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Experimental investigation of using ZnO nanofluids as coolants in a PEM fuel cell

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ABSTRACT

In this paper we report on an experimental study conducted on the thermo-electrical performance of a small-scale (i.e. 2.4 kW) Proton Exchange Membrane Fuel Cell (PEMFC), in which both conventional 50/50 water-Ethylene Glycol (EG), and 50/50 water-EG based ZnO nanofluids were used as coolants. PEMFCs are a promising alternative to Internal Combustion Engines (ICEs) for automotive applications. However, among other challenges, the large-sized cooling system of PEMFCs (i.e. the radiator) imposes a great challenge for this application. Using nanofluids as coolants has the potential to address this challenge. Employing selected nanofluids as coolants, with maximum 0.5 vol% nanoparticle concentration, showed no change in the electrical power outputs of the stack based on its polarisation curve, whereas the cooling capacity of the system was improved 29% compared with that while using 50/50 water-EG as coolant. The experimental investigation reported here confirmed the earlier theoretical finding that the frontal area of the radiator (i.e. used for fuel cell cooling) could be reduced by about 27% when nanofluids (0.5 vol%) replaced conventional EG/water coolants. Using 0.5 vol% ZnO nanofluid also showed just less than 10% increase in the pumping power compared to when the conventional 50/50 water-EG was used as coolant. It is concluded in this study that up to 0.5 vol% ZnO nanofluid can be applied to the PEMFC cooling system without affecting any electrical performance of the system.

Introduction

Hydrogen fuel cell technology is an important emerging sustainable technology [1] even though despite its relatively low maintenance costs it still needs further reduction in the capital costs (at systems level) to become fully viable economically [2]. Among the various types of fuel cell (FC), PEMFCs are suitable candidates for use in sustainable automotive applications [3,4]. This is due to their key advantages such as high volumetric power density (e.g. 3.7 kW/l) [5], rapid start up (less than 30 s), low operating temperature (~60–80 °C) [6,7], high electrical energy conversion efficiency (over 50% based on the higher heating value of hydrogen) [8], compact size, low weight, long lifetime (close to ICEs), and the capacity to work in a discontinuous regime [9].

Consequently, major global automotive companies have now started to take the idea of hydrogen FC vehicles to a commercial level [10,11]. For example, the Toyota Mirai that is a hydrogen fuel cell vehicle, was unveiled in November 2014

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Los Angeles Auto Show, and also started selling in Japan from 15 December 2014. The first production Toyota Mirai vehicles have officially been started selling in Europe (UK, Denmark and Germany) and this model is now on sale in selected markets in California, USA [12–15]. Although significant progress has been made in the research area of PEMFCs, certain matters can still be addressed in order to improve the experience of applying this technology. Examples of these improvements are those related to durability, cost, and thermal management system [16,17]. Although the PEMFCs have a very high electrical energy conversion efficiency (up to over 50% based on the HHV of hydrogen), there is still a significant amount of heat generated; i.e. even equal to or more than the power generated by the fuel cell [9,18]. This can be up to 100 kW or more in a medium size passenger car using a hydrogen FC [16]. This heat must be effectively removed to avoid overheating of FC components, especially the membrane [19,20].

The relatively low operating temperature (i.e. ~60 °C) of PEMFCs [21,22], leads to a small temperature difference between the coolant and surrounding ambient. For this reason usually large size radiators are used in fuel cell cars to compensate for this small temperature difference. The enhanced thermal conductivity of nanofluids compared with that of conventional coolants such as water/EG mixture, offer potentials for reducing the size of the heat exchanger used in the fuel cell cooling systems [23]. This is considered to be a great advantage in terms of fuel cell system packaging as well as reducing the overall mass and cost of the FC system. The suspended nanoparticles not only increase the thermal conductivity of the fluids, but they may also increase the electrical conductivity as well. In PEMFCs, the generated electricity creates an electrical field that causes the polarisation of the coolant, and consequently the electricity may leak through the coolant flow. The electrical conductivity of a suspension can either increase or decrease depending on the background electrolyte, the particle size, the particle loading and the charge of the particle [24]. For the applications of nanofluids as a coolant in PEMFC, it is desirable to increase the thermal conductivity of the coolant while minimising the electrical conductivity.

The steady-state operation of PEMFCs depends on creating a right balance between the heat generation and removal of the stack (i.e. maintaining the stack's temperature at a desirable level) [25,26]. Insufficient or non-effective cooling can lead to excessive local cell temperature that leads membrane dehydration, shrinking, or even permanent damage of the cells. Maintaining uniform temperature distribution is critical for efficient operation of a PEMFC (i.e. 60–80 °C) [27,28].

Owing to the fact that nanofluids offer a higher heat transfer capacity, it would allow for smaller size and better positioning of the heat exchanger in automotive applications [29]. Furthermore, the initiative taken by DoE and industrial effort made by Dynalene (without any published results) have proven the potential of nanofluids as PEMFC coolants that suggests the necessity of further research on it [16,30–32].

Very recently the researchers are trying to apply nanofluids as coolants in the fuel cell applications though only limited studies have been conducted theoretically and experimentally. Zakaria et al. [33] numerically analysed the thermal enhancement for a single PEMFC using 0.1–0.5 vol% concentration of 50/50 water-EG based Al_2O_3 nanofluids using coolant flows with the Re numbers in the range of 30–150. The cooling plates were subject to a constant heat flux of 100 W. They found 7.3% and 4.6% heat transfer enhancement with 0.5 vol% and 0.1 vol% nanofluids respectively compared to that of the base fluid. However, they experienced almost twice the pumping power while using 0.5 vol% Al_2O_3 nanofluids at Re 150 compared with that of the base fluid. Zakaria et al. [34] investigated the heat transfer enhancement of 50/50 and 60/40 water/EG based Al_2O_3 nanofluid with the concentration of 0.1 vol% and 0.5 vol% in a single cooling plate of a PEMFC where a 100 W heating pad was used as a source of heat mimicking the fuel cell heat generation. They found heat transfer improvement of up to ~21% and ~23% with the 0.5 vol% concentration for 60/40 and 50/50 water-EG based Al_2O_3 nanofluids respectively, compared with that of the base fluid (i.e. water/EG). Along with the thermal enhancement, they also observed higher pressure drop for 0.5 vol% 60/40 and 50/50 water-EG based Al_2O_3 nanofluids compared with that of the base fluid. They concluded that the water/EG based Al_2O_3 nanofluid can be potentially suitable to be used as a coolant in PEMFC.

The above-mentioned researchers tried to investigate the effects of using nanofluids as coolants in single-cell PEMFC (i.e by using heating pads to mimic the fuel cell heat generation). However, there is no any experimental study reported in the literature on the effects of using nanofluids (i.e. as coolants) on thermo-electrical performance of real PEMFC at stack level.

The potential and challenges of using nanofluids as PEMFC coolants have been investigated theoretically by Islam et al. [35] for automotive applications. A brief overview of this study has been provided in Section Overview of previous theoretical modelling on using nanofluid-based coolants in PEMFCs of this article. As an extension and validation of the theoretical results, the present research is an attempt to investigate experimentally the feasibility of using nanofluids as fuel cell coolants. The thermal and electrical performance of a 2.4 kW PEMFC has been investigated by using 50/50 water-EG based ZnO nanofluids in the nanoparticle concentration range of 0.05–0.5 vol%. The experimental results of this research are compared to the findings of our previous theoretical study, and throw light upon the effect of using nanofluids (as coolants) on the electrical performance of a PEMFC.

Overview of previous theoretical modelling on using nanofluid-based coolants in PEMFCs

By applying a semi-analytical, one-dimensional and steady state model of PEMFCs cooling systems, the potential advantages of using nanofluids over conventional coolants (e.g. mixture of water and ethylene glycol) were investigated previously by the authors [36]. This simulation model, which was created in MATLAB, consists of sub-models of a PEMFC stack (both electrical and thermal), heat exchanger, and