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Ejector design and performance evaluation for recirculation of anode gas in a micro combined heat and power systems based on solid oxide fuel cell

Liso Vincenzo*, Nielsen Mads Pagh, Kær Søren Knudsen

Aalborg University, Pontoppidanstræde 101, 9220 Aalborg, Denmark

HIGHLIGHTS

► An ejector model for SOFC-based mCHP system is presented.
► A novel ejector designing procedure is provided.
► A validation method for ejector designing is proposed.
► Ejector and mCHP system performances are discussed.

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ABSTRACT

In this paper, a theoretical analysis of an ejector for micro combined heat and power systems based on Solid Oxide Fuel Cell (SOFC) for small-scale residential applications is presented. A novel detailed procedure for the ejector designing is provided and its effectiveness is validated through a comparison with testing results. The ejector geometry is analysed in terms of component efficiency. The SOFC system performance with regard the recirculation of anode gas is finally discussed.

Results show that fuel inlet temperature and the diameter of the ejector mixing chamber of the ejector largely affect the ejector performance. A large mixing chamber diameter allows a high entrainment ratio but causes a worse ejector efficiency suggesting a highest efficiency still ensuring the required entrainment ratio.

At system level, it is shown that the degree of fuel pre-reforming affects the recirculation ratio. Besides, if anode gas recirculation is implemented the system capital cost decreases due to reduction in size of ancillary components. The high electrical efficiency achieved by the system reduces the heat output and makes it more attractive when less heat is demanded.

1. Introduction

Ejectors are able to transfer momentum and energy from a high energy primary fluid to a low energy secondary fluid through the work provided by turbulent mixing and entrainment. Ejectors were first applied in steam-driven locomotive, later they have been used in vapour compressor refrigeration and heat pump industry [1]. Nowadays ejectors are applied in the food, chemical and oil industries [2]. Recirculate part of the exhaust anode gases in SOFC-based mCHP systems by means of ejector is also a viable option. In this case, instead of generating steam for the reforming reaction externally, the steam produced in the electrochemical reactions at the anode can be used in the pre-reformer process.

By re-using part of the heat, the recirculation of anode gases lowers the mCHP heat output of the system. This can make SOFC-based systems a competitive technology in hot countries where little heat is needed during the winter, or in cases where the mCHP is added to a pre-existing natural gas boiler.

Riensche et al. [3] reported that the main advantages of anode gas recirculation are no external steam production, a reduced number of cells in stack due to lower in-cell fuel utilization, and a lower steam concentration in the exhaust gas improving the overall system efficiency. An additional advantage is that the demineralized and deionized water used to produce steam can be re-used instead of being added by an external operator. The disadvantage is that higher compression energy for the fuel ejector is

* Corresponding author. Tel.: +45 21370207.
E-mail address: vli@et.aau.dk (L. Vincenzo).

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Nomenclature

A	area (m^2)
AGR	anode gas recycle ratio
C_{pd}	pressure recuperation coefficient diffuser (−)
C_{pm}	pressure recuperation coefficient mixing (−)
LHV	lower heating value
Ma	Mach number
mCHP	micro combined heat and power system
k_P	specific heat gas ratio
P	pressure (bar)
r,R	radius (m)
SOFC	solid oxide fuel cell
STCR	steam to carbon ratio (−)
S/C	steam to carbon ratio (−)
R_g	gas constant (J $kmol^{-1}$ K^{-1})
R_u	universal gas constant 8314 (J $kmol^{-1}$ K^{-1})
V	velocity (ms^{-1})
$\dot{V}$	volume flow rate (m^3 s^{-1})
W_{comp}	compressor work (N m^{-2})

Greek symbols

ρ	density (kg m^{-3})
η_{el}	electrical efficiency (−)
γ	heat capacity ratio (−)
Ψ_p	Isentropic coefficient of primary flow (−)
ξ_{exp}	friction loss coefficient in mixing process (−)
ω	recirculation Ratio (−)

Subscript

D	diffuser
dp	designing point
M	mixed
P	primary
t	throat
S	secondary
0	ejector inlet
1	primary flow at nozzle throat
2	nozzle exit
3	mixing chamber inlet
4	mixing chamber outlet
5	ejector exit

necessary to achieve the recycle. This is common in case the system is used for residential applications as the natural gas is distributed at relatively low pressure compared to the industrial gas distribution grid.

In this specific application ejectors require features such as high recirculation ratio, low pressure increment and high temperature of operation. The primary fluid is methane preheated to 400–500 °C, while the secondary one is the cell exhaust anodic flow, mainly composed of carbon dioxide and steam at a temperature around 900 °C.

Ejector design can be performed using different levels of detail. This ranges from conservation equations applied to a control volume consisting of the ejector to CFD analysis of a given geometry and operating conditions.

The majority solves the one dimensional mass, momentum and energy conservation equations applied to the ejector control volume with the assumption that the flow is incompressible, inviscid and adiabatic [4,5]. This approach was later further developed by applying one dimensional CFD in Ref. [6]. As discussed by Zhu et al. [7], the secondary flow area in SOFC anode gas ejector applications is larger than in previous applications and a one dimensional approach therefore leads to larger errors in performance simulations. Zhu et al. [7] presents an ejector design and simulation method applying a two dimensional velocity model for the secondary flow to account for the increased importance of two dimensional due to a larger secondary flow area. The model is applied to a pressurized SOFC system with an electrical output of 240 kW.

In the present work a mass, momentum and energy balance is added to model the mixing chamber and the diffuser. This modification gives a better indication of the ejector outlet gas characteristics (P, V, T) which is important when a system analysis is carried on. In fact, previous models such as the one by Zhu et al. [7,8] or Marsano et al. [2] do not consider the gas properties at the diffuser outlet. Next a system analysis is conducted in order to estimate the benefit in terms of efficiency gain of the recirculation.

The ejector performance can be defined into three modes of operation, i.e., back flow, subcritical and critical modes depending by operating conditions [9]. In the subcritical mode and back flow mode, the flow is characterized by unexpected fluctuations and a decrease in the required STCR for reforming process and fuel cell.

For this reason the ejector model described in this work is assumed operating in critical mode. In this condition the pressure of the actuating fluid is equal or higher than the pressure of the induced fluid in the mixing section entry and the secondary flow is accelerated by the primary flow and always shocks at the mixing chamber inlet.

2. Aim and methodology

The aim of this work is to study the recirculation of anode gas in a SOFC-based mCHP system for single family application with an electric output of 1 kW. Ejector models have previously been developed for bigger plant scale. In fact, in Refs. [2,10] models for a SOFC-based mCHP with an electric output of 250 kW are presented. Comparing to the model in Ref. [7], in the present model mass, momentum and energy balance are added in the mixing chamber and diffuser in order to calculate the gas properties at the diffuser outlet.

Based on the this model, a novel designing procedure for the ejector is defined; next the design data obtained in the present work are compared with those obtained by Marsano et al. [2] assuming that the ejector operates on the three dimensional operating surface showed by Ref. [11]. The designing parameter (i.e. throat diameter, mixing chamber diameter…) is evaluated in a parametric study also in terms of ejector efficiency. Finally a system analysis in conducted on a small scale SOFC-based mCHP plant.

3. Ejector performance parameters

In this study the following indicators are considered in order to evaluate the ejector performance.

The entrainment ratio represents the proportion of entrained flow compared to the primary flow and it is defined as:

$$\omega = \frac{\dot{m}_S}{\dot{m}_P} \tag{1}$$

where $\dot{m}_S$, $\dot{m}_P$ are the mass flow rates of the primary flow and the secondary flow. As the secondary flow molar composition is not fixed, also the entrainment ratio changes during the operation.