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

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Introduction

- Due to intermittency of renewable energy sources, 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 energy storage system to nuclear power plant, the operational flexibility of the nuclear power plant can be greatly enhanced.
- 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.
- Part et al. first suggested the mechanical integration of LAES with nuclear power plant by coupling steam turbine to air compressor of LAES.
- During off-peak hour, steam is bypassed from nuclear steam cycle and operates steam turbine which is mechanically connected to air compressor. Air is compressed and liquefied by exchanging heat with cold energy storage system. During peak hour, air is evaporated and expanded through an air turbine to generate electricity.
- Since energy storage systems are mainly operated at part-load condition, it is important to evaluate the off-design performance of LAES.
- In this study, the off-design performance of LAES is evaluated during discharge cycle with off-design modelling of each components: liquid air pump, evaporators, heat exchanger, and air turbines.
- 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.

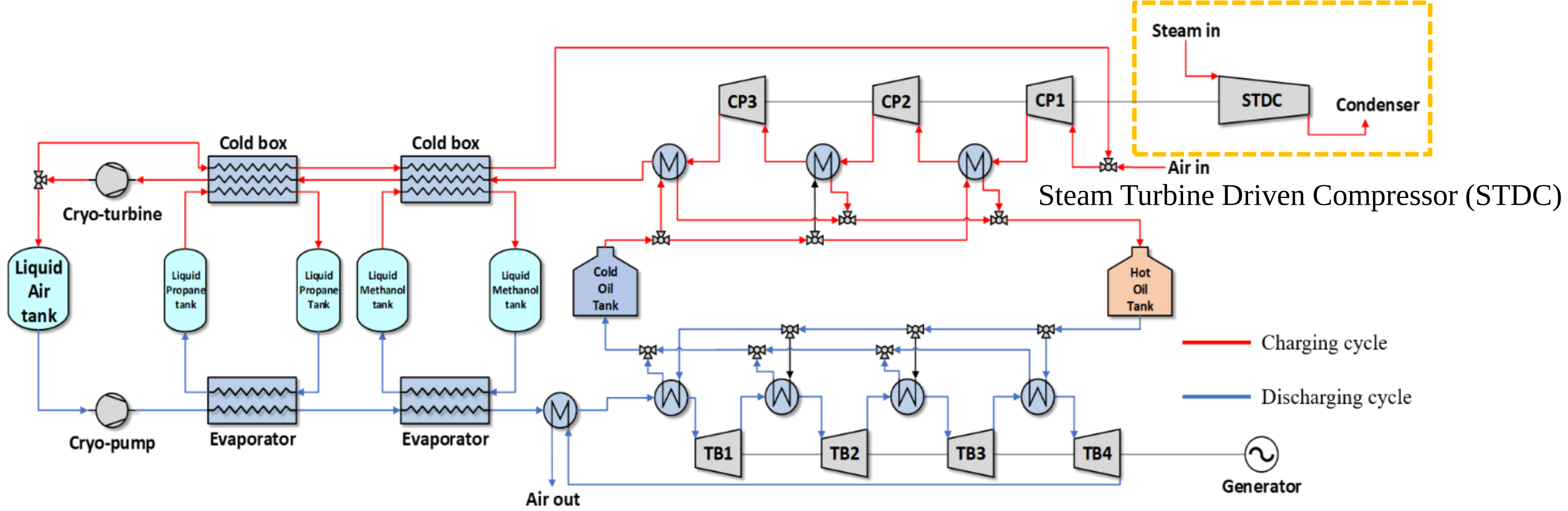

Fig. 1. Diagram of mechanically integrated LAES system with NPP

Methodology

❖ Cryogenic pump

- Cryogenic pump is designed according to affinity law, which relates pressure ratio and mass flow rate.

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

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

where PR is pressure ratio, p is polynomial coefficient, m is mass flow rate, η is pump efficiency, off is off-design condition, and on is on-design condition : $p_1 = -0.3, p_2 = 0.3, p_3 = -0.4, p_4 = 0.06, p_5 = 1.3, a_1 = -1, a_2 = 2, and\ a_3 = 0$.

❖ Evaporator and air-oil heat exchanger

- The evaporator and air-oil heat exchanger are modelled by $\epsilon - NTU\ method$. A performance of heat exchangers is evaluated by calculating NTU and effectiveness. A general counterflow model is used and effectiveness is calculated as follows.

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

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

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

where C_r *is specific heat ratio, NTU is number of heat transfer unit, m is mass flow rate,* c_p *is heat capacity, hot is hot side, and cold is cold side.*

❖ Air turbines

- To calculate off-design performance of air turbines, Flugel formula is used to approximately describe the mass flow dependency of the turbine performance. Efficiency and expansion ratio of air turbines are calculated as function of mass flow rate. RPM is assumed as a constant at part-load condition.

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

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

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

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

where PR is expansion ratio of turbine, n is RPM, m is inlet mass flow rate, t is set as 0.3 adopted from previous research and α is RPM correction coefficient.

❖ Throttling valve

- Throttling valve is used to regulate inlet pressure of turbine. At part-load condition, throttling valve prevents the reduction of turbine efficiency through volumetric flow rate control. Throttling valve is modelled by isenthalpic process.

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

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

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

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

Results

- For calculating off-design performance, on-design cycle results are used from the previous work.

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 efficiency	90%
Pump efficiency	85%
Round-trip efficiency	51.8%
Liq. Air inlet temperature	-194.0℃
Oil inlet temperature	241.6 ℃
Propane inlet temperature	-59.1℃
Methanol inlet temperature	14.8℃

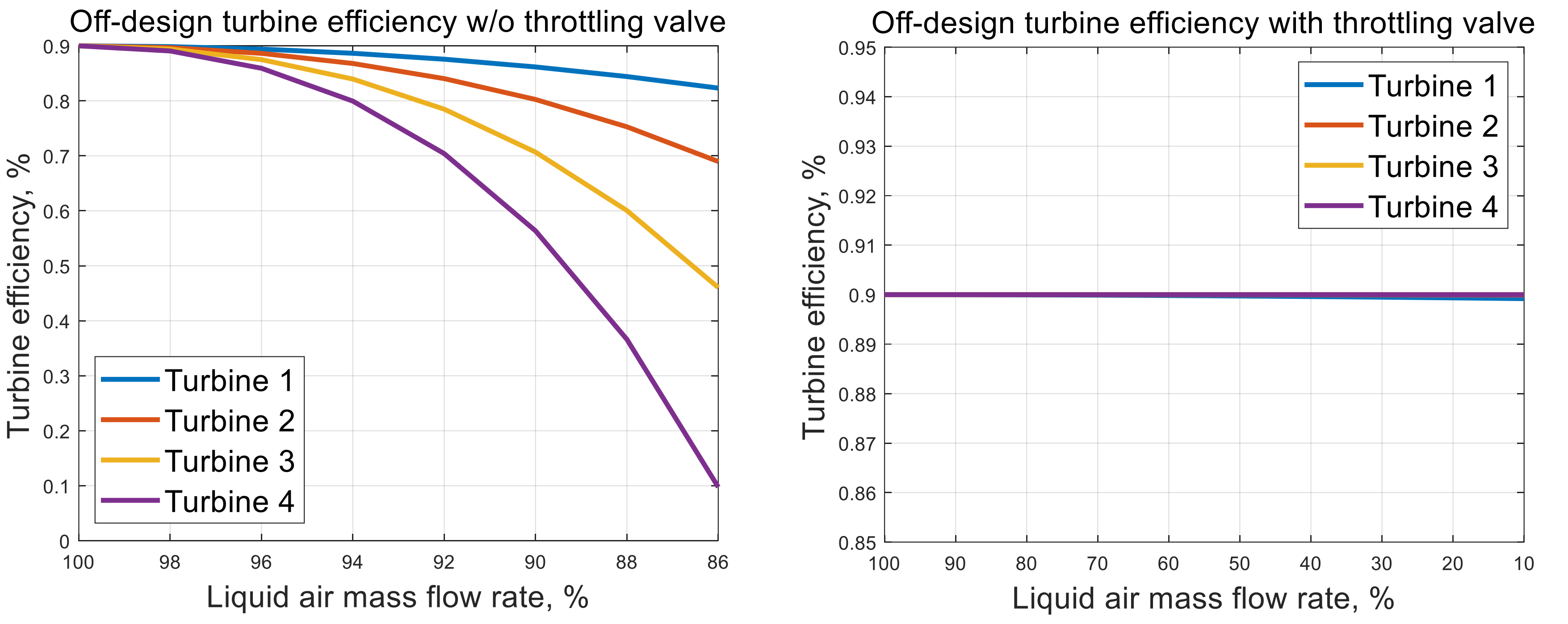

Fig. 1. Influence of throttling valve on the turbine efficiency

- Fig. 1. illustrates the influence of throttling valve on air turbines. In the absence of throttling valve, the efficiency of turbines are dramatically decreased. On the other hand, when throttling valve is applied, it can be seen that the efficiency of turbine remains constant at the rated value.

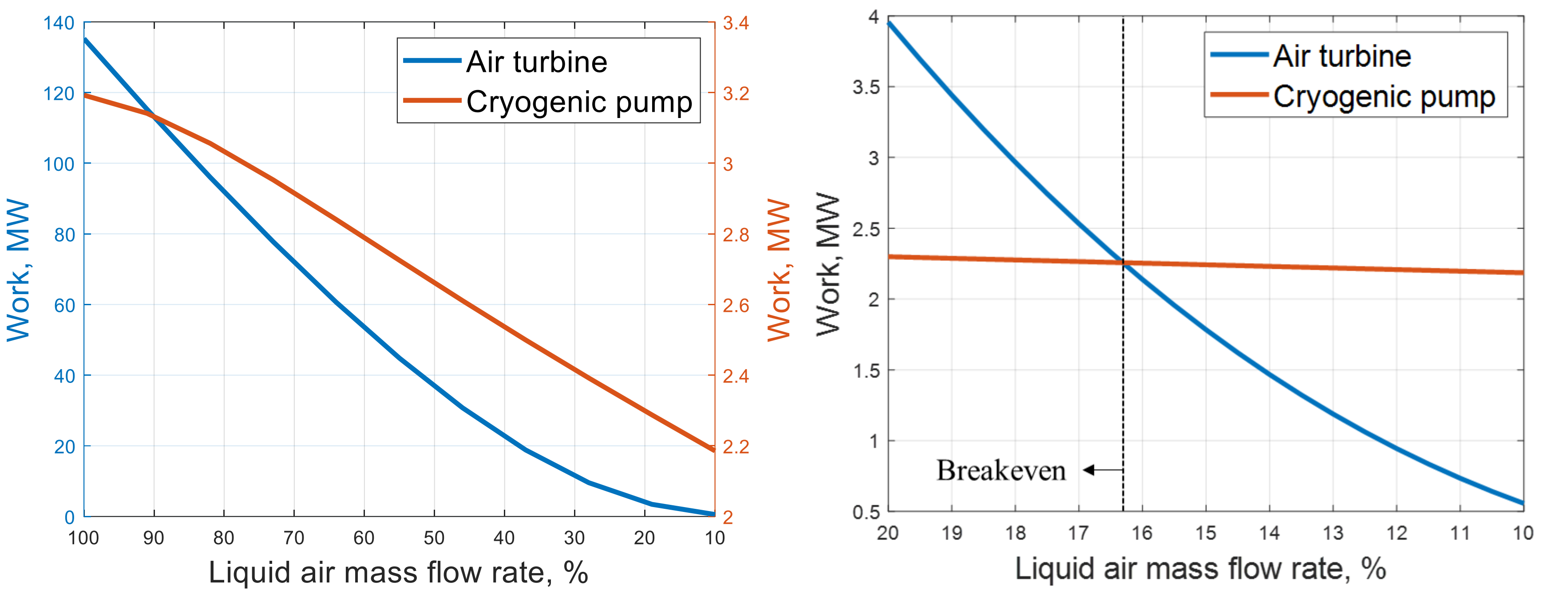

Fig. 2. Influence of air mass flow rate on work of air turbine and cryogenic pump (left) and breakeven point of LAES (right)

- Mechanical works of air turbine and cryogenic pump are illustrated in Fig. 2. In the case of air turbines, work 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.
- The breakeven point of LAES can also be checked from off-design analysis. As shown in Fig. 2, 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%

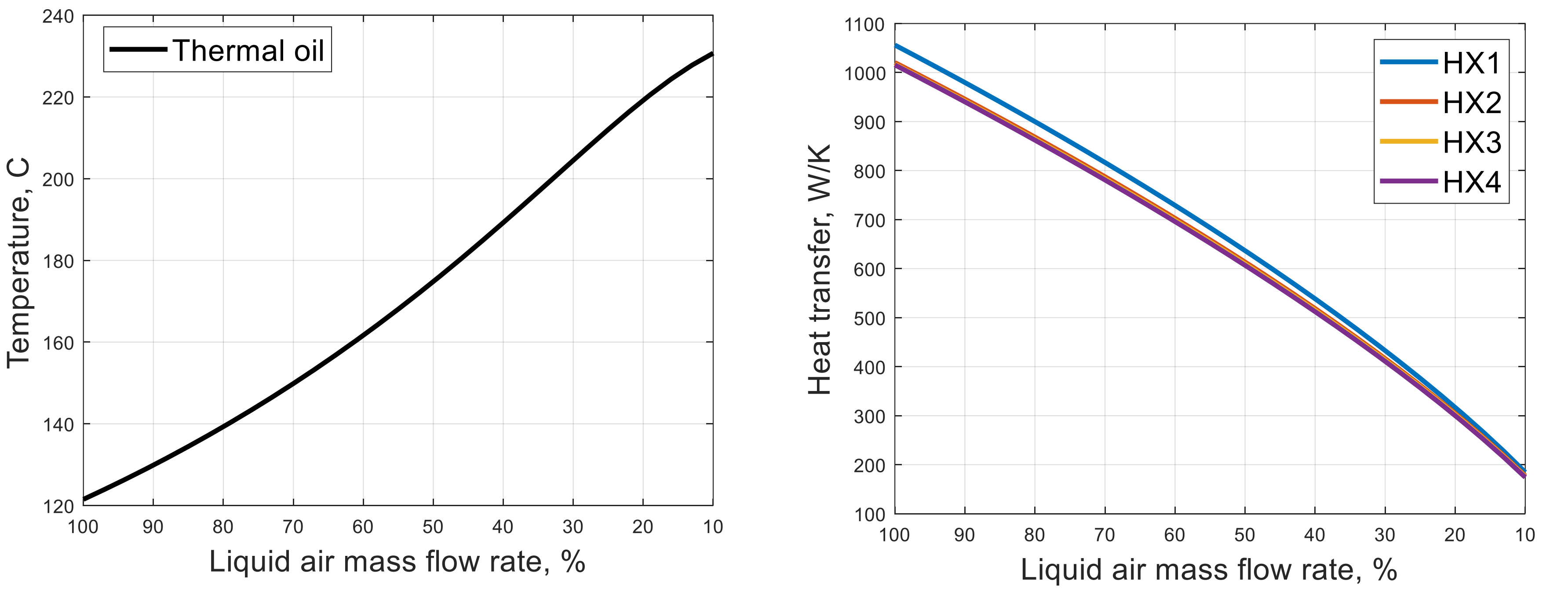

Fig. 3. Influence of air mass flow rate on temperature of thermal oil (left) and overall heat transfer coefficient of air-oil HX (right)

- Fig. 3 shows the temperature of thermal oil storage tank with air mass flow rate. The temperature of thermal oil increases after air-oil heat exchanging. This is because the overall heat transfer coefficient is decreased leading to less heat transfer to air. Therefore, the mass flow rate of thermal oil should be controlled for enhancing part-load performance of discharging cycle.

Conclusion

- In this study, off-design performance of LAES in discharging cycle is investigated.
- Off-design modelling of cryogenic pump, heat exchanger and air turbine are presented.
- As air mass flow rate decreases, the work of air turbine and cryogenic pump are decreased smoothly.
- From the analysis, the breakeven point appears as 16.2% of rated air mass flow rate.
- And the drop of overall heat transfer coefficient makes less heat transfer to air, therefore, the control strategy should be investigated to achieve optimum heat transfer.

Acknowledgement

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