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Literature Review of Thermal Control and Utilization
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Fuel cells (FCs) are quiet, compact power generators without moving parts, which use hydrogen and oxygen to make electricity, and at the same time, can provide thermal energy. Although FCs are a key component of hydrogen systems and the power generation efficiency of the fuel cell is at most 50%, the rest of the energy is converted into thermal energy. That is, in general equal amounts of thermal and electrical energy are generated by a system using a fuel cell. Therefore, effective use for the waste heat of fuel cells is necessary to enhance the value of the system.

Wu and Wang [1] pointed out that with relatively low-quality waste heat, proton exchange membrane fuel cells (PEMFC) are unlikely to be widely used for high voltage stationary power generation. They are, however, particularly suitable for small-scale domestic CHP (combined heat and power) / or CCHP (combined, cooling, heating and power) applications – the simplest thermal load of which is hot water. In the case of solid oxide fuel cells (SOFC), the high operating temperature makes internal reforming possible and they produce high-grade waste heat suited well to CCHP applications. However, the high temperature also creates some difficulties: expensive alloys for components are required, and start-up takes a very long time.

In terms of thermal control and utilization of the hydrogen system, three kinds of system are introduced and reviewed here: 1) CHP/CCHP system with PEMFC, 2) CHP/CCHP system with SOFC, and 3) thermal coupling of PEMFC with a hydride storage tank.

1) CHP/CCHP system with PEMFC

Bao et al. [2] numerically analyzed water and thermal management in a PEMFC system of which the main components include the cell-stack, radiator, and humidifier. They pointed out that the air stoichiometric ratio and the cathode outlet pressure are key parameters for the water and thermal management of FC system. As the air stoichiometric ratio (i.e. flow rate) increased and the cathode outlet pressure increased, the cell-stack performance is improved. The thermal loads of heat exchanger (radiator) also depend on these two parameters. The optimum air stoichiometric ratio and cathode outlet pressure should be obtained by taking into consideration the parasitic power of the system such as the fan power of radiator. However, the parasitic power is much less than that of the air compressor, so the trade-off between the cell-stack performance and the air compressor power is dominant.

"The Large-scale Stationary Fuel Cell Demonstration Project in Japan" [3] helped advance the performance of residential PEMFC systems steadily during the four-year period from 2005 to 2008, culminating in the milestone of a market launch in 2009. In this project, a unit consists of a reformer, PEMFC, and a hot water tank. Fossil fuel (natural gas, liquefied petroleum gas, or kerosene) is reformed to hydrogen and 1kW PEMFC operates at each residential site. Electricity produced by the PEMFC is only used within the household where the PEMFC is installed. In order to supply both electric power and heat efficiently, many residential PEMFC systems operate in the so-called Daily Start and Stop (DSS) mode: they start in the morning, operate during the day, and shut down sometime in the evening as the hot water tank becomes full. Thus, the FC power generation is largely dependent on the heat demand. In summer, the power generating time and power output decrease as the heat demand goes down. This means the FC power supply ratio (supply divided by household demand) generally declines in summer even though the electricity demand goes up in summer.

There is also a demonstration micro-CHP project in Lolland, Denmark — the "Hydrogen Community Lolland" [4]. In the first phase of this project (2005 - 2007), micro-CHP using two PEMFCs (electrically rated at about 2kW and 7.5kW) were coupled with two 4kW PEM electrolyzers and gas (hydrogen and oxygen) storage units. Hydrogen was produced by the PEM electrolyzers using wind power (via grid) and stored in a low-pressure tank (~5bar). Oxygen was also stored in a tank and utilized in a water purification process for municipal waste water. In the second phase (beginning in 2008), approximately 13 PEMFC micro-CHP systems will be installed in residential houses, and there will be a hydrogen pipeline connecting the hydrogen tank and each residential site. Although the control strategy of this system is not clear, they have a lot of options compared to that of the Japanese project. This is because they have a relatively large tank of hydrogen storage (25 Nm^3) and electricity generated by PEMFC can be exported to the grid.

Beausoleil-Morrison and Ferguson et al. [5,6] proposed introducing thermally activated cooling (TAC) equipment into residential CHP systems for utilizing excess heat in summer to deliver useful cooling to the dwelling using CCHP technology.

Lessons learned

In general, the utilization of waste heat from a PEMFC is not easy and limited to the on-site demand because the operating temperature is relatively low (~80°C). On the other hand, the start-up time is short. Although the hot water supply is the most realistic option to date, the versatility and autonomy of the system can be improved when the thermal energy can be utilized within the system. Thermal coupling of PEMFC and a metal hydride tank is one prospective option.

2) CHP/CCHP system with SOFC

Riensche at al. [7, 8] carried out an energetic and economic analysis of SOFC cogeneration power plant in the range of around 200 kW of capacity. How the costs of electricity (COE) and plant efficiency depend on changes in different cell operation parameters were determined. This included the influence of increases in air temperature in the stack, the degree of internal reforming, cell voltage and fuel utilization (i.e., the fraction of fuel entering the stack that reacts electrochemically). A detailed analysis of the variation of cell parameters in case of a simple flow without gas recycling (the base case) revealed that:

1) when external reforming is replaced by complete internal reforming the COE reduces by nearly 50%,

2) when the air temperature increases inside the stack from 100 to 150K, the COE reduces by about 20%,

3) when the fuel utilization is adjusted from 80% to an optimal value of 65%, the COE reduces by about 5%.

Akkaya et al. [9] numerically analyzed a SOFC/GT CHP system composed of a SOFC stack, a gas turbine (GT), and a heat recovery steam generator.) Important parameters such as fuel utilization factor, current density, air compressor pressure ratio, and minimum temperature difference between the temperature the gas flow at the pinch point[1] and the saturation temperature were analyzed across a wide range of values to gain an insight into their influence on the performance of the system. In addition, to evaluate the design performance of the system, a new criterion is proposed, namely, the exergetic-performance coefficient (EPC) that is defined as the ratio of total exergy output to the loss rate of availability.

Yu et al. [10] presented a model analysis of CCHP system consisting of an internal reforming SOFC stack, heat exchangers, a combustor, and an absorption chiller. This total system provides power, cooling and/or heating simultaneously. The results show that the cooling efficiency increased when the current density is increased, while the electrical efficiency and total efficiency decreased under the same conditions. The

[1] The point where gas flows to the economizer (where waste heat is extracted) from the evaporator that supplies water vapour to the reformer.

electrical efficiency and total efficiency reaches a maximum value when the fuel utilization factor is 0.85, while the cooling efficiency reaches a minimum value.

Lessons learned

In contrast to the system using PEMFC, there are many options in constructing a cogeneration system using the SOFC because the operating temperature is relatively high (800~1000°C). Systems can include a gas turbine, a steam generator, and an absorption chiller. Although the most important parameter depends on the configuration of the system, the fuel utilization is a significant parameter regardless of the configuration. An optimal value of fuel utilization may lie between 0.65 and 0.80.

3) Thermal coupling of PEMFC with a metal hydride storage tank

Jiang et al. [11] studied the dynamic behaviour of a thermally coupled metal hydride tank storage and PEMFC system used in a hybrid electric vehicle. Their simulation results show that a relatively small increase in the operating temperature of a metal hydride bed, by transferring heat from the FC to the metal hydride tank, had a significant and positive effect on increasing the pressure in the bed. This sustained higher pressure improved the utilization of stored hydrogen because the pressure of the bed was able to stay above the lowest operating pressure of the FC for a longer period of time.

T. Førde [12] presented modelling and simulation work on integrated electrolyzer/metal hydride tank/ FC systems, based on an integrated system operated by Takasago Thermal Engineering Co. of Japan. A case study where hydrogen is produced via water electrolysis during night time with grid power, stored in a metal hydride tank, and converted back to electricity with a FC during daytime, was simulated in detail using verified models with calibrated system parameters. A special control strategy that regulates the water flow rate through the metal hydride, keeps the hydrogen gas pressure in the bed sufficiently high.

M. Masuda et al. [13] proposed another control strategy using the same system configuration as Førde, in which an endothermic reaction of metal hydride during hydrogen discharge is used for cooling in a commercial building. The system has three sources of cooling: turbo chillers using power from the FC, absorption chillers using waste hot heat from the FC, and an endothermic reaction of the metal hydride. The system performance is compared to the existing technology such as the ice storage system (ISS) and the co-generation system combined with absorption chillers (CGS). The simulation results show that the proposed system achieves higher total energy efficiency.

Lessons learned

As described above, the thermal coupling of PEMFC with a hydride storage tank is a prospective option for an enhancement of system versatility. In general, transferring heat from the FC to the metal hydride tank during desorption is appropriate for a stationary application. The desorption of hydrogen absorbs heat and is useful in locations where it is relatively hot and cooling is valuable.

Conclusions

The type of fuel cell used depends more on the heat requirements of a site than on the electrical requirements. Exporting electricity to the public network allows much more flexibility for controlling fuel cell systems and improves their efficiency. Using heat for cooling increases the running time of a fuel cell.

If metal hydride storage is used, heat from the fuel cell can be used to increase the pressure and improve the release of hydrogen. Heat from metal hydride storage can also be used for heating or cooling. The use of metal hydrides as a storage medium therefore may be most appropriate when heat can be supplied or utilized when the hydride is being charged or discharged, respectively.

Different means of measuring the performance of fuel cell systems are proposed. There is often a compromise to be achieved between the efficiency of heat or power produced and the overall efficiency.

The demands of the users of a hydrogen system play a key role in the control strategy and performance of a system and can be regarded as a human/technical interface.

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Thermal coupling PEMFC and hydride tank

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