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Concept of Liquid Air Energy Storage System Integrated Molten Salt Reactor

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1. Introduction

The world set a goal to achieve carbon neutrality by 2050. According to data from the World Resources Institute, the energy sector accounts for about 73% of global carbon emissions [1]. Therefore, in order to achieve carbon neutrality, carbon emission reduction in the energy sector should be the first priority. However, there are limits to variable renewable energy to replace coal-fired and gas energies due to intermittent problem. Therefore, a clean energy source that are available at all times is essential. Nuclear energy, which emits the least fine dust and carbon dioxide among the base load energies, can play an important role.

Molten salt reactor (MSR), one of the Generation-IV reactors, has the highest potential when considering technology, safety, and economic feasibility [2]. The MSR has a high core power density for compactness. Molten salt has a lower chemical reactivity than liquid sodium and has a high boiling point. Thus, high temperature operation is possible and high thermal efficiency can be achieved. In energy production, there is a principle called energy return on investment (EROI), in which a higher number indicates better efficiency, when the energy generated is divided by the energy required to generate that energy. Solar energy has a score of 10, while coal-fired scores between 18 and 43. The estimated EROI of MSRs is at about 1200, meaning its energy efficiency scores higher than every other method of energy production [3].

According to the International Energy Agency report, global energy demand is projected to increase by more than 25% during the period 2017-2040 [4]. Along with the increase in energy demand, the demand for energy storage systems is rapidly increasing in order to provide stable power supply. However, the existing pumped storage hydropower and batteries have a clear capacity limit, so these are insufficient to meet increased demand. Therefore, liquid air energy storage system (LAES) is promising as a large capacity energy storage. LAES has high energy density. This is similar to batteries, around 20 times higher than CAES. Another advantage with LAES is that it does not require any scarce or toxic materials and does not produce toxic waste [5]. In this study, the integration concept of the MSR and LAES are proposed.

2. LAES Integrated MSR

When the grid encounters overgeneration, the energy of MSR is stored in LAES (charging mode). When the grid is under peak demand, then the stored energy is released from the LAES to generate surplus power and fed to the grid directly, under the discharging mode. Even if the MSR has load-following capability, the advantage of storing energy during overgeneration is that it has enough energy to prepare for a sudden increase in power. Fig. 1 shows the principle of charging and discharging mode.

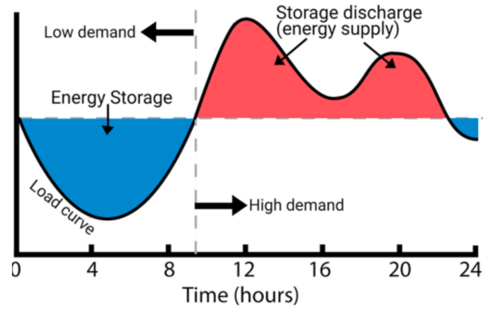

Fig. 1. Charging & Discharging mode of ESS [6]

In this section, layouts of LAES integrated MSR are described. The layouts differ with respect to the charging mode and discharging mode. During the discharging mode, many layouts are possible depending on the usage of high temperature heat from the MSR.

2.1 Charging Mode

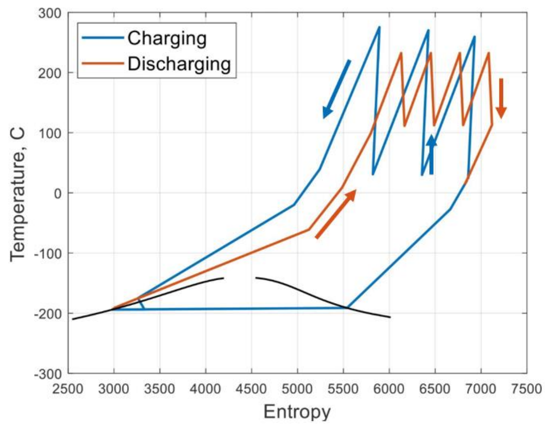

Fig. 2. Example of T-s diagram of LAES [7]

The LAES has five stages: compression, liquefaction, storing, evaporation, and expansion. Fig. 2 is an example T-s diagram showing the thermodynamic behavior of LAES. The charging mode includes compression and liquefaction. Compressors are used to store electric energy by converting it into mechanical energy in the form of compressed gas. In general, an electric motor is used to drive compressors. However, there is a limit to using it for large capacity energy storage in terms of technical and economic feasibility. To overcome this

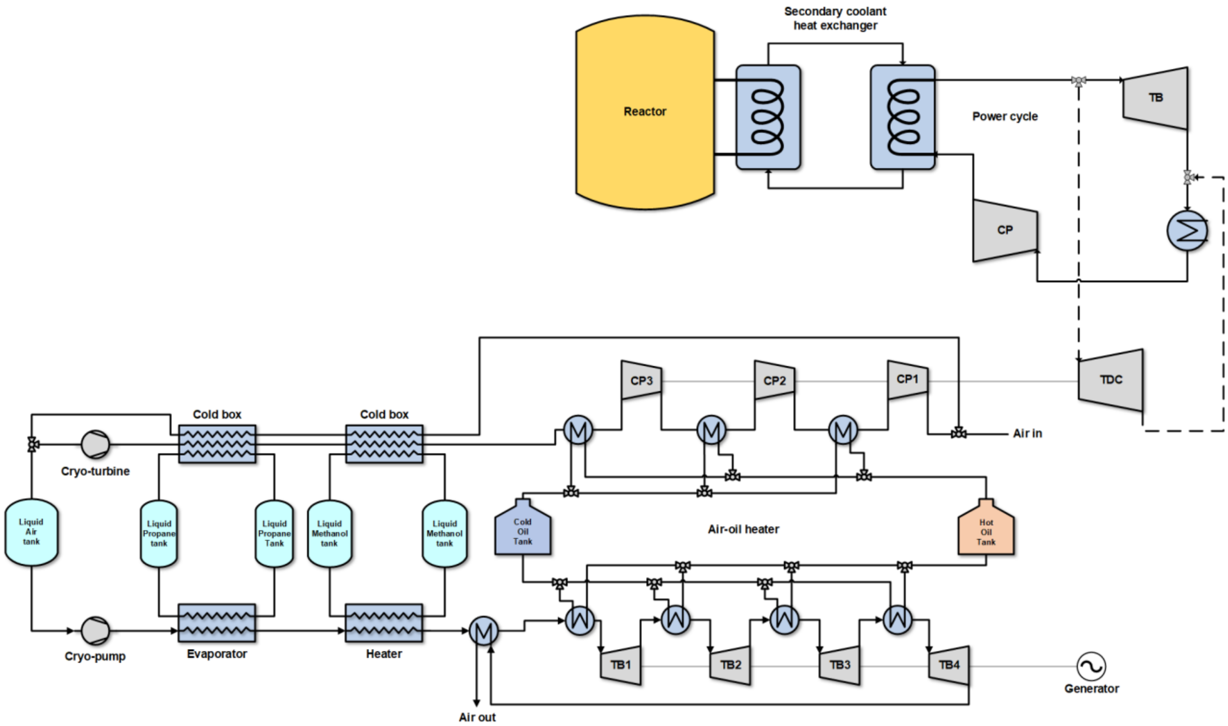

Fig. 3. LAES integrated MSR (charging mode and discharging mode 1)

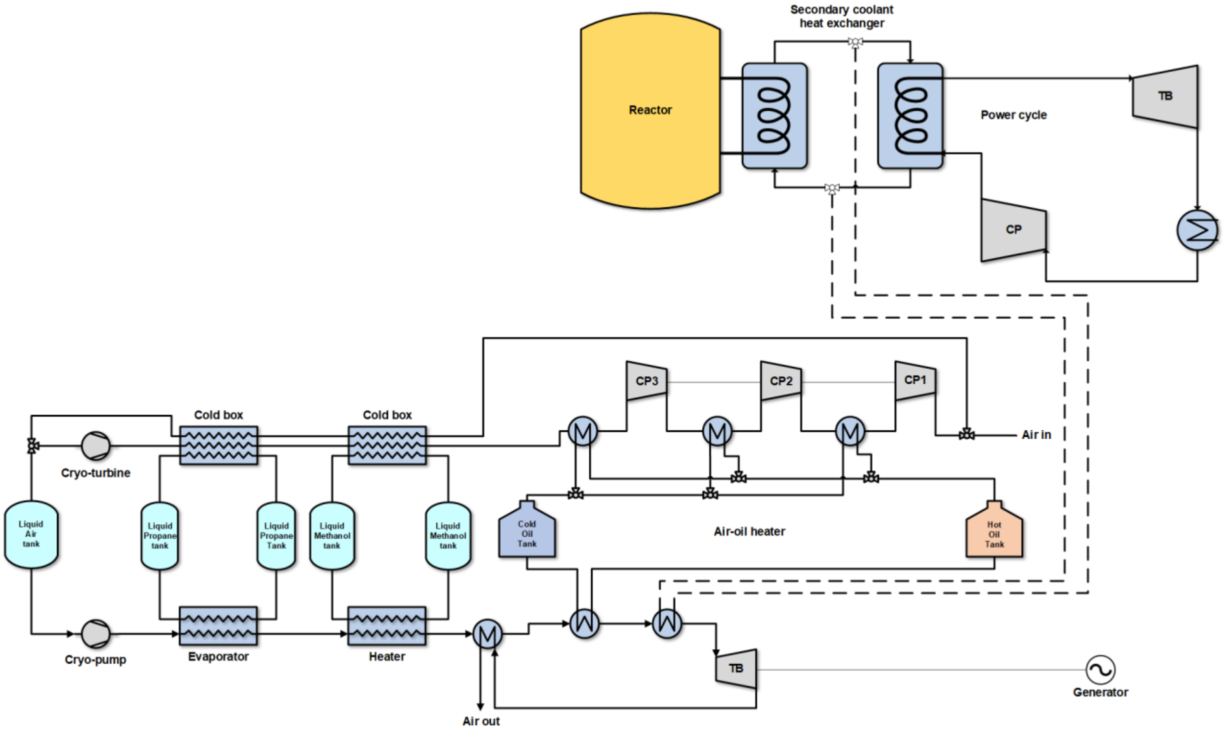

Fig. 4. LAES integrated MSR (discharging mode 2)

problem, a turbine driven compressor (TDC) is presented [8]. A fraction of working fluid in the power conversion system of the MSR are bypassed and drives the TDC and returns (Fig. 3). This naturally reduces the MSR power and transfers energy to the LAES.

The layout and fluids of the LAES were referenced in the previous study [6]. With the TDC, air is compressed and therminol VP-1 absorbs the heat generated through compression. Cold compressed air is additionally cooled down to cryogenic temperature using propane and methanol. By expanding to atmospheric pressure, liquid air is made and stored in the tank.

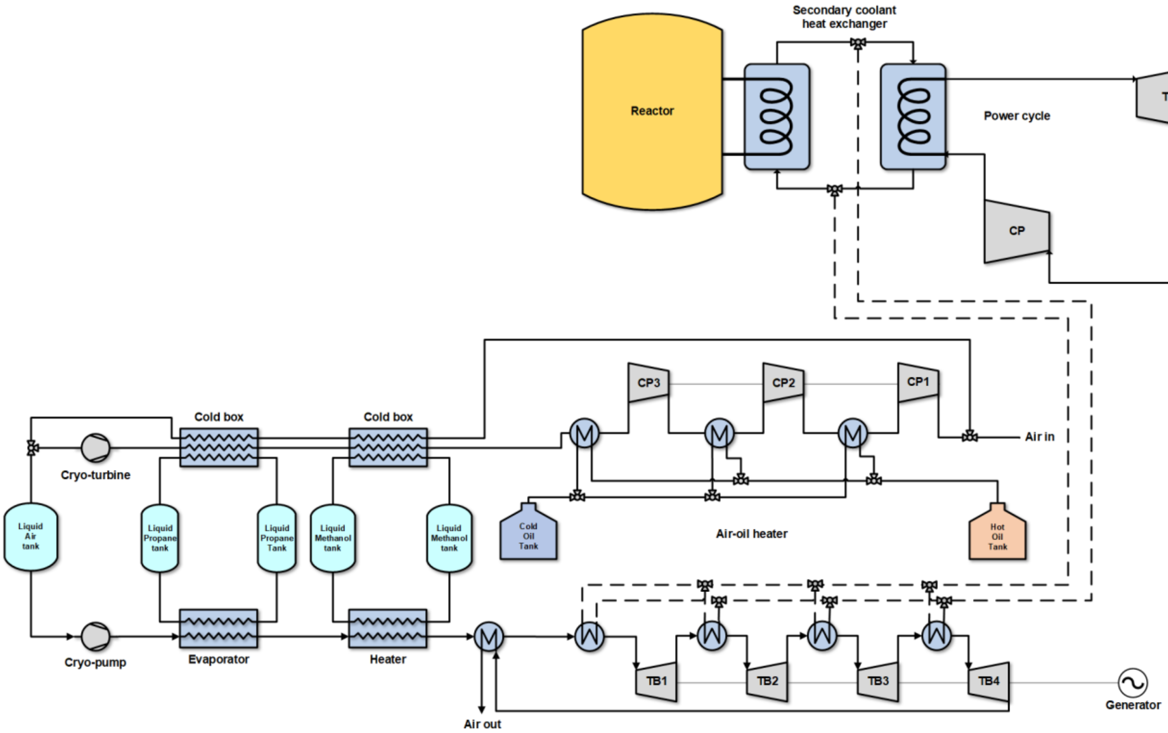

Fig. 5. LAES integrated MSR (discharging mode 3)

2.2 Discharging Mode

The discharging mode includes evaporation and expansion. Cryo-pump compresses liquid air to critical pressure of air. Generally, the heat stored during charging mode is used (Fig. 3). Compressed liquid air is evaporated by heat from cold storage tank. Evaporated air is heated by therminol VP-1 tank. Then, the air expands to generate electricity using the air turbine. At this time, MSR operates a full-load. This integration is commonly known as mechanical integration.

The MSR has high operational temperature close to 600 °C. Thus, the high temperature heat can be used as shown in Fig. 4 and Fig. 5. By bypassing some of the fluid from the secondary loop of the MSR, it is used as a heat source for the air turbine. Since the heat source flow rate of the power conversion system of the MSR is reduced, part-load operation is performed. These are thermal & mechanical integrations.

2.3 Power Generation at Discharging Mode

Table I: LAES conditions

	Unit	Value
Compressor efficiency	%	85
Turbine	%	92
Cryo-turbine efficiency	%	80
Cryo-pump efficiency	%	80
Pressure drop in heat exchanger	%	1
Pinch of heat exchanger	K	5
Mass flow rate of air	kg/s	100
Mass flow rate ratio of VP-1		0.64
Mass flow rate ratio of propane		0.98
Mass flow rate ratio of methanol		0.49
Propane minimum temperature	K	93
Propane maximum temperature	K	214
Methanol minimum temperature	K	214
Methanol maximum temperature	K	288
Ambient temperature	K	298
Ambient pressure	kPa	101
Compression pressure	MPa	23

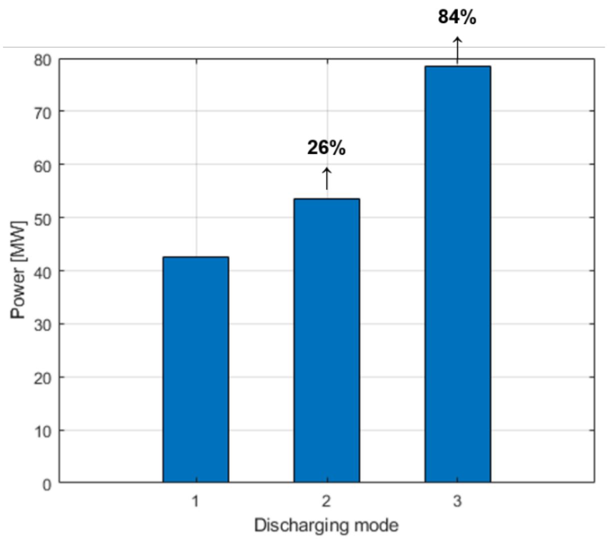

Fig. 6. Power generation in each discharging mode

The condition in Table I were used to compare power generation with respect to the discharging modes. Since the discharging modes do not affect the charging mode, the compressor work used in the charging mode is always the same, and its value is 74.67MW.

In the case of discharging mode 1, which uses only the heat stored in the charging mode, the generated power is 42.55MW. In discharging modes 2 and 3, the air turbine inlet temperature is assumed to be 650°C. The generated power in discharging mode 2 and 3 is 53.50MW and 78.37MW, respectively. Fig. 6 shows generated power in each mode and how much it increases (%) compared to discharging mode 1.

3. Conclusions and Further Works

For the global goal of achieving carbon neutrality and the increasing energy demand, this study presents an integration concept and layouts of the MSR with LAES. In the charging mode, the TDC is used for large capacity energy storage. In the discharging mode, the layouts utilizing the high temperature heat of the MSR were proposed and a preliminary analysis was conducted on how much power it could generate compared to the conventional LAES.

As a result, a significant amount of additional power can be generated. However, in these cases, the power generation of the MSR is reduced. In particular, in the case of discharging mode 3, the power reduction may be quite large. It is necessary to select a power conversion system of the MSR and further analyze how much power reduction occurs. It is important to optimize the power produced from LAES and the power reduced in MSR system.

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