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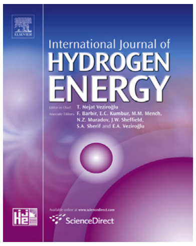

Experimental thermal analysis on air cooling for closed-cathode Polymer Electrolyte Membrane fuel cells

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ABSTRACT

This work explores the strength and limits of using separate air cooling for closed-cathode Polymer Electrolyte Membrane (PEM) stacks. Evaluating the thermal behavior of the designs based on stack temperature profiles alone would lead to inaccuracy as the initial temperatures and the stack thermal powers are different. Thus, the thermal behavior of the cooling modes was qualitatively analyzed via heat transfer analyses. An experimental approach is reported here using three stacks with varied cooling channel geometry and aspect ratio. Two stacks were designed on parallel multi channel (20 and 40 channels) straight flow configuration. The third stack applied the concept of non-linear laminar flow trajectory for the cooling channels. The 3-cell stacks were constructed with an active area of 240 cm^2. The cooling mode applied a cooling fan coupling of positive and negative pressure flows. Air flows were between Reynolds number of 200 and 400 while the humidity varied at 50% and 90%. The analytical methodology converted the first-order temperature profiles into second-order heat transfer profiles. The steady-state parameters studied were temperature uniformity, cooling response, average cooling rate, cooling effectiveness, cooling flux, the heat transfer coefficient and the mean local temperature difference. The width of analysis has successfully identified the dynamic capabilities of the individual cooling plate designs for further practical considerations.

Introduction

Hydrogen has been identified as a transition fuel in complementing the oil supply shortage with a prediction of a large scale introduction for hydrogen fuel cell application by 2020. The green aspects of hydrogen fuel cells, where only heat and water are produced as byproducts, places the technology as an ideal replacement to conventional power conversion systems [1]. The Polymer Electrolyte Membrane Fuel Cell (PEMFC) is one of the fuel cell types that offer numerous advantages according to its application. It is very flexible with respect to power and capacity needs and proven capable of long service life, good ecological balance and very low self-discharges [2]. It is favored in many applications as it offers high power density, quick-startup and low operating temperatures as well as

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Nomenclature

A	cell active area, cm^2
$A_{s,ch}$	surface area of a single cooling channel, m^2
B	a fuel cell parametric coefficient
C_{cg}	specific heat of carbon graphite, J/kg K
$c\dot{O}_2$	concentration of oxygen at the gas/catalyst interface, mol/cm^3
E_{cell}	actual cell potential, volts
E_{Nersnt}	the thermodynamic potential of the cell in an open circuit, volts
E_{tn}	the thermoneutral voltage, volts
$E_{w,exit}$	energy of water at the cathode exit, W
$\Delta E_{air,cathode}$	total energy change of the reactant air exit stream, W
F	Faraday's number, 96,485 Coulombs/mol
ΔG°	free reaction enthalpy at 298 K, 237.3 kJ/mol
H_{fuel}	heat value of the hydrogen, kJ/kg
$h_{f@Tw,exit}$	saturated liquid enthalpy of water at cathode stream exit temperature, kJ/kg
$\bar{h}$	effective heat transfer coefficient, W/m^2 °C
I	load current, ampere
J	actual current density, A/cm^2
J_{max}	maximum current density, A/cm^2
l	thickness of the membrane, mm
M_{O_2}	molar mass of oxygen, 32 g/mol
M_w	molar mass of water, 18 g/mol
m_{cg}	total mass of carbon graphite plates, kg
$\dot{m}_{air,exit}$	rate of reactant air at the cathode exit, kg/s
$\dot{m}_{air,inlet}$	rate of reactant air at the cathode inlet, kg/s
$\dot{m}_{O_2}$	rate of oxygen consumed in the reaction, kg/s
$\dot{m}_w$	rate of water formation, kg/s
n	number of electrons
n_{cell}	number of cells in the stack
n_{ch}	number of cooling channels in the stack
n_{O_2}	number of moles of oxygen consumed in the reaction, mol
n_w	number of moles of water formed in the reaction, mol
P_{el}	electrical power, W
P_{fan}	fan power, W
P_{H_2}	supply pressure of hydrogen into the stack, bar
P_{O_2}	partial pressure of oxygen supply into the stack, bar
P_{th}	stack generated thermal power, W
$\dot{Q}_{c,avg}$	average cooling rate, W
$\dot{Q}_{c,transient}$	transient stack cooling rate, W
$\dot{Q}_{gen}$	generated heat from the reaction, W
$\dot{Q}_{stack,avg}$	averaged stack heat change rate, W
$\Delta\dot{Q}_{stack}$	change of stack heat content for the duration of the time step, W
q	cooling flux, W/m^2
$R^{electronic}$	resistance to electron flow in a fuel cell, 0.0003 Ω
R^{proton}	resistance to proton flow through the electrolyte, Ω
r_m	specific resistivity of the membrane to electron flow
ΔS	reaction entropy at 298 K, 163.33 J/mol K
$T_{air,in}$	coolant air temperature at stack inlet, K
$T_{air,exit}$	coolant air temperature at stack exit, K
T_x	representative zonal surface temperature, K
T_{avg}	average cooling plate temperature, K
T_i	initial temperature reading, K
T_{i+1}	temperature reading at end of single time step, K
T_{i+n}	temperature reading at end of operation
T_s	stack operating temperature, K
T°	reference temperature of air at 298 K
$\Delta T_{cathode}$	reactant air inlet-exit temperature difference, K
Δt	time step, s
$\sum t$	total operation time, s
U_T	temperature uniformity index
V_{act}	activation over voltage, volts
V_{cell}	actual cell voltage, volts
V_{conc}	mass concentration over voltage, volts
V_{ohm}	ohmic over voltage, volts
V_{rev}	reversible cell voltage, volts
ε	cooling effectiveness
η_{FC}	energy conversion efficiency, %
λ	parameter based on PEM fuel cell membrane humidity

rapid response to varying operational loads [3]. Currently, a PEMFC with a net power density of one kW/L has been achieved [4] which is the result of breakthrough in all aspects of PEMFC engineering.

Commercialization and interest of fuel cells have just aggressively started at the turn of the century, and apart from full-scale car prototype developments, PEM fuel cell stacks with power outputs less than 3 kW are much in demand. The popular applications include backup power systems and small-scale or demonstration vehicles, mainly conducted by research institutions and academia. From this initial culture, there is a potential market for small-sized PEMFC stacks with power output ratings of up to 3 kW. The main advantage air cooling systems holds over water-cooled systems is that it is more compact, increasing the overall system size by usually less than 50%, whereas water-cooled systems generally increases the system size by more than 200%. Therefore, for portable and limited space applications, air-cooled fuel cells are very much desirable.

Thermal engineering of PEMFC

Fuel cells primarily generate heat from the entropic heat of reactions, the irreversibilities of the electrochemical reactions, ohmic resistances and heat from the condensation of water vapors [5]. The sum of the entropic heat, irreversible reaction heat and ohmic heating is comparable to the power output of a PEM fuel cell. Roughly, they account for 55%, 35% and 10% of the total heat release, respectively [6]. The magnitude of thermal energy is associated with the