SOFC Auxiliary Power Units (APUs) for Vehicles

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ABSTRACT
In this project the solid oxide fuel cell SOFC anode support was used as auxiliary power units APU on-board both luxury passenger car and line-haul heavy duty trucks, the total powers demand on-board both application were 7KW and 3KW for luxury passenger car and line-haul heavy duty trucks respectively. The calculations perform for two DC voltage systems 12/14 VDC and 36/42 VDC, the others parameters such as mass flow rate of air, gases, water production and heat production were calculated for two applications and two DC voltage systems, the efficiency of the fuel cell was 61% relative to the LHV of hydrogen.

INTRODUCTION
Fuel cells are increasingly touted as the dominant automotive propulsion technology of the future. Almost every international automotive company has launched major fuel cell vehicle development programs. However, it is becoming apparent that the high initial costs of fuel cells preclude their introduction to the mass market for some time. A new approach is needed that focuses on niche markets. One such market is auxiliary power units (APUs). Fuel cells as APUs offer potential advantages in overall energy efficiency, emissions, and costs. For each particular APU application, fuel cells have a unique set of requirements and characteristics.

The list of APU research and development initiatives and demonstrations in Table 1 is suggestive of the broad range of APU applications. Markets for automotive APUs are likely to include applications where the vehicle engine is currently operated inefficiently in order to provide accessory power (e.g. heavy-duty truck idling) or where non-propulsion diesel engines are currently run to supply power (e.g. refrigeration units). Many heavy-duty vehicles idle regularly to power the cabin’s climate control and electric accessories, and some passenger vehicles, such as law enforcement vehicles, also idle for long durations to power lights and communications systems. Other vehicles that operate tools and machinery may idle their engines for extended.

There are parameters in determining where and how fuel cell APUs might be attractive include operational characteristics of the auxiliary power (total power requirement, time of use, etc.) and market variables (total vehicle cost, sales, and trends).

Table 1 Major Fuel Cell Research & Development Initiatives

<table>
<thead>
<tr>
<th>Participants</th>
<th>Application</th>
<th>Size</th>
<th>Fuel cell system</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW, International Fuel Cells</td>
<td>Passenger car, BMW 7-series</td>
<td>5 kW</td>
<td>Hydrogen, PEM</td>
</tr>
<tr>
<td>Ballard, Daimler-Chrysler</td>
<td>Class 8 Freightliner S/T</td>
<td>1.4 kW</td>
<td>Hydrogen, PEM</td>
</tr>
<tr>
<td>BMW, Delphi, Global Thermolectric</td>
<td>Passenger car</td>
<td>1-5 kW</td>
<td>Gasoline, SOFC</td>
</tr>
<tr>
<td>Delphi, CALSTART, Aerovironment</td>
<td>Class 8 truck</td>
<td>5 kW</td>
<td>Diesel, SOFC</td>
</tr>
<tr>
<td>SunLine Transit, Southwest Research Institute</td>
<td>Class 8 International Truck</td>
<td>5 kW</td>
<td></td>
</tr>
<tr>
<td>EXCELLSiS,</td>
<td>Military Class 8 vehicle</td>
<td></td>
<td>Diesel, PEM</td>
</tr>
<tr>
<td>DaimlerChrysler, EXCELLSiS</td>
<td>Passenger car, Mercedes S-Class</td>
<td>3 kW</td>
<td>Hydrogen, PEM</td>
</tr>
<tr>
<td>Virginia Tech Univ., Energy Partners</td>
<td>Hybrid-electric passenger car</td>
<td>20 kW</td>
<td>Hydrogen, PEM</td>
</tr>
<tr>
<td>Department of Defense, U.S. Army</td>
<td>Portable “soldier power”</td>
<td>5-500 W</td>
<td>PEM</td>
</tr>
</tbody>
</table>

PROBLEM STATEMENT
A fuel cell-based APU becomes a promising alternative to conventional power generation (electrical energy produced via ICE and an alternator in combination with battery storage), because of the increased demand for electrical power in passenger vehicles, stringent fuel consumption requirements and environmental sustainability. It becomes obvious that the
on board storage of fuel has to be used for the fuel cell system and has to be reformed on board. On board reforming makes the APU a complex integrated system consisting of a stack, air supply, fuel processor, electrics as well as heat and water management.

A fuel cell-based APU that supplies energy to a vehicle’s electrical system can be developed using either a Proton Exchange Membrane Fuel Cells (PEMFCs) or a Solid Oxide Fuel Cell (SOFC). Fuel sources for the APU can vary from gasoline, diesel, methanol, ethanol, natural gas, liquid petroleum gas to hydrogen. Direct hydrogen is utilized in several PEFC systems. Use of a direct hydrogen process is suitable for applications in hydrogen fueled engines or in trucks, where a more complicated refueling process is viable. APU applications in passenger vehicles should use the same fuel for the APU as for the propulsion system. Customers should not be expected to refill the vehicle with a two separate fuels. One of the most advanced gasoline fueled systems is based on a SOFC. However, faster start-ups and a better thermo cycle provide some compelling advantages for PEMFC based APUs in mobile applications.

Figure 1 shows a schematic diagrams for used APUs based on SOFC.

LITERATURE SURVEY
Nicholas et al [1] explore the potential use of fuel cells in auxiliary power units (APUs) on-board various types of cars and trucks – in luxury passenger vehicles, law enforcement vehicles, contractor trucks, specialized utility trucks, recreational vehicles, refrigerated trucks, and line-haul heavy duty trucks. They analyze power requirements, volume and weight targets, costs, market sizes, and potential benefits for several fuel cell technologies and fuels. The attributes of market applications are matched with fuel cell attributes to assess the market potential of fuel cell APUs. Although data are insufficient and more analysis is needed, they find that several market applications could play key roles in introducing fuel cell technologies to the transportation sector.

Michele Bagnoli et al [2] presents a methodology for a preliminary investigation on either sizing and operating management of the main components of an on-board power system composed by: (i) PEM fuel cell, (ii) hydrogen storage subsystem, (iii) battery, (iv) grid interface for the connection to an external electrical power source when available, and (v) electrical appliances and auxiliaries installed on the vehicle. A model able to reproduce the typical profiles of electric power requests of on-board appliances and auxiliaries has been implemented in a computer program. The proposed methodology helps also to define the sizing of the various system components and to identify the fuel cell operating sequence, on the basis of the above mentioned load profiles.

Grube et al [3] compare the present status of on-board electricity supply in conventional passenger cars with variants, based on the starter-generator and the auxiliary power unit (APU). The results of a process engineering analysis define the potential efficiency of electricity generation with solid oxide fuel cell (SOFC) based systems. In addition to the load profiles of the auxiliaries, the driving cycle must be defined within the framework of a model-based dynamic drive train simulation, in order to finally determine the fuel consumption per kilometre in dynamic operation. As a result, the fuel consumption of the variants investigated is presented and the possibilities for applying fuel cell APUs and starter-generators assessed.

David et al [4] reviews some of the recent work related to fuel cell APUs for large trucks. The paper also examines what characteristics are important to consider in the design and integration of a fuel cell APU and outlines the strategy and methodology taken by the University Of California Institute Of Transportation Studies in designing and building a viable demonstration fuel cell APU.

PROJECT DESCRIPTION
This project describe the use of solid oxide fuel cell (SOFC) as auxiliary power units (APUs) in transportation section, the SOFC will be used in luxury passenger vehicle and line-haul heavy-duty trucks as electrical power supply instead of conventional alternator used in internal combustion engine (ICE). The electrical load on-board luxury passenger vehicle is varying between 5 KW -7KW according to session’s winter or summer, the design of fuel cell will be based on the maximum electrical load (7KW), and 3 KW is adequate to supply the maximum same-time peak power for in-cabin accessory demand on-board line-haul heavy-duty trucks.

Fuel cell specifications
From the characteristic curve of cell voltage and current density for SOFC, at 0.8 V the current density will be 0.7 Acm⁻². The specification of SOFC such as material, thickness and mass for each component inside the stack can be shown in table 2.

The area of a fuel cell assumes to be 80 cm², and then the current will be the product of current density and area.

\[ I = 0.7 \text{ A cm}^{-2} \times 80 \text{cm}^2 = 56 \text{A} \]
The electrical power extract from each cell is equal to the voltage of cell multiplies the current of cell as shown below:

\[ P_e = V_c \times I_c = 0.8(V) \times 56(A) = 44.8W \]

Table 2 SOFC components

<table>
<thead>
<tr>
<th>SOFC component</th>
<th>Material</th>
<th>Thickness (cm)</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>Ni_{0.35}(ZrO_2)_{0.65}</td>
<td>0.1</td>
<td>40.8</td>
</tr>
<tr>
<td>Cathode</td>
<td>La_{0.84}Sr_{0.16}MnO_3</td>
<td>0.01</td>
<td>3.22</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>(ZrO_2)<em>{0.90} (Y_2O_3)</em>{0.10}</td>
<td>0.002</td>
<td>1.11</td>
</tr>
<tr>
<td>Interconnect</td>
<td>Ferritic steel(Fe+Cr+Ni)</td>
<td>0.2</td>
<td>88.5</td>
</tr>
<tr>
<td>End plate</td>
<td>Ferritic steel(Fe+Cr+Ni)</td>
<td>1</td>
<td>790</td>
</tr>
</tbody>
</table>

1. Luxury Passenger Vehicles

The electrical load on modern cars continues to increase. New accessories and power demands include on-board communication systems (e.g., navigation information, internet connections), heated seats, and additional entertainment devices (DVD, television). Increasing at about 6% per year, the on-board electric power demand for light duty vehicles is approximately 2 kW. These increasing electric power demands have prompted the auto industry to explore a transition from 12/14-V systems to 36/42-V systems. In determining the most appropriate APU size for near-term electrification of passenger cars, table 3 show that the power demands for all accessories and amenities that might be required while the vehicle is at rest and lists the maximum total power requirement for an APU in a luxury passenger car in winter and summer conditions. As indicated, the total maximum APU power could be as high as 5-7 kW. Further electrification of vehicles and the introduction of more amenities such as on-board refrigeration and multimedia capabilities (DVD, television, Internet) would require even more power.

The number of cells equal to the maximum electrical load divided by electrical power extract from each cell as indicated in the formula below

\[ No of cell = \frac{7000(W)}{44.8(W)} = 156.25 \times 157 \]

There for, the total electrical power and voltage extract from fuel cells is equal to the number of cells multiply by the power and voltage extracted from each cell respectively.

\[ P_{total} = 157 \times 44.8 = 7033.6(W) \]

\[ V_{total} = 157 \times 0.8 = 125.6(V) \]

Table 3 Accessory Power Requirements for APUs of Luxury Passenger Vehicle

<table>
<thead>
<tr>
<th>Accessory</th>
<th>Power (W)</th>
<th>Power required for APU in summer (W)</th>
<th>Power required for APU in winter (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear wiper</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Infoelectronics</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Windshield pump</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Heated steering wheel</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power sunroof</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck closer</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windshield wipers</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Air pump</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power door locks</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine coolant pump</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS pump</td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lights</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Power windows</td>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric fan</td>
<td>800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rear defrost</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Power seats</td>
<td>1,600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steer by wire</td>
<td>1,800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brake by wire</td>
<td>2,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heated front seats</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Heated windshield</td>
<td>2,500</td>
<td>2,500</td>
<td>2,500</td>
</tr>
<tr>
<td>Catalyst heating</td>
<td>3,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electro-mechanical valve control</td>
<td>3,200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air conditioning</td>
<td>4,000</td>
<td>4,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Active suspension</td>
<td>12,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>38,210</td>
<td>5,190</td>
<td>6,690</td>
</tr>
</tbody>
</table>

The analysis will consider the accessories are operating at two DC systems 12/14 VDC or 36/42 VDC.

The total current consumed by the application is equal to the total electrical power extracted from fuel cells divided by the operating voltage of the application.
For 12/14 VDC
\[ I = \frac{7033.6(W)}{12(V)} = 586.13(A) \]

For 36/42 VDC
\[ I = \frac{7033.6(W)}{36(V)} = 195.38(A) \]

To determine the number of cells in each stack divide the operating voltage by the cell voltage as in the next formula:

For 12/14 VDC
\[ n = \frac{12(V)}{0.8(V)} = 15 \]

For 36/42 VDC
\[ n = \frac{36(V)}{0.9(V)} = 45 \]

\( n \) : number of cell in stack

The number of stacks needed is equal to the total voltage extracted from fuel cells divided by the operating voltage.

For 12/14 VDC
\[ N = \frac{125.6(V)}{12(V)} = 10.47 \]

For 36/42 VDC
\[ N = \frac{125.6(V)}{36(V)} = 3.49 \]

\( N \) : number of stack

For 12/14 VDC the number of stacks is equal to 11 and the number of cells in each stack is equal to 15, and for 36/42 VDC the number of stacks is equal to 4 and the number of cells in each stack is equal to 45, thereby the total number of cells are 165 and 180 for 12VDC and 36VDC respectively and the total power 7392W and 8064W for 12VDC and 36VDC respectively.

For both systems, the cells will be connect in series inside the stack and the stacks will be connect in parallel, so that the product of stacks and the current from each cell must equal the total current consumed by the application.

The volume of the stack is equal to the product of the area of the cell and the height of the stack which can be calculated during the next formula:

\[ h_{stack} = (h_{interconnect} + h_{anode} + h_{electrolyte} + h_{cathode}) \times n_{cell} + 2 \times h_{endplate} \]

Used the data in table 2 and Substitute \( n_{cell} \) 15 and 45 for 12/14 VDC and 36/42 VDC respectively then.

\[ h_{stack} = 6.68cm, 16.04cm \] for 12 and 36 VDC respectively

\[ V_{stack} = 534.4cm^3, 1283.2cm^3 \] for 12 and 36 VDC respectively

\[ V_{total} = 5878.4cm^3, 5132.8cm^3 \] for 12 and 36 VDC respectively

The mass of the stack can be calculated by using the same formula for the height of the stack.

\[ M_{stack} = (M_{interconnect} + M_{anode} + M_{electrolyte} + M_{cathode}) \times n_{cell} + 2 \times M_{endplate} \]

\[ M_{cell} = 3.58Kg, 7.59Kg \] for 12 and 36 VDC respectively

\[ M_{total} = 39.38Kg, 30.36Kg \] for 12 and 36 VDC respectively

The power to volume ratio and the power to weight volume for each system can be represented as follow:

\[ \frac{power}{volume} = 1196.5 \frac{(W)}{(L)} \] for 12 and 36 VDC respectively

\[ \frac{power}{weight} = 178.6 \frac{(W)}{(Kg)} \] for 12 and 36 VDC respectively

**Oxygen and Air Usage**

The amount of oxygen and air are determined in term of total electrical power of cells, voltage of each cell and stoichiometry by using the following relations

\[ O_2 usage = 8.29 \times 10^{-8} \times \frac{7392(W)}{0.8(V)} = 7.66 \times 10^{-4} Kgs^{-1} \]

\[ Air usage = 3.57 \times 10^{-7} \times \frac{7392(W)}{0.8(V)} = 3.3 \times 10^{-3} Kgs^{-1} \]

\[ O_2 usage = 8.29 \times 10^{-8} \times \frac{8064(W)}{0.8(V)} = 8.36 \times 10^{-4} Kgs^{-1} \]

\[ Air usage = 3.57 \times 10^{-7} \times \frac{8064(W)}{0.8(V)} = 3.6 \times 10^{-3} Kgs^{-1} \]

**Air Exit Flow Rate**

The exit air flow rate equal the difference between the air inlet flow rate and oxygen usage.

\[ Exit air flow rate = 3.3 \times 10^3 - 7.66 \times 10^4 = 2.53 \times 10^3 Kgs^{-1} \] for 12 VDC

\[ Exit air flow rate = 3.6 \times 10^3 - 8.36 \times 10^4 = 2.76 \times 10^3 Kgs^{-1} \] for 36 VDC

**Hydrogen Usage**

The amount of hydrogen usage in term of total electrical power of cells, voltage of each cell and stoichiometry by using the following relations

\[ H_2 usage = 1.05 \times 10^{-8} \times \frac{7392(W)}{0.8(V)} = 9.702 \times 10^{-5} Kgs^{-1} \]
for 36VDC  

\[ H_2 \text{ usage} = 1.05 \times 10^{-8} \times \left( \frac{8064(W)}{0.8(V)} \right) = 1.058 \times 10^{-4} \text{Kgs}^{-1} \]

Water Production  
The amount of water production in terms of total electrical power of cells and voltage of each cell

for 12VDC  

\[ \text{Water production} = 9.34 \times 10^{-8} \times \left( \frac{7392(W)}{0.8(V)} \right) = 8.63 \times 10^{-4} \text{Kgs}^{-1} \]

That means the amount of water produced for one hour is  
\[ = 8.36 \times 10^{-4} \times 60 \times 60 = 3 \text{Kg} \]

for 36VDC  

\[ \text{Water production} = 9.34 \times 10^{-8} \times \left( \frac{8064(W)}{0.8(V)} \right) = 9.41 \times 10^{-4} \text{Kgs}^{-1} \]

That means the amount of water produced for one hour is  
\[ = 9.41 \times 10^{-4} \times 60 \times 60 = 3.39 \text{Kg} \]

Heat Produce  
The amount of heat produced in terms of total electrical power of cells and voltage of each cell

for 12VDC  

\[ \text{Heat rate} = 7392 \times \left( \frac{1.25(V)}{0.8(V)} - 1 \right) = 4158W \]

for 36VDC  

\[ \text{Heat rate} = 8064 \times \left( \frac{1.25(V)}{0.8(V)} - 1 \right) = 4536W \]

Efficiency  
The efficiency can be calculated according to the following relationship

\[ \text{efficiency} = \mu_f \times \frac{V_c(V)}{1.25(V)} = 61\% \]

Where \( \mu_f \) is the fuel utilisation (typically about 0.95) and \( V_c \) is the voltage of a single cell within the fuel cell stack. This gives the efficiency relative to the LHV of hydrogen.

2. Line-haul heavy-duty trucks  
The heavy-duty truck idling case is the best understood of the APU applications. The potential benefits of APUs in military, line-haul commercial, and intermodal trucks include increased fuel efficiency, and reduced maintenance, emissions, and noise.

Drivers of heavy duty trucks idle their main engines primarily to power climate control systems (heating and cooling in cabin) and electric accessories (televisions, lights, computers, etc.). Some alternatives, including small heating and air conditioning units and diesel-powered electricity generators, have been purchased for up to 5% of these trucks. The lack of widespread adoption of these alternatives is poorly understood but has been anecdotally attributed to high initial cost, loss of payload for trucks due to APU weight, system durability, and lack of awareness of the extent of idling repercussions.

A recent survey of truck drivers revealed that likely in-cabin peak power demands for these trucks could total 4-6 kW. As indicated in Table 4, the 3 kW power may be adequate to supply the maximum same-time peak power for in-cabin accessory demand.

Repeated same calculation using the application load 3KW  
The number of cells equal to the maximum electrical load divided by electrical power extract from each cell as indicated in the formula below

\[ \text{No of cells} = \frac{3000(W)}{44.8(W)} = 66.96 = 67 \]

Therefor, the total electrical power and voltage extract from fuel cells is equal to the number of cells multiply by the power and voltage extracted from each cell respectively.

\[ P_{\text{total}} = 67 \times 44.8 = 3001.6(W) \]

\[ V_{\text{total}} = 67 \times 0.8 = 53.6(V) \]

The analysis will consider the accessories are operating at two DC systems 12/14 VDC or 36/42 VDC.

The total current consumed by the application is equal to the total electrical power extracted from fuel cells divided by the operating voltage of the application.

For 12/14 VDC  

\[ I = \frac{3001.6(W)}{12(V)} = 250.13(A) \]

For 36/42 VDC  

\[ I = \frac{3001.6(W)}{36(V)} = 83.38(A) \]
To determine the number of cells in each stack divide the operating voltage by the cell voltage as in the next formula.

\[
\text{For } 12/14VDC \quad n = \frac{12(V)}{0.8(V)} = 15
\]

\[
\text{For } 36/42VDC \quad n = \frac{36(V)}{0.9(V)} = 45
\]

\(n: \text{number of cell in stack}\)

The number of stacks needed is equal to the total voltage extracted from fuel cells divided by the operating voltage.

\[
\text{For } 12/14VDC \quad N = \frac{53.6(V)}{12(V)} = 4.47
\]

\[
\text{For } 36/42VDC \quad N = \frac{53.6(V)}{36(V)} = 1.49
\]

\(N: \text{number of stack}\)

For 12/14VDC system, the number of stacks is equal to 5 and the number of cells in each stack is equal to 15, and for 36/42 VDC system the number of stacks is equal to 2 and the number of cells in each stack is equal to 45, thereby the total number of cells are 75 and 90 for 12VDC and 36VDC respectively and the total power 3360W and 4032W for 12VDC and 36VDC respectively.

For both systems, the cells will be connect in series inside the stack and the stacks will be connect in parallel, so that the product of stacks and the current from each cell must equal the total current consumed by the application.

The volume of the stack is equal to the result of the product of the area of the cell and the height of the stack, which can be calculated during the next formula.

\[
h_{\text{stack}} = (h_{\text{interconnect}} + h_{\text{anode}} + h_{\text{electrolyte}} + h_{\text{cathode}}) \times n_{\text{cell}} + 2 \times h_{\text{endplate}}
\]

Used the data in table 2 and Substitute \(n_{\text{cell}}\) 15 and 45 for 12/14 VDC and 36/42 VDC respectively then.

\[
h_{\text{stack}} = 6.68cm, 16.04cm \quad \text{for } 12 \text{ and } 36 \text{VDC respectively}
\]

\[
V_{\text{stack}} = 534.4cm^3, 1283.2cm^3 \quad \text{for } 12 \text{ and } 36 \text{VDC respectively}
\]

\[
V_{\text{total}} = 2672cm^3, 2566.4cm^3 \quad \text{for } 12 \text{ and } 36 \text{VDC respectively}
\]

The mass of the stack can be calculated by using the same formula for the height of the stack.

\[
M_{\text{stack}} = M_{\text{interconnect}} + M_{\text{anode}} + M_{\text{electrolyte}} + M_{\text{cathode}} \times n_{\text{cell}} + 2 \times M_{\text{endplate}}
\]

\[
M_{\text{stack}} = 3.58Kg, 7.59Kg \quad \text{for } 12 \text{ and } 36 \text{VDC respectively}
\]

\(M_{\text{total}} = 17.9Kg, 15.18Kg \quad \text{for } 12 \text{ and } 36 \text{VDC respectively}\)

The power to volume ratio and the power to weight volume for each system can be represented as follow

\[
\text{power / volume} = \frac{1123.35(W)}{(L)} \quad \text{for } 12 \text{ and } 36 \text{VDC respectively}
\]

\[
\text{power / weight} = \frac{167.69(W)}{(Kg)} \quad \text{for } 12 \text{ and } 36 \text{VDC respectively}
\]

### Table 4 Line-haul Sleeper Truck Power Requirements

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Average appliance power (W)</th>
<th>Estimated maximum same-time power requirement (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air conditioner</td>
<td>2,200</td>
<td>2,200</td>
</tr>
<tr>
<td>Battery charger</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Coffee pot</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>CD player and speaker</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Computer</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Converter</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Drill</td>
<td>750</td>
<td></td>
</tr>
<tr>
<td>Fan</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Frying pan</td>
<td>1,350</td>
<td></td>
</tr>
<tr>
<td>Stove</td>
<td>1,000</td>
<td></td>
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<tr>
<td>Water pump</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Hair dryer</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>Light bulb</td>
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<td>100</td>
</tr>
<tr>
<td>Microwave</td>
<td>1,500</td>
<td></td>
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<tr>
<td>Radio</td>
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<td>200</td>
</tr>
<tr>
<td>Refrigerator</td>
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<td>350</td>
</tr>
<tr>
<td>Television</td>
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<td>100</td>
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<tr>
<td>Toaster</td>
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<td></td>
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<tr>
<td>VCR</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>12,600</td>
<td>2,950</td>
</tr>
</tbody>
</table>

### Oxygen and Air Usage
The amount of oxygen and air are determined in term of total electrical power of cells, voltage of each cell and stoichiometry by using the following relation

\(O_2 \text{ usage} = 8.29 \times 10^{-6} \times \left( \frac{3360(W)}{0.8(V)} \right) = 3.48 \times 10^{-4} \text{Kgs}^{-1}\)

\(Air \text{ usage} = 3.57 \times 10^{-7} \times \left( \frac{3360(W)}{0.8(V)} \right) = 1.5 \times 10^{-3} \text{Kgs}^{-1}\)
for 36VDC

\[ O_2 \text{ usage} = 8.29 \times 10^{-8} \times \left( \frac{4032 \ (W)}{0.8 \ (V)} \right) = 4.18 \times 10^{-4} \ \text{Kgs}^{-1} \]

\[ Air \ usage = 3.57 \times 10^{-7} \times \left( \frac{4032 \ (W)}{0.8 \ (V)} \right) = 1.8 \times 10^{-5} \ \text{Kgs}^{-1} \]

**Air Exit Flow Rate**

The exit air flow rate equal the difference between the air inlet flow rate and oxygen usage

\[ Exit \ air \ flow \ rate = 1.5 \times 10^{-3} - 3.48 \times 10^{-4} = 1.12 \times 10^{-3} \ \text{Kgs}^{-1} \] for 12VDC

\[ Exit \ air \ flow \ rate = 1.8 \times 10^{-3} - 4.18 \times 10^{-4} = 1.38 \times 10^{-3} \ \text{Kgs}^{-1} \] for 36VDC

**Hydrogen Usage**

The amount of hydrogen usage in term of total electrical power of cells and voltage of each cell

for 12VDC

\[ H_2 \ usage = 1.05 \times 10^{-8} \times \left( \frac{3360 \ (W)}{0.8 \ (V)} \right) = 4.41 \times 10^{-5} \ \text{Kgs}^{-1} \]

for 36VDC

\[ H_2 \ usage = 1.05 \times 10^{-8} \times \left( \frac{4032 \ (W)}{0.8 \ (V)} \right) = 5.292 \times 10^{-5} \ \text{Kgs}^{-1} \]

**Water Production**

The amount of water production in term of total electrical power of cells and voltage of each cell

for 12VDC

\[ \text{Water production} = 9.34 \times 10^{-8} \times \left( \frac{3360 \ (W)}{0.8 \ (V)} \right) = 3.92 \times 10^{-4} \ \text{Kgs}^{-1} \]

That meaning the amount of water produced for one hour is

\[ = 3.92 \times 10^{-4} \times 60 \times 60 = 1.4 \text{Kg} \]

for 36VDC

\[ \text{Water production} = 9.34 \times 10^{-8} \times \left( \frac{4032 \ (W)}{0.8 \ (V)} \right) = 4.71 \times 10^{-4} \ \text{Kgs}^{-1} \]

That meaning the amount of water produced for one hour is

\[ = 4.71 \times 10^{-4} \times 60 \times 60 = 1.7 \text{Kg} \]

**Heat Produce**

The amount of heat produces in term of total electrical power of cells and voltage of each cell

for 12VDC

\[ \text{Heat rate} = 3360 \times \left( \frac{1.25 \ (V)}{0.8 \ (V)} \right) - 1 = 1890 \text{W} \]

for 36VDC

\[ \text{Heat rate} = 4032 \times \left( \frac{1.25 \ (V)}{0.8 \ (V)} \right) - 1 = 2268 \text{W} \]

**Efficiency**

The efficiency can be calculated according to the following relationship

\[ \text{efficiency} = \mu_x \times \frac{V_c (V)}{1.25(V)} = 61\% \]

Where \( \mu_x \) is the fuel utilisation (typically about 0.95) and \( V_c \) is the voltage of a single cell within the fuel cell stack. This gives the efficiency relative to the LHV of hydrogen.

Most of electrical accessories in luxury vehicle and line-haul heavy-duty trucks are operating at direct current (DC) 12/14 VDC or 36/42 VDC; the others are operating at alternating current (AC), so sometimes need to inverter to convert from DC to AC or DC to DC converter beside to these components it necessary to have power controller and battery to storage electricity as shown in figure 2. The SOFC not able to provide rapid increase in the output to support load pick up, so the recharge batteries used to support transient and peak load, taking in our consideration the peak loads are short duration.

Fig. 2 schematic diagram for electrical components

SOFC is integrated to another systems for supply the requirements load, these system are fuel and fuel processing, air and gases system.

The main function of fuel and fuel processing system is to reforming the fuel before enter to the fuel cell, most of ICE working either gasoline or diesel, so the reforming device must added to reform the fuel and delivered to the cell, and may be in some fuel cells needed to extra processing to treating the fuel before enter to the cell such as water gas shift and preferential oxidation.
The main function of air and gas system is to supply the SOFC by the necessary flow rate of air and gas using suitable pumps, fan, compressor and blower. In addition, the energy of exhaust gases from a fuel cell can sometimes be harnessed using a turbine, making use of what would otherwise go to waste.

The two management issue must take in our consideration when applied SOFC in transportation section, these are water and thermal management, the water production and thermal energy from the anode side can be used in reforming process or in some application on-board vehicle required heat as shown in figure 4.

CONCLUSIONS

SOFC as APUs on-board luxury passenger vehicle and line-haul heavy-duty trucks reduce emission, fuel consumption, noise and extended main vehicle engine life. The SOFC is more efficient than the engines in ICE. both the power to volume and power to weight ratio grater than the value in the literature (50-100 W/L and W/Kg) because both volume and mass were for fuel cells only, without considering the weight and volume for others component such as reforming component and electricity devices which will decrease these two ratio. When compared the total volume and mass for same application and different VDC the 36/42 was better, there for it more useful to expand the system from 12/14 VDC to 36/42 VDC also when compared the number of stacks for the two applications the 12/14 VDC was double the 36/14 VDC. Eventually the SOFC will become a viable candidate for providing electrical power for over the road, eliminating the need for the current inefficient engine driven alternators by improving fuel consumption and reduce emissions.

REFERENCES


