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Invited review

# Review on recent liquefied natural gas cold energy utilization in power generation cycles

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**Abstract:**
Liquefied natural gas (LNG) needs to be gasified before supplied to the users, and considerable amount of cold energy, about 830 kJ/kg, will be released during this process. Recovery of LNG cold energy bears significance of energy-saving and environmental protection. Among the many ways of using LNG cold energy, power generation is the most effective and suitable one for large-scale applications. Many novel power generation cycles have been designed for utilizing LNG cold energy so far. This paper reviews the recent researches on LNG cold energy utilization in power generation, and discusses 15 novel power generation cycles utilizing LNG cold energy.

## 1. Introduction

### *1.1 Brief introduction to LNG*

The future energy will be characterized by cleanliness and efficiency. According to the data from World Energy Outlook 2017 (IEA, 2017) by International Energy Agency, the world energy demand will expand 30% till 2040, and natural gas, which will be increased by 45%, will become the largest single fuel in the global mix in the Sustainable Development Scenario.

Natural gas, a mixture of paraffinic hydrocarbons, which contains more than 98% $CH_4$, is a low density, low sulfur content and clean fuel (Kumar et al., 2011). For convenient storage and long-distance transportation, natural gas is usually converted to LNG, which takes up about 1/600 the volume of natural gas, by cooling the natural gas to approximately $-162°C$ at close to atmospheric pressure (Cengel et al., 2006; Mokhatab et al., 2013). Before used, LNG must be vaporized again, during which large amount of cold energy, about 830 kJ/kg (Franco, 2015), will be released at 1 atm. It is increasingly important to take advantage of this cold energy, since the consumption of LNG is continuously increasing.

### *1.2 LNG cold energy utilization*

The cold energy of LNG can be applied to all the processes that need cold, such as power generation (Oshima et al., 1978; Griepentrog et al., 2008; Shi et al., 2009; Shi et al., 2010; Liu et al., 2012; Song et al., 2012; Choi et al., 2013; Dong et al., 2013; Rao et al., 2013; Wang et al., 2013; Zhang et al., 2013; Arsalis et al., 2014; Gmez et al., 2014; Shu et al., 2014; Franco et al., 2015; Stradioto et al., 2015; Gmez et al., 2016; Sung et al., 2016; Bao et al., 2017; Ghaebi et al., 2018), cryogenic air separation (Bian et al., 2011; Xu et al., 2013; Xu et al., 2014; Mehrpooya et al., 2015; Zheng et al., 2015; Mehrpooya et al., 2016; Tesch et al., 2016; Ebrahimi et al., 2017; Mehrpooya et al., 2017), seawater desalination (Cravalho et al., 1977; Shaik et al., 2006; Wang et al., 2012; Cao et al., 2015; Chang et al., 2016; Cherchi et al., 2017; Lin et al., 2017), cold storage (Messineo et al., 2008; Messineo et al., 2011), refrigeration (Mehmet, 2002; Kalinowski et al., 2009; He et al., 2015; Meysam et al., 2015; Ansarinasab et al., 2016), liquid $CO_2$ capture (Aspelund et al., 2009; Zhang et al., 2010; Al-Musleh et al., 2015; Gmez et al., 2016; Chen et al., 2017), dry ice manufacture, light hydrocarbon separation (Gao et al., 2011; Li et al., 2015), cool storage ( Chen et al.,

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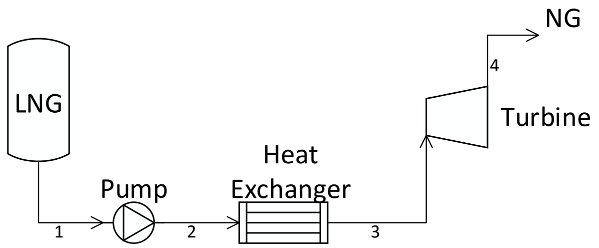

**Fig. 1.** Schematic diagram of the LNG direct expansion cycle.

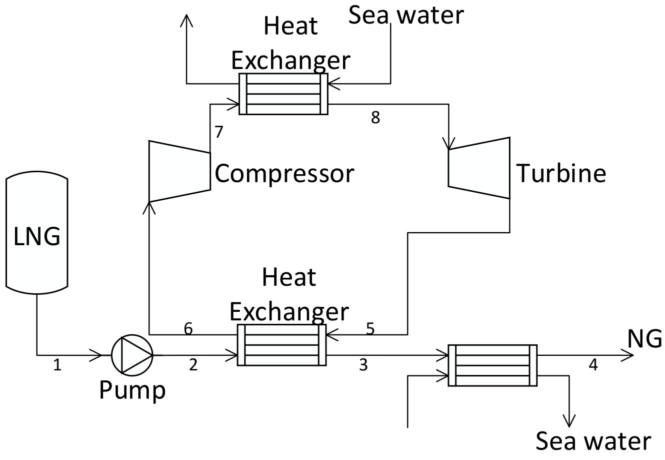

**Fig. 2.** Schematic diagram of the Rankine cycle utilizing LNG cold energy.

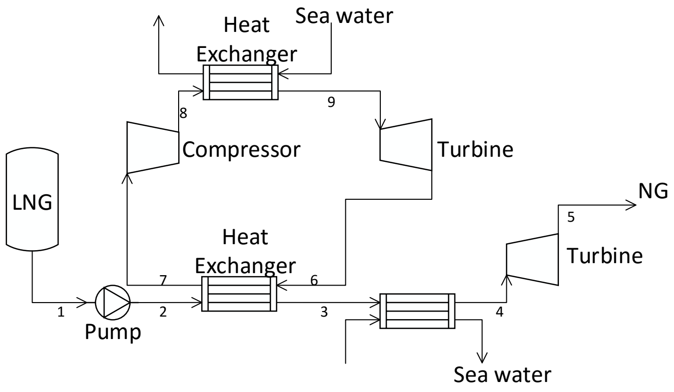

**Fig. 3.** Schematic diagram of the combined cycle using LNG cold energy.

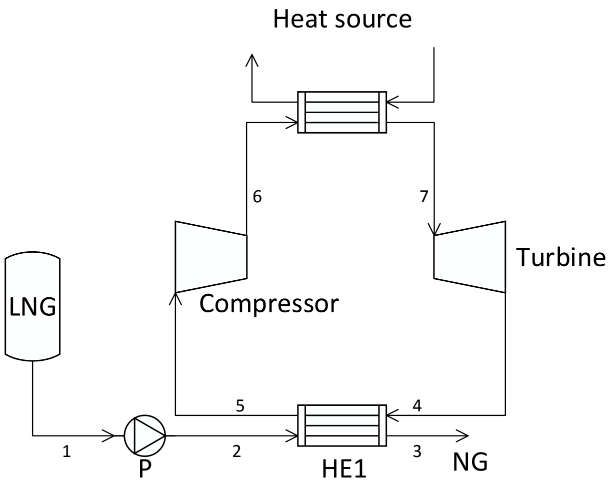

**Fig. 4.** Schematic diagram of the Brayton cycle utilizing LNG cold energy.

2017; Park et al., 2017), cryogenic comminution and so on. Among these applications, the application in power generation is the most widely used way, and the most suitable way for large-scale applications.

### *1.3 Basic power generation cycles utilizing LNG cold energy*

The study of LNG cold energy utilization for power generation dates back to 1970s, in which many power cycles have been proposed, including direct expansion cycle, Rankine cycle, combined cycle, Karina cycle, Brayton cycle, thermoelectric power generation and so on. Fig. 1 to Fig. 4 show the schematic diagram of the basic cycles (direct expansion cycle, Rankine cycle, combined cycle and Brayton cycle) for power generation utilizing LNG cold energy, details of which are discussed as follows.

The direct expansion cycle is the simplest one, and the schematic diagram is shown in Fig. 1 (Franco et al., 2015). LNG is first compressed to a high pressure by pump (1-2), then evaporated in the evaporator (2-3), thereafter the vapor is used to drive the turbine-generator (3-4), and finally the vapor is supplied to the users (4). Direct expansion cycle does not utilize the cold energy of LNG, only using the LNG pressure energy, so the efficiency is low.

Rankine cycle is another common way to utilize LNG cold energy, of which the schematic diagram is shown in Fig. 2 (Franco et al., 2015). In Rankine cycle, LNG is used as low-temperature source (the condenser), in which the working fluid is condensed (5-6). After condensed, the working fluid is compressed to a high pressure (6-7), and then evaporated in a heat exchanger by the heat from sea water (7-8).The vapor drives the turbine-generator (8-5) and produces electricity. This power generation cycle saves the energy for cooling water and avoids release of heat to the environment.

Since the Rankine cycle only uses LNG cold energy without using the pressure energy and the vaporization curve of LNG and the condensation curve of the working fluid does not match well, the efficiency is very low.

Combined cycle is a combination of direct expansion cycle and Rankine cycle, and the schematic diagram is shown in Fig. 3, in which the direct expansion cycle is represented by route 1-2-3-4-5, and the Rankine cycle is represented by route 6-7-8-9.The efficiency of this cycle is higher than that of a single cycle (Choi et al., 2013).

Brayton cycle, of which the schematic diagram is shown in Fig. 4, is a different way to utilize LNG cold energy for power generation. This cycle uses LNG cold energy to cool

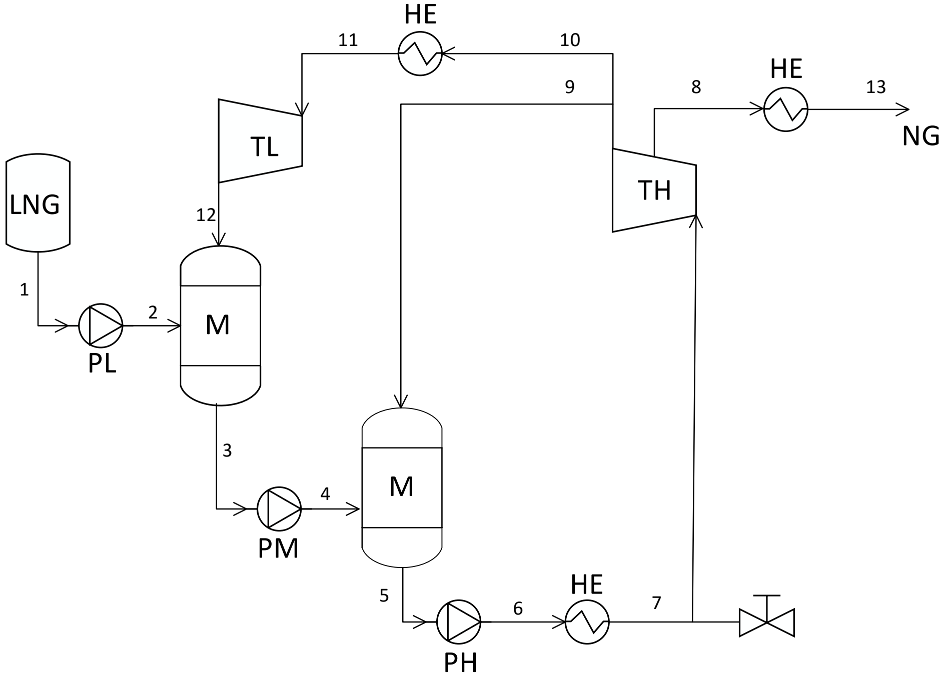

**Fig. 5.** Schematic diagram of the multi-pressure configuration. M: Mixing heat exchanger; PL/PM/PH: Low/medium/high pressure pump; HE: Heat exchanger; TL/TM/TH: Low/medium/high pressure turbine.

the inlet gas of the compressor in the Brayton cycle (4-5), saving the energy consumption of the compressor. It improves the efficiency of power generation (Zhang et al., 2009).

## 2. Recent advanced power generation cycles using LNG cold energy

Although LNG cold energy is utilized in the basic power generation cycles, the efficiency is still not satisfactory. There have been a lot of researches focusing on improving the efficiency of the power generation cycles, and many advanced power generation cycles utilizing LNG cold energy were proposed. In this review, only the researches after the year of 2010 is discussed, and some previous research can be referred to (Griepentrog et al., 1976; Angelino et al., 1978; Krey, 1980; Najjar et al., 1991; Najjar et al., 1993; Wong, 1994; Kim et al., 1995; Chiesa et al., 1997; Hisazumi et al., 1998; Miyazaki et al., 2000; Deng et al., 2004; Kaneko et al., 2004; Wang et al., 2004; Zhang et al., 2006; Shi et al., 2007; Bai et al., 2008; Lu et al., 2009; Shi et al., 2010; Tsatsaronis et al., 2010).

### *2.1 Multi-pressure LNG direct expansion cycle*

The conventional LNG direct expansion cycle only has a simple expansion at a single pressure level. For obtaining higher efficiency, it is necessary to introduce more complex thermodynamic cycles. Alessandro Franco et al. proposed a new direct cycle with two or three pressure levels of LNG (Franco et al., 2015).

The schematic diagram of the proposed two-pressure level direct expansion cycle is shown in Fig. 5. LNG was compressed by low-pressure pump first (1-2), then mixed with NG from low-pressure turbine, becoming a higher-temperature LNG. Then LNG was compressed by medium-pressure pump (3-4), and mixed with NG from high-pressure turbine, becoming a higher-temperature LNG. Afterwards, the LNG was compressed up by a high-pressure pump, and then vaporized through the heat exchanger. The vapor then drove the turbine-generator and produced electricity (7-9). At this point, LNG was divided into three shares: users, mixer and low pressure turbine. Their analysis indicated that LNG's power generation potential was about 120 kJ/kg for this system under ideal conditions.

They also analyzed a more complex system, a direct cycle with three pressure levels, as shown in Fig. 6. Compared with the two-pressure level direct expansion cycle, a recovery heat exchanger was added between the high-pressure pump and heat exchanger (6-7), and a medium-pressure turbine was added between the high-pressure turbine and low-pressure turbine (11-14). The power generation potential of LNG was reported to be 160 kJ/kg.

The pressure loss of the traditional direct expansion method is very large, while this method utilized the pressure energy at different pressure level, by which the efficiency was greatly improved. This system is not very complex, and has practical value.

### *2.2 A cogeneration cycle utilizing LNG cold energy*

Griepentrog et al. proposed a new power generation cycle, shown in Fig. 7 (Griepentrog et al., 2008), which combined a cogeneration cycle with a Brayton cycle utilizing LNG cold

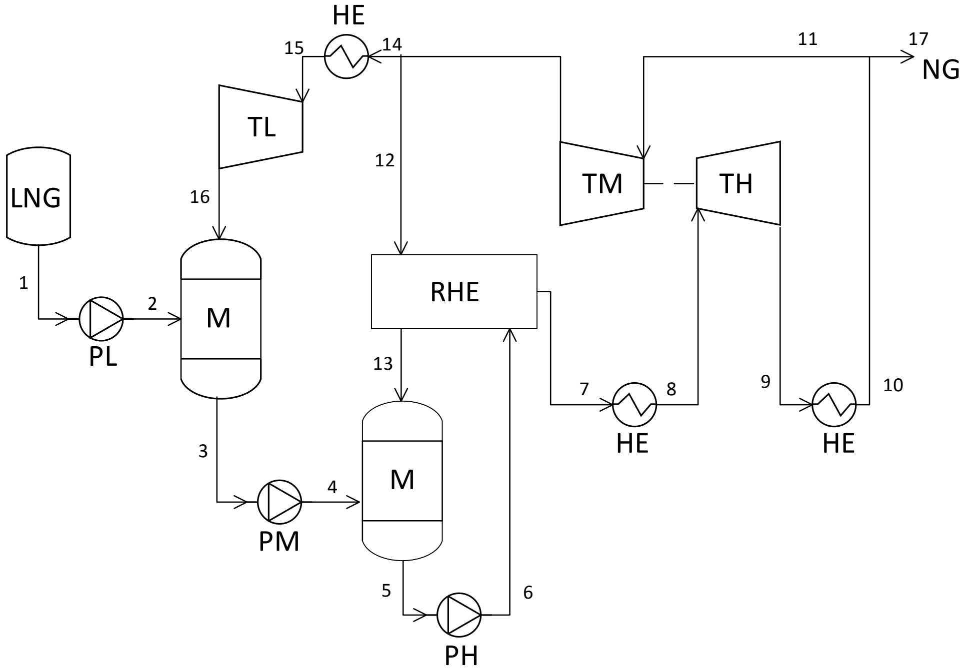

**Fig. 6.** Schematic diagram of the multi-pressure configuration with RHE.

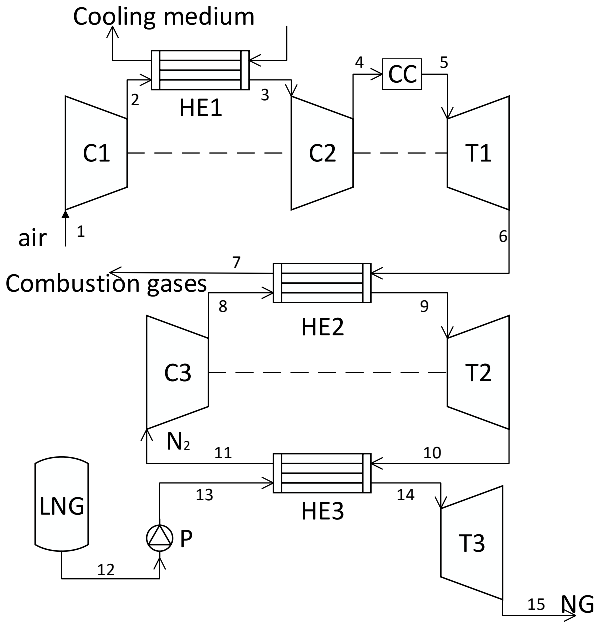

**Fig. 7.** Schematic of the cogeneration system utilizing LNG. C: Compressor; CC: Combustor chamber; HE: Heat exchanger; T: Turbine.

energy. A nitrogen Brayton cycle was established between LNG evaporator and the gas turbine, with the high-temperature gas exhaust from gas turbine as the heat source, LNG as the cold source, and nitrogen as the working fluid. This cycle recovered the cold energy of LNG and increased the general efficiency of the combined cycle. Under ideal condition, the production efficiency and the exergetic efficiency of this system were reported to be 56.4% and 49.54%, respectively.

As shown in Fig. 7, nitrogen was compressed by compressor (11-8), and then heated by the exhaust from the gas turbine (8-9), and finally drove turbine to work. The next cycle began when nitrogen was cooled by LNG (10-11). LNG was heated and evaporated by hot nitrogen (13-14), and the vapor drove the turbine to work (14-15), and finally supplied to the users.

By introducing the nitrogen Brayton cycle, this system recovered the heat of exhaust gas from gas turbine by two means: heating and power generation. This cycle improved the power generation efficiency. However, more LNG cold energy was wasted too much at the condenser.

## 2.3 A combined-cooling- heating-and-power generation cycle utilizing LNG

Arsalis et al. proposed a combined-cooling-heating-and-power (CCHP) system utilizing LNG as fuel, and also utilizing LNG cold energy for cooling compressor inlet air (Arsalis et al., 2014). The exergetic efficiency was 41.9% for this system, higher than the traditional system by about 25%.

The schematic diagram of the proposed CCHP system is shown in Fig. 8. The air was cooled by LNG at the inlet of the compressor before entering the combustor (2-3). In the combustor, LNG and air burned together to produce high-temperature gas, driving turbine generator (6-7) to produce electricity. The heat of the exhaust gas can be used for heating in winter (8), or used as a heat source for absorption refrigeration (10).

This system only used the cold energy and combustion energy of LNG, while the pressure energy was wasted. The

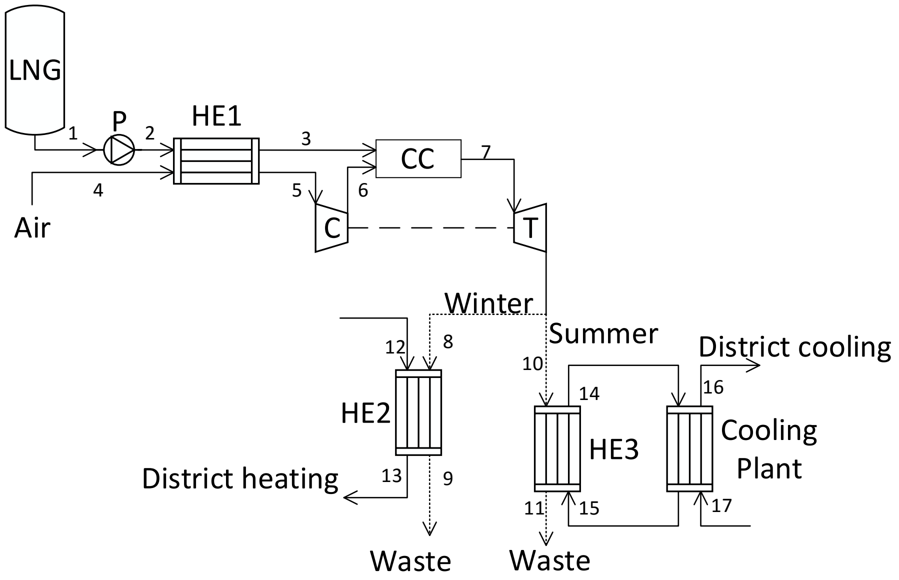

**Fig. 8.** Schematic diagram of the new CCHP system with LNG. C: Compressor; CC: Combustor chamber; HE: Heat exchanger; P: Pump; T: Turbine.

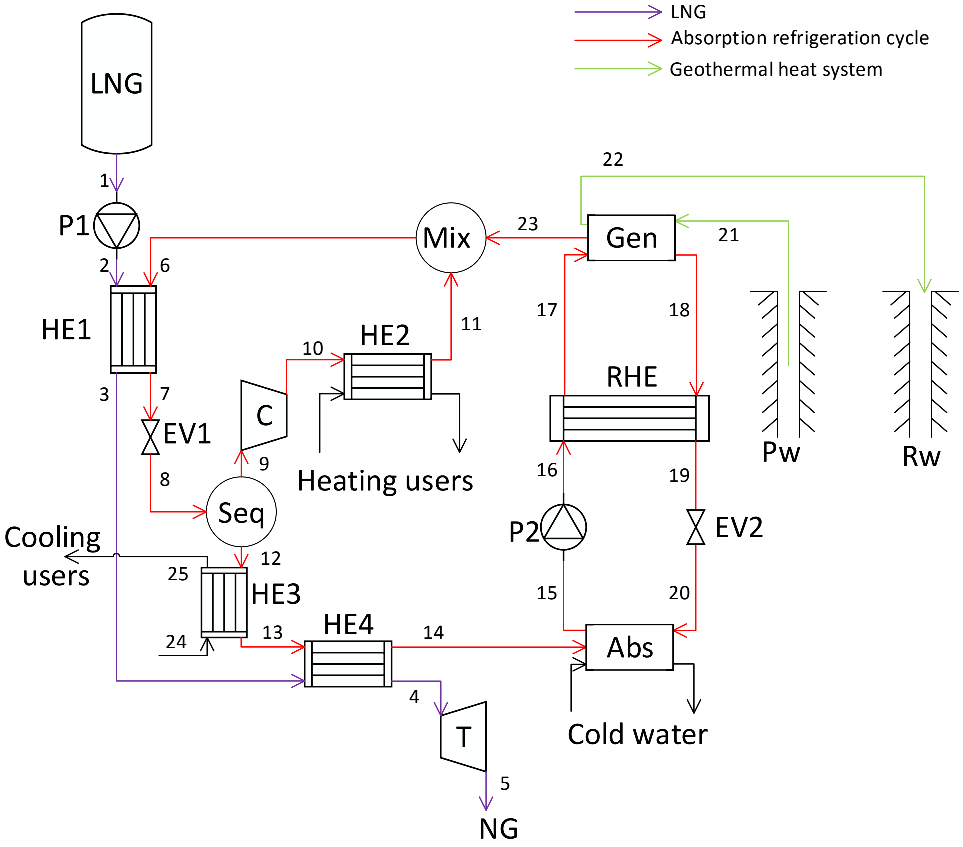

**Fig. 9.** Schematic diagram of the trigeneration system utilizing LNG. Abs: Absorber; C: Compressor; EV: Expansion valve; Gen: Generator; HE: Heat exchanger; Mix: Mixer; P: Pump; Pw: Producing well; RHE: Recovery heat exchanger; Rw: Recharge well; Seq: Separator; T: Turbine.

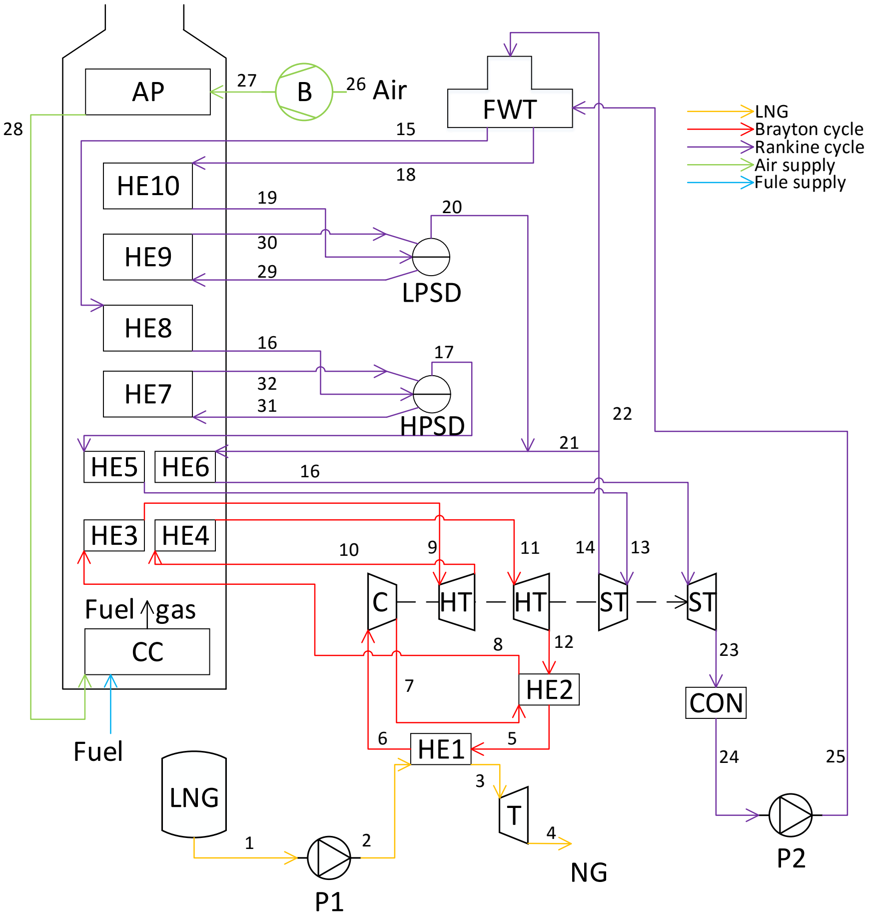

**Fig. 10.** Schematic diagram of the combined power generation cycle utilizing LNG cold and pressure energy (Type I) AP: Air preheater; B: Blower; C: Compressor; CC: Combustion chamber; CON: Condenser; FWT: Feed water tank; HE: Heat exchanger; HPSD: Low pressure steam drum; HT: Helium turbine; LPSD: High pressure steam drum; P: Pump; ST: Steam turbine.

efficiency of this system can be further improved, such as by driving the turbine to work before LNG entering the combustion chamber.

## 2.4 A trigeneration cycle utilizing geothermal heat and LNG cold energy

Ghaebi et al. proposed a trigeneration cycle for power generation, with geothermal heat as the heat source, and LNG cold energy as the cold source (Ghaebi et al., 2018). The thermal efficiency of this system was reported to be 85.92%, with the exergetic efficiency being 18.52%.

The schematic diagram of the proposed trigeneration cycle is shown in Fig. 9. LNG was compressed to a high pressure by pump (1-2), after which a part of LNG was evaporated in the heat exchange HE1 (2-3). Afterwards, all LNG vaporized in the heat exchanger HE4 (3-4). Finally, LNG vapor drove turbine to work (4-5). In the absorption refrigeration part, the heat source of the generator was geothermal. The refrigerant was evaporated in the generator and the steam flew into the mixer, mixing with high temperature refrigerant steam (from 11), and then cooled by LNG in the heat exchanger HE1 (6-7) and entered the separator after depressurization (7-8). After the separator, the refrigerant steam was divided into two routes: In the first route, the relatively high-temperature steam was compressed (9-10) to a higher temperature, and then entered the heat exchanger HE2 (10-11), providing heat to the heating users, and finally entered the mixer. In the second route, the relatively low temperature fluid entered the heat exchanger HE3, providing cold energy to the cooling users (12-13) through liquid evaporation. LNG was then completely vaporized in heat exchanger HE4 (13-14), and finally the refrigerant steam flew back to the absorber (14).

By the combination of absorption refrigeration cycle, geothermal and LNG cold energy utilization, this trigeneration system can be used for heating, cooling as well as power generation. This system is very energy-saving, but very complex.

## 2.5 The combined power generation cycle utilizing LNG cold and pressure energy (Type I)

Gómez et al. introduced a power generation cycle, which was composed of a closed helium Brayton cycle, a steam Rankine cycle, and a LNG direct expansion cycle, as shown in Fig. 10 (Gómez et al., 2014). In this power generation cycle, LNG was used to cool the inlet gas of compressor in the

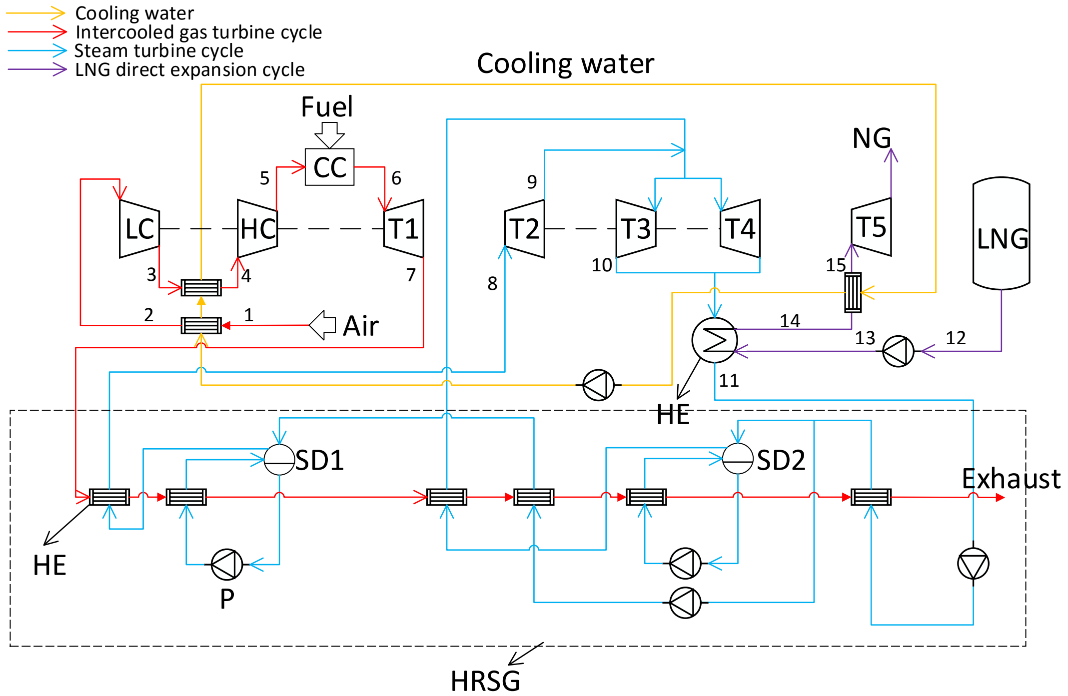

**Fig. 11.** Schematic of the combined power generation cycle utilizing LNG cold and pressure energy (Type II). CC: Combustion chamber; HC: High pressure compressor; HE: Heat exchanger; HRSG: Heat recover steam generator; LC: Low pressure compressor; P: Pump; SD: Steam drum; T: Turbine.

Brayton cycle. It was proved that the thermal efficiency of the power plant can be as high as 56.72%.

This system fully utilized the heat of high-temperature gas in multi stages, proving heat source for closed helium Brayton cycle, high-pressure steam Rankine cycle, low-pressure steam Rankine cycle, and air preheater, which achieved much higher thermal efficiency.

## *2.6 The combined power generation cycle utilizing LNG cold and pressure energy (Type II)*

Shi et al. proposed a new power generation cycle by introducing the use of LNG cold energy to the traditional combined cycle (Shi et al., 2010). The new system was composed of a Brayton cycle with intermediate cooling, a steam Rankine cycle and a LNG direct expansion cycle, as shown in Fig. 11. As shown in the figure, the inlet cooling and intermediate cooling for Brayton cycle (red line) and outlet cooling for Rankine cycle (blue line) were added by indirect utilization of LNG cold energy. LNG evaporated with the exhaust heat from Brayton cycle and Rankine Cycle, and was then supplied to the users.

This system is a consortium of three cycles. The system takes advantage of waste heat and LNG cold energy, and also supplies natural gas and saves the electricity needed for the sea water pump. As reported, the net electrical efficiency and the overall work output of the new system can be increased by 2.8% and 76.8 MW compared with those of the conventional combined cycle, respectively.

## *2.7 A combined power generation cycle utilizing LNG cold energy and combustion energy*

Stradioto et al. proposed a different new power generation cycle utilizing LNG cold energy, which is sketched in Fig. 12 (Stradioto et al., 2015). Two integration alternatives, alternative 1 (1-4-5-6) and alternative 2 (2-3-4-5-6) were investigated. In the first alternative, the air was cooled by LNG at the inlet of the first compressor (7-8) and at the inlet of the second compressor (9-10) in the Brayton cycle (purple line). In the second alternative, LNG was used to condensate the high-temperature steam at the outlet of the last turbine (17-18) in the Rankine cycle (red line), in addition to the same cooling position in the first alternative.

Two integration alternatives were compared to a reference case without any use of the LNG cold potential. As their analysis showed, the efficiency of the first alternative was 55.45%, and that of the second one was 58.31%, while that of the reference case was 49.22%. When considering the thermal energy for LNG regasification, the thermal efficiency of the first and second alternative reached 62.76% and 86.34% respectively, and the exergy efficiency reached 57.55% and 67.13% respectively. The disadvantage of this system is the waste of the pressure energy of LNG.

## *2.8 A power generation cycle for LNG cold energy utilization and $CO_2$ capture (Type I)*

Gómez et al. proposed a new power plant cycle for utilizing of LNG and capturing $CO_2$, which is sketched in Fig. 13

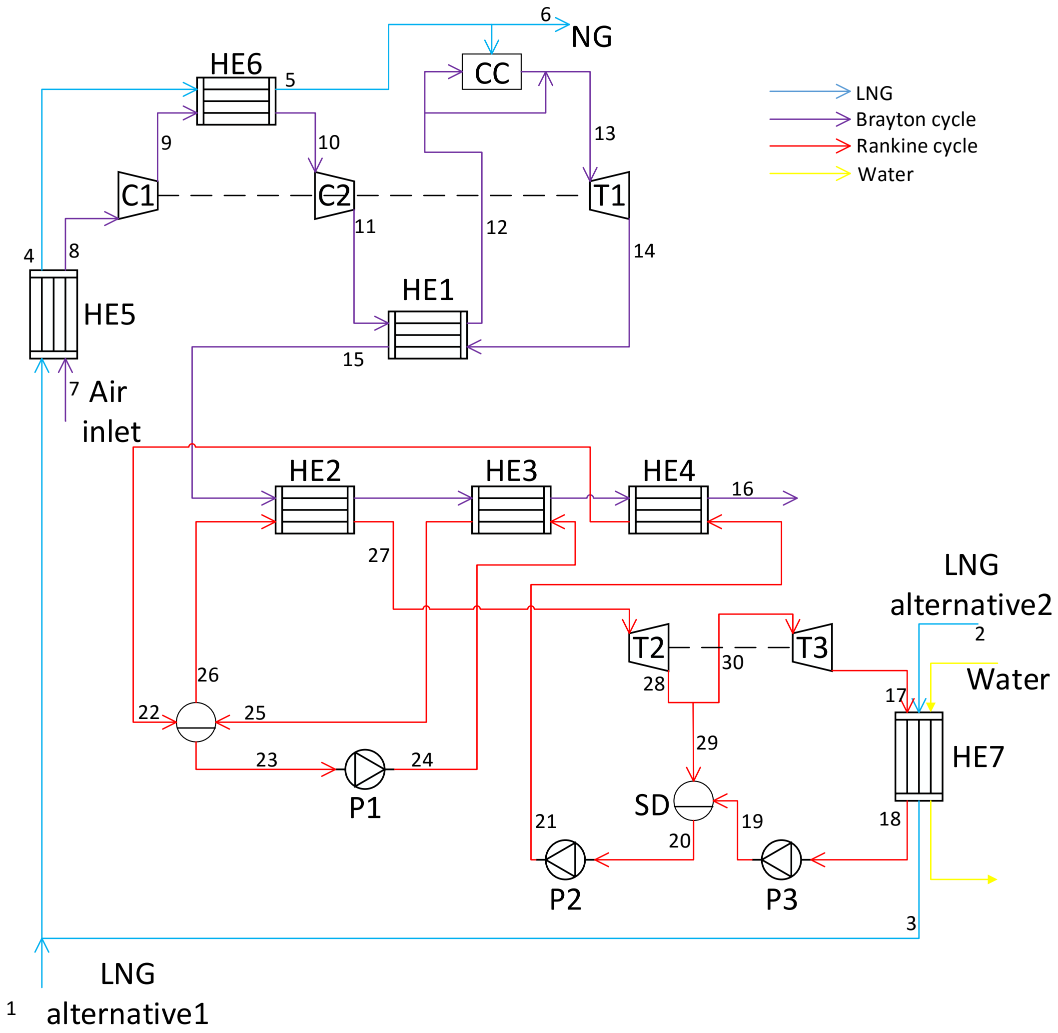

**Fig. 12.** Schematic of the combined power generation cycle utilizing LNG cold energy and combustion energy. C: Compressor; CC: Combustion chamber; HE: Heat exchanger; P: Pump; SD: Steam drum; T: Turbine.

(Gómez et al., 2016). In this power generation cycle, LNG cold energy was used by four means: cooling inlet air in the Brayton cycle (11-12), LNG direct expansion cycle (4-5), as fuel in the whole system (in the boiler), and as cold source for condensing $CO_2$ (in HX6). Since the cold energy of LNG was fully utilized, it was proved that the efficiency of the power plant reached 65%; and since the $CO_2$ was liquefied by LNG and could be easily handled, $CO_2$ emission was almost zero.

A similar combined cycle for $CO_2$ capture can also be referred to Xiang's research (Xiang, et al., 2018), in which the energy and exergy efficiency of the proposed system was reported to be 55.3% and 52.9% respectively.

### *2.9 A power generation cycle for LNG cold energy utilization and $CO_2$ capture (Type II)*

Zhang et al. proposed another power plant for LNG cold energy and $CO_2$ capture. The schematic diagram of the proposed power generation cycle is shown in Fig. 14 (Zhang et al., 2010), in which the main body of this system is a $CO_2$ power cycle. In the $CO_2$ power cycle, liquid $CO_2$ was pressurized by the pump 2 and then supplied to evaporator (1-2), where liquid $CO_2$ was heated to steam (2-3). If necessary, the cooling capacity of $CO_2$ here could be used for refrigeration. Afterwards, the $CO_2$ mixed with oxygen from compressor 2 and then preheated in RHE before entering the combustion chamber together with LNG from HE3 (3-4-5-6-7-8). High-temperature gas was produced in the combustion chamber, and the gas drove turbine to produce electricity (8-9). Then, the high-temperature gas was cooled in the HE4, after which the liquid water was separated in SE2 (10-11-12). The anhydrous gas was compressed and then supplied to the condenser, in which the $CO_2$ was condensed by LNG (13-14). Part of the liquid $CO_2$ was captured in the separator (25-26-27), and another part continued to circulate (1).

This system is ingenious to combine the $CO_2$ power cycle with the LNG cold energy utilization, in which $CO_2$ can be withdrawn from the cycle without consuming additional power. This is also a versatile and energy-efficient system. As reported, the energy efficiency of this system can reach 59%.

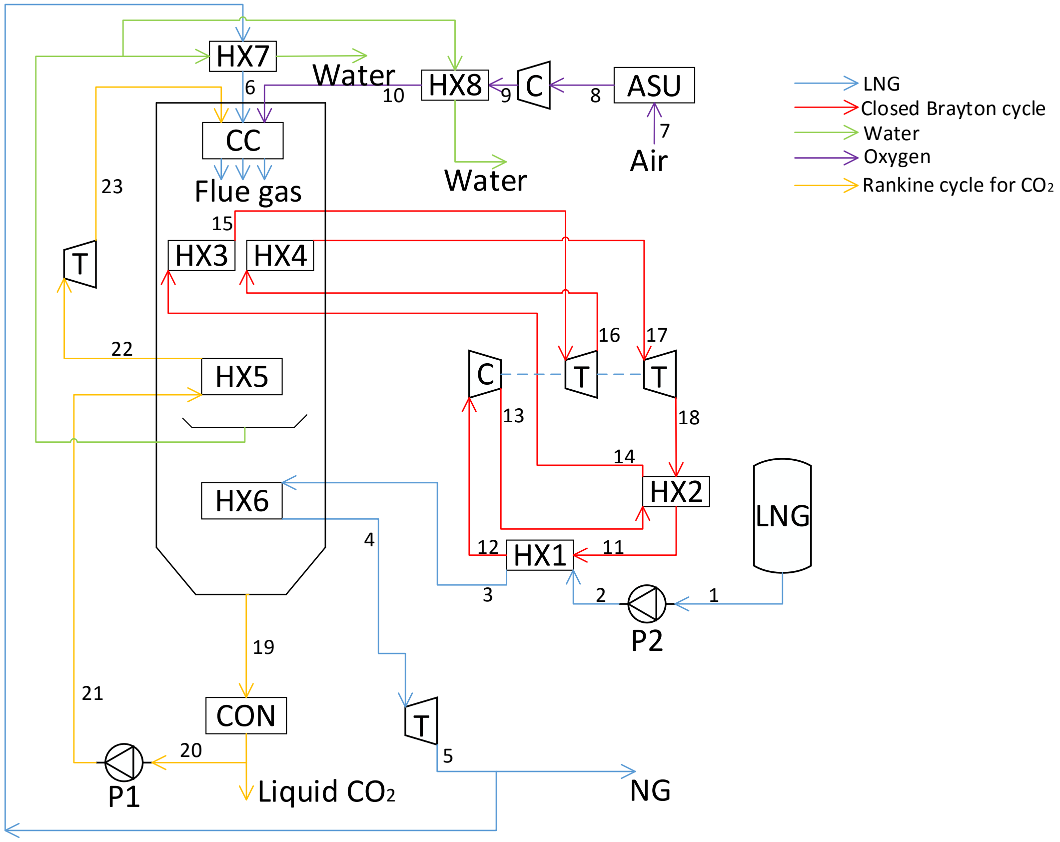

**Fig. 13.** Schematic diagram of the new power plant for LNG cold and $CO_2$ capture. ASU: Air separation unit; C: Compressor; CC: Combustion chamber; CON: Condenser; HE: Heat exchanger; P: Pump T: Turbine.

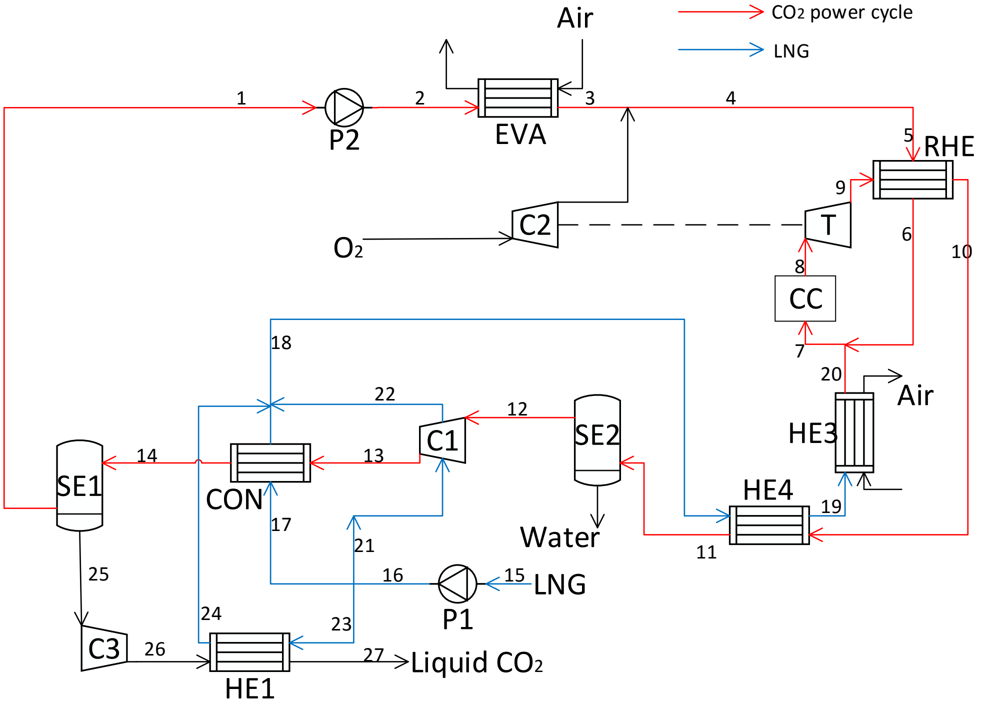

**Fig. 14.** Schematic of the new power plant for LNG cold energy and $CO_2$ capture (Type II). C: Compressor; CC: Combustion chamber; CON: Condenser; EVA: Evaporator; HE: heat exchanger; P: Pump; RHE: Recovery heat exchanger; SE: Segregator.

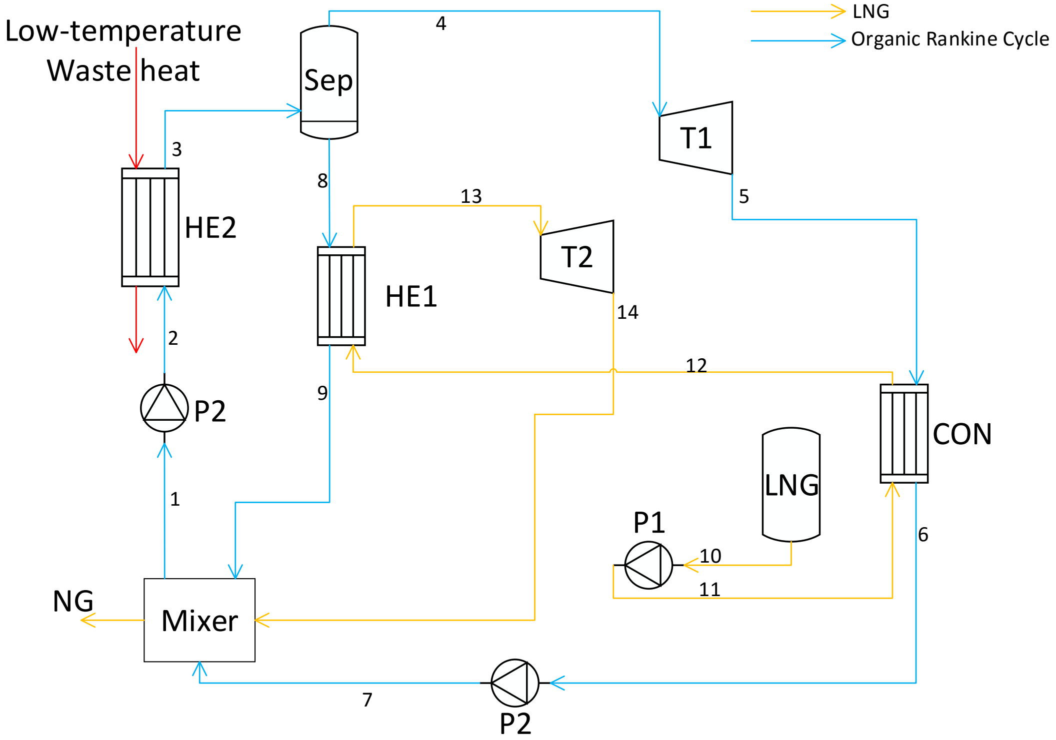

**Fig. 15.** Schematic of the combined power cycle with low-temperature waste heat and LNG cold energy. CON: Condenser; HE: Heat exchanger; P: Pump; Sep: Separator; T: Turbine.

## 2.10 A combined cycle utilizing low-temperature waste heat and LNG cold energy

Shi et al. (Shi et al., 2009; Wang, 2013) proposed a new power generation cycle, in which an ammoniawater mixture organic Rankine cycle and an LNG direct expansion power cycle were included, as shown in Fig. 15. Ammonia-water solution was pressurized by the pump 2 to and then supplied to heat exchanger HE2 (1-2), where ammoniawater solution was heated by low-temperature waste heat (2-3) and evaporated. The mixture was separated in the separator, after which ammonia-rich vapor drove the turbine T1 to work and produce electricity (4-5), while weak ammonia-water solution flew back to the mixer (8-9). Afterwards, the weak ammonia solution and the ammonia rich vapor were cooled by LNG (11-12 and 12-13). The ammonia rich vapor was condensed, and then transported back to the mixer, while LNG vapor drove turbine T2 to work and produce electricity (13-14).

In this system, low-temperature waste heat can be recovered and cold energy of LNG can be fully utilized as well. As analyzed, the first and second law efficiency reached 39.33% and 55.62% respectively.

## 2.11 A Cascade Rankine cycle for LNG cold energy recovery

Since the phase transition temperature of the working medium for Organic Rankine Cycle (ORC) is constant, the vaporization curve of working medium and the vaporization curve of LNG do not match well, and thus the energy efficiency is very low. Choi et al. proposed a new cycle, namely Cascade Rankine cycle (Choi et al., 2013). In this cycle, the LNG cold energy was divided into multiple levels. Fig. 16 and Fig. 17 show the schematic diagrams of the two-stage cascade Rankine cycle and three-stage cascade Rankine cycle respectively. In each Rankine cycle, seawater and LNG were used as the heat source and cold source respectively.

The energy efficiency was greatly improved by this cascade Rankine cycle. In Choi's study, eleven designed cycles, including two-stage and three-stage cascade were compared, showing that the three-stage Rankine cycle with propane as working medium had the highest efficiency. The thermal efficiency and exergy efficiency reached 12.5% and 65.2% respectively. It was also found that the efficiency generally increased as the number of stages increased, but the complexity of the system also increased.

Based on this study, Bao et al. studied the effect of the number of LNG condensing stages on the efficiency of cold energy recovery (Bao et al., 2017). In their study, seven systems, including direct expansion cycle, organic Rankine cycle (ORC), combined cycle, and four different multi-stage cycles (two-stage organic Rankine cycle, three-stage organic Rankine cycle, two-stage combined cycle, three-stage combined cycle) were studied. It was found that, efficiency generally increased as the number of stages increased; and that the efficiency of the combined cycle was the highest in the same stage, so the efficiency of three-stage combined cycle was the highest.

This type of cascade Rankine cycle uses multi-stage ORC for full utilization of LNG cold energy, and the disadvantage

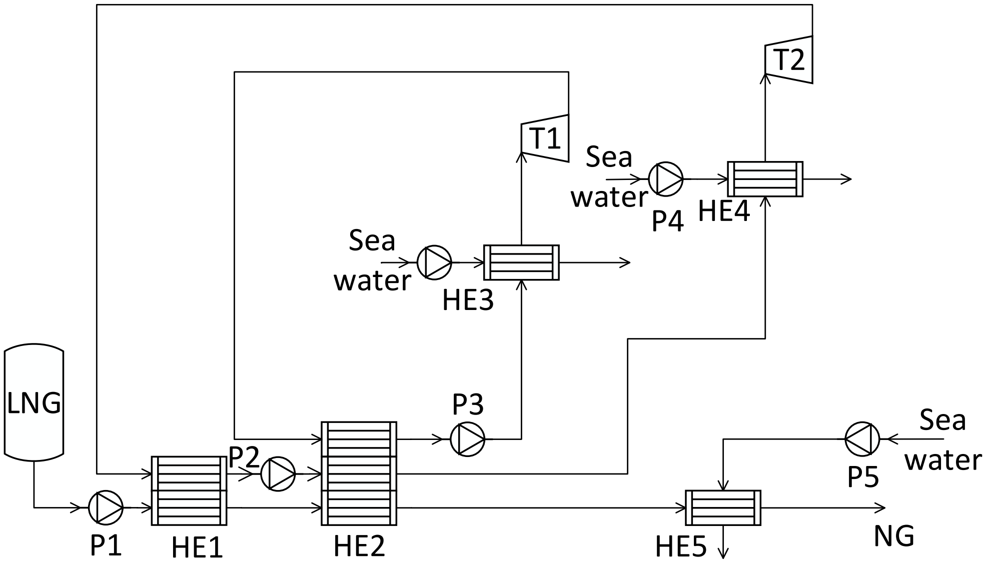

**Fig. 16.** Schematic diagram of the two-stage cascade Rankine cycle.

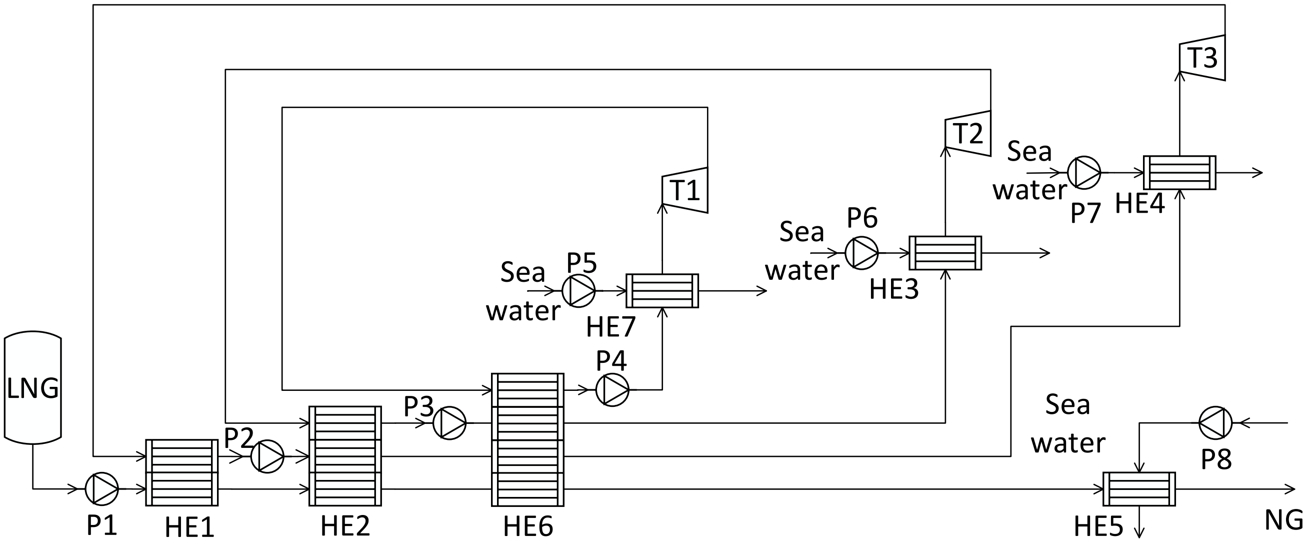

**Fig. 17.** Schematic diagram of the three-stage cascade Rankine cycle.

is the waste of pressure energy of LNG.

## 2.12 A dual-loop ORC utilizing engine waste heat and LNG cold

Sung et al. proposed a new dual-loop ORC cycle (Sung et al., 2016), based on the dual-loop ORC for engine waste heat by Shu et al. (2014). The proposed cycle, named DL-ORC, was a dual-loop cycle based on the dual fuel engine of a LNG carrier, as shown in Fig. 18. The dual-loop was composed of a high temperature loop (HT-ORC) and a low temperature loop (LT-ORC). The heat source of the HT-ORC was the waste heat of the engine exhaust, and the cold source was the sea water. While, the heat source of the LT-ORC was the waste heat from the engine cooling water, and the cold source was the LNG cold energy. As shown in Fig. 18, the LT-ORC (blue line) absorbed heat from high-temperature cooling water of the engine in HE2 (9-10) and released heat to LNG in the HE1 (7-8); While, HT-ORC absorbed heat from exhaust gas of the engine in HE5 (13-14) and released heat to sea water in the heat exchanger HE4 (11-12).

With n-pentane and R125 as the working fluids for HT-ORC and LT-ORC respectively, the proposed cycle was proved to produce a power output that was 4.15% of the original engine output. Besides this, an optimized scheme was also proposed, in which a preheater and regenerator were added to the HT-ORC, as shown by the dotted line in Fig. 18. Route (18-19) was the preheating process and (15-16) was

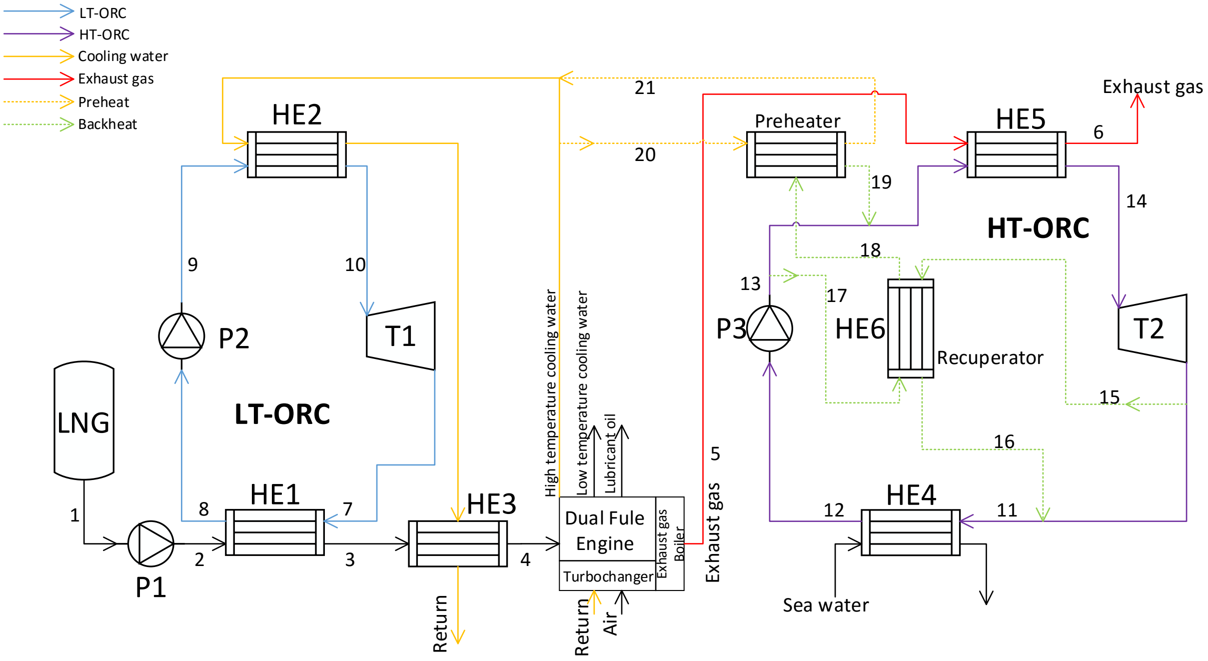

**Fig. 18.** Schematic of the dual-loop ORC system. HE: Heat exchanger; P: Pump; T: Turbine.

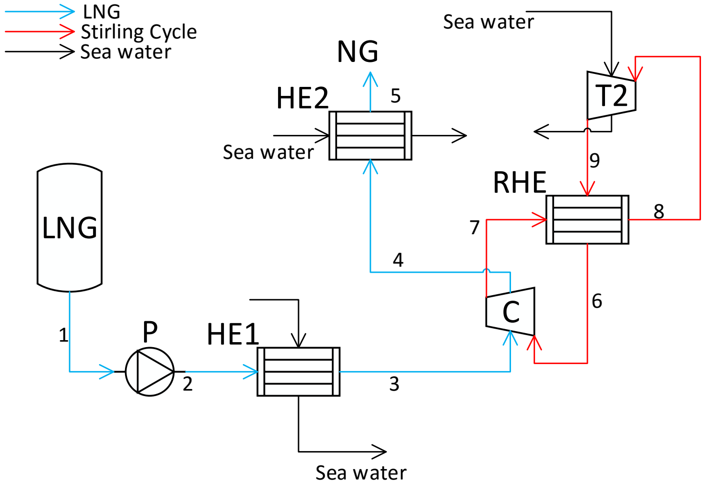

**Fig. 19.** Schematic of the Stirling cycle with LNG cold. C: Compressor; HE: Heat exchanger; P: Pump; T: Turbine.

the regenerative process. The output power of the optimized scheme was reported to be 5.17% of the original engine output.

## *2.13 A Stirling cycle utilizing LNG cold energy*

Dong et al. proposed a LNG-based Stirling cycle (Dong et al., 2013) based on Oshima's research (Oshima et al., 1978), in which the sea water was used as the heat source and LNG cold was used as the cold source. The working medium was nitrogen in Stirling cycle. The schematic diagram of the proposed Stirling cycle is shown in Fig. 19, in which the Stirling cycle was represented by the red line (6-7-8-9). LNG was pressurized to vaporization pressure through the pump, then heated to saturation temperature in heat exchanger HE1, and then cooled the nitrogen in compressor T1 and partially vaporized, and finally completely evaporated to NG in heat exchanger HE2 before supplied to the users.

As analyzed, the power output of the Stirling cycle was greater than that of Senboku Daini cryogenic power station in Japan by 14.97%. Since a large portion of the LNG cold energy has been lost to the sea water, the air separation unit can be introduced to make full use of the LNG cold energy instead of sea water heat exchanger.

The waste heat from other systems can also be introduced as the heat source in this cycle. Wang et al. proposed a

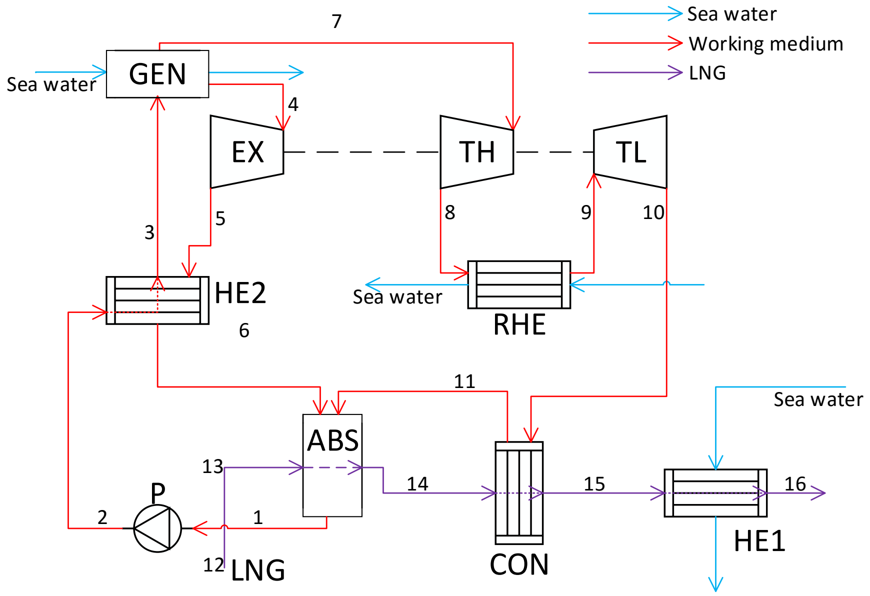

**Fig. 20.** Schematic of the cryogenic power cycle with binary working medium for LNG cold. ABS: Absorber; CON: Condenser; EX: Expander; GEN: Generator; HE: Heat exchanger; RHE: Recovery heat exchanger; TL/TH: Low/high pressure turbine.

thermoacoustic Stirling electricity generator ( Wang, et al., 2017) for dual-utilizations of LNG cold energy and low-grade waste heat. As reported, the optimized system was able to reach an output electric power of 2.3 kW with the highest exergy efficiency of 0.253 at 4 MPa helium gas.

## *2.14 A cryogenic power cycle with binary mixture utilizing LNG cold energy*

The condensation curve of the multi component mixture is better matched with the LNG vaporization curve. If a multi component mixture is used as a refrigerant in a power generation cycle with LNG cold, the higher efficiency can be obtained. Liu et al. proposed a cryogenic power cycle for LNG cold energy recovery (Liu et al., 2012), based on the principle of absorption refrigeration. The binary mixture of Tetrafluoromethane ($CF_4$) and propane ($C_3H_8$) were employed as the working fluids. $C_3H_8$ was used as an absorbent, and $CF_4$ was used as an evaporator. The sea water was used as the heat source and LNG as the code source.

The schematic diagram of the proposed cycle is shown in Fig. 20 The $CF_4$ rich vapor was absorbed by $CF_4$ weak solution in an absorber. Then the concentrated solution was pressurized by the pump to the generator (1-2-3), and the solution was preheated during the process (2-3). In the Generator $CF_4$ was evaporated by the heat from the sea water, after which the $CF_4$ rich vapor drove the high-pressure turbine to work (7-8), and the $CF_4$ weak solution was then expanded in EX (4-5) and rejected heat in HE2 (5-6) and finally mixed with $CF_4$ vapor in the absorber. Then the low pressure vapor was once again heated by the sea water (8-9), and drove low-pressure turbine to work (9-10). Finally, the $CF_4$ vapor condensed in the condenser and came back to the absorber (10-11).

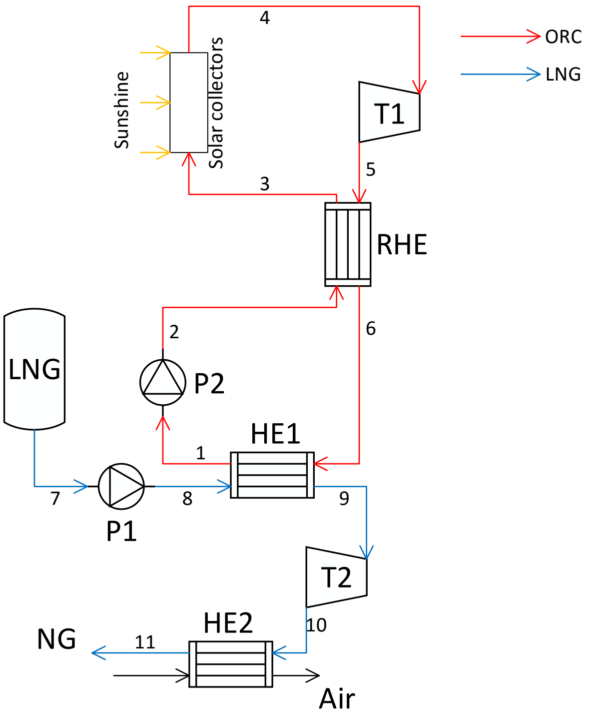

**Fig. 21.** Schematic of the solar and LNG cold energy combined cycle. HE: Heat exchanger; P: Pump; RHE: Recovery heat exchanger; T: Turbine.

Zhang et al. simulated the effects of different refrigerants on the Rankine cycle power generation by HYSYS (Zhang et al., 2015). It was found that the maximum power generation using the mixture was higher than that using the single refrigerants. Different proportions of mixed refrigerants led to different power generation. It was found that the power generation using single working fluid were in sequence of: Ethane > propane > ethylene > methane; and if a mixture was

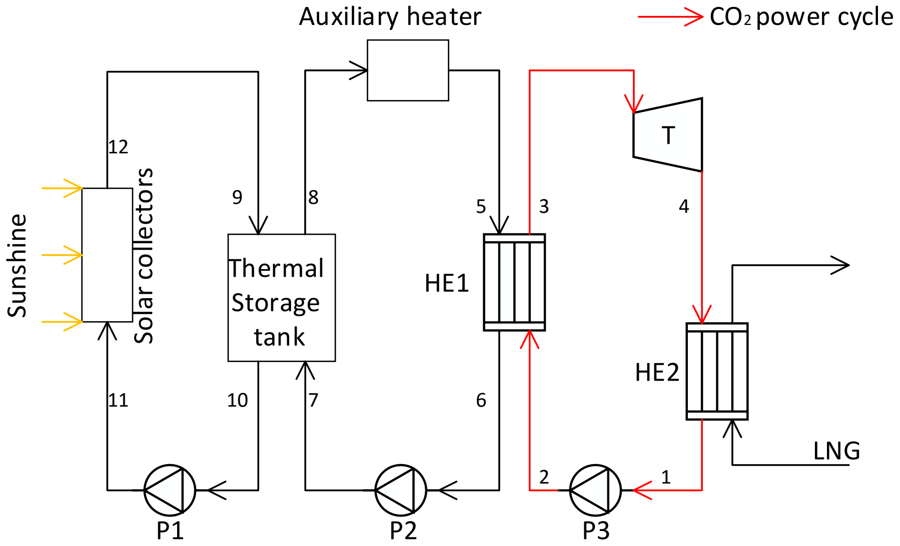

**Fig. 22.** Schematic of the $CO_2$ power cycle with solar and LNG. HE: Heat exchanger; P: Pump; T: Turbine.

used, when the proportion of methane/ethane was determined, the net generating capacity of the system increased first and then decreased with the increase of propane content, while when propane content was determined, it increased first and then decreased with the increase of methane/ethane.

### 2.15 Solar and LNG cold energy combined ORC

Rao et al. proposed an organic Rankine cycle utilizing both solar energy and LNG cold energy, in which the organic Rankine cycle and LNG direct expansion cycle were combined, as shown in Fig. 21 (Rao et al., 2013). In the figure, ORC was represented by the red line, and LNG direct expansion cycle was shown by blue line. The energy efficiency of this combine ORC was higher than that of single cycle.

Since the solar energy is unstable, Song et al. proposed a transcritical $CO_2$ power cycle with solar energy as the cold source, and with a regenerator system (Song et al., 2012). This system can run continuously. The schematic diagram of the proposed cycle is shown in Fig. 22. The solar energy was stored in the thermal storage tank, and transmitted to the $CO_2$ power cycle through the heat storage system.

This system is more environmental friendly and energy-efficient. But the selection of heat storage materials is difficult. The efficiency of the system depends on the progress of solar technology and regenerative technology.

## 3. Summary

With the increasing demands of LNG all over the world, the utilization of the cold energy and pressure energy contained in LNG bears great significance. In the area of power generation, the cold energy of LNG is usually used as the heat sink, and pressure energy can directly drive turbine work, both increasing the efficiency of the system and reducing the cost of LNG regasification. In addition, the power generation system can be combined with the liquid carbon dioxide system, even the air separation system for a better utilization of LNG cold energy. A lot of researches have been conducted to improve the efficiency of the power generation, which is reviewed in the paper. And 15 recent power generation cycles using LNG cold energy are discussed, which provides reference to the designer or researchers in this area.

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