Proposal of the Atmospheric Pressure Turbine (APT) and High Temperature Fuel Cell Hybrid System

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Solid oxide fuel cell (SOFC) has been extensively developed in many countries as an ultra-high efficient energy converter. Such high temperature fuel cell can be operated as a hybrid system of integrating of turbo machinery. A major decision is whether to place the cell stack in pressurized or unpressurized section. This paper discusses the exhaust energy recovery from fuel cells by use of turbo machines under unpressurized conditions, working with inverted Brayton cycle in which turbine expansion, cooling by heat exchanger and draft by compressor are made in an open cycle mode. It is denoted as “atmospheric pressure turbine (APT)”.

Key Words: Atmospheric Pressure Turbine, Inverted Brayton Cycle, Solid Oxide Fuel Cell, Hybrid System

1. Introduction

Gas turbines operate on the Brayton cycle, which begins with compression, heat addition and terminate in expansion. In the inverted Brayton cycle, the processes are reversed in which expansion first occurs and then heat of the working gas is extracted by a heat exchanger and sucked by a fan or compressor. The working principle of this cycle has been explained fully by Hodge(1) and Wilson(2). However, no body has paid attention because the thermal efficiency of cycle is very low. No hardware of test rig has been constructed. On the contrary, many efforts have been concentrated only on the Brayton cycle, mainly in improving the performance of turbomachinery and combustors for the past decades in the real world.

Users of gas turbines have spread in many other sectors than aircrafts, which include land industries, marines, vehicles and electric power generation. Heat energy of exhaust gas would be extremely large and therefore retrieved by co-generation system in modern industrial gas turbines. The co-generation is made by hot water and/or steam as a result of using hot gas as a heat source at turbine exit. Gas energy must be once changed and stored into the state of hot water and vapor for use in the co-generation in a system of Brayton. On the other hand, there may be a possibility for re-utilization of exhaust gas directly as a shaft horsepower working with gas substance if the inverted Brayton cycle can be adequately used.

The authors have already conducted the basic experiment on the inverted Brayton cycle(3), and proceed to evaluate conceptually its applications and potentialities of a new combination of Brayton/inter cooled inverted Brayton cycle on a basis of thermal efficiency(4), (5).

Hybrid heat engines are power generation systems in which a heat engine, such as a micro gas turbine, is combined with a non-heat-engine, such as a fuel cell. The resulting system exhibits a synergism in which the combination performs with an efficiency that far exceeds that which can be provided by either system alone. Thus the combination performs better than the sum of its parts. The hybrid system has been extensively analyzed over the past few years(6) – (11). They have revealed that this combination is capable of providing remarkably high efficiencies. This attribute, combined with an inherent low level of pollutant emission, suggests that hybrid systems are likely to serve as the next generation of advanced power generation systems.

The solid oxide fuel cell (SOFC) is a simple electrochemical device that operates at 1000°C, and is capable of converting the chemical energy in natural gas fuel to the electric power at high efficiency more than 50% when operating in a system at atmospheric pressure. Since the SOFC exhaust gas has a temperature of approximately 850°C, the SOFC generator can be synergistically
integrated with a gas turbine (GT) engine-generator by supplanting the turbine combustor and pressurizing the SOFC, thereby enabling the generation of electricity at efficiencies approaching 60% or more. Conceptual design studies have been performed for SOFC/GT power systems employing a number of the small recuperated gas turbine engines that are now entering the marketplace.

Recently recuperative inverted Brayton cycle has been proposed by authors and denoted ATP (Atmospheric Pressure Turbine). This paper addresses the coupling of an APT with an SOFC in its present state of revolution.

2. APT (Atmospheric Pressure Turbine)

2.1 Inverted Brayton cycle

The jet engine for aviation and the gas turbine are working on Brayton cycle, as shown in $Ts$ diagram of Fig. 1. They take the air in the state of 1, and exhaust at the state of 4. This is an open cycle. If this process is followed inversely as shown in $Ts$ diagram of Fig. 2, it begins from turbine expansion first, and an axial horsepower can be extracted. This is called inverted Brayton cycle. However, no body has paid attention because the thermal efficiency of cycle is very low at that time.

2.2 Intercooling of compression process

The technique of cooling at intermediate processes of compression has been sometimes employed to raise the overall thermal efficiency of gas turbines. However, lowering of air temperature in entering combustor requires much larger fuel flow rate than that before cooling, particularly in case of high turbine inlet temperature and high values of adiabatic efficiency of turbomachinery with large pressure ratio. Therefore, the intercooling gives sometimes no benefit. On the contrary, there is no burning in the inverted Brayton so that the thermal efficiency becomes always higher as the strength of a heat sink by the intercooling is much more increased. It can be fairly said that the inter-cooling is surely an effective way to improve the thermal efficiency only in the inverted Brayton machine. It is revealed that three steps of inter cooling may be most efficient from a viewpoint of engineering. The thermal efficiency of 30 percent or more would be possible at turbine inlet temperature of 1 273 K with component efficiency of 0.9, which is an 8% improvement in thermal efficiency from the uncooled cycle mentioned previously. In the above discussions we assume no flow loss in all cooling down processes for simplicity. It can be then considered that such losses would be included in compressor and/or turbine adiabatic efficiency.

2.3 Atmospheric pressure turbine

The proposed atmospheric pressure turbine (APT) is illustrated in Fig. 3. The suction air preheated in the recuperator by exchanging heat with turbine exhaust gas. And thereafter, the combustion process takes place at ambient pressure as opposed to the conventional gas turbine, where the combustor operates at elevated pressure (more than 3 bar in micro gas turbine). In the APT, the larger specific volume results in larger dimensions and fortunately this makes it possible to count on better component efficiencies such as compressor and turbine compared to those of micro gas turbine, which is similar in size.

Moreover, it is an advantage that turbine inlet is at atmospheric pressure and a possibility of paving the way for use of the unused heat source or utilization of the energy sources for which the operation under pressurized condition was difficult. For this reason, authors dub herein the whole cycle as an APT (Atmospheric Pressure Turbine).

Figure 4 is a calculation of indicating the effect of pressure ratio of APT on thermal efficiency for three values of turbine inlet temperature (TIT). It is assumed that
the temperature efficiency of 0.95 may be possible in the
gas-to-liquid heat exchange, the pressure loss coefficient
of 0.03 at each passage of heat exchangers, and adiabatic
efficiencies of compressor and turbine are fixed to 0.85.
More than 35% optimum thermal efficiency is possible at
TIT of 1 000°C.

3. Hybrid System

The system layout and Ts diagram of the SOFC/APT
hybrid system are shown in Figs. 5 and 6, respectively.
SOFC, which uses a natural gas as fuel, is located at up-
stream of the turbine. Exhaust heat is recuperated by the
heat exchanger with suction air at ambient temperature
and pressure. Furthermore, a fraction of natural gas is
burned with suction air and the combustion gas flows into
the cathode. A natural gas also flows into an anode after
preheating.

Since the exhaust gas from SOFC contains residual
fuel, it is burned in another burner located downstream
of SOFC, therefore TIT can be raised further. In this cal-
culation, as the turbine inlet temperature is fixed constant,
fuel flow rate is assumed not to be constant. Moreover,
although the electric efficiency of SOFC is influenced by
cell operating pressure, pressure is fixed at atmospheric
pressure in the hybrid system here. While, the influence
of the cell reaction temperature is assumed to be linear
function(12).

As a reaction within SOFC is an exothermic, exces-
sive heat is used to preheat suction air so that it leads to
decrease of the required fuel flow. Figure 7 shows the overall
thermal efficiency and SOFC working temperature versus
the pressure ratio of APT with turbine inlet temperature
of 1 273 K, temperature efficiency of a cooler of 0.8, adia-
batic efficiencies of turbomachinery of 0.85, and 5 percent
pressure loss in SOFC. At these conditions, more than 65
percent overall thermal efficiency can be expected.

From this figure, the optimum pressure ratio of APT
is found to 3.6 at fuel utilization factor of 0.85. This value
is reasonable for APT system. In the case shown above,
SOFC working temperature is around 800°C, so that the
additional fuel must be burned at the burner to keep tur-
bine inlet temperature at 1 273 K.

The effect of heat loss from SOFC on the thermal ef-
ciency is shown in Fig. 8. When a pressure ratio is fixed,
the thermal efficiency is decreased by 0.5 percent for one
percent increase of the heat dissipation loss from SOFC.
The effects of heat loss from SOFC on thermal efficiency is shown in Fig. 8. The influence of fuel utilization factor on air/fuel ratio is shown in Fig. 9 for three values of air utilization factor at the turbine pressure ratio of 3. The air/fuel ratio increases with the fuel utilization factor.

The relation between turbine inlet temperature and air utilization factor is shown in Fig. 10. In the analysis, the power output level is assumed to be rather small (less than 100 kW) so that the turbine blade cooling is not supposed. The turbine inlet temperature, therefore, is limited to less than 1 273 K. From this figure the air utilization factor is found to be approximately 0.3 and the required air/fuel ratio is greater than 50.

Figure 11 shows the overall thermal efficiency. Due to limitation of turbine inlet temperature, then air utilization factor of 0.3, the expected value is 0.65 approximately.

The fuel utilization efficiency versus turbine pressure ratio is depicted in Fig. 12 with three fuel utilization factor. The optimum pressure ratio for maximum fuel utilization efficiency decreases with increases of fuel utilization factor. This is favorable terms for APT. The maximum fuel utilization efficiency of 0.78 approximately can be expected.

Here, the hot water/fuel flow rate ratio is shown in Fig. 13. The cooling of turbine exhaust gas is a key factor for APT (or inverted Brayton cycle). In this analysis, the fresh water of 15°C is assumed to be used as cooling medium and heated up to 80°C. If there can be much hot water, it means that higher fuel utilization efficiency can be realized.
4. Conclusions

The following conclusions can be made based on the analyses performed in this study.

(1) The total thermal efficiency (electric efficiency) based on a SOFC/APT hybrid power system can be expected more than 65 percent. The fraction of APT output to overall output is approximately one fifth.

(2) The optimum pressure ratio of a hybrid system becomes low compared to that of individually operating APT. This is attributed predominantly to the decrease of the recuperative heat by the temperature drop of exhaust gas at turbine outlet.

(3) It is found that the operating conditions for SOFC/APT hybrid system are as follows; air utilization factor of 0.3, fuel utilization factor of 0.8 for fixed turbine inlet temperature of 1273 K and turbine pressure ratio of 3.

(4) Since the reforming reaction in SOFC proceeds at high temperature environment, it becomes important to reduce heat dissipation loss. When a pressure ratio is fixed, the thermal efficiency is decreased by 0.5 percent for 1 percent increase of the heat dissipation loss from SOFC.

References