Plant Minimum Stable Load (Pmin) Test for Ilijan CCPP

Si Moon Kim†, Wan No Yun, Cheol Ho Jang, Se Ik Park

KEPCO Research Institute, Korea Electric Power Corporation, 105 Munji-Ro Yusung-Gu, Daejeon 34056, Korea
† smoonk@kepco.co.kr

Abstract

This paper describes the test results of plant minimum stable load (Pmin) for Ilijan Power Plant. The test was conducted on May 13 through 14, 2015 to investigate the plant operating and equipment condition in accordance with “Ilijan Plant Performance Test Procedure on Plant Minimum Stable Load” [1]. This paper also contains the assessment of the impact of Pmin to plant operating parameters and possible technical operating issues when operating at lower loads and to recommend the safe minimum load operation of Ilijan per block. In addition, this paper describes the performance calculation results of efficiency and heat rate depending on the load level.

Keywords: Performance test, combined cycle, combustor, turbine cooling air, inlet guide vane

I. INTRODUCTION

MHI 501G gas turbine of Ilijan combined cycle power plant (CCPP) is the first commercial model of Mitsubishi Heavy Industries (MHI) in the world and also the world’s first proto-type gas turbine adopting the combustor steam cooling which is more difficult to control during low load operation but is more efficient at base load operation. The Ilijan plant is designed to operate as a base load plant with 1,200 MW guaranteed net capacity through two blocks at 600 MW that are configured with two gas turbine to one steam turbine. Ilijan plant is currently registered at Pmin 300 MW/block under the Wholesale Electricity Spot Market (WESM) that is only possible with one gas turbine (GT) to one steam turbine (ST) configuration. The Ilijan plant should be registered with a Pmin under all units operating condition (2 GT and 1 ST per block). With all units operating condition, the minimum load that the Energy Conversion Agreement (ECA) with National Power Corporation (NPC) can guarantee is up to 900 MW or 450 MW/block (2 GT & 1 ST) [2]. Based on Energy Regulatory Commission (ERC) rules, any power generation company can only change the WESM Pmin registration upon conducting a generator test by an acceptable independent party filed to the ERC in order to reflect it in the Certificate of Compliance (COC). The Ilijan Pmin test shall determine the minimum demand in MW per block with all Units in operating condition and can reliably sustain for an indefinite period of time. South Premiere Power Corp. (SPPC) requested to ERC that the minimum load should be reset through their nomination of KEPCO Research Institute (KEPRI) as a third party to conduct the test wherein ERC has approved subject to their witnessing together with PEMC, NGCP, NPC, PSALEM and SPPC representatives. This performance test was carried out by KEPRI after concluding service contract between SPPC and KEPRI.

II. MINIMUM STABLE LOAD (Pmin) TEST

A. Test Description

This section describes the performance test scheme and the calculation results of minimum stable load (Pmin) test for Ilijan power plant. Performance test was conducted at the Ilijan power plant site by KEPRI on May 13-14, 2015. This test was conducted for overall plant net electric power output and overall plant net heat rate and efficiency. All tests were conducted and calculated in accordance with the performance test procedures [3][4] and codes [5]-[9]. For the purpose of identifying plant performance level depending on the loads, net power output and net efficiency were calculated and corrected to reference conditions. The tests and the corresponding results are described in this section including the data summary.

B. Test Preparations

Before initiating the performance test, all of the associated equipment were checked, cleaned and adjusted as close as possible to new and clean conditions. Steam and other leakages if any, were corrected. The off-line cleaning of the gas turbine compressors was performed. The inlet guide vanes were checked and cleaned manually, if necessary. Condenser tubes were cleaned by the condenser tube cleaning system (CTCS). The performance test was conducted at normal valve line up conditions based on normal operation. The performance test was conducted at as close as the reference conditions. Power block one was normally operated at same conditions as one. Both power blocks were operated with the same test load at steady state condition so as not to have an influence on the result of the performance test.

C. Operating Conditions for the Test

The performance test was carried out by block basis under the following operating conditions of the plant.

D. Test Measurements

Measurements of operating parameters using temporary and station instrumentation were collected using a Data Acquisition System (DAS) and Plant Distributed Control System (DCS).
Averages and raw data of the collected data for each test run are used for performance test calculation. Primary measurements used for the calculation are listed in Table 2.

### E. Performance Test Calculations

The measured performance at the test conditions was corrected back to the reference conditions by using respective correction curves. The corrected performance was calculated as following.

1) Corrected net C/C plant power output

\[
kW_{NCC(R)} = \frac{kW_{NCC(C)}}{K1 \times K2 \times K3 \times K4 \times K5 \times K6 \times K7 \times K8}
\]

where,

- \( kW_{NCC(R)} \): Corrected net C/C plant output (kW)
- \( kW_{NCC(C)} \): Calculated measured net C/C plant output (kW)
- \( K1 \): Correction factor for ambient temperature
- \( K2 \): Correction factor for ambient pressure
- \( K3 \): Correction factor for relative humidity
- \( K4 \): Correction factor for seawater temperature
- \( K5 \): Correction factor for lower heating value
- \( K6 \): Correction factor for generator power factor
- \( K7 \): Correction factor for generator frequency
- \( K8 \): Correction factor for degradation

### Table 1. Operating conditions

| Fuel          | Block load       | Plant operating configuration |
|---------------|------------------|------------------------------|
| Natural Gas   | 100% of 600 MW   | GT: 2 Unit operations ST: 1 Unit operation |
|               | 70% (420 MW) of 600 MW | GT: 2 Unit operations ST: 1 Unit operation |
|               | 66% (400 MW) of 600 MW | GT: 2 Unit operations ST: 1 Unit operation |

### Table 2. Primary measurements

| Measurement | Types          | Notes                                      |
|-------------|----------------|--------------------------------------------|
| Plant Net Electrical Output | Station | 2 revenue meters at switchyard            |
| Ambient Air Temperature       | Temporary     | 2 RTD per GT at the air inlet filter       |
| Barometric Pressure           | Temporary     | 1 per block on the shaft centerline        |
| Humidity Meter                | Temporary     | 1 per plant at the inlet filter            |
| GT Fuel Gas Flow Rate         | Station       | gas station meter                          |
| GT Fuel Gas Pressure          | Station       | gas station meter                          |
| GT Fuel Gas Temperature       | Station       | gas station meter                          |
| Fuel Gas Composition          | Station       | gas station GC                             |
| Sea Water Temperature         | Station       | DCS/control room                           |

### Table 3. Performance test results at 100% load

| Block   | Item                  | Unit   | Test Run-1    | Test Run-2    | Average    |
|---------|-----------------------|--------|---------------|---------------|------------|
| Block #1| Net power output      | Measured kW | 594,047     | 593,357       | 593,702    |
|         |                       | Corrected kW | 587,662      | 586,174       | 586,918    |
|         | Net efficiency (LHV)  | Measured %  | 54.82        | 54.68         | 54.75      |
|         |                       | Corrected %  | 54.72        | 54.60         | 54.66      |
| Block #2| Net power output      | Measured kW | 600,114      | 600,284       | 600,199    |
|         |                       | Corrected kW | 593,143      | 592,260       | 592,702    |
|         | Net efficiency (LHV)  | Measured %  | 55.18        | 55.12         | 55.15      |
|         |                       | Corrected %  | 55.11        | 55.04         | 55.07      |
| Plant   | (Block #1 & 2)        | Net power output | Measured kW | 1,194,161   | 1,193,641  |
|         |                       | Corrected kW | 1,180,805     | 1,178,438     | 1,179,621  |
|         | Net efficiency (LHV)  | Measured %  | 54.75        | 55.15         | 54.95      |
|         |                       | Corrected %  | 54.92        | 54.82         | 54.88      |

### Table 4. Performance test results at 70% and 66% load

| Block   | Item                  | Unit   | 70% Load   | 66% Load   |
|---------|-----------------------|--------|------------|------------|
| Block #1| Net power output      | Measured kW | 419,144     | 396,838    |
|         |                       | Corrected kW | 413,874     | 392,965    |
|         | Net efficiency (LHV)  | Measured %  | 51.12       | 48.53      |
|         |                       | Corrected %  | 51.04       | 48.48      |
| Block #2| Net power output      | Measured kW | 420,285     | 398,011    |
|         |                       | Corrected kW | 414,504     | 393,922    |
|         | Net efficiency (LHV)  | Measured %  | 51.52       | 48.84      |
|         |                       | Corrected %  | 51.46       | 48.79      |
| Plant (Block #1 & 2) | Net power output | Measured kW | 839,429     | 794,838    |
|         |                       | Corrected kW | 828,378     | 786,888    |
|         | Net efficiency (LHV)  | Measured %  | 51.32       | 48.69      |
|         |                       | Corrected %  | 51.25       | 48.63      |
2) Calculation of measured net C/C plant heat rate

\[ HR_{NCC(c)}(c) = \frac{W_{fg(c)} \times LHV_{g(m)}}{kW_{NCC(c)}} \]

where,

- \( HR_{NCC(c)} \) Calculated measured net C/C plant heat rate (kJ/kWh)
- \( W_{fg(c)} \) Calculated fuel gas mass flow rate to the power station (kg/h)
- \( LHV_{g(m)} \) Natural gas LHV based on the analysis of gas components (kJ/kg)
- \( kW_{NCC(c)} \) Calculated measured net C/C plant output (kW)

3) Corrected net C/C plant heat rate

\[ HR_{NCC(R)}(R) = \frac{HR_{NCC(c)}(c)}{C1 \times C2 \times C3 \times C4 \times C5 \times C6 \times C7 \times C8} \]

where,

- \( HR_{NCC(R)} \) Corrected net C/C plant heat rate (kJ/kWh)
- \( HR_{NCC(c)} \) Calculated measured net C/C plant heat rate (kJ/kWh)
- \( C1 \) Correction factor for ambient temperature
- \( C2 \) Correction factor for ambient pressure
- \( C3 \) Correction factor for relative humidity
- \( C4 \) Correction factor for seawater temperature
- \( C5 \) Correction factor for lower heating value
- \( C6 \) Correction factor for generator power factor
- \( C7 \) Correction factor for generator frequency
- \( C8 \) Correction factor for degradation

F. Summary of the test results

Multiple loads were tested for Pmin test at the Ilijan power plant. The performance tests were completed in compliance with the test procedure and the results are summarized in Table 3 and 4. The results presented are based on an average fuel analysis taken from the station gas chromatograph. The analysis was derived from ten-minutes composition data recorded in the flow computer.

As shown in Fig. 4, all of the tested combined cycle efficiencies depending on loads are satisfied with ECA guarantee values. This performance results represent the plant performance is not so much degraded as anticipated.

III. TECHNICAL REVIEW OF OPERATING PARAMETERS

A. Combustor Cooling System

1) System

- Combustor TP Liner (see Fig.5 [10]) is cooled with steam produced in HRSG (see Fig.6 [10])
- Cooling steam supplied from IP SH or HP back-up steam (auxiliary steam at start-up)

2) Considerations

This steam cooling technology is the world’s first and has many advantages, but there are several critical disadvantages as follows. GT M501G combustor is cooled by using the steam produced in HRSG. During gas turbine start-up, gas turbine combustor is warmed by auxiliary steam produced from start-up Boiler, as gas turbine load goes up, gas turbine is cooled using HP back-up steam and CR (IP) steam. Combustor TP Liner is very thin plate consisted of two layers and operated at very high
temperature. Therefore, it is even more susceptible to the change of cooling steam temperature than conventional air cooling method. A consequence of lowering the gas turbine load is decreased exhaust gas temperature. Thus HRSG steam temperature decreases and cooling steam temperature for combustor would also decrease. Consequently, HP back-up steam with attemperator will be added to IP SH steam. This could cause frequent change of metal temperature and thermal shock. If the crack or partial overheating of combustor TP liner happens, it could result in the catastrophic failure of gas turbine blades. Therefore, we should inspect the change of steam temperature and the amount of attemperator as the load of gas turbine decreases.

3) Results

As HP backup steam supply increases, steam temperature tends to swing (see Fig. 7). Even though the load change is very slow, temperature swing happened during test. If combustor TP liners are cooled improperly or insufficiently, it could be damaged in the form of overheating or cracking due to thermal shock, and then hot gas path components could be damaged consequently.

B. Turbine Cooling Air (TCA) System

1) System

Gas turbine rotor disc (see Fig. 8) [10] and blade (see Fig. 9) [10] is cooled with turbine cooling air. Turbine rotor cooling air is cooled using HRSG feed water in TCA cooler (see Fig. 10) which is very important to prevent the overheating of rotating blade.

2) Considerations

As the load of gas turbine changes, the pressure and flow of feed water change. Therefore, turbine cooling air system could be unstable due to frequent opening/closing of dumping valve. Since the unstable status of turbine cooling air system could have fatal impact on hot gas path components of gas turbine, we should investigate further whether the system is stable or not at low load operation.

3) Results

During the test, TCA feedwater control system was set with manual mode for block #2. Since the load change rate was so slow, turbine cooling air system was relatively stable.
C. Inlet Guide Vane (IGV) and Combustor Bypass System

1) System

IGV controls the airflow into the gas turbine and maintains exhaust gas temperature. Combustor bypass system has an important role to establish stable combustion through bypassing the compressed air in the combustor during low load operation. As gas turbine load decreases, fuel supply to combustor also decreases in order to maintain the combustion stability.

2) Considerations

It is needed to verify if exhaust gas is in the allowable temperature range depending on IGV opening and CBV opening ratio during the load change.

3) Results

At CC 450 MW load, gas turbine power output is 138 MW, exhaust gas temperature can be maintained with IGV control. However, at CC 420 MW load, gas turbine power output is 128 MW, the IGV is already fully close. Under this condition, exhaust gas temperature control is impossible (see Fig. 13). When gas turbine load further goes down to beyond 138 MW, IGV is fully closed and CBV (combustor bypass valve) starts to open to maintain the combustion stability through bypassing the compressed air through combustor as shown in Fig. 14. Since exhaust gas temperature control is impossible in the range of 420-450 MW, this also results in gas turbine metal temperature change under 420 MW due to changes in combustor cooling steam conditions. As the CBV opens, the gas turbine exhaust temperature goes down and the produced steam from HRSG goes down as well. Consequently, stable operations of the steam turbine may not be achieved.

D. Gas Turbine Combustion Instability

Regarding combustion instability, it is better for the gas turbine to operate at loads higher than 138 MW. Combustion instability is one of the key parameter to be monitored for safe operation of gas turbine. Stability of combustion can be changed easily by inlet air condition to the combustor using IGV opening. During major overhaul period, KEPRI has tuned the combustion instability by adjusting fuel split ratio, IGV opening and so on. However, there was a suspicious point (around 135 MW) related to IGV opening feedback signal. It looks like hysteresis
phenomena as shown in Fig. 15. When the grid requests the load to maintain the frequency around 135 MW, rapid change of gas turbine power output causes the combustion instability due to hysteresis of IGV. This is the reason why it is important to set the minimum load limit of the gas turbine.

IV. CONCLUSION

MHI 501G gas turbine of Ilijan CCPP is the first commercial model of MHI in the world. Maintaining the gas turbine proper operating condition on site has been a challenge for several years while abnormal operating conditions have contributed to faster deterioration of components of the gas turbine unit. Therefore, this machine including the hot gas parts has to be operated carefully and set an allowable minimum load limit in gas turbine safe operating point of view. Moreover, Ilijan gas turbine is the world first proto-type gas turbine adopting the combustor steam cooling. Because cooling steam is supplied from HRSG, steam temperature decreases as gas turbine power output decreases. Consequently, cooling steam system control such as steam source and changeover time is not so smooth and may result in faster deterioration and damage to the combustor transition piece at loads below 420 MW per block.

Under combined cycle power output 450 MW with gas turbine corresponding load of 138 MW, exhaust gas temperature control is difficult to control as IGV is already at full closed condition. Although it is better to set the plant with 450 MW/block load, it is also possible to operate at the minimum load of 420 MW/block but it is highly recommended that the change of load should be slow from 450 MW to 420 MW and vice versa since the more the load on gas turbine is lowered, the lower exhaust gas temperature.

The 400 MW/block is not recommended due to the aforementioned reasons since the operation at this load shall contribute to early failure on the gas turbine components and other related system. It is therefore concluded that Ilijan Pmin may be set to 420 MW/block considering also that it had already operated to as low as 413 MW/block as corrected based on ambient design conditions during the 70% load test and also on a daily 420 MW load dispatch basis considering the ambient conditions.

In addition, based on the thermal efficiency review of the plant, the actual test efficiency was way beyond the guaranteed level of the Ilijan ECA as the load goes down. Although the high natural gas consumption may not be a factor in determining the technical Pmin, KEILCO and the relevant affected agencies have to agree on this operating condition of the plant.

It is advisable for the plant operator to continue to check the gas turbine combustion parts and related system during scheduled inspection to further analyze any impact of the low load cyclic operation at the recommended minimum load setting.

REFERENCES

[1] “Ilijan Plant Performance Test Procedure on Plant Minimum(Pmin) Stable Load”, KEPRI, 2015.
[2] “Final Report on Plant Pmin Reduction”, KEPCO Ilijan Corporation, 2013.
[3] “Guidelines for the Performance Testing of Thermal Power Plants”, Korea Electric Power Research Institute (KEPRI), 2006.
[4] “Report on the Precision Thermal Diagnosis after Planned Preventive Maintenance”, KEPRI, 2005.
[5] ASME PTC 6.2, ‘Steam Turbine in Combined Cycles’, ASME, New York, 2011.
[6] ASME PTC 46, ‘Overall Performance Test Code’, ASME, New York, 1996.
[7] ASME PTC 22, ‘Gas Turbines’, ASME, New York, 2005.
[8] ASME PTC 4.4, ‘Heat Recovery Steam Generators’, ASME, New York, 2008.
[9] ASME PTC 22, ‘Gas Turbines’, ASME, New York, 2005.
[10] “Advanced Technologies of M501G Gas Turbine”, Mitsubishi Heavy Industries, LTD., 2007.
[11] “Heavy-Duty Gas Turbine Operating and Maintenance Considerations”, GE Power Systems, 2003.