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# Operation of an on-site fuel cell power plant using natural gas with excess carbon dioxide

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**Abstract**

In this study, carbon dioxide content of pipeline gas supplied to an on-site fuel cell power plant in the Greater Taipei area is higher than that specified by the manufacturer. This lowers the heating value of the fuel input and thus affects the start-up operation, the energy-conversion efficiency of the power plant, and the transient response to a stepped increase in output power. This paper reports the operation characteristics of the fuel cell power plant under these conditions. It is found that the local gas can be used to operate the fuel cell, but at a reduced net output power. © 1998 Elsevier Science S.A. All rights reserved.

*Keywords:* Fuel cells; Power plants; On-site power; Power-generation efficiency; Natural gas; Carbon dioxide

## 1. Introduction

Fuel cells are the fourth major power-generation technology after hydro, thermal, and nuclear technologies [1]. In spite of their success in space missions [2] since the 1960s, however, fuel cells have not enjoyed similar advancement in terrestrial applications. Other than the two MW-class phosphoric acid fuel cell power plants installed by the Tokyo Electric Power [1,3] in the 1980s for purposes of demonstration as dispersed-type, power-generation applications, their capacity remains in the range of a few hundred to a few thousand kilowatts [4–6], with emphasis on building a fleet of fuel cell power plants of 200-kW capacity [7,8] to penetrate the market of power generation. Even with the more promising molten carbonate fuel cells, the largest capacity of such system to date is still close to 2 MW [9]. But with increasing diminution of fossil fuel resources, as well as ever increasing demands for power generation and environmental concerns worldwide, there is a great need for on-site power plants of smaller capacity that have complete control over power quality, high efficiency in energy conversion, reduction in transmission and distribution losses, and relatively less intrusion to the environment in terms of noise, air and other pollutants [10]. Among present power-generation technologies, fuel cells are very promising [11] because of their automatic and unattended operation, as well as their capability for co-generating electricity and steam.

A phosphoric acid fuel cell power plant manufactured by the ONSI Corporation (model PC25B) is installed in the premises of the Power Research Institute of the Taiwan Power for the study of the possible use of fuel cells as on-site power generation in the densely populated Greater Taipei area. The carbon dioxide content of the pipeline gas supplied to the site is higher than that specified by the manufacturer; this results in a lower heating value of the fuel for the power plant. Consequently, the operations of the power plant are affected in terms of longer start-up time, lower energy conversion efficiency as well as reduced maximum output power. The designed capacity of 200 kW of the power plant can only be achieved with special procedures. This paper reports the characteristics of the fuel cell power plant in start-up and steady-state operations, as well as its transient response to a step increase of output power using natural gas with excess carbon dioxide.

## 2. Operation of on-site fuel cell power plant

The fuel cell power plant installed in this study can be operated in either idle, grid-independent, or grid-connected mode [12]. When the power plant enters the idle mode of

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operation, it is considered as running except that the output power is zero. The total power generated by the fuel cell stack is consumed by the operations of the balance of plant such as the electric heaters which supply heat to sustain the operating temperature of the fuel cell stack, as well as the pumps and blowers that transfer liquids and gases to ensure the functioning of the power plant. For the grid-independent mode of operation, the output of the power plant follows the load to which the power plant is connected. In this study, for the benefits of experimentation, the independent load is a boiler with electric heaters grouped in bundles of different capacity [13] so that steady operations at this different levels of power consumed in the study can be achieved. In the case of the grid-connected mode, the output level of the power plant is set by the operator, and the power plant constantly monitors the conditions of the grid and reacts accordingly with little deviation. Should any abnormal conditions arise in the grid, the power plant is put into a special operation state in which the output power is stopped but remains connected to the grid. If conditions return to normal within a pre-defined time delay, grid-connected operation is resumed at the output power previously set. Otherwise, the power plant disconnects from the grid and either goes to the idle or the grid-independent mode of operation, depending on the instruction given by the operator. It should be noted that for both grid-independent and grid-connected modes of operation, there is still a portion of power generated by the fuel cells to sustain the operations of the balance of plant, so called ‘parasitic power’. Further details of the operation of the power plant, can be obtained from the original manual of the power plant published by the manufacturer [12].

A schematic diagram of the fuel cell power plant is illustrated in Fig. 1. The pipeline gas, after going through the hydro-desulfurising process, mixes with a fixed ratio of steam. The resulting mixture is sent to the reformer and the shift-conversion reactors successively, by the steam ejector EJT010 for the respective reforming and shift-conversion reactions. After these chemical processes, the product viz., hydrogen-rich gas, is fed into the anodes of the fuel cells. With the air going into the cathodes of the fuel cells, d.c. current is produced by electrochemical reactions. The opening of the steam ejector, (measured by the valve ZT010) determines the amount of fuel gas to be converted into hydrogen for the subsequent input to the fuel cells. Therefore, the maximum power generated by the fuel cells fuelled by the pipeline gas of fixed heating value is limited by the maximum opening of the valve ZT010. The unspent gas from the anodes, still rich in hydrogen, is burnt in the

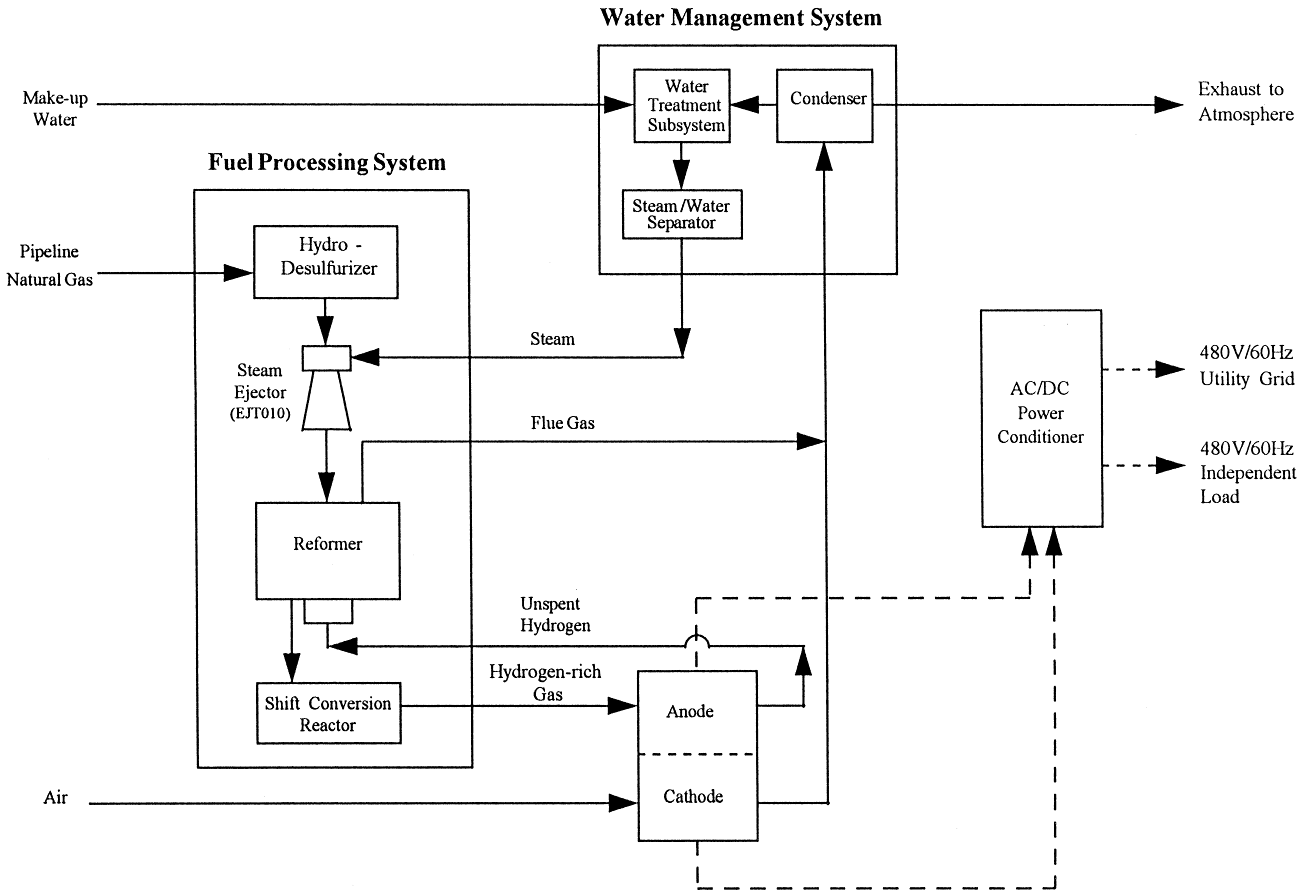


Fig. 1. Schematic diagram of fuel cell power plant.

combustion chamber of the reformer, supplying heat necessary to support the endothermic reforming reactions. The flue gas from the combustion chamber then combines with the cathode effluent and the mixture goes through a condenser where water is reclaimed for use in the steam-reforming process.

A close examination into the system reveals that there are two solenoid valves parallel to the control valve that supply air to the cathodes of the fuel cells. They will be fully opened when a sudden increase of flow of air is needed, as in the case of a sudden surge of output power resulting either from direct instruction from the operator when the power plant is in the grid-connected mode of operation, or as commanded by the independent load during the grid-independent mode of operation. Simultaneously, the flow of anode gas is also increased. The source of extra hydrogen needed for the electrochemical process comes from the product gas of the abovementioned chemical reactions that is held in the piping of the system initially, and is supplemented by the influx of pipeline gas through further opening of the steam ejector EJT010 going into the reformer and the shift-conversion reactor. After the system stabilizes, the two solenoid valves supplying extra air to the cathodes close, the opening of the steam ejector gradually moves towards its steady-state value, and the system is back to normal operation. This particular operation has to be monitored closely because, as a safety precaution, the power plant will be automatically shutdown when ZT010 is measured out of range for more than 5 s. Therefore, the opening of the steam ejector can be considered as a crucial element in the operation of this fuel cell power plant, not only in limiting the maximum power output but also in limiting the rate of increase of output power, especially when the power plant approaches its designed maximum capacity of 200 kW. In such cases, special care has to be exercised in monitoring the status of the opening of ZT010, and small incremental steps of output power can only be made after the opening of ZT010 returns to its steady-state value at the corresponding output power.

As an on-site power plant, model PC25B is designed for automatic, unattended operation, governed by the built-in microprocessor which constantly monitors and controls the operations of the individual components of the power plant according to the procedure designed by the manufacturer. A CRT together with a keypad, installed on the front panel of the power plant, provides the interface for communicating operator commands and displaying operating status. An exact duplication used as an external control station can be set up in a separate location no further than 4.5 km away, such as the control room in this study with a fibre-optic link [14]. A printer port is provided below the keypad so that data shown on the CRT can be transcribed if needed. The displayed data are renewed every 2 to 3 s, but old data of prescribed time settings can be traced in the rolling memory which is designed to hold the history of the performance of the power plant for up to 25 h. Since the software program for transferring the data of the power plant taken by the built-in microprocessor to a separate data-acquisition system for permanent recordings is not available, manual recordings are necessary for analyzing the performance of the power plant, especially for studying its transient responses.

## 3. Experimental method

Understandably, the use of fuel with a different heating value changes the rate of energy input to the power plant at the same designed rate of fuel flow. The start-up time, as well as the maximum output power, of the fuel cell power plant are thus affected accordingly. Further, as will be seen later, the lowering of the heating value of the fuel in this study is the result of the relatively high content of carbon dioxide. This, in turn, increases the partial pressure of carbon dioxide, an inert gas in the electrochemical reaction process, in the anode gas and thus decreases the energy conversion efficiency of fuel cells, as predicted by thermodynamical studies [15,16]. Hence, experiments are set up to study the influence of high carbon dioxide content of the fuel on the start-up and steady-state operations of the fuel cell power plant, as well as on its transient response to a stepped increase in output power.

### *3.1. Start-up*

Normal start-up operation of the fuel cell power plant usually takes about 4 to 5 h, as it is intended to raise the temperature of each component of the power plant from the cool-down state to the respective operating temperature in a moderate fashion, thus ensuring even temperature distribution in each component throughout the heating-up process. Most of the time spent in the start-up process is to heat up the reformer as well as the steam/water separator. At this stage, the temperature of the reformer is raised by burning fuel gas in the combustion chamber. The temperature of the steam/water separator is increased by the water which circulates the low-temperature assembly (LTA) and the coolers in the fuel cell stack, and this water is mainly heated by the four electric heaters in the thermal-management system. Consequently, the fuel cell stack is also brought to its operating temperature by this heat-up process at this stage. It should be noted that, if necessary, the temperature of the fuel cell stack is also maintained by these four electric heaters throughout the operations of the power plant. Hence, the temperature of the reformer and the steam/water separator is closely monitored and recorded during the start-up process in this study.

### *3.2. Steady-state operation*

In order to obtain steady-state results in this study, the power plant is either operated in the idle mode, or in the grid-independent mode when it is connected to the boiler mentioned above over a prolonged period of time in order to minimize disturbances from the open grid. Data are collected through downloading the information on the CRT to a printer for permanent record. These results form the basis of the operation characteristics of the power plant at different levels of output power since they represent the ultimate performance of the fuel cell power plant at the corresponding output power without outside interruptions.

### *3.3. Transient response to a stepped increase in output power*

During grid-connected mode of operation, in the event when the power plant resumes sending the original output power to the grid after interruptions from the grid are cleared within pre-defined time delay, the operation of the fuel cell power plant resembles a stepped increase in output power from its idle mode of operation. Hence, experiments are designed to study the transient response, as well as the maximum output power of the power plant, under such situations. The power plant is first put on idle mode of operation for a prolonged time to achieve steady-state conditions. The net output power is set to a predetermined level before the power plant is abruptly changed from the idle mode to the grid connected mode of operation at the net output power under study, and the data are recorded for further analysis.

The transient response of the fuel cell power plant in both gross and net output power, reformer temperature, as well as the opening of the steam ejector is the main concern of this operation. These data are thus recorded periodically, in shorter intervals initially and gradually in longer periods as the data become more stable. They represent the critical characteristics of the power plant, either in the performance of output power, or in the maximum capacity of the power plant; overshooting the limits set up by the manufacturer would cause serious damage to the installation, thus prompting a shutdown of the power plant automatically by the built-in microprocessor.

## 4. Results and discussion

An analysis of a gas sample taken from the pipeline at the site of the fuel-cell power plant is composed in Table 1 with the specification recommended by the manufacturer [12]. The gas used in this study meets most of the specification except for the high percentage of carbon dioxide, which lowers the heating value of the fuel. The gas does, however, meet the specification provided by the local gas distributor (Chinese Petroleum Corporation, private communications) who also supplies pipeline gas to the densely populated Greater Taipei area. Hence, performing experiments on the on-site fuel cell power plant may well assist a study of the feasibility of applying this new power generation technology in the heart of Taiwan where power is needed most.

### *4.1. Start-up*

Fig. 2 shows the temperature of the reformer during the heat-up process in the start-up operation after the burner is ignited. A similar plot supplied by the manufacturer [12] using nominal gas of slightly higher heating value (8900 kcal $m^{-3}$) is also presented for the purposes of comparison. The temperature rise of the reformer in this study follows the reference information for the first hour, but significantly slows down after 600°C is reached. The total heat-up time for the reformer to reach the designated temperature of 760°C (1400°F) is $\sim$3 h, as against 2.5 h stated in the manual [12]. Hence, initially, the heat-up process of the reformer is little affected by the heating value of the fuel gas, but as the reformer reaches higher temperatures, the effect is more pronounced.

Table 1
Specification and analysis of pipeline gas

| Constituent | Specification, max. | This study |
|---|---|---|
| Methane ($CH_4$), vol.% | 100 | 81.56 |
| Ethane ($C_2H_6$), vol.% | 10 | 4.63 |
| Propane ($C_3H_8$), vol.% | 5 | 1.53 |
| Butanes ($C_4H_{10}$), vol.% | 1.25 | 0.56 |
| Pentanes, hexanes, ($C_5H_{12}$, $C_6H_{14}$, $C_6+$), vol.% | 0.5 | 0.07 |
| Carbon dioxide ($CO_2$), vol.% | 3 | **11.23** |
| Oxygen ($O_2$), vol.% | 2.5 | – |
| Nitrogen ($N_2$), vol.% | 4.0 | 0.42 |
| Total sulfur, ppmv | 30 max/6 ave. | 3.06 |
| Ammonia ($NH_4$), ppmv | 1 | n.a. |
| Chlorine ($Cl_2$), ppmw | 0.05 | n.a. |
| Supply pressure, cm aq. | 10 ~ 36 | ~ 23 |
| High heating value, kcal $m^{-3}$ | 8720 (min) | 8610 |

n.a.: Not analyzed.

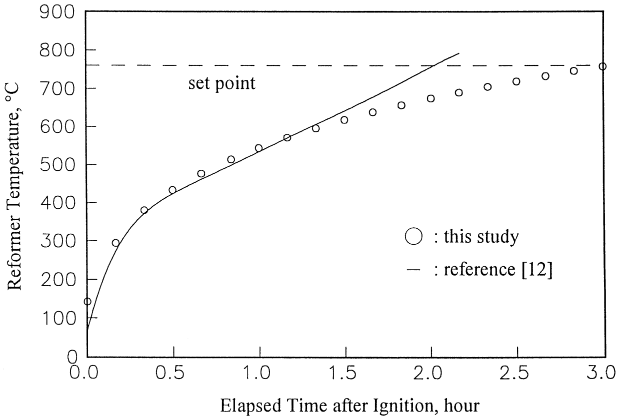


Fig. 2. Temperature profile of reformer during start-up.

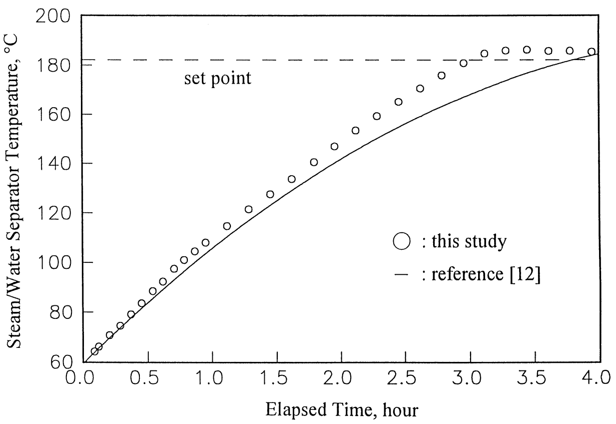


Fig. 3. Temperature profile of steam/water separator during start-up.

The temperature of the steam/water separator during the start-up process is presented in Fig. 3, in which the respective reference information from the manufacturer [12] is also plotted. The temperature rise of the steam/water separator in this study is slightly faster than the reference. Since the steam/water separator is mainly heated by the electric heaters in the thermal-management system, it is concluded that the temperature rise of the steam/water separator during the start-up process in this study is not affected by the heating value of the fuel.

### 4.2. Steady-state operation

Table 2 summarizes the operation characteristics of the fuel cell power plant at different percentages of the rated capacity under steady-state conditions. The parameters listed are important indicators of the operation of the fuel cell power plant and the data represent its ultimate stable performance at different levels of output power. These operation characteristics include net and gross output power, current and voltage of the fuel cell stack, rate of consumption of natural gas, rate of flow of air in the combustion chamber of the reformer, temperature of the reformer as well as the steam/water separator, degree of opening of the steam ejector as measured in percentage of opening of the valve ZT010, the reformer efficiency, and the energy conversion efficiency of the fuel cell power plant.

Most parameters increase as the percentage of rated capacity of the power plant increases, with some exceptions such as the voltage of the fuel cell stack which decreases as the d.c. current increases, as predicted by electrochemical studies [1]. Since the voltage only drops slightly as the current increases, however, the product of voltage and current, which is the total power generated by the fuel cell, increases as the stack current increases. The temperature of the steam/water separator decreases slightly as the net output power increases, and the opening of the steam ejector is recorded because this limits the maximum output power, as explained earlier. Further, although the opening is only 70% at the net output power of 150 kW, it will be seen later that this value could be as high as 90% for a brief period of time during a stepped increase from the idle mode of operation to the same net output power. Hence, the maximum output power of the fuel cell power

Table 2
Summary of operation characteristics of the fuel cell power plant under steady-state conditions

| | Rated capacity, % | | | | | | |
|---|---|---|---|---|---|---|---|
| | Idle | 12.5 | 25 | 37.5 | 50 | 62.5 | 75 |
| 1. Output power, kW | | | | | | | |
| net | 1.0 | 28.6 | 55.3 | 74.8 | 104.2 | 126.2 | 154.2 |
| gross | 56.8 | 85.7 | 104.8 | 104.9 | 121.1 | 141.4 | 69.0 |
| 2. Stack current, A | 253.0 | 391.2 | 486.5 | 481.5 | 565.0 | 675.1 | 840.0 |
| 3. Stack voltage, V | 230.8 | 222.2 | 219.2 | 220.7 | 217.2 | 214.2 | 207.4 |
| 4. Fuel consumption, $m^3$ $h^{-1}$ | 18.8 | 27.4 | 33.3 | 32.7 | 38.3 | 46.0 | 57.4 |
| 5. Burner air flow, kg $h^{-1}$ | 93.6 | 113.2 | 138.1 | 130.7 | 143.6 | 170.7 | 209.1 |
| 6. Steam/water separator temp., °C | 188.2 | 183.9 | 181.9 | 181.7 | 180.3 | 179.6 | 175.5 |
| 7. Reformer temperature, °C | 815.4 | 820.7 | 824.6 | 823.2 | 827.5 | 846.4 | 874.2 |
| 8. Steam ejector opening, % | 22.4 | 26.3 | 29.5 | 29.0 | 33.4 | 42.7 | 70.1 |
| 9. Reformer efficiency, % | 74.6 | 79.4 | 79.4 | 82.1 | 80.4 | 80.0 | 80.3 |
| 10. Electrical efficiency, % | 0.7 | 14.6 | 22.6 | 31.5 | 37.4 | 37.3 | 36.79 |

plant using pipeline gas in the present study is limited to 150 kW for a normal operation without unscheduled shutdown initiated by the full opening of the steam ejector. The reformer efficiency increases slightly as the net output power increases in the range of the lower half of the rated capacity, but remains fairly constant after the net output power of the power plant rises above 100 kW. It should be noted that most of these parameters are related more closely to the gross output power in contrast to the commonly used parameter of the net output power, because the gross output power is representative of the true conditions of the fuel cell stack.

The energy-conversion efficiency of the power plant at different net output power under steady-state operation in this study is presented in Fig. 4 in comparison with the reference information furnished by the manufacturer [12]. The data of the present study using a gas of higher carbon dioxide content is systematically less than that of the reference information, as predicted by thermodynamic studies. The parasitic power of the fuel cell power plant at different levels of net output power under the steady-state operation in this study, measured by the difference in gross and net output power of the power plant, is shown in Fig. 5. The power generated by the fuel cells is largely consumed by the balance of plant at lower output power, until the net output power of the power plant reaches 100 kW, after which the parasitic power is stabilized at around 15 kW. On detailed inspection of the distribution of the power consumed by the different parts of the power plant, it may be seen in Fig. 5 that a large portion of the power is used by the electric heaters in the thermal-management system to keep the temperature of the fuel cell stack at its operating temperature during low output power. For example, in the case of idle mode of operation, where there is no power output and the power generated by the fuel cells is completely consumed by the power plant itself, three heaters are used simultaneously and use approximately 43 kW of electricity out of a total 57 kW of parasitic power. The use of heaters diminishes to about 36 kW in a total 50 kW of parasitic power in when the net output power is 55 kW, and to 14 kW when only one heater is on in the case of 75 kW net output power during which the parasitic power is 30 kW. Beyond the net output power of approximately 100 kW, all four heaters are off because the heat generated by the exothermic electrochemical reactions in the fuel cells is able to sustain the operating temperature of the stack. Hence, the parasitic power of the power plant when operating above 50% of the rated capacity remains relatively constant at about 15 to 16 kW. This parasitic power supports the operations of pumps and blowers transferring fluids and gases in the fuel cell power plant.

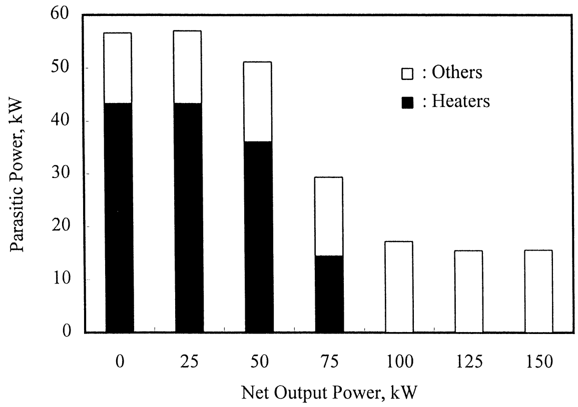


Fig. 5. Parasitic power and electric heater consumption of fuel cell power plant.

The temperature of the reformer at different levels of d.c. current generated by the fuel-cell stack under steady-state operations is shown in Fig. 6. A plot showing the set point of the reformer temperature at different levels of d.c. current, as furnished by the manufacturer [12], is also presented. On increasing the d.c. current of the fuel cell stack, as in the case of increased total power generated by the fuel cells, the temperature of the reformer is raised slightly so that more hydrogen can be produced for the use of input to the fuel cells as anode gas in high-power generations.

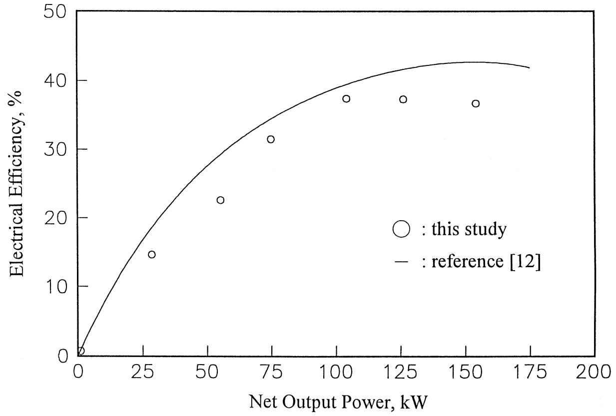


Fig. 4. Electrical efficiency of fuel-cell power plant.

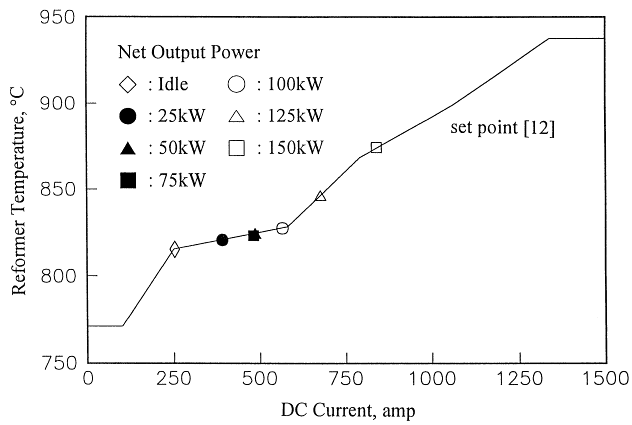


Fig. 6. Reformer temperature vs. d.c. current.

### *4.3. Transient response to a stepped increase in output power*

A critical operation characteristic of the fuel cell power plant in its transient response to a stepped increase in output power is the time required for the power plant to reach the total net output power designated. It is not the scope of this study, however, to measure this real elapsed time to the extent in cycles per second, as it would require more sophisticated instrumentation. The results, as presented in Fig. 7, show that the net output power of the power plant reaches the designated value almost instantaneously in all three cases after the instruction from the operator is made. By contrast, the gross output behaves differently: it takes close to 4 min for the gross output power to reach its steady-state value at a net output power of 100 kW, whereas in the case of net output power of 150 kW, the gross output power reaches its steady-state value almost instantly. As expected, at a net output power of 125 kW, the time taken for the power plant to reach steady-state in gross output power is between the above two values. This is reasonable, as the experiment is designed to change the operation of the power plant from the idle mode under steady-state conditions to the grid-connected mode of operation at a designated level of net output power. In Section 4.2, it was found that the parasitic power of the fuel cell power plant in the idle mode of operation is quite large. By contrast, the parasitic power of the power plant is reduced drastically as the net output power rises above 100 kW. The difference, as seen earlier, is the power used by the electric heaters in supplying heat to sustain the temperature of the fuel cell stack. It is known that the heat generated by the exothermic electrochemical reactions in the fuel cell at a lower net output power (i.e., 100 kW) is less than that at a high net output power (i.e., 150 kW). Therefore, the gross output power of the power plant takes longer to settle to its steady-state value in the case of the lower net output power, and this time diminishes as the net output

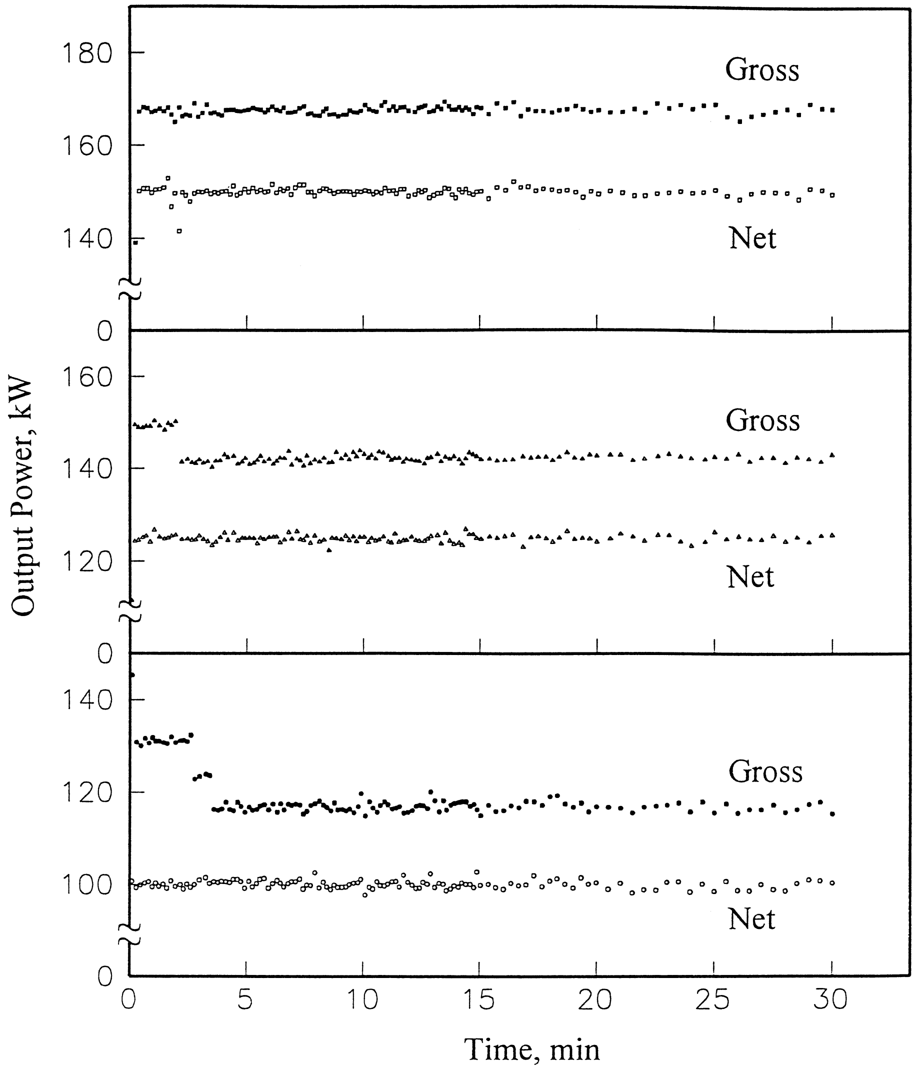


Fig. 7. Transient response of the fuel cell power plant in net and gross output power.

power increases when the fuel cell power plant is abruptly changed from its steady idle operation to the grid-connected mode of operation.

As seen earlier, there is a rise in the reformer temperature from 815 to 874°C when the fuel cell power plant changes from the idle mode of operation to a net output power of 150 kW under steady-state conditions. Therefore, in order to operate this power plant within safety limits, close attention should be given to the transient response of the reformer temperature during a stepped increase in output power. The results are presented in Fig. 8. On a stepped change from a steady idle mode of operation to a low level of net output power, e.g., 100 kW, the temperature of the reformer overshoots the target value and then recedes. After a few damping cycles, it approaches a steady-state value within a comparatively short time of 30 min. In the case of stepped changes from a steady idle mode of operation to higher net output power such as 125 kW and 150 kW, the rise in reformer temperature is more complicated. Nevertheless, the time required for the reformer to reach its steady-state operating temperature is approximately the same as before, viz., 30 min. The control logic for the rate of increasing the reformer temperature under this operation condition is not available from the manufacturer. It can only be suggested that limiting the rate of increase of the reformer temperature certainly protects the structure of the reformer, which is important to the operation of the fuel cell power plant.

As mentioned above, the other concern over the operation of the fuel cell power plant in its transient response to a stepped increase in net output power from the steady idle mode of operation is the avoidance of an unscheduled shutdown due to the steam ejector becoming fully opened. Fig. 9 shows the response in the opening of the steam ejector to the command in changing the power plant from a steady idle mode to a grid-connected mode of operation at a net output power of 100, 125 and 150 kW, respectively. The data show that the steam ejector opens more than the steady-state value initially at lower net power output and then returns to this value in a relatively short time. At a higher output level of 150 kW; however, the steam ejector first opens to the steady-state value for the first 7 to 8 min and then opens much wider to an almost 90% opening for a brief period of time and then closes back to the steady-state value. The experiment at 125 kW shows a combination of the two scenarios mentioned above. Again, it is not the aim of the present study to investigate the control logic designed by the manufacturer. The results prove, however, that because of the full opening of the steam ejector, the power plant using the pipeline gas in this study is able to perform a sudden increase from an idle mode to a grid-connected mode of operation at a net output power of 150 kW without shutting down the system.

From a comparison of the results of the operation of the fuel cell power plant in its transient response to a stepped increase in output power, as shown in Figs. 7–9, it is found that the electric power output reaches its designated value much faster than the corresponding chemical reactions that support the change to be stabilized. It takes seconds for the power plant to send out the designated value of output power (Fig. 7), whereas it takes almost 30

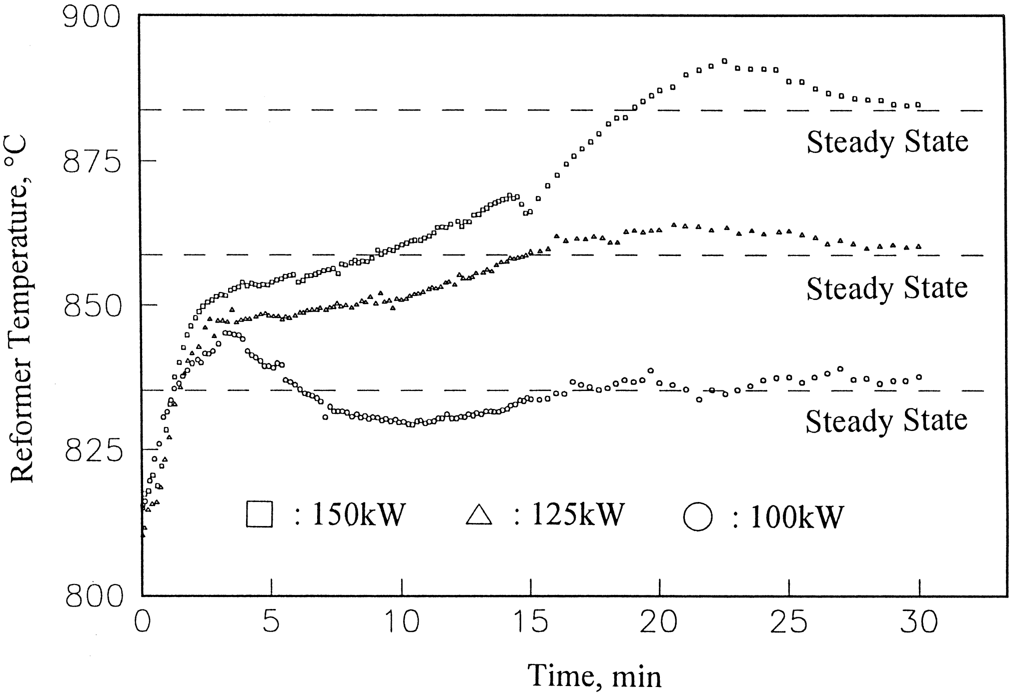


Fig. 8. Transient response of fuel cell power plant in terms of reformer temperature.

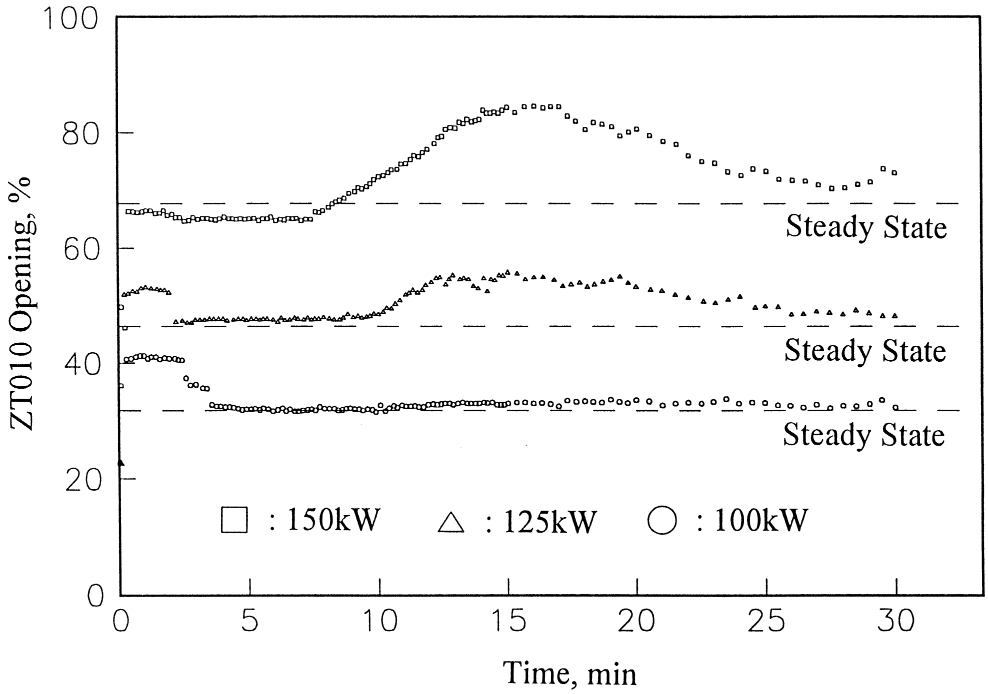


Fig. 9. Transient response of fuel cell power plant in terms of opening of valve ZT010.

min for the reformer to be steady (Fig. 8) and about the same time is taken for the opening of the steam ejector to reach its steady-state value (Fig. 9). This indicates of the stabilized chemical reactions in the fuel-processing section.

## 5. Conclusions

From experiments performed on using natural gas with excess carbon dioxide in the start-up and steady-state operations, as well as the transient response to a stepped increase in output power of an on-site fuel cell power plant, the following four major conclusions can be drawn.

(i) The use of pipeline gas with an excess carbon dioxide content on the operation of an on-site fuel cell power plant extends the start-up time, lowers the energy conversion efficiency and reduces the maximum output power.

(ii) In operating an on-site fuel cell power plant, it is crucial to monitor the opening of the steam ejector, as it may cause unscheduled shutdown of the power plant. In the present studies, when using fuels of marginal heating value, the rate of increase of output power should be limited to avoid automatic shutdown of the power plant due to full opening of the steam ejector, especially when the net output power is close to the rated capacity of 200 kW. In such cases, the opening of the steam ejector corresponding to the similar levels of the output power under steady-state conditions can be used to determine the rate of increase of the net output power.

(iii) For a stepped increase in output power, the time needed for the power plant to generate the net output power at a designated level is much shorter than that required for the chemical reactions to supply the necessary reactants for electrochemical power generation.

(iv) The pipeline gas supplying to the Greater Taipei area in Taiwan can be used to operate on-site fuel cell power plants similar to the one studied here, but at a reduced net output power.

## Acknowledgements

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## References

[1] A.J. Appleby, F.R. Foulkes, Fuel Cell Handbook, Van Nostrand-Reinhold, New York, 1989.
[2] M. Warshay, P.R. Prokopius, The fuel cell in space, yesterday, today and tomorrow, J. Power Sources 29 (1990) 193–200.
[3] K. Shibata, The Tokyo Electric Power Company (TEPCO) fuel cell evaluation program, J. Power Sources 37 (1992) 81–99.
[4] E.A. Gillis, American fuel cell market development, J. Power Sources 37 (1992) 45–51.
[5] H. Nymoen, PAFC demonstration plants in Europe: first results, J. Power Sources 49 (1994) 63–76.

[6] K. Shibata, K. Watanabe, Philosophies and experiences of PAFC field trials, J. Power Sources 49 (1994) 77–102.
[7] J.M. King, Jr., L.J. Bonville, G.J. Sandelli, Application of continuing phosphoric acid fuel cell technology growth to an improved PC25 power plant, Program and Abstracts, 1994 Fuel Cell Seminar, 1–4, November 28–December 1, 1994.
[8] D. McClelland, T. Cook, C. Berry, P. McGrath, S. Legedza, K. Spitznagel, S. Sanders, B. Herzog, R. Quick, A. Plonka, D. Rider, L. Wittrup, R. Brown, First commercial fuel cell fleet: experience, lessons learned, and future perspective, Program and Abstracts, 1994 Fuel Cell Seminar, 11–14, November 28–December 1, 1994.
[9] M. Faroogue, R. Bernard, P. Patel, A. Shok, C. Yuh, J. Doyon, H. Maru, Direct carbonate fuel cell development, Program and Abstracts, 1994 Fuel Cell Seminar, 234–237, November 28–December 1, 1994.
[10] G.P. Merten, S.P. Breen, Application Guide for Fuel Cells in Commercial Buildings, Gas Research Institute, Chicago, 1985.
[11] Y.C. Cheng, Y.T. Cheng, Feasibility study on the applications of phosphoric acid fuel cells to commercial buildings, Monthly J. Taipower's Eng. 559 (1995) 36–49, (in Chinese).
[12] PC25B On-Site Fuel Cell Power Plant—Service Manual, FCR-12966, ONSI, South Windsor, CT, 1994.
[13] PAFC Power Plant Peripheral Equipment and System Planning and Design Manual (in Chinese), Fu-Tai Engineering, Taipei, 1994.
[14] PC25B On-Site Fuel Cell Power Plant—Installation Manual, FCR-12917, ONSI, South Windsor, CT, 1994.
[15] J.H. Hirschenhofer, D.B. Stauffer, R.R. Engleman, Fuel Cells—A Handbook, US Department of Energy, Morgantown, WV, 1994.
[16] C.Y. Hsuan, A thermodynamic analysis of solid oxide fuel cells (in Chinese), MS Thesis, Yuan-Ze Institute of Technology, Chung-Li, Taiwan, 1995.