Journal of Power Sources 292 (2015) 95–103

Contents lists available at ScienceDirect

Journal of Power Sources

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

Polymer electrolyte membrane fuel cell efficiency at the stack level

Piotr Piela [a, *], Jens Mitzel [b]

[a] Mościcki Industrial Chemistry Research Institute, Rydygiera 8, 01-793 Warsaw, Poland
[b] German Aerospace Center, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

HIGHLIGHTS

- A new definition of PEMFC stack efficiency is proposed.
- The definition is useful for fuel cell system design.
- The definition is tailored to three practical PEMFC applications.
- The new stack efficiency is determined experimentally for a 480-W stack.

ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
20 April 2015
Accepted 13 May 2015
Available online 19 May 2015

Keywords:
Fuel cell efficiency
Fuel cell stack
PEMFC
DMFC
Fuel cell system

ABSTRACT

A redefinition of the fuel cell efficiency at the fuel cell stack level has been proposed for polymer electrolyte membrane fuel cells. The new definition takes into account not only the electrical efficiency of the stack but also the theoretical energy expenditures for bringing the stack feed streams to conditions required by the stack as well as the loss of fuel in the stack. A proposed general formula for the new stack efficiency has been adapted to three practical cases: the stationary combined heat and power, power-only mobile, and direct methanol fuel cell applications. The redefined stack efficiency has been determined experimentally for a practically sized H_2-fueled PEMFC stack and compared with the customary electric, or thermal, efficiency of this stack. Calculations have shown that the new stack efficiency can be very different from the electric efficiency, carrying additional information useful to a fuel cell system integrator.

1. Introduction

With various polymer electrolyte membrane fuel cell (PEMFC) stacks becoming increasingly available, there is need for the fuel cell system integrator to be able to compare their performance. The question arises, how one should compare different fuel cell technical solutions in general. The essential driver for the fuel cell technology is the efficiency of the conversion of the fuel chemical energy to useful, non-thermal energy [1]. Therefore, a convenient figure of merit for comparisons of particular fuel cell stacks among each other should be based on their energy conversion efficiency. Other two important factors deciding the ultimate merits of a fuel cell stack are the cost of the hardware per watt of output power and the lifetime of the hardware. Both these factors can be introduced into an integrated benchmark figure using established methods of cost engineering [2]. In this work, only the energy conversion efficiency factor is considered.

It is important to note that the common stack ‘electric’ (or ‘thermal’) efficiency, i.e., the stack operating voltage divided by the theoretical thermal stack voltage [1,3], does not carry all the information necessary to predict the performance of the stack in a system. To recognize this, consider two PEMFC stacks with the same electric efficiency at the same power density but under different feed conditions, one close to ambient and the other at conditions far from ambient. Their performance in a fuel cell power system will obviously not be the same. Therefore, the goal of the following discussion is to define, as the figure of merit, a compound energy conversion efficiency figure that will allow discriminating between stacks also according to their different operating conditions. The figure takes into account all the energy and fuel losses in a practical fuel cell system caused by the stack and not by the balance-of-plant (BoP) elements of the system.

Besides its own energy conversion characteristics and hydraulic properties the PEMFC stack has certain feed-stream requirements

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* Corresponding author.
E-mail address: piotr.piela@ichp.pl (P. Piela).

http://dx.doi.org/10.1016/j.jpowsour.2015.05.043
0378-7753/

List of symbols

A, B, τ	parameters in empirical equation giving saturated water vapor pressure at $t_{location}$; $[A]$ = Pa, $[B]$ = none, $[\tau]$ = °C
$c_{\mathrm{MeOH},device.port}$	methanol concentration at *device port*; mol m^{-3}
C_p	molar heat capacity of gas at constant pressure; J mol^{-1} K^{-1}
C_V	molar heat capacity of gas at constant volume; J mol^{-1} K^{-1}
ΔH	HHV enthalpy change of *ideal* fuel cell reaction (full combustion) at stack inlet conditions; J mol^{-1}
ΔH^*	effective HHV enthalpy change of fuel cell reaction at stack inlet conditions; J mol^{-1}
$\mathbf{\Delta U}$	rate of internal energy change of gas; W
$f_{\mathrm{CO_2}}$	rate of CO_2 at DMFC cathode-side exhaust; mol s^{-1}
F	Faraday's constant; C mol^{-1}
γ_{medium}	ratio of constant-pressure- to constant-volume heat capacities of *medium*; dimensionless
η_{BoP}	overall efficiency of fuel cell system BoP; dimensionless
η^*_{BoP}	energy conversion efficiency of fuel cell system BoP; dimensionless
η_F	faradaic efficiency of fuel cell reaction; dimensionless
$\eta_{fuel,BoP}$	fuel efficiency of fuel cell system BoP; dimensionless
$\eta_{fuel,Stack}$	fuel efficiency of stack; dimensionless
$\eta_{fuel,System}$	fuel efficiency of fuel cell system; dimensionless
η_{Stack}	generalized electrical stack efficiency; dimensionless
η^*_{Stack}	energy conversion efficiency at stack level; dimensionless
η^{**}_{Stack}	energy conversion efficiency at stack level including reactants humidification losses; dimensionless
η_{System}	fuel cell system efficiency; dimensionless
I	measured stack current; A
I_x	DMFC methanol crossover current; A
λ_{fuel}	fuel stoichiometric ratio; dimensionless
$\dot{n}$	molar rate of gas flow; mol s^{-1}
$\dot{n}_{fuel,Stack}$	molar rate of fuel consumed by stack; mol s^{-1}
$\dot{n}_{fuel,System}$	molar rate of fuel consumed by fuel cell system; mol s^{-1}
$\dot{n}_{w,medium}$	molar stream of water vapor added to *medium*; mol s^{-1}
N	number of cells in stack; dimensionless
$p_{medium,device.in}$	absolute pressure of *medium* at *device* inlet; Pa
$p_{medium,low}$	absolute pressure of *medium* in low-pressure supply plenum; Pa
$p_{medium,out}$	absolute pressure of *medium* at stack outlet; Pa
$p_{swv,location}$	saturated vapor pressure of water at $t_{location}$; Pa
$P_{c,medium}$	minimum power expense to compress stream of *medium*; W
P_e	measured electric power output of stack; W
P_h	calculated heat power output of stack; W
P_{mcloss}	minimum (theoretical) power expense for stack feed streams conditioning; W
$P_{p,medium}$	minimum power expense to pump *medium* through stack; W
P_u	stack useful power; W
$P_{u,net}$	fuel cell system net useful power; W
$P_{w,medium}$	minimum power expense to humidify stream of *medium*; W
P_x	power equivalent of crossover methanol stream; W
$Q_{in,medium}$	molar heat of vaporization of water at stack inlet conditions of *medium*; J mol^{-1}
R	universal gas constant; J mol^{-1} K^{-1}
$t_{location}$	temperature at *location*; °C
$T_{location}$	absolute temperature at *location*; K
U	stack voltage measured at stack electrical terminals; V
$U_{th.}$	thermal stack voltage; V
$v_{medium,device.in}$	standard ambient (SATP) volumetric stream of *medium* at *device* inlet; m^3 s^{-1}
$v^*_{medium,device.in}$	actual volumetric stream of *medium* at *device* inlet; m^3 s^{-1}
V_{medium}	standard ambient (SATP) molar volume of *medium*; m^3 mol^{-1}
z	number of electrons exchanged in fuel cell reaction (2 for H_2-air, 6 for DMFC); dimensionless

and characteristics. These requirements define a certain level of the stack electric efficiency and of the stack by-product heat. The characteristics of the feed streams often imply certain minimum (*theoretical*) energy expenditure in the system, which should be reasonably accounted for in the stack-level efficiency because it can be entirely “blamed” on the stack. For example, if above-ambient pressures are required by the stack and the feed plenum is under an ambient pressure, the *theoretical* compression work has to be considered as a *stack* loss. At the system level, the compressive loss will be higher and the difference between the actual and the theoretical compression work will be the energy loss for compression *assignable to the system BoP*.

The second aspect is the fuel efficiency, i.e., the ratio of fuel converted to useful energy to total fuel consumed. While it is customary to ascribe all the fuel losses in a fuel cell system to the BoP, it should be recognized that the stack can be responsible for the majority of the fuel losses. The proposed compound stack efficiency will also take this into account.

Moreover, the PEMFC stack-level efficiency definition should be tailored to the particular application and technology, as in some cases the thermal output of a stack can be considered a useful energy, while in some other cases it cannot. Furthermore, an active system has different stack losses than a passive system; and the direct methanol fuel cell (DMFC) technology poses different conditions than the H_2-PEMFC technology.

The above thoughts are translated in this contribution into a general formula for the stack-level PEMFC efficiency, which is then adapted to three specific cases: H_2-air operation in a stationary combined heat and power (CHP) system, a mobile (automotive and portable) system, and a DMFC system. H_2-air stack efficiency has also been determined experimentally for a practically sized H_2-fueled PEMFC stack subjected to polarization tests under different conditions.

2. Stack-level fuel cell efficiency redefinition

Fig. 1 presents a schematic of the fuel cell power system viewed from the efficiency standpoint. The system is composed of the fuel cell stack and the BoP. Chemical energy is delivered as reagents and the system converts that energy into the electricity and heat. The heat may be considered a gain or a loss depending on the application.

We can distinguish two types of reaction energy losses in the system: stack losses and BoP losses. The stack losses consist of the stack polarization loss and the losses from the fuel cell reaction itself. The latter losses consist of the entropy “loss” (the