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THERMAL MANAGEMENT IN SOLID OXIDE FUEL CELL SYSTEMS

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ABSTRACT

In a solid oxide fuel cell (SOFC) system operated at relatively high-temperature, its thermal management is a key issue due to the following twofold reasons; one is based on appropriate/safe operations and maintenance of the system, while the other relates to efficient use of thermal energy which is necessary for high-performance distributed power generation. In this paper, the thermal management of the SOFC system is discussed basically and systematically. First, the mass and energy balances of the SOFC system are analyzed on the basis of a simplified model. Next, according to the quantitative knowledge obtained by the above analysis, all the components included in the system are discussed. That is, in addition to various heat exchangers for fuel, water/steam vapor, air and exhaust gas, thermal problems relating to a reformer, cells/stack and insulation of the entire system are addressed.

1. INTRODUCTION

Development of a solid oxide fuel cell (SOFC) system recently shows remarkable progress particularly in the field of distributed generation systems (Singhal & Kendall, 2003). Since the efficiencies of the fuel cells do not strongly depend on the output power, SOFCs with small output power on the order of 1kW are available in laboratories. Also, the SOFCs with larger output power on the order of 10-100kW have been extensively studied. Because of the relatively higher operating temperature of the SOFCs than those of other kinds of fuel cells, they have advantages such as high-efficiency cogeneration and preferable combination with turbines. Hence, the hybrid systems consisting of a SOFC and a turbine are considered to be one of the most ideal distributed generation systems (Suzuki & Iwai, 2003).

Although the operation temperature of the ordinal SOFC using yttria-stabilized zirconia (YSZ) as electrolyte material is 900-1000 °C, intermediate-low-temperature types working around 700 °C have been currently developed using

- scandia-stabilized zirconia (ScSZ)
- lanthanum gallate
- rare-earth-doped ceria (ReDC)

as alternatives of YSZ. The operation at intermediately low temperature, that is, still higher than those of other kinds of fuel cells but lower than those of the conventional SOFC, is attractive in terms of quicker start-up and shut-down, and also of reduced thermal stress and applicability of metallic materials and glass-based sealants (Eguchi 2004).

At present, development of advanced materials for electrolyte, both anode and cathode electrodes and interconnect is a main concern for the researchers in this field to achieve a high-performance and robust stack. In SOFC systems, however, thermal management of the entire system is also crucially important. This is because the thermal management is required first for appropriate/safe operations and maintenance of the system and second for efficient use of energy which is required to the distributed power generation system. Nevertheless, to the authors' knowledge, comprehensive information on the thermal management on the SOFCs is very limited, while Shah (2003) and Magistri et al. (2005) discuss the related problem. Therefore, in this paper, we aim at describing the thermal management in the SOFC systems basically as well as systematically.

2. PRELIMINARY REMARKS

2.1 Overall Thermal Management and Heat Sources

Prior to the discussion of the various components included in the system, we first refer to the fundamental aspects of the SOFCs.

Clearly, the one of the most principal points of the thermal management is to maintain the stack temperature at a certain level to obtain the reasonable ion conductivity of the electrolyte.

Therefore, associated with the above-mentioned point, it is also important to effectively insulate the whole system or the container from the surroundings.

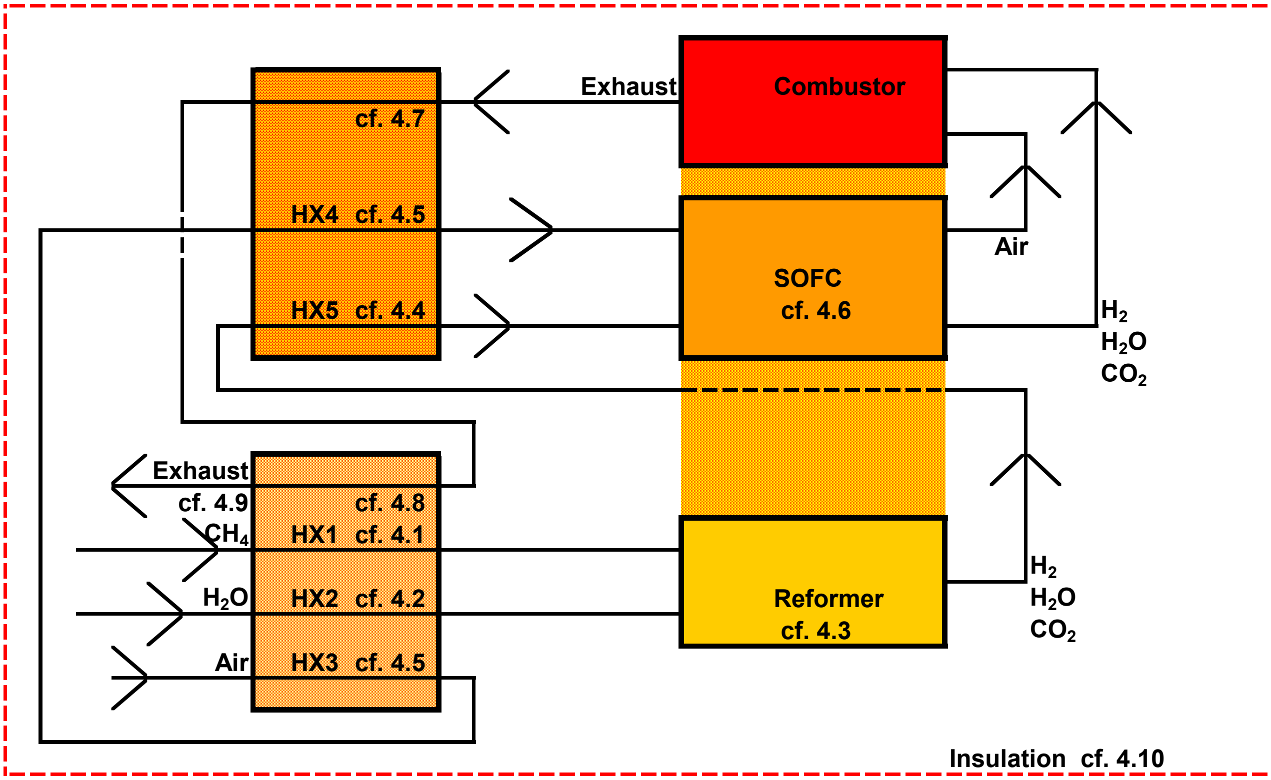

Figure 1 Simplified model of SOFC system.

In view of the quick response of the system, however, it should be noted to reduce the heat capacity of the whole system or the container as much as possible.

Next, attention is focused on the heat source. The major heat sources inside the SOFC system are the cells themselves. Certain portion of thermal energy is released as a result of electrochemical reactions at the electrodes, while the overpotential losses and the Joule heating further increase the cell temperature. There is another important heat source that is obtained by the combustion of the fuel exhausted from the cells. In the SOFC, not all supplied fuel is consumed in the cell. Fuel utilization factor, or the fuel consumption rate, is typically around 0.8 (could be less) and the rest of the fuel is burnt downstream the cell, producing additional thermal energy.

2.2 Components in SOFC System

Figure 1 shows a model of a SOFC system on which quantitative as well as qualitative discussion is made in the following chapters. Unlike the actual SOFC systems, components shown in Fig. 1 are simplified just to have nearly equivalent functions corresponding to the actual one; individual heat exchangers required for various working fluids are divided into two groups depending on the working temperature. According to the flows of the working fluids, we discuss the components listed below. Each number at the end of each component (i.e., 4.1 - 4.10) corresponds to the section number where it is discussed.

- preheater for fuel (HX1): 4.1
- steam generator (HX2): 4.2
- reformer: 4.3
- superheater for hydrogen (HX5): 4.4
- preheater for air (HX3 & HX4; low-temperature sides): 4.5
- cells and stack: 4.6
- recuperator for exhaust gas at high temperature (HX4; high-temperature side): 4.7
- recuperator for exhaust gas at low temperature (HX3; high-temperature side): 4.8
- waste heat recovery (Exhaust): 4.9
- insulation: 4.10

3. QUANTIFICATION OF MASS AND ENERGY FLOW IN SYSTEM

To obtain a quantitative image of the system, we consider the mass and energy flow of the system. The system studied is a simple and ideal one. The following assumptions were made to find its basic feature. Fuel is pure methane supplied at room temperature. It is preheated and supplied to the reformer with water vapor. The steam reforming and shift reaction expressed as follows

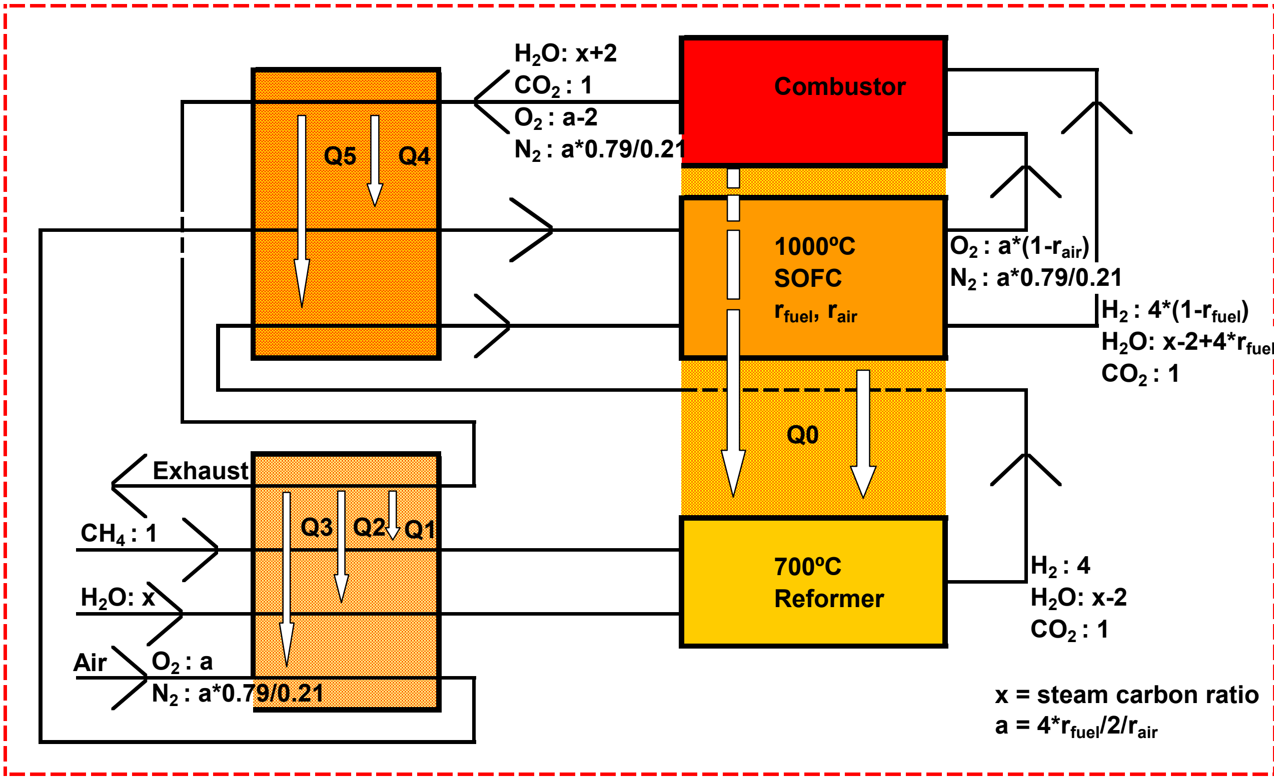

Figure 2 Mass (mol) balance of SOFC system.

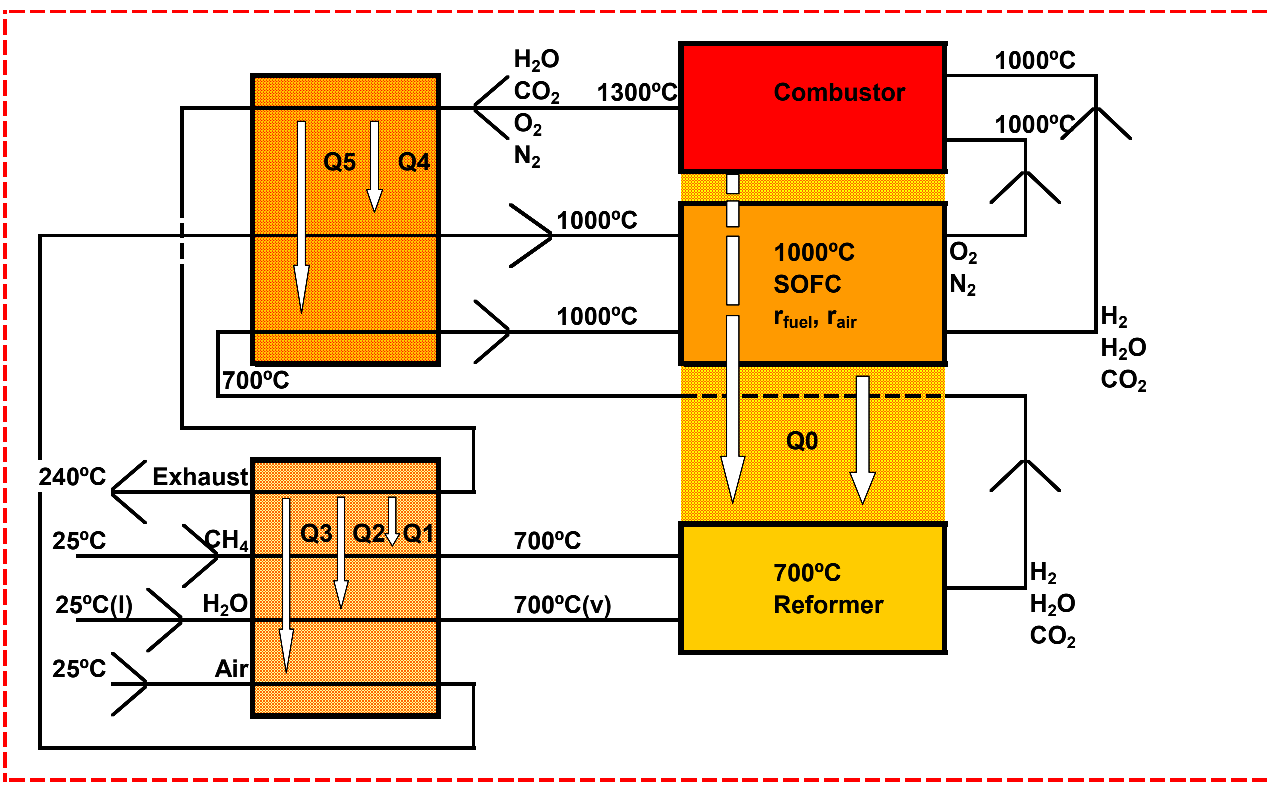

Figure 3 Energy balance of SOFC system.

Reforming reaction: $CH_4 + H_2O \leftrightarrow 3H_2 + CO$

Shift reaction: $CO + H_2O \leftrightarrow H_2 + CO_2$

are assumed to completely move to right hand side in the reformer, producing reformed fuel made of only hydrogen, steam and CO_2. The S/C (steam carbon) ratio at the reformer inlet is x. Reformed fuel is further heated and fed to SOFC where hydrogen in the fuel reacts electrochemically with oxygen ion. Not all hydrogen is consumed in fuel call. r_{fuel} is the fuel utilization factor, and typically takes a value around 0.7-0.8. Hydrogen that is not consumed in the SOFC is burned in the combustor in the simplified system considered. The required amount of air can be calculated if we set an air (oxygen) utilization factor, r_{air}. Supplied air is a mixture gas of N_2 and O_2 which molar fraction is 0.79 : 0.21.

Figure 2 shows the amounts of chemical species at various locations of the system for one mol input of methane calculated under the above assumptions. A symbol a in Fig. 2 is the amount of oxygen supplied. Molar fraction of steam (H_2O) in the exhaust gas and exhaust gas temperature are important information when a latent heat recovery is planned.

Figure 3 shows the energy balance of the system. Here we further assume the followings. SOFC is a single stack of 50 cells connected in series. Each cell has 100cm^2 active area. It is operated at a current density of 300mA/cm^2. Total overpotential loss in single cell is 0.2 V. Utilization factors of fuel and air are set at r_{fuel} = 0.75 and r_{air} = 0.25, respectively. S/C ratio, x, is 3. Operating temperatures of the reformer and SOFC are assumed to be constant and uniform at 700ºC and 1000ºC, respectively.

Heat generation by shift reaction in the reformer, electrochemical reaction and overpotential losses in SOFC, combustion of the remaining hydrogen are estimated on the basis of the above assumptions; some portion of it is supplied to the reformer, as shown as Q_0 in Fig.3, to drive the steam reforming process that is a strong endothermic reaction. If the rest portion of the generated heat is used to raise the gas temperature, it reaches around 1300ºC. Thermal energy of this hot gas is utilized to preheat the fuel and air flows as shown in Fig.3 as Q_1 to Q_5. Under the above-mentioned conditions, the exhaust gas temperature is estimated to be around 240ºC.

Figure 4 shows the energy generation in a system described above. Negative value means consumption of energy. As can be seen, this system generates about 1 kW output power. The system efficiency is about 47% (LHV). Figure 5 shows the molar fractions of the exhaust gas for the same condition. Molar fraction of H_2O is about 0.15. From the view point of latent-heat recovery, a higher molar fraction of H_2O is preferred. The effects of air utilization factor and S/C ratio on the molar fraction of H_2O in the exhaust gas are shown in Fig. 6, keeping the fuel utilization factor at 0.75. Clearly the molar fraction of H_2O is higher for a larger S/C or air utilization factor. Larger S/C ratio, however, requires vaporization of additional amount of H_2O

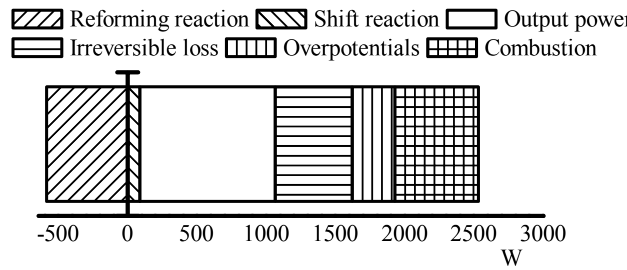

Figure 4 Energy generation in a system.

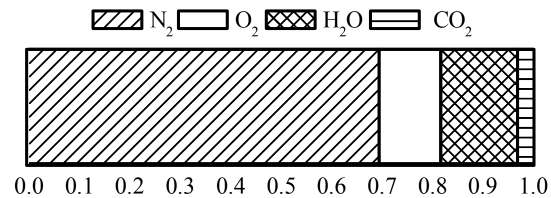

Figure 5 Molar fraction of exhaust gas.

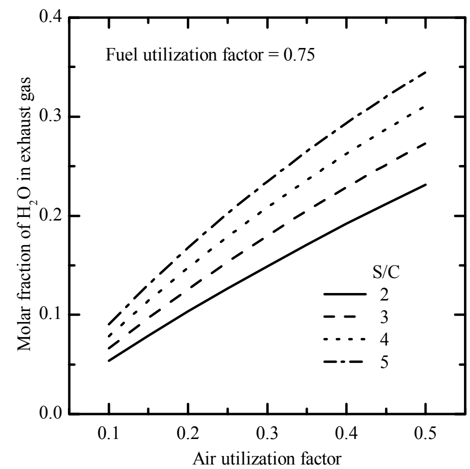

Figure 6 Molar fraction of H_2O in exhaust gas.

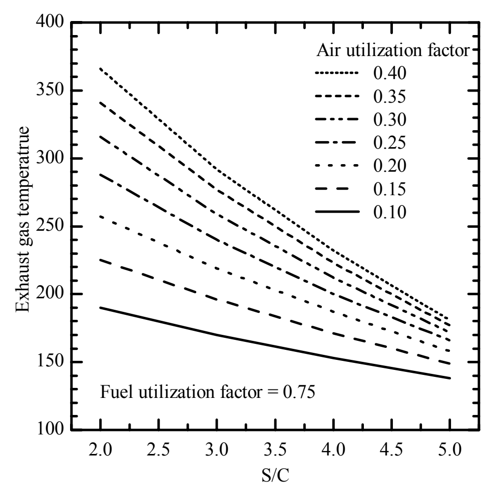

Figure 7 Exhaust gas temperature estimated for fuel utilization factor 0.75.

which consumes additional thermal energy and consequently makes the exhaust gas temperature lower. This can be clearly confirmed from Fig. 7 that shows the effects of air utilization factor and S/C ratio on the exhaust gas temperature. Increase in the air utilization factor has favorable effect to increase the exhaust gas temperature, and it is more prominent at smaller S/C ratio. Larger S/C ratio also results in a lower molar fraction of H_2 in the fuel flow, that results in a lower EMF. Therefore we basically want to choose lower S/C ratio within a limit where coking does not take place, and want to increase air utilization factor. Increase of air utilization factor actually means the decrease of air flow rate which saves pumping power of air flow too. However, it may make the thermal control of the cells more difficult because the air flow has a role as coolant of the cells.

4. THERMAL MANAGEMENT

In this chapter, we will address the features and required functions to the components listed in 2.2.

4.1 Preheater for Fuel (HX1)

Methane should be heated up to 600 °C to drive reforming reaction at the reformer. This is done by heat exchange between the methane and the burned gas. The pressure of supplied fuel (methane) would be different at each place (country). Unnecessary pressure drop must be avoided in any case; this is more important at a place where the supplied pressure is low. Use of additional compressor is an option but it directly affects the system cost.

4.2 Steam Generator (HX2)

Water vapor is needed to reform the fuel (methane). Clean water is supplied at room temperature and it is heated, vaporized and further heated to reach the reforming temperature. Therefore HX2 in Fig.2 is actually a combination of steam generating part (evaporator) and its heating part. Steam and methane is separately heated and introduced to the reformer in this figure, but they may be mixed and heated up together before they enter the reformer. The steam carbon ratio of this fuel flow is x. A larger x results in a smaller molar fraction of hydrogen in the fuel flow resulting lower electro motive force. Too small x on the other hand may cause coking problem on the anode electrode.

4.3 Reformer

When internal reforming is employed, enough steam should be supplied for steam reforming reaction, and also the system needs to have an evaporator to produce the steam. Steam reforming is a strong endothermic reaction and consumes roughly 20% of the heat generated in the system, which makes the thermal management of the system more complicated. Heat supply to the reformer needs to be ensured on a change of the system operating condition. Concerning the fuel processing for fuel cells, an excellent review is presented by Song (2002).

4.4 Superheater for Hydrogen (HX5)

The reformed fuel is super heated to reach the SOFC temperature. A high-temperature heat exchanger between the reformed fuel and the burned gas is needed.

4.5 Preheater for Air (HX3 & HX4; low-temperature sides)

Air needs to be preheated before it is introduced to the SOFC. This is done by heat exchange between the fresh air and the burned gas. Because air flow has a role as coolant to adequately remove heat generated at the cells, its amount and temperature at the SOFC inlet are important factors and must be controlled. There is a lower limit for the cell inlet temperature to keep effective ion conductivity of the electrolyte. Therefore its temperature at the preheater outlet should not be too low.

Due to the change of the system operating condition such as load change etc. the air flow rate may be changed during the operation, which may increase the difficulty in designing the heat exchanger, since above-mentioned temperature control should be achieved at any operating condition. Small heat capacity of the heat exchanger itself is desired. Lowering the pressure drop is beneficial to reduce pumping power. Unless the system is a pressurized one, the pressure difference between hot and cold flows is small.

4.6 Cells and Stack

The one of the weak points of the SOFC is that the electrolyte material of the cell is ceramic. Hence, thermal stress associated with non-uniform temperature distribution due to rapid external heating is not desirable. The relatively long transient time for start-up and shut-down, usually more than 10 hours, is required because of this problem.

Furthermore, since the cell is composed of three layers with different thermal expansion ratios (anode, electrolyte and cathode), it deforms or may crack in the worst situation even if the uniform temperature condition. Although the deformation is better than the crack, the insufficient contact for electrical current is a serious problem for the SOFC. Deformation can also cause problem in sealing the flows.

To obtain high conductivity for ion, the cell should be kept at high temperature allowable to the material; however, the local hot spot which shorten the life time of the cell should be avoided also for steady-state operation. Under the condition without external heating, the cell temperature is determined by the balance of

- heat generation due to electrochemical reaction,
- heat generation due to overpotential and,
- Joule heat
- cooling mainly by air flow.

If internal reforming is applied it affects the cell temperature as the steam reforming is a strong endothermic process. Increasing the air flow rate is an easy and straightforward choice to establish a uniform temperature distribution, which requires more pumping power though. Optimization of the air flow passage is important for effective use of the coolant (air).

Problem that is not apparent in a cell level can arise in a stack level. Temperature distribution in stack level can become non-uniform due to the heat loss to surroundings and its heat supply to the reformer. Fuel and air flows should be supplied evenly to cells in a stack. The importance of taking the deformation problem into account is not limited for the cells. It is important for other parts of the system like interconnects, headers, manifolds etc. just like high-temperature heat exchangers. To avoid flow leakage and trouble in collecting current, the thermal expansion coefficient of materials must be chosen as close as possible.

4.7 Recuperator for Exhaust Gas at High Temperature (HX4; high-temperature side)

In fuel cells, not all the supplied fuel is consumed and typically 20 to 30 % of fuel remains unused. Recirculation of the remaining fuel is one option. In a simple system considered in this paper, however, it is burned at the combustor resulting highest temperature in the system. Enthalpy of the burned gas should be effectively used to keep high system efficiency. High temperature heat source is required in the system to heat up the air and fuel flow entering the fuel cell.

4.8 Recuperator for Exhaust Gas at Low Temperature (HX3; high-temperature side)

Other requirements for thermal energy include preheating of methane, water evaporation, steam preheating, air preheating at relatively low temperature and reforming reaction. In this paper we treat that the heat required for reforming process is directly supplied from SOFC and combustor as indicated as Q_0 in Fig.3. Preheatings at relatively low temperature are completed by heat exchange with the burned gas led from the high temperature heat exchanger outlet.

4.9 Waste Heat Recovery (Exhaust)

Waste heat recovery is also important when the system is utilized as a cogeneration system. Use of absorption refrigerator is possible for larger system. For a small system like the one treated in this paper, energy recovery as hot water is the most realistic option. The heat exchanger will be between liquid water and exhausted gas. Latent-heat recovery will be important since the exhaust gas contains some portion of water steam. Although the molar fraction of H_2O in the exhausted gas is depending on the operating conditions as shown in Fig.6, it typically takes value of 0.1 to 0.15. From the Fig.8 which shows the Dew point at a partial pressure of steam vapor, the steam in the exhaust gas begins to condense around 45 to 55°C. This is relatively low and we want to increase the molar fraction of H_2O in exhaust gas.

When air utilization factor and S/C ratio are kept constant, larger fuel utilization results in a larger molar fraction of H_2O. However as a power generating device a larger fuel utilization factor is generally preferred in fuel cell system. Therefore increase of the air utilization factor seems to be advantageous as show in Fig.6. One possible drawback is that a larger air utilization factor means a smaller amount of air as coolant of the cell. It may cause a trouble in controlling the cell temperature and its distribution.

4.10 Insulation

In a developing stage of the SOFC system, more attention is paid to run or keep running the system than to study its details like energy budget. Because SOFC is a high temperature-type fuel cell, the temperature difference between the cell and surroundings is large which leads a possible leak of a large amount of thermal energy. Eliminating such thermal loss to the surroundings is a very important issue not only because it affects the exhaust gas temperature but, in the worst case, a system may have trouble to sustain its operation temperature if thermal leak becomes larger. Clearly the situation is more severe for small systems owing to larger relative surface area. Power generation efficiency of SOFC system seems promising but a bad handling of the thermal energy will limit the total energy efficiency.

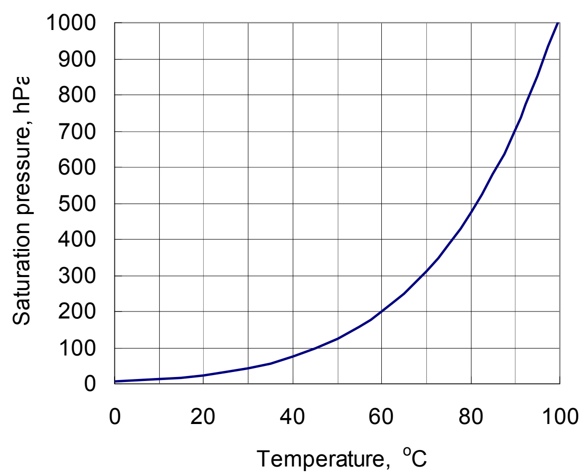

Figure 8 Temperature vs saturation pressure of water (Dew point vs partial pressure of steam vapor).

5. ADDITIONAL CONSIDERATIONS AND OPTIONS

Above discussion is based on a very simplified system shown in Fig.1. Reflecting the fact that it is not yet clear how the SOFC system will be used in the future, there are many variations in actual systems discussed today; capacity, cell geometry, operating temperature, operating pressure, sealing, fuel variation, reforming method, fuel/air recirculation, waste heat utilization etc. In general, a simple system configuration is preferred to ensure its robustness and reduce its cost. For example, reducing the number of the heat exchangers will lower the cost. Followings are some other points not mentioned in the above sections.

- System dynamic analysis needs to be conducted in detail. How the operating condition changes and what are their effects?
- Intermediate temperature SOFC will open a way to use of metallic components. It will lower the cost of the system.
- Thermal radiation is believed to play an important role but its effects are not fully understood. Further investigations are needed.
- To increase power density of the system, planner type geometry has advantage. Higher power density means a higher heat generation density and therefore thermal management will become more severe and important.
- Small systems are likely to be operated in cogeneration mode. It is important to find effective ways to use waste heat.
- Small systems will experience start-up/shut-down more frequently. Durability will be an important issue.
- To improve time response of the system, heat capacities of cell/stack and heat exchangers need to be reduced.
- Concerning the issue related to the hybrid system with microturbines, the reader should consult the papers by McDonald (2000, 2003).

6. CONCLUSIONS

The thermal management of an SOFC system has been discussed. On the basis of the simplified analysis, the fundamental characteristics of the flows of working fluids and thermal energy balance in the system have been clarified. Heat-exchangers required for the system are listed and their features and functions have been discussed. Related to the temperature control of the cells/stack, cell/stack-level thermal problems have been addressed.

NOMENCLATURE

a	: air amount $= 4\,r_{fuel}/(2r_{air})$ [mol]
Q_0	: heat supplied to reformer [W]
Q_1	: heat exchanged between exhaust gas and CH_4 [W]
Q_2	: heat exchanged between exhaust gas and H_2O [W]
Q_3+Q_4	: heat exchanged between exhaust gas and Air [W]
Q_5	: heat exchanged between exhaust gas and H_2 [W]
r_{air}	: air utilization factor
r_{fuel}	: fuel utilization factor
x	: S/C (steam carbon) ratio

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