Reheating as an option to increase the efficiency of a novel power generation system based on ammonia oxy-combustion

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Abstract
Ammonia is a promising hydrogen-based energy vector. In the HiPowAR project, an innovative system is developed, based on oxy-combustion of ammonia in a membrane reactor and expansion of the obtained nitrogen-steam mixture. The system combines high temperature and pressure (typical of gas turbines) and large expansion ratio (typical of steam cycles). This work studies the impact of reheating, which proves advantageous, with stronger benefits at lower temperature.

Introduction

The need to reduce carbon emissions is driving the research for cleaner sources of energy. In this framework, storing excess renewable power into synthetic fuels has been identified as a necessary strategy to decouple generation and use of power in both time and space. Although H_2 is recognized as the benchmark clean synthetic fuel, using hydrogen derivatives might reduce storage and transport costs. Among these, ammonia (NH_3) has the advantage of zero carbon emissions upon oxidation.

The potential use of ammonia as a clean energy vector has driven research towards its use as a fuel in power generation systems, both combustion- and fuel cell-based [1,2]. The HiPowAR project aims at using ammonia in a novel system, which applies oxy-combustion by supplying pure oxygen to the oxidation chamber by means of integrated oxygen transport membranes (see Figure 9-left). The oxygen membrane material primarily considered is $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF) [3]. The resulting hot and pressurized nitrogen-steam mixture (about 90%mol H_2O) is expanded to produce useful work [4]. Liquid water is recirculated to moderate the temperature in the membrane reactor (MR).

A high system efficiency is expected, combining a high maximum cycle temperature, due to the internal combustion typical of gas turbines, and a large expansion ratio, possibly sub-atmospheric, as typical of steam Rankine cycles. Moreover, the techniques used in either cycle can be used to increase the system efficiency, like blade cooling, usually implemented in gas turbines to increase the turbine inlet temperature (TIT), or bleeding and reheating, which are often used in steam Rankine cycles.

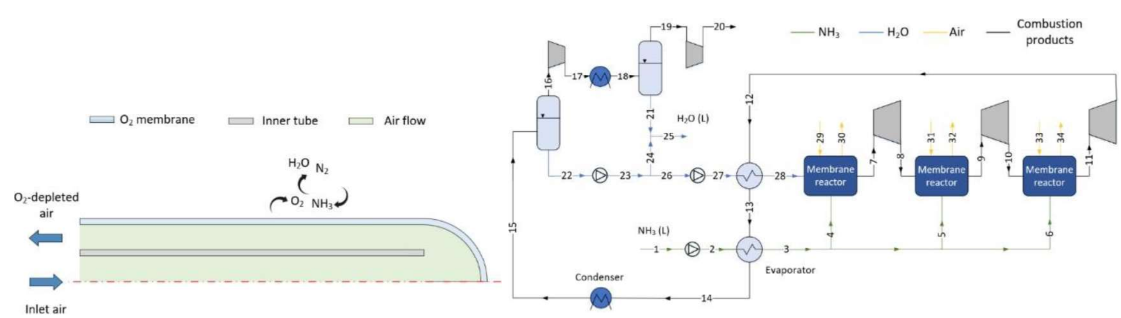

Figure 9 – (left) Double capillary oxygen membrane used within the membrane reactor to deliver pure oxygen for ammonia oxidation; (right) HiPowAR system configuration with double reheating, scheme A.

System description, Methods, and Data

The purpose of this work is to evaluate the effects of reheating on the efficiency of the HiPowAR system. Figure 9-right shows the configuration of the HiPowAR system including a double reheating process. Ammonia is oxidized using pure O_2 in a series of three MRs, each composed of several tubular membranes. The hot gas-steam mixture is sequentially expanded, down to sub-atmospheric pressure (0.1-0.12 bar). After heat recovery and water condensation, the off-gas (mainly N_2) is compressed to ambient pressure (#20). Liquid water (stream #28) is recovered and used as temperature moderator.

The model is implemented in Aspen Plus®, assuming reasonable values for polytropic efficiency and heat losses. Two system configurations are investigated. In scheme A, the maximum system pressure (streams #27 and #2) is selected to guarantee a 10°C pinch-point temperature difference in the ammonia evaporator, which thus exploits waste heat. In scheme B, the evaporator is removed and liquid ammonia is sent to the MRs and a larger maximum cycle pressure is employed (50 bar).

Results and Discussion

Results are shown in Table 2, focusing on system electric efficiency (η_{el}), which account also for additional loss terms like gearbox, electric generator efficiency, and auxiliaries' consumption.

The maximum cycle temperature significantly increases the system efficiency, as in conventional power generation systems (note that in the 1350°C case, ceramic materials should be used for the expanders, since blade cooling is not present). Scheme B performs slightly better than scheme A, except for the 850°C case with no reheating, where the minimum system pressure is kept at 0.3 bar to avoid liquid droplets formation during expansion. In scheme A the design of reactors and expanders is simplified, thanks to the lower maximum pressure. In all cases, reheating significantly increases the system efficiency due to the lower irreversibilities related to the introduction of heat in the cycle. The benefits of reheating are more evident for scheme B due to the larger expansion ratio, which increases the fraction of heat that is introduced at relatively large temperature. Finally, reheating is more impactful when the maximum cycle temperature is lower (cases at 850°C), which is attributed to the larger irreversibility related to the introduction of heat in the cycle when the TIT is relatively low.

Table 2 – Effect of reheating on the system electric efficiency for different turbine inlet temperature (TIT), for both scheme A and B.

TIT [°C]	Reheating	Scheme A			Scheme B		
		p_{max} [bar]	p_{min} [bar]	η_{el} [%]	p_{max} [bar]	p_{min} [bar]	η_{el} [%]
1350	No	16	0.12	54.1	50	0.1	54.8
1350	Yes	14	0.1	58.8	50	0.1	60.2
850	No	16	0.12	42.1	50	0.3	40.7
850	Yes	14	0.1	48.2	50	0.1	50.2

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