Applied Thermal Engineering 89 (2015) 1–10

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Experimental determination of the heat transfer coefficient for the optimal design of the cooling system of a PEM fuel cell placed inside the fuselage of an UAV

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HIGHLIGHTS

- Heat transfer coefficients to refrigerate a HT-PEMFC stack are calculated.
- Experiments are performed in 2 wind tunnels, for 3 form factors and real conditions.
- The calculated heat transfer coefficient varies from 8 to 44 W m^{-2} K^{-1}.
- Results at sea level are suitably extrapolated for a target altitude of 10 km.
- Flow area is optimized as a function of the power required to cool the stack down.

ARTICLE INFO

Article history:
Received 9 February 2015
Accepted 2 June 2015
Available online 10 June 2015

Keywords:
Heat transfer coefficient
Polymer electrolyte membrane fuel cell (PEMFC)
Hydrogen
Heat transfer management
Unmanned aerial vehicles (UAV)

ABSTRACT

The objective of this research is to calculate the heat transfer coefficients needed for the further design of the optimal cooling system of a high-temperature polymer electrolyte membrane fuel cell (HT-PEMFC) stack that will be incorporated to the powerplant of a light unmanned aerial vehicle (UAV) capable of reaching an altitude of 10,000 m. Experiments are performed in two rectangular tunnels, for three different form factors, in experimental conditions as close as possible to the actual ones in the HT-PEMFC stack. For the calculations, all the relevant thermal processes are considered (i.e., convection and radiation). Different parameters are measured, such as air mass flow rate, inlet and outlet air temperatures, and wall temperatures for bipolar plates and endplates. Different numerical models are fitted revealing the influence of the diverse relevant non-dimensional groups on the Nusselt number. Heat transfer coefficients calculated for the air cooling flow vary from 8 to 44 W m^{-2} K^{-1}. Results obtained at sea level are extrapolated for a flight ceiling of 10 km. The flow section is optimized as a function of the power required to cool the stack down to the temperature recommended by the membrane-electrode assembly (MEA) manufacturer using a numerical code specifically developed for this purpose.

1. Introduction

An important percentage of the alarming amount of CO_2 currently emitted to the atmosphere corresponds to the transport sector. In particular, aviation-generated CO_2 is projected to grow in approximately 6% by 2050, due to the increase in global travel demand [1]. Fuel cells can be a clean alternative for their use in the aeronautic sector [2]. For unmanned aerial vehicles (UAVs), powerplants based on proton exchange membrane fuel cells (PEMFCs) have been recently tested in flights of very short duration at low ceiling [3–5]. However, flights of small UAVs at a cruising altitude of 10 km pose some challenges related to the variation in atmospheric conditions, namely: very low atmospheric and partial oxygen pressures, temperature below −50 °C, and very dry air humidity [6]. Efficiency and durability of a PEMFC is mainly affected by the accurate management of the mass and heat transfer processes that take place inside the device. Focusing on heat transfer, the working temperature of a PEMFC is normally adjusted to the one

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http://dx.doi.org/10.1016/j.applthermaleng.2015.06.003
1359-4311/

Nomenclature

Latin alphabet

A	area (m^2)
a	numerical coefficient
Bi	Biot number
b	exponent of Reynolds number
C	constant
c	exponent of Prandtl number
C_p	specific heat (J kg^{-1} K^{-1})
D_{eq}	equivalent diameter (m)
F	heat transfer area (m^2)
g	gravity acceleration at sea level (9.80665 m s^{-2})
H	air enthalpy (J kg^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
K	minor losses coefficient
k	thermal conductivity (W m^{-3} K^{-1})
L	length of the stack (m)
L_C	characteristic length (m)
$\dot{m}$	mass flow rate (g s^{-1})
Nu	Nusselt number
Δp	pressure drop (Pa)
P	perimeter (m)
Pr	Prandtl number
Q	heat flux (W)
R	air gas constant (287 m^2 s^{-2} K^{-1})
Re	Reynolds number
T	temperature (K)
V	velocity (m s^{-1})
$\dot{W}$	power consumption (W)
Z	altitude (m)

Greek letters

α	temperature gradient at troposphere (−0.0065 K m^{-1})
ε	emissivity
δ	plastic thickness (m)
ρ	density (kg m^{-3})
σ	Stefan–Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4})
λ	thermal conductivity (W m^{-1} K^{-1})

Subscripts

a,i	air inlet
a,o	air outlet
air	air
conv	convection
dis	dissipated heat
duct	wind tunnel
f	flow
FC	fuel cell
met	metal
log	logarithmic
plas	plastic
rad	radiation
SL	sea level
w	wall
wet	wet

recommended by the membrane-electrode assembly (MEA) manufacturer. In the present research, a high temperature (HT) PEMFC stack is considered, which allows raising the operating temperature above 140 °C. This facilitates heat rejection due to the larger temperature difference between the stack and the surroundings [7]. As a result, the cooling system can be simpler, increasing the powerplant mass-specific and volume-specific power densities. This is a very important point for light UAVs where weight is an essential issue.

The heat transfer problem analyzed in the present research is to control the working temperature of a HT-PEMFC stack in the range from 140 °C to 180 °C when a constant electric power is demanded. The stack will be located inside the fuselage of the UAV, in order to protect the different elements of the powerplant from the very low ambient temperature during flights at an altitude of 10 km. The UAV considered has a total airframe mass of 3 kg, a wingspan of 4 m, and the fuselage has a diameter of 200 mm and a length of 1.6 m [8]. A photo of this UAV is depicted in Fig. 1 in a low altitude flight with an internal combustion engine.

In a broader sense, the problem under study consists in the determination of the heat transfer coefficient of a prismatic three-dimensional object inside an enclosure. The experimental

Fig. 1. Photo of the UAV considered in the present research.

estimation of the heat transfer coefficient implies the measurement of the heat transferred by either direct (steady state) or indirect (transient) techniques [9]. Transient techniques involve the measurement of the temperature change with time at a location near to or at the body. An example of this method is the determination of the surface temperature analyzing the emitted radiation intensity and wavelength using infrared cameras [10,11]. A direct heat transfer measurement method is the energy supply technique, in which the temperature of a solid surface is measured while actively providing heat [12,13]. Other methods for the direct measurement of the heat transfer coefficient are the use of thin film heat flux sensors [14–16] or the one based on naphthalene sublimation that has been used to measure the convective heat transfer coefficient on the horizontal roof of a real building [17].

First studies on the determination of the heat transfer coefficient date back to the first half of the XX Century [18–20]. Since then, a large number of papers have been published describing correlations for the heat transfer coefficient as a function of the object geometry and the flow characteristics, as summarized in many textbooks [21,22]. Calculation of the heat transfer coefficient is widely reported in the literature for unconfined flows in an ample variety of application problems such as in machine tools and manufacturing processes [23–27], cooling of the human body [28,29], to refrigerate buildings [30–32] and electronic devices [33–35], or over cylinders or spheres [36–38]. In all these studies, either Nusselt number (Nu) is expressed as a function of non-dimensional groups, typically Reynolds (Re) and Prandtl (Pr) numbers, or the heat transfer coefficient is given as a function of dimensional variables including temperature difference or coolant velocity. However, they are likely to be inaccurate in this case, because they do not consider form factors or tunnel blockage effects. In fact, many of them have been tested in this work with poor