Benefit analysis of organic Rankine cycle power generation by using waste heat recovery in Refinery

Qian Ma [1,*], Yongzhen Chen [2], Anqi Liu [3], Qingzhe Jiang [1,4]

[1] State Key Laboratory of Heavy Oil Processing and Beijing, China University of Petroleum, Beijing 102249, China
[2] Key Laboratory of Photochemical Conversion and Optoelectronic Materials, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China
[3] Research Institute of Safety & Environment Technology, China National Petroleum Corporation, Beijing 102206, China
[4] School of International Trade and Economics, University of International Business and Economics, Beijing 100029, China

Abstract. Under the goal of achieving "carbon neutrality", increasing energy-saving and reducing emissions has become a long-term strategy to ensure the sustainable development of China's social economy. The unrecycled waste heat leads to a high energy penalty in refinery. This paper presents an Organic Rankine Cycle (ORC) power generation technology, which through the thermodynamic cycle to recover the waste heat from the Aromatics Complex units. This process is simulated and analysed from the environmental point. The results indicate that the application of ORC in aromatics combined units can indirectly save 41040 tons of coal every year. The annual emission of CO_2 is reduced by 94455 tons. The proposed ORC system provides technological route for refineries to achieve waste heat recovery, thus advancing the green transition of the petrochemical plants.

1. Introduction

Nowadays, the increasing pressure with regard to energy security and environmental pollution (especially CO_2 emissions), requiring nations to seek lower-carbon development path. CO_2 emissions cause a major concern [1,2] and are responsible for various extreme weather events [3]. The international community has reached a consensus on CO_2 reduction to build a low-carbon future. As a traditional energy producer and major carbon emitter, China's carbon neutrality commitment puts forward new requirements for domestic refineries to fulfill their "carbon" responsibilities. As a producer and consumer of traditional energy, refinery has always been the top priority in the field of energy conservation and emission reduction [4]. According to incomplete statistics, refineries' energy consumption accounts for 16% of China's total energy consumption [5,6], ranking in the forefront of major energy consumers. Studies have shown that compared with Japan's energy utilization rate (60%), China's energy utilization rate is only about 30% [7]. The main reason for this difference is that China does not make full use of waste heat.

The waste heat accounts for a large proportion of the total energy consumption of the refinery, and some are even as high as 60% [4]. If it cannot be well utilized, it is bound to cause a waste of energy, resulting in the high comprehensive energy consumption and environmental pollution of the refinery. So that the economic benefits cannot be optimized, which is contrary to low-carbon direction. In the refining and chemical fields, this low-grade energy that has not been reutilized mostly discharged into the environment at the cost of consuming cold utilities.

With the complex development of petroleum processing process, resulting in the Aromatics Complex has become a high energy consuming unit in the refinery [4]. As part of the CO_2 mitigation strategy, introduction of waste heat recovery technology in refineries would considerably reduce CO_2 emission indirectly. Therefore, it is imperative to find some technological options to recover this huge fraction of the energy that is untapped and the potential gain from efficiently utilizing the waste heat is appreciable for refineries' low-carbon development.

Organic Rankine Cycle (ORC) is a state-of-the-art technology for converting the low-grade heat to power via the work of organic working fluids, which has proven to be promising for waste heat recovery [8,9]. In recent years, it is being progressively adopted as commercially-matured technology since there have been many applications in recovery waste heat from industrial processes, such as biomass or coal fired combined heat and power (CHP) plants [10], geothermal plants or micro-CHP [11,12]. However, few studies have focused on waste heat recovery in refineries. This work is motivated by recognizing the gap and provide targeted solution to promote the reutilization of refineries' waste heat, thereby improving the energy efficiency and reducing the emission of the refineries.

* Corresponding author: maqiancup@126.com

2. Model and methodology

This section illustrates the modeling of the ORC system. Besides, the key performance indicators to evaluate the impact of the ORC power generation system on energy conservation and emission reduction of refinery.

2.1 Model description

As shown in Figure.1, the modeling process consists of condenser, evaporator, organic expander and working fluid pump. The saturated liquid working fluid is pumped to a high-pressure state in the working fluid pump and heat exchanged with the waste heat source in the evaporator. The organic working fluid is heated and becomes saturated or superheated vapor. Then, it enters the expander and drives the expander to rotate to generate electricity. Finally, the exhaust gas after work enters the condenser and it is condensed into saturated liquid through cooling water, followed by pressed into the evaporator via the pump for the next cycle.

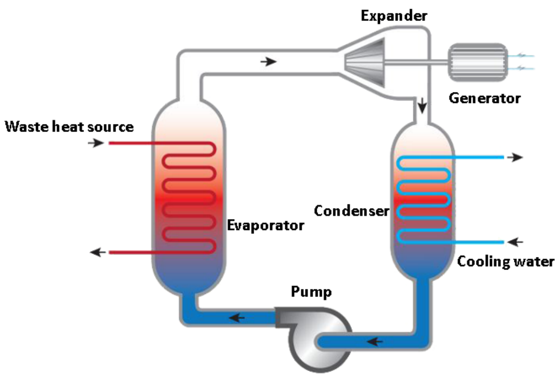

Figure 1. Process diagram of ORC system.

2.1.1 Waste heat sources.

Based on the research and summary of the waste heat distribution of key process units (Aromatics Complex) in refinery, the main waste heat sources of ORC system as shown in table 1.

Table 1. The waste heat from the aromatic's combination unit

Item	Waste heat sources	T_{start} (°C)	T_{target} (°C)	Heat load (MW)	Heat-capacity flow rate (kW/°C)
H1	Distillation column	197.8	190.5	83.4	11426
H2	Xylene column	247.8	226.2	57.3	2655
H3	O-xylene column	201.8	189.3	11.66	933.19
H4	Extraction column	140	83	27.7	486.62
H5	Raffinate column	129	101.3	54.37	1963
H6	De heptane column	235.7	175	13.96	229.8
H7	Toluene column	125.6	115.3	17.03	1650.78
H8	Heavy aromatics column	177.7	167.8	10.84	1095.2

2.2 Key performance indicators

It is assumed that the mainly energy consumption of the refinery is coal. The CO_2 reduced by using the electricity output by ORC system can be calculated by equation as followed:

$$M_{coal} = hP_{net}C_{coal} \quad (1)$$

$$E_{CO_2} = E_{substitution} - E_{generation} = hP_{net}\beta_{CO_2} \quad (2)$$

Where, h is the annual operation time of ORC system, 8000 h. P_{net} is the net power output of ORC system, M_{coal} is coal consumption and C_{coal} is coal coefficient based on standard coal power generation. β is the carbon emission coefficient of each emission, which represents the emission to the atmosphere per unit of electricity produced, and the unit of power is kW · h.

$$E_{NO_X} = hP_{net}\beta_{NO_X} \quad (3)$$

$$E_{CH_4} = hP_{net}\beta_{CH_4} \quad (4)$$

$$E_{CO} = hP_{net}\beta_{CO} \quad (5)$$

3. Results and discussion

We focus on the evaluation of the contribution of ORC system to refinery energy conservation and emission reduction. We take coal power as the benchmark and calculate the emission reduction effect based on the emission factor methods. For the waste heat power generation system of high energy consumption units in refinery, the total power generated by waste heat utilization is 15.17 MW and the net power output is 13.54 MW. If the net power output is converted into standard coal consumption and unit coal consumption for power generation is 380 g/kW · h [13], the recovery of waste heat of aromatics combined units in refinery can indirectly save 41040 tons of coal per year (Calculated by equation 1-2). In addition, if these waste heat sources are not utilized, it can only be cooled by air cooling or water cooling. According to the calculation of circulating water cooling, more circulating water (about11630 t/h) is required, which can save 18.61 million yuan per year (0.2 yuan / ton) [14]

The greenhouse gas emission factors of coal are shown in table 2 [15]. According to the equations (2-5) defined in section 2.2, the energy consumption saved and the carbon emission reduced are shown in Table 3. The results show that through recovery of waste heat in aromatics combined units the annual emission of greenhouse gas CO_2 is reduced by 94455 tons, followed by NO_X and CH_4, which are reduced by 1418 tons and 312 tons, respectively. It can be seen that the ORC system can significantly reduce the heat load that dissipated to the environment, thereby increasing the overall efficiency of the system. Those results demonstrate that the recovery of waste heat is of great significance to promote the development of low-carbon refinery, which achieving energy conservation and emission reduction.

Table 2. Carbon emission coefficients for coal

Parameters	β_{CO_2}	β_{CH_4}	β_{CO}	β_{NO_X}
Carbon emission coefficients (kg/kW·h)	0.872	2.89*10^-3	1.05*10^-3	1.31*10^-2

Table 3. Emission reduction evaluation of the ORC waste heat recovery system

Working fluid	Power output	Save coal consumption	CO_2 reduction	NO_X reduction	CH_4 reduction	CO reduction
R600	$1.08*10^8$/kWh	41040/t	94455/t	1418/t	312/t	113.4/t

4. Conclusion

In this study, we proposed an ORC power generation system to recover the waste heat of the refinery. It can indirectly save 41040 tons of coal in the refinery every year. The annual emission of CO_2 and NOx are reduced by 94455 tons and 1418 tons, respectively. It can be seen that the reutilization of waste heat contributes to refineries' transition toward a cleaner and lower-carbon future, which provides technical support for the global push of "carbon neutrality".

Acknowledgments

This work was supported by the China National Petroleum Corporation (CNPC) (Grant No. 2016E-1209). We also thank the CNPC Research Institute of Safety & Environment Technology for access to their database.

References

1. Lee, M.Y., Hashim, H., 2014. Modelling and optimization of CO2 abatement strategies. J. Clean. Prod. 71, 40e47.
2. Ren, T., Patel, M.K., 2009. Basic petrochemicals from natural gas, coal and biomass: energy use and CO2 emissions. Resour. Conserv. Recycl. 53, 513-528.
3. Mei H, Li YP, Suo C, Ma Y, Lv J. Analyzing the impact of climate change on energy-economy-carbon nexus system in China. Applied Energy 2020; 262:114568.
4. National Statistical Bureau of the People's Republic of China, China Statistical Yearbook 2018. Beijing: China Statistics Press; 2018.
5. IEA and UNIDO. Technology Roadmap: Carbon Capture and Storage in Industrial Applications; 2011.
6. BP. 2017 BP Statistical Review of World Energy [accessed 06 June 2018], https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.
7. Zhang MQ. Organic Rankine Cycle power generation using low temperature waste heat in refinery and its benefit analysis. Petroleum processing and petrochemicals 2020; 51(12): 92-95.
8. Li YR, Du MR, Wu CM, et al. Economical evaluation and optimization of subcritical
9. organicRankine cycle based on temperature matching analysis . Energy, 2014, 68: 238-247.
10. Wang E H, Zhang H G, Fan B Y, et al. Study of working fluid selection of organic Rankine
11. cycle (ORC) for engine waste heat recovery. Energy, 2011, 36(5): 3406-3418.
12. Einara Blanco Machin, Daniel Travieso Pedroso et al. Biomass integrated gasification-gas turbine combined cycle (BIG/GTCC) implementation in the Brazilian sugarcane industry: Economic and environmental appraisal. Renewable Energy, 2021, 172(5): 529-540.
13. Franco A. Power production from a moderate temperature geothermal resource with
14. regenerative organic Rankine cycles. Energy for Sustainable Development, 2011, 15: 411–419
15. Algieri A, Morrone P. Comparative energetic analysis of high-temperature subcritical and trans critical organic Rankine cycle (ORC). A biomass application in the Sibari district. Applied Thermal Engineering, 2012, 36: 236–244.

16. Liu X. A proposed coal-to-methanol process with CO2 capture combined Organic Rankine Cycle (ORC) for waste heat recovery. Journal of Cleaner Production, 2016, 129: 53–64
17. China Price Information Network [accessed 06 June 2018], http://www.chinaprice.com.cn/
18. Shen CC.Establishment of evaluation model for low temperature waste heat recovery and utilization in oil refining enterprises. Qingdao: China University of Petroleum; 2013 (in Chinese).