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Comparison of a fuel-driven and steam-driven ejector in solid oxide fuel cell systems with anode off-gas recirculation: Part-load behavior

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HIGHLIGHTS

- We model an SOFC system with anode off-gas recirculation.
- A steam and fuel driven ejector are used for recirculation.
- Carbon formation limits the part load of a fuel driven ejector system.
- The condensation temperature limits the part load of a steam driven ejector system.
- A steam driven concept increases the electrical efficiency.

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ABSTRACT

This paper investigates the use of ejectors for recirculating anode off-gas in an SOFC system, focusing on the part-load capability of two different systems. In the first system, recirculation was enabled by a fuel-driven ejector. The part-load threshold of this system was determined by carbon formation and was 77.8% assuming a fuel utilization of 70% and suitable ejector geometry. The second system was based on a steam-driven ejector. The simulation results for this system showed an improved part-load capability of 37.8% as well as a slightly improved electrical efficiency. Here, the minimal part load was determined by the condensation temperature of the condenser used in the system.

1. Introduction

Global energy consumption is growing day by day. As our natural resources are limited, highly efficient energy systems, such as solid oxide fuel cell (SOFC) systems, are needed. SOFCs are high-temperature fuel cell technologies and have been under development for a number of years. To increase the initial efficiencies, improvements have been made on the cell and system levels, increasing efficiencies up to 60% [1–4]. The recirculation of anode off-gas is one method of achieving a large efficiency jump as it improves system fuel utilization. Peters et al. [5] compared different concepts with and without anode off-gas recirculation. Their results show that electrical efficiency is up to 16% lower in systems with no anode off-gas recirculation.

The most frequently chosen concepts for driving anode off-gas recirculation systems are the use of blowers and ejectors [5]. AVL developed and manufactured a high-temperature prototype blower that operates at a maximum gas temperature of 600 °C [6]. The blower rotates at 120,000 rpm and has an efficiency of 50%. With this AVL's SOFC system reaches an electrical efficiency of around 50%. Versa Power Systems and FuelCell Energy have built an SOFC system with a high-temperature blower that handles gas temperatures of up to 700 °C [1,4]. Their SOFC module operates at a DC efficiency of 64%. Halinen et al. [2] presented an SOFC system with an electrical efficiency of 43%. This system has a power output of 7.1 kW and uses a high-temperature blower for recirculation. Dietrich et al. [7] demonstrated a 300 W SOFC system with anode off-gas recirculation running on a propane-driven ejector. They

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Abbreviations

A	area
AC	alternating current
D	diameter
DC	direct current
m	mass flow rate
n	molar flow rate
O/C	oxygen-to-carbon ratio
p	pressure
RR	recirculation ratio
SOFC	solid oxide fuel cell
T	temperature
u	velocity
uf	fuel utilization
Δp_{Loss}	pressure drop
ω	entrainment ratio
ξ	coefficient of resistance

Subscripts

P	primary pressure
S	secondary pressure
0	inlet
1	nozzle throat
2	nozzle outlet
3	mixing chamber inlet
4	mixing chamber outlet
5	ejector outlet

achieved an efficiency of 41%. Immisch et al. [3] tested a propane-driven ejector system. Their SOFC system enabled a gross efficiency of 61% with an electrical power output of 950 W.

However, blowers and ejectors have to operate under high temperatures of around 600 °C–900 °C. This necessitates high-temperature blowers, seals and bearings that can withstand high temperatures and simultaneously have a long lifetime. Moreover, the expected maintenance is high. Currently, these requirements cause costly prototype blowers and there are only a few companies, such as those shown in Refs. [1,4,6,8], who develop and assemble them.

For this reason, ejector concepts were developed and tested in SOFC systems [3,7,9]. The main advantages are reduced space demand, the lack of moving parts [3,10] and lower maintenance [10]. The key challenge of an ejector in an SOFC system is the part-load behavior, as carbon formation can occur in the ejector, pre-reformer and fuel cell [3,11,12] due to the recirculated amount of steam, hydrogen, carbon monoxide and carbon dioxide. Since the ejector geometry has a strong influence on recirculation, several modeling methods have been developed over the last few years [11,13–18] to investigate ejector behavior. Most of these methods solve the one-dimensional mass, momentum and energy equations with respect to the control volumes of the nozzle, mixing chamber and diffusor [13–15,17]. A common assumption is an incompressible, adiabatic and reversible flow. A different approach was presented by Ferrari et al. [18], who solved the one-dimensional equations using CFD methods. Zhu et al. [16] developed an ejector model using isentropic thermodynamic energy equations and a two-dimensional function for the fluid velocity at the ejector inner walls. The two-dimensional function takes into account the velocity distribution in the mixing chamber of the high-pressure mass flow, on the one hand, and the recirculated mass flow, on the other hand. With this, it is possible to consider a larger recirculated mass flow area and thus to reduce simulation errors [16].

Zhu et al. [11] showed that a high fuel utilization in the stack can enable a lower part load because of a higher electrochemical steam production, a higher amount of steam in the recirculated flow and thus worse conditions for carbon formation. For a fuel utilization of 85% in combination with a steam-to-carbon ratio limit of 2, they simulated a part load of around 54% with their pressurized SOFC system. Values of the part load of the other considered fuel utilizations were not mentioned. Based on the same ejector model, a fuel utilization of 80% and an oxygen-to-carbon ratio limit of 2.2, Liu et al. [12] calculated a potential part load of 60%.

Although papers have already been published in the area of ejector analyses, there are few results on the part-load behavior of an SOFC system. Thus, the aim of this paper is to model the part-load behavior at different fuel utilizations for a fuel-driven and a steam-driven ejector in an anode off-gas recirculation system. The concept of a steam-driven ejector is based on the ideas of Drenckhahn [19] and Ledjeff [20], who proposed an anode off-gas recirculation system with a steam-driven ejector to reach higher efficiencies. The ejector model is based on the work of Zhu et al. [16], where we have added our own calculation of the diffusor part.

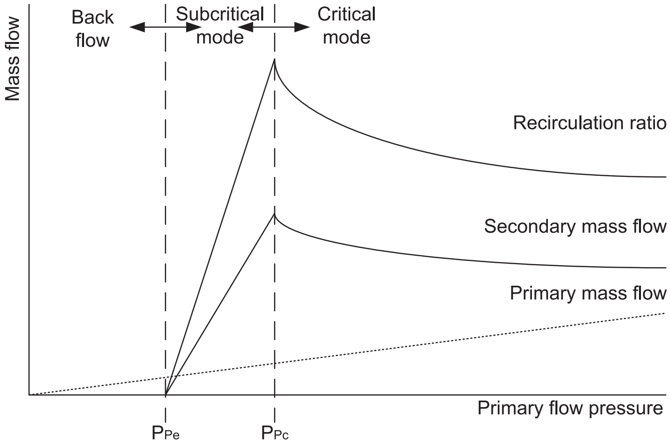

Fig. 1. Ejector characteristics in different modes.

2. Ejector model specification

As shown in Fig. 1, the ejector has three different operational modes depending on the primary pressure, i.e. back flow, subcritical and critical mode [16]. Generally, the primary mass flow increases with the primary pressure in all three modes. In the back flow mode ($0-P_{PE}$), there is no recirculated mass flow (secondary flow) because the pressure in the mixing chamber is higher than the secondary pressure. A primary pressure just above P_{PE} (see Fig. 1) carries the secondary mass flow away, thus starting the ejector.

In the subcritical mode ($P_{PE}-P_{PC}$), the secondary flow increases strongly and reaches its highest value at the transition to the critical mode, where the primary pressure corresponds to P_{PC}. At this point, the entrainment ratio ω, defined as the ratio of secondary flow to primary flow, also reaches its highest value. The entrainment ratio reacts very sensitively to the primary pressure in the subcritical mode.