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Thermodynamic considerations on self-regulating characteristics of a cold neutron source with a closed thermosiphon

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ABSTRACT

The present report describes that a cold neutron source (CNS) having a closed-thermosiphon cooling loop shows a self-regulating characteristic under thermal disturbances if the effect of the moderator transfer tube is negligible. Due to this property, the liquid level in the moderator cell is kept almost constant under thermal disturbances.

The thermodynamic meaning of the self-regulating property in the idealized closed-thermosiphon and the effect of the moderator transfer tube to the self-regulation are described.

Keywords:cold neutron source;thermosiphon;self-regulation;
moderator transfer tube;liquid hydrogen;liquid deuterium.

I. INTRODUCTION

The cold neutron source(CNS) is a facility to increase the cold neutron flux by cooling the moderator where the cold neutrons are extracted. Although there is a wide choice of materials as a cold moderator, liquid hydrogen and liquid deuterium have been used in many research reactors including HFR in ILL[1,2]. The principal design criteria are the safety security of personnel and the reactor, as well as the maximum increase and a stable supply of the cold neutron flux.

Recently, very cold neutrons (VCN) and ultra cold neutrons

(UCN) have been used in the field of fundamental physics. VCN are also extracted from CNS using vertical VCN guide tube, and they are further converted to UCN by using UCN turbin[3]. The superfluid helium-4 UCN source makes use of cold neutrons with the wavelength of about 9 A as the incident neutrons[4]. For this facility, CNS is also available for providing the intense cold neutrons of the wavelength of about 9 A.

From the studies on the safety and the functions of CNS described in the previous paper[5], it became evident that CNS with a closed-thermosiphon cooling loop using liquid hydrogen or liquid deuterium as a cold moderator is one of the best selections in respects of the safety and the function.

Keeping the liquid level stable in a moderator cell and preventing sudden bubbling are the important functions of CNS for supplying the stable and steady cold neutrons. Cryogenic system with a closed-thermosiphon loop is appropriate for this purpose[6]. Figure 1 shows a simplified flow diagram of a cold neutron source with a closed thermosiphon. This is a hydrogen cold system consisting of the condenser, the moderator transfer tube and the moderator cell. Gaseous hydrogen or mixture of hydrogen and deuterium is liquefied in a condenser located in a separated region from the moderator cell, and liquid moderator is transported to the moderator cell through the moderator transfer tube (a two-phase countercurrent flow tube).

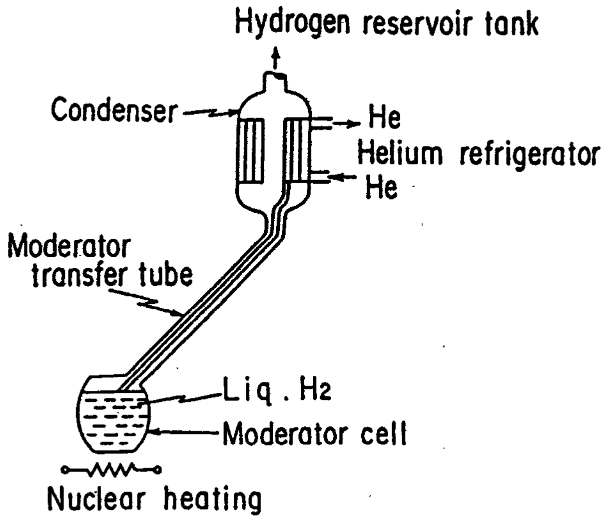

Fig. 1. Schematic diagram of the hydrogen cold system for a closed-thermosiphon.

The moderator transfer tube is required to satisfy the certain conditions for the purpose mentioned above[7].

An alternative cooling system without the transfer tube of liquid moderator is also considered and practically adopted at HFBR CNS in BNL[8]. In this system, the moderator cell itself acts as the heat exchanger with the cold helium gas, and gaseous hydrogen is transported to the cell and liquefied there. A peculiar advantage of this system is that no work is demanded for the mass transfer and thus the cooling capacity liquefying hydrogen vapor evaporated is equal to the heat absorbed in liquid hydrogen. The temperature difference between liquid and vapor is negligible and the heat-exchange efficiency is maximum. We need not suffer from the problems relating to the moderator transfer tube such as the flooding phenomena.

However, if the heat deposition rate due to nuclear heating in the wall of the moderator cell is larger than the critical value, or the thickness of the chamber wall is great, the maximum temperature in the inner position of the wall becomes higher than the boiling point of the hydrogen. Not only the removal of nuclear heating but the storage of liquid hydrogen become, hence, impossible.

An another disadvantage of this system is that a large temperature difference between the liquid moderator and the refrigerant is required to remove a large quantity of heat generated in the liquid moderator. This brings the difficulty of keeping the liquid hydrogen from solidifying at the time when the heat load decreases suddenly, and further an excessive heat load is brought due to the additional cooling pipes.

CNS with a closed-thermosiphon cooling loop is considered to be more appropriate than that with the moderator cell acting as a heat exchanger for a high power research reactor by the reasons mentiond above.

The hydrogen system of the closed-thermosiphon loop works as a constant volume loop which consists of the reservoir tank and the hydrogen cold system. The cryogenic system consists of a helium refrigerator and the hydrogen system. The boiling point of the moderator such as hydrogen and deuterium is determined by the pressure of the closed system and these quantities are related to each other through the vapor pressure curve. Boiling point rises as a pressure of the system increases. Cooling power of the helium refrigerator increases also with a rise of the temperature of the cooling system.

When the additional thermal load is applied to the hydrogen cold system, for example owing to the reactor power fluctuations, the pressure in the system rises due to the more evaporation of a liquid moderator, and therefore the boiling point rises with it. Since the helium temperature at the outlet of the condenser rises, the liquefaction capacity of the condenser apparently increases with a refrigerating power increase of the refrigerator. Therefore, the effect of the thermal load increase is mostly compensated.

Such a cryogenic system is called here to have a self-regulation to the thermal load fluctuations[9].

We first discuss the thermodynamic meaning of the self-regulation of the idealized closed-thermosiphon.

II. SELF-REGULATING POWER OF THE IDEALIZED CLOSED THERMOSIPHON

The idealized closed-thermosiphon behaves as though the effects of the transfer tube neglected as shown in Fig. 2.

For this case, the mass balance equation for the hydrogen vapour M[gm] can be written as:

$$dM/dt=\{Q-UA(T-T_{He})\}/\Delta H \quad (1)$$

where Q[J/s] is a quantity of nuclear heating and U[W/cm^2·K], A[cm^2], T_{He}[K], ΔH[J/gm] are the total heat transfer coefficient of the condenser evaluated at the bulk fluid temperature T[K], the area of the cryosurface, the temperature of the helium coolant and the latent heat of evaporation of hydrogen. The first term on the right-hand side represents the quantity evaporated per unit time and the second term stands for the condensing vapour quantity. In addition, it is reasonable to assume that the state equation for an ideal gas holds for a hydrogen vapour. A much simpler analysis follows for a pressure P[atm] of the system assuming a constant T_{He} and a constant volume of the control vessel V[cm^3] as:

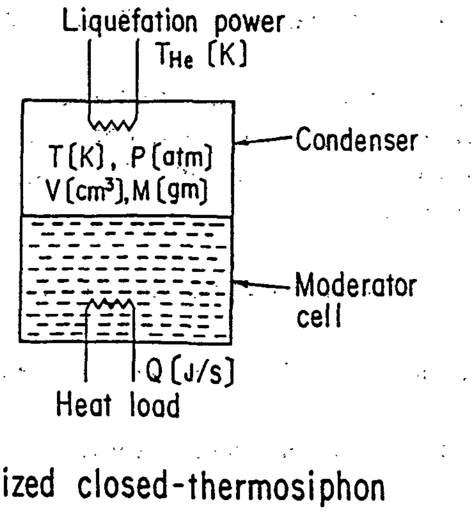

Fig. 2. Diagram of the idealized hydrogen cold system.

$$dP/P=dM/M+dT/T \quad (2)$$

Upon substitution the Clausius-Clapeyron relation

$$dP/dT= (\Delta H\, P)/(RT^2), \quad (3)$$

into Eq. (2), with a gas constant R[J/gm·K], the following results

$$dM/M=\{\Delta H/(RT^2)-1/T\}dT \quad (4)$$

where ΔH is assumed to be constant. If we represent quantities at the steady state with a subscript 0 and consider a small deviation from the steady state, then the following equation (6) can be obtained from Eq. (4) with reasonable assumptions $T \simeq T_o$ and

$$\Delta H/(RT_o^2)>>1/T_o \quad (5)$$

$$M=M_o\{1+\Delta H(T-T_o)/(RT_o^2)\}. \quad (6)$$

From Eq. (1), the mass balance at the steady state $T=T_o$ is given as

$$dM_o/dt=\{Q_o-UA(T_o-T_{He})\}/\Delta H \ . \tag{7}$$

For the infinitesimal change of the bulk temperature, the following expression can be obtained by subtracting the respective terms in Eq.(7) from the corresponding terms of Eq.(1);

$$d(M-M_o)/dt=\{(Q-Q_o)-UA(T-T_o)\}/\Delta H. \tag{8}$$

From Eq. (6), it also follows that

$$T-T_o=(M-M_o)RT_o^2/(M_o\Delta H). \tag{9}$$

From substituting Eq. (9) into Eq. (8), with $m=M-M_o$ and $q=Q-Q_o$, it follows for the dynamic expression of the idealized closed-thermosiphon that

$$\Delta H \ dm/dt+\eta \ m=q \ , \tag{10}$$

where

$$\eta=UART_o^2/(M_o\Delta H)$$

represents the liquefaction power of the condenser.

Equation (10) can be used as a starting point for the discussion about the self-regulating characteristic as a cold neutron source.

If we suppose that the stepwise heat load $q_1(=Q_1-Q_o)$ is applied at $t=0$, a change of the vapour quantity is given using (10) with $\tau=\Delta H/\eta$ as

$$m=(q_1\tau/\Delta H)(1-\exp(-t/\tau)). \tag{11}$$

We can easily find the behavior of m for $t\to\infty$ from Eq. (11), i.e., an another equilibrium state resulting in $m=q_1/\eta$. The greater the value of $(1/\tau)$ which relates to the liquefaction power of the condenser, the more rapidly the new equilibrium state is established. Therefore, τ means the relaxation time and we call here $1/\tau$ the self-regulating power of the idealized closed-thermosiphon.

If we introduce a sinusoidal heat load $q=q^*\sin \omega t$, we obtain the solution of Eq. (10) as

$$m=(q^*\tau/\Delta H)\{\sin \omega t-\omega\tau\cos \omega t+\omega\tau\exp(-t/\tau)\}/\{1+(\tau\omega)^2\}. \tag{12}$$

The neglect of the third term leads to the solution after the transient state,

$$m=\{(q^*\tau/\Delta H)/(1+(\omega\tau)^2)^{1/2}\}\sin\{\omega\tau-\tan^{-1}(\omega\tau)\}. \qquad (13)$$

It can be seen from Eq. (13) that the phase lag of the output relative to the input approaches to $\pi/2$ for $\omega \to \infty$. When $1/\tau$ is large, that is, the liquefaction power of the condenser η is large, Eq. (13) is approximated by

$$m \simeq (q^*\tau/\Delta H)\sin\omega t. \qquad (14)$$

This indicates that the cryosystem follows the change of the heat load without a significant phase lag if the cryosystem fulfills the condition required by Eq. (10). Furthermore, if $\eta \gg q^*$, i.e., the liquefaction power of the condenser is sufficiently larger than the heat load, the change of the liquid quantity due to a heat load change is small. This means that the liquid level in the moderator cell is almost stable against the disturbances of the heat load applied to the cryosystem.

It is concluded that the cryosystem has a self-regulating characteristic as a cold neutron source if the moderator transfer tube fulfills certain conditions necessary for holding Eq. (10) in which the effect of the moderator transfer tube is neglected and further the liquefaction power is sufficiently larger than the heat load applied to the system.

III. EFFECTS OF A MASS TRANSFER IN THE MODERATOR TRANSFER TUBE WITH A CONSTANT FLOW RESISTANCE

When the effects of the mass transfer in the moderator transfer tube is negligible, the time lag due to the mass transfer is also negligible and the cooling loop behaves as if there were not the moderator transfer tube. The smaller the diameter or the longer the length of the moderator transfer tube is, the more steeply the flow resistance becomes large due to the pressure drop increase. The flow resistance brings about the time lag to the liquefaction power increase of the condenser owing to the pressure rise of the cooling system and the behaviour of the cooling system deviates from the ideal one described by the equation (10).

We assume that the cooling system became a steady state. In this case, the steady flow of the hydrogen vapor from the moderator cell to the condenser through the moderator transfer tube is established under the heat load of Q[W]. If we express the values at the moderator cell and the condenser by the subscripts 1 and 2 respectively, and the flow resistance by $r[cm^{-1}\cdot s^{-1}]$, the flow rate $W_f[g_m/s]$ of the hydrogen vapor can be expressed in the form

$$W_f=(P_1-P_2)/r \qquad (15)$$

where P[dyne/cm^2] is the pressure of the system. The mass of the hydrogen vapor is given by equations

$$dM_1/dt=(Q/\Delta H)-W_f \qquad (16)$$

$$dM_2/dt=W_f-UA(T_2-T_{He})/\Delta H \qquad (17)$$

where U[W/cm^2·K] is an overall heat transfer coefficient, A[cm2] being a heat transfer area, and T_{He} the refrigerant temperature. The 2nd term in the right hand side of the equation (17) is writtten by

$$UA(T_2-T_{He})/\Delta H=(UART_{20}^2/(M_{20}\Delta H^2))M_2+\{UA(T_{20}-T_{He})/\Delta H-UART_{20}^2/\Delta H^2\}$$

$$=\eta M_2+\alpha_c \qquad (18)$$

where the subscript 0 represents the value in a stationary state and the constant value α_c is the 2nd term of the right hand side. It follows by substituting the equation (18) into the equation (17) that

$$dM_2/dt=W_f-\eta M_2-\alpha_c \qquad (19)$$

The following equation refering to the quantities $m=M-M_0$, $q=Q-Q_0$ and $w_f=W_f-W_{f0}$ is obtained by rearranging terms from equations (15), (16), (19)

$$dm_1/dt=(q/\Delta H)-(K_1m_1-K_2m_2)/r \qquad (20)$$

$$dm_2/dt=(K_1m_1-K_2m_2)/r-\eta m_2 \qquad (21)$$

where K is the conversion factor from the pressure to the hydrogen mass, being now assumed to be constant. If we eliminate m_2 from the eq. (20) and m_1 from the eq. (21), expressions refering to respective quantities at the moderator cell and the condenser are obtained,

$$d^2m_1/dt^2+2h(dm_1/dt)+k^2m_1=(1/\Delta H)(dq/dt)+(L_1/\Delta H)q \qquad (22)$$

$$d^2m_2/dt^2+2h(dm_2/dt)+k^2m_2=(L_2/\Delta H)q \qquad (23)$$

where,

$$2h=(K_1+K_2)/r+\eta,\ k^2=K_1\eta/r,\ L_1=K_2/r+\eta,\ L_2=K_1/r \qquad (24)$$

For simplicity, we assume that the heat load changes sinusoidally in the following way

$$q=q^{o}\sin\omega t \quad (25)$$

In this case, it is easy to obtain the particular solutions m_1', m_2' for equations (22), (23), then solutions are

$$m_1'=(q_1/\sqrt{(k^2-\omega^2)^2+4h^2\omega^2})\ \sin\{\omega t+\tan^{-1}(\omega/L_1)-\tan^{-1}(2h\omega/(k^2-\omega^2))\} \quad (26)$$

$$m_2'=(q_2/\sqrt{(k^2-\omega^2)^2+4h^2\omega^2})\ \sin\{\omega t-\tan^{-1}(2h\omega/(k^2-\omega^2))\} \quad (27)$$

where

$$q_1=(q^0/\Delta H)\sqrt{L_1{}^2+\omega^2}\ , \quad q_2=(q^0/\Delta H)L_2 \quad (28)$$

On the other hand, the general solution of the equation (22) can be expressed in three different forms according to the conditions imposed to the constant factors as follows:

(i)when $h^2-k^2<0$, the general solution m_1'' is obtained by setting $h^2-k^2=-\zeta^2$

$$m_1''=\exp(-ht)\{C_1\cos\zeta t+C_2\sin\zeta t\} \quad (29)$$

where C1, C2 are arbitrary constants determined from initial conditions. This solution exhibits the damped oscillation.
(ii)when $h^2-k^2>0$, the solution is written in the form using $\gamma^2=h^2-k^2$

$$m_1''=C_1\ \exp\{(\gamma-h)t\}+C_2\ \exp\{-(\gamma+h)t\} \quad (30)$$

This solution tends to zero when $t\to\infty$.
(iii)when $h^2-k^2=0$, the solution is

$$m_1''=\exp(-ht)\{C_1+C_2t\} \quad (31)$$

The general solution m_2'' for the equation (23) is written like m_1''.

The response of the hydrogen mass at the moderator cell and the condenser to the sinusoidal heat load applied to the system can be expressed by the particular solutions (26), (27) exclusive of the transient period. The following becomes clear from these solutions:
(i)When the variational frequency ω of the heat load is equal to k, the quantities of the hydrogen vapor at the moderator cell and the condenser approach their maximum value, that is, the resonance phenomenon appears. In this case, the phase lag at the condenser is $\pi/2$ and larger by $\tan^{-1}\{(\sqrt{K_1\eta/r})/(K_2/r+\eta)\}$ in magnitude than that at the moderator cell. (ii)At lower value of the flow resistance in the moderator transfer tube and $\omega<k$, then

the maximum quantity of hydrogen vapor becomes small and the phase lag at the condenser is approximately $\tan^{-1}\{(K_1+K_2)\omega/(K_1\eta)\}$ and nearly equal to that at the moderator cell. Thus, the system shows characteritics like the case in which the effects of the moderator transfer tube is negligible. (iii)The vapor quantities and phases are generally different between the moderator cell and the condenser. Therefore, the self-regulating characteristic disappears when the effect of the mass transfer through the moderator transfer tube is not negligible.

IV. CONCLUSION

We discussed about the thermodynamic meaning of the self-regulating power of the closed-thermosiphon type CNS when the effect of the mass transfer through the moderator transfer tube is negligible.

It is concluded that the cryosystem with a closed thermosiphon has a self-regulating characteristic as a cold neutron source if the effect of the moderator transfer tube is negligible and the liquefaction power of the condenser is sufficiently larger than the heat load applied to the cryosystem.

The self-regulating characteristics disappear when the flow resistance through the moderator transfer tube is large, because a resonance phenomenon and a large phase difference between the hydrogen vapor quantities of the moderator cell and of the condenser occur in this case.

V. ACKNOWLEDGEMENT

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Q(G.S.Bauer): Can you give an estimate for the minimum cross section of the transfer lines per unit length and unit heat input required to allow stable operation?

A(T.Kawai): It's very difficult to answer to this question correctly and practically. We can only suggest from the following points of view, that is, flooding constraints, pressure drops and flow patterns in the transfer pipe. However, this is calculated result, not experimental one, and further bubbling phenomena is not included.