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Development and performance test of a small trailer-mounted moveable natural gas liquefier

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ABSTRACT

A portable small liquefier for natural gas or coal-bed methane liquefaction has been designed and tested. The liquefier is very compact, and the compressor is directly mounted on a trailer. The liquefier is based on a mixed-refrigerant liquefaction cycle with R22 precooling. Most of the components in the liquefier are easily available off-the-shelf refrigeration products. An oil-lubricated single-stage R22 screw compressor is used for the mixed-refrigerant compression. An aluminum plate-fin heat exchanger with four flow passages was designed as the core of the cold box. The liquefier was tested for about 4 months by circulating pure methane as the natural gas resource. A maximum liquefaction capacity of 15,000 Nm^3 was achieved with a minimum specific power consumption of about 0.54 kW h/Nm^3. This liquefier can be used in various applications such as small natural gas or coalbed methane exploitations, distributed peak-shaving, and boil-off gas reliquefaction. These can also be used as a flexible distributed liquefaction center with a set of small liquefiers.

1. Introduction

Many small natural gas reserves can be used to meet the increasing demand for clean energy resources. Shale gas, coal-bed methane, landfill gas and other unconventional natural gas resources have low production rate at a small number of wells, low pressure, and sometimes unsteady output. Therefore, pipeline transportation is not economically practical for such gas resources. Small compact and mobile natural gas liquefiers have many merits for use with these gas resources. Small liquefiers can also be used to reliquefy the boil-off gas (BOG) from liquefied natural gas (LNG) tank.

Small or mini liquefaction capacities are around 10 metric tons per day (around 14,000 normal cubic meters per day). The challenge of developing small natural gas liquefiers is mostly due to the initial manufacturing cost and operating energy efficiency. Use of off-the-shelf components to construct the liquefaction facility will shorten the manufacturing time and reduce the cost. The efficiency is then highly dependent upon the optimization of the refrigeration technology.

There are many reports on theoretical analysis of natural gas liquefaction systems [1–4], but not many concerning practical developments of small natural gas liquefiers. The Gas Technology Institute (GTI) reported on the development of a pre-commercial natural gas liquefier with a liquefaction capacity of 1000 gallons per day [5], which is equal to about 2000 normal cubic meters per day (Nm^3/d). The liquefier was built based on a single mixed-refrigerant liquefaction process, with a natural gas engine to drive a commercially available refrigeration screw compressor. A custom-tailored aluminum plate-fin heat exchanger was used to construct the cold box. All the liquefier components were put on a skid. The best testing performance burned about 25% of the natural gas to liquefy the remaining 75%. Neksa et al. from SINTEF [6,7] recently reported development of a natural gas reliquefaction plant for LNG carriers. The system used a mixed-refrigerant refrigeration cycle with one vapor–liquid separator. Copper brazed plate heat exchangers in a two-stream counter-current flow configuration were used in the cold box. Their system [7] used an ordinary two-stage cascade refrigeration cooler to provide about −35 °C precooling. An oil-injected screw compressor was used to drive the liquefaction plant. When using ethylene as the BOG, 14.4 metric ton/d liquefaction capacity was achieved. No directly measured energy efficiency data was reported.

This paper describes a small natural gas liquefier designed and tested in the Technical Institute of Physics and Chemistry (TIPC), Chinese Academy of Sciences (CAS). The main objective of this liquefier was for coalbed methane liquefaction. The details of the liquefier design, refrigeration process, and testing are presented in the following sections.

2. Liquefier system design

2.1. Refrigeration system configuration

The liquefier uses a single-stage mixed-refrigerant refrigeration cycle precooled by an R22 vapor-compression refrigeration system.

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A schematic of the process flow configuration is given in Fig. 1. The liquefier has a compressor unit and a cold box. The compressor unit has two compressors which are both single-stage oil-lubricated screw compressors commonly used in refrigeration and air-conditioning applications. Explosion-proof measurements were made on the electric engines of the two compressors. The precooling refrigeration system is an ordinary vapor-compression refrigerator with R22 as the refrigerant. Of course, the R22 can be replaced by propane (R290) in the future development from an environmental protection point of view. A shell-and-tube heat exchanger is used as the R22 refrigerator evaporator and also as the precooler of the mixed-refrigerant process. The R22 system provides 5 °C precooling of the main mixed-refrigerant at summer ambient conditions. The lowest precooling temperature in the winter is about −15 °C.

The R22 system normally uses an ordinary oil separator to separate oil entrained in the high-pressure R22 refrigerant stream. The mixed-refrigerant system uses an enhanced oil separator after the main compressor outlet. A 5 ppm oil residue in the mixed-refrigerant flow after the oil separator is announced by the manufacturer. An additional vapor–liquid separator based on the fractionating effect was then integrated into the cold box unit to avoid so much oil entering the cold section. The multi-component mixture used was optimized for the liquefaction heat loads.

Two air coolers, both aluminum plate-fin heat exchangers, are used in the main compressor unit, one for the R22 precooling stage and the other to cool the main mixed-refrigerant stream. The air cooler in the precooling stage has four fans to cool the refrigerant. The main mixed-refrigerant refrigeration stage has two fans.

The cooled high-pressure mixed-refrigerant stream enters the cold box where the main heat exchanger has four flow streams. The high-pressure mixed-refrigerant passes downward through the heat exchanger becoming a two-phase flow and mostly liquid at the heat exchanger bottom outlet. The condensed high-pressure refrigerant is then expanded through a valve to a two-phase state. The two-phase low-pressure refrigerant enters the bottom of the heat exchanger, flowing upward to cool the high-pressure refrigerant and the natural gas stream by evaporation. The low-pressure refrigerant vapor then exits the heat exchanger and returns to the main compressor suction to complete a circuit.

2.2. Methane circuit

A methane circulating system was designed to test the liquefier performance, as illustrated in Fig. 1. Methane gas is compressed by the circulating compressor which has two additional oil-separators to ensure good oil separation. The high-pressure methane gas passes through an after cooler and then enters the main heat exchanger. It flows downward and liquefies, exiting the exchanger at the bottom. The high-pressure liquefied methane enters a LNG tank when it flashes into a two-phase state. The low-pressure liquid enters the vaporizer and vaporizes by accepting heat from the ambient. Meanwhile, the low-temperature evaporator gas enters the heat exchanger through the BOG passage to cool the coming hot streams and leaves the heat exchanger at the top. These two superheated methane vapor streams mix together and return to the circulating compressor suction.

2.3. Design point and component selection

The liquefaction heat loads for processing one liter of liquid methane per hour at different pressures are shown in Fig. 2. The specific total heat load decreases with increasing gas pressure, especially the phase change heat load (latent heat load). In most existing LNG plants, the resource gases pressure generally range from 4 to 5 MPa or even higher. However, for some gas resources, especially coalbed methane, their well outlet pressures are quite low. Such low pressure gas resources have a trade-off between the energy consumed to elevate the gas pressure and the liquefaction. A moderate pressure range from 0.8 to 1.3 MPa was chosen here for the coalbed methane.

The liquefier capacity was designed to be about 10,000 Nm^3/d. Process flow simulations with ProII gave an optimum design circulation flow rate of the mixed-refrigerant of 4500 Nm^3/h. The

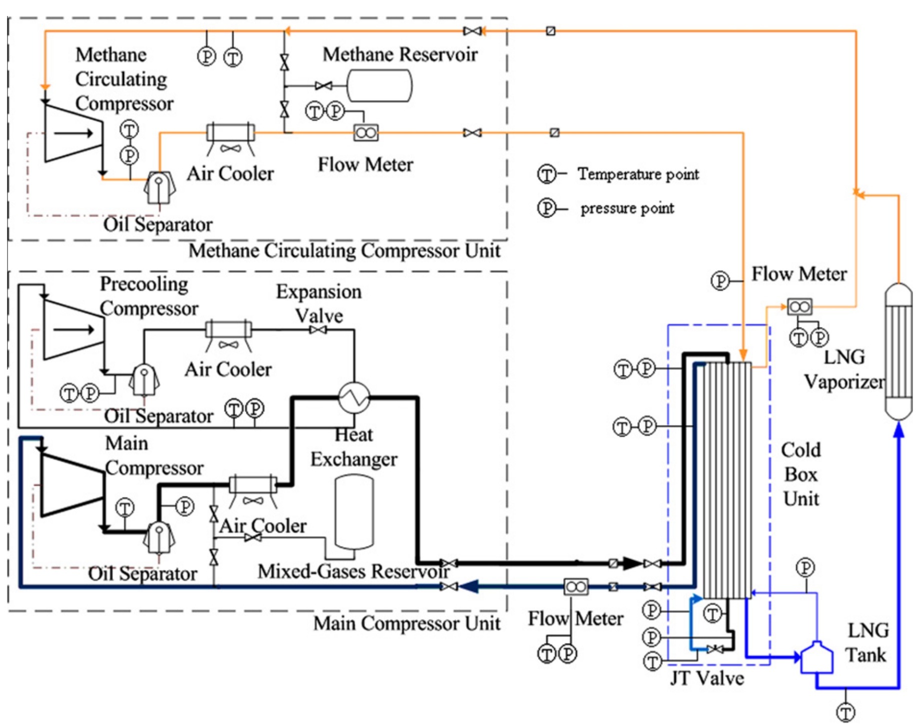

Fig. 1. Schematic of the liquefier process and test system.