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Utilization of blast furnace flue gas: Opportunities and challenges for polymeric membrane gas separation processes

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ABSTRACT

New programs seeking to improve energy efficiency and reduce GHG emissions from the steelmaking industry are studying alternative uses for blast furnace gas such as the VALORCO project in France. One promising alternative is CO_2 and CO utilization in which emissions are used for the production of valuable products, like industrial intermediates and fuels synthetized from CO or CO_2 or both. A gas separation and concentration technology is necessary to recover industry emissions and produce gas stream(s) suitable for carbon utilization technologies. This paper describes the application of commercially available polymeric gas separation membranes to blast furnace gas. Data for two commercially available membranes, a H_2 selective glassy polyimide membrane from UBE industries and a CO_2 selective rubbery composite membrane from MTR Inc. along with a process economic modelling have been used for the calculation of product composition paths and associated costs depending on product purity and recovery. Relatively low separation costs, from 15 to 33 EUR/Ton separated CO_2, seem promising for the use of membrane technology as a concentration tuning box prior to carbon utilization technologies, notably for mid to high CO_2 purity requirements, and allow to simultaneously achieve CO_2 capture and CO recovery.

1. Introduction

Industry is responsible for approximatively one-third of global final energy use and around 40% of total energy-related CO_2 emissions. Despite continuous efficiency increase in energy utilization, overall growing industrial production has led the CO_2 emissions to rise [1]. This is particularly true for the iron and steel industry, where the production increase in the past two decades is closely related to the development of emergent economies such as China and India. Global steel production almost doubled between 2000 and 2014, going from 0.85 MTons/year to 1.67 MTons/year [2]. GHG emissions depend on the production technology. Two production technologies account for most of the steel produced globally: Integrated steel mills based on the Blast Furnace–Blast Oxygen Furnace (BF-BOF), and the Electric Arc Furnace based on recycled steel or scrap. Integrated steel mills dominate global production with over 70% of crude steel worldwide being produced by this process and the increase in steel production over the past decades was mainly achieved by an increase of production by this technology [2]. BF-BOF technology consumes between 13 and 14 GJ/ton of steel and can produce up to 1.9 t of CO_2 per ton of steel depending on energy efficiency and the percentage of carbonated energy according to local conditions [3].

Gas emissions in a conventional steel mill come mainly from three streams: Coke oven gas, blast furnace gas and blast oxygen furnace gas. Fig. 1 shows a simplified flowsheet of a conventional mill illustrating these three sources.

Blast furnace gas (BFG) emissions are the most important in volume and represent around 69% of the emitted CO_2. BFG is mainly composed of 20–28% CO, 17–25% CO_2, 50–55% N_2 and 1–5% H_2 [3]. It is typically burned for heating and power generation often being mixed with natural gas, coke oven gas or blast oxygen furnace gas to increase its heating value.

Energy and emissions concerns have led to research programs seeking to improve energy efficiency and reduce GHG emissions from the steelmaking industry. Recent works have studied the sequestration of CO_2 from iron and steel off gases [4–9]. New programs are studying alternative uses for blast furnace gas in order to reduce emissions such as the VALORCO project in France. One promising alternative is CO_2

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Nomenclature

a	Annuity coefficient for equipment [Dimensionless]
a_m	Annuity coefficient for membrane module [Dimensionless]
A_H	Heat exchange surface [m^2]
A_m	Membrane area [m^2]
$CAPEX$	Capital expenditures [EUR]
C_{cap}	Annual capital costs [EUR/year]
C_{CO2}	Specific CO_2 separation cost [EUR/Ton CO_2]
C_{cw}	Annual cooling water cost [EUR/year]
C_{en}	Annual electricity cost [EUR/year]
C_o	Compressor base cost [USD]
$C_{O\&M}$	Annual operation and maintenance investment cost [EUR/year].
C_{tot}	Total annual costs [EUR/year]
C_{vp}	Vacuum pump cost factor [EUR/kW]
D_i	Diffusion coefficient of component i in the polymer membrane [m2/s]
ER	Exchange rate [EUR/USD]
HX_o	Heat exchanger base cost [USD]
ICF	Indirect cost factor [Dimensionless]
I_{Hex}	Heat exchanger investment cost [EUR]
I_c	Compressor investment cost [EUR]
I_m	Membrane surface investment cost [EUR]
I_{mf}	Membrane permanent frame investment cost [EUR]
I_{vp}	Vacuum pump investment cost [EUR]
J_i	Molar flux of component i permeating trough the membrane [mol/(m2s)]
K_{cw}	Cooling water cost factor [EUR/m^3]
K_{el}	Electricity cost factor [EUR/kWh]
K_i	Sorption coefficient of component i in the membrane [mol/(m3Pa)]
K_m	Unit cost of membrane module [EUR/m^2]
K_{mf}	Base frame cost [EUR]
K_{mr}	Membrane replacement cost [EUR/m^2]
$M_{CO2year}$	Annual separated CO_2 [Tons/year]
MDF_C	Compressor module factor [Dimensionless]
MDF_{HX}	Heat exchanger module factor [Dimensionless]
MF_C	Compressor material factor [Dimensionless]
MF_{HX}	Heat exchanger material factor [Dimensionless]
l	Thickness of the dense membrane layer carrying the separation [m]
$OPEX$	Operational expenditures [EUR/year]
P_{cpr}	Compression power consumption [kW]
PF	Pressure factor [Dimensionless]
P_i	Permeability of component i in the membrane [mol.m/(m2.s. Pa)]
$\overline{P_i}$	Permeance of component i [mol/(m2.s. Pa)]
P_{mf}	Membrane frame pressure [bar]
P_{out}	Outlet gas pressure [bar]
P_{tot}	Total energy consumption [kW]
P_{vp}	Vacuum power consumption [kW]
$\overline{P_0}$	Permeance of a base component (fastest) [mol/(m2.s. Pa)]
p'	Membrane module upstream pressure [Pa]
p''	Membrane module downstream pressure [Pa]
$p_{i(0)}$	Partial pressure of component i at the feed side of the membrane [Pa]
$p_{i(l)}$	Partial pressure of component i at the permeate side of the membrane [Pa]
Q	Gas flowrate along the upstream side [mol/s]
Q_f	Feed gas flowrate [mol/s]
Q_p	Permeate gas flowrate [mol/s]
q	Dimensionless flow [Dimensionless]
s	Dimensionless membrane surface [Dimensionless]
t_{op}	Operation time per year [h/year]
UF	Update factor [Dimensionless]
W_{tot}	Total water consumption [m^3/h]
x	Molar fraction at the upstream side [Dimensionless]
x_f	Feed gas mole fraction [Dimensionless]
x_o	Retentate gas mole fraction [Dimensionless]
y	Molar fraction at the downstream side [Dimensionless]
y_p	Permeate gas mole fraction [Dimensionless]
α_i	Ideal membrane selectivity [Dimensionless]
θ	Dimensionless stage cut of the membrane separation [Dimensionless]
ν	Membrane annual replacement rate [Dimensionless]
ψ	Pressure ratio [Dimensionless]

and CO utilization in which emissions are used for the production of valuable products, like industrial intermediates and fuels synthetized from CO and or CO_2, either by chemical or biological transformations. This alternative would need a low energy, clean, safe separation technology (or technologies) capable of treating high volumes at economical rates.

Technologies typically applied for CO_2 and CO separation share common characteristics in their operation, the main difference being the separation agent itself and the nature of its interactions with the gas species to be separated. These separation processes include chemical absorption by amine systems in the case of CO_2 retention, and by copper salt solutions for CO; physical absorption for CO_2 by selexol or Rectisol processes; adsorption processes like pressure swing adsorption (PSA) or vacuum pressure swing adsorption (VPSA) over CO_2 and/or CO selective adsorbents; cryogenic separation, and membrane separation. To our knowledge, only two recent research programs have proposed separation technologies for the specific case of the iron and steel industry and have carried out tests on pilot level installations, both within CO_2 capture and storage scenarios. The european ULCOS program proposed a modification of the Blast Furnace, by which the blast furnace is fed by an oxygen stream instead of air thus eliminating the N_2 in the off-gas. This off-gas goes to a capture unit for CO_2 and the residual gases, containing CO, are recycled back to the BF as reducing gases. This is known as a Top Gas Recycled Blast Furnace (TGR-BF). For the capture step, a combination of PSA and cryogenics in order to achieve the purity necessary for CO_2 storage was proposed [8]. The Japanese COURSE 50 program has proposed a PSA process in which

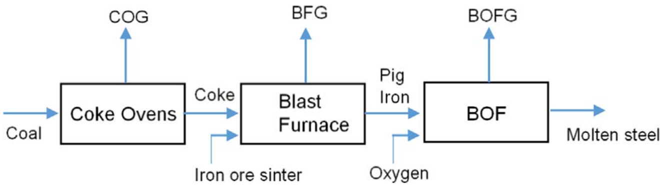

Fig. 1. Simplified flowsheet of an integrated steel mill.