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Techno-economic analysis: Ethane steam reforming in a membrane reactor with H_2 selectivity effect and profitability analysis

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ABSTRACT

With the increased production of shale gas through a new drilling technology of hydraulic fracturing, much attention has been directed to various utilization methods for ethane accounting for about 7% of shale gas. As an efficient utilization method for ethane, ethane steam reforming in a membrane reactor is proposed in this paper to provide improved reactant conversions and product yields thus leading to a reduced operating temperature. To assess techno-economic feasibility of ethane steam reforming in a membrane reactor, parametric studies focusing on a H_2 selectivity and economic analysis predicting profitability from cash flow diagrams based on a purified hydrogen in Korea were performed simultaneously providing very useful design and economic guidelines to implement a membrane reactor for ethane steam reforming.

Introduction

Natural gas including C_1, C_2, C_3 and C_4+ has been extensively used in various chemical plants as precursors for a wide range of chemicals such as hydrogen, ethylene, propylene, etc.. As shown in Table 1, methane is a primary component in natural gas followed by ethane and propane [1]. Until now, most of research efforts have been paid to methane for methane dry reforming (MDR) [2–5], methane steam reforming (MSR) [6–10], methanol synthesis [11–13] and less attention was directed to other minor components like ethane, propane, etc. in natural gas. However, with the increased production of shale gas through a new drilling technology of hydraulic fracturing [14–19], significant attention has been paid to utilization of ethane which accounts for about 7% of shale gas [20].

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Table 1 – General composition of wet and dry natural gas [1].

Components	Composition (vol%)	
	Wet	Dry
Methane	84.6	96.0
Ethane	6.4	2.00
Propane	5.3	0.60
Isobutane	1.2	0.18
n-butane	1.4	0.12
Isopentane	0.4	0.14
n-Pentane	0.2	0.06
Hexanes	0.4	0.10
Heptanes	0.1	0.80

As for ethane utilization, ethane cracking is the most widely used method to produce ethylene, which is the critical precursor for various polymeric materials [21–25]. However, the increased production of ethane from shale gas has initiated the various applications to use ethane and ethane steam reforming (ESR) is one of them. From ESR, hydrogen can be produced which can be further used for ammonia synthesis, methanol production as well as fuel cells.

In ESR, ethane reacts with water producing carbon monoxide and hydrogen as shown in Eq. (1).

$$C_2H_6 + 2H_2O \rightarrow 2CO + 5H_2 \quad (1)$$

The ESR is an endothermic reaction requiring a huge amount of energy for the reaction and this results in increased costs caused by required heat for the reaction. To overcome this limitation, a membrane reactor (MR) combing a reactor and a separator together was proposed. With the use of a MR, higher conversions at a fixed temperature or lower temperatures for the same conversions compared to a conventional packed-bed reactor (PBR) were achieved in various applications via shift of equilibrium driven by *Le Chatelier*'s principle [2,26–30]. Gallucci et al. [2] performed MDR in a MR with Pd–Ag tubular membranes and reported that CO_2 conversion was close to the equilibrium value and the carbon deposition was lower than a traditional reactor. Lee et al. [26] studied computational fluid dynamics studies using COMSOL Multiphysics® modeling software for MDR in a MR and showed axial and radial temperature and concentration gradients observed within a reactor suggesting practical guidelines to design a MR. Haag et al. [27] carried out MDR and reverse water gas shift (RWGS) reaction using a conventional reactor and a MR and enhanced methane conversion was observed in the MR compared to the conventional reactor. Patrascu and Sheintuch [28] investigated the effect of a feed flow rate, pressure, and sweep flow for MSR using a foam catalyst in a Pd MR and 90% conversion and 80% hydrogen recovery were obtained for a feed flow of 0.25 NL min^{-1} at wall temperature of 525 °C, pressure of 10 bar, S/C = 3 and a sweep flow rate of 0.7 NL min^{-1}. Lee et al. [29] studied methanol steam reforming with Pt-loaded hydrogen selective membranes and compared their results with silica composite membranes without the Pt intermediate layer and Pt-loaded membranes on CO removal efficiency. They reported that methanol conversion increased up to 20% in a MR compared to the one in a conventional reactor. Lim et al. [30] studied the effect of pressure and hydrogen permeance on ethanol steam reforming using Na–Co/ZnO catalysts and palladium- and silica-based membranes and found that conversion enhancements in a MR were 26, 29, and 48% for pressure of 1, 5, and 10 atm in comparison with a PBR. With all these proven benefits of employing a MR, the objective of this paper is to assess the techno-economic feasibility of employing a MR mostly fitted with Pd membranes [31–36] for ESR specially focusing on process simulation and economic analysis.

Fig. 1 shows the overview for utilization of ethane from natural gas or shale gas for ESR in a MR. Ethane extracted from natural gas or shale gas is reacted with water in a MR to produce H_2, which can be further used for fuel cell stacks, hydrogen fueling stations, and chemicals. From the use of a MR, improved reactant conversions and H_2 yields can be expected compared to a conventional PBR due to *Le Chatelier's*

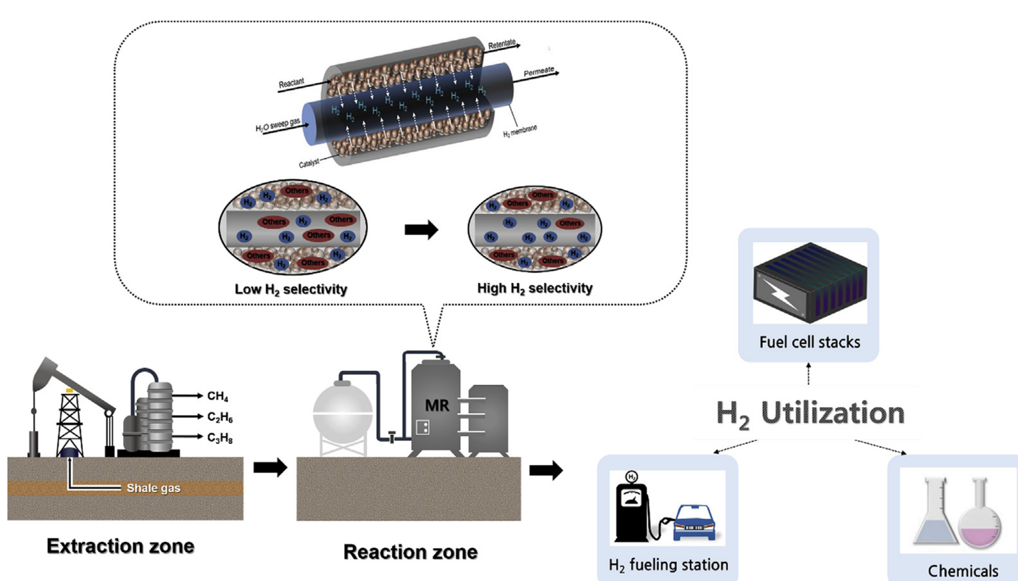

Fig. 1 – Overview of ethane steam reforming (ESR) with a H_2 selective membrane reactor (MR).

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