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An Investigation of the Performance of a Hybrid Turboexpander-Fuel Cell System for Power Recovery at Natural Gas Pressure Reduction Stations

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In order to supply natural gas from long-distance pipelines to local distribution systems it is necessary to reduce the gas pressure. The expansion process produces a temperature decrease which can cause problems on the low pressure side. Therefore, the gas supplied to the pressure reduction system must usually be preheated. A new type of pressure reduction system involving a hybrid turboexpander and fuel cell system has been considered here. In such a system, a Molten Carbonate Fuel Cell running on natural gas is used provide additional electrical power and to partially preheat the gas before it flows through the turboexpander. In studying such a system the natural gas supply for a typical smaller Canadian city has been considered.

1. Introduction

Natural gas is usually transported over long distances at high pressures in pipelines. In order to distribute the gas at points along the pipeline the pressure must be reduced before it supplied to local distribution systems. Currently most pressure reduction stations in North America use expansion valves to produce this pressure reduction. The expansion process produces a temperature decrease which can cause problems on the low pressure side. To avoid these problems the gas must be preheated before passing through the expansion valve. In most cases this is done using a natural gas-fired boiler. To reduce the net energy consumption in the pressure-reduction process the pressure drop can be achieved by passing the gas through a turboexpander which generates electrical power. With a turboexpander system, in most cases, the gas must also be preheated and a natural gas fired boiler is again used for this purpose. A hybrid turboexpander and fuel cell system is a new approach to reducing the energy use in pressure reduction stations. In such a system, a Molten Carbonate Fuel Cell (MCFC) running on natural gas is used to partially preheat the gas. The addition of a fuel cell to the turboexpander system increases both power production and system efficiency. Such a system has been developed by Enbridge Inc. and Fuel Cell Energy and is currently in operation at Enbridge’s headquarters in Toronto, Canada.

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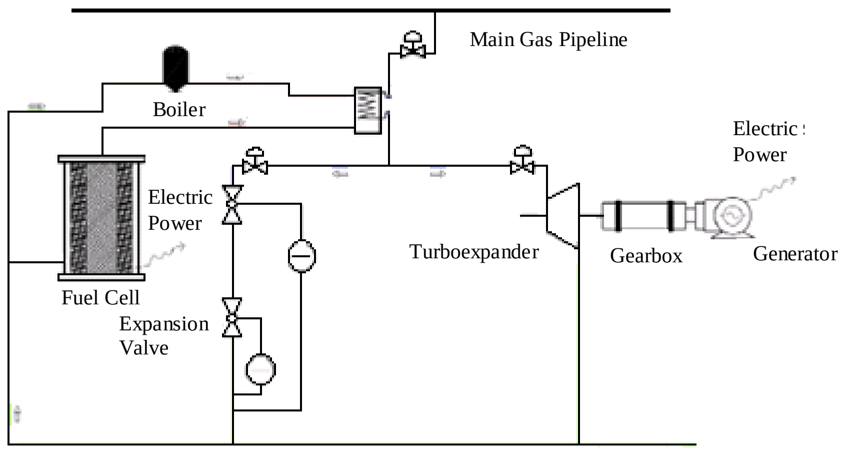

Figure 1: Schematic layout of a hybrid turboexpander-fuel cell system.

The main objective of the present work was to investigate the factors affecting overall performance of hybrid turboexpander and fuel cell pressure reduction systems. MCFCs operate at high temperatures typical MCFC temperatures being close to 650°C. The high temperature operation of the fuel cell allows waste heat to be extracted (O'Hayre et al., 2005). The heat from the fuel cell makes it an excellent candidate for a pressure regulating system using a turboexpander, the fuel cell augmenting or replacing the boiler. Figure 1 shows a schematic of a pressure regulating system using a fuel cell and turboexpander. In such a system high pressure natural gas is diverted to the station from a main pipeline. Before the gas is expanded it passes through a heat exchanger where its temperature is boosted. The preheated gas then flows either to the turboexpander or to the expansion valve or to a combination of the two. The flow allocation depends on the flow limits of the turboexpander. The turboexpander drives a generator in order to produce electric power for the grid. Low pressure natural gas is diverted to the fuel cell. The gas is internally reformed into a hydrogen-rich gas stream that is used by the fuel cell. Electricity from the fuel cell is supplied to the grid. Heat is extracted from the fuel cell. Additional heat is extracted from the boiler if necessary. A heat exchanger then uses this heat to preheat natural gas arriving at the station. The gas exits from the turboexpander or expansion valve at an acceptable temperature and pressure and then passes to the lower pressure distribution network.
The pressure ratio, flow rate, and temperature are important factors in determining the performance of such a hybrid system. To investigate the possible use of such a system in a natural gas supply system for a smaller Canadian city data on gas usage supplied by Utilities Kingston (a smaller city in Ontario with a population of approximately 130,000) was used to perform a simulation of a proposed hybrid natural gas expansion station for the city.

Pressure regulator stations have been modeled in previous work (e.g. Rami et al., 2007) in order to determine optimal operating conditions. In previous work, modeling techniques for conventional and condensing boilers have mainly been based on manufacturer's efficiency curves. A more robust model for in depth simulations has been developed for condensing boilers (Hanby, 2007). Typical of the previous work on modeling turboexpanders for pressure reduction power recovery is that undertaken by Pozivil (2004). That model assumed a steady state. The calculations were based on the isentropic efficiency of the turboexpander, a set flow rate and set inlet and outlet gas conditions. Outputs of the model included electric power. An investigation into the heat exchange network integration in a natural gas expander plant was conducted by Konukman and Akman (2005). The modeling of MCFC systems has been widely investigated. Current models range from very detailed to the modeling of the fuel cell as a simplified component in a larger system (Baranak and Atakül, 2007). Investigations of the effect of load perturbations on the plant efficiency of an MCFC have been made. The simulation results show that operational constraints are satisfied for load cycling over the top 75% load range. Plant electric efficiency is near to the expected value of 50% over this range (Lukas, Lee and Ghezel-Ayagh, 2000). A dynamic simulation of a direct reforming MCFC stack has been carried out (Lukas, Lee and Ghezel-Ayagh, 1999).

2. Present Study

The present study used gas flow data from Utilities Kingston to perform a simulation of a proposed natural gas expansion station in the city. This data was typical of the highly fluctuating and seasonally dependent gas flow situations encountered in Canada. Using this data, performance characteristics of various types of system were simulated. The simulation results include electric power produced and the gas heating requirements over the course of a year. The main objective of this research was to investigate the factors affecting overall performance of hybrid turboexpander and fuel cell systems.

The options considered in the current study for pressure reduction stations in Kingston are:

1. Keep the current expansion valve system
2. Install a turboexpander
3. Install a hybrid turboexpander plus fuel cell system

The first option would retain the current standard pressure let down station. No power would be generated from this system. The station would continue to provide reliable pressure reduction for all flow conditions. Emissions from the combustion boilers would remain. This option does not require any investment in addition to that required for the normal operation and maintenance of the system. The second option considered involves the installation of a turboexpander in parallel with expansion valves in order to deliver reliable pressure reduction with power generation by the turboexpander. Pressure reduction by the system would be reliable for all flow conditions as expansion valves would operate in combination with the turboexpander. Heating requirements would be larger compared to the standard system, resulting in increased combustion emissions from the boilers. This option would require a substantial initial investment but would provide revenue by the sale of the produced electric power. The final option is the installation of a turboexpander in parallel with expansion valves as well as a fuel cell integrated with the heat exchange network. Heating requirements would remain comparable to the single turboexpander option and be fulfilled by the fuel cell and boiler. The efficiency of the system would be greatly improved as waste heat from the cell would be utilized. The integration of a fuel cell into the turboexpander pressure reduction system would require a larger capital investment but would provide more revenue from additional produced electric power.

Data on the operation of a natural gas pressure let-down station for Kingston for several years was provided by Utilities Kingston. This data included hourly measurements of flow rates, inlet pressures and gas temperatures. A time span of one year was selected for analysis and the data used in this study was from 2004. In the simulations the fuel cell system was assumed to operate at a fixed power output.

2.1 Expansion Valve System

This system does not produce any electric power. Fuel consumption over the simulated year was approximately 59339 m^3. This amount of fuel represents about 0.08% of the total gas flow though the station over the year (78647349 m^3). Using a cost of fuel of \$0.40/m^3 the net cost of fuel for this system over a year totals \$23,735.40.

2.2 Single Turboexpander and Boiler System

Total power production of this system over the simulated year was approximately 934908 kWh. Fuel consumption by the boiler over the simulated year was approximately 207232 m^3. This amount of fuel represents about 0.26 % of the total gas flow though the station over the year (78647349 m^3). Again using a cost of fuel of \$0.40/m^3 and a price of electricity of \$0.11/kWh, the net income from this system over a year totals \$10,597.50.

2.3 Single Turboexpander and Boiler System

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Table 1 Effect of turboexpander design flow rate on the performance of a hybrid turboexpander-fuel cell system

Minimum Flow m^3/h	Design Flow m^3/h	Maximum Flow m^3/h	Average Turboexpander Power kW	Maximum Turboexpander Power kW	Fuel Cell Power kW	Average Efficiency %
1250	2500	3500	57.5	76.7	300	65.3
5000	10000	14000	121.0	305.9	300	66.9
6000	12000	16800	131.1	365.2	300	66.4
7500	15000	21000	134.4	457.6	300	65.3
10000	20000	28000	123.1	566.4	300	63.5
11500	23000	32200	107.6	657.5	300	62.2

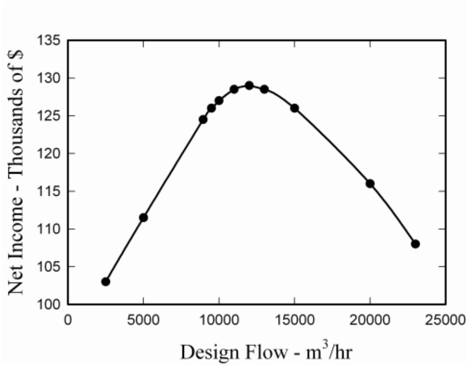

Figure 2: Effect of turboexpander design flow rate on the net income generated over a year by a hybrid turboexpander-fuel cell system.

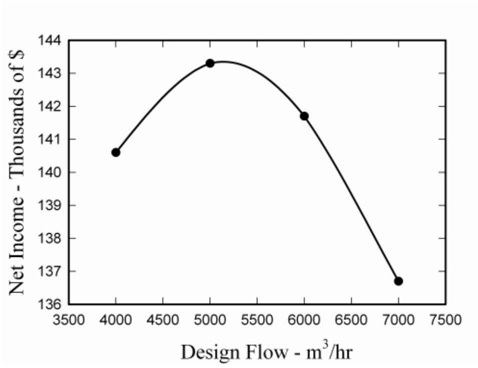

Figure 3: Effect of turboexpander design flow rate on the net income generated over a year by a hybrid turboexpander-fuel cell system with two identical turboexpanders.

Table 2 Effect of turboexpander design flow rate on the performance of a hybrid turboexpander-fuel cell system with two identical turboexpanders.

Min. Flow	Design Flow	Max. Flow	Total Max. Flow	Average Turbo-expander Power	Maximum Turbo-expander Power	Fuel Cell Power	Average Efficiency
m^3/h	m^3/h	m^3/h	m^3/h	kW	kW	kW	%
2000	4000	5600	11200	125.4	235.8	300	71.1
2500	5000	7000	14000	136.6	291.1	300	70.8
3000	6000	8400	16800	138.0	344.5	300	70.0
3500	7000	9800	19600	135.2	408.2	300	68.7
5750	11500	16100	32200	142.0	631.6	300	66.9

2.4 Single Turboexpander and Fuel Cell System

Attention next turned to the hybrid Single Turboexpander/fuel cell system. Table 1 and Figure 2 show performance of such a system with turboexpanders of various design flows. It will be seen from Figure 2 that for this system the highest income for the year is approximately $129,000.

2.5 Dual Turboexpander and Fuel Cell System

Simulations were also undertaken for a system that involved two identical turboexpanders with a fuel cell in order to investigate a system capable of operating over a wider range of flows than the system with a single turboexpander. Results for the dual turboexpander system are given in Table 2 and Figure 3. The fuel cell outputs and inputs are identical to those in the previous simulation case. As Figure 3 shows, the highest income for the year for this system is approximately $143,000.

3. Conclusions

The following conclusions can be drawn from the results obtained using the input data provided by Utilities Kingston for 2004:

1. An existing expansion valve system was simulated as a base case for comparison. The total fuel usage over the one year simulation period for this system was 59339 m^3 and the net cost of fuel for the system over the year was $23,735.
2. The simulation indicated that the addition of a turboexpander to the expansion valve system would produce a net income over the year of $10,597.
3. The addition of a fuel cell to a pressure reduction system has significant effects on its performance. The maximum efficiency of a 12000 m^3/h turboexpander increased by about 10% after the addition of a fuel cell. Difficulties in accommodating fluctuating flow rates and maximizing power recovery over periods of both high and low flows can be overcome by using multiple turboexpanders. This also increases the average system efficiency relative to that for a single turboexpander system.
4. The hybrid turboexpander and fuel cell system was simulated with various sizes of turboexpanders. The sizing of the turboexpander proved to have a significant effect on the overall performance of the system. Based on these results, the system with a turboexpander having a design flow of 15000 m^3/h produced the highest average power over the simulation period. The simulated system using a turboexpander with a design flow of 12000 m^3/h generated the highest net income. Similar relationships were observed with dual turboexpander systems. The highest average power generated occurred with a two turboexpanders system with each turboexpander having a design flow of 11500 m^3/h. The highest net income generated over the simulation period was obtained using a two turboexpanders system with each having a design flow of 5000 m^3/h.

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