Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

A Trade-off Study on Insulation Structure for High-Temperature Tank of Thermal Energy Storage Verification Test Facility

Jung Yoon*, Hyeonil Kim, Yong-Hoon Shin, Jewhan Lee
Korea Atomic Energy Research Institute, Versatile Reactor Technology Development Div., 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon
Corresponding author: jyoon@kaeri.re.kr

1. Introduction

As the proportion of renewable energy increases, the nuclear power, a large-capacity power generation source responsible for base load, needs to be flexible power generation to meet energy demand, and efforts to maximize energy utilization are required for sustainable growth. In general, nuclear power generation does not consider load-following operation due to the risk of system impact, and responds to external factors by adjusting the amount of steam flowing into the turbine when necessary. Since nuclear power has a low ratio of fuel cost to power generation cost, the economic benefit that can be obtained from changing the power is not crucial. Therefore, the development of a Nuclear-Renewable Hybrid Energy System (NRHES) is important that can utilize excess thermal energy in a way to flexibly control electrical power while maintaining thermal power.

In KAERI, the thermal energy storage (TES) verification test facility to investigate the performance of a large-capacity TES facility based on liquid metal is considered and the design is on-going. Since one of the main purposes of this test facility is to store thermal energy for long enough time with minimal heat loss, its insulation design is one of the most important aspect, and it is especially important to evaluate the insulation performance in the high-temperature tank, which serves to store thermal energy.

In this study, evaluations for the selection of insulation structure that satisfies the given thermal fluid conditions for various insulation structures presented for high-temperature tanks were performed.

2. Methods and Results

The TES verification test facility plays a role in simulating a series of operations related to the charge, storage, and utilization of thermal energy. Liquid sodium is used as the working fluid, and the major components constituting the test facility are a loop heater as a heat source, a high-temperature tank for storing thermal energy, a sodium-to-air heat exchanger as a heat sink, a low-temperature tank for storing sodium that has lost thermal energy, an expansion tank to accommodate pressure changes in the system, and an electronic pump to transport sodium. The required amount of liquid sodium and the size of the TES tank calculated according to the design requirements[1] for thermal storage of the test facility[2] are as follows. Fig. 1 shows the piping & instrument diagram of the TES verification test facility[3].

- TES capacity: 1.25MWh
- Required time for TES: 10hrs
- Rated power: 125kWt
- Working fluid: Liquid sodium
- Operating temperature: 200~700℃
- Required sodium mass: 7,157kg
- TES tank volume: 12.05m^3 (includes the cover gas region to accommodate pressure change due to temperature change and residual sodium region to prevent thermal shock)
- TES tank size: 3,000mm(D)×2,000mm(H)

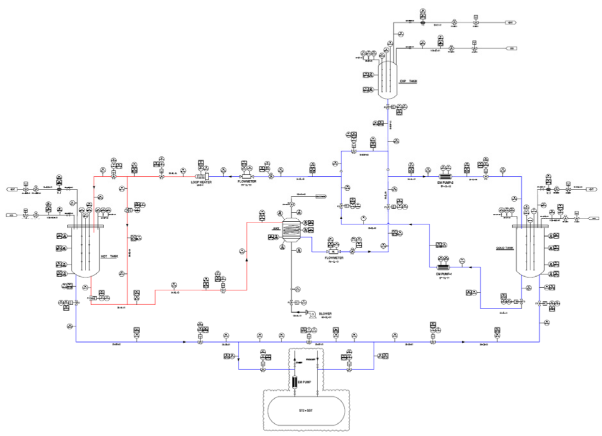


Fig. 1. Piping & instrument diagram of TES verification test facility

2.1 Methodology

Heat transfer of the system with the composite wall[4] can be expressed in a form similar to the electrical resistance in an electrical circuit as follows.

$$q = \Delta T / R_{tot} = UA\Delta T$$

where $q, \Delta T, R_{tot}$ are heat transfer, temperature difference, and total thermal resistance, respectively. When the above equation is applied to a plate, tank or pipe containing insulation, the circuit is configured in a series form as shown in Figure 2, and the total thermal resistance, conduction, convection, and radiant thermal resistance can be expressed by the following equations.

$$R_{tot} = R_{cond} + R_{conv} + R_{rad}$$

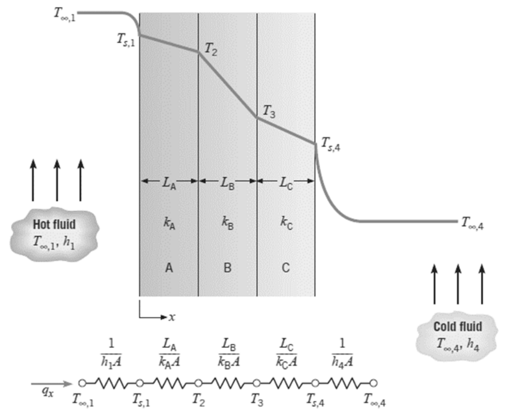
$$R_{cond} = \frac{L}{kA}, R_{conv} = \frac{1}{hA}, R_{rad} = \frac{1}{h_r A}$$
(for plane wall)

$$R_{cond} = \frac{ln(r_O/r_i)}{2\pi kL}, R_{conv} = \frac{1}{2\pi rhL}, R_{rad} = \frac{1}{2\pi r h_r L}$$
(for cylindrical wall)

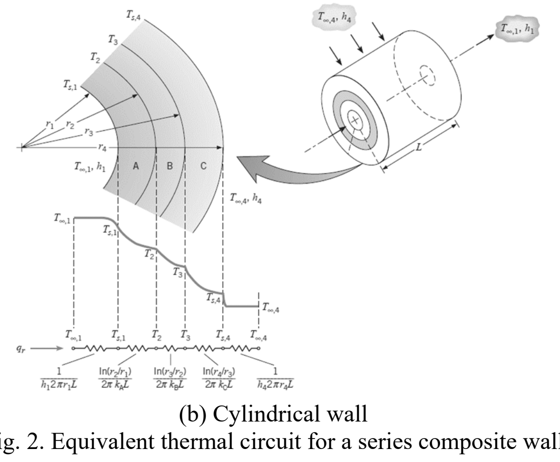
Where $R_{cond}, R_{conv}, R_{rad}, r, L, A, k, h, h_r$ are thermal resistance of conduction, convection, and radiation, radius, length, area, thermal conductivity, convective heat transfer coefficient, and radiative heat transfer coefficient, respectively. Since the insulation thickness is relatively small compared to the TES tank diameter, thermal resistance can be calculated by assuming as the heat transfer in a plane wall. But in order to derive more realistic results, thermal resistance is calculated by assuming as the heat transfer in the cylindrical wall. Using the above equations, the thickness of the insulating material satisfying the target surface temperature of the outermost wall can be calculated as follows.

$$T_s = T_a + \frac{q}{2\pi r_o hL}$$

Where T_s, T_a, r_o are surface temperature of outermost wall, ambient temperature, and outermost wall radius, respectively.



(a) Plane wall



(b) Cylindrical wall
Fig. 2. Equivalent thermal circuit for a series composite wall

2.2 Calculation of Insulation Thickness

In order to determine the thermal insulation structure of the high-temperature tank, methods for securing an insulation structure with a thin thickness and excellent insulation performance were reviewed. However, since the space for the test facility is narrow and the manufacturing cost are also limited, the possibility that some of the given requirements may not be satisfied is considered.

First, commercially available insulators are investigated as shown in Table 1. Cerak wool[5] is the most used insulation material in industrial applications because of its high operating temperature and reasonable price. Ultratherm[6] and Flextherm[7] are fumed silica and perlite-based microporous type products. They have the lowest thermal conductivity among the commercial insulators investigated. However, they have disadvantages in that they are expensive and difficult to supply due to custom manufacturing. The difference between the two products is their thermal conductivity and formability. Aerogel[8] is a silica-based insulating material in the form of gel, and has a lower thermal conductivity than Cerak wool, and has the advantage of being easy to install because it can be cut. However, there is a disadvantage in that the maximum usable temperature is lower than other products. Perlite[9] is an ultra-light, pure inorganic material that is rapidly heated and expanded at a high temperature of 1100°C or higher by crushing the amorphous minerals generated as magma flows into the surface of the lake or sea and cools rapidly to appropriate particle size. Generally, perlite powder is used in compressed solid form, and it is also used in the form of double-wall vacuum insulation to reduce heat transfer by filling the space between double walls with perlite powder and creating a vacuum in the inner space. This method is widely applied to cryogenic tanks because the thermal conductivity of perlite decreases significantly as the temperature decreases.

Table I: Insulation Materials Comparison

Material	Conductivity* (W/m-K)	Max. temp. (°C)	Max. thk. (mm)
Cerak Wool	0.1459	1,260	50
Ultratherm	0.0391	950	25
Flextherm	0.0507	950	15
Perlite	0.210	900	Powder
Aerogel	0.0892	650	10

* Values at 700°C

Second, it was checked whether the design requirements presented in Reference [1] were satisfied by calculating the thickness of the insulation structure that satisfies the given conditions for several combinations of insulation materials below. A schematic of the insulation structure of case 3 is representatively shown in Fig. 3

- Case 1: Cerak Wool only
- Case 2: Ultratherm - Cerak Wool
- Case 3: Flextherm - Aerogel - Cerak Wool
- Case 4: Double wall vacuum insulation
- Case 5: Cerak Wool - Aerogel

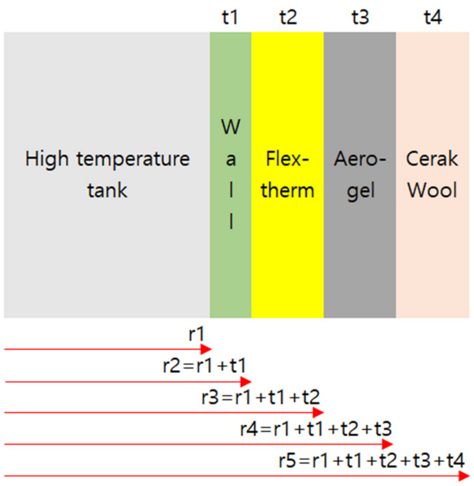


Fig. 3. The schematic of insulation structure (Case 3)

The radius and wall thickness of the high-temperature tank are 1.5m and 10mm, respectively, the material is STS316L, and the thermal conductivity is 23.65W/m-K (based on 700°C). The fluid temperature inside the high-temperature tank is 700°C, and the ambient temperature is 20°C. The air-side convective heat transfer coefficient is generally between 5 and 25W/m^2-K, but 10W/m^2-K is used in this study. The outermost wall temperature is set to 50°C, which is the temperature at which the operator does not get injured even when in contact for more than 100 seconds, referring to ASTM C 1055[10]. In order to obtain conservative results, the thermal conductivity of each insulation material at 700°C is used except for case 5. Case 5 is a realistically selectable option, and the thermal conductivity at the actual surface temperature of each insulation material is used in this case.

Table 2 shows the calculated results of the thickness of the insulating material, the outermost wall temperature, the heat loss per unit length, and the ratio between heat loss and rated power that satisfies the outermost wall temperature requirement for the above conditions. Table 3 shows the thickness of each insulation material considering the production thickness for each product. The temperature distributions at each wall surface are also shown in Fig. 4.

Table II: Insulation Thickness Calculation Results

Case	Thk. (mm)	Max. temp. (°C)	Heat loss (W/m)	Q/Q_{rated} (%)
C1	300	48.95	3,293	2.63
C2	150	51.04	3,238	2.59
C3	150	52.35	3,375	2.70
C4	390	49.52	3,525	2.82
C5	150	57.15	3,875	3.10

Table III: Insulation Thickness at Each Layer

Case	Insulation Thickness (mm)			
	1st layer	2nd layer	3rd layer	Total
C1	300	-	-	300
C2	50	100	-	150
C3	50	50	50	150
C4	390	-	-	390
C5	100	50	-	150

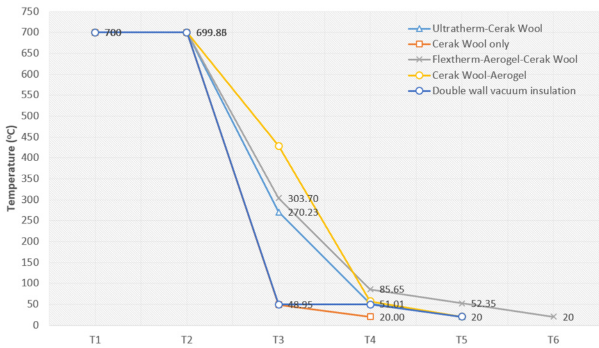


Fig. 4. Temperature distribution at each wall surface

In case 1, the outermost wall temperature is below the limit of 50 degrees. However, the total thickness of the insulation material is 300mm, which excessively exceeded 150mm[1], the maximum allowable thickness of the insulation material set in consideration of the space for the test facility.

In Cases 2 and 3, the outermost wall temperature slightly exceeds the limit, but the total insulation thickness satisfies the limit. Of course, the temperature limit can be satisfied, but considering the thickness of the product, it is judged to be acceptable without additional insulation. Nevertheless, these cases cannot be selected due to the cost and supply/demand issues of these insulation materials.

In Case 4, the thickness of the insulation that satisfies the outermost wall temperature is 390mm, which is the thickest, so it cannot satisfy the requirements. In addition, it is found that it is not suitable to consider the double-wall tank and ancillary equipment (vacuum pump, vacuum gauge, etc.) for maintaining the space between the double walls in a vacuum because those cost to much.

In case 5, it is found that the thickness limit of the insulating material is satisfied, but the temperature limit of the outermost wall is not satisfied. Nevertheless, it is judged that this case is the most suitable compared to other cases if it is considered various aspects such as cost, space, etc.

3. Conclusions

For the high-temperature tank of the TES verification test facility, an insulation structure to minimize heat loss was established. The insulation type and thickness that satisfy the given thermal fluid condition were also determined. The results of this study will be used to evaluate the arrangement of test facilities and heat loss.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) (2021M2D1A1084836) and the National Research Council of Science & Technology (NST) (No. CAP20032-100) grant funded by the Korea government (Ministry of Science and ICT).

REFERENCES

[1] J. Yoon et al., Design Requirements of Thermal Energy Storage Verification Test Facility, Internal Report, Korea Atomic Energy Research Institute, CAP-TS130-DR-01, 2020.
[2] J. Yoon et al., Design Report of Thermal Energy Storage Tank for Thermal Energy Storage Verification Test Facility, Internal Report, Korea Atomic Energy Research Institute, CAP-TS130-ER-01, 2021.
[3] J.M. Kim et al., Piping and Instrument Diagram of Thermal Energy Storage Verification Test Facility, Internal Report, Korea Atomic Energy Research Institute, CAP-TS130-DW-01, 2021.
[4] F. P. Incropera et al., Principles of Heat and Mass Transfer 7th Edition, John Wiley & Sons, New York, pp.131-134, 2014.
[5] Cerak Wool, https://www.kccworld.co.kr/products/insulators/cf.do, KCC.
[6] Ultratherm, https://www.kdone.co.kr/ceratech/product_view?Seq=114, Kyungdong One.
[7] Flextherm, https://www.kdone.co.kr/ceratech/product_view?Seq=146, Kyungdong One.
[8] Aerogel, http://www.aerogel.co.kr/01_product/menu0103.php, Aerogel Korea.
[9] Perlite as High Temperature Insulation, https://www.perlite.org/wp-content/uploads/2018/03/perlite-high-temp-applications.pdf, Perlite Institute.
[10] ASTM, Standard for Heated System Surface Conditions that Produce Contact Burn Injuries, C1055-99, 1999.