Proceedings of the International Gas Turbine Congress 2003 Tokyo
November 2-7, 2003

IGTC2003Tokyo TS-153

The development of operation system of a liquid-fueled micro gas turbine

Yuji MORI, Shigehiko KANEKO, Tatsuo WATANABE

Department of Mechanical Engineering
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN
Phone: +81-3-5841-6430, FAX: +81-3-5689-8054, E-mail: mori@fiv.t.u-tokyo.ac.jp

ABSTRACT

A control system for the purpose of safe operation and characteristic evaluation of a liquid-fueled micro gas turbine was developed. By methods through a personal computer, the control system for a micro gas turbine was constructed. The control system consists with functions of sequence control, rotational speed control, load-torque control, and a protective apparatus based on condition monitoring. The integrity of these functions were experimentally tested and based upon test results, future developmental objectives were determined.

INTRODUCTION

Due to the fact that the use of waste-heat is impossible for large power plants located away from the city, through the viewpoint of efficient utilization of energy, the popularization of a distributed cogeneration system is requested. Especially, micro gas turbines have the advantage suitable for distributed cogeneration systems, where the cost per generated energy is low and that the temperature of waste heat is higher than that of gas engines.

By the use of biomass gas as fuel for the micro gas turbine, we have geared toward constructing a power generation system that is environmentally friendly. Furthermore, in the near future, we plan to attain a highly efficient hybrid power generation system by combining the micro gas turbine with fuel cell technology. For the operation and evaluation of these power generation systems, a control system, which enables operation with high safety and analysis of measured data, is desired. We have then pursued the development of an operation control and measured data analysis system by a personal computer. The purpose of this study is to report the development of operation system, and it was done for the liquid-fueled micro gas turbine installed in the laboratory. Condition monitoring and operation system was developed first, and load control function for the characteristic evaluation was added later. Therefore, in this document, the monitoring operation control system and load control system will be explained separately in two parts.

Manuscript Received on September 20, 2003

MICRO GAS TURBINE INSTALLATION

Here, experimental facility used in the development of the control system is explained. A micro gas turbine developed here is simple gas-turbine cycle with biaxial turbines. It is 5kW electric generating power unit using the jet engine for the model plane, which is driven by the liquid fuel, in the gas generator division. The gas generator comprises a single stage radial compressor, a combustor and a single stage radial turbine. The power turbine is connected with the inverter motor through speed reducer. Figure 1 presents a schematic view of the micro gas turbine installation. The equipments for control of the micro gas turbine are fuel pump, fuel shut-off valve, lubricant pump, air valve and glow plug. By cutting off the fuel shut-off valve, the supply of the fuel is stopped when any abnormality is detected. The air valve is opened in starting and cooling, and the compressed air is jetted to the compressor blades to force the rotor to drive. The glow plug is used at the ignition stage. These equipments are controlled by the voltage signals from PC. The 25 sensors are installed at the micro gas turbine installation in order to measure rotational speed, temperatures and pressures of working fluid, fuel flow, temperatures and pressures of lubricating oil, etc. Figure 2 presents a photograph of micro gas turbine installation.

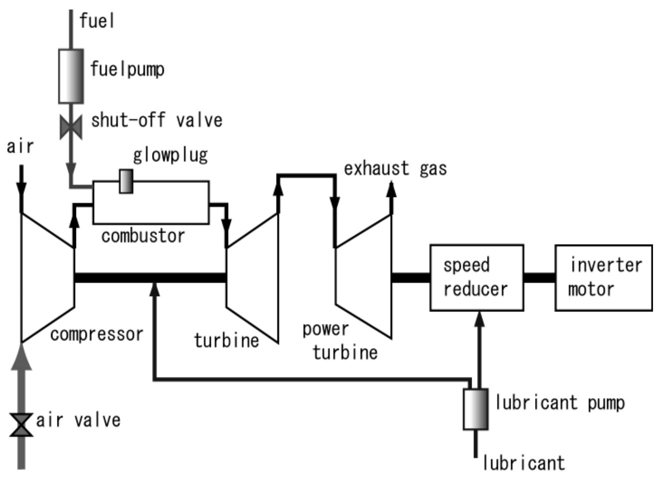

Figure 1: Schematic view of the micro gas turbine installation

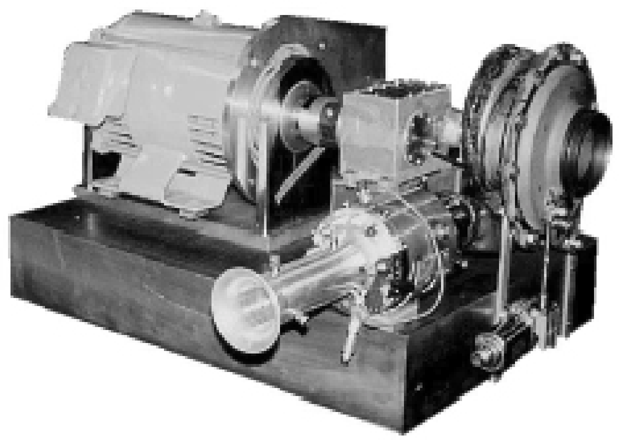

Figure 2: Photograph of the micro gas turbine installation

MONITORING AND OPERATION SYSTEM

Outline of the system

Figure 3 presents a schematic view of the system. The controlled object of the system consists of the micro gas turbine, the equipments such as fuel pump and sensors. The signals from the sensors are incorporated into PC, in which a LabVIEW based program deals with recorded data and sends the operational signals to the equipments.

The purpose of the monitoring and operation system is safe operation of the micro gas turbine. When the system was constructed, we referred to the control method of commercial ECU. The operation test was carried out using commercial ECU, and from its result, the functions of commercial ECU were grasped. The protection control for the emergency shutdown and the sequence control of the operation are main functions of commercial ECU. However, the adjustment of the rotational speed has to be carried out manually, and it is not convenient. Then, the following three functions should be given to the monitoring and operation system, which are sequence control of the operation, desired value follow-up control of the rotational speed and protection control for the emergency shutdown. The protection control is strengthened by the addition of monitoring parameters, in order to raise the safety. In the following, the function of the monitoring operation system is concretely described.

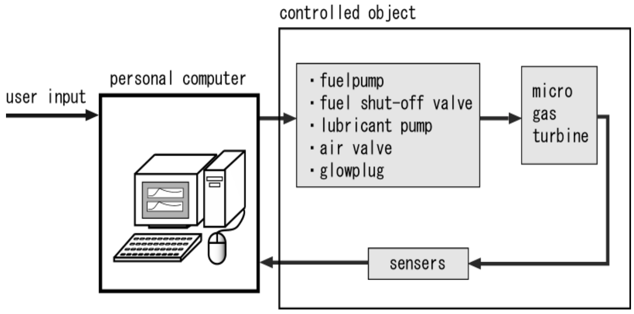

Figure 3: Schematic view of the monitoring and operation control system

Sequence control

The purpose of the sequence control is to carry out the operation from starting to stop in accordance with predetermined order. Figure 4 shows the flow chart of the sequence control, and it is composed of five parts i.e. standby, starting, run, stop and cooling.

When the starting order from the user is given, it is confirmed that the micro gas turbine is in the standby state. In the starting sequence, PC starts to output signals to the equipments, and the ignition operation is done. After the ignition is confirmed, by controlling the fuel pump voltage, the gas generator rotational speed is increased and stabilized at idle speed. In the abnormal case in which the ignition cannot be confirmed or climb rate of the rotational speed is small, it is considered being the starting failure. Succeedingly, the micro gas turbine perfectly stops by cutting off the fuel. When the starting succeeds, operation mode moves to run sequence. When the stop order by the user is given in run sequence, it shifts to the stop sequence. In the stop sequence, the fuel is cut off after the rotational speed has been stabilized at the predetermined speed (normal stop). In an emergency, the gas turbine is made to stop by cutting off the fuel without following the procedure of the normal stop. Either it will be emergency stop or normal stop, the cooling by the compressed air is carried out.

Figure 5 presents a schematic drawing showing output signals to the equipments. It is possible to change the setting of the sequence by adjusting the operating parameters such as timing, threshold, etc.

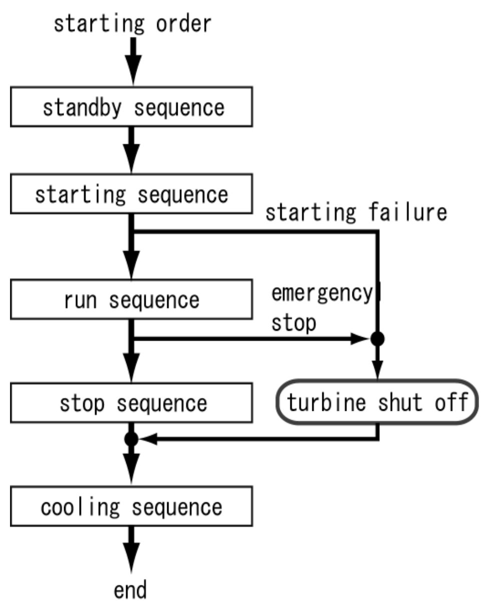

Figure 4: Flow chart of the sequence control

Rotational speed control

The purpose of the rotational speed control is that measured gas generator rotational speed follows the desired value set by the user. The binary control scheme was applied. In this method, thresholds are set at the value of $\pm 5\%$ from the desired value. Every 0.1 second, the measured value is compared with the thresholds. When measured rotational speed is lower, the fuel supply is increased. On the other hand, when measured rotational speed is higher, the fuel supply is decreased. The amount of fuel change is sufficiently small for the safety.

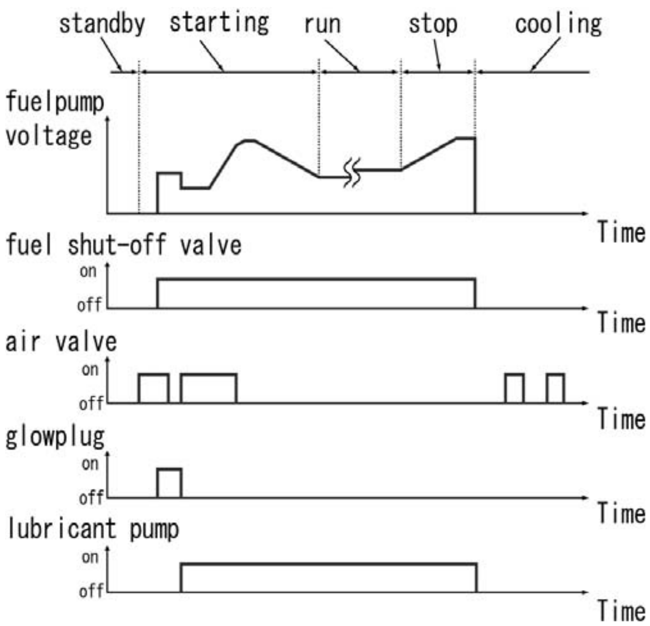

Figure 5: Output signals to the equipments

Protective control

The purpose of the protective control is condition monitoring and emergency shutdown in the abnormal state. Monitoring parameters and their limits were predetermined. Every 0.1 second, measured value are compared with these limits. When the abnormality is detected, and fuel supply to the micro gas turbine is shut down.

Table 1 shows 11 Monitoring parameters. On the gas generator rotational speed, the upper limit was determined from permission of the bearings, and the lower limit was from rotational speed at which self-sustaining was possible. The upper limit of the output shaft rotational speed was determined from the rated speed of the inverter motor. On the turbine inlet temperature and the power turbine outlet temperature, the upper limit was determined from material allowable temperature. The lower limit of the turbine inlet temperature was also set in order to detect the blow off of the flame in the combustor. As for turbine inlet temperature, calculated value was monitored because the reliability of measured value was not sufficient. On the lubricating oil, temperatures and pressures are monitored to confirm no abnormality in bearings and oil feeding system.

After outbreaks of emergency stop, detected abnormality histories are preserved for the user to refer after the operation.

Operation confirmation by a running test

A running test of the micro gas turbine was carried out in order to confirm the functions of the developed operation system. Figure 6 shows the time histories of the gas generator rotational speed, turbine outlet temperature, fuel flow and fuel pump voltage from the starting to the stop. The DC motor drives the fuels pump. The voltage input from the PC to the DC motor is known as the fuel pump voltage. In this case, the starting sequence began about 23 seconds after measurement started, and it ended after the 70 seconds. About 10 seconds after that, the operation was being stopped according to the stop order given by the user. Thus, it was confirmed that the sequence control normally functioned.

Figure 7 shows an example when the protective control operates. In the about 36 seconds after the measurement started, the turbine outlet temperature exceeded the upper limit, which was judged as abnormal, and the fuel was cut off. One can find that the protective control also fulfils its role.

In Figure 6 and 7, transient waveform indicating the voltage applied on the fuel pump does not coincide with instantaneous fuel flow. The fuel flow is proportional to the rotational speed of the fuel pump, which is determined by the applied voltage and the fuel line pressure. Thus, when the voltage applied on the fuel pump is constant, the increasing or decreasing of the fuel line pressure allows the fuel flow to decrease or increase. Therefore, the voltage applied on the fuel pump does not coincide with instantaneous fuel flow. Additionally, there is a time delay between the fuel pump voltage and the fuel flow due to the long fuel line from the fuel pump to the combustor.

Table 1: Monitoring parameters

Monitoring parameter		Value
Gas generator rotational speed [rpm]	upper limit	130000
	lower limit	66000
Output shaft rotational speed [rpm]	upper limit	10000
Turbine inlet temperature [℃]	upper limit	900
	lower limit	300
Power turbine outlet temperature [℃]	upper limit	900
Fuel flow [ml/s]	upper limit	5
Lubricant oil pressure of gas generator [kPa]	lower limit	0.1
Lubricant oil temperature of gas generator [℃]	upper limit	100
Lubricant oil pressure of power turbine [kPa]	lower limit	1.5
Lubricant oil temperature of power turbine [℃]	upper limit	100

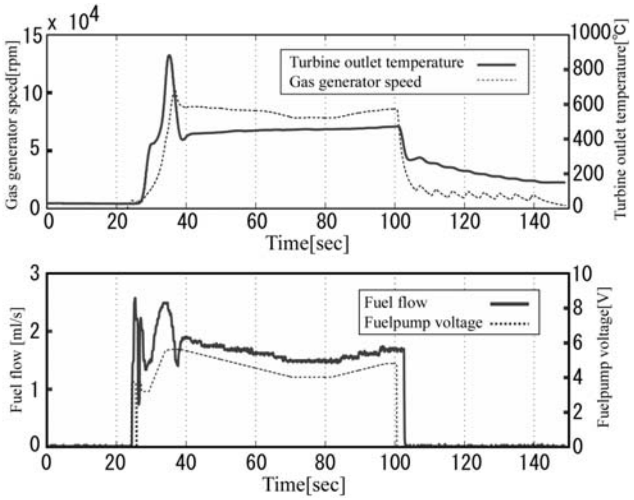

Figure 6: Gas generator rotational speed, turbine outlet temperature, fuel flow and fuel pump voltage in the test operation

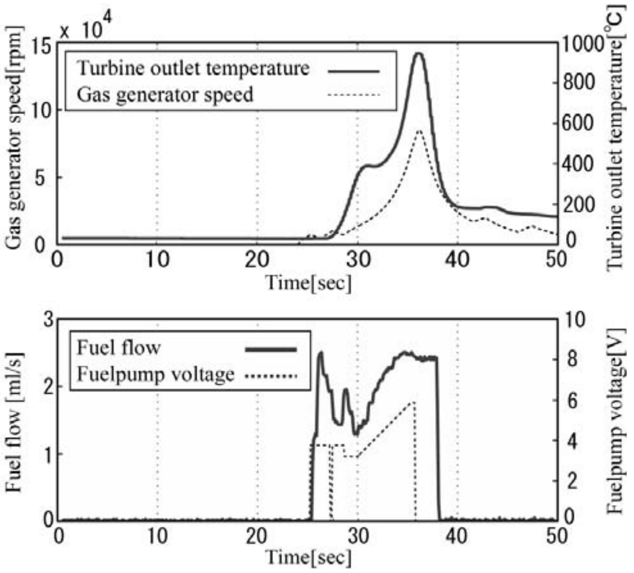

Figure 7: Result of an emergency stop

LOAD CONTROL SYSTEM

Outline of the system

Load control function is added to the system described previously. The purpose of the load control system is that the measured load-torque follows the desired value set by the user. By this system, evaluating characteristics of the micro gas turbine becomes possible.

The load-torque is controlled using eddy-current dynamometer connected with the output shaft. The relationship between output shaft rotational speed, load-torque and exciting current quantity of the dynamometer was examined from a running test by commercial ECU. The result is shown in Figure 8. It was proven from Figure 8 that the load-torque increased with the increase of the output shaft rotational speed (Ro) and the exciting current quantity. From this result, it was clarified that rotational speed control of the output shaft and the exciting current quantity are necessary for the load control system. In the following, the function of the load control system is described in detail.

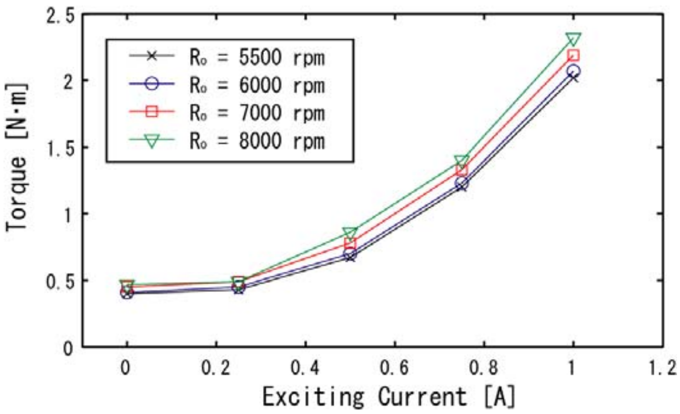

Figure 8: Relation of load-torque, exciting current and output shaft rotational speed

Rotational speed control

In this study, the transfer function of the controlled object was approximated from the step response. Figure 9 shows the response of output shaft rotational speed for the step input to the fuel pump applied voltage. We adopted Ziegler-Nichols method to approximate transfer function of the system from the step response. In this method, the largest gradient of the step response is R. The time of the point where the largest gradient tangent associates with the abscissa axis is L. The steady-state value of the response is K. And T is equal to K divided by R. If the transfer function of the controlled object is approximately shown by first delay and dead time, it is formulated as

$$G(s) = \frac{K}{1+Ts} e^{-Ls} \tag{1}$$

From Figure 10, K, L, T is determined as

$$K = 2340$$
$$L = 4.34 \tag{2}$$
$$T = 8.87$$

PI control method was applied for controlling output shaft rotational speed. The transfer function of PI controller is formulated as

$$C(s) = K_P + \frac{K_I}{s} \tag{3}$$

The parameters of PI controller were determined by simulation with Simlink. We determined the value of the parameters, with which the response for the step input did not exceed the desired value greatly. The parameters are determined as

$$K_P = 0.00025$$
$$K_I = 0.000037 \tag{4}$$

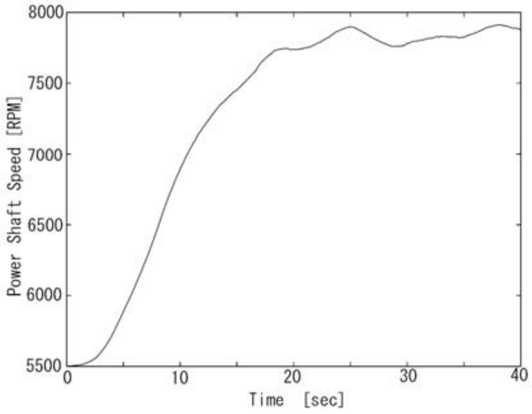

Figure 9: Response of output shaft speed for the step input to the fuel pump voltage

Load control

A binary control method was applied for controlling load-torque. In this method, upper limit and lower limit are set around the desired value. Every 0.1 second, the measured value is compared with these limits. When measured load-torque is smaller than the lower limit, the exciting current quantity is increased. On the other hand, when measured load torque is larger than the upper limit, the exciting current quantity is decreased.

Operation confirmation by a running test

A series of running test of the micro gas turbine was carried out in order to confirm the functions of developed control system. Figure 10 and 11 show time histories of no-load running test and load running test, respectively. In the load running test, the desired value of the output shaft rotational speed was set at 6000rpm, and the step size of load-torque increment or decrement is set at 1Nm. In Figure 11, it is found that the output shaft rotational speed lies in the range within the desired value of ±2.5 %, and the load-torque also followed the desired value. Therefore, it was confirmed that the rotational speed control and the load control functioned normally. Succeedingly, an example of emergency shutdown under the load running test is shown in Figure 12. The system judged the state of the micro gas turbine as abnormal, because the gas generator rotational speed exceeded its upper limit 130000rpm. Then, the fuel was cut off. Thus, it was confirmed that the protective control also functions normally.

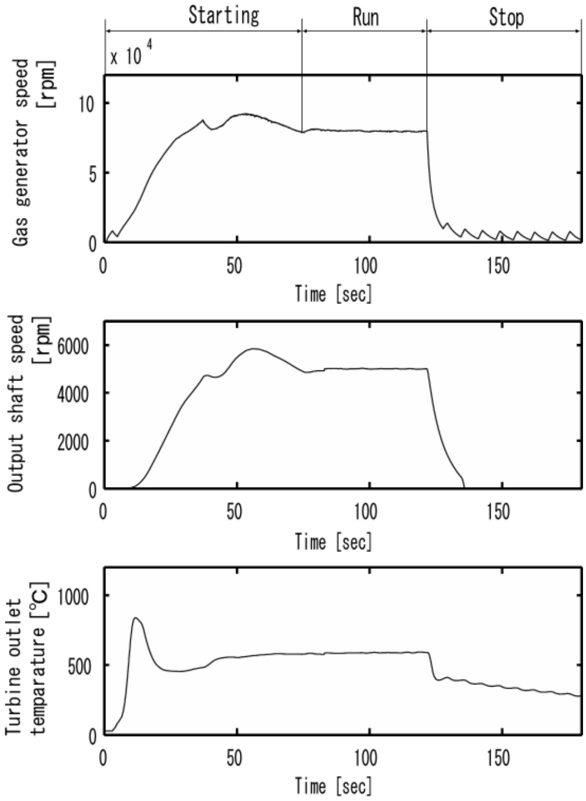

Figure.10: Time history of no-load running test

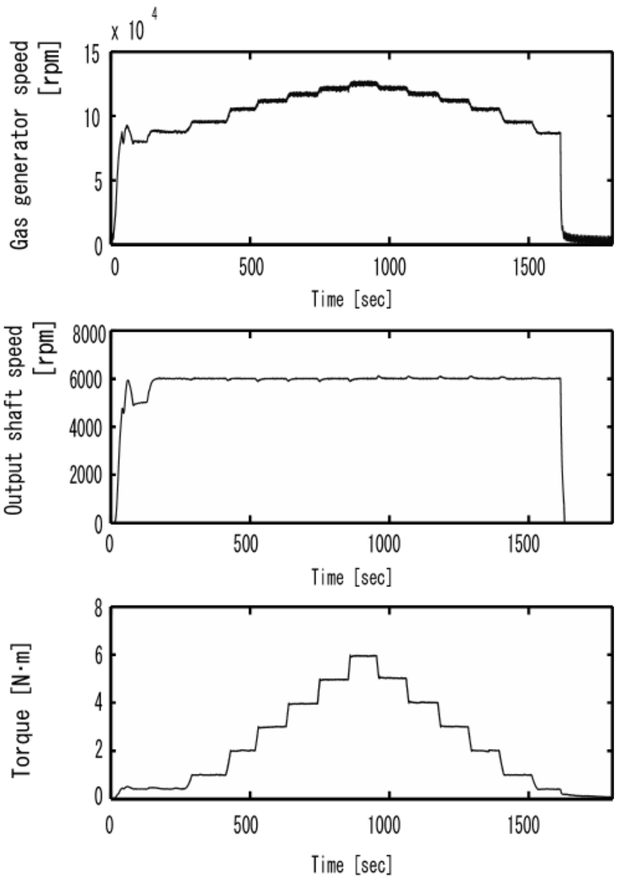

Figure 11: Time history of load running test

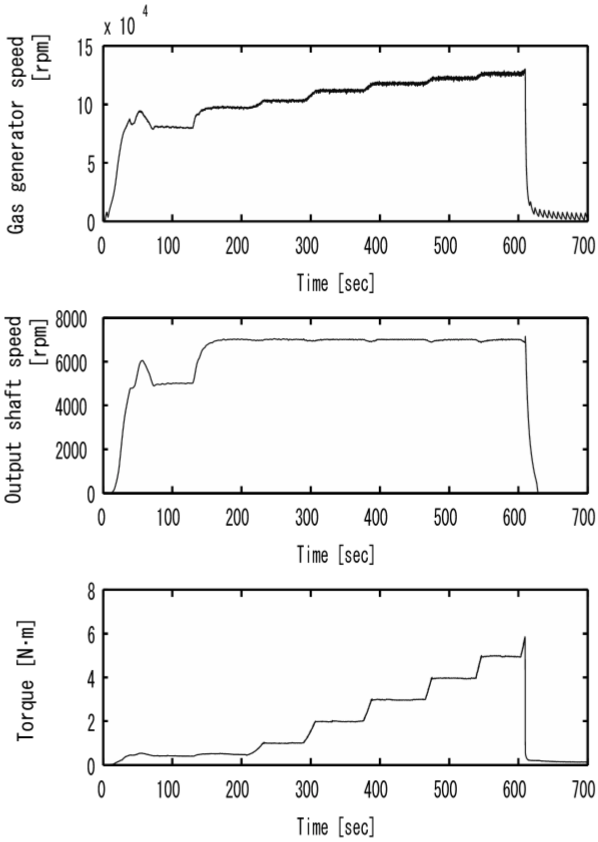

Figure 12: Time history of an emergency stop in load running test

CONCLUSION

We have developed a monitoring and operation system and a load control system for a liquid-fueled micro gas turbine. Through experimental testing, it was shown that the monitoring and operation control, rotational speed control, load control of the micro gas turbine were sufficiently possible. Simultaneously, the objectives to be improved in future for developing a system were clarified. On the monitoring and operation system, the improvement will be done to set proper operation parameters.

During test runs, the phenomenon where the temperature abnormally rose in the beginning was mainly observed. In addition to this phenomenon, there were many start-up failures due to excessively high temperatures. As of now, the success rate of start-up is low. In order to increase the success rate, it is necessary to optimize the parameters. In addition, on the protection control, the judgmental method for more precise abnormality detection is necessary.

ACKNOWLEDGMENT

The authors would like to thank Zhaoquan XU at the university of Tokyo, whose work made this paper possible.

REFERENCES

Hitoshi Inomata, Shigehiko Kaneko, 2001, “The development of Monitoring and control system of Micro gas turbine,” 29th Gas turbine annual meeting, The Gas Turbine Society of Japan, pp.77-82.

Toshiharu Sugie, Masayuki Fijita, 1999, “Introduction to feedback control”, Corona Publishing Co., Tokyo, pp.154-155