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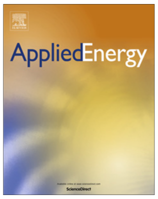

Experimental and numerical analysis of gas distribution in molten carbonate fuel cells

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HIGHLIGHTS

- Flow rate distribution in a MCFC stack is analyzed to determine improvement actions.
- The flow field inside a MCFC package of 150 cells is experimentally studied.
- Flow rate distribution inside anodic and cathodic manifolds is numerically modelled.
- Flow maldistribution for different operating conditions is assessed for both anodic and cathodic manifolds.
- Different design solutions to get more uniform gas distribution inside the cell package are analyzed.

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ABSTRACT

Flow maldistribution through the cell package affects the efficiency of the fuel cells, thus limiting the reliability and the diffusion of such a technology. This subject is a key-point in the progress of the fuel cells, so deserving the greatest attention and the most thorough research. This paper faces the issue by evidencing the possibility to improve the quality of flow distribution through an appropriate design based on the use of numerical methods. In particular, this research deals with the gas flow rate distribution in a Molten Carbonate Fuel Cell (MCFC) and with the effect on maldistribution of baffles inserted into the inlet manifolds. To this extent, an experimental set-up was built to analyze the flow field inside the cell: the test section reproduces full-scale inlet manifolds for the anodic and cathodic supply of a MCFC stack of 150 cells. Experimental runs covered start-up as well as loading conditions. Air was used to simulate actual flow conditions inside the fuel cell package, basing similarity on inlet Reynolds numbers equivalence. Gas flow rate distribution has been evaluated by measuring the exit velocity at the outlet of the experimental set-up, operating at different working conditions for both cathode and anode, with and without the presence of baffles inside the inlet manifolds. Uneven distributions were observed for high mass flow rates at the cathode manifold without baffle. For the anode, manifold flow distribution resulted acceptably uniform for all working conditions. The baffle improved the distribution for both cathode and anode manifold; particularly, sharp peaks of velocity observed for cathode in the absence of the baffle disappeared at all. Then, velocity and flow rate distributions were modelled by means of a 3D computer code. In order to validate the accuracy of the model, calculated results were compared with experimental data; as a result, their agreement was very good and suggested the opportunity of a manifold design based on a numerical approach. The numerical model was finally utilized to predict flow rate distributions for all working conditions, by taking into account the detailed actual geometry of the manifolds. Numerical analysis of flow rate distribution by means of specific indexes permitted to better understand critical conditions and the reasons of maldistribution. The model was finally used to analyze various design solutions and get a more uniform gas distribution of flow rates. Thus, the numerical modelling can be effectively used during FC plants' design to analyze the flow distribution, by taking into account devices and systems in order to improve the uniformity of the distribution. In this way, the numerical modelling permits to avoid expensive and time-consuming experiments, and to optimize, with a limited effort, the manifolds according to the cell package characteristics and mass flow rates.

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Nomenclature

Latin letters

A	area
C	Courant number
$c_{i,CK}$	empirical constant
c_μ	empirical constant
D_h	hydraulic diameter
f	local drag coefficient
I	number of elementary areas
k	turbulent kinetic energy
$\dot{m}$	mass flow rate
$\dot{m}^*$	dimensionless mass flow rate
M	number of rows
MD	maximum deviation
N	number of columns
P_k	production of turbulent kinetic energy
p	pressure
Q	volume flow rate
S	external force
STD	standard deviation
t	time
t_d	time scale
t_p	production time scale
u	velocity
u'	fluctuating velocity
u_z	longitudinal velocity
$\bar{u}_z$	mean longitudinal velocity
U	measured velocity
U^*	dimensionless measured velocity
v	supply duct velocity

Greek letters

β	momentum coefficient
γ	kinetic energy coefficient
δ_{ij}	Kronecker's delta
ε	rate of energy dissipation
ν_{turb}	eddy turbulent viscosity
ρ	density
$\sigma_{k,s}$	empirical constant
$\sigma_{\varepsilon,s}$	empirical constant
τ	total shear stress

Acronyms

AFC	Alkaline electrolyte Fuel Cell
CFD	Computational Fluid Dynamics
CK	Chen and Kim
HTR	High Temperature Reformer
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PEFC	Polymer Electrolyte Fuel Cell
PISO	Pressure Implicit with Splitting of Operators
RANS	Reynolds-Averaged Navier–Stokes equations
RFR	Reduced Flow Rate
SHR	Sensible Heat Reformer
SOFC	Solid Oxide Fuel Cell
STUP	STart-UP condition

1. Introduction

Today, fuel cells are one of the most promising systems for the production of electricity, because of their high conversion efficiency of the chemical energy of the reactants into electrical energy and of the low emission of pollutants from exhaust gases [1–3]. In fuel cells the continuously fed gases (hydrogen, pure or from hydrocarbons, and atmospheric oxygen) electrochemically react producing DC power, steam and heat. The high efficiency is just due to the process of direct conversion of chemical energy into electrical energy, which takes place without the intermediate thermodynamic cycle, typical of the traditional systems [4].

Different kinds of fuel cells are nowadays being developed, distinguished on the basis of the used electrolyte, whose ionic conductivity characteristics determine the operating temperature of the cell. Moreover, the type of electrolyte determines the electrodes' structure and the composition of the reacting gases. Thus, there are different kinds of fuel cells (polymer electrolyte – PEFC; alkaline electrolyte – AFC; phosphoric acid – PAFC; molten carbonate – MCFC; solid oxide – SOFC), each one characterized by different electrochemical reactions and by its own operating temperature [5].

The activities of industrial development of fuel cells have addressed the research and the testing of innovative design solutions for both single-cells as well as for stacks composed of multiple cells electrically connected in series. In particular, in the development of fuel cells stacks, research activities have been oriented towards a natural evolution on systems gradually bigger in size, and therefore in power [6,7].

In these systems the need for the gas distributors to ensure a controlled distribution of the flow inside the cell package, i.e. the channels formed by the plates which separate fuel and oxidant, has rapidly increased [8,9]. This is because a uniform distribution of the flow on both the cathode side (fuel) and the anode side (oxidizing) is usually a condition for ensuring an efficient system operation free from thermal stress [10]. Moreover, a better control of flow distribution can further allow to optimize the working conditions in the different zones of the cell package, not only in order to avoid critical phenomena (e.g. hot spots) but also to enhance the global efficiency of the cell. The regulation of the local flow rate through the different rows makes possible to feed the cell package in accordance with the spatial map of key operating parameters [11].

Therefore, the problem of reducing the flow rate maldistribution in the cell packages is an increasingly topical subject in FC field, because of the increased expectations for higher energy efficiency and of the demand for manufacturing reliability. This leads to the need to widen the knowledge about distribution manifolds and, in particular, to develop appropriate computational tools. In fact, whereas experimental studies are at the same time very expensive, largely time consuming, and scarcely effective in optimizing the project design, theoretical methods allow to rapidly analyze different options and to simply develop the industrial design; nevertheless they need to be accurately validated.

In this sense, a large number of papers have been devoted to techniques able to analyze and predict the fluid flow in distribution manifolds, including numerical [12,13], quasi-analytical [14] and analytical [15] methods. At the same time, wide areas of development still remain in the field, since the complexity of involved phenomena makes the problem far from being solved.

The purpose of this paper is to analyze the distribution of anode gas and cathode gas in a MCFC stack. The study was carried out both experimentally, by evaluating the effect produced on the distribution by baffles arranged inside the manifold, and theoretically, by means of the numerical simulation of the flow field inside the manifold. The numerical method, based on a well-established discretization technique and validated by a strong experimental activity, is addressed to the solution of such a pressing technical