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Model for optimal management of the cooling system of a fuel cell-based combined heat and power system for developing optimization control strategies

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HIGHLIGHTS

- An optimal fuel cell-based cogeneration cooling system control model is proposed.
- An artificial neural network and a 3D lookup table for data updating are employed.
- An algorithm based on dynamic Hermite functions is used for 3D data interpolation.
- The model can predict coolant outlet temperatures and hydrogen consumption rates.
- The model is very accurate and can be used to develop new optimization strategies in real time applications.

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ABSTRACT

This paper is focused on the development of a model for achieving optimal control of the cooling system of a polymer electrolyte membrane fuel cell (PEMFC)-based cogeneration system. This model is developed to help facilitate the development and application of control strategies to maximize the energy efficiencies of PEMFCs, so that the costs associated with electric and thermal generation can be reduced. The results of experimental analysis conducted using an actual PEMFC-based combined heat and power system that can produce 600 W of electrical power are presented. Then, the development and validation of a simulation model of the experimental system are discussed. This model is based on a combination of an artificial neural network (ANN) with a non-linear autoregressive exogenous configuration and a 3D lookup table (LUT) that updates the data input into the ANN as a function of the electrical power demand and the flow rate and input temperature of the coolant fluid. Due to the nonlinearity of the data contained in the 3D LUT, an algorithm based on linear interpolation and shape-preserving piecewise cubic Hermite dynamic functions is implemented to interpolate the data in 3D. As a result, the model can predict the outlet temperature of the coolant fluid and hydrogen consumption rate of the PEMFC as functions of the inlet temperature and flow rate of the coolant fluid and the electrical power demand. The proposed model exhibits high accuracy and can be used as a black box for the development of new optimization strategies.

1. Introduction

The need to improve energy production systems has led to the development of more efficient and smaller distributed generation technologies that use energy from renewable sources and cogeneration cycles. In this context, the most frequently employed technologies are internal combustion engines, gas micro-turbines, Stirling engines, and fuel cells (FCs) [1,2].

Among all combined heat and power (CHP) technologies, FCs stand out because they use energy resources effectively owing to their high efficiencies [3]. They also allow the use of different fuels from very different primary resources that favour integration with renewable modalities. Among all existing types of FCs, polymer electrolyte membrane FCs (PEMFCs) show great potential for integration into CHP systems [4–6]. Among the characteristics of PEMFCs, fast dynamics, low operating temperatures, high efficiencies at partial load, high power densities, and easy scalability are particularly notable [7].

To operate a CHP system optimally, it is essential to develop models

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Nomenclature

A	cross-sectional area of the cooling circuit inlet
A_s	stack surface area exposed to the ambient
B_i	elements of Bernstein polynomials
C_p	specific heat at constant pressure
D_h	hydraulic diameter
F	volume force vector
h	heat transfer coefficient
h_{ii}	basic Hermite functions
I	identity matrix
k	thermal conductivity
L	height of the stack
m	tangent
$\dot{m}$	mass flow
Nu	Nusselt number
p	fluid pressure
P_w	wetting perimeter
P	power
Pr	Prandtl number
q	conductive heat flux
Q	heat
Ra	Rayleigh number
Re	Reynolds number
S	strain rate tensor
t	time
T	temperature
u	fluid velocity vector
v	kinematic viscosity
V	stack volume

Acronyms

ANN	Artificial neural network
CHP	Combined heat and power
DC	Direct current
FC	Fuel cell
FEM	Finite element method
LUT	Lookup table
NARX	Nonlinear autoregressive exogenous
PCHIP	Piecewise cubic Hermite interpolating polynomial
PEMFC	Polymer electrolyte membrane fuel cell
SLPM	Standard litres per minute
SVM	Support vector machines

Greek symbols

α_p	thermal expansion coefficient
∇	fluid divergence
Δ	slope of secant line
ρ	density
τ	tensor of viscous forces
μ	dynamic viscosity

Subscripts

a	ambient
bl	boundary layer
conv	convection
el	electrical
in	inlet
out	outlet
s	surface
th	thermal power

and operation strategies that take into account fuel price and electric tariff variations, which significantly affect the operating costs of CHP systems. There are several operational strategies for CHP system operation, the most commonly employed being the electricity-led, heat-led, time-led, peak saving, and load levelling strategies. Taking into account the costs associated with electricity, fuel, operation, maintenance, start-up, shutdown, etc., by means of one operational strategy or another, the objectives are to maximize the energy efficiency and minimize the total system costs.

In the current literature, several works that present models, operation modes, and optimization strategies intended to improve the efficiencies and reduce the costs of CHP systems can be found [8–21]. However, the vast majority focus on CHP systems that are not expressly based on FCs, so the models used do not adjust with sufficient accuracy to the characteristic behaviour of this technology.

The simulation model employed is a key factor when developing an optimal operation strategy for a PEMFC-based CHP system, so it must be able to predict the electrical and thermal efficiencies of the FC under different operating conditions with sufficient accuracy. It should be noted that the efficiency of an FC depends mainly on the electric power generated and operating temperature [22]. Furthermore, it must be taken into account that as the electrical power increases, so do the consumptions of several auxiliary elements to maintain the necessary electrochemical reactions, such as the hydrogen and air compressors, which lowers the electrical efficiency. On the other hand, as the operating temperature increases, the kinetic reactions in the catalysts are improved and the electrochemical conductivity of the membrane is increased, which leads to a higher electrical efficiency. The operating temperature also affects the degradation of the PEMFC components, particularly the membrane-electrode assembly [23,24]. However, if the nominal operating temperature (~80 °C) is not exceeded, the contribution of the temperature to the degradation of the electrolyte can be assumed to be insignificant [25].

Another aspect influenced by the operating temperature is related to the formation and transport of the water obtained as a by-product of the electrochemical reactions. However, the effects of water on PEMFC degradation can be practically eliminated by using advanced materials or effective strategies for water management in cells [26,27].

There are several cooling methods for controlling the operating temperature of a PEMFC, such as cooling by increasing airflow at the cathode, cooling by forced ventilation, cooling by using dissipating surfaces, liquid cooling, and phase-change cooling [28,29]. However, for a PEMFC-based CHP system, the refrigeration system must allow for the recovery of the waste heat extracted from the FC stack. The usable systems include liquid and phase-change cooling systems. Although phase-change cooling systems have some advantages over liquid cooling systems, if the PEMFC is integrated into a CHP system, a liquid refrigeration system is more appropriate due to the greater cooling capacities and greater flexibility in terms of the control of such systems [28].

Bearing in mind all of the above, it can be assumed that the operating temperature of a PEMFC can be managed by controlling the cooling system within the operation limits in order not to compromise the materials, so the temperature only affects the energy efficiency of the system.

On one hand, if a PEMFC system is operated using an electricity-led strategy, the electrical efficiency could be optimized simply by keeping the stack temperature as high as possible, within the operating limits.