"FUEL CELLS"

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ABSTRACT

The current state of development of fuel cells as potential power sources is reviewed. Applications in special fields with particular reference to military requirements are pointed out.

ntroduction

The present day electrical power production is based on a three stage conversion process (Carnot Cycle-Steam Engine): the transformation of chemical energy of the fuel into thermal energy by combustion, transformation of the thermal energy into mechanical work in a heat-engine, and lastly transformation of the work into electrical energy by means of a generator. The overall efficiency of this system is restricted by incomplete combustion, heat losses, inherent limitations of the mechanical devices, and thermodynamic limitations of the heat engines. Some of these limitations resulting in efficiency losses could be avoided if the chemical energy of the fuel were converted directly to electrical energy (by fuel cells). Electrochemical cells employing common fuels or products derived from fossil fuels have been studied on laboratory scale for a number of years[1]. The theoretical efficiency in such devices could be 100 per cent and efficiency as high as 95 per cent of the fuel consumed have been demonstrated, as compared to 40—45 per cent in the conventional power plants.

The history of fuel cell dates back from W. Grove's cell in 1839. However, it was W. Ostwald who first called for the replacement of heat engines by fuel cells, in a meeting of the Bunsen Society in 1894. From 1910 until World War II, the foremost contributor to fuel cell knowledge was Emil Baur. The work of Baur and his colleagues covered nearly all types of cells, most significant amongst them are two high-temperature cells designed to use carbon or coal directly but because of short life of these cells they met with indifferent success. Among the modern investigators one of the distinguished persons who has been working on fuel cell since 1932 is F.T. Bacon. However the tempo of fuel-cell research gained momentum after 1947 when O.K. Davtyan published a report outlining some very interesting results of fuel cell research by the U.R.S.S. Academy of Sciences.

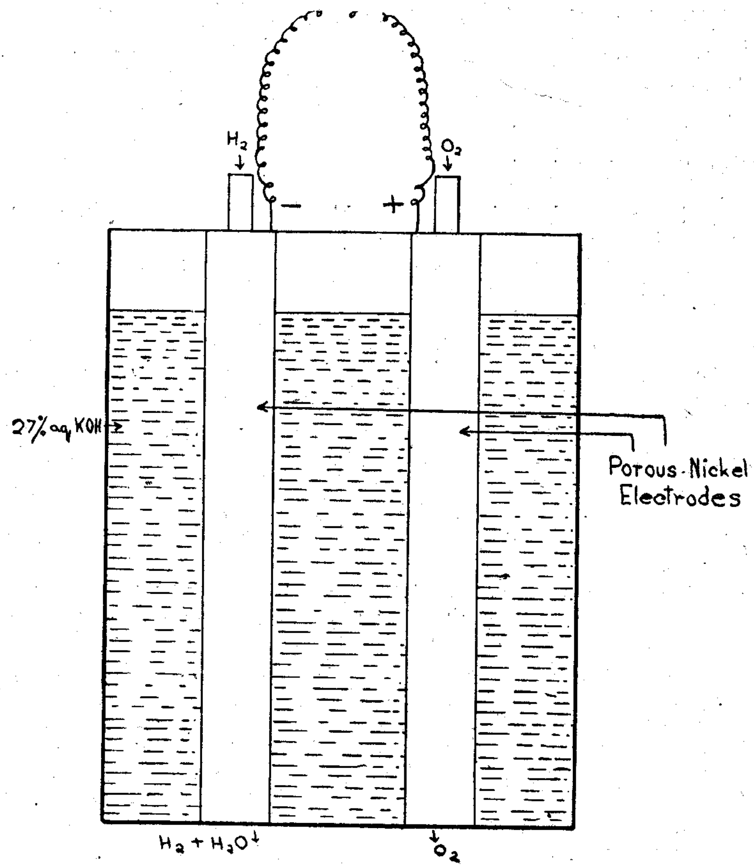
With the increasing research on fuel cells different modifications of the fuel cells have been developed during the past decade and in order to evaluate fuel cells a number of methods of classification have been used. The important ones are: (1) Direct or indirect (also called 'redox') cells. In the direct type the fuel is consumed directly within the cell, whereas in the indirect or redox type the products derived from the conventional fuel are used and it involves mostly the oxidation reduction reactions. (2) The one based on the electrolyte as aqueous or nonaqueous; (3) those based on the operating conditions such as temperature and pressure. The various classes overlap. Those falling under the latter class are the most important. They are further subdivided as: Low Temperature cells (room temp—100°C), Medium Temperature Cells (150°—250°C) and High Temperature Cells (500°—1100°C); Atmospheric Pressure Cells and High Pressure Cells.

Principle and Operation

Precisely, a fuel cell is an electrochemical device in which the chemical energy of a conventional fuel is converted directly and usefully into low-voltage direct-current electrical energy. A conventional fuel may be a fossil fuel or products derived from it. It may be one of the natural gases (hydrocarbons) or hydrogen; with oxygen or air serving as oxidant. In this device a fuel is supplied to a negative electrode and oxidant to positive electrode. The two electrodes are connected through and electrolyte which prevents mixing of fuel and oxidant but provides electronically insulating and electrolytically conducting medium.

The fuel cell is solely a converter of energy. The fundamental principles of operation are essentially the same as those in all galvanic cells based on two half-cell reactions—one involving oxidation and releasing electrons, the other involving reduction and requiring electrons.

A promising fuel cell is the hydrogen-oxygen (hydrox) cell. Bacon's hydrox cell[2], for example, requires pure hydrogen and oxygen for successful operation and uses aqueous potassium hydroxide solution as electrolyte. The electrodes are made of porous sintered nickel (catalyst) and the main cell parts are nickel plated steel or pure nickel. The surface of the nickel cylinders adsorb the gases thus acting as gas electrodes. These gases are consumed while the metal



$$H_2 \longrightarrow 2.H.\ \text{Chemisorbed} \xrightarrow{2.OH^-} 2H_2O + 2\bar{e}$$

$$\tfrac{1}{2}O_2 + 2\bar{e} \longrightarrow O^{--}.\ \text{Chemisorbed} \xrightarrow{H_2O} 2.OH^-$$

$$H_2 + \tfrac{1}{2}O_2 \longrightarrow H_2O$$

ideally remains unchanged. The adsorbed layer of oxygen is more active than the molecular oxygen and can combine with water in the electrode to form hydroxyl ions. At the negative electrode, hydroxyl ions combine with water in the adsorbed hydrogen to form water and liberate electrons. Electrons thus released are made to do work on their way to the oxygen electrode.

Performance Requirements

For an ideal fuel cell the performance requirements may be stated as: maximum performance under practical conditions for maximum time. Here current density must be reasonably high, for otherwise an impracticably large cell has to be built. High useful work is required for a long time from unit electrode area. It immediately follows that the cell should have low internal resistance so that I^2R losses are minimised (where R is the resistance and I the current). This condition is favoured by high conductivity of the electrolyte and by close spacing of the electrodes. The remaining important performance requirements are: (1) Reactivity requirements and (2) Invariance requirements. The reactivity requirements relate to the rates and mechanism of electrode reactions. The above two sets of requirements are related. For example, for obtaining high reactivity high temperatures are needed and hence it will usually be more difficult to keep the fuel cell invariant[3].

Electrode reaction kinetics

To obtain good fuel efficiency, fuel cells must be operated with an internal loss of about 20—30% of the open circuit voltage. Voltage loss within a cell is caused by three main factors—activation polarisation, mass transport polarisation; and ohmic resistance[4].

The reaction between gas, electrolyte, and the electrode can take place only at three phase boundary. While in theory this boundary is just a line having but one dimension in space, in reality a finite reaction zone must exist (Grove had already pointed the difficulty to obtain anything like surface of action). In the present day fuel cells, the usual method of extending the area of reaction zone is to fabricate the electrode as an electronically conducting porous structure which separates the gas (fuel or oxidant) and electrolyte phases [5,6,7].

The design of the electrodes for long operating life at high current densities is by far the most serious problem facing fuel cell workers. Each electrode material, reactant gas, and electrolyte system is unique, involving particular methods of obtaining the required poresize distribution in a form consistant with fabrication in an usable form[8].

The role of a catalyst at the anode in a fuel cell is two fold. It must rapidly chemisorb the fuel gas in such a manner as to make it more susceptible to oxidation by the active species of the electrolyte and at the same time it should act to minimize the loss of free energy due to chemisorption. Details of the catalysis in fuel cell have been discussed by Young and Rozelle[9]. The way the chemisorbed atom reacts with the ionic species in the electrolyte is a subject much less understood. Efforts have not been made yet to establish the mechanism experimentally.

Invariance Requirements

As regards this part of the performance requirements there are three important factors: (*i*) No corrosion or side reaction, (*ii*) Invariant electrolyte, and (*iii*) No change in electrodes.

Ion-exchange membrane electrolyte cells are being investigated to meet the maximum of performance requirements.

Development of Fuel Cells

In recent years considerable success has been achieved in research and developmental work on the low and medium temperature fuel cells.

Experimental fuel cell operating at room temperature and atmospheric pressure has been developed by National Carbon Co. (U.S.A.). It produces 20 watts of power at 6 volts and uses hydrogen and air. It is enough to light three bicycle lamps [10].

M/s Shell Petroleum England have developed a hydrox cell with a radically different electrode[11]. This low-temperature cell develops 3·5 kw/cu. ft., about 4 times the present output of low temperature cells. At room temperature the cell achieves a current density of 70 amperes/sq. ft. and at 60°C the c.d. is doubled. A 20-cell unit has been built with individual cells only 0·167 in. thick. Shell believe that power to weight ratio up to 50 w/lb are possible with its new electrode. (The best ratio to date for low temperature cell is 10 w/lb).

Another fuel cell under development is designed to use easily stored organic liquid and has a theoretical output of 1000 whr/lb[12]. Esso Research & Engineering have published details for producing fuel cell for about $10. The fuel cell uses CH_3OH as fuel, KOH as electrolyte and oxygen as oxidant[13].

Recently, General Electric have revealed details of their new "Solid Electrolyte" fuel cell. The cell has an acidic ion-exchange membrane covered with Pt-Pd coating which acts as catalyst. The cell operates at 0·8V[14]. A full scale chemical power plant under development for U.S. Navy will use sodium-amalgam-oxygen combination. The prototype power plant develops about 75 kw. Together with fuel storage space it will weigh between 2 and 3 lb/kwhr[15,16].

A very significant advancement made in energy conversion is the Bio-chemical fuel cell developed by U.S. Govt. Scientists. The cell uses a mixture of sea water and organic matter as fuel and bacterial cells (or enzymes) as catalyst. The oxidant is oxygen[17].

Another feature is now being studied which makes fuel cells interesting in the possibility of regeneration. Storage problem of fuel can be solved if the reaction products are dissociated and regenerated by the use of solar or nuclear energy.

Bacon's cell has reached the highest state of development up to the present in the case of Medium Temperature Cells[2,18]. Very little success has been achieved as regards the high temperature cells. These cells are mostly tried for generation of electric power from fossil fuels. Gorin has pointed out that no theoretical reason exists to prevent the attainment of a high output high temperature fuel cell. Considerable experimental effort is required to determine whether this can be achieved in practice[19].

Applications

The applications of direct conversion of chemical into electrical energy remain to be determined by future development. However there are two broad aspects of fuel cells applications namely (*a*) Central Power Station and (*b*) Special Applications.

Central Power Station—The practicability of central power station seems to be remote on economic grounds. In this case a cheap fuel source such as coal is to be used and the cells using coal operate at temperatures much higher than their surroundings. This results in loss of heat and consequently loss of efficiency. Efforts are being made to use carbon monoxide and hydrogen as fuel by gasification of coal. Experiments are being carried out in U.K., USSR and USA in this respect.

Special Applications—As regards special applications each fuel cell will find applications based on its particular virtues. Fuel cells may be used in any thing from locomotives to space ships. This may be considered in a little detail.

Transportation—In public transportation the fuel cell propelled vehicle poses a number of advantages over Gasoline or Diesel Engines; higher speed, more rapid acceleration, quietness, absence of noxious exhaust gases. Further the cell is not damaged by heavy overload which arises when starting a vehicle. Besides these when the vehicle is stopped temporarily in traffic the fuel cell is consuming practically no fuel, whereas the petrol or Diesel Engine continues to do so[20]. From these considerations fuel cells may find wide applications in powered vehicles.

Fuel cells of 25—500 Kw may be suitable for small cars. Hydrocarbon/air and hydrogen/oxygen cells are compared theoretically for powering small electric cars. For buses, trucks and locomotives, Carbonaceous fuels are preferable given a power density factor of 25—40 W/lb.[21,22]. A fuel cell that could operate efficiently on gasoline or oil could be recharged by refilling of its tanks[23]. Today many automobile manufacturing companies in U.S.A. are interested in fuel cells and are carrying out research projects on them[24].

Tractors—A demonstration was given in the U.S. in October 1959 of a farm tractor driven by a battery of fuel cells supplied with propane and other gases (probably hydrogen) and oxygen. It has 1008 cells in series and works at quite low temperature[25].

Machining Operations—At Cambridge, a demonstration took place in August 1959 of the high pressure hydrox cells, in which a 40-cells