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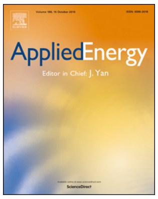

Numerical analysis of an ion transport membrane system for oxy–fuel combustion

Donghwan Shin, Sanggyu Kang*

University of Science and Technology, Daejeon 34113, Republic of Korea
Korea Institute of Machinery and Materials, Daejeon 34103, Republic of Korea

HIGHLIGHTS

- Thermodynamic analysis of the ITM system.
- Development of a two dimensional numerical ITM model.
- Parametric analysis for the ITM.
- Performance comparison of the proposed system with two other ITM systems.

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ABSTRACT

Ion transport membranes (ITM) have been studied as a promising air separation unit (ASU) technology for oxy–fuel combustion owing to their high oxygen permeability. Even though the power consumption of the ITM is lower than that of cryogenic ASU, it still consumes a high proportion of the overall system power.

In this study, a numerical analysis of the ITM system has been conducted using Aspen Plus® to determine the optimal system design for minimizing the power consumption to separate oxygen from air. Since the oxygen permeation through the ITM is driven by the oxygen partial pressure gradient between feed and permeation side, three ITM systems that have different pressure gradients across the membrane have been presented and their performances compared. The effects of the contributing parameters, such as thickness, pressure, temperature, and air flow rate on the oxygen permeation rate have been investigated. ITM performances of the counter and parallel flow configurations have been compared. The system that operates under atmospheric pressure at the feed channel and under vacuum pressure at the permeate channel yields the lowest power consumption for obtaining the same oxygen permeation rate among other pressure conditions.

1. Introduction

As carbon dioxide has been regarded as a key contributory factor to global warming [1], many researches have been conducted over the past decades on carbon capture and storage (CCS) [2]. The CCS technology can capture the CO_2 emitted from the power generation process in the industrial sites. Oxy–fuel combustion has received attention as a strong candidate for CCS technology because of the simple CO_2 separation process compared to other technologies, such as pre-combustion and post-combustion [3]. Many tests for 20–500 kW oxy–fuel research and development (R&D) and 250 MW_e demonstration plant projects conducted at the laboratory scale were conducted in Janschwalde, Brandenburg, Germany [4]. However, the net system efficiency of the oxy–fuel combustion could be significantly reduced owing to a large amount of energy consumption in separating the oxygen from air.

The cryogenic air separation unit (C–ASU) is a mature technology used to produce high purity oxygen for oxy–fuel power plants [5,6]. C–ASU is the only currently available technology used to produce high amounts of high-purity oxygen for oxy–fuel power generation systems at a commercial scale. However, because the cryogenic process requires considerable amounts of energy, it could decrease the net system efficiency down to 8–12% compared to the conventional air–fuel combustion power cycles [7]. C-ASU technology have to be replaced with alternative technologies to significantly reduce the cost of oxygen production [8].

Due to the considerable power consumption of the C–ASU, many researchers have been focused on the development of the ion transport membrane (ITM) as an alternative technology for the C–ASU. Several

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* Corresponding author at: Korea Institute of Machinery and Materials, Daejeon 34103, Republic of Korea.
E-mail address: kyu2613@kimm.re.kr (S. Kang).

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Nomenclature

A	membrane surface area [cm^2]
C	heat capacity [kW/K]
C_V	molar concentration of the oxygen vacancy [mol/cm^3]
D	diameter [cm]
D_V	oxygen vacancy bulk diffusion coefficient [cm^2/s]
D_v^0	bulk diffusion pre-exponential constant [cm^2/s]
E_D	bulk diffusion activation energy [kJ/mol]
E_f	forward surface exchange activation energy [kJ/mol]
E_r	reverse surface exchange activation energy [kJ/mol]
F	Faraday constant [96485 C/mol]
f	Darcy friction factor
h	enthalpy [kJ/kg]
$\dot{h}$	electron hole
j_{O_2}	oxygen permeation rate [mol/cm^2·s]
k	specific heat ratio
k_f	forward surface exchange rate coefficient [cm/atm^n·s]
k_f^0	forward surface exchange pre-exponential constant [cm/atm^n·s]
k_r	reverse surface exchange rate coefficient [mol/cm^2·s]
k_r^0	reverse surface exchange pre-exponential constant [mol/cm^2·s]
L	thickness [cm]
L_c	characteristic length [cm]
l	membrane length [cm]
$\dot{m}$	mass flow rate [kg/s]
$\dot{N}$	molar flow rate [mol/s]
O_O^x	lattice oxygen ion
p	power [kW]
p_{O_2}	oxygen partial pressure [bar]
Δp	pressure drop [Pa]
$\dot{Q}$	heat transfer rate [kW]
Re	Reynolds number
R	resistance [Ω]
$\boldsymbol{R}$	ideal gas constant [8.314 kJ/kmol·K]
T	temperature [K]
v	velocity [cm/s]
$V_O^{\cdot\cdot}$	oxygen vacancy
$\overrightarrow{X}$	mole fraction

Greek letters

ε	heat transfer effectiveness
σ_i	ion conductivity [S/cm]
ρ	density [kg/m^3]
μ	dynamic viscosity [kg/m·s]
η	efficiency

Subscripts

cold	cold side
comp	compressor
diff	bulk diffusion
elec	electrical
ex	surface exchange
f	feed/Forward
h	hydraulic
hot	hot side
i	inner
in	inlet
max	maximum
mech	mechanical
min	minimum
o	outer
out	outlet
p	permeate
pump	vacuum pump
r	reverse
turb	turbine

Superscripts

0	standard condition
′	feed stream
″	permeate stream

types of ITM have been developed, such as $La_xSr_{1\text{-}x}CO_yFe_{1\text{-}y}O_{3\text{-}\delta}$ (LSCF), $La_xCa_{1\text{-}x}FeO_{3\text{-}\delta}$ (LCF), $La_xSr_{1\text{-}x}MnO_{3\text{-}\delta}$ (LSM), $La_2NiO_{4+\delta}$ (LNO), $Ba_xSr_{1\text{-}x}Co_yFe_{1\text{-}y}O_{3\text{-}\delta}$ (BSCF), and others. Each membrane has different oxygen permeability and stability characteristics [9]. Membranes which have high-oxygen permeability usually have low stability [10]. Researchers have been trying to enhance both the oxygen permeability and the chemical/mechanical stability [11–16]. Among the various types of ITMs listed above, BSCF has the highest oxygen permeability, which is approximately equal to 9.5 cm^3/cm^2·min at 925 °C [17]. Even though BSCF can sustain more than 1000 h without degradation under oxygen permeation conditions [18], this membrane still possesses a lower stability compared to other materials with increased stability [9]. In order to commercialize the BSCF membrane modules as an ASU, their thermal/chemical stability and mechanical durability should be enhanced further [19,20].

Generally, ITMs are usually operated based on a three-end or a four-end mode [21]. In the four-end mode, the sweep gas is flowing through the permeate side. In order to obtain high-purity oxygen in the four-end mode, an additional process is necessary to separate the oxygen from the sweep gas mixture. Thus, the four-end mode is mostly used for the reforming process instead of the oxy–fuel combustion [22–24]. In the three-end mode, it is not required to supply the sweep gas to establish the oxygen partial pressure gradient between the feed and permeate channels because this mode maintains the partial pressure gradient by manipulating the total pressure of the feed and permeate channel by the compressor and the vacuum pump, respectively [25]. The thermal energy used to heat up the sweep gas is not required in the three-end mode. The three-end mode could be more suitable for incorporation into the oxy–fuel combustion power cycle compared to the four-end mode.

Numerous researchers have been trying to combine the ITM model with other power generation cycles, such as steam turbine and gas turbine. Engels et al. conducted a simulation of the oxy–fuel power plants using the BSCF membrane [21]. They determined the oxygen permeation rates using a modified Wagner equation. The ITM performances at the three-end and four-end modes were also compared. Fiaschi et al. presented the ITM autothermal reactor (ATR) integrated with the gas turbine [26]. They analyzed the effect of the steam to carbon ratio and the effect of the inlet air temperature on the performance of the ITM reactor. They also compared the reactor's performance at several cycles. Anantharaman et al. proposed the use of various power generation cycles combined with an ITM [27]. System modeling and simulations have been conducted using Aspen HYSYS® and GT PRO®. Colombo et al. presented a numerical study on the system design and the partial-load performance of the oxy–fuel combustion cycle using the ITM [28]. They also conducted a dynamic simulation using ITM combined with the gas turbine power cycle, and captured the transient behavior of the system characteristics [29].