

Cascaded Transcritical/Supercritical CO₂ Cycles and Organic Rankine Cycles to Recover Low-Temperature Waste Heat and LNG Cold Energy Simultaneously

Haoshui Yu, Donghoi Kim, Truls Gundersen

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 CO₂ 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 CO₂ (tCO₂) cycle or supercritical CO₂ (sCO₂) 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 tCO₂ cycle and sCO₂ cycle are different from that of an ORC. The tCO₂ cycle and the sCO₂ 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 tCO₂ cycle, sCO₂ 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 tCO₂/ORC performs better compared with cascaded ORC/ORC and cascaded sCO₂/ORC for the case study.

Keywords—LNG cold energy, low-temperature waste heat, organic Rankine cycle, supercritical CO₂ cycle, transcritical CO₂ 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 CO₂ cycles may perform better to convert low-temperature waste heat into electricity because of better temperature glide matching between waste heat and CO₂ without pinch limitations. CO₂ 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 CO₂ is a vital problem in practice. CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ capture process are considerably improved in the cycle. However, the results show that temperature driving forces between LNG and CO₂ 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 CO₂ 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.

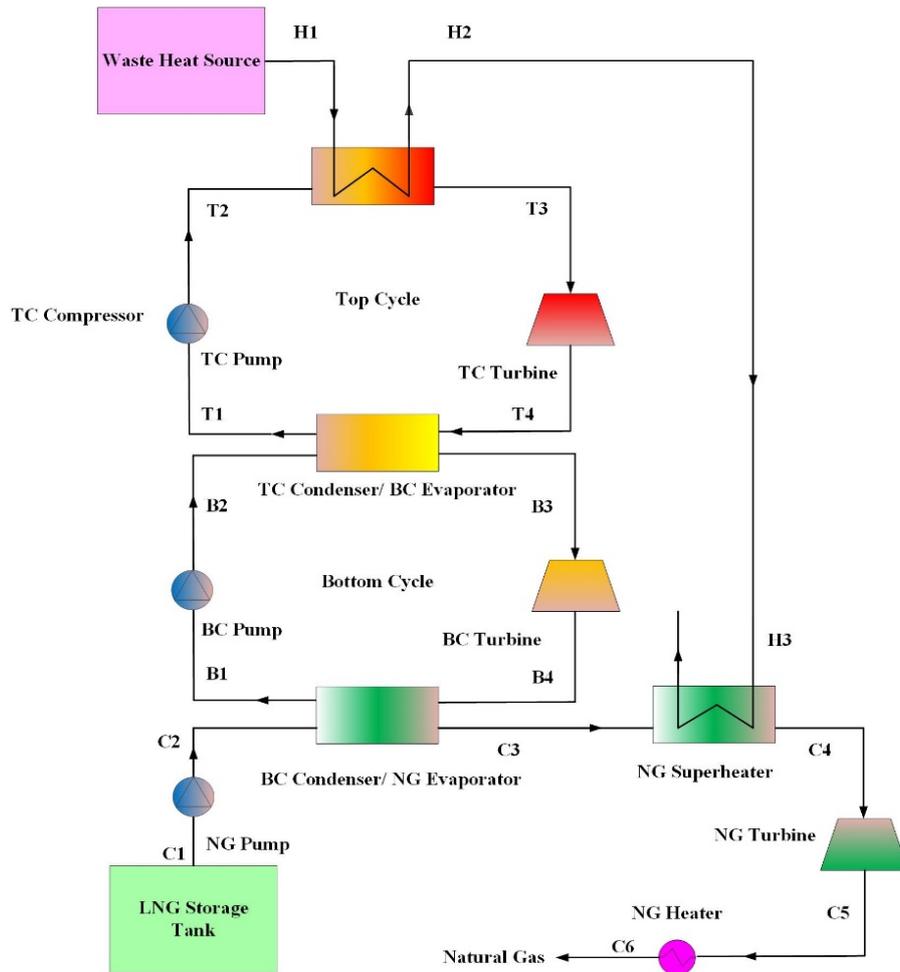


Fig. 1 Layout of the proposed cascaded power cycles

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 CO₂ cycle cannot be used for power generation. The TC can be a transcritical CO₂ (tCO₂) cycle, a supercritical CO₂ (sCO₂) cycle, or an ORC.

The T-S diagram of ORCs, tCO₂ cycle and sCO₂ cycle can be found in Figs. 2-4, respectively. Both the sCO₂ and tCO₂ cycles have heat addition above the two-phase region, thus waste heat matches better with the CO₂ cycles since pinch points are avoided. However, due to CO₂ critical properties, the sCO₂ and tCO₂ 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 tCO₂ cycle and ORC, and

combined sCO₂ 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.

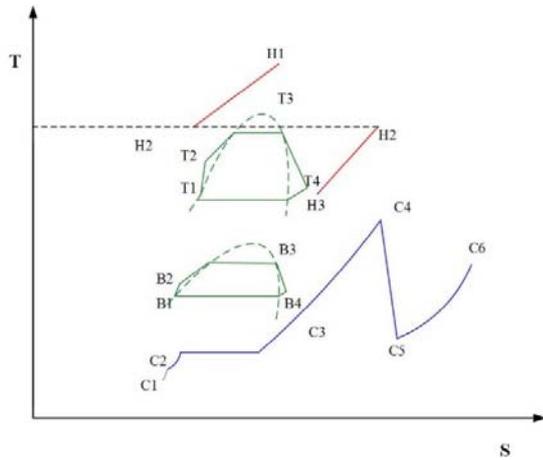


Fig. 2 Temperature-Entropy diagram for cascaded ORCs

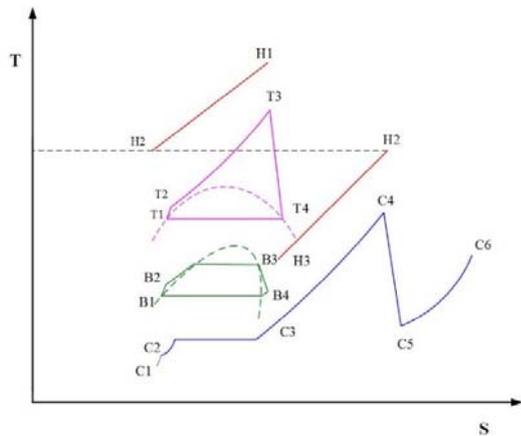


Fig. 3 Temperature-Entropy diagram for cascaded tCO₂ cycle and an ORC

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 CO₂) 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.

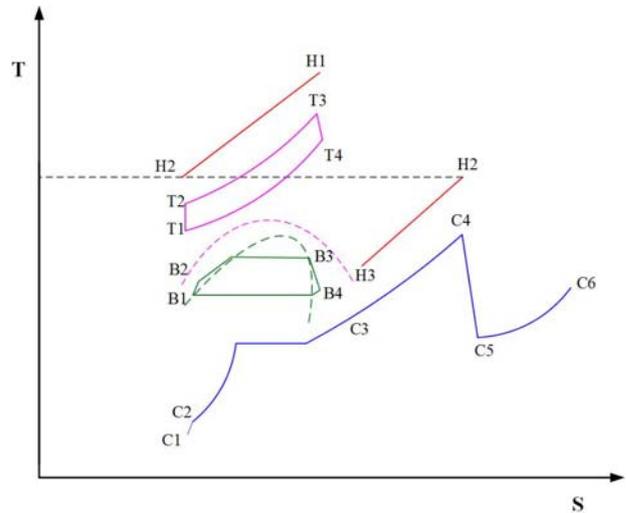


Fig. 4 Temperature-Entropy diagram for cascaded sCO₂ cycle and an ORC

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 tCO₂/ORC combination, the condensation temperature of CO₂ 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 tCO₂/ORC. However, for the sCO₂/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 sCO₂/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 tCO₂/ORC combination performs better than the other two cascaded cycles. Even though the natural gas expansion work in the tCO₂/ORC alternative is less than that of sCO₂/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, tCO₂/ORC and sCO₂/ORC cycles are presented and optimized with net power output as the objective function. The results show that the tCO₂/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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