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Experimental study for power generation in liquid air energy storage system integrated to PWR steam cycle

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1. Introduction

Currently, to reduce carbon footprint, the energy production from renewable energy (RE) sources is increasing worldwide. According to the International Energy Agency (IEA), RE is forecasted to reach a global share of over 70% by 2050 [1]. However, it has disadvantage of intermittency as it is highly influenced by the environment and weather conditions. Thus, energy storage system (ESS) is required.

Especially, much attention has been paid to ESS integrated to a Pressurized Water Reactor (PWR) steam cycle due to economics and safety [2, 3]. Among ESSs, liquid air energy storage system (LAES) is one of the most attractive ESSs due to high round-trip efficiency (RTE), high energy density, great power rating and sufficient capacity [4]. The authors showed the feasibility of LAES integrated to PWR steam cycle from a thermodynamic analysis [5, 6].

LAES was experimented many times such as liquid air storage tank and packed bed in a cold box. However, with the exception of Highview Power, there are no laboratory-scale experimental studies of the liquid air power generation process for LAES discharge [7, 8]. Thus, it is imperative to further investigate the required time of LAES for responding to demand, in order to evaluate the potential of LAES more realistically

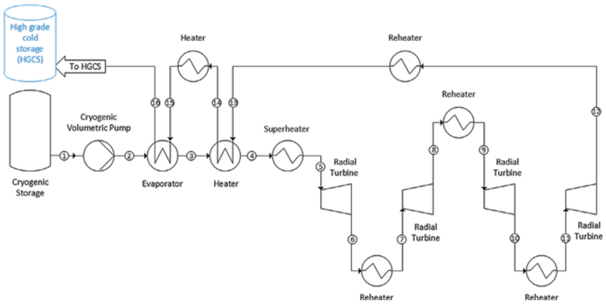

Fig. 1. Layout of discharge process in LAES pilot plant [5]

Therefore, a basic power generation experiment in a laboratory scale is conducted and reported in this paper. As this is a basic laboratory-scale and preliminary experimental study, the liquid air power generation experiment is carried out using nitrogen, the main gas that makes up air. The main objective of this paper is to evaluate how low temperature gas turbine operates under LAES condition.

2. Experimental setup for liquid nitrogen turbine power generation

2.1 System description

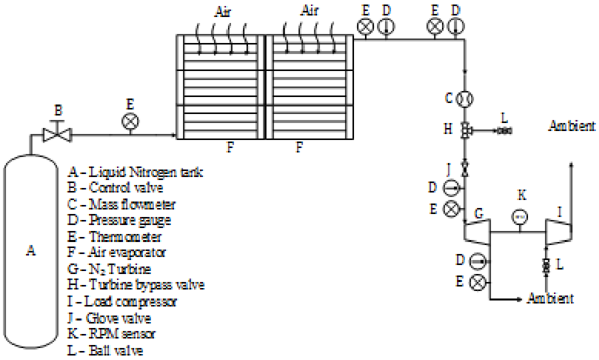

Fig. 2. Schematic diagram of liquid nitrogen power generation experimental apparatus

In Fig. 2, it shows the schematic diagram of liquid nitrogen power generation experiment. The apparatus consists of gaseous nitrogen cylinder, regulator, air evaporator, globe valve, nitrogen turbine and air compressor. The experimental apparatus is a system in which liquid nitrogen from a liquid nitrogen tank is evaporated through an air heated evaporator and the gaseous nitrogen drives a nitrogen turbine. Then, the power generated from the nitrogen turbine drives the air compressor which is connected on the same shaft. The work consumed in an air compressor provides information of how much the turbine generated work from nitrogen flow.

Table I: Design parameters and values

Design Parameters	
Parameters	Values
Pressure of liquid nitrogen tank	0.6MPa
Temperature of liquid nitrogen tank	-176.8℃
Temperature of ambient air	25℃
Mass flow rate of liquid nitrogen	0.1kg/s
Isenrotpic efficiency of nitrogen turbine	75%
Pressure of nitrogen turbine inlet	0.5MPa
Pressure of nitrogen turbine outlet	0.1MPa

RPM of nitrogen turbine	100000RPM

Table II: Temperature and Pressure of Main points

Main points	Temperature	Pressure
Outlet of Liquid N_2 Tank	-176.7℃	0.6MPa
Outlet of Air Heated Evaporator	5℃	0.55MPa
Inlet of N_2 Turbine	5℃	0.5MPa
Outlet of N_2 Turbine	-67.3℃	0.1MPa

The nitrogen mass flow rate of this experimental apparatus is determined by the pressure ratio of the nitrogen turbine, and the nitrogen turbine outlet pressure is fixed at atmospheric pressure. Thus, the turbine performance is determined by the turbine inlet pressure. In this apparatus, the inlet pressure of nitrogen turbine is controlled by the globe valve.

Based on the design conditions shown in Table I, the experimental apparatus at the steady-state is designed. Table II shows the steady-state properties of each main points. The low temperature gas turbine has been designed with a pressure ratio of 5, a flow rate of 0.1 kg/sec, and a rotating speed of 100,000 rpm. The detailed design information of the turbine is shown in Table III below. As discussed in the previous section, the inlet pressure of the turbine determines the flow rate and speed. This is the basis for the selection of the experimental scenario.

Table III: Nitrogen turbine design parameters and values

Design Parameters	
Parameters	Values
Type	Radial
Diameter	0.04m
Ns	0.6
Ds	3.2
Height of Blade	2mm
Velocity of Nozzle inlet	51.2m/s
Velocity of Nozzle outlet	307.4m/s
Mach numbert	0.98
Diameter of Shaft	0.02m

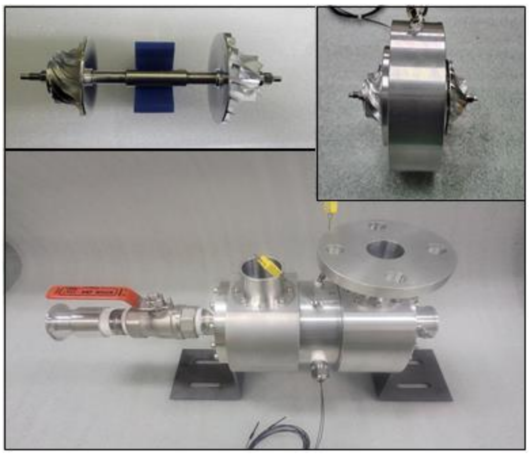

Fig. 3. Exterior and interior view of the nitrogen turbine module

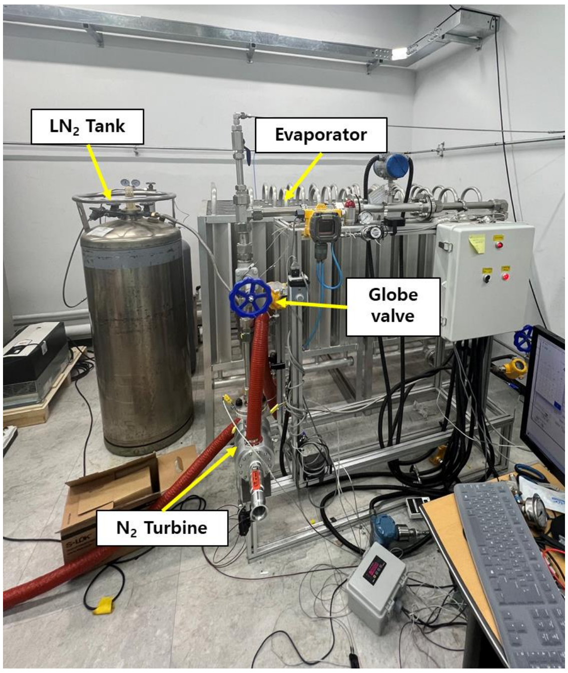

Fig. 4. Liquid nitrogen turbine experimental apparatus

Figures show the nitrogen turbine and a panoramic view of the liquid nitrogen turbine test facility. In Figure 4, the gaseous nitrogen is provided by the liquid nitrogen tank. When liquid nitrogen flows out from the tank, the pressure inside the tank drops and it is difficult to maintain steady state. Thus, nitrogen from a nitrogen gas tank and regulator are used to maintain the pressure inside the liquid nitrogen tank.

2.2 Experiment

As explained, the flow rate and rpm are determined by the nitrogen turbine inlet pressure, which is regulated by a globe valve prior to the turbine inlet. As the turbine inlet pressure changes, the load and flow properties are measured.

1. From 0 to 75 seconds, the liquid nitrogen tank is opened and the globe valve is closed to fill nitrogen in two evaporators and piping.
2. The globe valve is opened with small increments from 75 to 150 seconds to bring the inlet pressure of the nitrogen turbine to the design pressure of 5 bar.
3. It remains open from 150 to 200 seconds, and at 200 seconds the globe valve is closed slightly to reduce the inlet pressure of the turbine to 3 bar.
4. 220-250 seconds, the globe valve is opened to match the turbine inlet pressure to 5 bar.
5. Finally, at 250-280 seconds, the globe valve is fully closed to terminate the experiment.

3. Results and Discussions

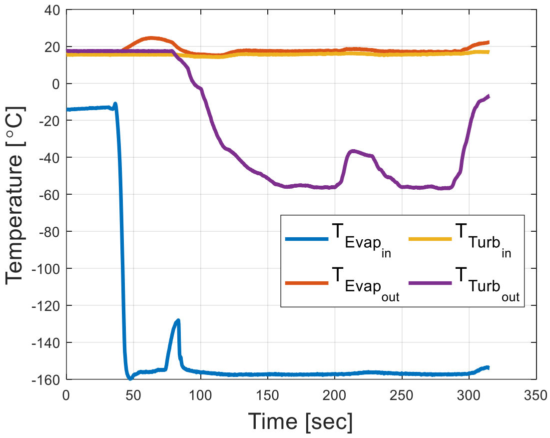

Fig. 5. Temperature of experimental loop

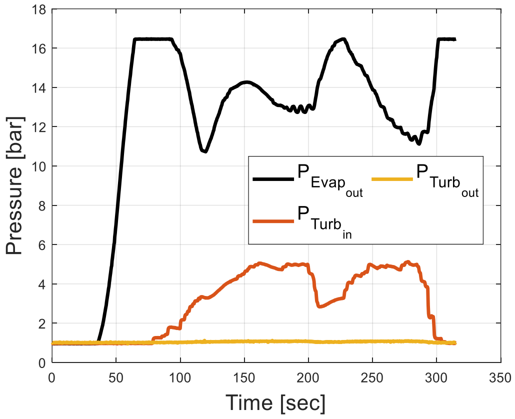

Fig. 6. Pressure of experimental loop

Figure 5 shows the inlet and outlet temperatures of the evaporator and nitrogen turbine. The inlet temperature of the turbine was at approximately 18°C and the outlet temperature at approximately -60°C. Furthermore, the evaporator outlet temperature remains at 18℃, indicating that sufficient liquid nitrogen has been evaporated. In other words, the performance of the nitrogen turbine is not available as a function of the turbine inlet temperature.

Figure 6 shows the pressures of major stations in the experimental apparatus. The evaporator outlet pressure should be high to ensure sufficient pressure supply to the nitrogen turbine using globe valve. It was found that the pressure ratio was maintained at the design pressure ratio of approximately 5 between 50-200 seconds and 250-280 seconds.

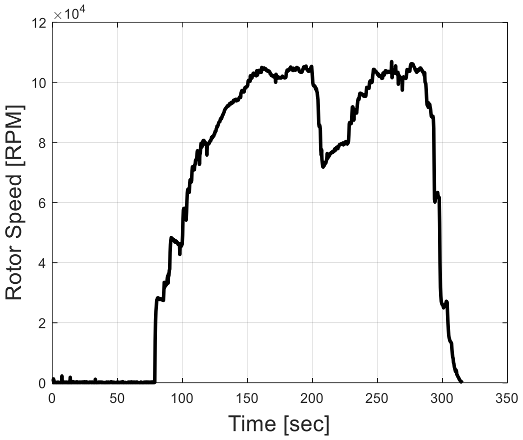

Fig. 7. RPM of nitrogen turbine

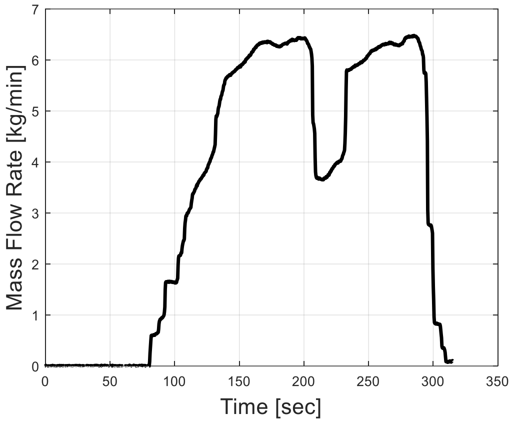

Fig. 8. Mass flow rate of experimental loop

The nitrogen turbine speed and mass flow rate versus time are shown in Figures 7 and 8. In Figure 7, it can be seen that the nitrogen turbine reaches its design speed of approximately 100,000 RPM. At the same time, in Figure 8, the measured flow rate is about 6.3kg/min, which is different from the design flow rate (6kg/min), but this is negligible considering the uncertainty of the flow meter.

At 220 seconds, both the rotor speed and mass flow rate are seen to change rapidly as the pressure changes. In other words, it means that the response time of the nitrogen turbine is fast. As nitrogen turbines are sensitive to inlet pressure, it is necessary to allow sufficient time for the pressure to stabilize during the start-up process.

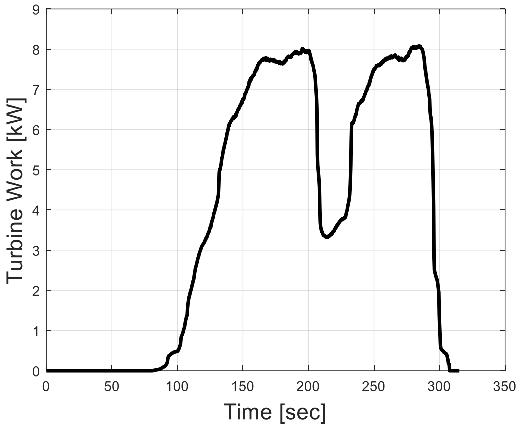

Fig. 7. Load of nitrogen turbine

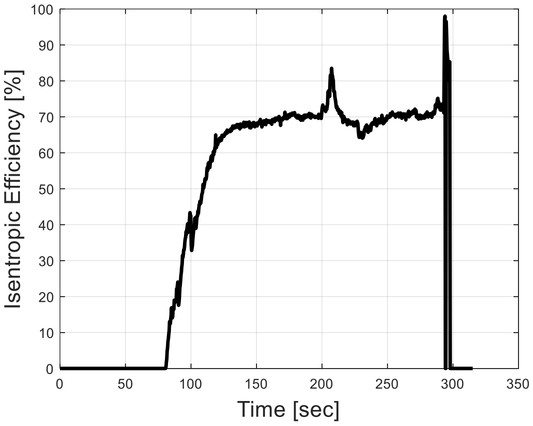

Fig. 7. Isentropic efficiency of nitrogen turbine

Both the load and the isentropic efficiency of the nitrogen turbine are calculated using the previously measured temperature, pressure and mass flow rate are shown in Figures 9 and 10, respectively. The power output of the nitrogen turbine is measured to be approximately 8 kW, which is close to the design value. The isentropic efficiency of the nitrogen turbine was assessed to be 71.7%, which is about 3.3% lower than the predicted value from the design.

The main reason for the difference between the design and measured values is due to heat loss via turbine casing. This requires additional insulation work. The instability of the turbine inlet pressure is thought to be due to the fact that the pressure inside the storage tank changes as the liquid nitrogen is consumed, making it difficult to maintain a steady state.

4. Summary and Future work

In this study, experiment of nitrogen turbine for power generation in LAES is analyzed. The nitrogen turbine operates 71.7% isentropic efficiency, 8kW load, 100,000 RPM and 6.3kg/min when the inlet pressure is 5bar.

This experiment is the first in Korea to confirm that it is possible to generate several kW of power using liquid nitrogen with high RPM turbine. This is the second experiment in the world for power generation, which is next to the Highview power experiment in the UK.

Further experiments under various conditions will be performed in near future. Eventually, experiments using air at low temperature will be conducted to closely simulate LAES, and it will be further investigated to analyze phenomena that may occur in a real system.

Acknowledgement

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