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Phase change material for thermal management of high-temperature proton exchange membrane fuel cells in electric vehicle

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Abstract

The current work examines the possibility of reducing the radiator size in high-temperature proton exchange membrane fuel cell vehicles by incorporating phase change material. Using pinch analysis optimisation, the research demonstrates that the radiator area in a Toyota Mirai car can be reduced by 4.7 times with the integration of D-mannitol (melting point 170°C) phase change material. The required quantity of D-mannitol accounts for only 0.62% of the vehicle's curb mass. Additionally, the work investigates the impact of operating temperature on radiator size, revealing that lower coolant inlet temperatures increase the minimum radiator area needed for sufficient heat dissipation. A 40°C increase in the inlet coolant temperature results in a 44% reduction in the radiator area. Consequently, a vehicle powered by low-temperature fuel cells (60−80°C) versus high-temperature fuel cells (120−180°C), under the same driving conditions, would require minimum radiator areas of 1.07 m^2 and 0.26 m^2, respectively. These results are expected to aid in the development of techno-economically feasible cooling systems in fuel cell vehicles.

Keywords: Thermal management; PEMFC; PCM; Radiator; Electric vehicle

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1. Introduction

Today, one of the main techniques for reducing carbon emissions in the transportation sector is automobile electrification [1]. To align with the International Energy Agency's agenda to limit the global temperature rise, it is required that the cumulative sale of electric vehicles (EVs) reach 1.8 billion by the year 2060 [2]. The escalating growth in the production and use of electrified vehicles is largely determined by energy storage technologies powering them like batteries and fuel cells. Compared to internal combustion engine (ICE) vehicles, which are characterised by low powertrain efficiency (with a maximum of 40% due to intermediate conversion into heat and associated thermodynamic losses) and significant emissions, fuel cell vehicles have superior efficiencies (with a minimum of 50% due to the direct conversion of chemical energy into electrical energy) and produce zero local emissions [3]. Fuel cell-based EVs also have the advantages of shorter refuelling time and longer driving ranges compared to battery EVs. However, currently, fuel cell vehicles require research efforts to develop less costly catalyst and electrode materials, better humidifiers, heat exchangers, etc., to improve the efficiency and durability of the system while reducing costs [4].

Nomenclature

a – acceleration, m/s^2
A – frontal area, m^2
C_d – drag coefficient
f_r – rolling friction
g – gravitational acceleration, m/s^2
m – vehicle curb mass, kg
v – vehicle speed, m/s

Greek symbols

α – road slope, °
ρ – air density, kg/m^3

Abbreviations and Acronyms

EV – electric vehicle
FCEV – fuel cell electric vehicle
ICE – internal combustion engine
PCM – phase change material
PEMFC– proton exchange membrane fuel cell
TDR – turn-down ratio
TMS – thermal management system

Effective thermal management of fuel cells in vehicles is important to operate the system at maximum efficiency. Literature reports that fuel cells generate a considerable amount of thermal energy, proportional to their electrical output. For example, a fuel cell with an efficiency of 50% and a capacity of 10 kW will produce 10 kW of electrical energy and 10 kW of thermal energy by electrochemical reactions [5]. This makes temperature regulation essential to prevent performance degradation in fuel cells that may happen due to the breakdown of the membrane and catalyst at elevated temperatures [6].

A proper thermal management system dissipates the generated heat and establishes a uniform temperature distribution across the fuel cell stack. Liquid cooling, typically with water and excess heat rejection via radiators, is the most widely adopted cooling strategy in fuel cell electric vehicles (FCEVs) [7,8]. However, compared to ICE vehicles for the same vehicle platform, fuel cell vehicles require a radiator with a 2−4 times larger frontal area [9,10]. A 60 kW Ford fuel cell vehicle powered by a proton exchange membrane fuel cell (PEMFC) is reported to require 1.5 times higher radiator area than a conventional vehicle to maintain the fuel cell within its optimum operating temperature range [11]. Similarly, Ahluwalia and group [12] reports the need for 125% higher frontal area in fuel cell vehicles as a result of their study on heat rejection from the vehicle with respect to stack temperature. The need for large radiators in fuel cell vehicles is primarily because of the minimal heat carried away by exhaust gases.

A large radiator necessitates a large frontal area, which increases the overall vehicle power demand. Various recent studies have researched improving the thermal management system compactness without compromising its efficiency. Prabakaran et al. [13,14], Su et al. [15] and Mohamed et al. [16] have proposed to improve the heat transfer via radiators by coupling spray cooling. Modifications in radiator design, such as improving the shape of the radiator intake grill and alternate fin structure have also been proposed by researchers [17,18]. However, the majority of these works report results of computational evaluations and require further optimisations and experiments before being commercialised.

Recent works have introduced the concept of phase change material (PCM) radiator thermal management system for fuel cell vehicles, where a PCM of suitable mass serves as a thermal reservoir, allowing for radiator size reduction [19,20]. PCMs can absorb and release large amounts of thermal energy (150−250 kJ/kg) during phase change. They are broadly categorised into three: organic PCMs, inorganic PCMs, and eutectic PCMs. Organic PCMs (e.g. paraffins, fatty acids) are biodegradable with low environmental impact, have good chemical stability as well as low toxicity, but exhibit low thermal conductivity (0.1−0.3 W/(m K)) and high flammability (limiting oxygen index ~ 17%). Meanwhile, inorganic PCMs (e.g. salt hydrates, metallic PCMs) have higher latent heat and thermal conductivity, non-flammability (limiting oxygen index ~60 %), and are 3−10 times cheaper compared to organic PCMs, but they show corrosiveness, supercooling issues, and potential environmental issues (harm soil/water if leaked, eutrophication risks). Eutectic PCMs are organic-organic, organic-inorganic, or inorganic-inorganic combinations that offer tailored melting points for specific applications [21,22].

The selection of PCMs for EV applications depends on key properties such as high latent heat, high thermal conductivity, high specific heat, melting point in the desired temperature range, minimum volume change during phase transition, stability, non-flammability, cost-effectiveness, etc. [13]. PCMs can easily integrate into existing vehicular thermal management systems (TMS) via encapsulation in polymer/aluminium modules, panels or shells with no major redesign. The high volumetric energy density of PCMs (180−300 MJ/m^3) allows compact placement in space constrained areas. Their near-isothermal operation allows rapid, effective buffering of transient heat loads, and their passive operation ensures minimal parasitic power requirement. The stored thermal energy has the potential to improve the energy efficiency of the system in scenarios such as cold start.

The current work investigates the potential for size reduction in radiators by implementing a PCM-based TMS in a high-temperature PEMFC-powered electric vehicle. High-temperature PEMFC vehicles are advantageous owing to enhanced electrochemical kinetics, higher carbon monoxide (CO) tolerance and simplified water management. Additionally, these systems also expel waste heat at a higher temperature, which can be recovered and utilised for direct heating [22,23].

In this study, the size optimisation of the PCM-radiator system components is carried out using pinch analysis. The key contributions of this research are: (i) determining the minimum radiator size for dissipating the heat from a high-temperature PEMFC stack, (ii) identifying appropriate commercial PCM and the mass necessary to compensate for the reduced radiator area,

(iii) defining a design space of feasible radiator sizes and corresponding PCM masses, allowing users to select the most suitable combination based on specific requirements, and (iv) analysing the effect of operating temperature on the TMS size.

2. Materials and methods

The study considers a light-duty 5-seater vehicle (Toyota Mirai) operated by a high-temperature PEMFC. For this work, it is assumed that PEMFC is the only power source in the vehicle. The vehicle specifications are given in Table 1. The vehicle follows a standard driving cycle (worldwide harmonised light duty test cycle − WLTC), so the analysis's results would also apply to real-world driving conditions. The power demanded by the light-duty vehicle can be estimated using the following formula [24]:

$$P_v = (0.5\rho C_d A v^2 + f_r m\cos\alpha + ma + mg\sin\alpha)v, \quad (1)$$

where: A – frontal area, a – acceleration, C_d – drag coefficient, f_r – rolling friction, g – gravitational acceleration, m – vehicle curb mass, v – vehicle speed, α – road slope, ρ – air density. To calculate the load demand by the vehicle, a road slope of zero is assumed.

Table 1. Specifications of system.

Parameter	Value
Mass of vehicle (kg)	1930
Frontal area of vehicle (m^2)	2.35
Coefficient of drag	0.29
Rolling friction coefficient	0.01
Coolant temperature at the inlet of fuel cell (°C)	170
Maximum rate of flow of a coolant (kg/s)	0.20
Specific heat of a coolant (kJ/(kg °C))	4.20
Environmental temperature (°C)	50
Allowed temperature rise in the stack (°C)	10
Overall heat transfer coefficient for radiator (kW/(m^2°C))	0.30
Fuel cell TDR (%)	20

Estimation of the power demand by the automobile gives an insight into the thermal energy generated by the fuel cell. The proposed thermal management system primarily consists of the PEMFC, coolant, radiator and heat exchanger containing PCM. The coolant exiting the PEMFC stack passes into a radiator and then through the PCM system to dissipate the thermal energy generated in the PEMFC stack. This ensures a uniform temperature for the coolant entering back into the stack. The drive cycle considered in this work and a schematic of the TMS are depicted in Fig. 1.

The pinch analysis technique adopted in this study is an algebraic optimisation method, by which the thermal management needs of the vehicle can be met with minimum resources. For this, the thermal energy generation by the PEMFC stack is compared with the heat rejected by the radiator size of the user's choice, to obtain the minimum PCM mass required for satisfactory thermal management. By using PCM, the excess thermal energy can be stored and reused at later periods to ensure the

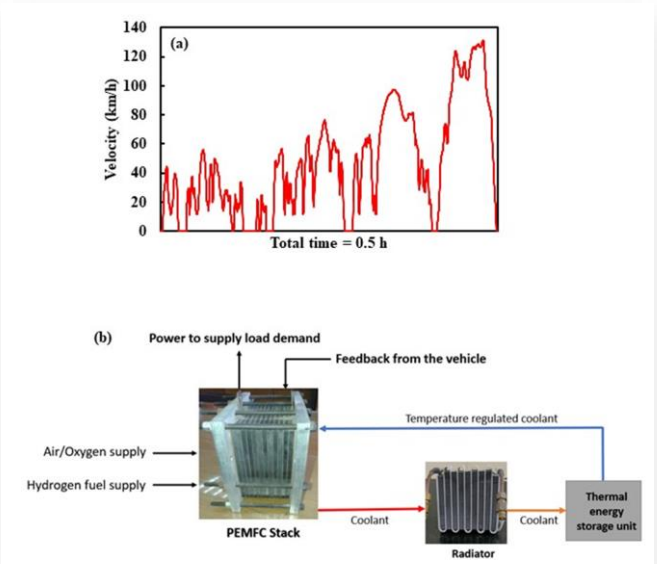


Fig. 1. (a) Worldwide harmonised light duty test cycle, (b) Illustration of the thermal management system.

thermal regulation of the coolant. This maintains the coolant temperature entering the PEMFC stack in the range of the desired operating temperature of the fuel cell. The PCM considered for this study is D-mannitol, which has a melting point of 170°C and a latent heat capacity of 297 kJ/kg [25].

The optimisation is subject to the constraints listed below:

1) The energy in the PCM unit at the start and finish of the driving cycle should be the same.
2) The minimum state of charge in the PCM unit at any given time should not be less than 0.
3) The overall heat transfer coefficient of the radiator unit lies between a lower limit (influenced by radiator turn-down ratio) and an upper limit.

The implementation of pinch analysis involves three major steps: calculation of thermal energy generated by the PEMFC stack, calculation of the cooling capacity of the radiator, and calculation of PCM mass. The parameters to be calculated in each step are summarised in Fig. 2 [19]. The software used for optimisation was the GRG Non-Linear Engine in Microsoft Excel.

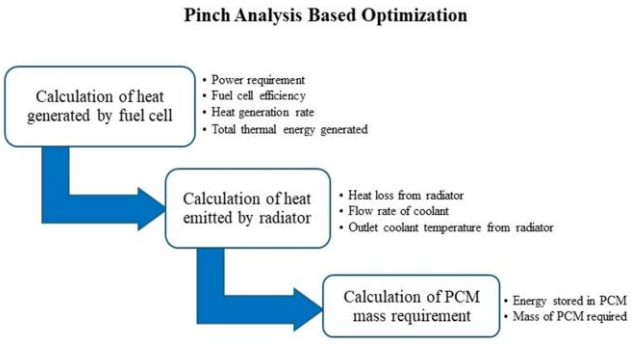


Fig. 2. Component-wise parameters to be evaluated for optimisation.

3. Results and discussion

The present study uses a PCM-based TMS to reduce the radiator size in fuel cell-powered vehicles. For this, a pinch analysis-based optimisation algorithm was adopted and applied to a standard drive cycle to study the effectiveness of the PCM system when used in a FCEV. A 1980 kg light-duty vehicle that follows a WLTC class-3 drive cycle (duration: 0.5 h) is considered here.

3.1. Sizing curve for the thermal management system

Sizing curves that depict the radiator area and corresponding PCM requirement are plotted to illustrate the feasible and infeasible operating regions. Each point on the sizing curve (Fig. 3) is the result of pinch analysis optimisation performed for a particular value of minimum radiator area. In each case, the mismatch between the cumulative thermal energy generated and the cumulative thermal energy dissipation by the chosen radiator size represents the cumulative thermal energy to be stored in the PCM unit. The points on the sizing curve and the region above it represent the feasible region. However, the region on the left and lower part of the sizing curve represents infeasible combinations of the radiator area and PCM mass either because of insufficient radiator size or due to limited PCM mass. It is seen that with respect to the constraints considered in this study, to ensure adequate heat dissipation through the radiator-PCM system, the radiator area should not be less than 0.26 m^2. Hence, the results show the possibility of decreasing the radiator area in a high-temperature powered PEMFC by 4.7 times when complemented with a suitable thermal energy storage system.

Pinch analysis results show that to dissipate the thermal energy generated by the stack with a radiator of area 0.26 m^2, 11.97 kg of D-mannitol PCM is essential. The required PCM mass corresponds to only about 0.62% of the vehicle's curb mass. The higher the radiator area, the lower the thermal energy to be stored and hence, the lower the PCM mass required. On investigating the sizing graphs for various radiator turn-down ratios (TDR), it is also evident that after a local minimum, there is a need for higher PCM mass despite the high radiator areas. The TDR constraint necessitates using additional PCM to store additional heat and ensure appropriate temperature regulation of the coolant.

3.2. Effect of operating temperature on the size of thermal management system

To understand the influence of the operating temperature of the fuel cell on the TMS size of the vehicle, it is required to perform a pinch analysis with different coolant temperatures. The TMS sizing is studied for cases of different inlet coolant temperatures entering the fuel cell unit. The analysis shows that the lower the inlet coolant temperature, the higher the minimum required radiator area for adequate heat dissipation. Furthermore, an increase in the inlet coolant temperature from 120°C to 180°C produces a drastic drop in the minimum required radiator area by 44.18%, while the required PCM mass declines by about 2%. Figure 4 shows the sizing curve for the radiator-PCM system for

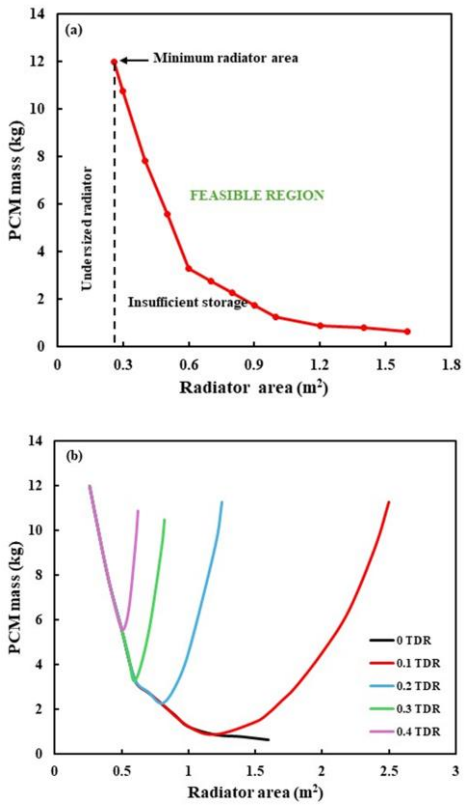


Fig. 3. (a) Sizing curve; (b) Sizing curves for various radiator turn-down ratios.

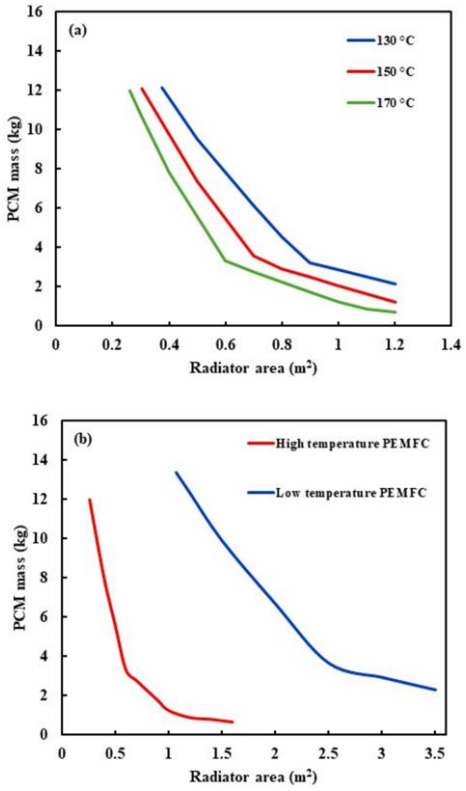


Fig. 4. Sizing curves for TMS in (a) high temperature PEMFC at various inlet coolant temperatures, (b) in high and low temperature PEMFCs.

the inlet coolant temperatures of 130°C, 150°C and 170°C. An increase in the coolant temperature by 40°C decreases the required radiator area by 0.12 m^2. This is because a greater temperature difference between the coolant and ambient air allows the same heat rejection with a smaller radiator area. Also, for a constant radiator area, PCM requirement increases with a reduction in the inlet coolant temperature. For instance, if we consider the TMS with the radiator areas of 0.5 m^2 and 1.0 m^2, it is evident that PCM requirement increases by ~2.0 kg (for 0.5 m^2) and ~0.80 kg (for 1.0 m^2) for every 20°C reduction in inlet coolant temperature.

In the same context, a comparison between the TMS (radiator-PCM) sizes for proton exchange membrane fuel cells, which work at low temperatures (60°C to 80°C) and high temperatures (120°C to 180°C) is also presented (Fig 4b). Due to the low difference between fuel cell operating temperature and ambient temperature, low-temperature PEMFCs require higher radiator areas when compared to high-temperature PEMFCs. To reduce the radiator size in these systems, paraffin wax and D-mannitol PCMs were selected for the low-temperature and high-temperature systems, respectively. The temperatures of the coolant entering the fuel cell were taken as 70°C (low-temperature PEMFC) and 170°C (high-temperature PEMFC). Pinch analysis optimisation was performed for the two systems for the same vehicle and driving conditions and the results are shown in Fig. 4b. From the figure, it is seen that while the minimum area requirement for the radiator in a high-temperature PEMFC system is 0.26 m^2, the low-temperature PEMFC system requires a radiator with at least 4.12 times larger area (1.07 m^2), even with the usage of maximum PCM. However, the mass of PCM required for the low-temperature PEMFC is only 11.70% higher than the mass of PCM required for the high-temperature PEMFC. Hence, irrespective of the type of PEMFC chosen for the FCEV, the mass of PCM required for maximum radiator area reduction does not exceed 0.70% of the vehicular curb mass.

4. Conclusions

The study explores the potential for reducing the size of the radiator in Toyota Mirai cars powered by a high-temperature proton exchange membrane fuel cell by incorporating a phase-change material into its thermal management system. This research makes a key contribution by using pinch analysis to determine the minimum size of radiator required to dissipate heat from a high-temperature PEMFC stack and defining a design space comprising radiator sizes and the corresponding masses of phase change material. The results show that by integrating 11.97 kg of D-mannitol PCM, the radiator area in the high-temperature fuel cell-powered vehicle can be reduced by 4.7 times. Additionally, the impact of fuel cell operating temperature on the vehicle's TMS size was also assessed. The analysis reveals that lower inlet coolant temperatures necessitate a larger minimum radiator area for effective heat dissipation. For instance, on increasing the inlet coolant temperature from 120°C to 180°C, there is a 44% reduction in the radiator area and a 2% decrease in the required PCM mass. Furthermore, if we analyse the same vehicle powered by a low-temperature fuel cell, the thermal management system would need a radiator with an area 4.12 times larger at minimum and a PCM mass 11.70% greater for appropriate heat dissipation.

The present study assesses the advantage of adding a PCM-based thermal energy storage unit in the TMS of a fuel cell vehicle. In addition to eliminating the disadvantages of using large radiators such as larger frontal area and increased fuel consumption, the usage of PCM can also improve the energy efficiency of the system through the utilisation of stored heat. The findings of this study are expected to contribute to the development of techno-economically feasible cooling systems for fuel cell vehicles, enabling more efficient and compact thermal management solutions.

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