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Analysis of a 50 kWe indirect methanol proton exchange membrane fuel cell (PEMFC) system for transportation application

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Abstract: Steady state and dynamic models of proton exchange membrane fuel cell (PEMFC) or solid polymer fuel cell (SPFC) systems have been developed for transport and stationary applications. This paper reports the results of a steady state analysis of a methanol-fuelled PEMFC vehicle with a maximum (electrical) power output of 50 kW. The model incorporates a methanol steam reformer, gas clean-up unit, fuel cell stack, compressor, expander, battery pack, and heat exchangers as well as electrical power handling, motor, gearbox, and final drive. Results are given for the reformer as a function of steam-carbon ratio and reformer temperature. A degree of optimization of the system was conducted by (a) the addition of preheat to the reformer and burner reactants and (b) the addition of condensers for the fuel cell exhaust gases. The effect of operating pressure was also investigated. It was concluded that only by proper thermal integration could the target electrical system efficiency of better than 45 per cent at rated power be achieved.

Keywords: proton exchange membrane fuel cell (PEMFC), PEMFC system, fuel cells, solid polymer fuel cell (SPFC), SPFC system, hydrogen, methanol fuel processor, hybrid vehicle system, electrical system efficiency, modelling and simulation

1 INTRODUCTION

Due to the global commercialization of the internal combustion engine (ICE), the transportation sector has become largely dependent on the petroleum industry. This has now resulted in transportation becoming a major contributor to urban air pollution and a significant contributor to greenhouse gas, carbon dioxide (CO₂) [1]. The consequences of both petroleum dependency and impact upon the environment have intensified the transportation sector's search for an alternative technology during the last three decades. The search has subsequently revived interest in electric traction as a viable and environmentally friendly replacement for ICEs. Fuel cells, with their promise of a clean and efficient power source, have the potential to supply the power for traction in an electric vehicle.

Since the resurgence of proton exchange membrane fuel cells (PEMFCs) in the early 1980s, PEMFC technology with its superior operational characteristics such as high efficiency, ultra-low emissions, part load characteristics, and modularity, has emerged as one of the best fuel cell technologies to break through into the transportation market. However, the lack of a hydrogen fuel supply infrastructure has hindered further commercial success and mass production of the PEMFC power technology. Today, the FreedomCAR/Freedom Fuel and the California Fuel Cell Partnership (CaFCP) programmes tackle these problems. The aim of the FreedomCAR/Freedom Fuel partnership programme is to focus on technologies to enable mass production of affordable hydrogen-powered fuel cell vehicles and the hydrogen supply infrastructure to support them, while the aim of the CaFCP programme is to demonstrate both vehicle technology and viability of alternative fuel infrastructure technology and to examine the path to commercialization [2, 3].

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Hence, the present lack of hydrogen supply and storage infrastructures has driven the development of vehicles with on-board hydrocarbon reformers. The choice of fuel and reformer type is crucial when designing an integrated fuel cell power system for a vehicle. Using conventional liquid fuels such as gasoline or diesel would solve the problem of fuel distribution infrastructure and refuelling. However, reforming of these fuels on-board a vehicle presents a number of challenges including system complexity, weight, and the presence of impurities in the reformat [4]. Alternatively, using liquid fuels such as methanol, which can be a renewable fuel, can provide 75 per cent hydrogen rich reformat (steam reforming) with a much less complex system, higher efficiency, and a more compact system for vehicle application [1, 4, 5].

To penetrate the well-established and competitive automobile market, a practical PEMFC vehicle system with a fuel processor needs to be well designed and integrated and its performance optimized. To accomplish these objectives, an analysis is required, not only to understand the system requirements and integration issues, but to optimize the performance of individual components to achieve the best overall performance. A steady state model of a 50 kWe PEMFC system incorporating a methanol steam reformer was developed to analyse the overall performance of an integrated system. The aim of the study was to achieve an electrical system efficiency ≥ 45 per cent (pre-drivetrain) at rated load. With the drivetrain losses estimated at approximately 5–10 per cent, the vehicle efficiency of ≈ 35 –40 per cent can be achieved, which is competitive with the future ICE (fuel-to-wheel efficiency > 23 per cent) and hybrid engines (fuel-to-wheel efficiency of 36 per cent) [6, 7].

2 PEMFC SYSTEM SPECIFICATION

A PEMFC system for a transportation application consists essentially of two main components, the power generator and the electric drivetrain. Figure 1 shows the schematic representation of a 50 kWe PEMFC system for a transport application. In this section, the data and the operating conditions of each component of the system are specified for use in the system analysis.

2.1 Fuel processor

The on-board vehicle fuel processor incorporates a methanol steam reformer (with an integrated burner) and a gas clean-up unit (CO preferential oxidation reactor).

2.1.1 Methanol steam reformer

Methanol is a favourable source of hydrogen for fuel cell applications since it has a high hydrogen density (high H–C ratio) and is a renewable and clean fuel that can be produced from any source of carbon and hydrogen. Furthermore, the absence of carbon–carbon bonds in methanol implies that methanol can be reformed at relatively low temperature and has a lower tendency for carbon formation compared with other higher hydrocarbons [8, 9]. Methanol processing can be approached either through a partial oxidation or steam reforming, or a combination of both of these processes, i.e. autothermal reforming. Steam reforming of methanol is the most developed and popular reformer technology used today. The low temperature operation, high hydrogen yield, and better integration of the reactor with the fuel cell system favours steam reforming over partial oxidation.

Reforming methanol to hydrogen involves a reaction of gaseous methanol and steam on heterogeneous catalytic surfaces. The reaction proceeds in two steps, the first being the decomposition of methanol to hydrogen

and the second step is the water shift reaction

The combination of these two reactions gives an overall reaction for methanol steam reformation [10]:

for gaseous reactants

for liquid reactants

A methanol steam reformer with suitable catalyst and ideal operating conditions should achieve nearly 100 per cent equilibrium conversion of methanol. Typical theoretical equilibrium proportions of $\text{H}_2/\text{CO}_2/\text{CO}$ respectively can be achieved within the temperature range 200–300 °C, pressure of between 3 and 5 atmospheres, and molar ratio of steam–methanol of greater than one [11, 12].

Fig. 1 Schematic representation of the PEMFC system for transport application (without any thermal integration)

In the current study, a reformer model was developed using the ASPEN PLUSTM software package [13] and the model was used to investigate the effect of the various reformer variables such as temperature, pressure, molar ratio, etc. and to establish the operating conditions for the steam reformer. The operating pressure of the reformer was determined by the fuel cell operating pressure, which is 3.0 bar(a) for this system analysis. The steam–methanol molar ratio was chosen on the criterion that the ratio would give a methanol conversion rate of greater than 95 per cent (% vol.) and a CO content of less than 1 per cent should be achieved. The effect of the molar ratio was optimized and the result is shown in Fig. 2. It is evident from Fig. 2 that the high rate of conversion of methanol and low CO content was achieved at molar ratios of between 1 and 5. However, the hydrogen content decreases over this range. To keep the molar ratio to its minimum (low heat of vaporization) and achieve the desired high methanol conversion (>95 per cent) and low CO content (<1 per cent), a molar ratio of 1.3 was chosen for this study. At this molar ratio the methanol conversion was greater than 99 per cent and the per cent by volume contents of CO and H₂ were 0.82 per cent and 68.82 per cent respectively.

The effect of temperature on the performance of the reformer was also studied at a pressure of 3 bar(a) and a molar ratio of 1.3. Figure 3 shows the equilibrium composition of the product gas at a

range of different temperatures. From Fig. 3 it is evident that a high level of hydrogen content was achieved between the temperatures of 175 and 215 °C and nearly 100 per cent conversion of methanol was attained at temperatures greater than 190 °C. On the basis of the thermodynamic equilibrium calculations, chemical studies, and previously published practical studies [11, 14–16], the reformer operating temperature was chosen as 200 °C.

The operating conditions of the methanol steam reforming for the PEMFC vehicle system analysis were chosen as 200 °C, 3 bar(a), and a molar steam–methanol ratio of 1.3. At this operating condition the methanol conversion rate was established as 99.92 per cent and the reformed gas equilibrium gas composition (by volume) was 68.82 per cent (H₂), 22.39 per cent (CO₂), 7.89 per cent (H₂O), 0.82 per cent (CO), and 0.08 per cent (CH₃OH).

2.1.2 Gas clean-up unit

The model used in this study incorporates the characteristics of the gas clean-up unit (GCU) developed by the Fuel Cell Group at Loughborough University. The GCU is designed to reduce CO concentrations to ppm level using a platinum–ruthenium (Pt–Ru)-based catalyst, supported upon a high-surface-area aluminium heat exchanger. CO oxidation reaction is related to both the operating temperature (120–200 °C) and O₂:CO molar ratio (1–4). The unit is capable of

Fig. 2 Equilibrium gas compositions for a range of steam–methanol ratios

Fig. 3 Equilibrium gas compositions for a range of different temperatures

reducing CO level to less than 15 ppm (< 5 ppm with dry gases) [17, 18]. The operating conditions of the GCU were chosen to be 160°C and an $\text{O}_2:\text{CO}$ molar ratio of 2.5. At these operating conditions, CO was assumed to be reduced to ≤ 10 ppm and the rest of the oxygen was used in CH_3OH and H_2 combustion.

2.2 PEMFC stack

A 50 kWe PEMFC stack was used in this vehicle system analysis to provide the electric power to the drivetrain. The stack design was based on a 200 cm^2 cell developed by Advanced Power Sources Limited and predicted future fuel cell performance. Table 1 shows the present and future fuel cell performance. The PEMFC stack had 700 cells and operated at 3 bar(a) and 80°C . The stack also used anode and cathode stoichiometries of 1.2 and 2 respectively.

Table 1 The present and future PEMFC performance

	PEMFC performance	
	Present	Future
Cell voltage (V)	0.730	0.850
Current density (A/cm^2)	0.489	0.420
Thermal efficiency, η_{th} (LHV*) (%)	58.25	67.82
Voltage efficiency, η_{v} (LHV) (%)	61.86	72.00

*LHV = lower heating value.

2.3 Compressor and expander

The compressor and expander isentropic efficiency for this system analysis was taken as 80 per cent, to reflect possible future performances of a compressor in a fuel cell system [19, 20]. The expander power was supplied to the compressor via a mechanical shaft, with a transmission efficiency η_s of 98 per cent. The model assumes that the working envelope of the expander matches that of the compressor and excess power from the expander was supplied to the system load (i.e. to the drivetrain) via a generator.

2.4 Electric vehicle drivetrain or powertrain

To calculate the vehicle efficiency in this system analysis, the efficiency of various components of the drivetrain only were considered [21]. To reflect the future performance of these components the following efficiencies were used in the steady state system analysis:

d.c./d.c. converter efficiency = 98 per cent

Motor electric efficiency = 95 per cent

Inverter efficiency = 98 per cent

Transmission losses = 1 per cent (99 per cent efficient)

2.5 Ancillary system

For this study of a fuel cell vehicle (without air-conditioning system), the ancillary load of 1.5 kW of electric power or 3 per cent of the fuel cell power was demanded from the d.c. link.

3 PEMFC VEHICLE SYSTEM ANALYSIS

A steady state model of a 50 kWe methanol PEMFC system was used to analyse the system performance and thermal integration of various system components in order to achieve the desired electric system efficiency (pre-drivetrain) of greater than 45 per cent. The performance of the PEMFC vehicle system without any thermal integration was first analysed and a number of efficiencies were calculated including the overall electric system efficiency. The second part of the analyses involved optimization of the system performance by integrating the thermal power with a network of heat exchangers and condensers.

The analyses were based on a net fuel cell output of 50 kWe, a lower heating value (LHV) for methanol of 630 MJ/kmole at 25 °C [22] and the following assumptions.

1. All calculations were made relative to a datum temperature of 25 °C.
2. The pressure drop over the various components of the system has been neglected.
3. 1 per cent reformer surface losses are assumed.
4. Electrical requirement for all the ancillary equipment was not considered.
5. Unreacted methanol in the reformed gas from the reformer was completely oxidized in the GCU.
6. All heat exchangers are assumed to have 1 per cent surface losses.
7. 100 per cent water was removed from the gas stream in the condenser.
8. No energy from the battery was consumed for the steady state analyses.

Steady state heat and mass balance calculations on individual components of the system were performed to determine the performance and efficiency of the components at their operating conditions. The analysis was based on a PEMFC vehicle system (see Fig. 1) in which the reformer and burner reactants were not pre-heated and the fuel cell stack exhaust gases were neither condensed nor pre-heated. (Hardware illustrated with the dashed lines in Fig. 1 was optional and only used when required.)

3.1 Fuel processor

3.1.1 Reformer reactants' flowrate

For 50 kWe power from the PEMFC stacks and an anode stoichiometry of 1.2, the hydrogen demand from the fuel processor was calculated to be 0.366 mol/s (491.70 standard litres per minute

(SLPM)). The equivalent methanol flowrate to satisfy the hydrogen demanded from the PEMFC stacks was determined to be 0.132 mol/s (0.319 litres per minute (LPM) at 25 °C). With molar ratio of steam–methanol of 1.3, the water flowrate was calculated to be 0.172 mol/s (0.186 LPM at 25 °C).

3.1.2 Methanol steam reformer and burner

The reformer reactants were fed to the reformer at a temperature of 25 °C. The burner was supplied with the stack exhaust gases (80 °C) and methanol from the tank. The oxygen demand by the burner was fulfilled by the cathode exhaust stream, which supplied ≈ 50 per cent more oxygen than required by the burner. The amount of supplementary methanol supplied to the burner was determined by performing a heat balance on the reformer and maintaining the reformer's temperature at 200 °C. The burner supplied the heat to the catalyst bed at 230 °C to ensure adequate heat transfer. The heat required for the reformer reaction was determined from the overall heat of reaction (equation (5)) at 200 °C [23]. For a methanol flowrate of 0.132 mol/s and a conversion efficiency of 99.7 per cent, the heat required to reform methanol at 200 °C was calculated to be 7.7 kW.

$$\Delta H_{473} = +58.4 \text{ kJ/mol}$$

(5)

From the reformer heat balance, the reformer efficiency η_{Ref} was found to be 69.61 per cent and the heat for the reformer reactions at 200 °C, $\Delta P_{\text{Ref}(473 \text{ K})}$, was determined to be 26.41 kW (including the heat required to heat the reactants to 200 °C). The definition of η_{Ref} and $\Delta P_{\text{Ref}(473 \text{ K})}$ are as follows

$$\eta_{\text{Ref}} = \frac{\text{Heat in the reformed gases}}{\text{Total heat into the reformer}}$$

$$\begin{aligned} \Delta P_{\text{Ref}(473 \text{ K})} = & (\text{Heat into the burner}) \\ & - (\text{Heat in flue gases} + \text{heat losses} \\ & + \text{heat of reaction}) \end{aligned}$$

3.1.3 GCU reactor

A heat and mass balance was carried out to determine the heat to be removed from the GCU in order to maintain a temperature of 160 °C. This was calculated to be 5 kW. (This heat power also contains thermal energy produced via combustion of all remaining CH_3OH and loss H_2 with excess O_2 in the GCU.)

3.1.4 Fuel processor efficiency

Fuel processor efficiency η_{FP} is a measure of the fuel processor performance compared to other subsystems. The efficiency is defined as follows

$$\eta_{FP} = \frac{\text{LHV of anode feed gas (kW)}}{\text{LHV of the fuel to the system (kW)}}$$

The fuel processor efficiency η_{FP} for the system presented in Fig. 1 was calculated to be 82.4 per cent.

3.2 PEMFC stack

A heat and mass balance for the fuel cell stack was carried out in order to determine the heat to be removed by the cooling system to maintain the stack temperature of 80 °C. The fuel cell data detailed in Table 1 were used in the heat and mass balance calculation. The anode and cathode stoichiometries were 1.2 and 2 respectively. From the heat balance, the cooling power required to maintain the stack at 80 °C was determined to be 15 kW. The relative humidities of the anode and cathode exhaust gas streams were also calculated using the partial pressure of the water vapour in these gas streams. These were found to be 138 and 120 per cent for anode and cathode outlet streams respectively.

3.3 Compressor and expander

For this steady state analysis, the isentropic efficiency of the compressor and expander were both taken to be 80 per cent. The air temperature at the outlet of the compressor (at a pressure ratio of 3) was calculated to be 163 °C. The corresponding compressor power was determined to be 6.2 kW. Including the mechanical transmission efficiency of the shaft ($\eta_s = 98$ per cent), the total power required by the compressor at a pressure ratio of 3 was found to be 6.4 kW. The expander power was also calculated for the pressure ratio of 3 and isentropic efficiency of 80 per cent. The flue gases at the temperature of 230 °C were expanded to a temperature of 125.3 °C. The power generated by the expander was 6.1 kW at a pressure ratio of 3. Additional power (0.26 kW) for the compressor was supplied via the d.c. link.

3.4 Heat exchangers and condensers

From Fig. 1 it can be seen that four heat exchangers were used in this system analysis. The performance of each heat exchanger was determined by considering only the inlet and outlet conditions of the fluid streams. Since in this study the reformer and burner reactants are not preheated, the excess thermal

power from the heat exchangers was not used. Heat exchangers 1 and 2 were used to cool down the reformed gases from 200 to 160 °C, and then eventually down to 80 °C, before being fed into the PEMFC stack. Heat exchanger 3 was used to cool down compressed air from 163 to 80 °C, while heat exchanger 4 was optional and not utilized in this particular study. Table 2 shows the performance of these heat exchangers. Condensers were not used in this study and the PEMFC stack exhaust gases were fed directly into the burner at 80 °C.

3.5 Electric vehicle drivetrain and ancillary system

In this study, the performances of the individual drivetrain components were modelled by their efficiency. Using the efficiencies of different components of the drivetrain stated in the previous section, overall drivetrain efficiency η_{O_dt} was determined to be 90.3 per cent. An ancillary load of 1.5 kW was also demanded from the system to support auxiliary components. This ancillary load of 1.5 kW corresponded to ancillary system efficiency η_{anc} of 96.9 per cent. Table 3 shows the individual component efficiency and power losses incurred by these components of the drivetrain and ancillary system.

3.6 Overall system heat balance and system efficiencies

An overall system heat balance of a vehicle system (as shown in Fig. 1) was carried out to determine the electrical system efficiency and vehicle efficiency

Table 2 Performance of the heat exchangers at 3 bar(a)

Heat exchanger no.	Properties		
	T_{in} (°C)	T_{out} (°C)	Heat available (kW)
1	200	160	0.75
2	160	80	1.44
3	163	80	3.63

Table 3 Drivetrain and ancillary system efficiencies and losses

Component	Efficiency (%)	Power loss (kW)
d.c–d.c. converter	98.00	1.00
Inverter	98.00	0.95
Motor	95.00	2.33
Transmission	99.00	0.44
Ancillary load	96.94	1.50
Overall	87.56	6.22

(fuel-to-wheel efficiency). The electrical $\eta_{\text{EL_Sys}}$ and vehicle η_{Veh} system efficiencies are defined as follows

$$\eta_{\text{EL_Sys}} = \frac{\text{PEMFC power (kW)} + \text{expander power (kW)}}{\text{LHV of the fuel to the system (kW)}}$$

$$\eta_{\text{Veh}} = \eta_{\text{EL_Sys}} \times \eta_{\text{O_dt}} \times \eta_{\text{anc}}$$

The results of the overall system heat balance of a methanol-fuelled PEMFC vehicle system with no reactant preheat and without the use of condensers are summarized in Table 4. A PEMFC vehicle system without any thermal integration achieved a vehicle efficiency of 38.4 per cent and an overall power balance (pre-drivetrain) of power/coolant/exhaust = 44/44/12 per cent, compared to an ICE at $\approx 33/33/33$ per cent (current ICE performance) [24]. The power/coolant/exhaust power balance represents percentage electrical power for mechanical work, percentage coolant power removed by the heat exchangers or cooling system, and percentage exhaust power removed from the system as unusable power. The 44 per cent coolant or waste heat power has to be utilized to optimize the system performance and attain the desired electrical system efficiency of >45 per cent in order to be competitive with the future ICE and its hybrid versions.

4 OPTIMIZATION OF SYSTEM PERFORMANCE

The system performance of the PEMFC vehicle system was optimized by integrating the thermal power with the use of a network of heat exchangers and condensers. Two case studies were carried out:

1. Effect of preheating the reformer and burner reactants.
2. Use of condensers for the fuel cell exhaust gases.

Table 4 Summary of results from the study of the PEMFC vehicle system (without any thermal integration)

System parameters	PEMFC vehicle system [at 3 bar(a)], no preheat and condensers
Total fuel power to the system (kW)	114.2
Fuel processor efficiency η_{FP} (%)	82.4
Electrical efficiency $\eta_{\text{EL_Sys}}$ (%)	43.8
Drivetrain efficiency $\eta_{\text{O_dt}}$ (%)	90.3
Ancillary efficiency η_{anc} (%)	96.9
Power to the wheels (kW)	43.8
Vehicle efficiency η_{Veh} (%)	38.4

4.1 Effect of preheating the reformer and burner reactants

In this case study the reformer and the burner reactants were preheated to the maximum possible temperature. Heat exchangers 1, 3, 4 and the GCU reactor were used in the reactants' preheat process. Figure 4 shows the thermally integrated PEMFC vehicle system and the heat treatment received by the reactants via various heat exchanges and the GCU reactor.

The reformer reactants (methanol and water) and burner methanol were heated to a temperature of 120 °C in heat exchanger HEX 4. The flue gas temperature was decreased to ≈ 60 °C and 7.7 kW of the thermal power was used in this heating process. The reformer and burner methanol was further heated to 160 °C by HEX 1. The methanol water was also further heated to 160 °C by combination of HEX 3 and the GCU reactor. The reason for heating the reactants prior to feeding them into the respective components was to reduce the amount of fuel consumed in the system and hence improve the system electrical and overall vehicle efficiencies. Table 5 shows the system performance after the thermal integration process.

The performance of the PEMFC vehicle system was optimized to achieve an improvement of approximately 18 per cent in both the electrical and vehicle efficiencies. This improvement in efficiency was achieved by both preheating the methanol and water to a maximum possible temperature of 160 °C and minimizing the total fuel power to the system to 96.6 kW from 114.2 kW. Around 15 kW of thermal power was required to preheat the reactants to 160 °C and the majority of the power was coming from flue gases at 120 °C, GCU reactor at 160 °C, and heat exchanger HEX 3 at 163 °C. However, the consequence of burning less fuel in the burner was that less power was recovered via the expander from the flue gases and hence an extra 2 per cent compressor power was demanded from the d.c. link. A thermally integrated

Table 5 Summary of results after the thermal integration process

System parameters	PEMFC vehicle system [at 3 bar(a)], with preheating
Total fuel power to the system (kW)	96.7
Fuel processor efficiency η_{FP} (%)	96.7
Electrical efficiency $\eta_{\text{EL_Sys}}$ (%)	51.7
Drivetrain efficiency $\eta_{\text{O_dt}}$ (%)	90.3
Ancillary efficiency η_{anc} (%)	96.9
Power to the wheels (kW)	43.8
Vehicle efficiency η_{Veh} (%)	45.3

Fig. 4 Schematic representation of the thermally integrated PEMFC vehicle system

PEMFC vehicle system also achieved an electric system efficiency $\eta_{\text{el_sys}}$ (pre-drivetrain) of 51.7 per cent and a competitive vehicle efficiency of 45 per cent. The overall power balance of this system was determined to be power/coolant/exhaust = 51.7/33.3/15 per cent. Compared to the system without any thermal integration, the electrical efficiency and exhaust power increased while the coolant power was reduced. The majority of the coolant power was low-grade thermal power at 80 °C from the fuel cell stack cooling system and the depleted flue gas power (60 °C). Hence, although the desired electrical efficiency of >45 per cent was achieved, a large amount of low-grade heat power and poor-quality exhaust power was unusable.

4.2 Use of condensers for the fuel cell exhaust gases

The use of condensers to cool and remove the water from the PEMFC stack anode and cathode exhaust gases was also investigated. The PEMFC stack exhaust gases were cooled down from 80 to 25 °C and the power in the gases (thermal and chemical) was reduced from 31.6 to 14.8 kW, i.e. 16.8 kW was extracted via the condensers. Figure 5 shows the thermally integrated PEMFC vehicle system with condensers. The consequence of using the condensers was that the power to the burner and the power in the flue gases were both reduced. Reduced power in the flue gases leads to less power being recovered via the expander and also less power being available for the reactants' heating process. For heating the reactants to 160 °C the process was configured differently because the thermal power in the flue gases was not sufficient to heat both water and methanol to 120 °C. The reformer and burner methanol was heated to 100 °C by HEX 4 and to 200 °C by HEX 1. Nearly 68 per cent of the thermal power was utilized in HEX 1 compared with 47 per cent in the PEMFC vehicle system without condensers. The flue gas temperature was decreased from 125 to 26 °C and

thermal power was reduced from 9 to 3 kW. The water was heated to 160 °C via HEX 3 and the GCU reactor, and 97 per cent of the thermal power from both these components was utilized.

The effects of condensing the water out of the stack exhaust gases were that the total fuel to the system was reduced by approximately 1 per cent and the thermal power of the flue gases was reduced from 33 to 14 kW for a system with condensers. This reduction in the quantity of the thermal power led to a reconfiguration of preheating the reactants to 160 °C. The reduction of total amount of fuel going into the system improved the system electrical efficiency from 51.7 to 52.2 per cent. Improvement in the electrical efficiency also improved the vehicle efficiency by 1 per cent, to 45.7 per cent. The overall power balance of this vehicle system was determined to be power/coolant/exhaust = 52.2/31.4/16.4 per cent. Compared to the previous system the thermal power of the water in the anode and cathode streams was available as coolant power at 80 °C from the condensers. The flue gas thermal power was completely depleted (26 °C) and became part of the exhaust power, which was increased from 15 to 16.4 per cent.

Table 6 summarizes the results of the steady state study and two thermal integration investigations of the PEMFC vehicle system. The Sankey diagram (Fig. 6) displays the power flows through the PEMFC thermally integrated vehicle system (with condensers). The diagram also illustrates where the fuel power was utilized and the thermal power was recycled and recovered.

5 EFFECT OF OPERATING PRESSURE

Choosing the appropriate operating pressure of a fuel cell system is critical, especially for a vehicle system, since it is very important to minimize any parasitic losses and maximize the vehicle efficiency. A low-pressure system investigation was carried out to

Table 6 Summary of results of steady state analyses of the methanol-fuelled PEMFC vehicle system

System parameters	PEMFC vehicle system [at 3 bar(a)]		
	None	Preheating	Preheating and condensers
Total fuel power to the system (kW)	114.2	96.7	95.7
Fuel processor efficiency η_{FP} (%)	82.4	96.7	99.2
Electrical efficiency $\eta_{\text{el_sys}}$ (%)	43.8	51.7	52.2
Drivetrain efficiency $\eta_{\text{O_dt}}$ (%)	90.3	90.3	90.3
Ancillary efficiency η_{anc} (%)	96.9	96.9	96.9
Power to the wheels (kW)	43.8	43.8	43.8
Vehicle efficiency η_{veh} (%)	38.4	45.3	45.7

Fig. 6 Sankey diagram for a 50 kW PEMFC thermally integrated vehicle system with condensers

study the effect of operating pressure on the performance of stack, compressor–expander system, and the overall PEMFC vehicle system. The investigation used an operating pressure of 1.25 bar(a) and the operating conditions of the PEMFC stack at 1.25 bar(a) were used. At a pressure of 1.25 bar(a), the PEMFC operating point was 0.678 V at a current density of 0.527 A/cm², which corresponded to thermal efficiency η_{Th} of 54 per cent. The performance of other subsystems such as fuel processor, compressor–expander, were kept the same.

Table 7 compares the results of this investigation with a vehicle system operating at 3 bar(a). The effect of operating pressure was more pronounced with the

compressor and expander system. The compressor power and expander power were reduced by 22 and 29 per cent respectively as the pressure was reduced from 3 to 1.25 bar(a). Although the parasitic load on the system was reduced at lower pressure, the electrical system efficiency and hence the vehicle efficiency was also decreased. The superior fuel cell efficiency at high pressure compensated for the high parasitic load by demanding less hydrogen from the fuel processor and hence less fuel was used in the high-pressure system. The fuel demand for the low-pressure system was also high because the quality and quantity of the thermal power was inadequate for the reactants' preheat process to the

Table 7 Effect of pressure on the performance of the PEMFC vehicle system

System parameters	PEMFC vehicle system with preheating and condensers	
	1.25 bar(a)	3.00 bar(a)
Cell voltage (V)	0.678	0.850
Current density (A/cm ²)	0.527	0.420
Thermal efficiency η_{Th} (LHV)	54.0	67.8
Compressor power (kW)	1.4	6.4
Expander power (kW)	1.4	4.6
Total fuel power to the system (kW)	127.8	95.7
Fuel processor efficiency η_{FP} (%)	89.9	99.2
Electrical efficiency η_{El-Sys} (%)	39.1	52.2
Drivetrain efficiency $\eta_{O,dt}$ (%)	90.3	90.3
Ancillary efficiency η_{anc} (%)	96.9	96.9
Power to the wheels (kW)	43.8	43.8
Vehicle efficiency η_{Veh} (%)	34.3	45.7

same temperature as the high-pressure system. The lower dew point or boiling point at lower pressure increased the thermal power demand for the preheat process and so the water could only be heated to 100 °C and the methanol to 160 °C.

The overall power balance for the lower-pressure system was calculated to be power/coolant/exhaust = 39.1/42.2/18.7 per cent. Compared with the high-pressure system (52.2/31.4/16.4 per cent), nearly 61 per cent of the fuel power was converted to thermal power. Most of this thermal power was available as low-grade heat at 80 °C from the fuel cell cooling system and condensers. The inferior fuel cell efficiency at lower pressure was mainly responsible for the large percentage of coolant power. The exhaust thermal power was mainly poor-quality thermal power in the flue gases at 38 °C. Hence, operation at high pressure was considered superior to a vehicle system operating at lower pressure.

6 CONCLUSIONS

1. Steady state and dynamic models of the PEMFC-powered vehicles have been developed and applied to a methanol-fuelled PEMFC 50 kW vehicle.
2. The model includes a methanol steam reformer, GCU, fuel cell stack, compressor, expander, heat exchanger, and an electric drivetrain.
3. The reformer was operated at a steam–carbon molar ratio of 1.3, which gave a methanol conversion of 99 per cent, H₂ content of 69 per cent, and CO content of 0.8 per cent. Operating temperature and pressure were 200 °C and 3 bar respectively.
4. The GCU reduced the CO content to ≤ 10 ppm.
5. The fuel cell stack design was based on a 200 cm² cell size, with 700 cells. The stack operated at 3 bar, 80 °C, and thermal efficiency η_{Th} (LHV) of 68 per cent.
6. The vehicle was modelled at steady state full power 50 kW.
7. The base model result was a vehicle efficiency of 38 per cent.
8. The addition of heat exchangers to permit thermal integration resulted in a vehicle efficiency of 45 per cent.
9. The addition of condensers to cool and remove water from the anode and cathode exhaust gases resulted in a vehicle efficiency of 46 per cent.
10. Reducing the operating pressure from 3 to 1.25 bar reduced vehicle efficiency to 34 per cent.

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APPENDIX

Notation

ΔP_{Ref}	power for the reformer reaction (kW)
η_{anc}	ancillary system efficiency (%)
$\eta_{\text{EL_Sys}}$	electrical system efficiency (%)
η_{FP}	fuel processor efficiency (%)
$\eta_{\text{O_dt}}$	overall drivetrain efficiency (%)
η_{Overall}	overall system efficiency (%)
η_{Ref}	reformer efficiency (%)
η_{s}	mechanical transmission efficiency of the shaft (%)
η_{Th}	thermal efficiency (%)
η_{Veh}	vehicle efficiency (%)