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Cascaded Transcritical/Supercritical CO_2 Cycles and Organic Rankine Cycles to Recover Low-Temperature Waste Heat and LNG Cold Energy Simultaneously

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***Abstract*—**Low-temperature waste heat is abundant in the process industries, and large amounts of Liquefied Natural Gas (LNG) cold energy are discarded without being recovered properly in LNG terminals. Power generation is an effective way to utilize low-temperature waste heat and LNG cold energy simultaneously. Organic Rankine Cycles (ORCs) and CO_2 power cycles are promising technologies to convert low-temperature waste heat and LNG cold energy into electricity. If waste heat and LNG cold energy are utilized simultaneously in one system, the performance may outperform separate systems utilizing low-temperature waste heat and LNG cold energy, respectively. Low-temperature waste heat acts as the heat source and LNG regasification acts as the heat sink in the combined system. Due to the large temperature difference between the heat source and the heat sink, cascaded power cycle configurations are proposed in this paper. Cascaded power cycles can improve the energy efficiency of the system considerably. The cycle operating at a higher temperature to recover waste heat is called top cycle and the cycle operating at a lower temperature to utilize LNG cold energy is called bottom cycle in this study. The top cycle condensation heat is used as the heat source in the bottom cycle. The top cycle can be an ORC, transcritical CO_2 (tCO_2) cycle or supercritical CO_2 (sCO_2) cycle, while the bottom cycle only can be an ORC due to the low-temperature range of the bottom cycle. However, the thermodynamic path of the tCO_2 cycle and sCO_2 cycle are different from that of an ORC. The tCO_2 cycle and the sCO_2 cycle perform better than an ORC for sensible waste heat recovery due to a better temperature match with the waste heat source. Different combinations of the tCO_2 cycle, sCO_2 cycle and ORC are compared to screen the best configurations of the cascaded power cycles. The influence of the working fluid and the operating conditions are also investigated in this study. Each configuration is modeled and optimized in Aspen HYSYS. The results show that cascaded tCO_2/ORC performs better compared with cascaded ORC/ORC and cascaded sCO_2/ORC for the case study.

***Keywords*—**LNG cold energy, low-temperature waste heat, organic Rankine cycle, supercritical CO_2 cycle, transcritical CO_2 cycle.

I. Introduction

LOW temperature waste heat is abundant in the process industries [1]. ORC is a promising way to utilize low-temperature waste heat. The choice of working fluid and operating conditions directly affects the performance of the system [2]. However, an important limitation of the ORC is the constant evaporation temperature, which results in a pinch point in the evaporator and poor performance for sensible heat sources. Transcritical and supercritical CO_2 cycles may perform better to convert low-temperature waste heat into electricity because of better temperature glide matching between waste heat and CO_2 without pinch limitations. CO_2 has no toxicity, no flammability, it is not explosive, easy to obtain, and when used in a cycle it has no negative effect on the environment [3]. However, due to its low critical temperature, the condensation of CO_2 is a vital problem in practice. CO_2 power cycles have considerable potential for low-temperature heat recovery if the proper heat sink is available. Nevertheless, these cycles have not received as much attention as the ORC for low-temperature waste heat recovery. It is notable that ORCs and CO_2 power cycles favor low condensation temperature to increase the thermal efficiency. If the condensation heat is rejected at a lower temperature, the performance will be improved.

LNG is a good option to transport natural gas from supplier to consumers. Natural gas is liquefied to LNG by cryogenic refrigeration after removing acid gases and water [4]. One ton of LNG consumes about 850 kWh electricity [5]. Therefore, LNG contains a considerable amount of cold energy. It is estimated that one ton of LNG can generate about 240 kWh of electricity if its cold energy is fully utilized [5]. In most LNG terminals, the re-gasification process takes place with sea water or air as heat sources and large amounts of cold exergy is wasted during this process.

If low-temperature waste heat and LNG cold energy are utilized simultaneously, the performance of the whole system can be improved considerably. Lin et al. [6] proposed a transcritical CO_2 cycle to recover LNG cold energy and waste heat from gas turbine exhaust. Only one stage power cycle is considered in their study. Therefore, large exergy losses still exist in the final design. Lee et al. [7] designed a CO_2 Rankine cycle for waste heat recovery from a coal power plant and LNG cold energy utilization. Waste heat in the form of low pressure condensate and seawater acts as heat source and LNG acts as heat sink in the power cycle. Both power output and the energy penalty resulting from the CO_2 capture process are considerably improved in the cycle. However, the results show that temperature driving forces between LNG and CO_2 in the condenser are still very large, which indicates that the cold energy of LNG is not effectively utilized. Similarly, the simultaneous utilization of low temperature heat (solar energy [8], geothermal energy [3], etc.) and LNG cold energy using a transcritical CO_2 Rankine cycle have been investigated.

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However, these studies just focus on one stage Rankine cycles to recover the low temperature heat and LNG cold energy simultaneously. Large exergy destructions still exist during the LNG regasification in these systems. In addition, due to large temperature differences between the heat source and the sink, the one stage Rankine cycle shows very large pressure drops after expansion, which may result in mechanical problems and turbine design challenges. To overcome these shortcomings, we propose in this work to use novel cascaded cycles to recover low temperature heat and LNG cold energy simultaneously. Studies focusing on both low temperature waste heat recovery and LNG cold energy utilization with cascaded power cycles are quite limited in the open literature. The optimal design of the cycles is challenging due to the many degrees of freedom in the system. This study will investigate the cascaded power cycles for simultaneous utilization of waste heat and LNG cold energy.

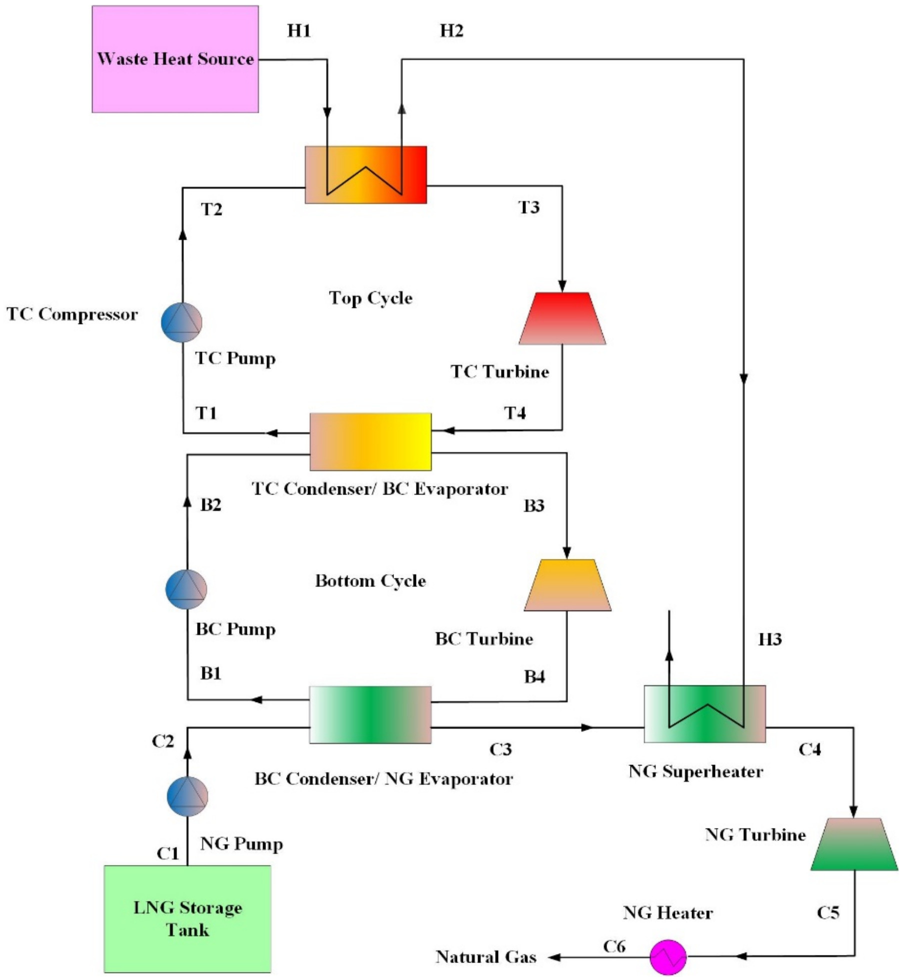

Fig. 1 Layout of the proposed cascaded power cycles

II. Cycle Description

The layout of the proposed novel cascaded power cycles is illustrated in Fig. 1. The higher temperature cycle to recover waste heat is called Top Cycle (TC), and the lower temperature cycle utilizing LNG cold energy is called Bottom Cycle (BC) in this study. Power cycles can be classified into subcritical, transcritical, and supercritical cycles according to the operating pressures. The main differences are as follows: both heat addition and heat rejection at subcritical pressures for subcritical cycles, both heat addition and heat rejection at supercritical pressures for supercritical cycles, and heat addition at supercritical pressure and heat rejection at subcritical pressure for transcritical cycles [9]. Due to the low critical temperature of carbon dioxide, the subcritical CO_2 cycle cannot be used for power generation. The TC can be a transcritical CO_2 (tCO_2) cycle, a supercritical CO_2 (sCO_2) cycle, or an ORC.

The T-S diagram of ORCs, tCO_2 cycle and sCO_2 cycle can be found in Figs. 2-4, respectively. Both the sCO_2 and tCO_2 cycles have heat addition above the two-phase region, thus waste heat matches better with the CO_2 cycles since pinch points are avoided. However, due to CO_2 critical properties, the sCO_2 and tCO_2 cycles cannot operate at cryogenic temperatures, and only the ORC is considered in the bottom cycle. Then, there are three possible configurations of the cascaded power cycle: combined ORC and ORC, combined tCO_2 cycle and ORC, and combined sCO_2 cycle and ORC. The T-S diagram of the three cascaded cycles investigated in this study is illustrated in Figs. 2-4 respectively. The TC recovers waste heat to produce electricity and acts as the heat source for the bottom cycle. The bottom cycle is an ORC and utilizes the LNG cold energy. LNG is pumped to a higher pressure and regasified in the condenser of the bottom cycle, then LNG is heated by waste heat before expansion to the target pressure. The performance of the system depends on the working fluid used in the ORC and the operating conditions of the system. The focus of this study is to compare the performance of these three configurations of cascaded power cycles.

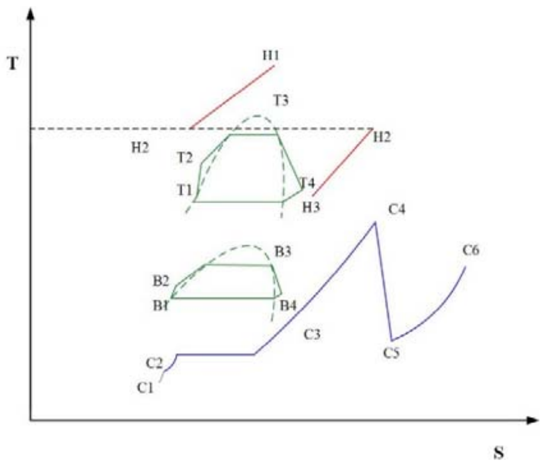

Fig. 2 Temperature-Entropy diagram for cascaded ORCs

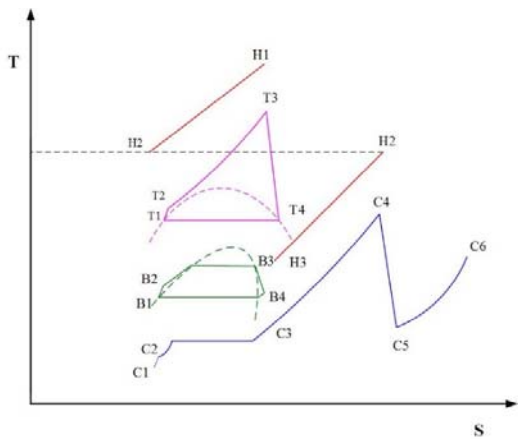

Fig. 3 Temperature-Entropy diagram for cascaded tCO_2 cycle and an ORC

It should be noted that the natural gas target pressure from LNG regasification terminals depends on the usage of natural gas. Table I shows the required pressures for different usage of natural gas [10]. In this study, we assume that natural gas is used for steam power stations and thus the target pressure is assumed to be 6 bar.

The following assumptions are made in this study for the analysis of the combined cycles. (i) LNG is composed of methane (0.95), ethane (0.02) and nitrogen (0.03), and the mass flow rate is assumed to be 1 kg/s [6]. (ii) The inlet temperature of waste heat (consisting of pure CO_2) is 150 °C and the mass flow rate is assumed to be 8 kg/s. (iii) The minimum approach temperatures for heat exchangers below, around and above ambient temperature are assumed to be 3 °C, 5 °C, and 10 °C respectively. The minimum Log Mean Temperature Difference (LMTD) of all the heat exchangers is set to 10 °C. (iv) The polytropic efficiency of turbines is assumed to be 80%, and the adiabatic efficiency of the pump is assumed to be 75%. (v) The pressure drops of unit operations are neglected.

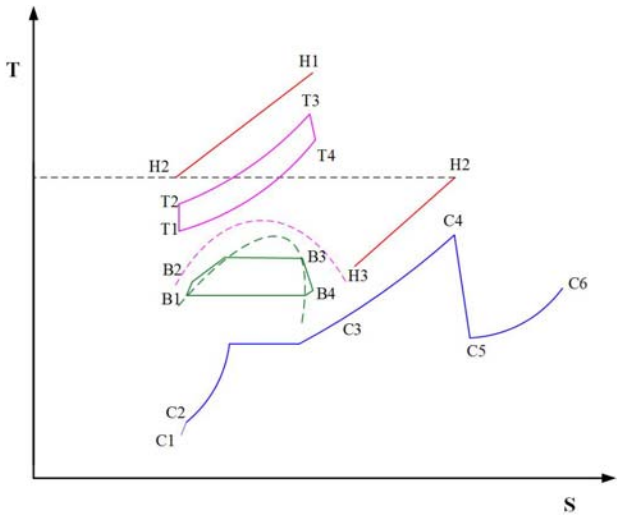

Fig. 4 Temperature-Entropy diagram for cascaded sCO_2 cycle and an ORC

TABLE I
PRESSURE SPECIFICATIONS OF DIFFERENT APPLICATIONS

Application	Pressure specification
Stream power stations	6 bar
Combined cycle stations	25 bar
Local distribution	30 bar
Long-distance distribution	70 bar

III. WORKING FLUID SELECTION FOR ORCS

There are several criteria, including physical and chemical properties, environmental and operational issues and economy for the selection of working fluid in ORCs. In this paper, the top ORC operates in the normal low-temperature range, thus the working fluid can be determined based on the open literature. Yu et al. [11] concluded that the working fluid whose critical temperature is slightly lower than the inlet temperature of the sensible waste heat performs better than other working fluids for sensible heat sources. Therefore, the TC working fluid selection depends on the waste heat source inlet temperature. R600a is adopted as the working fluid for the top ORC in this study, due to its good performance when the waste heat inlet temperature is 150 °C.

For the bottom ORC operating far below the ambient temperature, very few studies on the working fluid selection are available. The critical temperature of the working fluid should be around ambient temperature. To avoid vacuum operation, the condensation pressure should not be lower than ambient pressure. Therefore, the condensation temperature at ambient pressure should be close to the LNG evaporation temperature. Szargut and Szczygiel [12] proposed to choose ethylene as the working fluid for the bottom ORC.

For the tCO_2/ORC combination, the condensation temperature of CO_2 can be far below the ambient temperature, and the bottom ORC should operate at very low temperature. Then, the working fluid should condense at a temperature as low as the LNG temperature. As a result, ethylene is selected as the working fluid for the ORC in the tCO_2 /ORC. However, for the sCO_2/ORC and ORC/ORC combinations, the condensation temperature of the TC cannot be very low. Then, the bottom cycle should operate around ambient temperature. In our study, natural gas expansion is also considered. LNG evaporation temperature can be increased by increasing the pressure of LNG. Then, the expansion work generated by the natural gas can be increased. Therefore, a working fluid with higher critical temperature than ethylene should be selected. In this study, propane is selected as working fluid for the bottom cycle in the sCO_2 /ORC and ORC/ORC configuration, which is similar to [13].

IV. Performance Comparison of Different Configurations

All of the cascaded power cycles are modeled and optimized in Aspen HYSYS [14]. The Peng Robinson equation of state is selected to calculate the thermodynamic properties of all the working fluids and LNG. In Aspen HYSYS, simulation is performed first to get a feasible solution. A fair comparison should be done under optimal conditions of each cascaded power cycle. The built-in solver in HYSYS is used to optimize the flowsheet. The Hyprotech SQP method is selected as the optimization algorithm. Net power output rather than thermal efficiency is adopted as the comparison benchmark. The shortcoming of thermal efficiency as a criterion is that it only considers the cycle itself and does not take into account the heat source and heat sink in the process [15]. Thermal efficiency as a criterion to compare different cycles will be misleading for waste heat recovery. Therefore, the net power output of the system is more justifiable and reliable as a criterion to compare different power cycles for low-temperature waste heat recovery systems.

The performance of the cascaded power cycles studied is summarized in Table II. It is clear that the tCO_2/ORC combination performs better than the other two cascaded cycles. Even though the natural gas expansion work in the tCO_2/ORC alternative is less than that of sCO_2/ORC and ORC/ORC, the power generation of the TC and the bottom cycle justify the loss of natural gas expansion work. It can be seen that the LNG cold energy should be utilized at a lower temperature. However, these results are obtained with fixed conditions of waste heat and LNG. If the waste heat conditions vary, the conclusion may be different. In addition, the optimizer in Aspen HYSYS depends strongly on the initial value of all the variables. More powerful external optimization tools should be combined with Aspen HYSYS in future work.

TABLE II
Performance Comparison of Different Cascaded Cycles

Items	tCO_2/ORC	sCO_2/ORC	ORC/ORC
TC working fluid	CO_2	CO_2	R600a
BC working fluid	ethylene	propane	propane
TC pump work (kW)	23.7	42.2	6.0
BC pump work (kW)	5.7	2.3	3.2
LNG pump work (kW)	5.7	24.1	29.8
TC turbine work (kW)	160.9	91.8	48.5
BC turbine work (kW)	133.9	100.4	102.6
NG turbine work (kW)	129.8	230.1	245.6
Total net power output (kW)	389.5	353.7	357.7

V. Conclusions

This study has investigated the potential of cascaded power cycles to efficiently recover waste heat and LNG cold energy simultaneously. In this paper, cascaded ORC/ORC, tCO_2/ORC and sCO_2/ORC cycles are presented and optimized with net power output as the objective function. The results show that the tCO_2/ORC cycle performs best among the alternatives. The cascaded cycles can improve the energy efficiency of the system significantly. However, the waste heat and LNG specifications are fixed in this study. The results may change if different forms of waste heat are considered. However, similar procedures can be used to study various waste heat conditions. More detailed design and techno-economic optimization of the systems should be considered in future work.

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References

[1] H. Yu, X. Feng, Y. Wang, L.T. Biegler, J. Eason, A systematic method to customize an efficient organic Rankine cycle (ORC) to recover waste heat in refineries, Applied Energy 179 (2016) 302-315.
[2] H. Yu, X. Feng, Y. Wang, A new pinch based method for simultaneous selection of working fluid and operating conditions in an ORC (Organic Rankine Cycle) recovering waste heat, Energy 90 (2015) 36-46.
[3] J. Wang, J. Wang, Y. Dai, P. Zhao, Thermodynamic analysis and optimization of a transcritical CO_2 geothermal power generation system based on the cold energy utilization of LNG, Applied Thermal Engineering 70 (2014) 531-540.
[4] X. Shi, D. Che, A combined power cycle utilizing low-temperature waste heat and LNG cold energy, Energy conversion and management 50 (2009) 567-575.
[5] H. Liu, L. You, Characteristics and applications of the cold heat exergy of liquefied natural gas, Energy Conversion and Management 40 (1999) 1515-1525.
[6] W. Lin, M. Huang, H. He, A. Gu, A transcritical CO_2 Rankine cycle with LNG cold energy utilization and liquefaction of CO_2 in gas turbine exhaust, Journal of Energy Resources Technology 131 (2009) 042201.
[7] U. Lee, K. Park, Y.S. Jeong, S. Lee, C. Han, Design and analysis of a combined Rankine cycle for waste heat recovery of a coal power plant using LNG cryogenic exergy, Industrial & Engineering Chemistry Research 53 (2014) 9812-9824.
[8] Y. Song, J. Wang, Y. Dai, E. Zhou, Thermodynamic analysis of a transcritical CO2 power cycle driven by solar energy with liquified natural gas as its heat sink, Applied Energy 92 (2012) 194-203.

[9] J. Sarkar, Review and future trends of supercritical CO_2 Rankine cycle for low-grade heat conversion, Renewable and Sustainable Energy Reviews 48 (2015) 434-451.
[10] G. Bisio, L. Tagliafico, On the recovery of LNG physical exergy by means of a simple cycle or a complex system, Exergy, an International Journal 2 (2002) 34-50.
[11] H. Yu, X. Feng, Y. Wang, Working fluid selection for organic Rankine cycle (ORC) considering the characteristics of waste heat sources, Industrial & Engineering Chemistry Research 55 (2016) 1309-1321.
[12] J. Szargut, I. Szczygiel, Utilization of the cryogenic exergy of liquid natural gas (LNG) for the production of electricity, Energy 34 (2009) 827-837.
[13] I.-H. Choi, S. Lee, Y. Seo, D. Chang, Analysis and optimization of cascade Rankine cycle for liquefied natural gas cold energy recovery, Energy 61 (2013) 179-195.
[14] Aspen Technology Inc., Aspen HYSYS V9.0, Aspen Technology Inc.; Bedford, MA, 2016.
[15] Y. Chen, P. Lundqvist, A. Johansson, P. Platell, A comparative study of the carbon dioxide transcritical power cycle compared with an organic Rankine cycle with R123 as working fluid in waste heat recovery, Applied Thermal Engineering 26 (2006) 2142-2147.