achievable turbine power and system efficiency. The lowest outlet temperature of process stream was almost the same in case of pentanes and n-butane with value of 70 °C. The temperature of process stream at leaving the evaporator became higher as the pressure of the evaporator increased for every working fluid.

Regarding to the waste heat recovery (see Figure 1b, 2b and 3b) it can be stated that the highest amount of heat to be extracted from the process stream in the evaporator was 26.5 MW and obtained using isobutane working fluid at 10 bar. Figures also show that the heat recovery decreased with the increasing pressure. Results also displayed that the maximum power generated by the turbine and the maximum waste heat recovery did not coincide for every working fluid applied in the design boundaries.

On the basis of the previously presented results the isobutane seems to be the advantageous working fluid for the specified system.



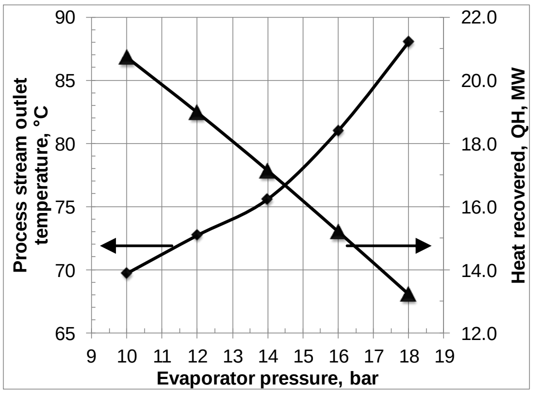
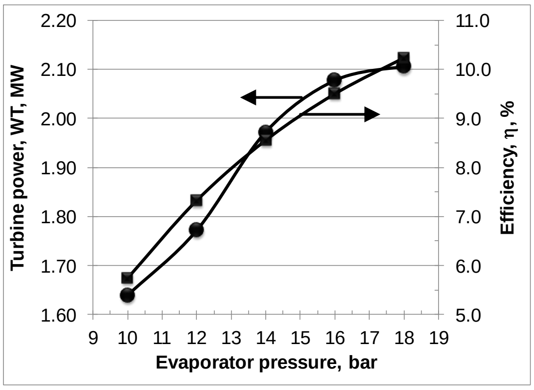


Figure 2a: Change of the turbine power and efficiency in function of evaporator pressure for butane

Figure 2b: Change of the process outlet temperature and heat recovery in function of evaporator pressure for butane



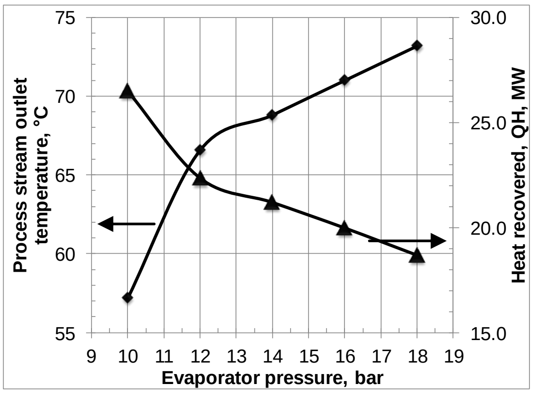


Figure 3a: Change of the turbine power and efficiency in function of evaporator pressure for isobutane

Figure 3b: Change of the process outlet temperature and heat recovery in function of evaporator pressure for isobutane

Beside the power generated by the turbine and the heat recovered in the evaporator, the heat exchanger area of the evaporator and condenser as well as the required cooling capacity of the condenser are also important to select the economically advantageous option. Considering the design parameters given in Section 2 and applying overall heat transfer coefficient of 300 W/m^2 °C for the evaporator and of 600 W/m^2°C for the condenser the heat exchangers areas and cooling requirements were calculated.

So that the results to be comparable values for the same heat recovery level (18.7 MW) are summarized in Table 1. Data show that the type of the working fluid greatly influenced the process parameters of the ORC system. Applying hydrocarbons to be in gas phase at ambient conditions (n-butane, isobutane) resulted higher system efficiency and power generated by the turbine comparing to those to be in liquid phase (n-pentane, isopentane).

The outlet temperature of the process fluid was same for all working fluids applied, and did not give possibility to differentiate between them.

The mass rate of the working fluid required to extract the specified heat from the process stream was different. The highest was in case of isobutane and the lowest in case of n-pentane. Because the mass rate of working fluid influence the power generated by the turbine, the power can be generated by one kg working fluid calculated, too.

Table 1: Important parameters of the ORC system for different working fluids obtained at same heat recovery level

Parameters	n-pentane	isopentane	n-butane	isobutane
Heat recovery, Q_H, MW	18.70	18.70	18.70	18.70
Efficiency, η, %	8.35	8.52	9.42	10.24
Turbine power, W_T, MW	1.53	1.64	1.90	2.10
Outlet temp. of process stream, °C	73	73	73	73
Working fluid mass flow rate, t/h	163	169	167	181
Evaporator pressure, bar	4	5	12	18
Expander outlet pressure, bar	1.12	1.45	3.70	5.20
Duty of the condenser, Q_C, MW	17.25	17.14	17.11	16.55
Pump power, W_P, MW	0.037	0.049	0.114	0.194
Evaporator area, A_H, m^2	3566	3794	4060	4233
Condenser area, A_C, m^2	3225	3265	3019	2942
Total area, m^2	6791	7059	7079	7175

These were 9.4 kW/kg, 9.7 kW/kg, 11.4 kW/kg and 11.6 kW/kg for the n-pentane, isopentane, n-butane and isobutane, respectively. It showed that the use of isobutane provided the highest turbine power on mass basis at the given process conditions.
Area of the evaporator was increased in the order of n-pentane, isopentane, n-butane and isobutane (3566 m^2 → 4233 m^2) despite the same heat recovery. Reasons of this are the different physicochemical properties of the working fluids and the different process conditions. In contrary this, the area of the condenser was lower for the butanes than those were for pentanes which correspond to the duty of the condenser.
The total area considered both the surface of evaporator and condenser was the lowest using the n-pentane and the highest for the isobutane. Area to be installed to obtain 1 MW power was also calculated dividing the power generated by the turbine with the total area. These were 4440 m^2/MW, 4300 m^2/MW, 3730 m^2/MW and 3420 m^2/MW for the n-pentane, isopentane, n-butane and isobutane, respectively. Based on these results it can be stated that the most appropriate working fluid is the isobutane at the given process conditions because on applying it the lowest heat exchanger area required for producing a unit of power.
In terms of cooling duty it can be said that the highest cooling capacity was required in case of the use of n-pentane, despite the fact that the mass flow rate of the n-pentane was the lowest. This clearly showed that the conversion of heat, which is recovered in the evaporator, into mechanical work in the expander was the less efficient applying the n-pentane as working fluid.
Based on the results obtained on calculating the process parameters for the working fluids the isobutane was the most appropriate for the ORC system at the given process conditions.
Economic evaluation of the ORC system was also performed for every working fluid applied. Because one of our objects was to obtain the highest power generated by the turbine the case was selected for the economic assessment that provided the highest power for every working fluid. Economic evaluation included the calculation of the capital expenditures of heat exchangers, expander and working fluid pump applying the equations given in the available literature (Couper et al, 2005). Additionally, it was considered that the power generated by the turbine used for producing electricity, which is contribute to the reduction in the utility costs. Calculation of the payback time was done dividing the CAPEX by the income, despite it was a simple approach it made possible the distinction between the working fluids.
Results of the economic evaluation are summarized in Table 2.
Data show that the highest attainable power generated by the turbine increased in the order of n-pentane, isopentane, n-butane and isobutane, resulting the same order in the electric power production and of course in income, too.

Table 2: Techno-economic evaluation of the ORC system for different working fluids obtained at the highest turbine power

Parameters	n-pentane	isopentane	n-butane	isobutane
Turbine power, W_T, MW	1.63	1.71	1.92	2.11
Capital expenditure, CAPEX, 10^3\$				
Heat exchangers	7790	8500	8580	9950
Expander	480	500	550	590
Pump	20	20	30	30
Sum CAPEX (2011)	8290	9020	9160	10,570
Income from electric power production				
Electricity cost, $/MWh	87	87	87	87
Electric power production , MWh/y	14,070	14,730	16,610	18,190
Income, 10^3\$	1225	1280	1446	1583
Payback time, year	6.8	7.0	6.3	6.7
CO_2 reduction t/y	2610	2730	3077	3370

In term of CAPEX data it can be stated that the cost of the heat exchangers represents the highest part (more than 90 %) within the total cost for every working fluid. Heat exchanger cost for isobutane was significantly higher comparing to that for n-butane. Reasons of this difference may be attributed to the different physicochemical characteristics and process conditions.

Based on the process parameters summarized in Table 1 the isobutane seemed to be the most appropriate working fluid. After preparing the economic assessment of the ORC system the n-butane became the most advantageous working fluid considering the calculated payback time. However, there is not significant difference in payback time for the selected working fluids, since the difference between the highest and the lowest values less than 1 y.

In the light of the data of the techno-economic evaluation it cannot be clearly decided what hydrocarbon is the most appropriate working fluid for the ORC system at the given process conditions. To make a clear decision on the working fluid further investigation is required including the detailed design of the system, optimization of the process parameters, considering the cooling cost of the process stream, etc.

The attainable reduction in the CO_2 emission was in the range of 2600-3400 t/y based on production of electricity by natural gas.The magnitude of reduction in the CO_2 emission could be one of the parameters those are considered at the decision. Data show that significant difference exists in the achievable CO_2 emission reduction for pentanes and butanes. Based on these results the application of butanes as working fluid may be favorable.

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