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Investigation of novel integrated air separation processes, cold energy recovery of liquefied natural gas and carbon dioxide power cycle

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A B S T R A C T

Cryogenic air separation unit (ASU) consume high amount of energy to produce oxygen and nitrogen with high purity. Liquefied natural gas (LNG) regasification process provides low temperature cryogenic refrigeration source which can be used in ASU with high efficiency. In this study two cryogenic air separation processes for production of high purity nitrogen and oxygen with low energy consumption are proposed and analyzed. The first proposed process is a two-column configuration which power consumption per oxygen production is 16.6% lower, compared to a convectional cryogenic air separation process. In the second one, liquefied natural gas cold energy is used for pre-cooling the feed air. This greatly reduces the energy consumption of the compressors located before the columns by more than 55.6% compared to the first proposed process, without much change in purity of the products. In the second process, energy saving in the air separation unit and power generation cycle is 2715 kW and 17,810 kW respectively. Both processes use an integrated heat exchanger which is both condenser of the high pressure column and reboiler of the low pressure column. With this integration latent heat of the pure nitrogen and pure oxygen can be exchanged in a two-column process configuration. The second proposed process is a hybrid with a carbon dioxide trans-critical power cycle. The liquefied natural gas cold energy is used for cooling the power cycle condenser. Energy and exergy analysis are carried out on the air separation unit and power generation cycle.

1. Introduction

In the liquefied natural gas (LNG) terminals, LNG should be vaporized and brought to a desired temperature and pressure before entering the pipeline network. In the old terminals, cold energy of LNG was released and wasted into the water or air without any recovering. Open rack vaporizers (ORV) and submerged combustion vaporizers (SCV) are some of these methods that waste the energy of LNG (Tsatsaronis and Morosuk, 2010; Mak and Ana, 2008). Using cold energy of the LNG during regasification has been studied for different industrial applications. Desalination of the seawater using LNG cold energy can reduces the energy consumption significantly (Xia et al., 2014; Wang and Chung, 2012). LNG cold energy can be used for various applications such as deep freezing agro food industry facilities or for space conditioning in the commercial and residential sector and supermarkets and hypermarkets (La Rocca, 2010; La Rocca, 2011). LNG typically contains some hydrocarbons heavier than the methane which can be separated by different processes such as using distillation columns (Mak and Ana, 2011; Winningham and Anderson, 2007). One of the most efficient and reasonable ways to exploit the LNG cold energy is supplying a portion of the required refrigeration in the air separation units. Operating temperature of the air separation unit (ASU) (−173 °C, −193 °C) (Cornelissen, 1997) is lower than the LNG (−162 °C) hence LNG cold energy can be used with high cold recovery efficiency compared to other methods. Two column cryogenic distillation, is one of the conventional methods for air separation. In this design we can save a lot of energy by combining high pressure column condenser and low pressure column reboiler (Zhu et al., 2009). There is an alternative procedure which uses three distillation columns (Shah, 2003). Kansha et al. (2011) suggested a process based on the self-heat recuperation technology for cryogenic ASU. Energy consumption decreases more than

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36% compared to the conventional cryogenic air separation process, when producing 99.99 mol% oxygen from the air. In van der Ham and Kjelstrup (2010) simple and rational exergy efficiency and exergy destruction for both two and three column designs are calculated that three-column design destroy 12% less exergy than the two-column design. A detailed exergy analysis of an ASU is investigated (Cornelissen, 1997). Some processes which cryogenic ASU is a part of the integrated gasification combined cycle (IGCC) are discussed and analyzed (van der Ham, 2012; Jones et al., 2011). Increasing purity of oxygen to 97% increases energy consumption linearly, but from 97% to 100% the energy consumption increases exponentially (Li et al., 2013). Using LNG cold energy in ASU is cost-effective and environmentally friendly because it decreases the required refrigeration in the process (Nakaiwa et al., 1996; Xiong and Hua, 2014). LNG cold energy utilization in ASU decreases the required power up to 50% (Nakaiwa et al., 1996). A novel one column cryogenic air separation process with LNG cold energy utilization that produces liquid nitrogen and oxygen is proposed (Mehrpooya et al., 2015). Energy consumption with LNG cold recovery is about 38.5% lower compared to a convectional cryogenic air separation process. Several methods which uses LNG cold energy as a cooling source in power generation systems have been proposed. A trans-critical CO_2 power cycle driven by solar energy, using LNG cold energy as its heat sink is investigated (Song et al., 2012). A combined power cycle and LNG cold energy utilization is suggested (Kim and Ro, 2000). Reducing the air temperature by LNG, depends on the temperature and humidity of the air. By using LNG cold energy, the produced power increases 8% for dry air and 6% for humid air (Relative humidity = 60%). Stirling cycle is selected for utilizing the LNG cold energy (Dong et al., 2013). Advanced exergetic analysis is done for a power generation cycle with LNG cold energy recovery (Tsatsaronis and Morosuk, 2010; Morosuk and Tsatsaronis, 2011). Carbon dioxide as a working fluid is environmentally friendly and size of the system is smaller compared to the Organic Rankine Cycles (ORC), also trans-critical CO_2 cycle produces more power (Chen et al., 2006). Supercritical CO_2 power cycle has higher yield compared to the conventional Rankine cycles (Liu et al., 2014). According to the properties of the CO_2 in the cycles that use LNG as a cold source, better performance compared to the other working fluids is achievable (Romero Gómez et al., 2014). CO_2 is used as working fluid in a power generation cycle. In this cycle seawater as a part of the required heat duty is used to increase the efficiency of cycle (Angelino and Invernizzi, 2009). Through regasification process, LNG in about -162 °C is available as a low temperature refrigeration source which can be used in various cryogenic processes. LNG cold energy recovery in air separation processes has not been investigated comprehensively. Also there are different ASU process configurations and each of them have specific characteristics. Improving LNG cold energy recovery in a new and efficient air separation process is the main objective of this study. In this paper, two cryogenic ASU are proposed and analyzed. Supercritical CO_2 power generation cycle is used in the second process. Both proposed processes produce high purity oxygen and nitrogen with low energy consumption. The second process is a hybrid of cryogenic ASU and supercritical CO_2 power generation cycle. Power cycle which uses a part of LNG cold energy can supply the required power in the ASU. Energy and exergy analysis are done for both processes. Effect of the sensitive parameters on the processes performance is discussed.

2. Conceptual design of the air separation unit

In the air separation processes, pure oxygen is the main product which can be extracted in gas phase, liquid phase or both of them. Nitrogen and Argon also can be gained as valuable byproducts of the process. Three common methods for separation of the air components are cryogenic distillation, pressure swing absorption and membrane separation. Cryogenic distillation method is used when extraction of the high purity products in a large volume is desired (Smith and Klosek, 2001). In this method, for liquefying the air a great deal of energy is required (Boehme et al., 2003). Various process configurations have been proposed which they are different in heat exchanger network and distillation columns. Purity and number of the products, heat integration between the process components, consumed power and capital cost are the parameters which can affect the process configuration selection. The main difference between the process configurations can be categorized as: number of distillation columns and their stages, phase (gas or liquid) and number of products, method of air compression and source of used external refrigeration. For the processes with liquid product, external refrigeration is necessary. But when the products are in the gas phase there is no need to use external refrigeration. In this study two processes which use two column configuration, are proposed and investigated. Products in the first process are in gas phase and consequently it doesn't use external refrigeration. But the produced pure oxygen in the second process is both in gas and liquid phases and LNG cold energy is used as external refrigeration source. Using LNG cold energy decreases the costs compared to the external refrigeration system. Simple control of the process and high purity of the products (even in the case of low pressure nitrogen) both in gas and liquid phases are of the advantages of this process.

2.1. Process description

ASU has the following steps: 1. Compression of the feed air. 2. Pre-cooling the compressed air (usually with air coolers). 3. Cleaning the air from the water vapor, CO_2 and other pollutants. 4. Cooling high pressure dry air to dew point temperature 5. Separation of the air components (O_2, N_2 etc.) by using one or more distillation columns.

2.2. Process description of the first process

Fig. 1 illustrates the process flow diagram. Air in the standard condition (25 °C and 101.5 kPa), streams 1 and 2, enters a three stage compressor and reaches to the desired pressure. Next it is cooled by the air coolers and cooling waters, so water vapor, CO_2 and other pollutants can be separated from the air. Streams 16b and 26b follow to E-1 and E-4 heat exchangers respectively. Next they are cooled to the desired temperature to enter the high pressure column, UC. The pressurized and cold gas (17), enters the lowest tray of the column. Stream 27 enters S-1 separator before following to the column. There are four streams (B1, R1, N1, and T1) exiting the high pressure distillation column. Stream N1 which is high purity nitrogen (99.84 mol%, 6870 Nm^3/h) passes through an expander and its pressure reduces. N1 can be used to reduce temperature of the feed air by passing through E-4 and E-1 heat exchangers. N4 stream, high purity nitrogen at 10.3 °C and 110 kPa, is product of the first proposed process. T1 stream enters E-3 heat exchanger (condenser of the UC column and reboiler of the LC column) to become liquid (T2). A portion of T2 stream returns to the UC column as reflux stream. Streams T3, R1, 29 and B1 enter E-2 heat exchanger. Next they are depressurized by V-7, V-8, V-9, and V-10 valves to enter the low-pressure distillation column, LC. H1 and S streams are gas and liquid outlets of the low pressure column, LC respectively. Top product of the LC column consists of nitrogen with high purity of 99.36 mol% in the gas phase. Because H1 stream, has low temperature it can be used as a cold side in E-2 and E-1 heat exchangers. H4 stream leaves the process at 10 °C and 110 kPa