High Pressure Combustion Test of Gas Turbine Combustor for 50MWth Supercritical CO_2 Demonstration Power Plant on Allam Cycle

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ABSTRACT

Toshiba Energy Systems & Solutions Corporation is developing a combustor and turbine for a novel power generation system that can capture CO_2 while generating power at high efficiency while using supercritical CO_2 (sCO_2) as working fluid. The combustor is designed to generate 1150degC and 30MPa at turbine inlet condition for a 50MWth demonstration plant. Direct combustion system generates sCO_2 combustion gas by high pressure oxy-fuel combustion method. To confirm combustion performance under sCO_2 environment and in order to validate the design, testing has been done at various conditions of inlet parameters. The experimental maximum conditions were about 90 bar and 900 degC at combustor exit conditions, and this is equivalent to the middle load condition of the turbine. This combustion test campaign covered from initial ignition to tested maximum load condition with good operation and performance, and we confirmed a successful combustion performance under sCO_2 environment of Allam cycle.

1. INTRODUCTION

As one of the measure to prevent global warming, the reduction of CO_2 emissions through thermal power plant is necessary. Increasing CO_2 emissions from a thermal power plant has been a problem, the industrial shift from thermal power supply to renewable power supply is expanding. However, to keep stable grid control, the renewable power supply may require a backup by thermal power generation, in which new construction opportunities are limited. Hence thermal power supply is counterpart of renewable power supply and the research and development for reducing CO_2 emissions have been continued as well.

One of the direction is increasing thermal efficiency, such as the combined cycle of gas turbine and steam turbine configuration, which results in a reduce fuel use, and can reduce CO_2 emissions. Furthermore, development of a more advanced cycle of unifying SOFC (solid-oxide fuel cell) and combined cycle power generation is carried out, and this is called the "triple combined cycle" which may improve thermal efficiency greatly [1]. CCS (carbon recovery and storage) is separating CO_2 in a combustion exhaust gas with a chemical method, and is one of the technology which reduces the CO_2 emissions from a thermal power plant. However, the energy for carrying out scavenging of CO_2 is required, therefore the thermal efficiency of a plant goes down. In order to transport CO_2 collected by this system and to use for commercial benefit, application of pressure is needed. This pressurization process requires large energy. Application of the supercritical CO_2 closed-cycle technology to a thermal power plant is one of the most effective method of generating power, without discharging CO_2 outside. Echogen electric power system develops the supercritical CO_2 cycle which adopted the heater and the non-combustion system [2] and Sandia National Laboratories are advancing research on an efficient Brayton cycle by the supercritical CO_2 cycle using solar heat, a nuclear heat source, and a fossil fuel heat source [3].

Supercritical CO_2 turbine system (Allam Cycle) proposed by NET Power can collect CO_2 with high purity, without losing the energy by compression, and can attain high thermal efficiency (equivalent to the existing combined cycle plant) [4][5][6][7][8][9]. In this cycle, natural gas and oxygen reacts to CO_2 and H_2O in a combustor. The exhaust gas then drives a turbine with the mixed gas of CO_2 and H_2O which are combustion gas. After the combustion gas that carried out turbine driving passes a recuperator, H_2O is separated, and it is compressed with a compressor, and part of CO_2 is separated and collected. After the temperature increase of the remaining combustion gas is carried out by a recuperator, it is again supplied to a combustor. This cycle enables realization of an ideal near-zero-emission power-plant system. NET Power, Exelon, McDermott, Oxy Low Carbon Ventures, and 8 Rivers are developing the plant using this new cycle, and are building the demonstration power plant. Toshiba is in charge of development of important high pressure combustor and turbine in this system. This project is advanced through the following three steps.

- Development of the Oxy-fuel combustion technology in supercritical CO_2.
- Operation of the 50MWth demonstration plant for the confirmation of performance, operability, and reliability of this cycle.
- Construction of a commercial plant, utilizing the knowledge of 50MWth demonstration plant.

Toshiba carried out the full pressure (30MPa) burning test of 10MWth burner of 1/5 scale [10][11], and manufactured the combustor and turbine for 50MWth demonstration plant.

Since the combustion test of the combustor of a real scale was carried out at the demonstration plant before operating plant, we report about these results.

2. OVERVIEW of SUPERCRITICAL CO_2 POWER GENERATION SYSTEM

The outline of this supercritical CO_2 power generation system is explained using Figure 1. In this system, natural gas, coal gasification gas, etc. can be used as fuel, and these fuel gases are burned with the oxygen separated from air with air separation unit. Fuel and oxygen burn in the condition of stoichiometric fundamentally, rotate a turbine with high pressure and high temperature combustion gas of carbon dioxide (CO_2) and steam (H_2O) from a combustor, and a turbine drive a generator. The combustion gas which came out of a turbine is cooled in a cooler inside of a cycle, a plant is operated while extracting CO_2 and H_2O generated from C (carbon) and H (hydrogen) which are contained in fuel. The method of extracting CO_2 only extracts CO_2 which circulates through the inside of a cycle. CO_2 can be extracted without adding energy. Toshiba has furthered design and examination about fundamental issue like material, basic structure, cooling method etc., to develop a combustor and a turbine. The gas turbine consists of seven stages of nozzles and blades, and one can of combustor. Since it becomes operation in 30MPa, the casing has adopted the double casing (double shell structure) which is experienced with a USC steam turbine. The gas turbine where it installed to the demonstration plant is shown Figure 2.

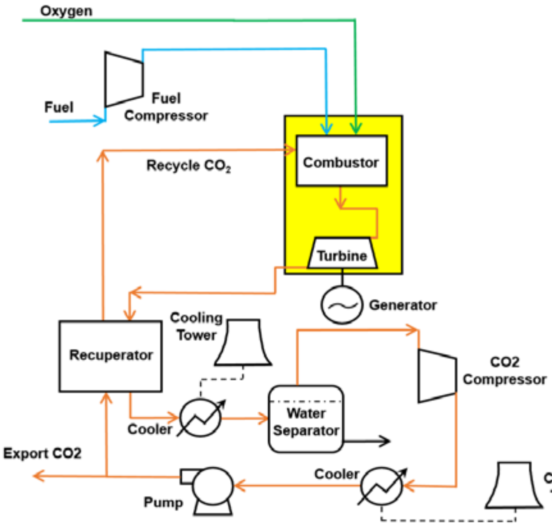

Figure 1: Allam Cycle Pilot Plant Flow Diagram

Figure 2: Installed Turbine at demonstration Plant

3. GAS TURBINE COMBUSTOR for SUPERCRITICAL CO_2 POWER GENERATION

In conventional gas turbine combustor which is widely used for power plant, the maximum working pressure is about 2 MPa, however, the maximum operation pressure of the gas turbine combustor in this supercritical CO_2 cycle power generation system has been 30MPa. Thus the main development subjects to a high pressure combustor is as follows.

1) Validate blow out point in CO_2 atmosphere include after passing a recuperator, and water (H_2O) is separated. After the remaining CO_2 is pressurized with a compressor and a pump, it is made to hot condition by a recuperator, and is again supplied to a combustor. Although a great portion of CO_2 circulates through the supercritical condition and combustion characteristic like unburned fuel etc...

2) Validate cooling characteristic for combustor wall metal temperature.

3) Validate combustion dynamics.

Since the combustion phenomenon in supercritical CO_2 atmosphere has many unknown points at 30MPa, on actual pressure conditions, the combustion test of output 1 / 5 scale model was carried out on actual pressure condition, and it has so far checked about the development subject. In addition, the combustion test was carried out using the actual scale combustor as a performance check before installing in an actual turbine.

3.1 Actual Scale Combustion Test

Since big amount of CO_2 is needed, the actual scale combustion test is carried out using facility of demonstration plant in U.S. Texas. The cycle is shown in Figure 3. Combustion test Rig is installed next to the turbine, the fuel for a combustion test has branched from the supply line to a turbine, and it is in the state where the gas turbine portion of the demonstration plant replaced combustion test rig, during the combustion test. Therefore, the exhaust gas from combustion test rig was sent to the actual recuperator and return to combustion test rig, thus combustion tests are carried out by closed cycle operating condition like an actual plant.

In a power plant, combustion gas works in a turbine and then temperature and pressure decline.

However, at combustion tests, since there is no turbine, the temperature is decreased by CO_2 dilution and the pressure is reduced by a simulated nozzle and a pressure control valve. Therefore, from restriction of a plant facility, maximum pressure is 10MPa and maximum temperature at the combustor outlet is also lower than full load rating, and it becomes a maximum of 55% of full load rating with a heat output. Under this restriction, grasp of the combustion characteristics and confirmation of operability from ignition to a supercritical condition can be carried out.

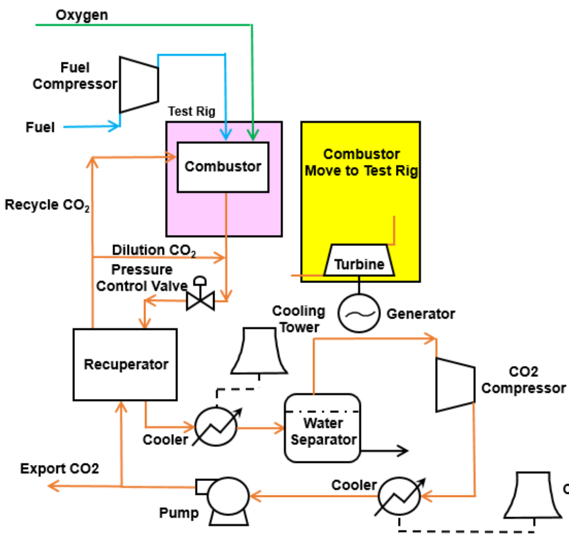

Figure 3: Flow Diagram of Full Scale Combustor Test

Sectional drawing of a combustion test rig is shown in Figure 4. The combustor consisting of a liner and a transition piece is the same size and form as what is installed in 50MWth turbine.

Combustion gas flows through the inside of the combustor of Figure 4 in the direction of a red arrow head, changes 90 degrees of flow directions in a transition piece, and flows toward the transition piece exit, i.e., a combustor outlet. The measurement section of thermometry and gas sampling, and the orifice which simulated first nozzle are set up at the combustor exit. The dilution section and pressure control valve for reducing temperature and pressure of combustion gas are installed at downstream of the measurement section. Combustion gas flows into the recuperator, after adjusting temperature and pressure. Moreover, the camera which can observe the inside of a combustor is installed in the portion of the blue arrow head of a transition piece part. The test rig appearance installed in the demonstration plant is shown in Figure 5.

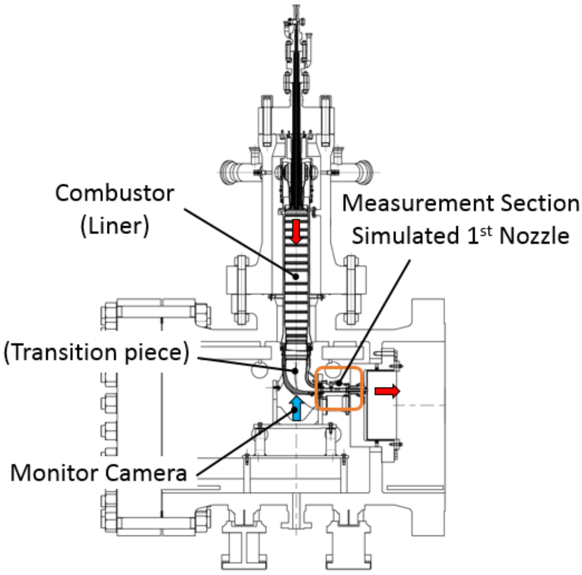

Figure 4: Cross section of Combustion Test Rig

Figure 5: Appearance of Combustion Test Rig

3.2 Ignition

In the conventional gas turbine combustor, the ignition plug of high tension is used for flame ignition. Although an ignition plug works at the time of ignition, after ignition, ignition plug is standing by in the position which can be bear high temperature flame. However, an ignition plug continues receiving the high pressure of a combustor. This combustor may be set to 30MPa on rated load conditions as mentioned previously, and an ignition plug may not bear this pressure. Therefore, the ignition method by laser is adopted. If one point is made to condense a high energy laser beam within a combustor, the gas of the portion will ionize and it will be in a plasma state. The fuel oxygen mixture is lit using this condensed energy. The schematic diagram of a laser ignition device is shown in Fig. 6. Since a laser transmitter installs out of the casing of an atmospheric pressure, it is not receive the influence of pressure, and irradiates with a laser beam in a combustor through the window used as a pressure bulkhead. The laser ignition system is verified in this combustion test, and it is confirmed that it is satisfactory of specification.

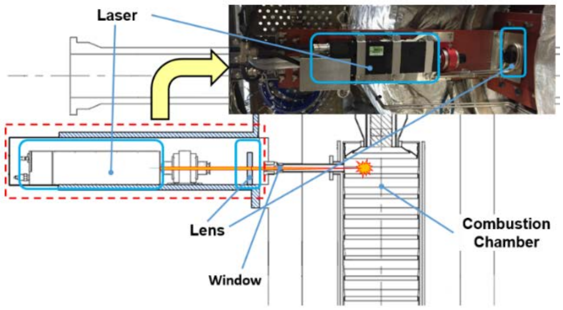

Figure 6: Laser Ignition System

3.3 Results of Combustion Tests

In this combustion tests, in addition to the operating condition of a gas turbine, it is also examined on the conditions which are separated from an operating condition about an equivalence ratio, supply oxygen concentration, the flow velocity, etc. Each flow rate data acquired at every 5 seconds, each pressure and thermal data acquired at every 2 seconds. Fig.7 shows the combustion exit temperature (left axis), and combustor inner pressure (right axis) versus time. Although automatic and manual control are possible for each flow of fuel, oxygen, and carbon dioxide, it mainly set up by manual control. Since it becomes automatic control when operating a turbine, quick load up is possible. Immediately after ignition, although combustor outlet temperature rises to 850°C, it is controlled toward a setting pressure and temperature, raising a burner internal pressure. Then, data is acquired, changing test conditions and after flame blow off, each flow conditions are set toward an ignition condition again.

Figure 8 shows the CO concentration at combustor exit versus combustor exit calculated temperature. These data is using what averaged the data acquired 5 minutes or more, after reaching a measurement condition. The equilibrium temperature calculated from the fuel, oxygen, and the carbon dioxide flow rate which are supplied to the combustor is used as the combustor exit temperature. Combustor exit temperature is at conditions 600degC or less, CO concentration at combustor exit is 300ppmvd or more. In the other temperature region, CO is less than 200ppmvd.

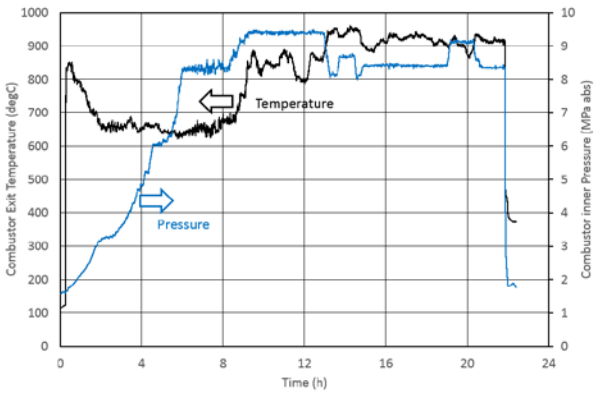

Figure 7: An Example of Trend Graph of Combustor Exit Temperature & Combustor Inner Pressure

Figure 9 shows combustion efficiency versus combustor exit calculated temperature. The combustion efficiency is calculated from the formula (1) using the concentration of CO and CH_4 at combustor exit. In addition, although the graphic display is not carried out, unburned CH_4 is 25ppmvd or less at any conditions. It is found that the combustion efficiency is below 99% at temperatures below 600degC, but approaches 100% at temperatures above 800degC, resulting in combustion efficiency equivalent to that of a conventional gas turbine combustor.

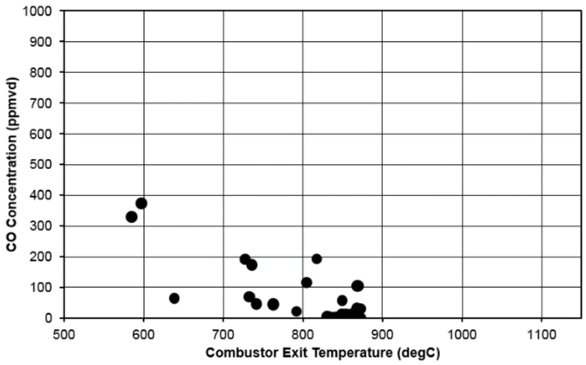

Figure 8: CO Concentration at Combustor Exit

$$\eta comb = \left(1 - \frac{Qco+Qch4}{Qfuel}\right) * 100 \quad -(1)$$

(Qco,Qch4: Calorific value of CO, CH_4 at the combustor exit, Qfuel: Heat input to the combustor)

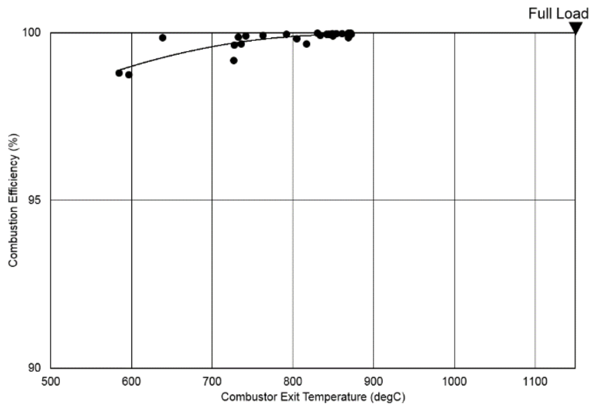

Figure 9: Combustion Efficiency

As Fig. 4 explained, the combustor consists of a liner and a transition piece, both are using the heat-resistant alloy, and the liner side adopts a slot film-cooling method, the transition piece side has adopted the whole surface film-cooling method, and it is using CO_2 as a coolant. The temperature of the metal outer surface of liner and the transition piece is measured by the thermocouples. The measured results show in Figure 10. The horizontal axis indicates position of measurement points, the vertical axis indicates measured temperature. In this combustion test, maximum heat load is 55%, and minimum load condition is 9%. As the heat load increases, the metal temperature increases, but it has been confirmed that the temperature is sufficiently low even at the maximum load of the combustion test. Also, the measured temperature is close to the design prediction value, and it can be predicted that the temperature will be sufficiently within the allowable temperature even under rated conditions.

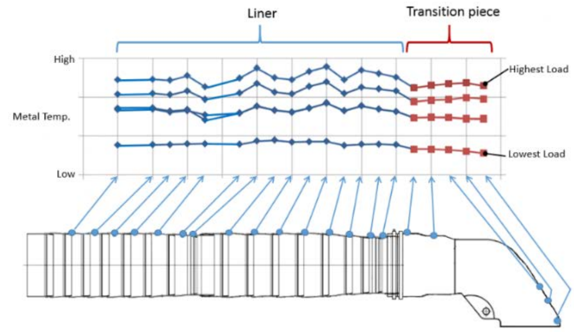

Figure 10: Distribution of Combustor Metal Temperature

4. CONCLUSION

Toshiba developed the turbine and combustor for the Allam Cycle supercritical CO_2 power generation system developed by NET Power, and carried out full scale combustion test with the actual combustor. The combustion tests are done from ignition to the maximum heat load of the test facility, and combustion characteristic and reliability are validated. The stable ignition performance is obtained by using the laser ignition system. The amount of CO at the exit of the combustor and the combustion efficiency are also validated as equivalent to those of the conventional gas turbine combustor.

The metal of the combustor is cooled enough in the combustion test range and close to the predicted temperature. This concludes that the prediction by heat transfer calculation in supercritical CO_2 is certain and the temperature in rated condition will fall within the allowable temperature.

This combustor is installed on the demonstration turbine and validation of the demonstration plant is conducted.

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