# Off-design analysis of Liquid Air Energy Storage System during discharge cycle

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## 1. Introduction

A nuclear power plant is a typical baseload power plant. The reason for this is that operating the nuclear power plant at rated power is usually more efficient and economic. However, due to intermittency of renewable energy sources, such as solar photovoltaic and wind power, flexible operation of nuclear power plants is inevitable for grid stabilization. One of the spotlighted technologies is the integration of energy storage system to nuclear power plant. By coupling an energy storage system to the nuclear power plant, it is reported that the operational flexibility of the nuclear power plant can be greatly enhanced [1].

Among the grid-scale energy storage systems, Liquid Air Energy Storage System (LAES) is increasingly popular because of its genuine advantages: high energy density, less geographical constraints, and long lifetime. Park et al. first suggested the mechanical integration of LAES with the nuclear power plant. The integration is established by a steam turbine-driven-compressor. During off-peak hour, steam is bypassed from nuclear steam cycle and operates steam turbine which is mechanically connected to an air compressor. Air is compressed by air compressor and liquefied by exchanging heat with the cold energy storage system. During peak hour, liquid air is evaporated and expanded through an air turbine to generate electricity. Energy storage systems mainly operate part-load for the stability of the grid. Therefore, it is important to evaluate the off-design performance of an LAES.

In this study, the off-design performance of LAES during discharge cycle is investigated while modeling off-design performance0 of each component. The importance of this study is to provide an operational strategy to meet a given demand by calculating generated work according to liquid air mass flow rate. Off-design modelling methods are provided for each component. Also, to improve the air turbine efficiency under part-load operation, volumetric flow rate control method is utilized by using a throttling valve. Breakeven conditions of LAES are also provided by comparing work consumed in cryogenic pump and produced from air turbines.

## 2. Methodology

Off-design performance of Liquid Air Energy Storage System (LAES) is evaluated with modelling of components: cryogenic pump, evaporator & air-oil heat exchangers, throttling control, and air turbines.

### *2.1 Cryogenic pump*

The cryogenic pump is modelled according to affinity law, which relates pressure ratio and mass flow rate [2].

$$\frac{PR_{off}}{PR_{on}} = p_1\left(\frac{m_{off}}{m_{on}}\right)^4 + p_2\left(\frac{m_{off}}{m_{on}}\right)^3 + p_3\left(\frac{m_{off}}{m_{on}}\right)^2 + p_4\left(\frac{m_{off}}{m_{on}}\right) + p_5 \qquad (eq.\ 1)$$

$$\frac{\eta_{off}}{\eta_{on}} = a_1\left(\frac{m_{off}}{m_{on}}\right)^2 + a_2\left(\frac{m_{off}}{m_{on}}\right) + a_3 \qquad (eq.\ 2)$$

And pump efficiency was modelled as a function of mass flow rate, by means of polynomial fitting from the curve available in [3]. The coefficients are $p_1 = -0.3, p_2 = 0.3, p_3 = -0.4, p_4 = 0.06, p_5 = 1.3, a_1 =$

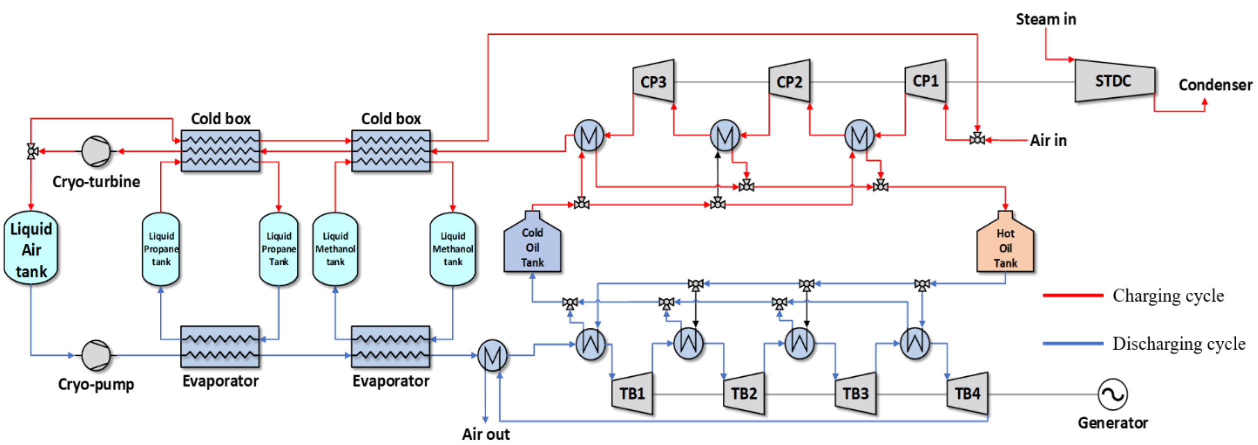


Fig. 1. Schematic diagram of liquid air energy storage system

$-1, a_2 = 2, and\ a_3 = 0$. And PR is pressure ratio and $\eta$ is pump efficiency. The off-design characteristics of cryogenic pump is obtained from affinity law as shown in Eqs. (1), (2).

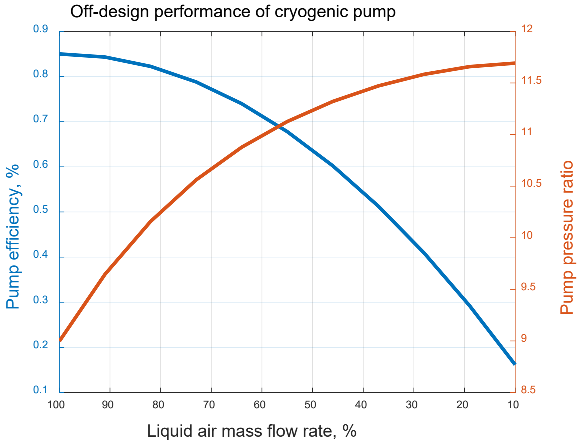


Fig. 2. Off-design characteristics of cryogenic pump.

*2.2 Evaporator and air-oil heat exchangers*

The evaporator and air-oil heat exchangers are modelled by $\varepsilon - NTU$ method [4]. Number of Heat Transfer Unit (NTU) is generally used when there is not enough geometric information of heat exchanger. A performance of heat exchanger is evaluated by calculating NTU and effectiveness. A general counterflow model is used and effectiveness ($\varepsilon$) is calculated as follows.

$$\varepsilon = \frac{1-exp(-NTU*(1-C_r))}{1-C_r\,exp(-NTU*(1-C_r))} \qquad (eq.\ 3)$$

$$C_r = \frac{C_{max}}{C_{min}}, C_{max} = max(c_{p.hot} * m_{hot}, c_{p,cold} * m_{cold}), C_{min} = min(c_{p.hot} * m_{hot}, c_{p,cold} * m_{cold}) \qquad (eq.\ 4)$$

$$\mathrm{NTU} = \frac{\mathrm{UA}}{C_{min}} \qquad (eq.\ 5)$$

*where $C_r$ is specific heat ratio of hot and cold side of HX.*

*2.3 Turbines*

To calculate off-design performance of air turbines, Flügel formula is used to approximately describe the mass flow dependency of the turbine [5]. Turbine efficiency and expansion ratio are calculated as a function of mass flow rate ratio. RPM is assumed as a constant at part-load condition. The efficiency and expansion ratio are described as follows.

$$\frac{\eta_{off}}{\eta_{on}} = (1 - t(1-n')^2)\frac{n'}{m'}\left(2 - \frac{n'}{m'}\right) \qquad (eq.\ 6)$$

$$n' = \frac{n_{off}}{n_{on}}, m' = \frac{m_{off}}{m_{on}} \qquad (eq.\ 7)$$

$$PR_{off} = \sqrt{1 + (PR_{on}^2 - 1) * \left(\frac{1}{\alpha} * \frac{m_{off}}{m_{on}}\right)^2 * \left(\frac{T_{off}}{T_{in}}\right)} \qquad (eq.\ 8)$$

$$\alpha = \sqrt{1.4 - 0.4\frac{n_{off}}{n_{on}}} \qquad (eq.\ 9)$$

*where PR is expansion ratio of turbine, n is RPM, m is inlet mass flow rate, t is set as 0.3 adopted from Ref [5], and α is RPM correction coefficient.*

*2.4 Throttling control*

Throttling valve is used to regulate inlet pressure of turbine [7]. At part-load condition, throttling valve prevents the reduction of turbine efficiency through volumetric flow rate control. The throttling valve is modelled by the isenthalpic process and volumetric flow rate is controlled as follows.

$$h_{on} = h_{off} \qquad (eq.\ 10)$$

$$\rho_{off} = \rho_{on}\frac{m_{off}}{m_{on}} \qquad (eq.\ 11)$$

$$P_{off} = f(h_{off}, \rho_{off}) \qquad (eq.\ 12)$$

*where h is inlet enthalpy, ρ is inlet density, on and off are on-design and off-design condition.*

*2.5 On-design point*

On-design cycle parameters were obtained from the previous works on thermodynamic optimization analysis of LAES [6]. Park et al. evaluated performance of LAES by analyzing sensitivity of air compression pressure and oil mass flow rate at rated power. The results are listed as follows.

Table 1. On-design cycle parameters

| | |
|---|---|
| Charging power | 260MW |
| Discharging power | 135MW |
| Liq. air mass flow rate | 269.3kg/sec |
| Oil mass flow rate | 593.1kg/sec |
| Propane mass flow rate | 314.7kg/sec |
| Methanol mass flow rate | 135.0kg/sec |
| Turbine expansion ratio | 3.0 |
| Pump pressure ratio | 87.3 |
| Turbine efficiency | 90% |
| Pump efficiency | 85% |
| Round-trip efficiency | 51.8% |
| Power density | 119.0kWh/m$^3$ |
| Liq. Air inlet temperature | -194.0°C |
| Oil inlet temperature | 241.6 °C |
| Propane inlet temperature | -59.1°C |
| Methanol inlet temperature | 14.8°C |

## 3. Results and Discussions

In this section, the influence of liquid air mass flow rate on the discharging cycle is evaluated. The effect of reducing liquid air mass flow rate from 100% to 10% is evaluated. For convenience of calculation, it is assumed that the mass flow rate of propane, methanol, and thermal oil is reduced with the same ratio of liquid air reduction.

*3.1 Influence of throttling valve on air turbines*

Fig. 3 illustrates the influence of throttling valve on air turbines. In the absence of throttling valve, the efficiency of turbines dramatically decreases and when it reaches 86% of rated mass flow rate, off-design calculations are not possible due to negative efficiency. On the other hand, when throttling valve is applied, it can be seen that the efficiency of turbine remains constant at the rated value.

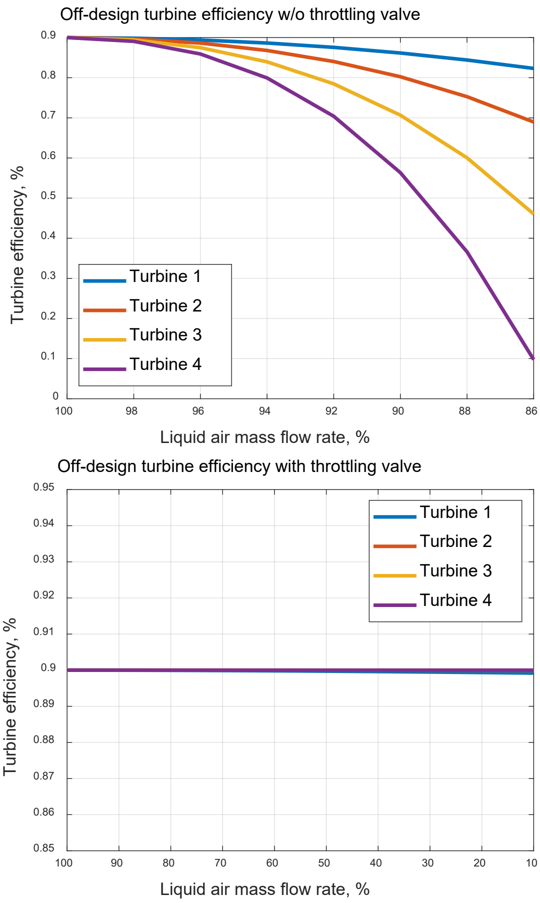


Fig. 3. Influence of throttling valve on the turbine efficiency.

*3.2 Influence of air mass flow rate on power generation*

Mechanical works of air turbines and cryogenic pump are illustrated in Fig. 4. In the case of air turbines, work of turbines is smoothly decreased due to volumetric flow rate control. In the case of cryogenic pump, the effects of efficiency drop and pressure ratio increase are simultaneous and competing, resulting in linear work reduction.

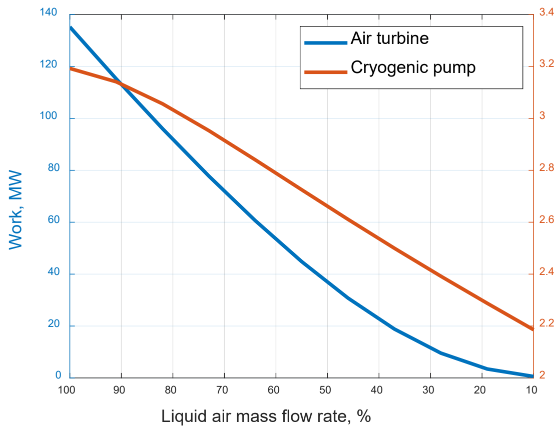


Fig. 4. Influence of air mass flow rate on work of air turbines and cryogenic pump

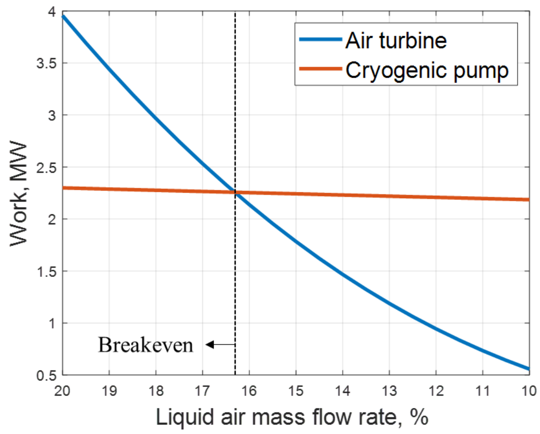


Fig. 5. Breakeven point of liquid air energy storage system

The breakeven point of LAES can also be checked from the off-design analysis. As shown in Fig. 5, the work of cryogenic pump is larger than that of air turbines until the air mass flow rate reaches 16.2% of the rated value. Therefore, the cryogenic pump can be operated through the motor until 16.2%, and cryogenic pump can be operated from the work of air turbine after 16.2%.

*3.3 Temperature of thermal oil storage tank*

Fig. 6 shows the temperature of thermal oil storage tank with air mass flow rate. When the oil mass flow rate is reduced to the same rate as liquid air, the temperature of thermal oil increases after air-oil heat exchanging. This is because overall heat transfer coefficient (UA) is decreased as mass flow rate decreases (Fig. 7). This result agrees well with the previous study on off-design analysis of heat exchanger, where overall heat transfer coefficient is proportional to the 0.8 power of mass flow rate [2]. Therefore, the mass flow rate of thermal oil should be controlled for enhancing part-load performance of discharging cycle.

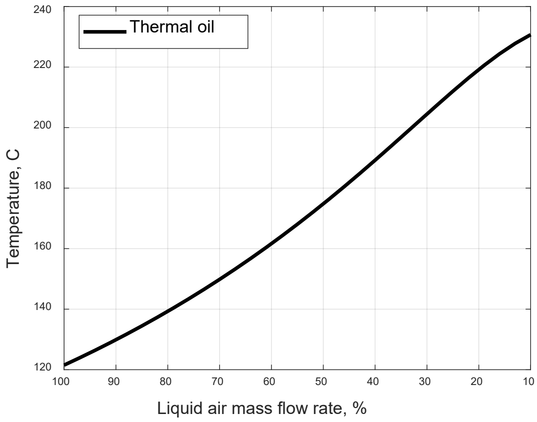

Fig. 6. Influence of air mass flow rate on the temperature of thermal oil storage tank

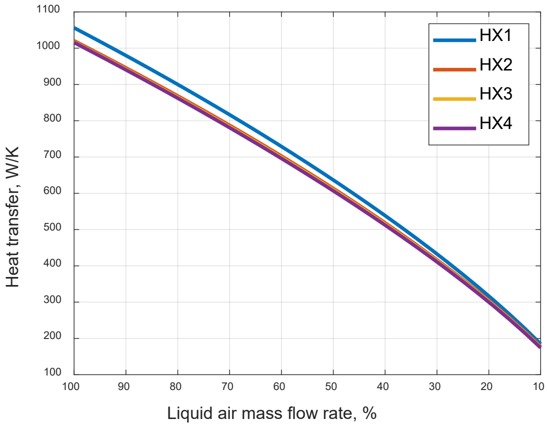

Fig. 7. Influence of air mass flow rate on overall heat transfer coefficient

## 4. Conclusions

In this study, the off-design performance of LAES discharging cycle is investigated. Cryogenic pump, evaporator, air-oil heat exchanger, and air turbines are modelled with thermodynamic equations. To prevent efficiency-drop of air turbines, volumetric flow rate control method is applied by utilizing a throttling valve. When applying throttling valve, it is found that efficiency of air turbines is well maintained at the rated value. As the air mass flow rate decreases, the turbine work decreases smoothly due to throttling valve control. In case of cryogenic pump, the pump work is linearly reduced by applying affinity law. From the off-design analysis, the breakeven point of LAES is also found. Before 16.2% of the rated mass flow rate, pump work is larger than that of the turbine. Therefore, cryogenic pump should be operated with the motor. After 16.2%, cryogenic pump can be driven by the generated work from air turbines. The influence of air mass flow rate on temperature of thermal oil is also investigated. Since the overall heat transfer coefficient is decreased when the mass flowrate is decreased, the temperature of thermal oil is increased which means reduction of heat transfer. Therefore, in the future, the control strategy of thermal oil mass flow rate should be investigated to enhance off-design performance of the discharging cycle under part-load condition.

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