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Evaluation of the Insulation Performance of Auxiliary System for STELLA-2

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) is carrying out the large-scale sodium thermal-hydraulic test program, so called STELLA (***S***odium in***T***egral ***E***ffect test ***L***oop for safety simu***L***ation and ***A***ssessment) from 2009 to demonstrate thermal-hydraulic performances and safety features and to produce base data for the specific design approval for the PGSFR (Prototype Generation IV Sodium-cooled Fast Reactor) which will be constructed by 2028 in Korea [1].

STELLA program consist of two phases. In the first phase of the program, separated effects tests for demonstrating the thermal-hydraulic performances of major components such as a decay heat exchanger (DHX), sodium-to-air heat exchanger (AHX) of the decay heat removal system, and mechanical sodium pump of the primary heat transport system (PHTS) had been successfully performed using STELLA-1 in 2015.

In the second phase, integral effects tests will be carried out using the STELLA-2 test facility which is underway with detailed design and will be constructed in 2018 [2].

Normally, the optimum thickness of insulation of piping or tanks of STELLA-2 shall be determined by the temperature of insulation surface which does not exceed 60℃ in steady state heat transfer. By the way, it is difficult to keep the optimum thickness of insulation when insulation is installed because the commercial insulation is usually produced at 2.5 cm unit. But, in order to set the operating conditions of STELLA-2 and determine the capacity of the preheating system of the piping or tanks, it is necessary to accurately predict the heat loss of the piping and tanks installed insulation.

The present paper describes the decision procedures of the insulation thickness, insulation surface temperature, and rate of heat loss with natural convection and radiation of the auxiliary system for STELLA-2. Also, insulation surface temperature and rate of heat loss with the reasonable insulation thickness of piping or tanks were evaluated.

2. Decision Procedures of the Insulation Thickness

The reasonable insulation thickness of piping or tanks was determined by some assumptions and temperature limit as following.

(1) Heat transfer by natural convection and radiation occurs on insulation surfaces.
(2) Rate of heat loss by natural convection and radiation is equal to rate of heat conduction from pipe or tanks surface to insulation surface in steady state.
(3) Temperature of insulation surface where personnel access is possible shall be maintained below 60℃(140℉) to secure the safety for those working in the field [3].
(4) Insulation thickness is selected among the commercial items, produced by 2.5 cm units, considering the material supply and installation of insulation.
(5) All of insulation thickness of tank are uniform although insulation thickness of lower end plate of tank should be thicker than that of upper end plate or cylinder part of tank.

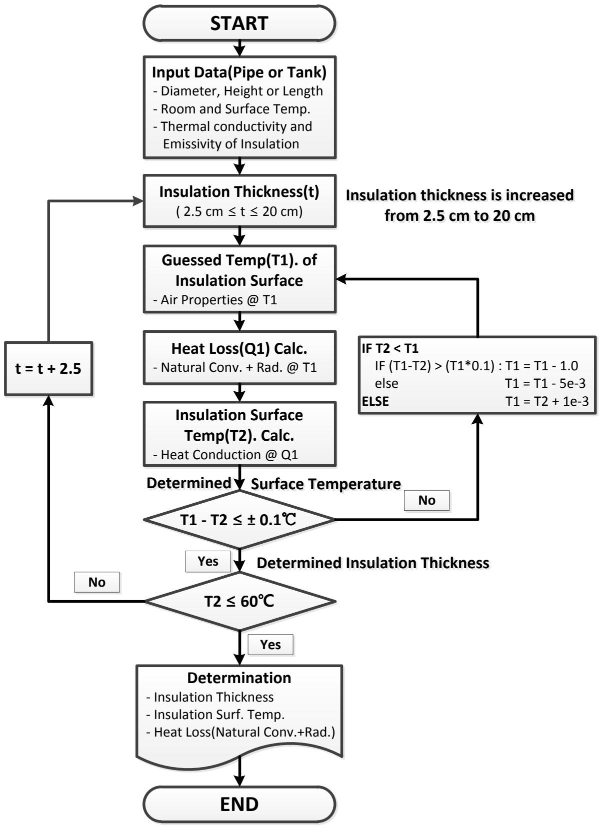

Fig. 1. Decision procedures of the insulation thickness, insulation surface temperature, and heat loss with natural convection and radiation.

Fig. 1 shows the decision procedures of the insulation thickness, insulation surface temperature, and rate of heat loss by natural convection and radiation on the insulation surface.

The total rate of heat loss from the outer surface of the insulated pipe or tank by natural convection and radiation becomes [4]

$$\begin{aligned} Q &= Q_{conv.} + Q_{Rad.} \\ &= hA_{Ins.}(T_{Ins.} - T_{\infty}) + \varepsilon A_s \sigma (T_{Ins.}^4 - T_{\infty}^4) \end{aligned} \quad (1)$$

where $A_{Ins.}$ or A_s is heat transfer area of pipe or tank, $T_{ins.}$ is a temperature of insulation surface, T_{∞} is room temperature, $\mathcal{E}$ is emissivity of insulation surface, σ is the Stefan–Boltzmann constant (5.67×10^{-8} W/m^2), and h, convective heat transfer coefficient, is expressed as

$$h = \frac{k}{D} Nu \quad (2)$$

where k is thermal conductivity of air, Nu is the Nusselt Number, and D is a diameter of a pipe or a tank.

In the case of horizontal cylinder, the Nusselt numbers (Nu) can be expressed as [5]

$$Nu = \left\{ 0.6 + \frac{0.387 Ra^{1/6}}{\left[1 + (0.559/Pr)^{9/16}\right]^{8/27}} \right\}^2 \quad \text{if } Ra \leq 10^{12} \quad (3)$$

$$Ra = Gr \cdot Pr = \frac{g\beta(T_s - T_{\infty})\delta^3}{\nu^2} \cdot Pr \quad (4)$$

where Ra is the Rayleigh number, Gr is the Grashof number, Pr is the Prandtl number (= Molecular diffusivity of momentum / Molecular diffusivity of heat), g is acceleration of gravity, β is a volume expansion coefficient of air, T_s is a temperature of insulation surface, δ is a characteristic length of cylinder or plate, and ν is a kinematic viscosity.

In the case of vertical plate and cylinder, the Nusselt numbers can be expressed as [5]

$$Nu = \left\{ 0.825 + \frac{0.387 Ra^{1/6}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}} \right\}^2 \quad (5)$$

A vertical cylinder can be treated as a vertical plate when [6]

$$D \geq \frac{35\delta}{Gr^{1/4}} \quad (6)$$

But, for vertical cylinders too small to meet this criteria (Eq. 6), the flat plate results for the average heat-transfer coefficient should be multiplied by a factor F to account for the curvature [7], where

$$F = 1.3[(\delta/D)/Gr]^{1/4} + 1.0 \quad (7)$$

In the case of upper end plate of tank, the Nusselt numbers (Nu) can be expressed as [4]

$$\begin{aligned} Nu &= 0.54 Ra^{1/4}, Ra = 10^4 \sim 10^7 \\ Nu &= 0.15 Ra^{1/3}, Ra = 10^7 \sim 10^{11} \end{aligned} \quad (8)$$

In the case of lower end plate of tank, the Nusselt numbers (Nu) can be expressed as [4]

$$Nu = 0.27 Ra^{1/4}, Ra = 10^5 \sim 10^{11} \quad (9)$$

Temperature of insulation surface derived from heat conduction law using the total rate of heat loss from the outer surface of the insulated pipe or tank by natural convection and radiation.

In the case of pipe, temperature of the insulation surface is expressed as

$$T_{Ins.} = T - \frac{Q \cdot \ln(\frac{D_{Ins.}}{D})}{2\pi k L} \quad (10)$$

In the case of tank, temperature of the insulation surface is expressed as

$$T_{Ins.} = T - \frac{2 \cdot t_{Ins} \cdot Q \cdot \ln(\frac{D_{Ins.}}{D})}{\pi k (D_{Ins.}^2 \cdot \ln(\frac{D_{Ins.}}{D}) + 4 \cdot t_{Ins} \cdot L)} \quad (11)$$

where D and $D_{Ins.}$ are diameter of cylinder or tank without or with insulation respectively, L is a pipe length or tank height, T is a temperature of pipe or tank surface, and $t_{Ins.}$ is insulation thickness.

3. Evaluation of the Insulation Performance

The STELLA-2 consists of main experimental systems such as model RV (Reactor Vessel), two of PSLS (primary heat transport system Pump Simulation Loop System), two of the model IHTS (Intermediate Heat transport System), two of the model ADHRS (Active Decay Heat Removal System), and two of the model PDHRS (Passive Decay Heat Removal System) and Auxiliary systems such as SST (Sodium Storage Tank), SPS (Sodium Purification System), liquid sodium charging and draining system, and gas supply and vacuum system.

The rate of heat loss with optimum thickness for main components and test loops of STELLA-2 was evaluated in previous works [8].

In this paper, insulation surface temperature and rate of heat loss with the reasonable insulation thickness for liquid sodium charging and draining system, and gas supply system among auxiliary systems of STELLA-2.

Table 1: Design Temperature of Piping and Tank

Subject			Design Temperature (℃)
Tank	RV preheating system		300℃
	Vapor trap		400℃
Sodium piping	RV charging / draining System Main draining	2 inch	400℃
	System charging/ branch	1 inch	400℃
	Overflow	3/4 inch	400℃
Gas Piping	Ar supply	1/2 inch	200℃
	Preheating	1 inch	300℃

Table 1 shows the design temperature of piping or tanks of sodium charging and draining system or gas supply system.

Table 2 shows the evaluation results about the Insulation thickness, insulation surface temperature, and rate of heat loss with natural convection and radiation.

Table 2: Insulation Thickness, Insulation Surface Temperature, and Rate of Heat Loss of Sodium Charging and draining system or Gas Supply System for STELLA-2.

Subject		Ins. Thick.	Ins. Surf. Temp.	Rate of Heat Loss (W)	
				Conv.	Rad.
RV preheating system		5 cm	56.6℃	1,357.4	490.4
Vapor trap		7.5 cm	49.6℃	63.1	21.9
RV charging / draining System Main draining Pipe	H	5 cm	55.8℃	89.6	25.9
	V	5 cm	57.6℃	87.6	27.4
System charging/ branch Pipe	H	5 cm	51.3℃	64.4	18.5
	V	5 cm	53.1℃	62.9	19.7
Overflow Pipe	H	5 cm	49.6℃	57.5	16.5
	V	5 cm	51.5℃	56.0	17.7
Ar supply Pipe	H	2.5 cm	44.9℃	28.2	7.6
	V	2.5 cm	47.6℃	26.7	8.6
Preheating Pipe	H	5 cm	42.6℃	42.8	12.8
	V	5 cm	44.0℃	41.7	13.7

※ H: Horizontal Pipe or Tank, V: Vertical Pipe or Tank

Fig. 2 shows the insulation surface temperature and rate of the heat loss with the insulation thickness variation.

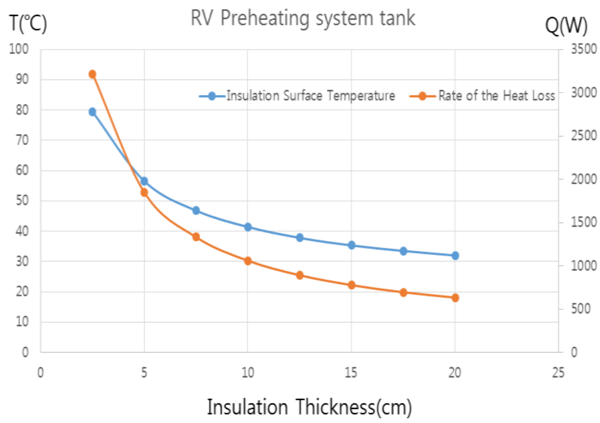

Fig. 2. Insulation surface temperature and rate of the heat loss with the insulation thickness variation.

4. Conclusions

The decision procedures of the Insulation Thickness to meet the design requirement and to secure performance and constructability of the insulation system was developed. Also, the insulation surface temperature and rate of heat loss of piping or tank of sodium charging and draining system or gas supply system for STELLA-2 was evaluated.

In the results, most of insulation thickness to meet the temperature limit of insulation surface except for vapor trap are 5 cm. In case that the thickness of insulation is thicker than 10 cm, improvement in the insulation performance was insignificant.

Considering that the insulation thickness of previous experimental facility was normally 10 cm or thicker than 10 cm, it is considered that the insulation of existing experimental facilities was installed too excessive because 7.5 cm of insulation thickness is enough even if we think conservatively.

In the case of STELLA-2, the total pipe length of sodium charging and draining system or gas supply system pipe is hundreds of meters. Therefore, if the insulation thickness is set to 7.5 cm, it is considered that there will be a great benefit from the economic viewpoint.

The results of this evaluation will be provided as guidelines for insulation design and installation. Also, it will be used as basic data for determining the heating system capacity of pipe or tanks of sodium charging and draining system or gas supply system after designing the piping layout.

5. Acknowledgement

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