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Design of an ion transport membrane reactor for gas turbine combustion application

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ABSTRACT

The use of ion transport membrane reactors to substitute the conventional gas turbine combustors is a promising technology for the applications of ZEPP. An ITM monolith structure reactor design is introduced in this study for substituting a conventional gas turbine combustor. Due to reactor symmetry, only 3D four quarters of four adjacent channels sharing one common edge are considered in all simulations using LSCF1991 membranes. Effect of feed and sweep flow rates have been considered and it was calculated in order to meet the power required for the reactor and keeping the reactor size as compact as possible. Effects of flow configurations, channel width and percentage of CH_4 in the permeate side flow are introduced under constant inlet gas temperature of 1173 K and fixed operating pressure of 1000000 Pa. The reactor geometry has been calculated based on the calculations of the minimum possible channel width. Counter-current flow configuration design resulted in improved oxygen permeation flux and improved heat transfer characteristics. However, this flow configuration resulted in unacceptable increase in the membrane temperature. It was found that any reduction in the channel width below 15 mm results in large increase in the viscous pressure drop. Also, increasing the amount of CH_4 in the permeate side over 5% was found to be non-applicable because of oxygen permeation flux limitation. The reactor length was fixed to 0.9 m to be similar to that of real gas turbine combustors with 25,000 channels for each stream. The present reactor design resulted in a reactor height of 3.35 m and overall volume and membrane surface area of 10 m^3 and 2700 m^2, respectively. The reactor is capable of delivering power ranging from 5 to 8 MWe based on cycle first law efficiency.

1. Introduction

Global climate change is one of the greatest challenges in the 21st century. The greenhouse gas making the largest contribution to global climate change from human activities is carbon dioxide (CO_2). CO_2 emissions from the fossil fuel-based large power plants are of main concern as they are the largest sources of CO_2 in the coming decades [1]. For decreasing greenhouse gas (mainly CO_2) emissions, several approaches have been evaluated and reviewed for capturing CO_2 in the utility industry, namely Carbon Capture and Storage technology (CCS), including pre-combustion capture, oxy-fuel combustion, and post-combustion capture. As a promising CCS technology, oxy-fuel combustion can be used to existing and new power plants. In oxy-combustion, a fuel is oxidized in a nearly nitrogen-free, diluted mixture such that the products consist mainly of CO_2 and water vapor, enabling a relatively simple and inexpensive condensation separation process and then CO_2 could be captured easily. There are two main approaches available to utilize the oxy-combustion technology, one of them is through the use of air separation units to separate O_2 which is used in the combustion process and the other application is the ion transport membrane (ITM) reactor technology [2].

The use of ion transport membrane reactors to substitute the conventional gas turbine combustors is a promising technology for the applications of ZEPP. As it is impossible to violate the mass conservation law, the conventional ZEPP combustion products exist in the same chemical composition as in ordinary power plants. Every atom entering a plant with fuel or oxidizer must leave the plant with emissions, effluents and ash. The only difference is that in the conventional ZEPP, all of the combustion products are in liquid, not gaseous form [3]. Attempts have been made in order to clean the exhaust gases after combustion however; they did not result in zero emissions. In case of using ITM reactors, the emissions are mainly CO_2 and H_2O and the separation of CO_2 is much easier and the concept of ZEPP is approached. A major industrial effort is currently devoted to the

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development of the mixed-conducting ceramic membrane reactor technology for partial oxidation of hydrocarbons, in particular, partial oxidation of methane to syngas [4,5]. Zebao et al. [6] examined the oxygen permeation through oxygen ionic or mixed-conducting ceramic membranes under reaction conditions with a model taking into account of different electrical transport mechanisms (p-type and n-type transports) and finite reaction rate. They concluded that with reaction consuming oxygen in one side of the membrane, the oxygen partial pressure in the reaction side decreases and the oxygen permeation flux increases with the increase in the reaction rate. Akin and Jerry [7] presented a simple mathematical analysis, coupled with experimental data, on the effects of hydrocarbon flow rate and reactivity with oxygen on the oxygen permeation in an ionic or mixed conducting ceramic membrane reactor for partial oxidation of hydrocarbon. They concluded that for a membrane with a fixed oxygen permeation mechanism, increasing gas flow rate lowers the conversion of oxidation reaction in the reaction side (equivalent to a decrease in reaction rate), causing a decrease in the oxygen permeation flux.

A detailed study has been conducted by Nemitallah et al. [8] aiming to understand the performance of an ITM reactor under the oxy-combustion conditions in the permeate side of the membrane using CH_4 as a fuel and CO_2 as sweep gas. They found that parameters such as the inlet gases temperature (feed and sweep), percentage of CH_4 in the sweep gas mixture and the reactor geometry can have great effects on the operation of ITM reactors. In contrast, they reported that there are some other parameters that are less important such as feed and sweep gas volume flow rates and oxygen partial pressure in the feed side. Mancini and Mitsos [9], a membrane reactor has been designed in order to meet the requirement of oxygen separation required for the combustion process in a power plant with power of the range 300–500 MW electric power. In their work, simulations have been done for different flow configurations and separation only versus reactive cases. Since reported maximum permeation rates have increased relatively recently [10], the expression in their study was scaled up by one order of magnitude (inside the model) such that it gives the maximum flux values found in the literature at maximum temperature and partial pressure difference. Essentially, their model assumes that the functional form of the oxygen flux is given by Xu and Thomson [11] and Smith and Norby [12], but they modified the flux expression to reflect recent permeation improvements. However, different oxygen persmeation model is used in the present study, the same scaling factor like that in [9,10] has been applied to the model in order to reflect the recent improvements in the oxygen permeation. The results in their work, [9], showed that although a reactive ITM significantly improves the partial pressure driving force, practical reactor engineering considerations indicate that this concept is not superior to counter-current separation-only ITMs, mainly because of the stringent temperature limitations of the membrane material. However, the temperature limit was acceptable in case of co-current flow. They showed in their work the important characteristics of ITM air separation systems for power cycles.

Little work was reported with a focus on examining the effects of reaction side conditions and flow configuration on oxygen permeation through the mixed-conducting ceramic membranes and none has been performed for 3-D membrane reactors. In the present study, focus is made on oxygen separation through ion transport membranes and then the combustion is made in the permeate channels with fuel in a mixture of $O_2/CO_2/H_2O$. The new reactor design introduced here is substituting conventional gas turbine combustor by a monolith structure ITM reactor. Optimization for the feed and sweep flow rates have been done in order to meet the power required for the reactor and keeping the reactor size as compact as possible. Effects of flow configurations, channel width and percentage of CH_4 in the permeate side flow are also introduced under constant inlet gas temperature and fixed operating pressure of 10 bars. The reactor geometry has been optimized based on the optimization of channel width. Accordingly, the number of permeate and feed channels has been calculated keeping the reactor size as close as possible to the size of a real industrial gas turbine. The monolith structure rector design introduced here is able to give power ranging from 5 to 8 MWe based on cycle first law efficiency.

2. Numerical Modeling

A monolith structure ITM reactor design is used in the present study with total number of feed and permeate channels of 50,000, 25,000 for each stream. Each channel has a square cross section of width of 15 mm based on the calculations of the minimum possible channel width as discussed in the coming section. The length of the reactor was fixed to 0.9 m, similar to that of industrial gas turbines. Due to symmetry in the monolith structure design, only four quarters of four adjacent channels sharing one common edge are considered in the simulations as shown in Fig. 1. Fig. 1 shows a traverse cross section, LSCF-1991 membranes were used to separate the oxygen from the stream containing the fuel, methane, and the sweep gas, CO_2 plus H_2O. More details about membrane specifications are listed in Table 1 and also in our previous work, [8]. The present reactor design results in reactor height of 3.35 m and overall volume and membrane surface area of 10.1 m^3 and 2700 m^2, respectively. In order to understand how an ITM reactor depends on the flow configuration, calculations are performed for co-current versus counter current at the same operating conditions. Equilibrium is assumed for simplicity because it provides upper-bound estimates on the wall temperature and reactive ITM performance in general.

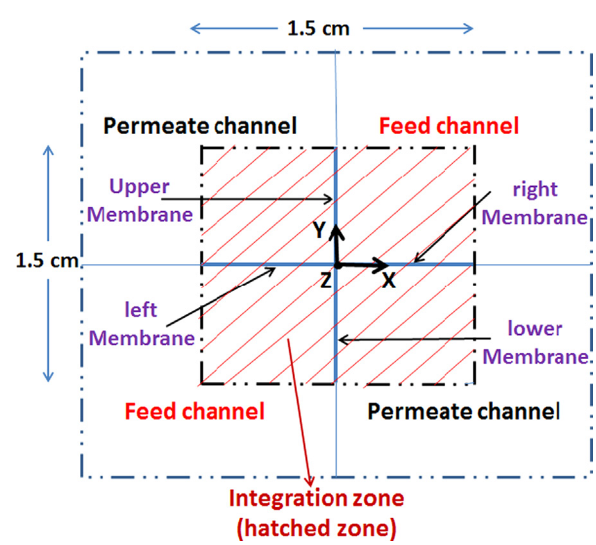

Fig. 1. Schematic diagram of a traverse cross section in four adjacent channels in the 3-D membrane reactor showing the membranes and the considered integration zone.

Table 1
Membrane specifications.

Parameter	Value
Membrane thickness	0.9 mm
Membrane material	LSCF-1991
density	6000 kg/m^3 [18,19]
Thermal conductivity	4 W/m/K [18,19]