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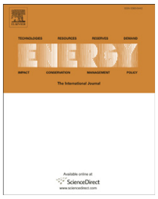

Optimal design and operation of membrane-based oxy-combustion power plants

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ABSTRACT

This article focuses on optimal design and operation of AZEP (advanced zero emissions power) cycles, both zero and partial emissions. The first-law efficiency is maximized as a function of CO_2 emissions with fixed ITM (ion transport membrane) size and consequently, variable power output. A two-step heuristic global optimization of the power cycle is performed. In the first step, the top cycle is optimized. In the next step, the bottoming cycle is optimized for fixed conditions of the top cycle. This procedure is repeated with different initial guesses for the optimization variables of the top cycle to obtain a near-global optimum. The optimization results in a significant increase in the efficiencies of AZEP100 and partial emissions cycles. This increase in efficiency is important with respect to viability of the partial emissions cycle compared to alternative power cycles. This viability is determined herein using a linear combination metric, which combines efficiency and CO_2 emissions. Optimization and simulations have shown that reducing the maximum membrane temperature results in an increase in the efficiency till membrane temperature reaches 850 °C, after which the efficiency starts decreasing. However, reduced temperature results in dramatic drop in net power output of the power plant.

1. CCS (Carbon-dioxide capture and sequestration) and ITM (ion transport membrane) technology

Global warming and anthropogenic emissions of CO_2 have motivated the search for efficient and feasible environment-friendly technologies for power generation, which contributes to about 65% of total anthropogenic CO_2 emissions [1]. Carbon-dioxide capture and sequestration (CCS) allows for the use of fossil fuels for power generation without the detrimental effects of associated CO_2 emissions. There are various CO_2 capture techniques classified as pre-combustion, post-combustion and oxy-combustion [2]. First-law efficiency of almost all CCS plants is significantly lower than the conventional combined cycle plants without carbon capture. CCS plants typically incur a penalty of 7–11 percentage points [3] compared to conventional combined cycle power plants. The most conventional CCS technique is post-combustion capture, which requires energy-intensive and expensive CO_2 separation process [4]. Oxy-combustion provides a promising method that reduces the thermodynamic and economic penalty associated with the CO_2 separation process [5].

In oxy-combustion, O_2 is separated from air prior to the combustion of the fuel–air mixture and fuel oxidation occurs in a nitrogen-free environment, with large recirculation of exhaust gases to control the temperature. The flue gas nominally consists only of CO_2 and H_2O, from which CO_2 can be separated relatively easily by condensation. Thus, the penalty associated with separation of CO_2 from the flue gas is greatly reduced [2]. Zebian et al. [6,7] considered a pressurized oxycombustion process and demonstrated that simultaneous multivariable optimization of the entire process is required to obtain high performance; they also demonstrated that the process is ideally flexible to coal variations [8] and part-load [9]. At present, large-scale separation of O_2 from air is done using cryogenic air separation methods, which however, are energy intensive, or more precisely have low second-law efficiency [10]. A promising alternative is the use of ion transport membranes (ITMs), which operate based on chemical potential differences, and use a high-temperature mixed-conducting (ionic and electronic) ceramic membrane [11]. This technology is motivated by the fact that the penalties incurred are much lower than the additional power requirement for cryogenic air separation [12].

This article focuses on multi-variate optimization of AZEP (advanced zero emissions power) plant [12–17] to study its viability. As shown by Mancini and Mitsos [18], most of the partial

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Nomenclature

AZEPXX	AZEP cycle with XX% CO_2 capture
CCS	carbon capture and sequestration
CPU	compression and purification unit
HHEX	high-temperature heat exchanger
HRSG	heat recovery steam generator
ITM	ion transport membrane
SQP	sequential quadratic programming

emissions cycles without optimization are not viable in the linear combination metric that they introduced, which combines CO_2 emissions and efficiency. A detailed description of the linear combination metric is given in Section 4.2. Optimization of the partial emissions power cycle is needed to assess its viability, compare also Zebian et al. [6]. In this work, for fixed ITM size, the first-law efficiency of the power cycle is maximized for various CO_2 emissions, which consequently results in variations of net power output. A two-step heuristic global optimization of the power cycle is performed. First, only the top cycle is optimized with a local solver. Then, the bottoming cycle is optimized, again with a local solver, using the inlet streams to the bottoming cycle fixed to the optimum operating condition of the top cycle. The two-step procedure is repeated with different initial guesses for the optimization variables of the top cycle to obtain a near-global optimum. The optimization study involves 6 constraints, and 14 variables for the zero emissions cycle. The partial emissions cycle has an extra optimization variable. The importance of multi-variable optimization is demonstrated by the improvement in efficiency and change in the viability status. Optimization also demonstrates the effect of membrane temperature on efficiency, as well as a trade-off between efficiency and power output per unit membrane area.

The remainder of this paper is organized as follows. A brief description of the AZEP cycle and the ITM model used herein are explained in Section 2. Section 3 gives a detailed description of the optimization formulation, including objective function, optimization variables and constraints. Results of the optimization, assessment of the partial emissions cycles and the effect of membrane temperature on efficiency are explained in Section 4. Section 5 gives the conclusions of the present study.

2. Modeling

2.1. ITM model

Oxygen separation in an ITM reactor consists of many complex physical processes. These include bulk gas phase convective transport, ordinary and Knudsen molecular diffusion through porous structures, heterogeneous molecule-lattice kinetic interactions, and bulk ion diffusion through the crystal lattice [11,18–22]. In order to be competitive with cryogenic methods, ITM technology requires thermodynamically strong integration schemes with the power plant [18,23]. Detailed CFD (computational fluid dynamics) studies capture the physical relationships between the state variables like temperature, pressure, etc., but require far too much computational time. Simplified black-box models, on the other hand, cannot provide high-fidelity results, and therefore, cannot accurately predict interactions between different ITM operational and design parameters. Therefore, a reduced-order ITM model [24] is used here, which can capture the most significant physical processes without imposing an extreme computational demand. A spatially-distributed quasi two-dimensional model implemented in JACOBIAN [25], based on fundamental conservation laws (mass and energy balance), semi-empirical oxygen transport equations, and fuel oxidation kinetics, is used in this work. Ref. [24] gives a detailed description of this model.

2.2. ITM oxy-combustion power cycle flow sheet

Several ITM-based power cycles including AZEP [12–17], ZEITMOP [26,27], ITM-ATR [28] and ITM oxy-coal [10] are described in the literature. Due to its high performance and compatibility, AZEP [4,12–18] is the most commonly studied ITM-based power plant in the literature. The AZEP concept can be used for both (essentially) zero emissions cycles and partial emissions cycles. For partial emissions cycles, the base flow sheet is the same as the zero emissions cycle with the exception of the inclusion of an after-burner after the "HHEX" (high-temperature heat exchanger) in order to increase the gas turbine inlet temperature to the maximum possible limit (herein assumed to be 1300 °C), which increases the efficiency and also increases the CO_2 emissions. Zero emissions AZEP cycles are denoted as AZEP100, which imply 100% CO_2 capture, whereas various partial emissions variants are denoted as AZEPXX where XX denotes the percentage of CO_2 emissions captured, e.g., AZEP72, in which 72% of CO_2 emissions are captured. The focus of this article is optimization of both zero and partial emissions AZEP cycles. This section gives a brief summary of the modeling methodology of zero and partial emissions AZEP cycles adopted here, of which a detailed description is given in Ref. [18].

AZEP can be seen as a combined cycle. The top cycle is a Brayton-like cycle with an ITM air separation unit and a combustor. Fig. 1 shows the zero and partial emissions concept, where the additional fuel stream "AFTRMETH" and after-burner are not there for zero emissions cycle. The air is compressed and split into two streams – "AIRMCM" and "AIRREST". The feed stream to the ITM is preheated by the recycled combustion products with a heat exchanger network (see "LHEX (low-temperature heat exchanger)–ITM–HHEX" shown in Fig. 1). "AIRMCM" is preheated to 700 °C in the heat exchanger "LHEX". This preheated feed stream provides oxygen to the permeate stream in the ITM. The "AIRRES" exiting the ITM (O_2 depleted stream) is further heated by the combustion products "RECYCLED" (which serves as the permeate stream in the ITM) and is directly expanded in the gas turbine in case of zero emissions cycle. In case of partial emissions cycles "AIRRES" after getting heating by "RECYCLED" is combusted in the after-burner with the additional fuel stream "AFTRMETH" and then expanded through the gas turbine. This is done in order to increase the gas turbine inlet temperature and thus increase the first-law efficiency of the power plant.

The permeate stream contains O_2 (from the feed stream) necessary to burn the required amount of fuel. In both variants, fuel flow rate into the combustor is calculated such that stoichiometric combustion takes place. Stoichiometric combustion is optimal as there is no excess fuel or O_2 left-over in the flue gas. If some amount of oxygen is unconsumed, it means that excess ITM area (above what is necessary) is used, and results in more ITM pressure drop. Unconsumed O_2 also results in more work to separate CO_2 from the flue gas, which also contains O_2. On the other hand, if fuel remains unreacted, efficiency directly drops, and thus unit electricity cost increases. Moreover, unreacted fuel would also necessitate the need for a complex gas separation process to separate out CO_2 from the flue gas. A part of "AIRREST" is used to cool the gas turbine and a part is used to regenerate thermal energy from the combustion products in the heat exchanger "BHEX". As described in Section 3.1, it is advantageous to extract the maximum possible power from the gas turbine and transport less thermal energy to the bottoming cycle. Therefore, the air outlet temperature from the heat

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