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Design and Experimental Realization of a Steam-Driven Micro Recirculation Fan for Solid Oxide Fuel Cell Systems

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The Laboratory for Applied Mechanical Design (LAMD) designed, manufactured, and experimentally tested a novel steam-driven anode off-gas recirculation (AOR) fan for solid oxide fuel cell (SOFC) systems up to 10 kW_{el}. Due to the dynamic steam-lubricated bearings, the AOR unit is expected to have a high lifetime, even at elevated rotational speeds and temperatures. Additional, the unit is oil-free, explosion-proof, very compact, and cheap to manufacture. The AOR fan diameter is at 19.2 mm and the nominal rotational speed is 175 000 rpm. The unit was coupled to a 6 kW_{el} SOFC system, reaching electrical gross DC efficiencies, based on the fuel lower heating value (LHV), of 66 % in part load (4.5 kW_{el} gross DC) and 61 % in full load (6.3 kW_{el}) for a global fuel utilization of 85 %. To the best of the authors' knowledge, this was the first time that a steam-driven AOR fan was demonstrated in-situ with an SOFC system.

Introduction

Solid oxide fuel cell (SOFC) systems can be enhanced with anode off-gas recirculation (AOR). AOR allows for a higher global fuel utilization, and thus higher efficiencies, while lowering the local fuel utilization, and thus increasing the fuel cell stack lifetime. The anode off-gas contains besides unreacted hydrogen, also water vapor (pH-neutral and deionized). In case of steam reforming, this water vapor supplied by the AOR can be used for the reforming process, instead of supplying water vapor from an external source, e.g., an evaporator.

Requirements for an anode off-gas recirculation unit

Such AOR needs a pressure rise unit (PRU) to overcome the pressure loss in the reformer, SOFC stack, as well as piping, valves, etc. Ideally, the PRU should comply with all of the specifications, listed as follows:

1. **Oil and grease-free:** Oil and grease can block channels in the reformer or the anode, but can also damage these components and increase the respective aging rate.
2. **Long lifetime**: Typically, SOFC stacks are designed to operate between five and 10 years with regular inspection intervals, whereas an SOFC systems

operate between 20 and 30 years. The ideal PRU would not require inspection, maintenance, or replacement.

3. **Temperature resistant:** Due to increased corrosion potential, the anode off-gas temperature should not fall below the dew point. This minimum temperature depends on the off-gas mixture and pressure, as well as the required safety margin.
4. **Low manufacturing cost:** Reducing costs is essential for the competitiveness of the SOFC technology.
5. **Low complexity:** Generally, low complexity leads to lower manufacturing and maintenance costs. Less complex systems can be more reliable.
6. **No anode off-gas leakage:** The anode off-gas is toxic (carbon monoxide) and also explosive (hydrogen); hence, leakage to the environment has to be prevented.
7. **Air-tightness:** The oxygen in the air in combination with the hydrogen in the anode off-gas can lead to explosions. It can also lead to nickel reoxidation in the reformer and anode, which leads to an increased stack aging rate.
8. **Explosion-proof:** the PRU should be explosion-proof, i.e., have no components that could possibly ignite a hydrogen / oxygen mixture.
9. **High flexibility:** The operation of the PRU should be flexible and independent of the state of the SOFC system.
10. **High component and system efficiency:** A high PRU efficiency can increase the SOFC system efficiency.

Commercial available anode off-gas recirculation fans

PRUs can be either ejectors (fuel or steam-driven) or fans (electrically or thermally-driven). The former excel in points 1-8, but limit the system flexibility due to the carbon deposition risk (fuel-driven ejector) or the condensation temperature of the AOR gas (steam-driven ejector) (1). According to the authors' knowledge, only electrically-driven, but no thermally-driven AOR fans are commercially available. Several different version exists for domestic-scale (~1-10 kW_{el}) SOFC applications:

- **Low-speed** (below 100 krpm) electrically-driven fans:
  - with ball bearings connected to the electric motor by a magnetic coupling (hermetic)
  - with ball bearings directly coupled to the electric motor
- **High-speed** (above 100 krpm) electrically-driven fans, directly coupled:
  - with hydrodynamic oil film bearings
  - with dynamic gas film bearings

Low-speed fans: Both Powell et al. (2) and Peters et al (3) used a side channel blower with magnetic drive from Airtech West and Vacuvane, respectively. Due to the magnetic coupling, the blower is explosion-proof, but the operation temperature and rotational speed are limited. Powell et al. (2) recirculated the anode off-gas at 145 °C and Peters et al. (3) at 160 °C, while the blower could achieve a maximum rotational speed of 15 krpm.

The Japanese company CAP CO offers a radial fan that is directly coupled to the electric motor (4). For an explosion-proof operation, pressurized dry purge gas, e.g., nitrogen, is added into the blower housing (5). However, such a gas is mostly not readily available for domestic SOFC installations. Due to the ball bearings and its limited lifetime at high speeds and high temperatures, the fan is limited in the achievable rotational speed (50 kprm). Hence, the specific speed according to Balje (6) has a relatively low value of 0.3, suggesting a low isentropic efficiency.

High-speed fans: Both higher rotational speeds and higher lifetime, even at elevated temperatures, can be achieved with dynamic gas film bearings. Hence, higher efficiency can be reached, since the radial fan can operate at the optimal specific speed on the order of 1 according to Balje (6). However, these type of bearings have the major drawback of low tolerance to misalignment due to relatively low bearing load capacity. Because of this, no AOR fans with both a magnetic coupling and gas film bearings are available off-the-shelve; all of them are directly coupled to the electrical motor, which is unfavorable for an explosion-proof operation.

The company AVL List (7) offers a radial fan with dynamic oil film bearings. AOR temperatures of up to 600 °C can be reached. The rotational speed is up to 120 krpm. However, oil can potentially destroy the SOFC stack and / or the reformer.

A solution to this problem are oil-free dynamic gas film bearings. Previous and current research projects by R&D Dynamics Corporation (8) and Mohawk Innovative Technology (9), respectively, use foil journal and foil thrust bearings as dynamic gas film bearings.

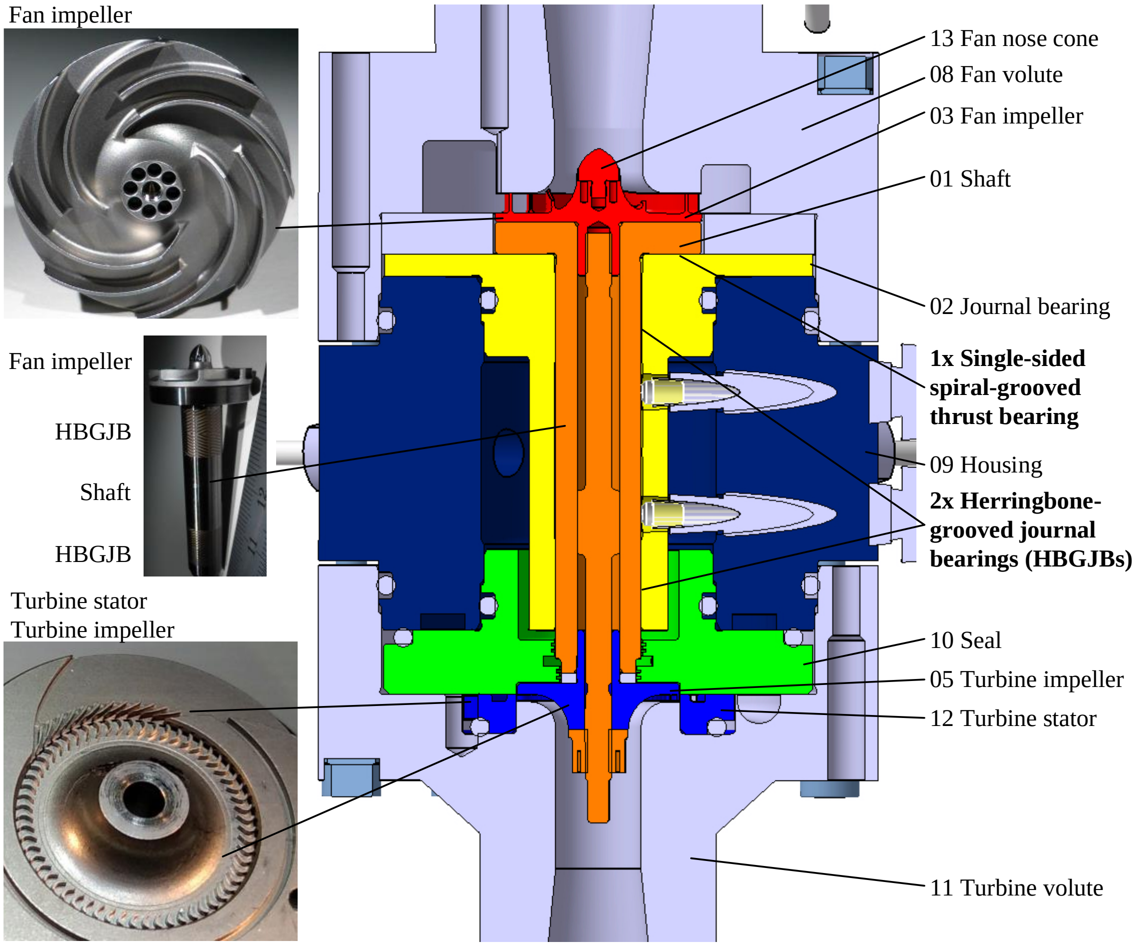

Figure 1. The concept of the novel fan-turbine unit (FTU).

Novel steam-driven anode off-gas recirculation fan

Since a high-speed fan with rotational speeds exceeding 100 krpm, dynamic gas film bearings, and a magnetic coupling is complex and challenging to realize, the authors decided to omit the latter. The unit is still explosion-proof, since the electrical motor is replaced by a small-scale steam turbine. The fan is thus steam-driven or more specifically thermally-driven, since system excess heat can be used for evaporation. Figure 1 shows the concept of this fan-turbine unit (FTU). The fan impeller (red part) is located on the top, the turbine rotor and turbine stator at the bottom (light blue parts). The shaft (orange part) connects the turbine and the fan impeller.

The fan design and its characterization with air at 200 °C is described by Wagner et al. (10,11). Table I lists the main geometrical parameters of both the radial fan and the radial-inflow turbine. The entire unit is manufactured with turning, milling, and surface finishing operations, i.e., grinding and honing. The unit design is based on achieving low manufacturing cost; the entire prototype manufacturing cost is 12 000 $.

Fan: The baseline fan impeller is designed for a total inlet pressure of 1.05 bar, a total inlet temperature of 200 °C, an inlet mass flow rate of 4.8 kgh^{-1}, and anode off-gas composed of water vapor, hydrogen, carbon monoxide, and carbon dioxide (61.4 %, 7.4 %, 2.6 %, and 28.6 % molar ratio, respectively). The design total-to-total pressure rise is 70 mbar for the design blade tip clearance of 0.05 mm. The pressure drop in the SOFC stack and in the reformer are determined based on experience: 30 mbar and 20 mbar, respectively. The authors estimate the overall pressure drop in heat exchangers and within the anode loop to be 10 mbar. In total, the AOR fan compensates for 70 mbar at the design point, thus accounting for a safety margin of an additional 10 mbar. The fan design is a trade-off between efficiency and low manufacturing cost. The fan rotor tip diameter is 19.2 mm and its design rotational speed is 175 krpm, corresponding to a specific speed of 0.8, as defined by Balje (6).

Turbine: The turbine impeller design is inspired by the work of Sato et al. (12). The baseline steam turbine impeller is designed for an inlet total pressure of 1.9 bar, an inlet total temperature of 220 °C, an inlet mass flow rate of 2.1 kgh^{-1}, resulting in an estimated power of 36 Watt. A partial-admission design (21 %) was chosen to increase the blade height, and thus to decrease the relative blade tip clearance. The turbine has a low reaction of 13 % (measured at the design point). This has mainly four advantages: 1.) the turbine power is increased compared to a similar 50 % reaction turbine, 2.) the turbine impeller thrust force is reduced, 3.) a partial-admission operation is possible, and 4.) the rotor blade tip clearance leakage rate is decreased, leading to a higher turbine isentropic efficiency. The turbine impeller tip diameter is 15 mm. Both the turbine rotor and stator are made of stainless steel and exclusively manufactured with turning and milling operations.

Shaft: The stainless steel shaft (8 mm diameter) with a diamond-like carbon (DLC) coating has two herringbone-grooved journal bearings (HBGJBs) and one single-sided spiral-grooved thrust bearing (SGTB). The grooves are manufactured with laser. During nominal operation, the self-acting bearings are lubricated with water vapor. At the design rotational speed (175 krpm), the journal bearing orbits are on the order of 0.001-0.002 mm, whereas the axial shaft displacement of the thrust bearing is on the order of 0.01 mm (depending on the actual thrust).

TABLE I. Geometrical parameters of the anode off-gas recirculation fan and the steam turbine.

Parameters	Radial fan	Radial-inflow turbine
Rotor tip diameter in mm	19.2	15.0
Number of rotor blades	4 (main) and 4 (splitter)	59
Number of stator blades	-	12 (admission of 0.21= (12+1)/61)
Rotor blade height in mm	1.90	0.59
Stator blade height in mm	-	0.70
Rotor blade tip clearance in mm	0.05+0.1 (shim)	0.13
Rotor blade thickness in mm	0.25	0.09 (LE) and 0.08 (TE)
Stator blade thickness in mm	-	0.25 (LE) and 0.08 (TE)
Rotor blade radial chord in mm	5.3 (main) and 3.3 (splitter)	1.0
Blade turning in °	13 (shroud) to 19 (hub)	102

Novel SOFC system

Figure 2 shows a schematic of an SOFC system with a steam-driven AOR fan with gas film bearings, the FTU. It has an intermediate-temperature SOFC with Ni-YSZ planar anode, YSZ / CGO double layer electrolyte, LSCF / CGO composite cathode, and FeCr metal interconnect / plates as bulk material. The feed gas to the system (stream 6 in Figure 2) is methane that is reformed via steam to form hydrogen. The steam for the reforming is provided by the FTU. The non-recirculated anode off-gas (stream 17) and the cathode off-gas (stream 4) are not mixed to increase the water vapor molar fraction in the off-gas (stream 18). This increases the condensation temperature, and thus the heat recovery within the system. The anode off-gas burner is provided with fresh incoming air (stream 32-33).

Since the condensed water can be used for the steam turbine, no external water source is required. A pump draws the necessary water (stream 24) and increases its pressure. Since the FTU is sensitive to particles and corrosion, a water treatment and water neutralization, respectively, would be necessary. The evaporator generates steam (stream 26) that is expanded in the turbine (stream 28). A small turbine-to-fan steam leakage rate occurs, which is assumed here to be 1 % of the mass flow rate of stream 26. The expanded steam is fed back to the anode off-gas (stream 31). The necessary heat for the anode off-gas preheating (heat flux 3 and 9), the reformer, and the evaporator (heat flux 7) can be provided by internal heat recovery from the anode off-gas (heat flux 6).

A similar methodology as proposed by Wagner et al. (13) was used to simulate and optimize this SOFC system. To reach the highest electrical net efficiency ($\eta_{el,net}$), an oxygen-to-carbon ratio (O/C) in the external reformer of 2, an external-to-total reforming fraction (ξ_{ext}) of 0.2, a reducing species (CO and H_2) fraction at the anode exhaust (stream 11) of 0.1, an air-fuel equivalence ratio (λ) of 1.1, a fan inlet temperature (T_{13}) of 200 °C, and a steam recirculation ratio (ξ_{sr}) of 0 was chosen. A steam recirculation higher than 0 leads to a dilution of the anode off-gas, and thus to a lower stack and system efficiency. The system electrical net efficiency is decreased by 1 percentage point for a steam recirculation ratio of 0.5. Separating the steam and the anode off-gas therefore is a major advantage of the FTU, compared to a steam-driven ejector system.

The simulation suggests an electrical net DC efficiency based on the fuel lower heating value (LHV) of 65.2 %, whereas it is 64.9 % (13) for the electrically-driven AOR fan. This correlates to an electrical gross DC efficiency of 68.7 %, a global fuel utilization of 92.5 %, and a local fuel utilization of the SOFC stack of 85 % (for both the SOFC system with thermally and electrically-driven AOR fan).

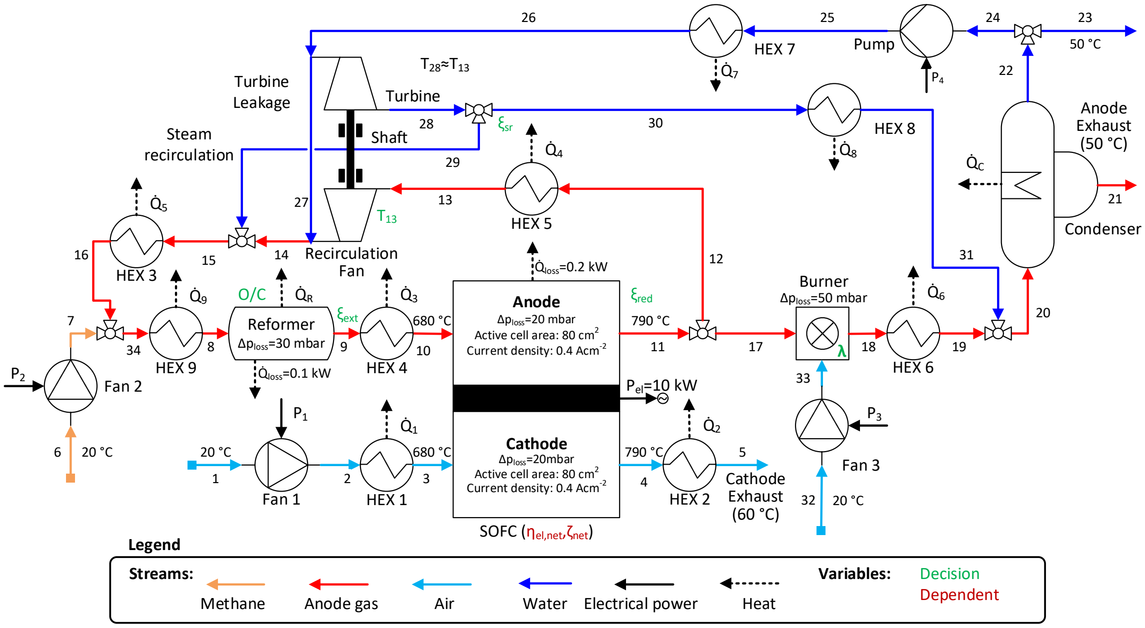

Figure 2. Schematic of an SOFC system with a steam-driven AOR fan.

Experimental realization of the steam-driven anode off-gas recirculation fan

The steam-driven FTU was successfully coupled with a 6 kW_{el} SOFC system in the facilities of SOLIDpower in Yverdons-les-Bains, Switzerland in 2018 (14). To the best of the author's knowledge, this is the first proof-of-concept of such a steam-driven AOR fan. For this proof-of-concept, a simplified system was realized. The major differences are as follows: 1.) The SOFC stack and the FTU were in separate electrical ovens and not together in an insulated passive hot box. 2.) The FTU was not thermally coupled to the SOFC system, but the evaporator (HEX 7 in Figure 2) was electrical. The actual SOFC system with the heat exchange from HEX 6 to HEX 7 was therefore not realized at this initial stage (simpler turbine control). 3.) Deionized water from a separate tank was used for the turbine and not the condensed water from the anode off-gas to simplify the experiments (not water treatment needed). This simplified system can therefore outline its potential in terms of electrical gross efficiency. The electrical net efficiency is inferior compared to a final system, as shown in Figure 2. However, the net efficiency was not determined during the experiments.

An electrical gross DC efficiency, based on the fuel LHV, of 61.4% in full load (6.3 kW_{el} gross DC) for a global fuel utilization of 85 % was obtained. The recirculation ratio (stream 12 divided by stream 11) was measured with two Venturi nozzles. Since it was 48 %, the local fuel utilization can be calculated to be 75 %. At this operational point, the AOR fan pressure rise was 65 mbar and the AOR mass flow rate 2.5 kgh^{-1} for a rotational speed of 165 krpm. The difference to the design value (70 mbar at 4.8 kgh^{-1}) is mainly due to three reasons: 1.) higher rotor blade tip clearance (0.15 mm instead of 0.05 mm, due to risk mitigation), 2.) lower fan inlet pressure (1.01 bar instead of 1.05 bar), and 3.) the lower rotational speed (165 krpm instead of 175 krpm). The turbine total-to-total pressure ratio was 1.8 and the mass flow rate 2 kgh^{-1}.

For the part load case, a fuel utilization of 0.7, 0.75, 0.8, and 0.85 was investigated, resulting in gross DC powers of 5.2 kW_{el}, 5.5 kW_{el}, 5.7 kW_{el}, and 5.9 kW_{el}, respectively, which is equivalent to a gross DC efficiency (LHV) of 55.5 %, 58 %, 60.5 %, and 62.4 %, respectively. Considering a quadratic extrapolation of these four cases, an electrical gross DC efficiency of 65.0 % could be obtained for a global fuel utilization of 92.5 %. This is 3.7 % lower than the results of the system simulation (68.7 %) presented in this paper and by Wagner et al. (13). However, a global fuel utilization of 92.5 % could not be achieved in the experiments, due to risk mitigation (difference in the cell potentials too high).

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