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Optimal design and operating condition of boil-off CO_2 re-liquefaction process, considering seawater temperature variation and compressor discharge temperature limit

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ABSTRACT

Low-temperature liquid CO_2 could boil off during ship transportation because of the heat ingress from the surroundings to inside the tank, which causes the tank pressure to increase. To maintain the operating pressure range of the tank, the re-liquefaction process is indispensable. Three design alternatives to the re-liquefaction process using boil-off CO_2 as a refrigerant are proposed and compared. A systematic procedure to find the optimal design of CO_2 re-liquefaction is provided considering operational constraints such as the cooling water temperature and compressor discharge temperature. The optimal operating conditions of the proposed processes are determined by solving nonlinear programming. The compressor power consumption as the operation energy for the CO_2 re-liquefaction ranges from 60 to 120 kW/t CO_2 given the operational constraints. As the seawater temperature is lower and the discharge temperature limit is higher, the proposed Alternative 2 design consumes less power than the other designs.

1. Introduction

Global energy demand is expected to increase continuously due to the increasing world population. Most of the energy demand is still covered by fossil fuel-based power plants, despite much effort to develop renewable energy technologies to meet the growing demand. The fossil fuel-based power plants inevitably emit enormous amounts of CO_2 which is a major cause of global warming (Freund, 2003). Among the various technologies for reducing CO_2 emission, carbon capture and storage (CCS) seems to be the most promising technology (IEA, 2013).

CCS consists of carbon capture, transport and storage. The capture process consumes about 70% of the energy required for the entire CCS chain and is also expected to reduce the electrical output of coal-fired power plant by 30–40% (Freguia and Rochelle, 2003). Accordingly, various types of capture technologies such as chemical absorption, membrane separation, and ionic liquid have been studied (Roussanaly et al., 2016; Wang et al., 2015; Zacchello et al., 2016). However, there exist only a few studies that discuss the issue of practical operations of transport and storage processes.

There are two main ways of transporting CO_2: pipeline and ship. Although trucks and trains could be considered, they are only suitable

Abbreviations: CCS, carbon capture and storage; IEA, International Energy Agency; JT, Joule–Thomson; MHX, multi-stream heat exchanger; P–H, pressure–enthalpy; SRK, Soave–Redlich–Kwong; ZEP, Zero Emission Platform.

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Nomenclature

C	Heat capacity
D	Decision variable
H	Enthalpy
J	Objective function
m	Mass flowrate
P	Pressure
PD	Pressure drop
PR	Pressure ratio
R	Ideal gas constant
T	Temperature
W	Compressor power consumption
z	Compressibility factor
γ	Heat capacity ratio

Subscripts

comp	Compressor
d	Discharge
i	Inlet
i + 1	Outlet
JTV	Joule–Thomson valve
max	Maximum
p	Constant pressure
t	Total
v	Constant volume

for small scale commercial tanks (Zahid et al., 2014). Several studies on the pipeline and ship transport have been proposed (European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), 2011; Luo et al., 2014; Metz et al., 2005; Roussanaly et al., 2014, 2013). Although these studies show that distance and capacity are the main criteria in choosing a transportation method, the choice is not simple. Either pipeline or ship could not always guarantee an optimal solution, because the total cost could vary considerably depending on how the transport chain is designed (Roussanaly et al., 2014). This study focuses on the ship transport because pipeline requires relatively higher investment cost (Roussanaly et al., 2014). In addition, the ship transport is flexible and less subject to regional constraints when the capture and storage site are scattered in various places. Furthermore, low-temperature liquid CO_2 could be utilized for integration of diverse ship applications (e.g., liquefied natural/petroleum gas carriers) (Aspelund and Gundersen, 2009; Yoo, 2017).

Ship transport consists of five stages: liquefaction, intermediate storage, loading, ship transport, and unloading. Captured CO_2 is commonly a vapor phase. It should be liquefied for ship transportation because the density of liquid CO_2 is much higher than that of the vapor phase. Liquid CO_2 is in a high-pressure and low-temperature state. Since the shipping is not a continuous process, cryogenic intermediate storage tanks are needed at onshore terminal. The storage tank should be cooled before loading low-temperature CO_2 to prevent physical and thermal damage to the tank wall (Lim et al., 2016). During the ship transport of CO_2, heat transfer occurs from the surroundings to the inside of the tank. It will not only cause vaporization of the liquid CO_2 but will also increase the vapor pressure in the tank. Thus, adjusting the internal pressure is necessary to avoid violating the design pressure of storage tank.

One attractive approach to maintaining the range of the design pressure is to recover the boil-off CO_2 and recycle it back into the storage tank in liquid form. From the viewpoint of making vapor CO_2 to liquid phase, the re-liquefaction process is similar to the CO_2 liquefaction process except for the feed condition. The feed condition for liquefaction is almost 1 bar and cooling water temperature; however, the feed in the re-liquefaction process depends on the liquid CO_2 transport condition. For example, if the liquid CO_2 condition is 6.5 bar and −52 °C, then this is the feed condition for the boil-off CO_2 re-liquefaction process. Depending on the feed condition, the optimal process design and operating condition could be varied.

Along with this feed condition, a key factor in determining the process design and operating condition of the re-liquefaction process is the cooling water temperature (Lee et al., 2015). Because the power consumption of compressors that represents the operating energy of the (re-)liquefaction processes is very sensitive to the cooling water temperature. Several processes on the ship or offshore platform can easily use pre-treated seawater as a coolant. Its temperature varies seasonally and even daily, also differs depending on the location of marine. Therefore, the optimal design and operating condition of the re-liquefaction process should be determined according to the variation in seawater temperature.

The cooling water temperature also determines the suction temperature of compressor in many chemical processes. When operating the liquefaction and refrigeration process containing compressors, the lower suction temperature of compressor could pressurize a wide range of pressure with a single compressor. This is because the discharge temperature of compressor decreases as suction temperature decreases. The reason why the compressor discharge temperature is important is that the compressor has its own discharge temperature limit according to the vendor's design specification. If the discharge temperature of the centrifugal compressor used in large-scale gas processes exceeds the limit, lubrication problems may occur. The centrifugal compressor temperature limit provided by many vendors is typically in the range from 100 to 140 °C (Brown et al., 2002; Girotto et al., 2004; Jeon and Kim, 2015a; Rozhentsev and Wang, 2001). The optimal operation strategies could vary depending on how the temperature limit is defined.

However, previous works on the re-liquefaction of boil-off CO_2 did not consider these two issues, which considerably affect the optimal design and operation. Chu et al. (2012) proposed a re-liquefaction process using ethylene and propane refrigeration cycles and optimized the recovery ratio. Jeon and Kim (2015a) reported a basic structure of re-liquefaction process using CO_2 as a refrigerant itself, and investigated the characteristics of three methods for determining operating conditions. Jeon and Kim (2015b) also investigated the impact of impurities on the re-liquefaction process. Lee et al. (2014) compared the operating energy for four design alternatives according to the pressure of liquid CO_2 and the maximum pressure. Yoo (2017) proposed a re-liquefaction process for the liquefied natural gas fueled CO_2 carrier. Although many researches on the CO_2 re-liquefaction process have been suggested, no study considering the variation in the seawater temperature and the discharge temperature limit of the compressors has been reported.

The present work provides the procedures for determining the optimal design and operating condition of the boil-off CO_2 re-liquefaction process for ship transportation considering the variation of the seawater temperature and the discharge temperature limit of the compressor as a key unit process. In addition, this work presents how operational constraints lead to improvement of process design from the concept of a simple re-liquefaction process. Furthermore, comparison of the operating energy for each design alternative is provided with taking into account two operational constraints.

2. Process description

2.1. *Liquid CO_2 and boil-off CO_2*

The pressure and temperature of liquid CO_2 for transportation must be higher than the triple-point pressure (5.2 bar) and lower than the critical-point temperature (31 °C). The pressure of liquid CO_2 for shipping used in the literature is mainly in the range from 6 to 20 bar, as shown in Table 1. The temperature of CO_2 in this pressure range varies from −52 to −20 °C. Under the assumption that the atmospheric temperature is 15 °C, a temperature difference of 35–70 °C exists. The heat ingress from the surroundings to the tank will not only cause vaporization