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A Study of Heat Removal System for CNS of Hanaro

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Abstract

KAERI is going to build up Cold Neutron Source facility in its 30 MW reactor Hanaro in order to provide its scientific community a full range of neutron experimental devices. The first phase of the project was a conceptual study carried out by KAERI through the collaboration with PNPI aiming at defining the main scientific and design option. The heat removal system considered in this conceptual study is the thermosiphon loop with single phase liquid circulation. The liquid moderator thermosiphon removes the radiation heat of about 1000 W from the source cell. Cold helium is supplied by 50 g from the cryogenic refrigerator, which is enough to remove the heat generated in the in-pile assembly. Thermosiphon running range is up to 1,500 W with liquid hydrogen, deuterium or their mixture. In this report design of heat removal system has been considered such as the decision of minimum diameter of cold loop, the overall heat transfer coefficient and the surface area of the heat exchanger, and thermosiphon running range etc.

1. Introduction

The cold neutron source will deliver cold neutrons to more than 10 instruments which will be placed in the cold neutron experimental building. These instruments will be used to develop the state-of-the art technology in polymer science, biology, colloidal chemistry, metallurgy etc. for consolidating the foundation of Korean industries in 21 century.

As the first step of heat removal system design for Hanaro cold neutron source, we consider the circulation system of mono-phase moderator. Two types of heat removal system are used all over the world, i.e circulation system of mono-phase and two-phase moderator. Although most cold source operating in the world except in Russia use two phase thermosiphon system, the choice of a mono-phase thermosiphon is justified by the fact that a two-phase moderator decreases the efficiency of cold neutron productivity. The driving force in the mono-phase thermosiphon system is less when compared with two phase circulation because it is only due to the difference of liquid density, so we have to be careful for the design of heat removal system including of heat exchanger. We are here concerning about the minimum diameter of thermosiphon, the surface area and the overall heat transfer coefficient of heat exchanger, and the running range.

2. Technical Parameters

2. 1 Heat Release

The cryogenic system of CNS shall dissipate the energy release in the liquid hydrogen as well as in the construction materials of the moderator cell, tubes due to heavy nuclear radiation in order that the moderator should be kept in the liquid phase. According to the calculation, the specific radiation energy releases in H_2, D_2, and several materials are shown in Table 1.

Table 1 Heat generation rate

Material	q_n	q_γ	q_β	$\sum q_i$ (W/g)
Para-H_2	0.42	1.27		1.69
Ortho-H_2	0.44	1.49		1.93
Ortho-D_2	0.16	0.24		0.40
Zr	0.05	0.42	0.01	0.48
Al	0.0005	0.56	0.43	0.99
Cu	0.09	0.36		0.45

2.2 Moderator Cell

The moderator cell with a hydrogen or with a hydrogen-deuterium mixture is the main part of the cold neutron source. Neutron capture cross section of the cell material should be small and should have sufficient strength at the cryogenic temperature. Aluminum and zirconium are good for the cell material, however zirconium is more preferable as it provides the same strength at less thickness of wall and has the welded seam without bulge. Zirconium permits to make the strong and light cell of the source. The cell is of simple design and consists of two elliptical bottoms and cylinder which is 134 mm in diameter with 0.5 mm wall thickness. The height of the cylinder part is 170 mm. Two supply pipelines enter through the top into the cell. The delivery of the hydrogen into the cell penetrate through the top and the cell volume to bottom. The distance between the bottom and the end of delivery pipe is 35 mm. The pipe lines, cylinder, elliptical top and bottom are welded by electron beam weld process. The average mixture temperature in the cell is about 19 K and operation pressure is about 0.15 MPa. The volume of the cell is approximately 3 liters. Moderator volume in the tubes with radiation heat release is about 1 liter. The weight of the cell is 380 g. The weight of supply moderator tubes is 430 g. Heat load considering the heat generation in Table 1 is shown in Table 2.

Table 2 Heat load

	Weight	H_2 Moderator	D_2 Moderator
Source cell	380 g	182.4	182.
Tubes	430 g	206.4	206.4
LH_2 in cell	3000 cm^3 x 0 .07 g/cm^3	354.9	
LD_2 in cell	3000 cm^3 x 0.165 g/cm^3		198
LH_2 in tube	1000 cm^3 x 0.07 g/cm^3	118.3	
LD_2 in tube	1000 cm^3 x 0.165 g/cm^3		66
Total Heat Load		862	652.4

2.3 Dimensions

Dimensions of cold neutron source have to be fitted for installing in Hanaro reactor. CNS cell is placed in the middle of the vertical experimental hole with inner diameter 157 mm and length 1200 mm.

3. Design of Heat Removal System

3.1 Thermosiphon

In the conceptual design phase of Hanaro cold source, a single phase thermosiphon was considered. Two-phase thermosiphon system is generally used for heat removal at many cold neutron sources such as in ILL, NIST, JAERI etc. The feature of a two-phase thermosiphon is that there are bubbles in the cell and moderator density is not very high, so the efficiency for producing cold neutron is decreased. And it has a little bigger size of condenser for liquefaction of moderator. On the other hand, moderator in the single phase thermosiphon is maintained as sub-cooled liquid, so the heat exchanger can be smaller than the condensing device in the single phase thermosiphon. The moderator temperature in the cell has to be lower than the boiling point and higher than the freezing point. The reference temperature for freezing and boiling of moderator at atmospheric pressure are shown in Table 3.

Table 3 Freezing and boiling temperature

Moderator	Freezing temperature	Boiling temperature
Hydrogen	13.9 K	20.4 K
Deuterium	18.7 K	23.6 K

3.2 Determination of dimensons of thermosiphon loop

1) Minimum diameter

Circulation in the closed thermosiphon is started when the driving force is equal to loop resistance. The driving force is determined by the height of region and difference of hydrogen density in warm and cold parts of loop.

$$\Delta\rho g h = \xi \frac{\rho v^2}{2} \frac{l_e}{d} \qquad (1)$$

where

$\Delta\rho$: density difference of moderator in the loop

h : height of cold part

ξ : hydraulic resistance coefficient

v : average moderator velocity

l_e : equivalent loop length

d : diameter of the loop tube

Resistance coefficient ξ is determined from the equations as follows :

$$\xi = \frac{0.316}{\mathrm{Re}^{0.25}} \quad \text{for} \quad 2400<\mathrm{Re}< 10^5 \tag{2}$$

$$\xi = \frac{0.184}{\mathrm{Re}^{0.25}} \quad \text{for} \quad 10^5<\mathrm{Re}<3 \times 10^5 \tag{3}$$

Mass flow of moderator in loop is determined by heat load and temperature difference

$$Q = c_p m \Delta T \tag{4}$$

The moderator velocity is derived from the equation (1).

$$v = \left[\frac{\Delta\rho g h d^{1.25}}{0.158\mu^{0.25}\rho^{0.75} l_e} \right]^{0.571} \tag{5}$$

where μ is the viscosity of the moderator.

The temperature difference of moderator is derived when this is put in the equation (5).

$$\Delta T = \frac{0.12 Q \mu^{0.143}}{c_p \rho^{0.572} \Delta\rho^{0.571} d^{2.713}} (l_e/h)^{0.571} \tag{6}$$

Thus, the minimum diameter of the loop tube for maximum heat load and maximum moderator temperature difference can be found as follows :

$$d_{\min} = \left[\frac{0.12 Q_{\max} \mu^{0.143} \left(\frac{l_e}{h} \right)^{0.571}}{c_p \rho^{0.572} \Delta\rho^{0.571} \Delta T_{\max}} \right]^{0.368} \quad (7)$$

2) Temperature difference

The minimum diameter $d_{\min}$ for thermal load $Q_{\max}$ can be calculated only after determining temperature difference of hydrogen in loop. The log mean temperature difference (LMTD) of heat exchanger is defined as

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)} \quad (8)$$

This can be stated verbally that it is the temperature difference at one end of the heat exchanger less the temperature difference at the other end of the exchanger divided by the natural logarithm of the ratio of these two temperature differences.
The temperature difference of hydrogen in the loop is determined by the equation

$$\Delta T_h = T_{h1} - T_{c1} - \Delta T_c - (T_{h2} - T_{c2}) \quad (9)$$

where the subscripts h and c mean hot and cold fluid, 1 and 2 express the positions.
From equation (8),

$$\ln \frac{\Delta T_1}{\Delta T_2} = \frac{\Delta T_1 - \Delta T_2}{\Delta T_m} \quad (10)$$

$$\Delta T_1 - \Delta T_2 = \Delta T_h + \Delta T_c \quad (11)$$

From equations (10) and (11),

$$T_{h2} - T_{c2} = (T_{h1} - T_{c1}) e^{-\beta} \quad (12)$$

where $\beta = \frac{\Delta T_h + \Delta T_c}{\Delta T_m} = \ln \frac{\Delta T_1}{\Delta T_2}$

Substituting equations (12) into equation (9) yields

$$\Delta T_h = T_{h1} - T_{c1} - \Delta T_c - (T_{h1} - T_{c1})e^{-\beta}$$

$$= (1 - e^{-\beta})T_{h1} - (1 - e^{-\beta})T_{c1} - \Delta T_c \qquad (13)$$

In equation (13), ΔT_c can be obtained from

$$\Delta T_c = \frac{Q_{max}}{c_c m_c} \qquad (14)$$

ΔT_h is a function of only β as a unknown variable, so it can be obtained easily by iteration.

The exponential term, which determines the efficiency of heat exchanger operation, play role only when thermal load is small and velocity of hydrogen is low. When thermal load increases, the term $(1 - e^{-\beta})$ approaches to 1. Thus, as a limit that the thermal load increases in heat exchanger, the temperature difference in heat exchanger becomes

$$\Delta T_h = T_{h2} - T_{c1} - \Delta T_c \qquad (15)$$

3) Surface area of heat exchanger

In order to design the heat exchanger, the surface area is the most fundamental data. And the surface area helps us to estimate if the heat removal system can be placed in the reactor pool or not. In addition, the equivalent length l_e can be decided only after obtaining the surface area.

The necessary heat exchanging surface is determined by the equation

$$A = \frac{Q}{U \Delta T_m} \qquad (16)$$

For determining the surface area of heat exchanger, the overall heat transfer coefficient must be known. Overall heat transfer coefficient, which is related to internal surface of thin-walled tubes

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}\frac{d_i^2}{d_o^2}} \qquad (17)$$

For turbulent flow in straight round tube, the Nusselt number is expressed as follows :

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33} \qquad (18)$$

where, $Nu = \frac{hd}{k}$.

The equation is valid for $0.7 < \mathrm{Pr} < 120$ and $4\mathrm{x}10^3 < \mathrm{Re} < 10^6$.

2) Overall heat transfer coefficient in the He side

For Chess-board arrangement of tubes,

$$Nu = 0.195\,\mathrm{Re}^{0.6}\,\mathrm{Pr}^{0.3} \qquad (20)$$

4. Results

4.1 Dimensions of thermosiphon loop

Hanaro CNS thermosiphon consists of heat exchanger, moderator cell and two adiabatic tubes which connect cell with heat exchanger. The calculation was made by using PC. And hydrogen and deuterium were considered as a moderator at heat load of 1,000 W which has a margin for the calculated heat load of 862 and 652.4 W. The heat exchanger is placed out of radiation zone. The length of tube below heat exchanger is equal to 1.3 m. The helium rate is 50 g /s at 14 K. The type of heat exchanger is recommended to be a counter flow because the temperature difference becomes bigger in this type. The length of the heat exchanger is 1.2 m and the diameter is 112 mm considering the space for installation in Hanaro reactor pool. By calculation, the minimum diameter for thermosiphon tube becomes 28 mm. At the minimum diameter, the temperature of liquid moderator may become the temperature near boiling point after heating in the cell.

In order to increase the thermosiphon capacity and decrease the moderator temperature in the upgoing tube, the inner diameter of tube is chosen as 30 mm. The average hydrogen temperature in the cell at 30 MW reactor power is 17.6 K, and mass flow rate in the thermosiphon is 35.6 g/s. In case of deuterium, the average temperature is 20.5 K, and the flow rate is 63.7 g/s. These are the upper and lower limit of operating temperature for deuterium-hydrogen mixtures as moderator. The base thermosiphon dimensions are as follows as Fig. 1, and the parameters obtained by calculation are shown in Table 4.

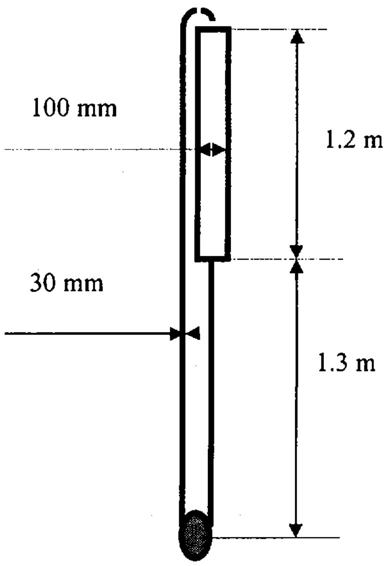

Fig. 1 Base thermosiphon dimensions

Table 4 Parameters of thermosiphon

Parameter	Value
Loop height	2.5 m
Loop diameter	30 mm
Height of heat exchanger	1.2 m
Diameter of heat exchanger	100 mm
Cold helium rate	50 g/s
Maximum heat rate	1500 W

	Moderator	
	Hydrogen	Deuterium
Heat load	862 W	652.4 W
Flow rate	35.6 g/s	63.7 g/s
Velocity in the upstream tube	0.7 m/s	0.54 m/s
Average temperature in the cell	17.6 K	20.5 K

4.2 Temperature in thermosiphon

Helium flow 50 g/s at 14 K is used for heat removal from hydrogen in a counter flow heat exchanger. Heat load is changed in the range from 700 W to 1,500 W. The cryogenic refrigerator has a capacity of 1,500 W for helium flow rate 50 g/s at 20 K return temperature. Temperatures of hydrogen and helium in the loop are shown in Fig. 2. The outlet temperature of helium for the given inlet temperature 14 K, can be increased to 20 K at heat load of 1,500 W. The hydrogen temperatures are rising when the heat load increases. The inlet temperature of hydrogen changes from 18 to 22 K, which is higher than boiling point at atmospheric. 22 K is the boiling temperature at 0.158 Mpa. Therefore the pressure in thermosiphon loop should be maintained higher than this pressure.
Fig. 3 shows the temperature range for deuterium. In this case, the inlet temperature of helium is rising to 17 K at 50 g/s so that deuterium cannot be reached the freezing temperature 18.7 K. At 1,500 W, the temperature can increase to 24.5 K, which is the boiling temperature at 0.131 MPa. Therefore the pressure in the thermosiphon loop in this case should be higher than this pressure.

5. Colclusion

We have studied basic parameters for design of heat removal system, especially the minimum diameter of loop, dimensions of heat exchanger and basic temperature ranges of moderators. Thermosiphon of liquid circulation can use hydrogen, deuterium or their mixture. The advantage is that this system can be placed without any interference to other existing devices in the Hanaro reactor pool. But we will review a two-phase circulation system in the near future too. Before we go forward for next design phase, we need a similar calculation for a two-phase thermosiphon. And also we shall prove the performance of the thermosiphon by some experiments.

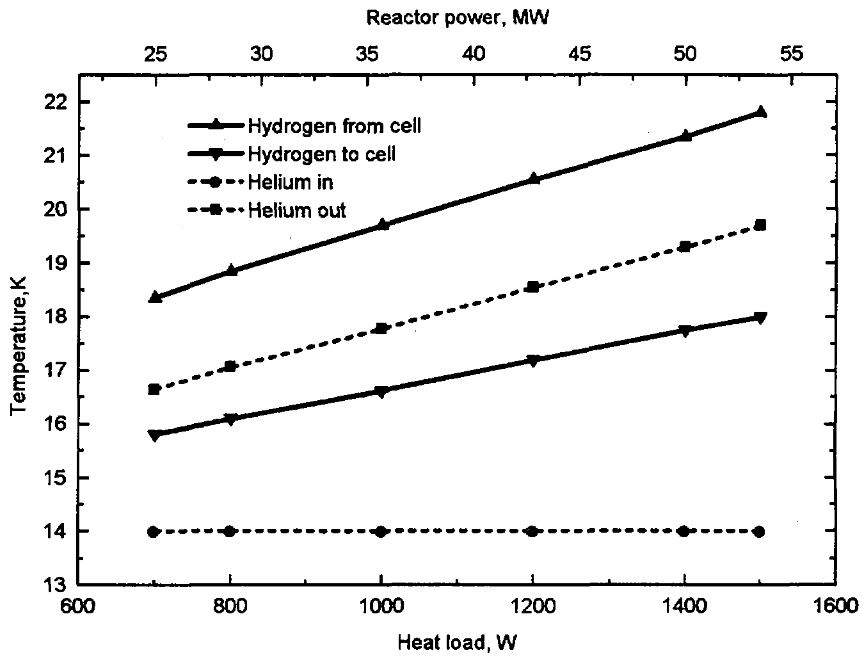

Fig. 2 Hydrogen and helium temperatures in the thermosiphon

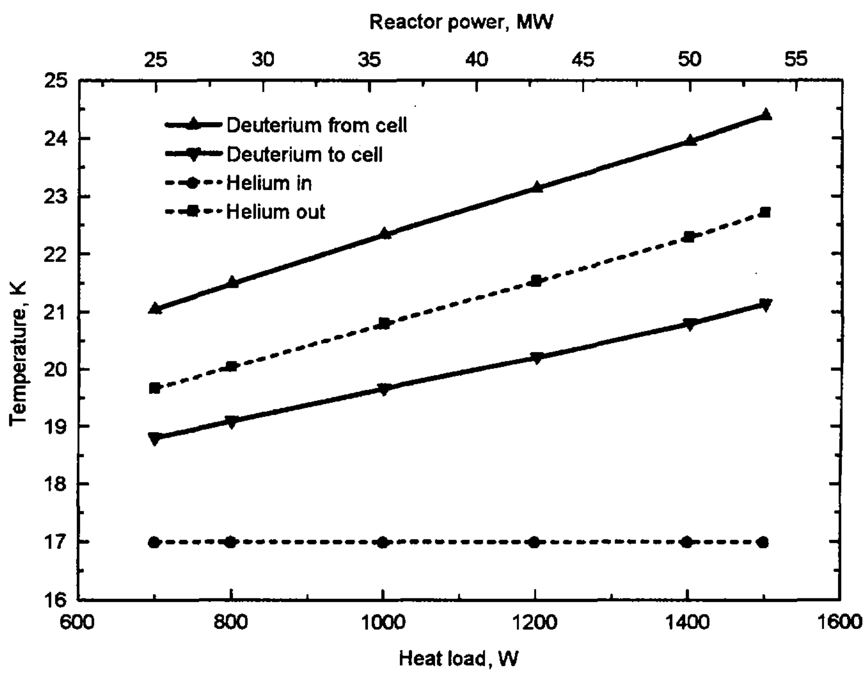

Fig. 3 Deuterium and helium temperatures in the thermosiphon

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