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Abstract

Today, the combustion of fossil fuels has supplied the vast majority of homes and buildings energy requirements. This has mainly been accomplished through the use of steam power plants. Although much has been done to improve efficiency and performance, there is still much room for improvement. Currently, conventional steam power plants are operating at approximately 30 – 40% efficiency. Another disadvantage is the pollutants contained in the products of combustion must be regulated to acceptable levels. This combined with the fact that steam power plants are not very modular, which in turn requires distribution of power has led to the research of more advanced power generation.

Recently, the need for a non-polluting power, efficient source, has increased attention to fuel cells. Of the different types of fuel cells, the “proton exchange membrane (PEM) fuel cell has received the most attention. PEM fuel cells operate at a low temperature; have high conversion efficiencies, and power densities making them perfect for supplying energy to homes and small buildings. The production of waste heat by PEM as well as other fuel cells is also beneficial. Waste heat can be used to serve many purposes such as: supplying space heating, hot water, or by regenerating a desiccant dehumidifier. The main disadvantage to fuel cell is cost. Right now capital costs, mainly for materials, is high which makes them unattractive. Recently however, the advantages of such an application have triggered an increase in research and development, which promises to drive costs down.

To demonstrate the advantages of PEM fuel cells. An analytical model is constructed, installing a PEM fuel cell to supply the space cooling, and electrical requirements to a small building on the University of Louisiana at Lafayette campus. The waste heat from the fuel cell will be used to regenerate a desiccant dehumidifier, to increase system efficiency.
Introduction

Today, over 80% of the electricity generated in the United States is produced by the combustion of fossil fuels. This is usually accomplished through a steam cycle, or Rankine cycle. The major components of this system include: i) boiler – which generates steam by transferring heat from the combustion of fossil fuels to water, ii) turbine – produces energy by the expansion of steam created in the boiler, iii) condenser – is where heat is transferred out of the now low quality steam, turning the steam back into a liquid, iii) pump – transports the liquid water back to the boiler, where the process is repeated.

The efficiency and performance of the Rankine cycle is limited by the Carnot efficiency. It is defined as:

$$\eta_{\text{CARNOT}} = 1 - \left( \frac{Q_L}{Q_H} \right) = 1 - \left( \frac{T_L}{T_H} \right)$$

Ideally, the efficiency would only be related to the temperature in the boiler and in the condenser as shown above (which even as an idealization could not reach 100%), but in practical Rankine cycles, limitations exist due to combustion efficiency, component efficiencies, and other “real world” factors as well. To include all of the losses just mentioned, a total system efficiency called the system efficiency can be calculated:

$$\eta_{\text{station}} = \frac{W_{\text{net}}}{(m_{\text{fuel}} \times HHV_{\text{fuel}})}$$

The reciprocal of this number can be taken to give the heat rate. Using the conversion of 1 Kw = 3412 Btu/hr, the heat rate of the system can be defined as:

$$HR = \frac{3412}{\eta_{\text{station}}}$$

As a result, a lower number means a better system performance. It will be shown later that a fuel cells performance can be measured in the same way.¹

Pollutants such as SOₓ and NOₓ that are released from the burning of fossil fuels have been shown to have devastating effects on the earth. As more research continues on the greenhouse effect, it is becoming general knowledge that the release of another pollutant carbon dioxide (CO₂), causes heating of the earth’s atmosphere.² Strict emissions laws are being passed that regulate these pollutants, which puts steam power plants at a further disadvantage.

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Steam power plants have another disadvantage of not being very modular systems, which makes them not justifiable for independent power generation of homes or office buildings. As a result, power has to be centrally generated, and then subsequently distributed through an electrical power network. Besides the system inefficiencies stated earlier, other losses are created such as: distribution in line losses, voltage conditioning and transformation losses, and local distribution losses. The values for these efficiencies typically range from 85-95%. This combined with the system efficiency; enable the total system efficiency to rarely exceed 40%.

Over the years, modifications have been made to the Rankine cycle to increase efficiency and performance. Some of the modifications include: Combined cycles such as the Brayton/Rankine cycle, reheat cycles, and feedwater heater cycles. These advancements have been shown to increase performance, but at a considerably increased capital investment. With the high value placed on the earth’s natural resources, other sources of energy have become the target for research and development. One area of technology receiving much attention at present is fuel cell conversion, a nonpolluting, efficient method which lends itself readily to integration with other energy systems for waste heat recovery.

Background

Fuel cells are electromechanical devices the produce electricity from paired oxidation / reduction reactions. They are essentially batteries except for the fact that battery life is dependent on the amount of reactant supplied. When the reactant runs out the battery is dead. Fuel cells on the other hand will keep producing energy as long as there is a steady supply of the reactant.

The operating characteristics are essentially in the reverse of electrolysis process where water is broken down into hydrogen and oxygen. In the fuel cell, hydrogen and oxygen are supplied, and are reacted by the aid of a catalyst to produce electricity, heat, and ultra-pure water. Technically the two chemicals do not have to be hydrogen and oxygen, the oxidation / reaction requires only an oxidizer and a reducer. The reason hydrogen and oxygen are chosen most often is due to the fact the oxygen is readily available from air, and hydrogen has fast reaction kinetics. There are several different types of fuel cells, each with their own characteristics. The Proton Exchange Membrane (PEM) however, shows the most promise for independent power generation, and will be the focus for this project.

PEM Thermodynamics

Shown below is a figure to illustrate the operational characteristics of a PEM fuel cell. As hydrogen enters the anode side of the cell it is oxidized by the aid of a catalyst:

\[ H_{2(g)} \rightarrow 2H^+ + 2e^- \]
When the hydrogen is oxidized, only the positive hydrogen ions are allowed to migrate through the electrolyte. The electrons are routed to the external circuit, and then back to the cathode. At the cathode, the electrons combine with oxygen (air), which results in the following reduction reaction:

$$2e^- + \frac{1}{2} O_{2(g)} \Rightarrow O^{2-}$$

Equilibrium is reached as the hydrogen ions diffuse through the electrolyte to get to the cathode:

$$2H^+ + O^{2-} \Rightarrow H_2O_{(liquid)}$$

The theoretical energy release can be determined by the enthalpy change $\Delta H$ in the overall reaction:

$$H_2 + \frac{1}{2} O_{2(g)} \Rightarrow H_2O$$

At 14.7 psia, and 77 F the Gibbs free energy, and enthalpy change is:

$$\Delta G = -237,141 \frac{KJ}{Kg - mole}$$

$$\Delta H = -285,830 \frac{KJ}{Kg - mole}$$

These conditions are used when fuel cells are operating below boiling point of water, or in other words produce a liquid product. For fuel cells operating at high temperatures,
the water produced will be in a gaseous state. When this is the case, the “lower heating
value” will be used.

From the second law of thermodynamics the maximum useful work (change in free
energy) that can be obtained from a chemical reaction is:

$$\Delta G = \Delta H - T\Delta S$$

The theoretical efficiency can be defined by the maximum work out divided by the
enthalpy input:

$$\eta_{fc} = \frac{\Delta G}{\Delta H}$$

Based on the higher heating value (a liquid water product) the maximum thermal
efficiency under standard conditions is 83 %. The change in free energy can also be used
to calculate the maximum reversible voltage provided by the cell:

$$E_{rev} = \frac{\Delta G}{jF}$$

Here $j = 2$, which is the number of electrons in the reaction, $F = 96,487$ Coulomb / mole
electrons, which is Faraday’s constant. The maximum reversible potential based on the
higher heating value is 1.229 volts.

**PEM Kinetics**

The potential of the cell is also limited by the kinetics of the reaction. The decrease in
cell potential is best illustrated on performance curve or Tafel plot. This is a plot that
represents the cell potential versus the current density. The current density is simply the
number of electrons flowing per second or current per unit area. The current density
illustrates how fast the reaction is taking place. Figure 2 on the next page shows a typical
performance curve for a fuel cell.
Figure 2 – Typical Performance Curve for a Fuel Cell

From the figure, it can be seen that there are three losses that decrease the cells potential: ohmic polarizations, activation polarizations, and concentration polarizations. These will be discussed individually below.

**Ohmic polarization** - In any electrical device, ohmic polarization exists. Basically it is the resistance to electron flow due to properties of the material. The effects of this type of polarization are easy to quantify through empirical testing of the fuel cell itself. Through testing, fuel cell developers have been able to reduce the effects of ohmic polarization by the use of more exotic materials, but obviously it tends to drive the cost up. The resistances in the fuel cell can be found in the electrolyte, (resistance of the flow of ions), in the electrodes, (resistance of the flow of ions and electrons), and in the physical connections of the cell (resistance of the flow of electrons).

**Activation polarization** – Activation losses occur within the fuel cell when a load is applied. When a load is applied there has to be a net positive charge across the electrolyte. This means that the reversible reaction must occur faster from left to right than right to left. The result is a slow charge transfer reaction across the electrode-electrolyte interface.

**Concentration polarization** - Concentration polarization occurs at very high current densities. At high current densities, there is rapid mass transport, which causes a rapid
decrease in voltage. This is because the reactants cannot diffuse through the electrode and ionize fast enough, and products cannot be exhausted quick enough.

**Efficiency**

Efficiency of the fuel cell can be derived just like any other power producing device: by taking power out and dividing it by power in. Earlier, the theoretical maximum efficiency was derived, here the efficiency as a function of the voltage output can be derived. From the reaction:

\[
H_{2(g)} \rightarrow 2H^+ + 2e^-
\]

\[
\eta = \left( \frac{n_{\text{electrons}} F V_{\text{output}}}{n_{\text{hydrogen}} \Delta H_{\text{HHV}}} \right)
\]

\[
\eta = \frac{2 F V_{\text{output}}}{\Delta H_{\text{HHV}}}
\]

where

\[
F = 96,487 \text{ Coulomb/mole}
\]

\[
\Delta H_{\text{HHV}} = -285,800 \text{ Joule/mole}
\]

\[
1 \text{ Volt} = 1 \text{ Joule/Coulomb}
\]

The above equation can now be simplified into the following form:

\[
\eta = \frac{V_{\text{output}}}{1.481}
\]

This equation not only takes into account the potential drop due to polarizations described earlier, but it takes into account the maximum thermal efficiency that was derived earlier, based on the higher heating value. Taking the reciprocal of this number will give the heat rate of the fuel cell. Another way to define efficiency is by multiplying the maximum theoretical thermal efficiency by the ratio of the terminal voltage to the theoretical voltage.

\[
\eta = \left( \frac{V_{\text{output}}}{E_{\text{rev}}} \right) \eta_{\text{theoretical}}
\]

In a fuel cell, most of what is not generated into energy is generated into heat. So once the efficiency is known, the waste heat can be calculated as follows:

\[
Q = m_H \Delta H_{\text{HHV}} (1 - \eta)
\]
where \( m_{H_2} \) is the flow-rate of hydrogen.

**Fuel Consumption**

Hydrogen consumption can be derived from coulomb’s law. By taking \( F = 96487 \, \text{C} / \, \text{gm-mol} \), we have

\[
L = \left( \frac{96,487 \, \text{Amp} \cdot \text{sec}}{\text{gm} \cdot \text{mol}} \right) \left( 1.008 \, \text{mol}_{H_2} \right) \left( \frac{454 \, \text{gm}}{\text{lbm}} \right) \left( \frac{1 \, \text{hr}}{3600 \, \text{sec}} \right)
\]

\[
L = 12,265 \frac{\text{Amp} \cdot \text{hr}}{\text{lbm}_{H_2}}
\]

By taking the current and dividing by the constant \( L \), will give the consumption of hydrogen in lbm/hr to be:

\[
m_{H_2} = \frac{I}{L}
\]

The above equation represents the hydrogen consumption for a single cell. To produce the required power, fuel cell stacks are made up of many cells, most often in series in which case the total mass consumption the equation would need to be multiplied by the number of cells (\( x \)).

\[
m_{H_2} = \frac{I}{L} x
\]

Once the mass flow rate of hydrogen is calculated, the amount of waste heat that is generated can be calculated as shown earlier.

**Fuel Reforming**

Pure hydrogen is not available in nature. It is a widely used chemical, whose production has been considered common technology for over a century. Utilization of hydrogen for energy purposes, has only been considered mainly for fuel cells in space. Hydrogen can be obtained from a number of fossils fuels, such as: coal, gasoline, diesel, and natural gas. It is obtained by using various techniques like: steam reforming, gasification, and partial oxidation. Steam reforming is the most common, and will most likely be the standard when fuel cells become a common source of energy. It will be discussed in detail below.

Steam reforming combines fuel (natural gas) with steam to produce carbon monoxide and hydrogen. The following reaction takes place:
\[ CH_4 + H_2O \rightarrow CO + 3H_2 \]

This reaction is endothermic, which means that some extra energy will be required to reform the fuel coming in. However, some of the waste heat could be used for the reforming process, which increase efficiency. In the above reaction, not only will hydrogen be produced from the reforming of the natural gas, but also some hydrogen will be produced from the steam.

Most of the carbon monoxide produced from the reforming process will combine with water to produce additional hydrogen:

\[ CO + H_2O \rightarrow CO_2 + H_2 \]

It is worth noting here that the pollutants produced from this process are considered trivial to those produced from combustion of fossil fuels.

Fuel cells offer many advantages when compared to conventional steam power generation. High power densities, extremely low pollution, modular installation, and the benefits of having valuable waste heat, which can be used for cogeneration or other applications. It will be discussed below what the specific plans are for this project.

**Project Analysis**

The major objective of this project is to install a PEM fuel cell in a campus building, and to compare the new concept to conventional power generation, distribution, and utilization methods. Funded by the Louisiana Department of Natural Resources, the fuel cell will supply the space cooling and electrical requirements of a small building on the University of Louisiana at Lafayette campus. To increase system efficiency, the waste heat from the fuel cell will be used to regenerate a desiccant dehumidifier. The following are the major steps involved with this project:

**Technology Assessment of PEM fuel cells:** This will cover the complete theory on PEM fuel cells. It will include topics such as: thermodynamics, kinetics, efficiency, fuel supply, fuel processing, materials, and construction. A basic summary of the assessment was presented above.

**Application Site Selection:** This will first include a preliminary survey followed by a more thorough survey that will include a more detailed analysis. The parameters for the preliminary survey will include: budget constraints, physical size, and waste heat recovery potential. The buildings selected in the preliminary survey will be further analyzed based on the following constraints: space cooling loads analysis for a more specific waste heat recovery potential, specific electrical requirements, natural gas availability, as well as a more detailed analysis of physical size, and budget constraints.
System Selection/Integration Study: This will include a vendor survey of the fuel cells available, and selecting the best fuel cell to be integrated into the building. Parameters will include: sizes of available fuel cell, cost, and integration for waste heat recovery.

System Installation/Performance Monitoring: Once the fuel cell system is installed and online, comparative studies to the power grid, and long term monitoring of the overall performance and efficiency will be performed.

Conclusion

The application of independent based fuel cell systems will operate at an estimated efficiency of 10-20% above conventional power generation without waste heat recovery while producing little or no pollutants. Additional savings can be incorporated when the ultra-pure water is used, as well as the utilization of waste heat to replace other various energy consuming systems within the building. Currently, the only major disadvantage to fuel cell systems is cost. However there is reasonable expectation that the cost balance will shift in favor of the new fuel cell technology in the next few years. Exotic materials and manufacturing techniques are required to enable fuel cells to perform properly. However, with the current extensive research being conducted, the price of this technology should be driven down to the point where it is eventually attractive to the buyer.

References


is focused in the area of fuel cells. He is employed by Frank’s Casing Crew, where he is responsible for the design of oilfield equipment using finite element analysis (FEA).

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William E. Simon is Professor and Head of the Department of Mechanical Engineering at the University of Louisiana at Lafayette. His research interests are in the aerospace and thermal science areas. He has 27 years of experience with NASA, and was heavily involved in and received numerous awards for his work on the Apollo, Space Shuttle, and Space Station programs.