Basic Design of High-Temperature Sodium Thermal Energy Storage(TES) Verification Test Facility

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1. Introduction

Recent growth of renewable energy shares in the electric grid inevitably causes perturbation on the existing energy market and the role of existing large-capacity power generations, such as nuclear power, needs to be changed to fulfil the energy demand in the market. Specifically, the need of flexible energy supply is increasing to solve the intermittency problems of renewables. The latest nuclear reactor design adopted the load following concept, but it is not enough to keep up with the increasing perturbations of renewables.

One of the effective solutions is to store the energy and to use when needed. Among various types of energy storage systems (ESS), the thermal energy storage (TES) is the most cost-effective way with its simplicity and efficiency in large-scale. There are many ways of connecting the TES to the power source, and/or to the grid itself to maximize the energy shares stabilization.

Current commercial TES in large-scale uses molten salts as base material. However, the industry is experiencing some issues regarding the long-term operation and maintenance, the cost of materials, and high-temperature applications[1]. The chemistry and chemical-related characteristics of molten salts are the difficult part during operation and maintenance. The corrosion aspect also makes this system costly more than expected. Moreover, there is the intellectual property on the specific chemical composition of use and thus resulting in more cost on the material itself. Lastly, the current molten salts are not suitable for the high-temperature application (over 600℃) since they are dissociated chemically at high temperature condition.

In Korea Atomic Energy Research Institute (KAERI), the liquid sodium based TES is considered as an alternative material for its excellent material compatibility and high-temperature usage, and its low cost. There are various R&D items on-going directly and indirectly.

In this paper, the sodium TES verification test facility is described as one of such efforts. The purpose of this paper is to introduce and discuss about the basic design of the facility and the scope is bound to only cover the TES, not the overall system connection to the grid.

2. Design Requirement

2.1 Functional requirement

The main function of the test facility is to simulate cycle operation including heat energy charging, holding for some time, and discharging for various usages. The charging and discharging rate of the input heat energy is at maximum 10 hrs[2]. This rate can vary with the operation scenarios.

2.2 Main design requirement

The heat capacity of the test facility is 1.25 MWh(th) and the medium for heat transfer is liquid sodium. The test facility consists of two tank systems, namely hot/cold tanks, and the design temperature of each tank is 650 ℃ and 200 ℃, respectively[2].

Among various candidate materials (Alloy 617, Alloy 800H, 316H, and 316L) for the structures in high temperature region, Stainless Steel 316L was selected to have cost competitiveness, which is very challenging attempts. For the other low temperature region, Stainless Steel 304 is selected. The nominal power output is 125 kWt and it takes 10 hrs to fully charge and discharge. The nominal flowrate is determined to be 0.2 kg/s and this is the optimum value from the test scale consideration.

The discharged sodium from cold tank flows through loop heater and moves into the hot tank to store the energy in sensible heat. While holding the heat energy, the target heat loss was set to be less than 5% for maximum 6 days. There are Argon cover gas zones and expansion tank to mitigate the pressure change with the temperature and the operation pressure is maintained below 103 kPa.

2.3 System arrangement requirement

There are two electro-magnetic pumps (EMP) to make necessary sodium flows for charging and discharging. These two EMPs should be installed in the cold legs for both charging line and discharging line due to their design temperature.For safe and convenient use of liquid sodium, the facility has dedicated lines of sodium supply and drain connected to the tanks. And the tanks positions should be higher than the lines for drain.

The flowrate is measured by Coriolis type flowmeter to assure the accuracy and should be also installed in the cold leg considering its design temperature. All the horizontal piping in the facility should be slanted by minimum 3%, so that the remaining sodium drain is possible with gravity[]. The valve is recommended to position in horizontal piping. In the case of inevitable vertical piping, the Y-type valve should be used.

2.4 Main components requirement

The main components of the test facility are the tanks and the sodium-to-air heat exchanger.

<u>Tank</u>

The design temperature for each tank is 650 ℃ and 200 ℃ respectively. The design pressure is 5 bar for both. The structural integrity must be assured to satisfy the high temperature design criteria under design transient conditions during the design life. There should be no penetration in the sidewall and the top head should be strong enough to support the instrumentations. The thermal insulation should be applied not only on the sidewall but also the bottom and the top of the tank. The target surface temperature is lower than 40 ℃. The thickness should be within 150 mm and the penetration is needed for nozzles and instrumentation.

<u>Sodium-to-air heat exchanger</u>

The design temperature and pressure is 650 ℃ and 5 bar. The material is 316L, same as the hot tank to reduce the cost for high temperature application. The heat exchanger adopts the shell and tube structure with helical tubes for sodium to maximize the heat transfer while assuring the structural integrity of thermal expansion. There is no need to use expensive bellows.

3. System Design and Layout

The system is basically two tank system where hot and cold tank are included. The fluid is heated up by the heat source and is stored in the hot tank until the time of energy need. When the energy demand comes up, the hot fluid flows through heat exchanger to dissipate the energy and moves on to the cold tank. It is very simple but effective principle.

3.1 System P&ID

The components and equipment layout is shown in Fig. 1. The arrangement follows the design requirements. The auxiliary systems, such as sodium purification system, argon gas supply system, and compressed air system for valve actuators, are not illustrated in the diagram. The mother loop for these systems is connected to the bottom tank and it includes all the required sub-systems related to the sodium handling and transporting.

The red lines in P&ID are the hot leg where the temperature is approximately 700 ℃ and the blue lines are the cold leg where the temperature is around 200 ℃. There is one expansion tank at the top to remove any gas pocket during system charging and to accommodate the pressure change caused by the temperature change.

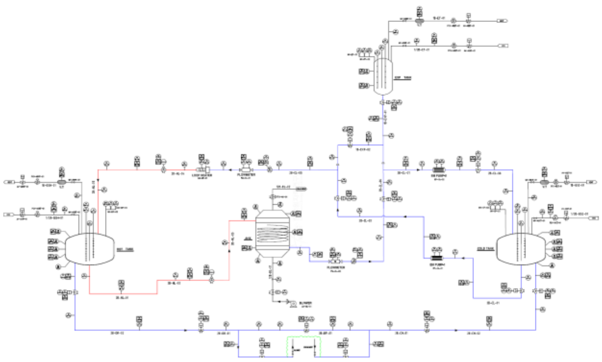

Fig. 1 P&ID of the facility[3]

3.2 Main component design

<u>Tank</u>

The tank capacity was determined considering the practical limitations of both the budget and the physical space. The tank contains the energy from the heat source for long-term storage and discharges the heat on demand.

- Heat capacity: 1.25 MWh
- Charging/Discharging time: 10 hrs
- Nominal power: 125 kWt
- Operating Temperature: 200 ~ 700 ℃

The required sodium volume can be calculated from the following equation.

$$E = mC_p\Delta T = \rho V C_p(T_h - T_c)$$

The calculated sodium volume for the tank is 9.13 m^3 and this is approximately 7156 kg assuming 700 ℃. To relieve the thermal shock while re-charging, some of the sodium should remain in the hot tank and additional cover gas space is also needed. Therefore, the final tank volume becomes 12.05 m^3.

The size of the tank is as follows[4].

- Diameter: 3,000 mm
- Height: 2,000 mm
- Thickness: 10 mm
- Material: 316L (hot) / 304 (cold)

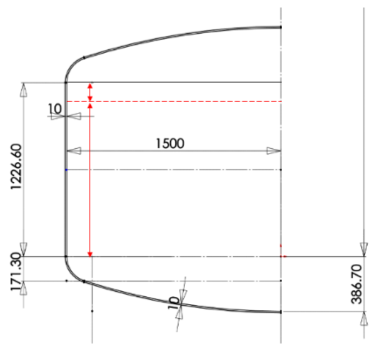

Fig. 2 Tank specification

<u>Heat exchanger</u>

The heat exchanger type was determined based on previous experience of various sodium experiments. The helical type shell-and-tube heat exchanger was designed to remove the heat and simulate energy applications.

The main design parameters are as follows.

- Heat transfer rate: 125 kW
- Overall heat transfer coefficient: 49.36 W/m^{2}K
- P/D: 1.71
- Effective tube length: 3.723 m
- Number of tubes: 60
- Tube ID/OD: 0.0114/0.0138 mm
- Nominal sodium flowrate: 0.2 kg/s

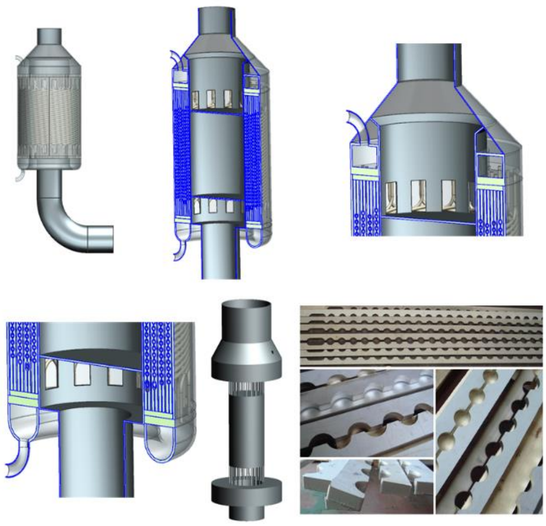

Fig. 3 Heat exchanger design

3.3 System layout

Main components and equipment are placed not to interfere the existing structure and the result of 3D layout is shown in Fig. 4.

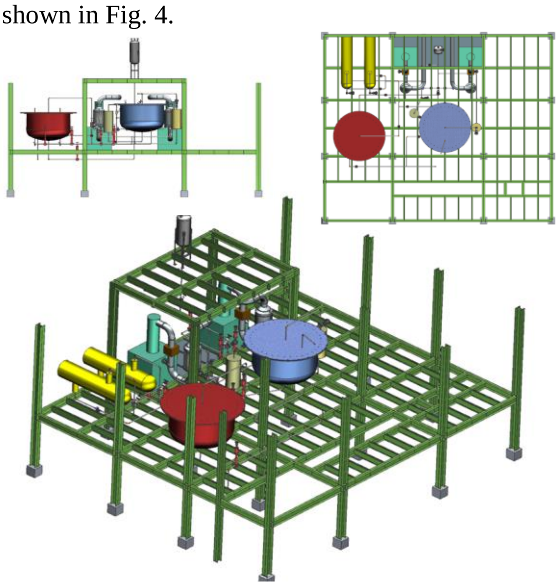

Fig. 4 3D layout of the facility

There is enough space for the maintenance and the sodium will be shared from the mother loop tank. The reason why this facility doesn't have its own space and beam structure is that sharing the common system with mother saves many things, such as additional cost and effort to re-apply for the license.

4. Summary and future work

The sodium TES is considered as an alternative to the current commercial TES using molten salts. For its performance verification, the experimental research is necessary with large enough scale to simulate the charging cycle. And also, with this facility, unexpected practical problems will be identified. The key of this verification research is to investigate the effectiveness of 316L material and to enhance the thermal insulation. The requirements were set and the facility was designed. According to the construction schedule, the specific design will be carried out in this year and further study on the test matrix and test conditions will follow. This will include the scenario analysis and various evaluations.

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