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Fuel cell power source for a cold region

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Abstract

Electric power generation at Maitri—the Indian Antarctic station is based on a conventional diesel generator. In spite of the high reliability and simplicity of operation, the main disadvantages of this kind of power source are its pollution potential and fuel transportation costs. In a place like Antarctica environmental protection requirements are of prime importance. Apart from gas pollution, they also suffer from various other problems such as degradation of performance due to sub-zero temperature of operation, noise pollution, solidification of lubricants and mechanical wear and tear. Fuel cells find an ideal application for alternate energy solution, and can maintain the pristine nature of Antarctica. With this objective in mind, Research & Development Establishment (Engineers), Pune, Defence Research & Development Organisation, Ministry of Defence, Government of India joined hands with Centre for Electro-Chemical & Energy Research, SPIC Science Foundation, Chennai and developed three prototype 500 W, 12 V, PEMFC fuel cell power sources for this application. PEMFC has been chosen for study and experimentation at Antarctica because the solid electrolyte Nafion-117 is used in this cell and the electro-chemical reaction is exothermic so that the fuel cell can be activated at low temperature.

PEMFC was first installed and successfully demonstrated during the XVII Indian Antarctic Expedition. Further studies continued during the XVIII Indian Antarctic Expedition and a series of scientific experiments were conducted in the areas of optimisation of humidification, temperature for reactants (hydrogen and oxygen), elimination of existing humidification system, feasibility of provision of air-cooling system in lieu of water cooling system, humidifcation of gases using membrane as a medium, charging/discharging characteristics of a metal hydride container for hydrogen storage, and performance of a dc–dc converter and static inverter under sub-zero temperature of operation. Based on the results of these experiments, the design of the fuel cell power source for cold region application has been finalised.

The paper deals with the design criteria and design factors to be considered for the fuel cell power source for cold region application and details of tests and test results that led to the final design concept for such an application. The paper also deals with a proposed hybrid power plant taking into account the exploitation of wind energy with a fuel cell and generation of hydrogen by an electrolyser and provision of hydrogen storage. © 2002 Published by Elsevier Science B.V.

Keywords: Low temperature applications; Hydrogen storage; System design

1. Introduction

The last two decades of the 20th century can be considered as a transition time for new methods of energy production. Energy, produced from fossil fuel (coal, oil and natural gas) is not environmentally friendly. Apart from this, the availability of fossil fuels becomes a limiting factor when population increases/and the demand for alternative energy sources like solar, nuclear power, wind energy and hydrogen and oxygen fuel cell is inevitable. The amount of energy produced from solar is limited. The energy efficiency is low. In the case of nuclear power, the waste generation is very dangerous to mankind. For safe and clean energy, fuel cell and wind energy are preferred.

The annual liquid fuel consumption of Maitri, the Indian Scientific Research Station in Antarctica is 360 kl (thousands of litres) out of which 240 kl is being used for power generation and remaining for central heating and for vehicle movement. It is evident from Fig. 1 that, the air pollution and noise pollution are greater due to power generation. This will affect the life of flora, fauna and the vital activity of mankind too. Fuel cell technology has been chosen as an alternate power source in the present study.

The PEM fuel cell provides an output potential around 0.5 V. To get meaningful voltages, many individual cells are connected in series (Fig. 2).

Research & Development Establishment (Engineers), Pune and SPIC Science Foundation, Chennai initiated work on fuel cells, particularly on PEMFC, because of its high power density, and operates relatively at low temperatures.

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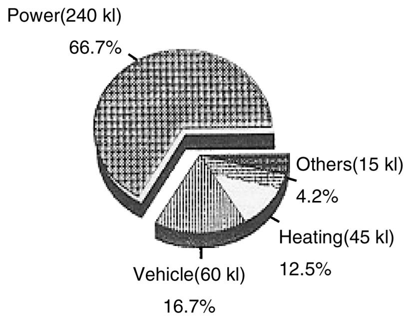

Fig. 1. Annual fuel consumption of Maitri.

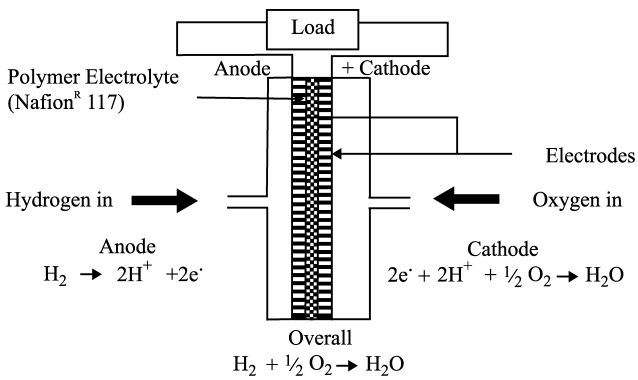

Fig. 2. Schematic of PEMFC operation.

2. Stack configuration and performance

A prototype 500 W PEMFC has been installed at Maitri, the Indian Scientific Research Station in Antarctica during the XVII Indian Antarctic Expedition. The fuel cell stack consists of 18 cells connected in series electrically. Highly conductive graphite plates are used as a current collector-cum-gas distributor. The cooling plate was introduced after every two cells. Nafion-117 was used as the electrolyte. Platinum is used as catalyst and its loading on both hydrogen and both the oxygen side is 1 mg/cm^2, respectively. Hydrogen and oxygen are stored in steel cylinders of 7 m^3 capacity at 150 kg/cm^2 and are fed to the cells through a two-stage pressure regulator, reducing and regulating the pressure to 1 kg/cm^2 via flow meters and humidifier bottles. The external flow circuit diagram of gases is shown in Figs. 3 and 4 shows the PEMFC stack under testing at Maitri.

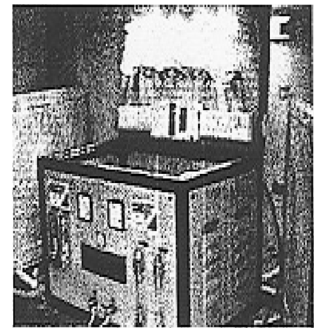

Fig. 4. PEMFC 500 W under testing with dc light load at Maitri.

The stack was kept at −35 °C. The moment gas was passed through the stack the open circuit voltage (OCV) is obtained instantly. The OCV obtained is around 18 V. As we increase the load, the stack voltage decreases. The load was increased till the stack voltage reaches 12 V. At the lowest temperature recorded at Maitri during this season −35 °C, the stack was started without any difficulty at this temperature. The stack was operated at various temperatures experienced during the entire season.

After installation and testing with the dc bulb load, the stack was connected to a Digitronics dc–dc converter for charging the batteries. The output of dc–dc converter is 15.6 V, which was used for charging the batteries. A typical battery charging circuit diagram using fuel cell is shown in Fig. 5. A fully discharged battery was connected to the output terminals of the converter and the battery was charged fully after three and half hours.

The power output of 500 W is obtained only when the stack was operated at 40 °C. When the stack was operated at

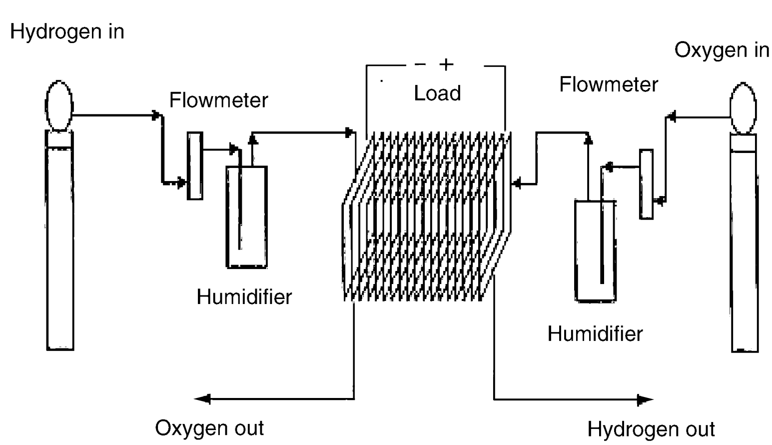

Fig. 3. PEMFC 500 W stack external flow circuit of gases.

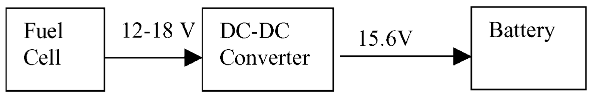

Fig. 5. Circuit diagram for battery charging.

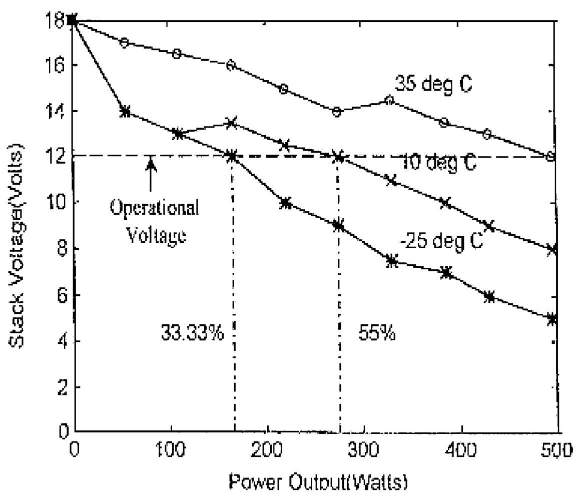

Fig. 6. Voltage regulation vs. power output at different operating temperatures.

−25 °C, the maximum power output generated was only 33.33% of the rated capacity. As the temperatures increased to 10 °C, the output is 50%. The maximum power output was obtained at 35 °C (Fig. 6).

3. Problems encountered

The starting of fuel cell at sub-zero temperatures was not a problem. However, the peripherals used for cooling the stack and external humidification systems have given a lot of problems. For the present stack design for cooling the stack, water is used as a coolant. At sub-zero temperatures, invariably the water froze. The same problem was encountered in the external humidifiers. The humidifier requires an additional power source to avoid freezing of water, to avoid the blocking of the incoming gases from the rotameter. At the end of each experiment, the stack has to be flushed with the nitrogen to avoid freezing of water within the stack.

Both the gas cylinders were kept outside, where the temperature varies from −5 to −40 °C. The diaphragm of the regulator is neoprene and at these temperatures, it gets hardened and leads to stopping of the outgoing gases from the cylinder.

4. Experimentation during the XVIII expedition

Further experiments were planned and carried out during the XVIII Antarctic Expedition.

4.1. Optimisation of humidification temperature for the reactants (hydrogen and oxygen) and elimination of the existing humidification system

The electrolyte used in the PEMFC is required to be humidified for better performance. The reactants (oxygen and hydrogen) used are generally passed through the water before the enter the inlet of the fuel cell. The present system is based on an external humidification system which requires electrical energy to maintain the humidification temperature. It also requires additional engineering hardware like pipelines, insulation and connectors, etc. For initial activation of fuel cell, the humidification bottle is heated through the strip heater. The water inside the bottle gets frozen almost everyday due to low ambient temperature. This gives additional problems to the fuel cell stack and more energy is needed to melt the ice, i.e. frozen water in the humidification bottle. In order to avoid this problem, after initial humidification of the stack, the water in the humidifier has been removed totally. Presently, all the experiments are being carried out without humidification. For the last 10 days, there is no change in the performance of the stack. In order to check the durability of the stack performance without humidification, the experiments was continued during winter period.

4.2. To study the air-cooling system in lieu of water cooling system

As the fuel cell reaction is exothermic, it generates a lot of heat. Hence, the stack has to be cooled to reduce the temperature for its better performance. The new fuel cell stack has been designed for water cooling and has a capacity of 500 W. To maintain the stack temperature around 40 °C, the water flow rate required is 350 ml/min in a place like Chennai, where the ambient water temperature is 25–30 °C. As the ambient temperature of water in Antarctica is very low even in summer (3–5 °C), the water flow needed to cool the stack is only 100 ml/min. When the temperature goes down to 0 °C and below, it again encounters problem of freezing of water. It requires additional energy source in order to melt the frozen water before it enters into the stack for cooling. It was, therefore, decided to use air-cooling system instead of water cooling. The small blower, Bosch Taiwan Model no. GBL 550 of capacity 2.7 m^3/min has been used for cooling the stack. The cold air is passed through the stack and the temperature of the stack is maintained around 40 °C by varying the air flow. Based on this experiment, it has been established that air can be used as a cooling media. However, this also requires additional power source. Since the highly chilled wind is always available, it is suggested to make use of this natural source for cooling the stack. Hence, the present PEMFC stack design needs modification which can be incorporated in the future stack design.

4.3. To study the humidification of gases using membrane as a medium

To humidify the hydrogen and oxygen gases, an assembly consisting of membrane placed between two grooved graphite plates was made. Gasses were passed through the graphite plate and was passed over one side of the membrane and water was passed over other side of the membrane. The initial humidity of the gases was measured without passing water in the experimental set-up. Then water was introduced through the graphite plates. The membrane took up water, in turn gases passed over the membrane got humidified by taking up the moisture from the membrane. This process was repeated twice to increase the humidity of the gases. It was observed that the gas humidity has been increased from 5 to 80%. This clearly indicates that the internal humidification is possible even at low water temperature.

The present humidification system requires external heating and other auxiliary sub-system. This adds weight to the fuel cell and also causes inconvenience for handling and operating the fuel cell at high temperature. For effective humidification and for simplification, it is suggested to design an internal humidification system, which can become the integral part of the fuel cell configuration.

4.4. To study the charging and discharging characteristics of metal hydride

A metal hydride unit is used for storing the hydrogen. From the safety point of view of handling, metal hydride is easier than direct handling of hydrogen cylinder. When the metal hydride is charged a heat is generated which is an exothermic reaction and when gas is released the system gets cooled, which is an endothermic reaction. Since the charging is exothermic, it takes longer time to charge metal hydride unit in hot regions of the country. It is found that, in a cold region like Antarctica, the charging is much easier since the unit gets cooled immediately due to prevailed climatic conditions. To study the behaviour of metal hydride in this environment, a few experiments on charging and discharging of hydride unit was carried out at various temperatures. The data has been collected for analysis and implementation for hydrogen storage.

4.5. Fuel cell coupled with dc–dc converter and inverter

Unlike other power sources, the fuel cell starting voltage and operating voltage are variable. In order to get a constant power output of dc or ac, we required a dc–dc converter for constant dc supply which will be useful for battery charging. The inverter output (ac) may be useful for a stand alone power source. For carrying out this experiment, two fuel cell units having voltage of 18 V each, were connected in series electrically which were in turn connected to a specially designed inverter with dc–dc converter. The input voltage from the fuel cell varied from 36 to 22 V. However, from the inverter at constant voltage of 230 V ac was produced. In addition to ac output, the constant dc output of 24 V was also produced. The ac load was used to glow the bulb in the Shivalik Hut. The dc load was used for charging the batteries. Direct current load has been used as a dummy load, i.e. for glowing 24 V bulbs. The monitoring of equipment will be continued during wintering also.

5. Experimental results

(a) The experiments were carried out with the old stack, without heating the humidification bottle. The cell voltages started decreasing after 2 h of operation because the stack temperature is higher than the humidification water temperature.

FC-1 scan data at stack temperature of 40 °C

Load (W)	Voltage (V)	Current (A)
0	17.98	0
68.625	15.25	4.5
133.855	14.09	9.5
182.28	13.02	14
213.3	11.85	18
210	10	21

Humidification water temperature = 3 °C.

(b) To improve the performance of the stack, the humidification temperature increased to match with stack temperature. The temperature of the humidification bottle was increased using a strip heater (trace heating cable). Since the wattage of the heater is low, the maximum temperature achieved was 40 °C. Stack temperature was maintained by passing the water (coolant) using gravity. The experiments carried out at various stack temperatures and the results are given in the following tables.

FC-1 scan data at stack temperature of −30 °C

Load (W)	Voltage (V)	Current (A)
0	18.36	0
63.48	14.42	4.4
126.72	13.2	9.6
160.58	11.57	14
185.4	10.3	18
195.3	9.3	21
208.75	8.35	25

Humidification temperature for both gases is 40 °C.

FC-1 scan data at stack temperature of −35 °C

Load (W)	Voltage (V)	Current (A)
0	18.38	0
68.2	15.5	4.4
138.24	14.4	9.6
187.6	13.4	14
221.22	12.29	18
230.79	10.99	21
233.75	9.35	25

Humidification temperature for both gases is 40 °C.

Based on our experience, water cannot be used as a cooling medium and for humidification as it gets frozen and requires additional heating. Hence, it was decided to carry out the experiments with air as a cooling medium.

(c) Air-cooling instead of water cooling:

Air-cooling with stack temperature of −40 °C

Load (W)	Voltage (V)	Current (A)
0	18.44	0
69.615	15.47	4.5
135.945	14.31	9.5
185.36	13.24	14
217.26	12.07	18
214.62	10.22	21

Humidification temperature is −40 °C.

Air-cooling was effective even with the existing design. However, this requires additional power source. It is decided to operate the system without cooling and humidification.

(d) Results of experiments with two stacks coupled in series:

Stack temperature: −25 °C

FC-1 voltage (V)	FC-2 voltage (V)	Overall voltage (V)	dc–dc converter output (V)	Current (A)	Load (W)
18	18	36	24	0	0
17.5	17.5	35	24	0	0
15.2	15.4	30.6	24	3.6	110
14.2	14.3	28.5	24	7.72	220
13.3	13.3	26.6	24	12.4	330
12.5	12.5	25	23	17.6	440

No humidification of gases and no cooling of stack.

(e) Results of experiments on internal humidification:

Humidification of gases using membrane as a medium

Reactants	Temperature	Water flow rate (ml/min)	No. of cells	Gas flow rate (m^3/h)	Relative humidity (%)
Oxygen	2.8	0	Nil	1	3.50
	2.8	90	1	1	51
	2.8	90	2	1	69
	2.8	90	3	1	80
Hydrogen	3	0	Nil	1	2.50
	3	90	1	1	82.50
	3	90	2	1	88
	3	90	3	1	90

(f) Discharging characteristics of metal hydride:

Metal hydride discharging

S. no.	Discharge time	MH unit pressure (psi)
1	0	80
2	4	70
3	6	65
4	9	60
5	14	55
6	17	50
7	21	45
8	25	40
9	30	35
10	42	30
11	46	20
12	75	10

Flow rate = 0.2 m^3/h; ambient temperature = 3 °C; wind chill = 5 °C; temperature of unit after 1 h charging = 16 °C; temperature after discharging up to 10 psi =14 °C.

Metal hydride discharging

S. no.	Discharge time	MH unit pressure (psi)
1	0	80
2	2	75
3	4	70
4	6	65
5	8	60
6	12	55
7	18	45
8	25	40
9	31	35
10	35	30
11	38	25
12	50	20
13	65	15
14	80	10
15	100	5
16	120	0

Flow rate = 0.4 m^3/h; ambient temperature = −3 °C; wind chill = −15 °C; temperature of unit after 1 h charging = 15 °C; temperature after discharging up to 10 psi = 8°C.

The PEMFC was able to start at −25 °C without any difficult. Based on the above studies, a large volume of data has been collected from Antarctica, the analysis of the results suggest that the future PEMFC stack needs a few modifications. These modifications are expected to simplify the operation, improve performance and avoid few engineering problems. Further, the wastage of the precious reactant can be minimised to a great extent. The following modification are contemplated.

(a) Air-cooling system in lieu of water cooling.
(b) Internal humidification of gases.
(c) Reactant re-circulation.

5.1. *Air-cooling system in lieu of water cooling*

As the fuel cell reaction is exothermic, it generates heat; hence, the stack has to be cooled to reduce the temperature for its better performance. The stack was kept exposed to ambient temperature at Antarctica (temperature always below 0 °C) and the problem encountered is freezing of water. It requires on additional energy source to melt frozen water before it enters into stack for cooling. To avoid these problems, either we will have to add anti-freezing liquid or to go for air-cooling system. The anti-freezing liquid like water–glycerol or mixture of alcohols with water can be used as a coolant, the working temperature varies from −60 to 50 °C. Cooling can be done either by gravity flow or by using a circulating pump. The other method is designing the stack for air-cooling, which requires some design changes in the coolant plates of the present stacks. Since high speed wind is always there in Antarctica, effective cooling of the fuel cell stack should be possible. Better to make use of natural source that is air-cooling.

5.2. *Internal humidification system*

The electrolyte used in the PEMFC requires to be humidified for better performance. The reactants used are generally passed through water before it enters the inlet of the fuel cell. The present system is based on an external humidification, which requires electrical energy to maintain the humidification temperature. It also requires additional engineering hardware like pipe lines, connectors and insulation, etc. This will be an integral part of the fuel cell stack.

5.3. *Reactants re-circulation*

In a place like Antarctica, the reactants should be used efficiently. The present fuel cell stack gas flow pattern is ‘once through’ mode so the excess gas passes through the stack is around 30%. From the safety point and also to minimise the excess of the reactant used, a re-circulating pump can be used. The outlet of both the gases are again fed to inlet of the fuel cell stack after compression. The power required for the pump is only 10% of the fuel cell output. The power can be drawn from fuel cell. With the help of this pump fuel cell can be operated for longer duration.

6. Proposed hybrid power plant system configuration

The development of future installation for power generation in Antarctica could be of hybrid in nature exploiting a combination of conventional and non-conventional energy resources. The system configuration could be taking into account exploiting of wind energy, in order to have a good integration. The proposed plant could be composed of the

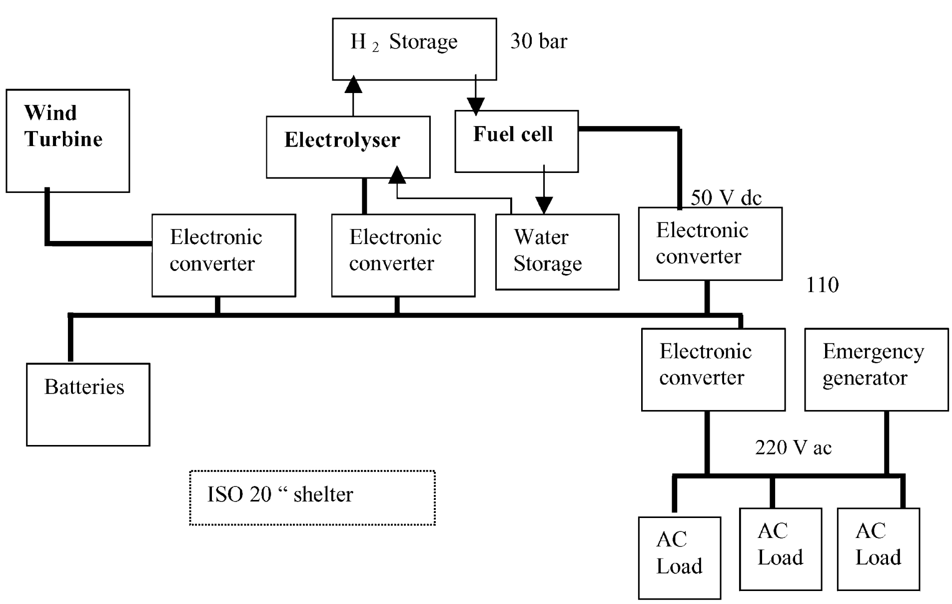

Fig. 7. Wind hydrogen plant.

following main components (Fig. 7):

- wind turbines generators;
- short-term storage: lead acid batteries;
- long term storage system, consisting in:
  - hydrogen production—electrolyser,
  - hydrogen storage—pressurised vessel,
  - hydrogen utilisation: fuel cell,
- climatised shelter;
- power electronic converter interfaces;
- emergency electric generators.

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