2nd Oxyfuel Combustion Conference

Integration of Ion Transport Membrane Technology with Oxy-Combustion Power Generation Systems

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1. Introduction

While much of the power industry's work on carbon capture and storage is focused on removing CO_2 from the post-combustion flue gas of conventional coal plants, two other advanced coal-power generation options are also expected to contribute substantially to a low-carbon energy future: integrated gasification combined-cycles (IGCC) and oxy-combustion. IGCC systems remove CO_2 from the fuel before it is burned, and oxy-combustion systems, which use high-purity oxygen rather than air for combustion, produce flue gas with high CO_2 concentration that is more amenable to direct capture.

Both of these advanced generation processes require large amounts of oxygen—a necessity that has worked against their competitive economics. Air Products and Chemicals, Inc. (AP) and the U.S. Department of Energy (U.S. DOE) National Energy Technology Laboratory (NETL) under a cooperative agreement, are working with the Electric Power Research Institute (EPRI) and a power generation industry collaboration to develop an innovative ion transport membrane (ITM) technology for oxygen production. The ITM technology is expected to increase efficiency and reduce costs for advanced coal-power generation applications. EPRI's role is to identify fundamental technical objectives for power applications, foster communication with power industry collaborative members, and complete specific technical tasks under the ITM Oxygen cooperative agreement.

2. ITM Technology

In the late 1980's, AP identified a class of perovskite ceramic materials with high flux and separation selectivity to oxygen that could form the basis for cost-efficient air separation membranes (termed ion transport membranes). These materials separate oxygen from air at high temperature in an electrochemically driven process. The oxygen in air is ionized on the surface of the ceramic and diffuses through the membrane as oxygen ions, driven by an oxygen activity (partial pressure) gradient to form oxygen molecules on the other side. The membrane is essentially 100% selective to oxygen, and all impurities such as nitrogen and argon are rejected.

These materials conduct electrons as well as ions, so no external source of electrical power is required – the entire separation is driven by an oxygen partial pressure ratio across the membrane. The air separation system that results

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from the use of such ceramic oxygen ITMs produces a hot, pure oxygen stream and a hot, pressurized, oxygen-depleted stream from which significant amounts of energy can be extracted.

Because of the requirement to feed a high-pressure oxygen-containing gas to the membrane separator and the production of the hot high-pressure off-gas stream, ITM Oxygen systems advantageously integrate with turbo-machinery-based power generation cycles. Compressed air, obtained directly from an air compressor or extracted from the compression side of a combustion turbine, is heated to between 1472 and 1650°F (800-900°C) and supplied to the membrane. A portion of the oxygen is extracted by the membrane, and the resulting oxygen-depleted non-permeate off-gas can be utilized in an expansion turbine to recover useful work. Additional heat recovery, for example in a heat recovery steam generator (HRSG), can result in an overall product mix of oxygen, power, and steam.

One implementation of an ITM Oxygen membrane is the direct integration with a combustion turbine (CT). A pressurized air stream is extracted from the compressor and heated by a direct or indirect process before being directed to the ITM unit. Oxygen-depleted off-gas from the ITM unit, at approximately the same pressure as the feed air, is reinserted into the CT for conversion of its thermal and hydraulic energy to shaft work. The compressed air not extracted from the CT continues directly through into the combustion section. By contrast, when air is fed to a cryogenic air separation unit (ASU) instead of the ITM Oxygen unit, some of the heat in the compressed air stream is rejected and most of the pressure energy is expended during the oxygen separation.

3. Development with the U.S. DOE

The potential for co-producing oxygen and power or producing oxygen with relatively little power input has interested the U.S. DOE and others in developing this technology further for advanced applications requiring low-cost oxygen. AP and the U.S. DOE entered into a Cooperative Agreement in 1998 to develop ITM Oxygen membrane technology in a multi-phase program.

The development effort has focused on identifying key technical objectives and addressing them comprehensively with a multi-disciplinary, multi-organizational team approach. The program addresses the following areas, among others: materials development, ceramic processing, integration of membrane systems with turbo-machinery, mechanical design, ceramic and system reliability, oxygen production performance, and process safety.

Phase 1 of the program, which focused on the technical feasibility of the approach, was completed in 2001. A material was chosen from a class of perovskite ceramics as the basis for further scale-up. The material has a combination of properties sufficient to meet commercial requirements for performance and operating life, including high oxygen flux, good material strength at high temperature, and resistance to chemical poisons such as sulfur. In addition, the material is amenable to standard ceramic processing techniques which facilitate the design, scale-up, and manufacture of multi-layer, planar wafer structures.

In Phase 2, commercial-scale modules were built by co-joining multiple wafers to form a unified ceramic device. The modules were also fitted with a terminating end cap and ceramic oxygen exhaust pipe. All ceramic joints are composed of the same ceramic material as the wafers, thus minimizing the potential for differential stresses across the body of the device. Each module is capable of producing 0.5 tons O_2/day (0.45 tonnes O_2/day) of virtually pure oxygen and is approximately the size of an (American) loaf of bread in height.

In the current Phase 3, the principal goal is to design, build, and test a planned 100 tons O_2/day (90 tonnes O_2/day) intermediate-scale test unit (ISTU), and integrate it with 5-15 MWe industrial turbomachinery. To achieve the planned ISTU, approximately one hundred 1 ton O_2/day (0.9 tonne O_2/day) ITM modules will be housed in the vessel. The separated oxygen is then cooled and released to the atmosphere, while the high temperature non-permeate – consisting primarily of nitrogen – is cooled against the incoming air before undergoing firing and expansion in the turbomachinery unit. The ISTU will be designed to test many different options (including those pertaining to both IGCC and oxy-combustion) and real-world operating conditions including start up and dynamic operation.

4. Oxy-Combustion Configurations

In support of this development effort, EPRI has undertaken a study to increase the fidelity of the plant-wide performance and cost predictions of ITM Oxygen-based greenfield oxy-combustion power plants with carbon capture and compression. The study includes comparisons with cryogenic-based ASU oxygen plants. The power plant models use a common design basis except when limits posed by the individual technologies warrant the use of a different design basis.

A matrix of six cases was evaluated, including three oxy-combustion cases with O_2 provided by a cryogenic ASU and three oxy-combustion cases with O_2 provided by an ITM Oxygen System. All of the oxy-combustion cases were based on supercritical pulverized coal combustion boiler technology with steam turbine throttle conditions 3515 psia (23.7 bar) / 1110°F (600°C) / 1150°F (621°C). The resulting oxygen concentration in the flue gas from the first case with cryogenic ASU is about 6% by volume. A second case was considered in which the flue gas was sent to a 2-stage flash CO_2 purification process, reducing the oxygen concentration to less than 3% by volume. All subsequent oxy-combustion cases also included a 2-stage flash CO_2 purification process. The cost associated with compressing the captured CO_2 to 2215 psia (152.7 bara) was simulated; CO_2 transport, storage, and monitoring were not considered.

5. Material for Presentation

An overview of the fundamentals of ITM technology and development progress will be presented. The overview will highlight the technical achievements in Phases 1 and 2 and summarize the progress of the ISTU in Phase 3. A description of the six oxy-combustion cases evaluated by EPRI and the performance and cost results will be presented.

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