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Investigating the influence of the pressure distribution in a membrane module on the cascaded membrane system for post-combustion capture

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ABSTRACT

Polyactive® membranes show promising properties for CO_2 separation from flue gas. An investigation of different module types using Polyactive® membranes was carried out for this paper. A test rig was built to explore, amongst other process parameters, the pressure drop in envelope-type membrane modules. The experimental data and simulation results were compared with quite good consistency. This validation enabled further simulations for different modules in a virtual pilot plant configuration. Applying the data from the pilot plant simulation to a reference power plant, the scaled-up cascaded membrane system was analyzed using different membrane modules. Considering the required membrane area, energy consumption and pressure drop in different modules, a counter-current membrane module configuration exhibited the best performance and had a marginal advantage in comparison with the chemical absorption process.

1. Introduction

Energy-related CO_2 emissions reached a record 31.2 gigatonnes in 2011, representing by far the largest source (around 60%) of global greenhouse-gas emissions measured on a CO_2-equivalent basis (World Energy Outlook, 2012). An update released by the World Bank warns about the potentially disastrous consequences that an increase of four degrees Celsius in the global temperature could have by 2100 (World Could Be 4 Degrees Hotter By End of This Century, 2013). Forecasts by the IEA and others show that "decarbonizing" electricity and enhancing end-use efficiency could make major contributions to the fight against climate change (Climate Electricity Annual, 2011). In spite of increased energy efficiency, the electricity demand is projected to increase substantially – by up to 50% between today and 2050. Renewable energy systems (RES) will generate at least 40% of the electricity required to meet this demand, and the rest will be generated by nuclear sources and fossils with carbon capture and storage (CCS) (Decarbonizing the European Electric Power Sector by 2050). CCS is a series of technologies and applications which capture CO_2 from large point sources, transport it via pipelines and ships and safely store it in geological formations, such as saline aquifers and depleted oil and gas fields (Metz et al., 2005a).

The principle of CCS is clear: continue using fossil fuels and capture and store the released CO_2 underground. However, the technology is currently still being developed and has yet to be demonstrated as feasible on a large scale at acceptable cost. Apart from high investment costs, a high CO_2 price or regulations will be required to encourage actual use of CCS, as a significant share of the power generated by a CCS plant is needed to drive its gas separation units, thereby lowering the plant's net efficiency and flexibility (Decarbonizing the European Electric Power Sector by 2050). In different regions in the world, post-combustion, pre-combustion and oxy-fuel combustion processes are considered options for CO_2 capture in the large-scale demonstration of CCS in the power generation sector. To date, no individual capture route or technology can claim a general competitive advantage over other processes (Climate Electricity Annual, 2011).

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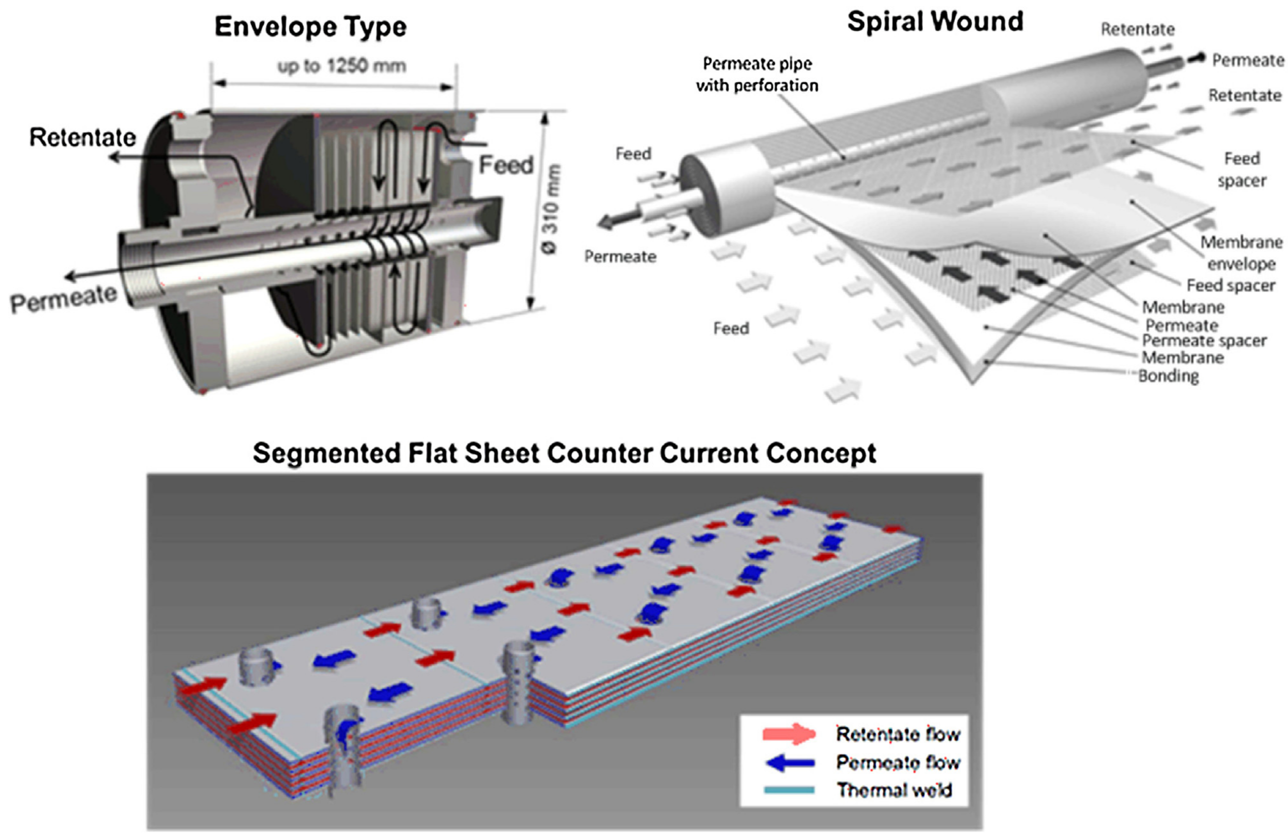

Fig. 1. Types of investigated membrane modules.

The competing technologies for post-combustion carbon capture are absorption, adsorption and membrane methods (Metz et al., 2005a; Post-Combustion CO2 Control U.S. Department of Energy, 2014). As the first-generation technology for CO_2 capture, amine absorption is a mature and proven purification technique that is widely employed in the industrial treatment of acid gases (Kohl and Nielsen, 1997). Nevertheless, the high energy consumption of the absorbent (monoethanolamine, MEA) regeneration step with efficiency losses of 10–14% points and corrosion problems associated with solvent degradation increase the operation and maintenance costs of this technology (Wang et al., 2011; Luis et al., 2012; Mangalapally et al., 2012; Svendsen et al., 2011; Blomen et al., 2009; Galindo-Cifre et al., 2009). Gas separation membrane technologies, a potential second-generation technology for post-combustion capture, are gaining more and more attention. The advantages of these technologies are their potentially lower environmental impact and the fact that membrane modules can be used as add-on equipment requiring with fewer modifications to power plants. The other potential advantage is that for low degrees of CO_2 separation, a membrane array demands a lower specific energy than that required for MEA absorption. Furthermore, membrane systems are easier to scale-up and more suitable for intermittent, dynamic operation. Membrane science and technology can be divided into two classes, namely materials research and process engineering. Many groups and researchers worldwide have been involved in materials and process development (Zhao et al., 2010; Bounaceur et al., 2006; Favre, 2007; Car et al., 2008a; Follmann et al., 2011; Ho et al., 2008; Deng et al., 2009; Hussain and Hägg, 2010; Merkel et al., 2010; Brinkmann et al., 2011; Kai et al., 2008; Powell and Qiao, 2006; Lin and Freeman, 2005; Reijerkerk et al., 2010; Brunetti et al., 2010; Bram et al., 2011), with some institutions covering the entire research and development chain from material synthesis to process engineering (Hussain and Hägg, 2010; Merkel et al., 2010; Abetz et al., 2006; Sijbesma et al., 2008).

Important progress has been achieved and relevant experience obtained in the past by testing membrane modules in real flue gas environments. In Europe, under the framework of the projects MemBrain (MEM-BRAIN Alliance, 2011), METPORE (METPORE, 2014), Nanoglowa (CO2 Capture Using Membrane Technology, 2015) and iCap (The iCap project), different polymer and ceramic membranes are being investigated to meet the harsh requirements in coal-fired power plants (Car et al., 2008a; Hussain and Hägg, 2010; Brinkmann et al., 2011; Reijerkerk et al., 2010; Bram et al., 2011). Membrane modules equipped with Polyactive® thin-film composite membranes (Car et al., 2008c; Brinkmann et al., 2013; Brinkmann et al., 2012; Brinkmann et al., 2010) in a parallel configuration ($12.5\,m^2$ and $1\,m^2$) are currently being tested in the EnBW power plant Rheinhafen-Dampfkraftwerk (Bram et al., 2011; METPORE, 2014). A 1 MW_{el} pilot-scale Polaris® membrane separation system at the Department of Energy's National Carbon Capture Center in Wilsonville, USA, was announced by the National Energy Technology Laboratory (NETL) in November 2012. It will test a post-combustion membrane capture technology on the largest scale in the world to date (Merkel et al., 2010; NETL Greenlights 1 MW Field Test For Membrane Capture Tech, 2012).

In order to realize the potential of gas permeation for industrial applications, advanced membrane module concepts are desirable. Membranes can be inserted into three major types of modules for gas separation applications: envelope-type, spiral wound, and hollow fiber modules (Favre, 2010; Melin and Rautenbach, 2003; Baker, 2012; Ohlrogge and Wind Brinkmann, 2010). In general, the membrane module must be used in commercial processes as a package with as much surface area per unit volume as possible, good flow distribution and efficient contact of the feed gas within the membrane. The main flow configurations in membrane