The Effect of the Fuel-Cell Unit Size on the Efficiency of a Fuel-Cell-Topped Rankine Power Cycle

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Dunbar, Lior and Gaggioli (1991) proposed a configuration of a fuel-cell-topped electrical Rankine power generating station and analyzed its performance. That study revealed that the fuel-cell topping improved plant efficiency to values up to 62 percent, versus the conventional plant efficiency of 41.5 percent. This work lays the foundation for a thermoeconomic analysis of such systems by relating exergy consumption to fuel-cell unit size, as follows: 1) the relationship between system efficiency (and hence fuel consumption) and fuel-cell unit size is presented for a number of fuel-cell operating conditions; 2) the relationship between fuel flow rate and fuel-cell unit size is shown; and 3) the exergetic effects of the major plant components are discussed as a function of fuel-cell unit size. The results reveal that specific fuel consumption may be reduced by as much as 32 percent when incorporating fuel-cell units into electrical power plants.

Thermodynamic Considerations

The fundamental (thermodynamic) reason for interest in fuel cells is the reduction of combustion irreversibility (Obert and Gaggioli, 1963; Dunbar, 1983; Dunbar and Gaggioli, 1990). The rate of exergy destruction (irreversibility) is directly proportional to the entropy production rate, and that is the product of the process rate with the driving force, divided by the absolute temperature (DeGroot and Mazur, 1962; Hirschfelder et al., 1954). When a fuel is burned in air at the rate R_f, the driving force for the reaction is the difference between the chemical potentials (μ) of the reactants and products—the chemical affinity (λ) of the reaction. The rate of useful power consumption during the combustion process is, thus, (Obert and Gaggioli, 1963; Degroot and Mazur, 1962; Hirschfelder et al., 1954)

$$\dot{A}_d = \frac{T_o}{T}(\mu_{\text{fuel}} + \mu_{\text{oxygen}} - \mu_{\text{products}})R_f = \frac{T_o}{T}\lambda R_f \qquad (1)$$

In ordinary combustion, a fuel is brought in direct contact with oxygen to react, producing oxidation products. The result is a conversion of chemical energy of the fuel to thermal energy of the products (Gaggioli, 1961). The amount of exergy destruction is quite large, of the order of 20–30 percent of the fuel exergy. More detail on combustion irreversibilities can be found in the paper by Dunbar and Lior (1990).

Fuel cells, on the other hand, lower the electrochemical potential value of either the fuel or oxygen by first passing ions through an electrolyte and producing electricity in this process. Consequently, the subsequent combustion reaction affinity is reduced, lowering the exergy destruction in that fuel oxidation process (Eq. (1)).

Analysis Technique

This case study evaluates the thermodynamic advantages of fuel cell units, given the plant configuration in Fig. 1 (Dunbar et al., 1991). This electrical power generating station consists of 1) the fuel-cell topping system inscribed within the dashed-line rectangle (including heat exchangers and the combustion chamber), and 2) a steam power cycle of a modern 300-MWe power plant (Gaggioli et al., 1975). More detail is given in the paper by Dunbar et al. (1991).

Partial oxidation of the fuel takes place within the fuel cell system. Having delivered an amount of electrical power, the product streams (depleted fuel and air) exit the fuel cell unit at a higher temperature and, following a heat exchange with "fresh" fuel and air in preheater no. 2 (via air-to-air and fuel-to-fuel heat exchangers), enter the combustion chamber. Mixing with any remainder of the plant fuel and air feed (streams 13 and 14 of Fig. 1), the fuel oxidation is completed there. The combustion product gas then flows through two heat exchangers, transferring the required heat to both the power cycle and the air in the air preheater.

For this case study (Dunbar et al., 1991), the fuel cell performance characteristics were assumed to be those of an older Westinghouse design of a solid-electrolyte fuel-cell battery containing 20 cells in series and operating at 1020°C (Archer et al., 1964), given for three fuel flow rates: 12.4 cm^3/s (Case A in the forthcoming analysis), 3.1 cm^3/s (Case B), and 1.4 cm^3/s (Case C). Hydrogen was assumed to be the power plant fuel.

The technique of analysis is as follows. The heat requirement

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Contributed by the Advanced Energy Systems Division for publication in the JOURNAL OF ENERGY RESOURCES TECHNOLOGY. Manuscript received by the AES Division, December 2, 1991; revised manuscript received September 9, 1992. Technical Editor: A. O. Arnas.

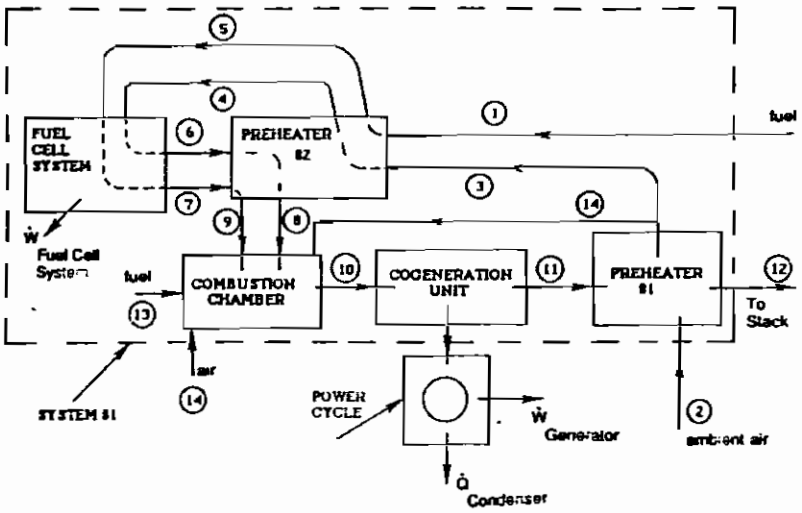

Fig. 1 Fuel-cell "topping" system plant configuration

of the power cycle is fixed at the value given by Gaggioli et al. (1975). The temperature values for the fuel and air entering the fuel cells, and the exiting product (stack) gases are specified (and constant throughout the analysis). A size for the fuel cell unit is chosen (a variable parameter of this study). Thus, once the fuel flow rate per array and the operating current are specified, the following quantities are fixed: 1) the total fuel and air requirements, and 2) the percentage of fuel oxidized in the cells, and hence the amount of remaining fuel which is to be burned in the combustor. Fuel flow rate per array, fuel cell operating current, and fuel cell unit size are thus the parameters for the performance analysis of the system shown in Fig. 1. More details of the analysis, and the modeling equations, were presented by Dunbar et al. (1991).

It should be noted that the plant configuration analyzed still requires optimization, but it does illustrate the possible improvements to plant efficiency when incorporating fuel cell units into electrical power generating (or cogenerating) plants.

The boundary conditions for the power plant were the following:

1 the incoming fuel and air temperatures = 25°C;
2 stack gas temperature = 135°C;
3 ambient reference temperature = 25°C;
4 all gas stream pressures are atmospheric;
5 all units, except the cogeneration heat exchanger, have adiabatic boundaries;
6 the cogeneration unit heat loss value is 13.01 MW (a typical value for modern boilers, Gaggioli et al., 1975);
7 100 percent excess combustion air, to match the air-fuel ratio of the fuel cell data employed (Dunbar, 1983);
8 stipulated energy exchange to the power cycle = 660.14 MW (Gaggioli et al., 1975);
9 the amount of heat transfer to the air in preheater no. 1 is fixed at a value of 87.92 MW (a value which assures that the hot and cold stream temperatures in the congeneration unit do not cross).

Results

The results of Dunbar et al. (1991) revealed that, for any given fuel-cell unit size and fuel flow rate per array, maximum system efficiency is experienced when the fuel-cell unit operates at the maximum power point. For the three Westinghouse experimental cases employed herein, the maximum power point is 1.1, 0.9, and 0.4 A for Cases A, B, and C, respectively. Thus, the results presented below are those obtained by assuming the fuel-cell unit operates at the maximum power point (for any given fuel flow rate per array).

Given the boundary conditions (for the gas side of the plant) of fixed fuel/air temperatures, fixed stack temperature, and a fixed power cycle heat requirement, a maximum fuel-cell unit size limit exists for each fuel flow rate per array case. Above this maximum size limit, more fuel would be fed to the plant than necessary for the energy requirements of the power cycle and electrical power output of the fuel-cell unit. This would raise the stack gas temperature, violating the boundary condition for this study.

The maximum fuel-cell unit size limits were found to be 6.4, 32.6 and 82.7 million arrays for cases A, B and C, respectively. These values coincide with the sizes employed in our previous study (Dunbar et al., 1991). In that study, all the incoming plant fuel/air was fed through the fuel cell unit, prior to complete oxidation in the combustion chamber (and hence, streams 13 and 14 of Fig. 1 were not present).

The global plant efficiencies, as a function of fuel-cell unit size, are displayed in Fig. 2. As shown in this figure (and proven theoretically in the previous study by Dunbar et al. (1991)), there is an opportunity for significant gains in efficiency through the use of fuel cell "topping units," wherein efficiencies of up to 62 percent are possible, versus the conventional plant efficiency of 41 percent. Note also, for the size range of Case A (0–6.4 million arrays), Case A efficiencies are greater than those of Cases B and C over the same size range. This behavior is consistent for all fuel flow rates (e.g., Case C efficiencies remain lower than Case B efficiencies until the fuel cell unit size is beyond the Case B range).

For the three evaluated cases, finite jumps are observed in the relationship between the number of arrays and the gain in efficiency. For example, for a fuel cell unit which contains 32.6 million arrays, Case B delivers a system efficiency of 57 percent. If one desires a higher efficiency, and is constrained by just three discrete fuel flow rates corresponding to cases

Nomenclature

R_f = fuel consumption rate, kmol/s
S_p = entropy production, kJ/K
T = temperature, K
T_o = reference temperature, K
λ = chemical affinity
$\dot{A}$ = exergy consumption rate, MW
μ = electrochemical potential, kJ/kmol

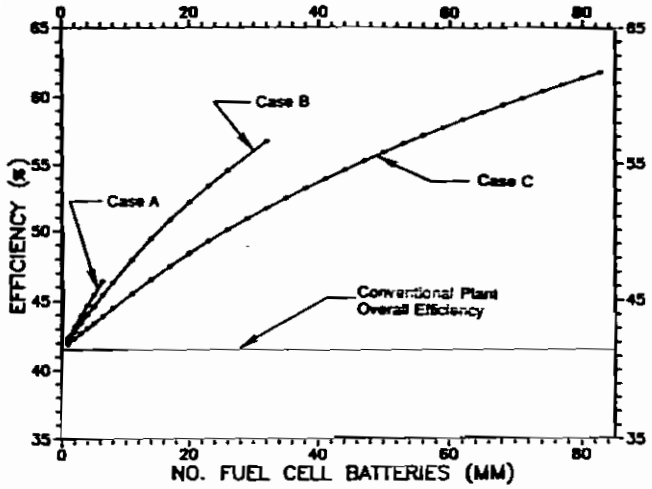

Fig. 2 System efficiency versus fuel-cell unit size

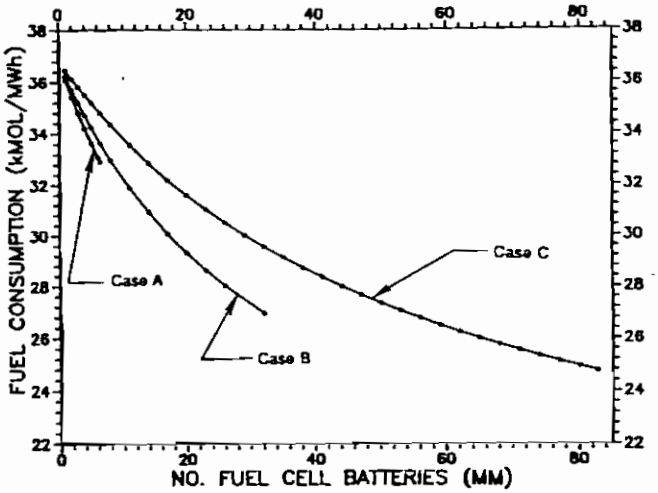

Fig. 3 Fuel consumption versus fuel-cell unit size

A, B, and C, the fuel cell unit size must jump to greater than 56 million arrays, where case C delivers 57 percent efficiency. This, however, would not be necessary in practice, since the fuel flow rate may be adjusted to a value between that of Cases B and C, delivering greater than 57 percent efficiency with a fuel cell unit which contains less than 56 million arrays.

While solid-electrolyte fuel cells of the type employed in this study are under study and pilot-plant operation in many countries, their mass-production costs are still unknown. In anticipation of the need to perform a thermoeconomic analysis on such electrical power generating stations, fuel consumption as a function of fuel cell unit size is displayed in Fig. 3. As shown, all three cases converge to the conventional power plant fuel consumption rate of 36.8 kmol/MWh as the current approaches zero, i.e., when no fuel cells are used. With the addition of the fuel cell unit, the specific fuel consumption may be decreased to values below 25 kmol/MWh (a 32 percent reduction).

In this figure, the ordinate (fuel consumption) may be regarded as an operating cost variable; the abscissa (fuel cell unit size) may be considered as a capital cost. Thus, Fig. 3, in that sense, provides the relationship between operating and capital costs. As expected, fuel consumption is reduced with increasing fuel cell unit size.

The results of sensitivity analysis of the performance of this power cycle were shown in the paper by Dunbar et al. (1991). These results, combined with those presented in the foregoing, can be used to estimate the fuel-cell unit sizes for operating conditions which were not considered here.

Conclusions

Topping conventional Rankine cycle power plants with fuel cells was shown to reduce specific fuel consumption by amounts up to 32 percent. It was shown here that for the largest fuel cell unit considered (one which contains 82.7 million arrays), the plant efficiency was 62 percent, almost 50 percent higher than the efficiency of the conventional power plant without fuel cell topping. Since newer fuel cells are actually somewhat more efficient than those modeled here, the predicted efficiency improvements and fuel-cell sizes are conservative. The overall system efficiency increases (and fuel consumption decreases) with fuel cell unit size, primarily because of the effects on combustion efficiency. In addition, it was shown in the previous study (Dunbar et al., 1975) that combustor efficiency increases with fuel cell current and there exists an optimal current at which overall plant efficiency is maximal. Although by no means sufficient, the results given lay the foundation for ensuing thermoeconomic analysis of such power plants. Based on the results presented herein, it is clear that future studies of electrical power generating stations which incorporate fuel cell units are a worthwhile venture.

Acknowledgments

The support of the University of Pennsylvania and of the Society of Automotive Engineers to one of the authors (WRD) is gratefully acknowledged.

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