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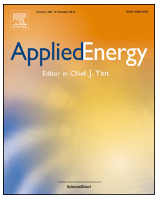

# An evaluation method of gas distribution quality in dynamic process of proton exchange membrane fuel cell

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## HIGHLIGHTS

- Gas distribution quality evaluation based on statistical analysis firstly proposed.
- Optimal working area is presented for stable cell performance under dynamic load.
- Specific areas where gas starvation prone to occur during load change identified.
- Provide basis for fuel cell optimal design, control and gas starvation diagnosis.

## ARTICLE INFO

*Keywords:*
Proton exchange membrane fuel cell
Dynamic loading
Gas distribution quality evaluation
Gas starvation diagnose

## ABSTRACT

The proton exchange membrane fuel cell is considered to be the best alternative to next generation power system due to its high efficiency without emission. It has been found that the lack of gas supply due to frequent load change and start-stop is a very crucial factor in fuel cell life decay and restricts its commercialization. Gas starvation is the state in which the reaction gas of proton exchange membrane fuel cell operates at a sub-stoichiometric level. The diagnosis of local gas starvation without additional expensive and intrusive sensors is still a tough problem not to be solved. In this paper, the area of gas starvation is calculated to evaluate the degree of gas starvation. A novel statistical analysis based method is applied as the index to measure the uniformity of the reaction gas concentration directly on the surface of electrode. The distribution quality of reaction gas under both steady-state and dynamic conditions was evaluated by simulating different operating conditions through the simulation model established. A suitable working area of the fuel cell under steady state is proposed to achieve more stable cell performance under load change conditions. The distribution quality of reaction gas concentration on the whole electrode surface under dynamic condition is evaluated to identify the specific areas where gas starvation is likely to occur. The results of this study will provide the basis for the optimal control and structural design of the fuel cell against dynamic gas starvation, and contribute to the long-life study of proton exchange membrane fuel cells.

## 1. Introduction

Major auto OEMs and component suppliers around the world are committed to R&D and promotion of new energy vehicles because of the environment protection demands, vehicle fuel diversity and gas fuel richness. Electric vehicles, hybrid vehicles and fuel cell vehicles are developing rapidly. Among them, the development prospect of fuel cell vehicles has been widely recognized [1] because of its advantages of rapid energy supplement, long passage range, high efficiency and low noise [2]. Proton Exchange Membrane Fuel Cell (PEMFC) can be used as a power source of fuel cell vehicles, which has the advantages of zero emissions, high efficiency, and low vibration and operating temperature [3]. However, the cost and longevity problems severely restrict the commercialization of vehicle-use PEMFCs [4]. PEMFC life can reach 30,000 h as a fixed energy source [5], however only 2500–3000 h when used as a vehicle power source [6]. Variable load, start-stop, idle speed, and high-power operating conditions are the main factors in the life decay of vehicle fuel cells according to a study by Prof. Pei et al. [7]. Among them, variable load is the main reason, as shown in Fig. 1. Frequent load changes lead to the increased of difficulty in water

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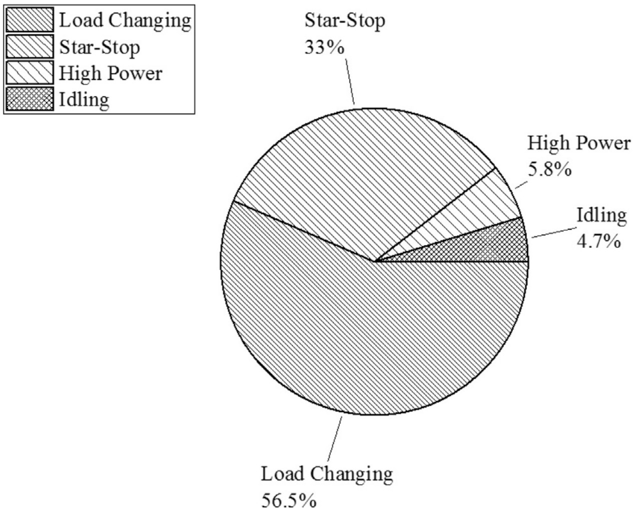

**Fig. 1.** PEM fuel cell performance degradation rate caused by different operation conditions [7].

management and gas supply, which in turn affects the lifetime of automotive PEMFCs [8].

Dynamic response capability is one of the key factors affecting the lifespan of vehicle PEMFC [9]. The fuel cell performance will be improved and the fuel cell lifetime will be extended through improving the dynamic response capability of the PEMFC [10]. Hamelin et al observed the undershoot and up-regulation of the PEM fuel cell voltage for the first time when the current is rapidly changing [11]. The response time constant of the voltage undershoot is composed of two phases. The first phase is the voltage undershoot lead by inability of the reaction gas to transfer in time and the time delay is about the order of a second. The second stage is that the fuel cell reaches a steady state, the time delay is about the order of 10 s [12]. Five groups of dynamic tests were conducted and found that external load changes the current output proportionally and reverses stack voltage accordingly [13]. The dynamic response of the single fuel cell is highly influenced by the non-uniform distribution of current density along the fuel-flow direction [14]. Chen Huicui et al. studied the voltage response of a proton exchange membrane fuel cell during dynamic load change by establishing an equivalent circuit model, which can be used to predict the voltage response during various load conditions [15]. Inlet relative humidity, inlet pressure, air excess ratio, operating temperature, flow field design are all factors that affect the dynamic response of the fuel cell. A study aims at the experimental and numerical evaluation of the effect of the key operating parameters on the transient performance of a fuel cell stack were carried out on a stack with 24 cells with a catalyst active area of 300 $\text{cm}^2$ [16]. The careful selection of the operating parameters is the key factor for ensuring efficient gas management. The results of an inlet humidification efficiency model reveal that the species distribution uniformities of the inlet humidification efficiency model reach the best when the PEMFC at 100% relative humidity [17]. Based on the data presented by Bosung Kim et al. [18], the optimal air stoichiometry was determined between 2.0 and 2.5, and the optimal air excess ratio was suggested between 1.65 and 2.0. Wu et al. [19] numerically explore how the changed flow field design by the arrangement pattern of the protrusive gas diffusion layer affects the cell performance for a full-scale serpentine channel. The optimal design can upgrade the PEM fuel cell performance about 12%. Improper operation condition was correlated with fuel starvation conditions [20], which will lead to carbon support corrosion, catalyst loss and seriously degrade the lifetime and performance of the fuel cell [21]. Therefore, gas starvation should be avoided in both the fuel cell structure design and optimization of operating conditions. There are many studies on online diagnosis [22] and quick diagnosis [23] for proton exchange membrane fuel cell system. Gas starvation diagnostic is particularly important as a prerequisite requires further research. It is divided into overall gas starvation diagnosis and local gas starvation diagnosis. The overall starvation diagnostic method includes detects carbon dioxide emissions [24], outlet gas flow [25] and output performance [26], etc. When the voltage of one or several single cells is extremely low or cell reversal is detected, means the appearance of the gas starvation phenomenon [27]. The method of gas starvation diagnosis by inverting the polarization curve based on the output performance is quick and easy to implement, yet not suitable for the severe gas starvation conditions. Single cell voltage inspection system can be applied to the diagnosis of overall gas starvation by monitoring the output voltage variation, current changes as well as air stoichiometric ratio. However, the above method cannot diagnose the local gas starvation [28]. Neutron imaging, gas chromatography, X-ray capture, and infrared capture methods have all been proposed for the diagnosis of gas starvation in fuel cells. However, compared to the above methods, the transparent PEMFC [29] is simpler, safer and applied to more kinds of situations. However, the thermal insulation properties of the transparent fuel cells are contrary to the thermal conductivity of carbon bipolar plates, which will cause significant changes in the surface properties of the fuel cell and affect water management. Based on the above considerations, a more non-invasive method can be obtained by recording and analyzing the noise generated during the fuel cell operation [30]. The acoustic emission generated when internal material is deformed and the generation of low-frequency impedance noise of fuel cell can be used as diagnostic indicators for gas starvation. The purge strategy is an effective method for improving the gas distribution quality by removing liquid water from the flow path [31]. Studies are aimed at determining the optimum purge parameters to ensure the best voltage stability with the lowest hydrogen consumption rate of the PEM fuel cell [32]. Optimization of the purge frequency [33] and the purge valve diameter [34] are both proved to be effective through simulation and experiments. Air stoichiometry is usually used as an indicator of the gas starvation degree. However, air stoichiometry cannot diagnose local oxygen starvation caused by excessive liquid water in the gas diffusion layer (GDL). The average current density distribution [35] is proposed to characterize gas starvation as the oxygen starvation generally accompanied with the phenomenon of non-uniform current distribution. Segmented electrodes, current density test pads, magnetic field sensors, printed circuit boards are common methods. Hu et al. [36] proposed the use of current density difference to simplify the current density distribution and was applied to the oxygen starvation problem of onboard diagnostic. Recently proposed brain heuristic computing paradigm, Reservoir Computing developed an efficient data-driven fault detection and identification method [37].

The characteristics of the polarization curve and dynamic response of the fuel cell are highly influenced by the distribution of the reaction gas during dynamic load. Current research on the gas distribution is mostly limited to the phenomenon description, lacking of systematic evaluation of its distribution quality. This paper will focus on the evaluation of the reactive gas distribution quality during the dynamic response of automotive PEMFC. An evaluation criteria of reactive gas distribution quality under different working conditions is established through theoretical derivation and model simulation. The gas starvation area, the range and variance of the reaction gas concentration distribution are used as evaluation indicators.

The second part clarified the phenomenon of insufficiency in gas supply. The method of evaluation was given. In the third part, a three-dimensional model was established. The model parameters were determined and the validity of the model was verified based on experimental data. The distribution quality of the reactive gas was evaluated under steady state and dynamic conditions in Part IV.