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Research paper

Proposal and design of a natural gas liquefaction process recovering the energy obtained from the pressure reducing stations of high-pressure pipelines

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Taking advantage of the refrigerating effect in the expansion at an appropriate temperature, a fraction of high-pressure natural gas transported by pipelines could be liquefied in a city gate station through a well-organized pressure reducing process without consuming any extra energy. The authors proposed such a new process, which mainly consists of a turbo-expander driven booster, throttle valves, multi-stream heat exchangers and separators, to yield liquefied natural gas (LNG) and liquid light hydrocarbons (LLHs) utilizing the high-pressure of the pipelines. Based on the assessment of the effects of several key parameters on the system performance by a steady-state simulation in Aspen HYSYS, an optimal design condition of the proposed process was determined. The results showed that the new process is more appropriate to be applied in a pressure reducing station (PRS) for the pipelines with higher pressure. For the feed gas at the pressure of 10 MPa, the maximum total liquefaction rate (y_{tot}) of 15.4% and the maximum exergy utilizing rate (EUR) of 21.7% could be reached at the optimal condition. The present process could be used as a small-scale natural gas liquefying and peak-shaving plant at a city gate station.

1. Introduction

It was reported that 663.9 billion cubic meters (bcm) of natural gas, 66.5% of the international trade in 2014, is transmitted by pipelines [1]. In order to be transported in a long distance, the natural gas is usually compressed to about 10–12 MPa [2,3] (even up to 20 MPa for offshore pipelines [4]) by gas turbine driven compressors. At city gate stations (CGS), the gas pressure will be reduced to 0.4–1.6 MPa for the safety of consumers. In the conventional pressure reducing processes, it is not made use of the potential energy of the high-pressure pipelines. Thus, recovering the energy in the high-pressure pipelines has attracted many researchers' attention recently. Generally, there are two ways to utilizing the large pressure drop in a PRS: (1) employing expanders in a PRS to recover the work output; (2) utilizing the refrigerating effect of the expansion of the high-pressure gas.

As well-known, replacing the throttle valves with expanders can recover a considerable amount of work during the pressure reducing process of the high-pressure pipelines. However, more remarkable temperature drop will happened in such process, and more thermal energy is consumed to preheat the feed gas in order to prevent the expanded natural gas from forming hydrate. Hence, the energy recovery efficient of such process will be weakened due to the additional energy consumption. Howard et al. [5] proposed a hybrid turbo-expander-fuel cell system to generate electricity, and a fuel cell utilizing natural gas as fuel is adopted to preheat the gas and yield additional electricity. Sanaye and Nasab [6] put forward a combined heat and power system mainly consisting of expander, gas engine and boiler to integrally improve the system thermal efficiency. The circulated water heated by the engine and boiler is used to preheat the feed gas. Recently, Neseli et al. [7] conducted the energy and exergy analysis of an electricity generation system at a high-pressure natural gas pressure reduction station in Aliaga PRS. A boiler was used to preheat the feed gas unexceptionally. Arabkoohsar et al. [8] put forward a turbo-expander combined with a solar energy heating set to improve the system performance.

Comparing with simply recovering power with expanders, utilizing the refrigerating capacity generated by the expansion of high-pressure gas may be more feasible and efficient. Lun and Xie [9] suggested employing a vortex tube at a CGS to reduce gas pressure, and to produce cooled natural gas at its cold end. Qian et al. [10] proposed a low temperature nitrogen refrigeration

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Nomenclature

e	specific exergy (kJ kg^{-1})
Ex	exergy flow (kW)
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg h^{-1})
p	pressure (kPa)
Q	heat (kW)
s	specific entropy (kJ kg^{-1} °C^{-1})
t	temperature (°C)
W	work (kW)
x	quality
y	liquefaction rate (%)

Greek symbols

Δ	change in a quantity
η	efficiency (%)

Subscripts

0	reference state
102–403	state points of ethylene
ex	exergy
in	inlet
out	outlet
tot	total

Acronyms

EUR	exergy utilizing rate (%)
HPNG	high pressure natural gas
LLHs	liquid light hydrocarbons
LNG	liquefied natural gas
MPNG	medium pressure natural gas

system to recover the cooling capacity yielded in a two-stage natural gas expansion process. The proposed system provides cooling capacity below 173 K for a waste rubber cryogenic pulverization plant. Shen et al. [11] put forward a small-scale LNG production system to recover the energy released in the pressure reducing process for the high-pressure pipelines. He and Ju [12] put forward a natural gas liquefaction process using the pipeline pressure, and the power consumption could be greatly decreased to 0.0398 kW h Nm^{-3}(LNG). After that, the same authors proposed a novel zero-energy-consumption natural gas liquefaction process for a CGS, and its maximum liquefaction rate (LR) and exergy utilizing rate (EUR) could be 12.61% and 19.61% respectively [13]. Recently, an improved process based on He and Ju's study [13] was proposed to pursuit higher LR (about 24.3%) and higher EUR (29.6%) by adopting a heat exchanger network [14]. However, it should be noted that there exist several limitations for applying the natural gas liquefaction processes in Ref.[13,14]: (1) The maximum feed gas pressure was limited to about 6500 kPa [12–14] to make sure the maximum allowable operation pressure of the turbo-expanders lower than 10 MPa. (2) The feed gas would be compressed before expansion in the proposed processes. Hence a starter motor is necessary to drive the compressor. (3) Taking into account of the safety of the expanders, the liquid fraction at the outlet of the turbo-expanders should be strictly controlled to a rational range (less than 10%). This situation has motivated researchers to carry out relevant studies on the design of new system to overcome these obstacles.

A new natural gas liquefaction process is proposed to recover the energy contained in the high-pressure pipelines with the pressure up to 10 MPa. A turbo-expander driven booster is employed as a work recovery device at a relatively high temperature. Throttle valves are used at low temperature. The flowrates of the natural gas, which are expanded to different pressures, can be flexibly adjusted by the throttle valves. Furthermore, the power output and input of the process could be internally balanced. The performance of the proposed system has been analyzed on the basis of the simulation in Aspen HYSYS.

2. Description of the proposed process

In China, the natural gas from a main transmission pipeline will undergo a dramatic pressure drop from 10 MPa to 0.4–1.6 MPa at a PRS. For a PRS with the processing capacity of 1,000,000 cubic meters per day (Nm^3/day), a new natural gas liquefaction system shown in Fig. 1 is proposed to recover the energy released in the pressure reducing process of high-pressure natural gas. A fraction of natural gas will be throttled to 1600 kPa and filled into a sub-high pressure pipelines, and the remaining part will be throttled to 450 kPa, a little part will be liquefied into LNG and LLHs. Assuming just 10% (i.e. 100,000 Nm^3/day) of the feed gas enters the medium pressure pipeline with the pressure of 450 kPa.

As shown in Fig. 1, the feed gas is precooled in the first heat exchanger (HX1), and expanded in a turbo-expander to an intermediate pressure (p_{103}). After being further cooled in the second heat exchanger (HX2), the gas (104) is partially condensed due to the liquefying of heavy components, and then enters the first gas-liquid separator (Separator1). The LLHs (401) is drained from the bottom of Separator1, and undergoes a further pressure reduction in a throttle valve (V-3). Two-phase mixture of light hydrocarbons (402) from V-3 enters the second separator (Separator2). The yielded liquid from Separator2 (LLHs) is stored at 450 kPa, and the top vapour (403) mixes with other two returning streams. The top product of Separator1 (105) is divided by a tee (TEE1) into three streams (201, 301 and 106). The stream 201 is expanded to 1600 kPa in a throttle valve (V-1), and then enters HX3, HX2 and HX1 sequentially as a cold stream. The stream 301 undergoes a pressure reducing from p_{103} to 450 kPa in another throttle valve (V-2), and then mixes with the stream 403 and another cold stream (112) exited from HX5. The mixed stream (113) goes through HX4, HX3, HX2 and HX1 sequentially as another cold stream. The stream 106 is further cooled in HX3, HX4 and HX5 to a lower temperature, and is expanded to 450 kPa in a throttle valve (V-0), then enters the third two-phase separator (Separator3). The bottom product of Separator3 is stored as LNG, and the top product (111) enters HX5 as a returned cold stream, which mixes with stream 403 and 302 at a mixer (MIX).

The returned stream (117) with the pressure of 450 kPa is exited from HX1, and is divided into two streams at a tee (TEE2): 100,000 Nm^3/day of natural gas (MPNG) will be filled into the medium pressure pipeline, and the remaining part (118) is re-pressurized to 1600 kPa by the turbo-expander driven booster. Finally, the two streams of natural gas with the pressure of 1600 kPa (HPNG1 and HPNG2) will be charged into the sub-high pressure pipeline.

The proposed process has the following characteristics. (1) The internal balancing of work and cooling capacity can be achieved without consuming any extra energy; (2) To maintain the internal balance of energy, the flowrates of 201 and 301 could be adjusted conveniently in accordance with the variation in the operating conditions. (3) Employing throttle valves as expansion devices at low temperature makes the process be tolerant with the liquid formation in the expansion process.