Applied Energy 189 (2017) 460–479

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

System integration, durability and reliability of fuel cells: Challenges and solutions

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HIGHLIGHTS

- Technical challenges and obstacles broken down during the scaling-up of fuel cells.
- Analysis of durability and reliability of fuel cell scaling-up using life cycle procedure.
- Three operating windows for different stages: components, individual cells, and stack.
- Operating window narrowing due to uneven flow distribution and dynamic load.
- Connection points among components, flow fields, cells, stack and system control.

ARTICLE INFO

Article history:
Received 30 October 2016
Received in revised form 12 December 2016
Accepted 15 December 2016

Keywords:
Flow field designs
Barriers
Reliability and durability
Process and system control
Scaling-up

ABSTRACT

The technical challenges and obstacles to scaling-up of fuel cells are diverse, including such issues as water, heat, materials, catalyst, and flow fields because of multiple chemical and physical interactions at the atomic level and stack system level. The current results and data, even assumptions and guidelines are separated, inconsistent or unconnected. The unconnected data is partly the result of different disciplines. This paper is a first attempt toward understanding and analyzing the massive but spread-out work, which has been done and reported in the literature on fuel cell performance, reliability and durability. In this, we analyze the procedure of fuel cell research and development, and break down the barriers of scaling-up into four different stages: component, individual cell, stack and system control. We find that there are three different operating windows at each stage of the components, individual cells, and stack. While the operating window of components (e.g., membrane) are defined as ranges of temperature and relative humidity (RH), the operating window of a cell must include channel velocity and pressure drop within the cell. The operating window of a stack becomes narrower than that of its individual cells due to uneven flow distribution and load change. We have also found that there are knowledge gaps in the different stages of development. A solution for fuel cell scaling-up and a connection can be built among the components, cells, stack, process and system control through the operating windows and flow fields. The concepts of the three operating windows and flow field designs can build a connection among properties of the material and structures of components (e.g., wettability, porosity, and hydrophobicity), flow field, cells and performance of a stack and macro operation conditions (e.g., pressure, humidity and flow rates). This clarifies key ambiguities and converges our future directions on how to bridge different stages or disciplines of research and development. These can provide a new insight for future research to address the key issues of durability and reliability that remain unsolved.

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http://dx.doi.org/10.1016/j.apenergy.2016.12.083

1. Introduction

Fuel cells are a low carbon technology because of their high efficiency, low noise, and clean operation. Fuel cells could be great sources of primary power if demonstrated to provide reliable power for long continuous periods of time. High-quality power and efficiency of fuel cells could be the most important marketing drivers for many applications, such as backup power, material handling and submarine engines. Ensuring their longevity and reliability could greatly advance fuel cell technology. The US Department of Energy (DOE) has established a durability target for fuel cells of mobile (5000 h, equivalent to 150,000 miles of driving) and stationary (40,000 h). However, the world-wide commercialization of fuel cells has not yet taken off [1–3]. Only a few fuel cell systems with adequate long-term performance and reliability have been demonstrated to the market. Their durability and cost have been noted as the two greatest barriers [4,5]. Therefore, it is a top priority that fuel cell systems designers must solve the issues of durability to function over the full range of operating conditions with less than 10% loss of performance [6,7].

Durability is defined as the lifetime within the repair rate and cost of planned repairs, overhaul and maintenance. However, this durability target is not sufficient as the key target for acceptance by end-users [1]. The end-user may focus more on reliability or availability. Reliability is different from durability. Reliability is defined as the ability of a product to perform the required function under stated conditions for a certain period of time, which is often measured by the probability of failure, frequency of failure, or in terms of availability, which describes the ability of a system or component to function well under stated conditions for a specified period of time. The reliability and availability of fuel cells may be more important than the durability for acceptance of end-users as unplanned repair and maintenance can cause delays in home, work or business activities, but this is not recognized in the strategic targets and communities [1,2,8]. In fact, for commercialization of any products, low reliability may result in decreasing market share and penetration. Therefore, the principles of reliability and validity are fundamental cornerstones of any products, systems or manufacturer since they directly influence the acceptance of products and capital return on investment [1].

Durability and degradation of materials and components have been extensively studied at various scales from single cell to stack with consideration to decreasing the costs and increasing durability and efficiency of the overall system design. Degradation and aging of any materials is unavoidable over time, but it is of concern that some materials exceed their designed degradation rates. The consequences of materials degradation are multiple: (1) the loss of system gross performance and efficiency, (2) the loss of the system availability, (3) increase of cost due to increasing maintenance and repair [1,9]. In an integrated system or stack, the malfunction of one component may affect another, and the malfunction of a cell may affect the operation of another cell. This type of interaction among components in a stack system leads to a difficulty in maintenance and repair. If one component fails, the whole stack system has to be de-assembled, leading to a substantial repair costs. For example: one has to disassemble a whole stack to replace a failed membrane in an individual cell even though one can identify which membrane failed. A single component failure could substantially increase the cost of the whole stack, i.e.: a composite stack failure rate of 10% could increase of the stack cost by 60% [10]. In practice, the cost of materials and components has been reduced. For example, the cost of the catalyst no longer dominates the price of most fuel-cell systems, although it is still significant [11]. Therefore, the study of reliability is not only for the improvement of stack quality and efficiency but also for substantial reduction of costs.

Research and development (R&D) and improvement of systems must enhance the durability and reliability of fuel cells. The specific R&D issues are classified into: (1) Innovative structures of components, such as a thinner catalyst layer and dimensions for easier water removal [12,13], a thinner but stronger membrane that not only facilitates easier water removal but also improves the reliability of the thin membrane [14,15], catalyst layer (CL) [16,17] and membrane electrode assembly (MEA) [18–21]; (2) New properties, such as porosity and hydrophobicity modifications to improve water and gas transport in the gas diffusion layers (GDL) [22–24]; (3) Flow field designs and water and heat management [2,25–29]; and (4) System modeling and control, especially of the role of the start-stop processes [30–34].

Although the failures in modes and mechanisms of fuel cells have been well realized [35], it is still difficult to communicate