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Feasibility Study of the Decay Heat Removal Capability Using the Concept of a Thermosyphon in the Liquid Metal Reactor

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Abstract — A new design concept for a decay heat removal system in a liquid metal reactor is proposed. The new design utilizes a thermosyphon to enhance the heat removal capacity and its heat transfer characteristics are analyzed against the current PSDRS (Passive Safety Decay heat Removal System) in the KALIMER (Korea Advanced LIquid MEtal Reactor) design. The preliminary analysis results show that the new design with a thermosyphon yields substantial increase of 20~40% in the decay heat removal capacity compared to the current design that do not have the thermosyphon. The new design reduces the temperature rise in the cooling air of the system and helps the surrounding structure in maintaining its mechanical integrity for long term operation at an accident. Also the analysis revealed the characteristics of the interactions among various heat transfer modes in the new design.

1. Introduction

The KALIMER (Korea Advanced LIquid MEtal Reactor) plant is the first LMR (Liquid Metal Reactor) plant in Korea, which is conceptually under development. KALIMER has a passive decay heat removal system called PSDRS (Passive Safety Decay Heat Removal System), which surrounds a reactor containment vessel and removes decay heat from the containment vessel using air flow induced by the temperature difference between inlet and outlet. The temperature difference induces density variation in the air between inlet and outlet regions, which provides a driving force for the air to flow naturally. The KALIMER's PSDRS is a passive system and provides a highly reliable provision to remove decay heat naturally without electric power and/or any operator's action. The configuration of the current PSDRS design in KALIMER is shown in Fig. 1.

In general, a passive system like PSDRS uses natural phenomena such as density difference and gravitational force etc. The passive feature imposes practical limitations in the sizes of the reactor thermal power and/or the reactor vessel. To overcome such constraints, several attempts were made[1][2]. A recent work[3] puts radiation structures into air flow channel to enhance heat transfer capacity of the passive system. This approach certainly introduced enhancement in the heat removal capacity but the enhancement also brings out increase in the cooling air temperature rise and it increases surrounding structure temperature, that is not desirable for the mechanical integrity of the structure.

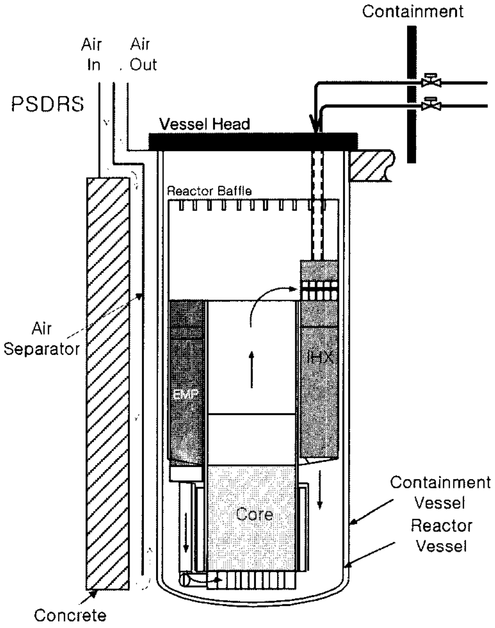

Fig. 1. Configuration of the PSDRS without a thermosyphon.

This study evaluated the feasibility of the application of a new idea of using thermosyphon to the decay heat removal system in KALIMER for enhancement of the heat removal capacity without yielding undesirable effects to structure. In this study, the air separator of the current design of KALIMER is modified by installing an evaporation region of a thermosyphon to the air separator. A thermosyphon is a passive component which transfers heat from an evaporation region to a condensation region. A flow path of an adiabatic region is connected between the evaporation and condensation regions. Using a thermosyphon the capability of the decay heat removal of PSDRS is increased considerably, the outlet temperature of the air is decreased and also the temperature of the concrete structure forming the air path boundary is decreased. This new idea can also be implemented with the previous idea of radiation structures[3] to have further enhancement when the heat removal capacity is important.

2. Feasibility Study

The concept of a thermosyphon is discussed and the feasibility study of its application to KALIMER is described in this section.

2-1. Thermosyphon

A thermosyphon is effective and inherent components in heat transport using natural phenomena, e.g. evaporation, condensation, gravity, and capillary force etc. Heat transport is achieved within the containing envelope by a series of processes, i.e., evaporation of a liquid, transport of the vapor to another part of the container, and condensation of the vapor and return of the condensate to the evaporator through a pipe by gravity or a wick of suitable capillary structure. The thermosyphon is operated by the gravitational force to return the condensate from the condensation region to the evaporation region. In KALIMER, thermosyphon can be applied to PSDRS. In this study, the PSDRS with a thermosyphon is used for a preliminary analysis.

A thermosyphon has some good aspects in heat transport and they are as follows.

○ high heat transfer rate
○ uniform surface temperature
○ good thermal response
○ versatility in the shape of container
○ simple configuration and compact structure

The operating range of a thermosyphon is dependent on the general properties of the working fluids. Helium, nitrogen, water, sodium, and silver are used as the working fluids and generally its operating temperature range is –200~2000℃. Water is applied for the temperature range of from 30℃ to 200℃. For practical design purposes, two basic components of a thermosyphon are considered and they are working fluid and container are considered for a suitable design[4].

Figure 2 shows a general concept of a two-phase closed thermosyphon. The heat absorbed through the evaporator section evaporates working fluid to vapor and the vapor moves to a condenser section by the pressure difference between the evaporator and condenser sections. The vapor is condensed to liquid at the condenser section, where heat is extracted outwards through the condenser wall and the condensate returns to the evaporator section by gravity. The adiabatic section provides a flow path for up-flowing vapor and down-flowing condensate. Previous studies

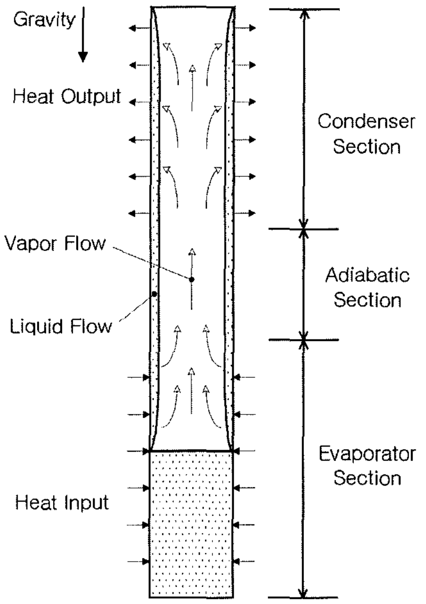

Fig. 2. Concept of closed thermosyphon mechanism with phase change.

on the thermosyphon show the possible ranges for heat flux and heat transfer coefficient are 0.32~32.0 kW/m^2 and 30~100 W/m^2-°C, respectively[5][6].

2-2. Application of a Thermosyphon to the PSDRS

PSDRS of KALIMER transports decay heat from the containment vessel outside the reactor vessel to the atmosphere using air flow induced naturally as shown in Fig. 1. The outmost region is a concrete wall and the air separator divides the space between the concrete wall and the containment wall to two regions, which are a downward cold air flow region and a upward hot air flow region. The air separator works as a separation wall between the counter-current air flows, an insulator forbidding heat transfer from the hot air region to the cold air region, and a heat transfer surface getting radiation heat from the containment wall then dissipating the heat to the air by convection. Figure 3 is a conceptual diagram for the heat transport mechanism in PSDRS. The heat transfer modes involved in PSDRS are a radiation mode between the containment vessel and the air separator (Rad) and convection modes between the containment vessel and the air flow (Conv1), the air separator and the air flow (Conv2). For a steady state, the radiation portion (Rad) is equal to the second convective one (Conv2). The total heat removed through the containment wall equals to the first convective term (Conv1) plus the radiation portion (Rad) or the second convective one (Conv2) at a steady state.

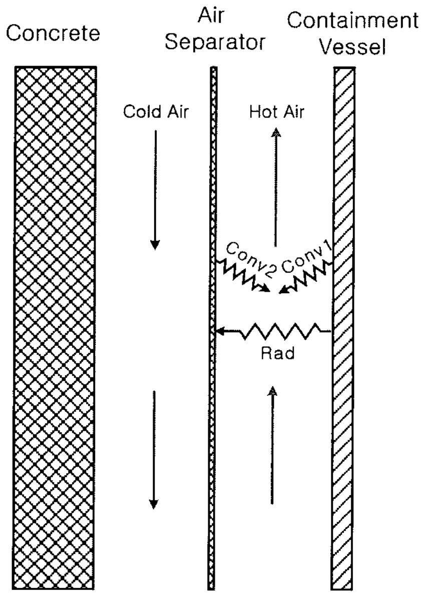

Fig. 3. Heat transfer mechanism in PSDRS without a thermosyphon.

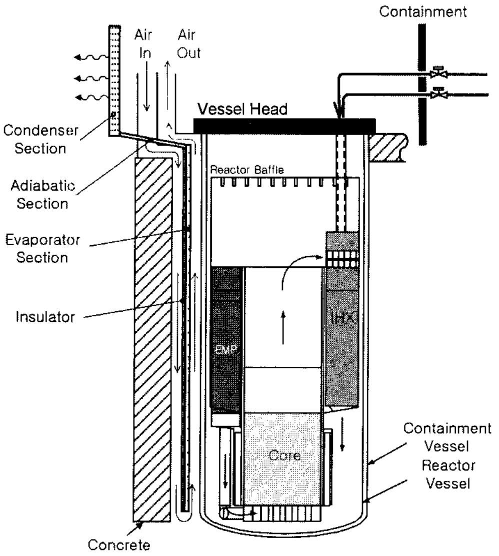

Fig. 4. Configuration of PSDRS with a themosyphon.

A schematic diagram for the new idea of PSDRS that uses a thermosyphon is shown in Fig. 4. The evaporator section of a thermosyphon is attached to the inner side of the air separator, which acts as an insulator between the cold air flow region and the evaporator section. Figure 5 is a conceptual diagram for the heat transport mechanism of the system with a thermosyphon. By introducing a thermosyphon to the air separator, another heat path is added to the system. In the current PSDRS design, all the heat from the containment vessel is eventually dissipated to the flowing air. In the system with the new idea, however, only a part of the heat from the containment vessel is dissipated to the flowing air and the remaining heat is dissipated to thermosyphon and the heat load to the flowing air is reduced.

In the analysis, two different average temperatures 515°C and 710°C are used for the inner reactor vessel wall and they represent normal and abnormal conditions, respectively. The different reactor vessel temperatures are combined with different operation tempera-

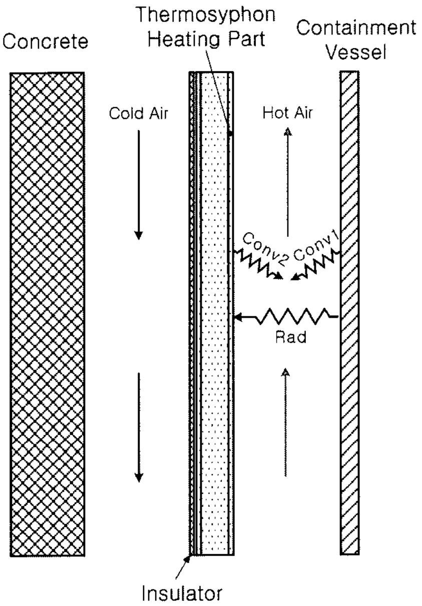

Fig. 5. Heat transfer mechanism in PSDRS with a themosyphon.

tures of the thermosyphon to check the sensitivity of the heat transfer characteristics. The wall temperature of the air separator is nearly equivalent to the operation temperature of the thermosyphon and determined in reality by the detail design of the thermosyphon such as the thickness of the evaporation region wall and condenser capacity. This temperature is, however, assumed to be 125°C and 150°C for the analysis considering the heat transfer characteristics of the system since the focus of this study is not for the general performance of a specific design but for the applicability of the concept of the PSDRS system with a thermosyphon.

The detailed heat transfer characteristics were comparatively analyzed for the current system and for the system with a thermosyphon using the computer code PARS[7][8]. The code PARS was developed to analyze the current PSDRS design and was modified in this study to consider the additional heat path of the new idea.

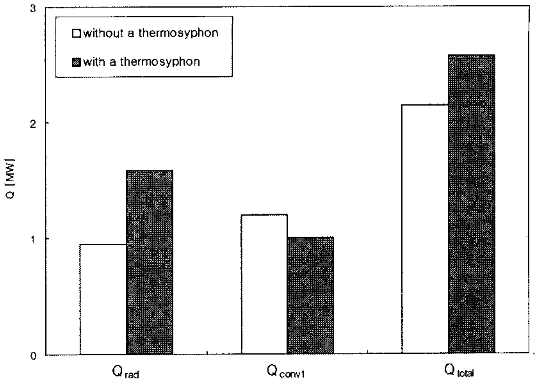

Fig. 6. Comparison of heat transfer rates from the containment vessel at a normal condition.

Table 1 summarizes the major results of the analysis. For the normal condition of 515°C, the table shows that the difference in the wall temperature of the air separator in the system with a thermosyphon does not cause much difference to the total heat removal capacity. The wall temperature for the system without a thermosyphon is internally determined in the PARS calculation.

For the system without a thermosyphon, the ratio between the radiation and convection heat transfer rates from the containment vessel is about 45 : 55 (refer Table 1) and the convection rate is larger than the radiation rate by 10%. This trend is, however, reversed for the system with a thermosyphon. Figures. 6 and 7 show radiation, convection, and total heat

Table 1. Summary of PSDRS heat removal characteristics for the two systems.

Case	T_{avg} (°C)			Q_{rad}		Q_{conv1}		Q_{total} (MW)	Air			
	RV	Wall[1)]	Air[2)]	MW	%	MW	%		T_{out} (°C)	$\dot{m}$	Q_{air} (MW)	Q_{air}/Q_{total}
without Thermosyphon	515	288	40	0.95	44	1.20	56	2.14	139	22	2.14	1.0
	710	462	40	1.84	47	2.02	52	3.86	160	23	3.86	1.0
with Thermosyphon	515	150	40	1.53	60	1.02	40	2.54	128	21	1.31	.52
	515	125	40	1.58	61	1.00	39	2.58	127	21	1.18	.46
	710	125	40	3.86	71	1.54	29	5.39	133	21	1.71	.32

Note 1) external surface temperature of the air separator.
2) inlet air temperature.

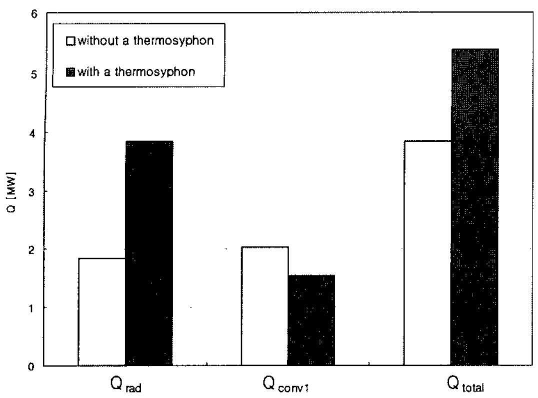

Fig. 7. Comparison of heat transfer rates from the containment vessel at an abnormal condition.

transfer rates for two different plant conditions. For the system with a thermosyphon, the ratio is about 65 : 35 and the radiation becomes the dominant heat transfer mode. While the flowing air removes all the decay heat from the containment vessel in the system without a thermosyphon, only 40% of the total heat is removed by the flowing air in the system with a thermosyphon.

Figure 8 compares the heat removal rate by flowing air for the two different plant conditions. The heat removal rate by flowing air becomes the sum of the convection heat transfer from the containment vessel (conv1) and from the air separator (conv2). It shows the heat load to the flowing air increases substantially in the system without a thermosyphon as the plant condition changes while the increase is marginal in the system with a thermosyphon as expected.

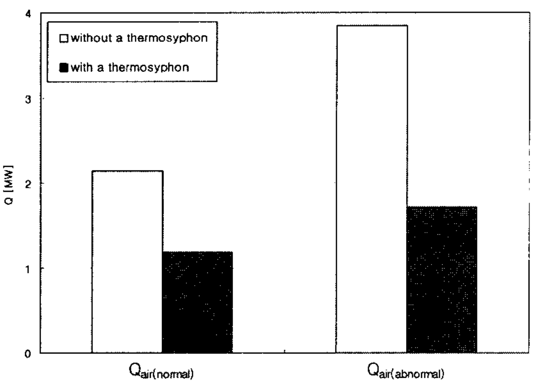

Fig. 8. Comparison of heat removal rates by the flowing air.

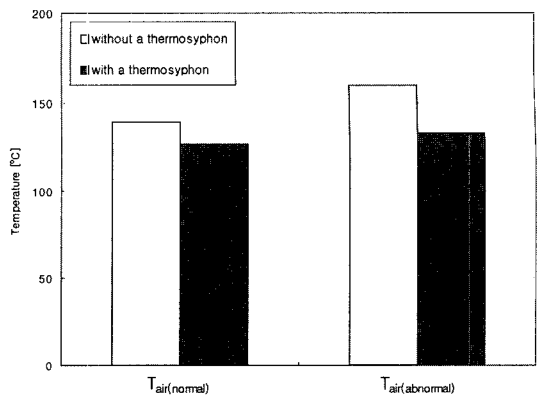

Fig. 9. Comparison of outlet air temperatures.

Figure 9 shows the comparison of the outlet air temperatures. The difference between the two systems is not large compared to the difference of the heat load to the flowing air. It comes from that the high load at the flowing air causes a high air flow rate as shown in Table 1 and the temperature rise becomes somewhat attenuated. The outlet temperature with a thermosyphon is, however, still lower than the temperature without a thermosyphon by around 30℃.

Most importantly, from Table 1 and Fig. 3 show that the total heat removal rate is increased by around 40% with installation of a thermosyphon in an abnormal condition. From this, the new idea of using a thermosyphon for removal of decay heat in a liquid metal reactor is quite promising in increasing the power capacity of a passive liquid metal reactor.

The practicality of the new idea is checked by the required size of a thermosypon system. If a forced convection or a water pool is used to remove heat from the condenser section, the size of the condenser is not relatively large. For a passive system, active forced convection, however, cannot be used. A water pool where the condenser section is immersed can be a possible candidate for a passive system, but a large water tank should be placed on a high location, which requires challenging structural design for the tank support. The more preferable option for the condenser cooling is the natural cooling by air, and the required size for this type of cooling is estimated. For a condenser heat load of 5 MW, that is approximately equal to the load at an abnormal condition, the required

Table 2. Size calculation for condenser section.

Calculation Condition					Result		
heat	tube length	temperature difference[1)]	diameter	pitch	area	number of pipes	volume of condenser
5 MW	10 m	50℃	2.5 cm	5cm	2×10^4 m^2	25,460	640 m^3 (8 m×8 m×10 m)

Note 1) temperature difference between the condenser surface and the ambient air.

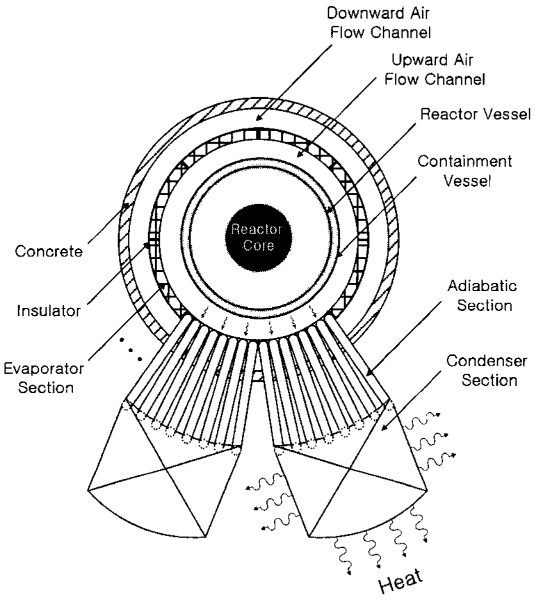

Fig. 10. Conceptual cross-sectional arrangement of the system with a thermosyphon.

size of the condenser section is about 8 m×8 m×10 m as shown in Table 2. For this estimation, the Churchill and Chu correlation[9] for laminar and turbulent natural heat transfer with the assumption of 10 m reference length and 50℃ reference temperature difference is used. The estimated size is comparable to that used in a commercial plant[10].

For the connection between the evaporator region and the condensor region can be made by a bunch of pipes and a possible cross-sectional arrangement of the system with a thermosyphon is shown in Fig. 10.

3. Conclusion

A new idea of using a thermosyphon for enhancing the decay heat removal for a liquid metal reactor is proposed and its preliminary heat transfer characteristics are analyzed. For the feasibility study, the thermosyphon is selected as a reference concept, which can be applied to the PSDRS of a LMR. The total heat removal rate with the new idea increases about 40% and the new idea is considered to be an effective method for enhancing decay heat removal capability.

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Nomenclature

Notations

Conv1 : convection heat transfer rate between the containment vessel and the flowing air
Conv2 : convection heat transfer rate between the air separator and the flowing air
$\dot{m}$: flow rate [kg/s]
Q : heat transfer rate [MW]
Rad : radiation heat transfer rate between the containment vessel and the air separator
RV : reactor vessel
T : temperature [℃]
TS : thermosyphon
σ : surface tension [N/m]
ρ : density [kg/m^3]
θ : contact angle [degree]

Subscripts

air : air
avg : average value
conv1 : convection heat transfer rate between the containment vessel and the flowing air
out : outlet
rad : radiation or radiation heat transfer rate between the containment vessel and the

air separator

total : total heat transfer

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