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System modelling and integration of an intermediate temperature solid oxide fuel cell and ZEBRA battery for automotive applications

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Abstract

The combination of a sodium-nickel chloride (ZEBRA) battery and intermediate temperature solid oxide fuel cell (IT-SOFC) to form a hybrid power system intended for automotive applications is examined with the aid of a fuel cell system model. The model allows the operating temperatures of the system to be assessed with a view to thermal integration with the battery. Efficiency curves for stacks and systems are described along with the temperature distribution around the system. Two types of IT-SOFC are compared, one operating in the 500–650 °C temperature region and one in the 700–850 °C region. The lower temperature IT-SOFC using external steam reforming, and the higher temperature system using partial internal steam reforming, both of methane fuel.

Keywords: Intermediate temperature solid oxide fuel cell; ZEBRA battery; Hybrid vehicle; System model

1. Introduction

The drive to reduce emissions and improve vehicle efficiency has motivated automobile manufacturers to investigate the use of alternatives to the internal combustion engine (ICE). By far the most promising and developed alternative to the ICE uses electrical traction motors powered by electrochemical devices. Electrical drive systems are found in pure electric, hybrid electric and fuel cell vehicles. The advantages of electric drive systems include: zero emissions at point of use (if battery powered or if a fuel cell operating on hydrogen is used), quiet operation, fast acceleration, recuperation of regenerative energy from braking and high efficiency drive trains and energy conversion. However, battery powered electric vehicles have a reputation for limited range, problems with slow recharging and lack of recharging infrastructure. Hydrogen fuelled fuel cell vehicles also suffer from range and refuelling infrastructure limitations as well as the necessity for the fuel cell system to be made large enough to accommodate the maximum power requirement, which may only constitute a small fraction of the drive cycle.

Project ABSOLUTE (Advanced Battery Solid Oxide fuel cell Linked Unit To maximise Efficiency), aims to combine a sodium-nickel chloride (ZEBRA) battery [1] and an intermediate temperature solid oxide fuel cell (IT-SOFC) [2] to form an all-electric hybrid package that surpasses the efficiency and performance of a purely fuel cell driven vehicle, as well as extending the range of a purely battery driven electric vehicle. The use of a solid oxide fuel cell is employed to provide fuel flexibility, while the high temperature nature of both the fuel cell and battery technology chosen is predicted to act in a synergistic fashion with respect to thermal and balance of plant integration.

Previous work [3,4] has considered the energy and power requirement of various vehicle types, operating over a range of driving conditions. The battery and fuel cell for the hybrid system were sized according to the criteria that the battery accommodates the peak power requirement and acts as an ‘energy buffer’, while the fuel cell is designed to satisfy the overall energy demand. In order to avoid the problems of stop/start operation and dynamic load changes on the fuel cell, a nominally ‘always-on’ strategy was taken for the IT-SOFC such that during non-drive time, the power from the fuel cell is used to recharge the battery.

In order to optimise the operation of the hybrid system, identify opportunities for integration between the fuel cell and battery

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and determine the net efficiency of the hybrid, a reliable model of the fuel cell system is required. This paper reports the use of a steady-state model developed using *gPROMS ModelBuilder* 2.3.5 [5] to determine the fuel cell efficiency, fuel consumption and the operating temperature at different parts of the system.

Our previous analysis identified that the fuel cell power needs to be in the range of ca. 1–5 kWe to accommodate vehicle types ranging from small city cars to small buses, when paired with a ZEBRA battery. The size of the battery depends on the size of the vehicle and the number of hours of drive-time per day (see Section 4). Work by Webasto and Delphi [6] has focused on the 5 kWe power level for the purpose of vehicle auxiliary power units (APUs) and comparable combined heat and power (CHP) system models in the 5 kWe range have also been published [7]. In order to suit the fuel cell power requirement for vehicle range extension and be of interest for vehicle APUs, a net rated power output of ca. 5 kWe was considered in the model.

1.1. Intermediate temperature solid oxide fuel cells

Conventional high temperature SOFCs, typified by developers such as Siemens Westinghouse [8] and Rolls Royce [9] operate in the temperature range of 900–1000 °C. These systems are often integrated with turbines to achieve high overall system efficiency and are therefore best suited to larger scale power production. For smaller scale applications, such as residential micro-CHP, there is a trend to move to lower temperature operation, in the so-called intermediate temperature (IT) range of 500–850 °C.

Lowering the operating temperature avoids some of the problems of high temperature SOFCs, namely poor thermal shock properties, limited redox cycling durability, long start-up times, sealing problems and limited materials selection.

Two general routes can be taken in order to lower the SOFC operating temperature while maintaining adequate performance. The dimensional thickness of the electrolyte can be reduced, so reducing the area specific resistance of the fuel cell, and/or materials development can bring about the same result by improving the ionic conductivity of the electrolyte at lower temperatures and the performance of the anode and cathode. Ceres Power Ltd. and Versa Power Systems (VPS) are two examples of companies that are developing IT-SOFCs for a commercial market. The approach pioneered at Imperial College, and further developed by Ceres Power Ltd., uses ceria gadolinia oxide (CGO) electrolyte of a thickness in the 10–30 μm range, the anode–electrolyte–cathode structure fabricated on a metallic support. This technology has achieved comparable performance to high temperature SOFCs while operating in the 500–650 °C range [10]. Versa Power Systems operate their technology at a higher temperature, which facilitates the use of internal reforming. Illustrative performance values of >300 mW cm^{-2} (0.76 V, 725 °C) on 35% internally reformed natural gas, place this technology at the threshold of the US DoE 2012 goal for SOFC commercial power generation [11].

1.2. The ABSOLUTE vehicle concept

The concept for the ABSOLUTE hybrid vehicle brings together a ZEBRA battery operating at ca. 300 °C and IT-SOFC technology working in the temperature range of 500–850 °C. The sizing of each system is designed so that the hybrid can supply the power required for satisfactory performance over the required drive cycle and to operate in a regime that is 'charge neutral' or 'fuel limiting', such that the range is not limited by the energy of the battery but by the fuel tank capacity and the ability to refuel. A detailed analysis covering the rationale behind the ABSOLUTE hybrid can be found in Refs. [3,4]; the main features of the ABSOLUTE hybrid concept are summarised as:

- The hybrid is 'battery dominant'—the high energy density of the ZEBRA battery allowing the battery to supply the immediate energy and peak power requirement, allowing use of a 'small' IT-SOFC to recharge the battery.
- The IT-SOFC is nominally always-on and operates at rated power for the majority of the time, i.e. the fuel cell provides constant power during the driving and non-driving time of the vehicle.
- The vehicle is intended to be run predominantly on hydrocarbon fuel (i.e. natural gas), although mains recharge is, of course, still an option for the battery.
- The high temperature operation of the fuel cell and battery is anticipated to be exploited for improving system efficiency by thermal integration of both systems.

2. Fuel cell system model

For practical operation, a solid oxide fuel cell must be embedded within a system incorporating a balance of plant (BoP) that supplies air and clean fuel (and steam for reforming) at the correct rate and temperature and removes or processes the depleted reactants, products and heat. A complete SOFC system is generally composed of fuel processing units, fuel cell stack(s), heat exchange equipment, a control system and power-conditioning unit (PCU).

Two different 5 kWe IT-SOFC systems are considered in this study: one representing a lower temperature (500–650 °C) IT-SOFC, the other in the higher temperature (700–850 °C) regime of operation. Methane is chosen as the fuel since this has been found to offer adequate vehicle range and high gasoline equivalent fuel economy [3], it is widely available (the UK having a particularly good natural gas infrastructure) and it is also of interest for comparison with stationary IT-SOFC systems that operate on natural gas.

The lower temperature system is chosen to operate with external steam reforming since internal reforming has yet to be demonstrated at this temperature. The higher temperature system uses partial internal steam reforming of methane. Steam reforming is chosen as the fuel processing method for both of the IT-SOFC technologies for the following reasons:

- Steam reformer technology is well developed.
- Steam reformers can be used with a wide range of fuels.

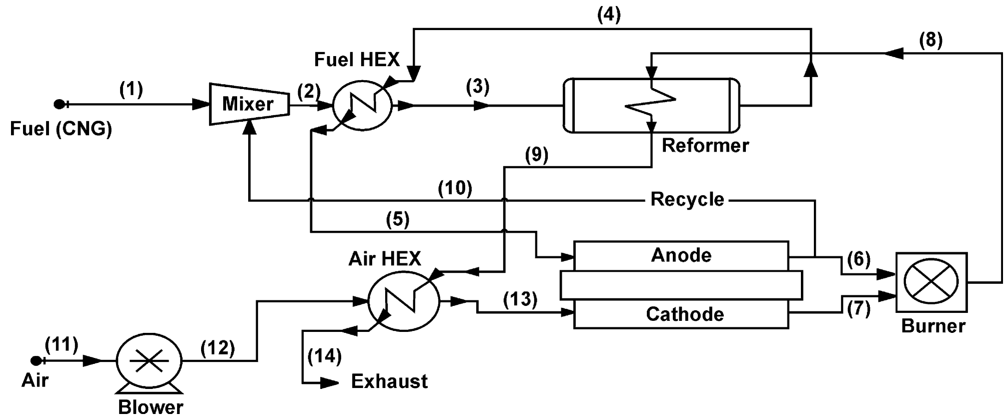

Fig. 1. Generic IT-SOFC balance of plant process flow diagram.

- No introduction of oxygen is required (as for partial oxidation).
- High hydrogen yield—the highest efficiency of all of the reforming technologies.
- In the case of the partial internal reforming option, the endothermic nature of the reaction has a cooling effect on the stack, so requiring less air for this purpose.

For automotive applications, the excess heat produced by the fuel cell (that in a stationary application could be used to supply heat to a home for example) cannot be used as usefully in a car (except to supply cabin heating or, in the case of the ZEBRA battery, to potentially maintain its operating temperature). For the ABSOLUTE hybrid, fuel cell system design is aimed at optimising the electrical power output and producing enough heat to supply the reformer and preheat the fuel and air streams.

The generic process system diagram for both of the IT-SOFC systems studied is shown in Fig. 1. The fuel feed is first mixed with steam, after which this mixture is pre-heated and partially or totally reformed before being fed to the anode side of the stack. Air is compressed and pre-heated before being fed to the cathode side of the stack. At the outlet of the stack, part of the anode off-gas stream is recycled to supply steam to the reformer while the remaining anode off-gas is fed, together with the air stream, to a burner where any remaining fuel is burned and the resultant hot stream is used to supply heat throughout the system. Overall, the system comprises an air blower, air and fuel pre-heaters, fuel mixer, reformer, IT-SOFC stack and afterburner. The system model has been developed and solved using *gPROMS ModelBuilder* 2.3.5 [5].

2.1. Air blower and fuel and air pre-heaters

It is assumed that the fuel is clean methane (desulphurised) and the oxidant is air. The fuel is assumed to be available at sufficient pressure to pass through the system. The air stream is available at atmospheric pressure; a blower is therefore required to service the system. The air blower is an important plant item, as it requires a significant amount of power (representing the major parasitic loss in the system) and if not carefully designed, can significantly decrease the overall system efficiency. Fuel and air pre-heaters are required, as the stack and the reformer do not tolerate a gas supply at low temperatures. This is due to the excessive cooling and consequent thermal stresses that such cold streams would cause. The two pre-heaters are modelled as counter-current heat exchangers. The fuel pre-heater recovers heat from the reformed fuel stream to heat the fuel/steam mixture before reforming and the air pre-heater recovers heat from the burner exhaust gas to heat the air stream after compression.

2.2. Reformer

Two reforming strategies are investigated; each is related to the fuel cell operating temperature. For the 500–650 °C system, an external reformer is used to convert the fuel into the H_2 and CO that can then be used as direct fuel in the stack. The higher temperature 700–850 °C IT-SOFC technology is assumed to allow direct internal reforming in the fuel cell anode. The advantage of this is that less air is required to cool the stack since the endothermic reforming reactions absorb part of the heat produced in the stack, thus increasing the system efficiency by reducing the power demand for the air blower. In practice, full direct internal reforming may lead to extreme local cooling effects at the entrance to the stack and higher hydrocarbons (that can be present in the fuel) may decompose at the high stack temperature, in which case the use of a small ‘pre-reformer’ is recommended to be used to avoid excessive thermal stresses as well as possible carbon deposition on the anodes [12].

The heated reformers (and pre-reformer) in these systems are modelled as a combination of a catalytic reactor with a heat exchanger, where the afterburner exhaust gas provides the heat necessary for the reforming reaction. For the 500–650 °C system, it is assumed that all the methane present in the fuel stream is reformed, subject to the condition that both the steam reforming and the water-gas shift reactions are at equilibrium at the exit of the stack. For the external pre-reformer in the higher temperature system, it is considered, similar to the direct internal reforming reaction in the stack fuel channel, that the methane steam reforming reaction follows the kinetics from Achenbach and Riensche [12,13] and that the water-gas shift reaction is in equilibrium.

2.2.1. Water balance

Since steam reforming is being used to convert methane fuel to H_2 and CO, water can also be considered as a 'fuel' for the system. It is therefore important that the water supply and the water 'balance' of the system are considered in the context of the application. For example, if all of the water required for steam reforming was supplied from a tank and there was no water recuperation from the fuel cell system, then a water tank several times the size of the fuel tank would be necessary. Such a requirement would not be acceptable for an automotive application, where space and weight are at a premium.

Water can be recuperated from the system by condensation from a process stream or by partial recirculation of the anode off-gas. There are two places in the process flow stream at which water condensation might be considered. The first is at the exit from the anode side of the stack and the second on the afterburner exhaust stream after the air pre-heater. The first has the advantage that the water mole fraction is high (typically >30%) at this point and the total anode flow rate is low compared to the cathode. However, the temperature is high and additional water will be produced from the unspent fuel after combustion in the burner, which would not be captured at this point. Condensation of water after the air pre-heater is from a much lower temperature but the total flow rate is much higher with a very low partial pressure of steam. Modelling investigations showed that condensation was not a practical approach at either point. This is because the amount of cold water required to cool down and condense the steam in the system would be prohibitively large and not compatible with a vehicular application.

Partial recirculation of the anode off-gas was therefore adopted for this system design. By recycling enough of the anode off-gas to accommodate the steam/carbon ratio requirement for the reformer, an independent source of steam can be avoided. This means that there is no need for a large water tank or pump. However, upon start-up a process would be required to introduce steam to the reformer before the fuel cell is operational and generating steam. While detailed system design is not the aim of this work, possible ways to recycle the fuel could include the use of an ejector driven by the pressurised fuel feed gas if this would prove to be appropriate for systems of this size.

2.3. IT-SOFC stacks

As can be seen from Fig. 1, the pre-heated air and fuel streams are fed to the corresponding gas channels in the stack, where the hydrogen produced (either in the external reformer or directly on the anode) is electrochemically oxidised to satisfy the load requirement.

The authors have previously reported on the development of two planar co-flow IT-SOFC stack models in the context of stationary CHP applications: an anode-supported direct internal reforming (DIR) high temperature IT-SOFC model [12] and a metal-supported low temperature IT-SOFC model [7]. These models consider the SOFC to be composed of fuel and air channels, positive–electrolyte–negative (PEN) structure and interconnect. Mass balances around the fuel and air channels and energy balances around the fuel and air channels, PEN and interconnect are considered. An electrochemical model that relates the fuel and air gas compositions and the various cell temperatures to voltage, current density and other cell variables is employed. It is assumed that only H_2 is electrochemically oxidised in the fuel cell, all the CO is converted through the water-gas shift reaction, assumed at equilibrium, and any CH_4 entering the fuel cell can only be reformed to H_2, CO and CO_2 but not electrochemically oxidised. The electrochemical model accounts for Ohmic losses across the PEN structure and for anode and cathode concentration, and activation overpotentials.

2.4. Afterburner

In practice, it is not possible to use all of the fuel entering the stack. As fuel is consumed within the stack, the remaining fuel is progressively diluted in steam and carbon dioxide. Therefore, to achieve a reasonable cell voltage and protect the anode from oxidation, a certain minimum hydrogen partial pressure is required, meaning that some residual fuel, determined by the fuel utilisation, is present in the stack anode off-gas. Therefore, an afterburner is provided after the stack, where the fuel and air exhaust streams are mixed and the residual fuel burned conventionally; this heat is then used to help service the BoP thermal requirements.

2.5. Parasitic load and heat loss from the system

In addition to the application load, a fuel cell system also has an electrical load associated with the valves, sensors, actuators and electronic control systems that are essential for operation of the system. To take this into account, the developed model considers a value of 200 W as the constant 'parasitic' load for the system. In addition, regardless of the application of thermal insulation to the system, a practical IT-SOFC will suffer a certain amount of heat loss. The greatest heat loss from the system will tend to occur from the hottest points. Thus, for the BoP configuration shown in Fig. 1, two point 200 W heat losses are introduced: one at the outlet of the afterburner and the other in the afterburner exhaust stream between the outlet of the reformer and inlet to the air heat exchanger.

2.6. Control units

An effective control strategy aims to avoid any possible failure conditions as well as to guarantee that the system responds promptly and in a stable fashion to any changes imposed. These can include limitations in temperature variation (to avoid thermal stresses in the stack for example), defining practical limits on fuel and air flow rates, or a maximum allowable variation of the electrochemical variables. Common requirements for the operation of a SOFC system include: controlling the average stack temperature; assuring that the air ratio always exceeds a minimum specified value, and guaranteeing that the steam to carbon ratio at the entrance of the pre-reformer always exceeds 2.5 to avoid carbon deposition. Stack temperature control is normally provided by varying the air flow rate.

As the aim of the present work is not to report on the dynamic operation of the proposed systems but rather to assess their performance under steady-state operating conditions, no controllers are included in the system. This is a relevant and reasonable rationale since the IT-SOFC in the ABSOLUTE hybrid is intended to nominally operate at constant load and be ‘always-on’. In the present model, the only variables that change as the current drawn from the stack varies, and so needs active control, are the air and methane mass flow rates. These are calculated such that both the air ratio and the system fuel utilisation are kept constant. In addition, the mass flow rate of the anode off-gas recycle stream is also calculated such that, at the entrance of the reformer, the steam to carbon ratio remains equal to 2.5.

3. Analysis of system results

In the present study, the performance of both IT-SOFC systems is analysed by determining stack and net system efficiency curves, the system and stack performance at rated power, and the stream temperature distribution around the two systems. Table 1 shows the required input operating conditions to the model for each of the IT-SOFC systems. These values remain constant throughout this analysis.

3.1. Sizing the fuel cell stack

To produce a useful voltage, individual cells are connected in series to form a stack. In practice, due to the limitation on the size of individual SOFC cells, several cells may be connected in parallel to form a ‘plate’ that is then joined in series to form the stack. For this model, each plate is taken to be constituted of a 2 × 2 array of 10 cm × 10 cm cells.

In order to size the stack for a required system net power, it is necessary to specify the operating point of the stack and have an estimate of the parasitic load incurred by the fuel cell system. The operating point is the voltage and current density at which the stack/cells will operate at the rated power. There are various factors that determine the optimum operating point, the values of which establish the efficiency, weight, volume and cost of the stack: the stack can be operated at a relatively high power density (with associated decrease in efficiency) or at a relatively low power density and made larger (increased weight, size and cost). In order to size the stacks modelled in this study it was initially assumed that the desired operating voltage would be ca. 0.7 V per cell. This value is considered to represent a trade-off between the power density (or cost) and efficiency of the system. Once the desired operating voltage is set, it is common practice to make use of voltage/current characteristic curves to determine the corresponding operating point current density value. These two values provide the power density delivered by the stack, which, once the stack total rated power output is set, determines the total stack cell area and the total number of plates per stack.

Table 1
Stack dimensions and system input operating conditions (high and low temperature IT-SOFC)

Parameter	500–650 °C	700–850 °C
Inlet fuel and air temperature (°C)	25	25
Fuel utilisation (%)	75	75
Air ratio	9	7
Steam to carbon ratio	2.5	2.5
Unit cells per plate	4	4
Cell dimensions (m × m)	0.1 × 0.1	0.1 × 0.1
Number of plates per stack	62	38
Operating point voltage (V)	ca. 0.7	ca. 0.7
Operating point current density (A m^{-2})	3000	5000
Desired rated power (kW)	ca. 5.3 kW	ca. 5.3 kW

Table 2
Rated power system performance factors (high and low temperature IT-SOFC)

Parameter	500–650 °C	700–850 °C
Net electrical DC power (W)	5006	5077
Air blower power (W)	380	300
Electrical DC efficiency (%)	48.7	48.1
Anode exhaust recycled (%)	65	64
Methane flow rate (g s^{-1})	0.21	0.21

Fuel cell voltage/current curves are normally inferred from single cell testing (or in this case modelling). However, the performance of such cells in a stack is different to single cells due to factors such as inhomogeneous temperature and fuel distribution. Therefore, the ability to predict the stack performance based on the data provided by such curves will largely depend on how close the operating conditions used for single cell testing match the average conditions experienced in the stack. This means that the pre-determined operating point current density value may not always return the initially required stack rated power. Voltage/current curves for each one of the IT-SOFC stacks studied here can be found in references [7,12], where the effect of temperature and fuel composition in single cell performance has been analysed. Table 1 reports the operating point initially chosen for each of the stacks and the calculated number of plates for a ca. 5.3 kWe rated stack power output (to allow for parasitic losses). Note that the aim of this study is not to compare the performance of the two IT-SOFC systems *per se* but rather to assess their feasibility as a potential fuel cell component for hybridisation with a battery for automotive applications; therefore the system results presented in Table 2 are not to be strictly compared.

3.2. Rated power performance for the high and low temperature IT-SOFC systems

Table 2 shows the performance factors at rated power for each of the IT-SOFC systems investigated and Table 3 for each of the stacks. It can be seen that since the higher temperature system allows internal reforming, the cooling effect of the endothermic reaction means that less air is necessary for cooling of the stack. This is reflected in the lower air blower power requirement.

Since the lower temperature IT-SOFC has a lower power density, a higher number of plates per stack are required to produce comparable power. However, it is important to recognise that reported cell thickness values are less for lower

Table 3
Rated power stack performance factors (high and low temperature IT-SOFC)

Parameter	500–650 °C	700–850 °C
Current (A)	120	200
Average current density (A m^{-2})	3000	5000
Stack voltage (V)	46.6	27.9
Average cell voltage (V)	0.75	0.73
Power output (W)	5586	5578
Electrical DC efficiency (%)	54.3	53.1

temperature metal-supported IT-SOFCs (around 200–300 μm) than for anode-supported higher temperature IT-SOFCs (typically 500–1000 μm), which means that the metal-supported stack could offer a higher volumetric power density, depending on the details of the stack design. Of course, the ultimate measure is that of *system* power density, including fuel storage, which requires further analysis. Table 4 shows the temperatures of the fuel, air and exhaust streams at different points around the fuel cell system for the high and low temperature IT-SOFC. The potential cost advantages of the lower temperature IT-SOFC system is highlighted here, where the lower temperatures observed around the system enables extensive use of lower cost stainless steel components.

3.3. Stack and system efficiency curves for the high and low temperature IT-SOFC

Fig. 2 presents the stack efficiency, the net system efficiency and the power required to run the air blower as a function of the net system power output for each of the systems. The net system efficiency is the net DC system efficiency (given that the battery requires only DC current from the fuel cell) and is defined as the ratio between the net (electrical) power produced by the system and the chemical energy in the inlet fuel feed. The net system power output is calculated as the total electrical power produced in the stack minus the electrical power necessary for the air blower and an additional constant value that accounts for the electrical parasitic losses in the remaining of the system

Table 4
System stream temperatures (high and low temperature IT-SOFC)

Stream	Temperature (°C)	
	500–650 °C	700–850 °C
Methane feed (1)	25	25
Fuel HEX inlet (2)	538	711
Fuel reformer inlet (3)	610	733
Fuel reformer outlet (4)	653	762
Fuel stack inlet (5)	583	740
Fuel stack outlet (6)	650	875
Air stack outlet (7)	647	862
Burner exhaust (8)	754	1002
Air HEX inlet (9)	651	962
Fuel recycle (10)	650	875
Air feed (11)	25	25
Air blower outlet (12)	38	38
Air stack inlet (13)	511	793
Exhaust gas (14)	205	267

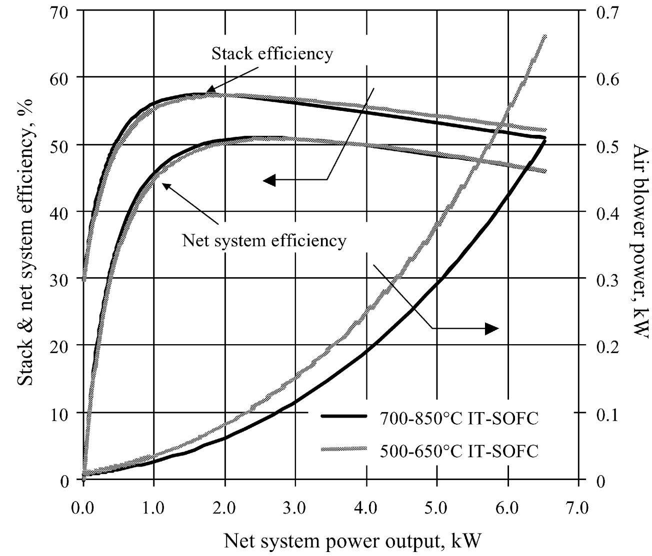

Fig. 2. Stack efficiency, net system efficiency and air blower power (high and low temperature IT-SOFC).

(see Section 2.5). The stack efficiency is assumed here to be the ratio between the total electrical stack power output and the chemical energy in the inlet fuel feed. The reported efficiency curves were obtained by varying the current drawn from the stack, while maintaining all the remaining inlet conditions fixed: inlet stream temperatures, system fuel utilisation, air ratio and steam-to-carbon ratio at the entrance of the pre-reformer (see Table 1).

As mentioned before, the calculation of the curves presented in Fig. 2 did not make use of any control procedure in the system, except for the fact that both the fuel utilisation and air ratio were kept constant at all times. This means that as the current density or system net power output decreases, the stack becomes more efficient, due to the decrease in voltage losses for lower current densities. A direct result of this is that less waste heat is produced and therefore the average temperature of the stack will decrease, as illustrated in Fig. 3. If temperature control were in place, the controller would decrease the amount of air flowing through the stack and restore the desired operating temperature.

It can be seen from Fig. 2 that, while in a typical single cell efficiency curve the efficiency increases continuously as the current density decreases, in this case there is a point after which the stack efficiency drops rapidly due to the steep drop in temperature observed in Fig. 3. As for the net system efficiency, the drop is even larger as the system parasitic losses start to become more pronounced in relation to the stack power. Note that, even though the net system efficiency reaches zero when there is no net power output, the same is not true for the stack efficiency, since the stack still needs to produce enough power to sustain the system parasitic losses.

The power required to run the air blower is shown in Fig. 2. This demonstrates how the parasitic loss associated with the blower increases with power output. However, note that an additional constant parasitic power loss is accounted for in the results presented in Fig. 2 and that it is mostly this parasitic loss that

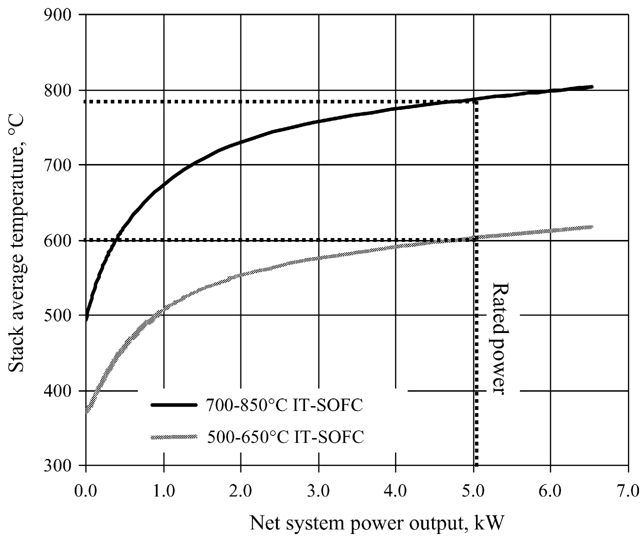

Fig. 3. Stack average temperature (high and low temperature IT-SOFC).

the system needs to sustain at low power outputs. As the aim of this work is to explore the requirements for operational modes other than the IT-SOFC being always-on and delivering constant power (i.e. stand-by mode, maximum power and the most efficient point of operation) the following section discusses the lower limit at which the system can still operate.

In terms of the performance of the two IT-SOFC systems, it can be seen that the net system efficiency of both systems is almost identical, each having a maximum net efficiency of ca. 51% at 2.5 kWe and of 48% at rated power. The electrical efficiencies of the modelled systems compare well with the targets set by Delphi of 41% system efficiency (5 kWe vehicle APU using partial oxidation reforming of gasoline).

3.4. Operating range and turn-down ratio

For the purpose of this work, it is important to be able to determine the turn-down ratio and lowest practical operating limit of the system in order to determine the efficiency and fuel consumption when the fuel cell is in stand-by mode. Stand-by mode is defined as the lowest power operation at which the fuel cell remains thermally self-sustaining and services the parasitic electrical requirement of the fuel cell system. The model shows the efficiency curves to be continuous down to zero efficiency (i.e. the fuel cell is purely servicing the parasitic load of the system with zero net power output). It is therefore implicit that the system is thermally self-sustaining down to this point. This is because, although only a small amount of electrical power is being generated by the fuel cell towards the lower limit of operation, the unconsumed fuel that is combusted in the afterburner provides enough heat to service the BoP thermal requirements.

However, practically, a lower limit on the power range needs to be set since lowering the power output results in a lowering of the temperature of the stack, as shown in Fig. 3. The definition of such a limit will depend largely on restrictions of the materials that compose the stack. If, for example, a turn-down ratio of 5:1 was needed for a given application, then a lower temperature limit of at least 505 and 675 °C for the lower and higher IT-SOFCs, respectively, would be necessary. This is within the general range of operation of the lower IT-SOFC but below the range for the higher IT-SOFC. However, the specifics of each technology would define the actual lower temperature of operation.

This point illustrates the advantage of extending the lower temperature limit of any SOFC technology, since this extends the turn-down ratio achievable. However, it should also be noted that other components in the BoP (e.g. heat exchangers) have their own turn-down limit dictated by factors such as temperature and stream flow rate which may dictate the lower operation power limit of the fuel cell system; this has not been considered in this analysis.

4. Discussion

4.1. Options for integration of fuel cell and battery

The electrical interconnection between the battery and fuel cell has been described previously [3,4]; in addition, several aspects of the stand-alone operation of both systems that warrant consideration for further integration have been highlighted. These include:

- Direct thermal integration between the battery and fuel cell.
- Using high-grade 'waste' heat from the fuel cell to heat the battery during start-up and to maintain its temperature during idle periods.
- Use of exhaust heat from the battery, when operational, to augment the pre-heating of air entering the stack.
- Using a single air blower to jointly cool the battery and supply air to the fuel cell.
- Control electronics integration.

The system model allows a closer inspection of the validity of thermal integration between the battery and fuel cell to be examined along with development of control options.

4.2. Thermal integration

The main drawback of using high temperature electrochemical power sources is that they need to be heated to the desired operating temperature and once there, maintained at that level. When not delivering power (during which time the battery requires cooling), ZEBRA batteries tend to lose heat at a rate of between 90 and 120 W (determined by the power required to be delivered to the embedded electrical heaters) through the thermal insulation and at the electrical connection points. The power to maintain the temperature of the battery would normally be provided by the battery itself or from a mains grid connection. For the ABSOLUTE hybrid, the IT-SOFC is intended to supply energy to the battery to maintain its temperature. This can be done electrically, using embedded electrical heaters within the battery or by using convective heating from the exhaust gas of the fuel cell.

Since the battery operates in the region of 270–350 °C, the heat from the IT-SOFC must be delivered at, or above, this temperature range in order to maintain the battery in a state of readiness. As can be seen from Table 4, the exhaust gas from the lower temperature IT-SOFC system is not of the requisite temperature, although the higher temperature IT-SOFC with an exhaust temperature of 267 °C is just high enough to keep the battery at a temperature from which battery operation could be realised within a short period of time.

The battery could potentially be positioned within the balance of plant (between the air pre-heater and stack for example) to harvest heat of the required temperature; however, an explicit knowledge of the thermal and mass flow characteristics of the battery would be required in order to achieve such a level of integration. Alternatively, the fuel cell could be run at a lower fuel utilisation, which would provide more fuel to the afterburner and allow the exhaust gas to increase in temperature. This, however, would be an uneconomical means of heating the battery since it is more efficient to consume the fuel electrochemically and heat the battery electrically. Therefore, heating of the battery via convective heating from exhaust gas from the fuel cell is not considered to be a promising option. However, there is scope for physical integration of the fuel cell and battery with the focus on packaging of each system into a space-saving 'single box' enclosure with low heat loss vacuum insulation technology.

The previous studies [3,4] showed that a vehicle requiring a 5 kWe fuel cell for charge neutrality over a 24 h period with 8 h of drive-time, would require a battery (or batteries) with a total energy capacity in the order of 80 kWh [3]. This battery requirement could be adequately serviced using three Z5 ZEBRA batteries [3,4]. Each battery loses up to 110 W of thermal heat when at temperature and not delivering power or being charged. Considering the electrical heating requirement for all three Z5 batteries and the associated control electronics (battery management interface, etc.), a load of ca. 400 W is estimated to be required to maintain the battery system at temperature. For the turn-down ratio value of 5:1 discussed in Section 3.4, this would mean that an IT-SOFC would have to consume fuel in excess of that required to maintain the temperature of the fuel cell and battery when operating in stand-by mode. As stated previously, a lower temperature limit of operation could allow for a higher turn-down ratio and therefore less fuel consumption in stand-by mode.

4.3. Single blower concept

The blower that supplies air to the stack and the blower that cools the battery when it is delivering power are both significant sources of parasitic loss and capital expense to both fuel cell and battery systems. If a single blower can be used to service all of the hybrid system's needs, a marked improvement in efficiency and reduction in installed cost could be achieved. If the system under consideration has three Z5 batteries, with each blower rated at 50 W, then a 150 W reduction in the parasitic losses of the battery can be realised. This assumes that the extra backpressure required to drive cooling air through the batteries does not derate the air blower.

4.4. Control electronics integration

Integration of control electronics is an obvious step to maximise efficiency. Various pieces of control electronics are necessary to operate the system including a battery management interface, a fuel cell management interface and a vehicle management unit. Power consumption and cost would be minimised if board level integration was implemented as well as improving reliability.

4.5. Modes of operation

The previous published analysis considered the fuel cell to be nominally 'always-on' and to operate at a constant load in order for the hybrid system to be charge neutral over a 24 h period [3]. This approach avoids the problems of repeated stop/start procedures and load transients; neither of which is conducive to SOFC operation using steam reforming.

For a vehicle that operates on a well-defined drive cycle from day to day (a bus or delivery vehicle for example), the size of the battery and fuel cell can be optimised for the application; in which case, the strategy of having the fuel cell 'always-on' and operating at its rated power results in efficient operation. However, if the drive cycle varies from day to day and the vehicle is to lie dormant without driving for extended periods of time, then it may be necessary to operate at partial load (to be charge neutral over the extended recharging period), enter a stand-by mode or to turn the fuel cell off altogether.

The decision as to when to turn-off the fuel cell or battery will depend on a number of factors including: length of non-drive time, notification period before vehicle is required to operate, access to mains recharge, fuel storage capacity, start-up time of battery and fuel cell, and the energy required to reheat the battery and fuel cell.

In order to fully assess the implication of the extended set of operation conditions, the system model will be coupled with a ZEBRA battery model to test the integration of these two systems and explore control strategies.

5. Conclusion

A system model for a 5 kWe IT-SOFC operating on methane is presented. Two temperature regimes of operation of the stack are considered, 500–650 °C using external reforming and 700–850 °C using partial internal reforming. The net system efficiency for each IT-SOFC type was found to be very similar. To suit the vehicular application of the system and avoid large amounts of water for reforming and water-cooling for condensation of water from exhaust gas, a partial anode off-gas recycle is considered in the model.

In terms of the battery/fuel cell system integration it was found that: direct thermal integration, involving the use of the hot exhaust gas from the fuel cell to maintain the heat of the battery, is not suitable for the lower temperature IT-SOFC (without wasting excess fuel or using a lower fuel utilisation), but potentially viable for the higher temperature IT-SOFC system. However, electrical heating of the battery via the fuel cell is thought to be the most practical solution.

This analysis suggests that an "always-on" IT-SOFC combined with a ZEBRA battery could make an effective power source for use in a vehicle. Based on the promising results from this analysis, a 'bench-top' demonstration system of a combined IT-SOFC and ZEBRA battery is currently being commissioned to test the integration of these two power sources and to explore control strategies.

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