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Self-regulating characteristics of cold neutron source with annular cylindrical moderator cell

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Abstract
The conditions, in which the ORPHEE type cold neutron source with an annular cylindrical moderator cell could have a self-regulating characteristics, were obtained through thermodynamic considerations. From a view point of engineering, it is not easy to establish these conditions because three parameters are involved even in an idealized system without the effect of the mass transfer resistance in the moderator transfer tube between the condenser and the moderator cell. The inner shell of the ORPHEE moderator cell is open in the bottom, but it is expected that only hydrogen vapor is contained in the inner shell and liquid hydrogen in the outer shell. The thermodynamic considerations show that such a state is maintained only when a liquefaction capacity of the condenser is large compared to heat load and three parameters are optimized with a good balance. We proposed another type of a moderator cell which has an inner cylindrical cavity with no hole in the bottom but a vapor inlet opening at the uppermost part of the cavity. In this structure, a self-regulating characteristics is established easily and the liquid level in the outer shell is maintained almost constant against thermal disturbances. Therefore it is enough to control one parameter, that is, the reservoir tank pressure corresponding to the liquefaction capacity of the condenser given by the refrigeration power of the helium refrigerator.

1 Introduction

Cold neutrons are commonly called as those having wavelengths longer than 4Å, which corresponds to the Bragg cutoff of beryllium. Cold neutrons have longer wave lengths compared to thermal neutrons and thus are suitable for studying polymer, bio-polymer, glass, functioning materials which have long range structures. They are polarized easily using magnetic mirrors working under low external magnetic fields of about 5 gauss because of their low kinetic energies [1, 2]. They are also used in the field of fundamental physics such as the measurement of neutron β decay due to their long flight time. However the intensity of cold neutrons is about 1 or 2 % of the total neutron flux in the thermal distribution in a conventional research reactor. A way to increase the cold neutron flux is to cool down moderator from which cold neutrons are extracted through the neutron guide tubes. The facility with such a function is called a cold neutron source(CNS). And now, many cold neutron sources are installed in research reactors.

Although there are several choices of materials as a cold moderator in principle, only liquid hydrogen and liquid deuterium are used except for supercritical hydrogen [3] due to their suitable cross sections and negligible radiation damage. When many neutron guide tubes or guide tubes with wide width are required to be installed for raising utilization efficiency of a research reactor, usually a large volume of liquid deuterium is used as a cold moderator due to its small absorption cross section. The largest CNS with liquid deuterium moderator, 29 ℓ in volume, was installed in HFR at ILL in 1972 [4].

However, when liquid deuterium is used, several problems are brought up: (1)nuclear heating becomes large as an inevitable result of usage of a large volume of liquid deuterium, (2)tritium is produced as a result of neutron absorption reaction, and then deuterium gas release through the reactor stack is limited even if its air contamination occurs, (3)deuterium gas is expensive and purity maintenance cost is also high.

Hydrogen is much useful except that an available volume is restricted because of its large absorption cross section for neutrons. For solving this problem, the moderator cell with a cavity was used in HFR in ILL and the cylindrical annulus type moderator cell was constructed at ORPHEE reactor in Saclay in 1993 [5]. In 1995 the spherical annulus one was constructed in NIST reactor in Gaithersburg [6]. Both are now working and show good gain factors of cold neutron fluxes. Super-critical hydrogen gas could not be used in such a type of moderator cell.

TRR-II project is now proceeding at INER(Institute of Nuclear Energy Research) in Taiwan. TRR-II reactor is a pool type reactor of 20 MW with a heavy water reflector. CNS with a cylindrical annulus type moderator cell is planned to be installed in TRR-II. On the other hand, the KUR(Kyoto University Research Reactor) of 5MW has a closed thermosiphon type CNS which shows a self regulating characteristics to the heat load fluctuations since flow resistance is neglible in the two-phase countercurrent flow tube (a moderator transfer tube) between the condenser and the moderator cell. The liquid level in the moderator cell is kept almost constant against heat load distubances [7, 8, 9, 10, 11, 12]. And good operational performance is obtained in combination with a simple feedback control, by which only pressure of the deuterium gas tank is controlled. We now plan to construct TRR-II CNS with a cylindrical annulus moderator cell which has a self-regulating characteristics against heat load disturbances.

The report describes thermodynamic considerations on a self-regulation of CNS with a cylindrical annulus moderator cell and derives the conditions in which the inner shell includes only hydrogen vapor and the outer shell liquid hydrogen.

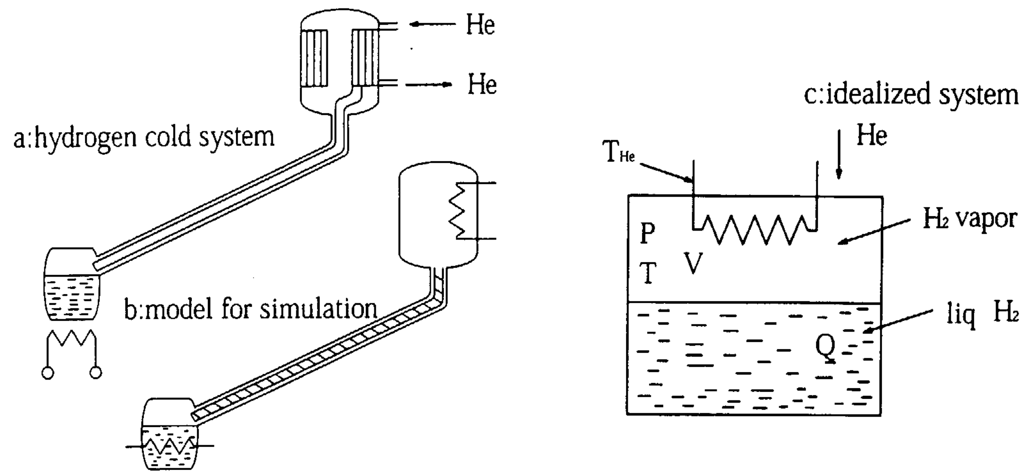

Figure 1: Closed thermosiphon CNS and its idealized system

2 The closed thermosiphon CNS with a self-regulation

The principal design criterion of CNS is the maximum increase of the cold neutron flux, and a stable supply of the cold neutron flux. For this purpose, the liquid level must be kept stable in a moderator cell with an appropriate size and shape, and sudden bubbling must be prevented. The idealized thermosiphon cooling system is shown in Fig. 1 which is a sort of heat pipe without a flow resistance between the condenser and the moderator cell.

The mechanism of self regulation is as follows: when an extra heat load is applied to the hydrogen cold system consisting of a condenser, a moderator transfer tube and a moderator cell, the pressure in the system rises by the evaporation of liquid hydrogen and the boiling point of hydrogen rises. The liquefaction capacity of the condenser is increasing with a rise of temperature, because the refrigerating power of the helium refrigerator increases linearly with temperature rise of the system [8, 12].

Therefore the effect of the thermal load increase is compensated and canceled. Such a CNS is called to have a self-regulation to the thermal load disturbances [7, 9].

However if a flow resistance in the moderator transfer tube is large, the pressure rise due to heat load increase in the moderator cell could not transfer to the condenser without time lag, and thus a self-regulation is not established. Countermeasures for reducing the flow resistance in the moderator transfer tube were considered [13] and applied to KUR CNS. In this case, the closed thermosiphon loop is described as an idealized system shown in Fig. 1-(C).

3 Thermodynamic considerations on a CNS with a cylindrical annulus moderator cell

Typical example of the CNS with a cylindrical annulus moderator cell is ORPHEE CNS represented shematically in Fig. 2. The moderator cell consists of two parts, one of which is the inner shell with a hole in the bottom and expected to contain only hydrogen vapor. Another one is the outer shell containing liquid hydrogen. However the mechanism for such a state to be maintained is not evident until now. Thermodynamic considerations is

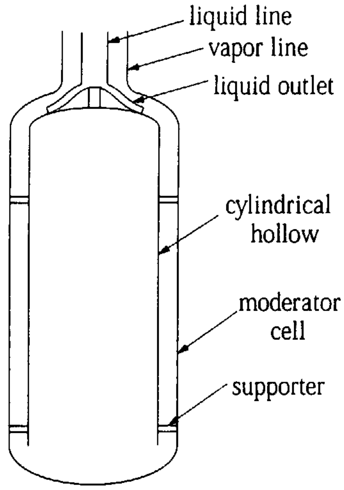

Figure 2: Cylindrical annulus type moderator cell.

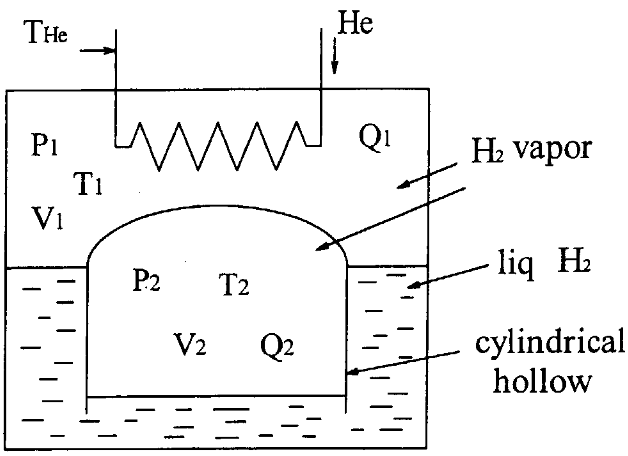

Figure 3: Idealized sysytem of CNS with a cylindrical annulus type moderator cell. The effects of the moderator transfer tube is not taken into account.

then applied to the idealized model and this point will be clarified. The idealized model of a cryogenic loop of CNS with a cylindrical annulus moderator cell is shown in Fig. 3.

The effects of the moderator transfer tube is not taken into account. For this case, the mass balance equation for the hydrogen vapour $M_1(g)$ in the outer shell can be written as;

$$\frac{dM_1}{dt} = \{Q_1 - U_1 A_1 (T_1 - T_{He})\}/\Delta\ H \tag{1}$$

where $Q_1(J/s)$ means heat load in the outer shell including nuclear heating and radiation, $U_1(W/cm^2 \cdot K)$ the total heat transfer coefficient of the condenser evaluated at the temperature $T_1(K)$ of hydrogen vapor in the outer shell, $A_1(cm^2)$ the cryo-area of the condenser, T_{He} the temperature of the helium refrigerant, $\Delta\ H$ the latent heat of evaporation of hydrogen. The first term of the right side of the equation represents the vapor quantity evaporated per unit time due to heat load and the second term stands for the liquefied vapor quantity. In the same way, the mass balance equation for the hydrogen vapour $M_2(g)$ in the inner shell is;

$$\frac{dM_2}{dt} = \{Q_2 - U_2 A_2 (T_2 - T_1)\}/\Delta\ H \tag{2}$$

where the subscript 2 means that the quantity is related to the inner shell, and thus A_2 expresses the surface area of the inner shell.

If we represent quantities at the steady state with a subscript 0, the following equations hold in the steady state ;

$$\frac{dM_{10}}{dt} = \{Q_{10} - U_1 A_1 (T_{10} - T_{He})\}/\Delta\ H = 0, \tag{3}$$

$$\frac{dM_{20}}{dt} = \{Q_{20} - U_2 A_2 (T_{20} - T_{10})\}/\Delta\ H = 0. \tag{4}$$

It is reasonable to assume that state equation for an ideal gas holds for hydrogen vapor.

$$\frac{dP}{P} = \frac{dM}{M} + \frac{dT}{T} \tag{5}$$

Substituting the Clausius-Clapeyron relation,

$$\frac{dP}{dT} = (\Delta\ HP)/(RT^2) \tag{6}$$

into Eq. (3.5) with the gas constant $R(J/mole \cdot K)$, the following results;

$$\frac{dM}{M} = \{\Delta\ H/(RT^2) - 1/T\}dT \tag{7}$$

where $\Delta\ H$ is assumed to be constant. Eq. (3.7) is integrated and results in;

$$MT = M_0 T_0 \exp\ \{\Delta\ H(T - T_0)/(RTT_0)\ \}. \tag{8}$$

When only small deviation from the steady state is considered, the following equation can be obtained from Eq. (3.8);

$$M = M_0\{1 + \Delta\ H(T - T_0)/(RT_0^2)\} \tag{9}$$

where we assumed that $T \simeq T_0$ and $\Delta\ H/(RT_0^2) \gg 1/T_0$. Eq. (3.9) is transformed as

$$T - T_0 = (M - M_0)RT_0^2/(M_0 \Delta\ H). \tag{10}$$

Thus the following expressions can be obtained by subtracting the corresponding terms in Eqs. (3.3), (3.4) from the respective terms of Eqs. (3.1), (3.2);

$$\frac{d(M_1 - M_{10})}{dt} = \{(Q_1 - Q_{10}) - U_1 A_1 (T_1 - T_{10})\}/\Delta\ H, \tag{11}$$

$$\frac{d(M_2 - M_{20})}{dt} = \{(Q_2 - Q_{20}) - U_2 A_2 (T_2 - T_{20}) - U_2 A_2 (T_1 - T_{10})\}/\Delta\ H. \tag{12}$$

Applying Eq. (3.10) to Eqs. (3.11), (3.12) with $m = M - M_0$ and $q = Q - Q_0$, the dynamic expressions controlling the idealized system with a cylindrical annulus moderator cell result;

$$\Delta\ H\frac{dm_1}{dt} + \eta_1 m_1 = q_1, \tag{13}$$

$$\Delta H \frac{dm_2}{dt} + \eta_2 m_2 - \eta_3 m_1 = q_2, \tag{14}$$

where,

$$\eta_1 = U_1 A_1 R T_{10}^2 / (M_{10} \Delta H),$$
$$\eta_2 = U_2 A_2 R T_{20}^2 / (M_{20} \Delta H),$$
$$\eta_3 = U_2 A_2 R T_{10}^2 / (M_{10} \Delta H).$$

η_1 symbolizes the liquefaction capacity of the condenser assuming a constant helium temperature, η_2 the liquefaction capacity of the inner shell, η_3 the effect of liquefaction capacity of the outer shell to the inner shell.

Eqs. (3.13), (3.14) are used as a starting point for discussing the self-regulation on a closed thermosiphon CNS with a cylindrical annulus moderator cell.

If we suppose that the stepwise heat load $q_1 = q_1^0$, $q_2 = q_2^0$ at $t = 0$ are applied to each regions and maintained thereafter, the changes of the vapor quantities in them are given using the relaxation term $\tau = \Delta H/\eta$ and the boundary condition, $m = 0$ at $t = 0$ as;

$$m_1 = (q_1^0/\eta_1)\{1 - \exp(-t/\tau_1)\}, \tag{15}$$

$$m_2 = \alpha_1\{1 - \exp(-t/\tau_2)\} - \alpha_2 \exp(-t/\tau_2) \times \{1 - \exp(t/\tau_2 - t/\tau_1)\}, \tag{16}$$

where,

$$\alpha_1 = q_2^0/\eta_2 + q_1^0 \tau_1 \tau_2 / (\tau_3 \Delta H),$$
$$\alpha_2 = q_1^0 \tau_1 / (\tau_3 \Delta H)\{\tau_1 \tau_2 / (\tau_2 - \tau_1)\}.$$

We could understand that Eq. (3.16) is much intricate compared to Eq. (3.15). From the result, we can easily find out the behaviour of m_1 for $t \to \infty$, that is, m_1 reaches an another steady state, $m_1 = q_1^0/\eta_1$. The greater the liquefaction capacity $(1/\tau_1)$ of the condenser, the more rapidly the new steady state is established. Therefore, τ means the relaxation time and we call $1/\tau_1$ the self-regulating power of the idealized system. In case of the large liquefaction capacity of the condenser, the change of m_2 is described as $m_2 = \alpha_1\{1 - \exp(-t/\tau_2)\}$. The larger the liquefaction capacity of the condenser, the more m_1 decreases quickly and T_1 also lowers. This leads to the apparent increase of the liquefaction capacity of the inner shell. And m_2 reaches also the new steady state. However, when the refrigerating capacity of the condenser is not so large, it is not so easy to control these parameters with a good balance in order to maintain the state in which the inner shell contains only hydrogen vapor and the outer shell the liquid hydrogen.

If we introduce a sinusoidal heat load like $q = q^0 \sin(\omega t)$ into the each regions, Eqs. (3.13), (3.14) turn into followings;

$$\frac{dm_1}{dt} + (1/\tau_1)m_1 = (q_1^0/\Delta H)\sin(\omega t), \tag{17}$$

$$\frac{dm_2}{dt} + (1/\tau_2)m_2 - (1/\tau_3)m_1 = (q_2^0/\Delta H)\sin(\omega t). \tag{18}$$

Solutions are as follows;

$$m_1 = \gamma_1 \sin\{\omega t - \arctan(\omega \tau_1)\}, \tag{19}$$

$$m_2 = \gamma_2 \sin\{\omega\ t - \arctan(\omega\tau_2)\} - \gamma_3 \sin\{\omega\ t + \arctan(\omega\tau_2)\} + \gamma_4, \tag{20}$$

where, in Eq. (3.19) the term $\omega\tau_1 \exp(-t/\tau_1)$ is neglected because we are interested in a state after the transient, and

$$\gamma_1 = (q_1^0/\eta_1)/(1+(\omega\tau_1)^2),$$

$$\gamma_2 = \{q_2^0/\Delta\ H + (q_1^0/\eta_1)/[\tau_3(1+(\omega\tau_1)^2)]\} \times \tau_2/\{1+(\omega\tau_2)^2\},$$

$$\gamma_3 = \{(q_1^0/\Delta\ H)\omega\tau_1^2/[\tau_3(1+(\omega\tau_1)^2)]\} \times \omega\tau_2^2/\{1+(\omega\tau_2)^2\},$$

$$\begin{aligned}\gamma_4 \ = \ & \{q_2^0/\Delta\ H + (q_1^0/\Delta\ H)\tau_1/[\tau_3(1+(\omega\tau_1)^2)]\} \times \omega\tau_2/\{1+(\omega\tau_2)^2\} + \\ & \{(q_1^0/\Delta\ H)\omega\tau_1^2/[\tau_3(1+(\omega\tau_1)^2)]\} \times \tau_2/\{1+(\omega\tau_2)^2\}.\end{aligned}$$

It can be seen from Eq. (3.19), (3.20) that the phase of the output, m_1, lags behind the input and its lag approaches to $\pi/2$ for $\omega \to \infty$, and m_2 consists of delayed and advanced terms by $\pi/2$. Thus, oscillating phenomena occur depending on the quantities of γ_2 and γ_3. Thus, it is not so easy to keep the state against the heat load fluctuations in which the inner shell contains only hydrogen vapor, and the outer shell liquid hydrogen. When η_1 is large, that is, τ_1 is small, Eq. (3.19) is approximated by

$$m_1 \simeq (q_1^0/\eta_1)\sin(\omega\ t)$$

and m_1 follows the heat load variation without a significant phase lag. When the liquefaction capacity of the condenser is 2.5 times larger than the heat load, 5% variation of the heat load results in only 2% variation of the liquid level of the moderator cell. In usual research reactors, the thermal power variation is less than 5 %. When the cryosystem fulfills this condition and three parameters, η_1, η_2, η_3, are adjusted with a good balance, m_1 and m_2 responds to the heat load variation with the almost same way. In this case, the state in which the inner shell contains only hydrogen vapor, and the outer shell liquid hydrogen is established. The small change of quantities of hydrogen vapor in both regions means that the liquid levels are almost stable against the heat load disturbances. Such a CNS has a self regulating characteristics under the negligible flow resistance in the moderator transfer tube, even if the moderator cell has an inner shell.

Therefore, we could design the CNS with a cylindrical annulus moderator cell having a self-regulating characteristics against the heat load variation, if the moderator transfer tube has only a negligible flow resistance.

4 Proposal of a self regulating CNS with a cylindrical cavity type moderator cell

The inner shell in the moderator cell of ORPHEE is open in the bottom. The hydrogen vapor evaporated due to the nuclear heating pushes out the liquid, and appropriate quantity of hydrogen vapor is contained in the inner shell. In this structure, many parameters

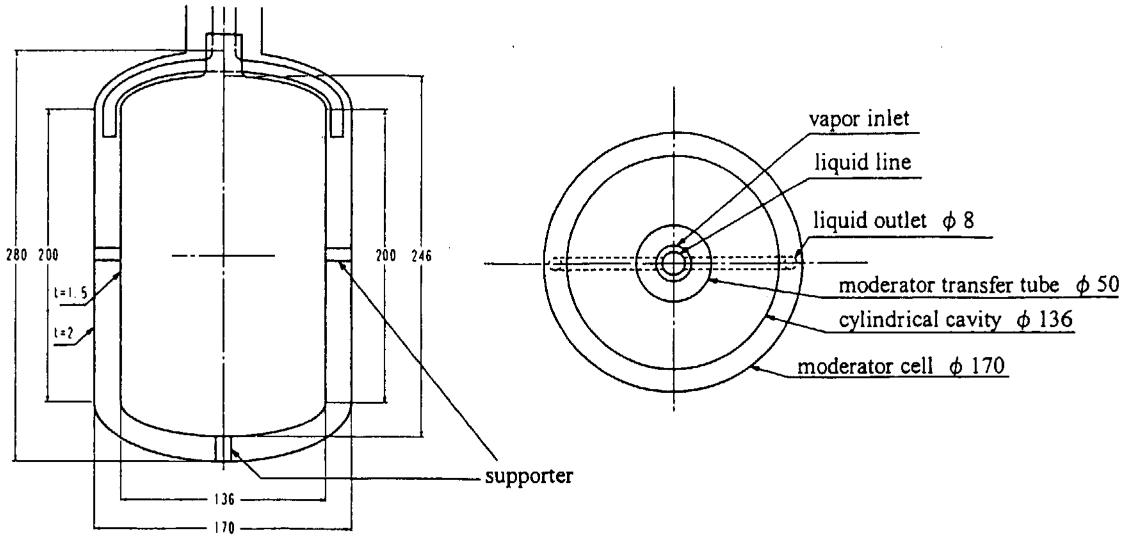

Figure 4: Example of a moderator cell structure with a cylindrical cavity. Dimension shown in the figure are arbitrary.

at least three must be optimized as mentioned above, for maintaining the state in which hydrogen vapor is in the inner shell and liquid hydrogen is in the outer shell. However it is not so easy to optimize three parameters depending on the structure and size of the moderator cell from the view point of engineering, because of the difficulties of the heat load simulation of the inner shell and the separation of the three effects during the mock-up test.

We propose the another selection of the moderator cell structure shown schematically in Fig. 4. The inner shell has no hole in the bottom and has a vopor inlet hole in the uppermost part of the inner shell. We call this type the cylindrical cavity moderator cell. Evaporated hydrogen vapor comes into the cavity through the vapor inlet hole. In this case, the dynamic equation controlling the liquid level of the outer shell is only Eq. (3.13), and solutions are Eqs. (3.15), (3.19). In this case the self-regulations is easily establised and liquid level in the moderator cell is maintained almost stably against heat load fluctuations. Therefore it is enough to control one parameter, that is, the reservoir tank pressure corresponding to the liquefaction capacity of the condenser given by the refrigeration power of the helium refrigerator. One parameter control is very easy in the closed thermosiphon. In practice, the temperature of the helium refrigerant at the exit of the refrigerator corresponding to the the liquefaction capacity of the condenser is modified or controlled by the difference between set and process values of the reservoir tank pressure using simple feedback control system.

Usually, we recommend the liquefaction capacity, η_1, of 2.5 times larger than the heat load, considering the factor (q_1^0/η_1) and the maximum amplitude of the nuclear heating fluctuations of 5 % in research reactors. When the single tube is used as the moderator transfer tube, the structure shown in Fig. 5 is recommended.

5 Effects of a mass transfer in the moderator transfer tube in case of a cylindrical cavity moderator cell

When the effects of the mass transfer through the moderator transfer tube is negligible, the time lag due to the mass transfer is also negligible and the closed-thermosiphon loop

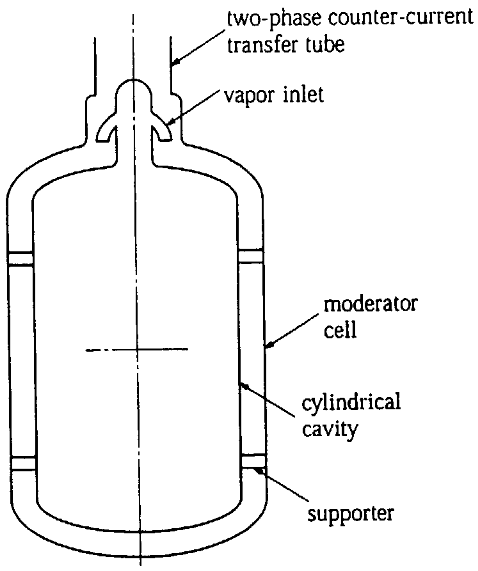

Figure 5: Example of a moderator cell structure with a cylindrical cavity when a single tube is used for a moderator transfer tube.

behaves as if there were not the moderator transfer tube. The smaller the diameter and the longer the length of the moderator transfer tube is, the more steeply the flow resistance becomes large because of the pressure-drop. The pressure rise in the condenser lags behind that resulted from evaporation of liquid hydrogen in the moderator cell. This results in the time lag of the increase of the liquefaction capacity of the condenser. The behavior of the system deviates from that of the idealized one described by the Eq. (3.13).

We assume that the closed thermosiphon loop of the CNS with a cylindrical cavity moderator cell is in a steady state. In this case, the steady flow of hydrogen vapor from the moderator cell to the condenser through the moderator transfer tube is established under the heat load of $Q_{10}(W)$. If we express the values at the moderator cell (the outer shell) and the condenser by the subscripts 1 and 2 respectively, and the flow resistance by $r(cm^{-1}\cdot s^{-1})$, the flow rate $W_f(g/s)$ of the hydrogen vapor can be expressed in the form:

$$W_f = (P_1 - P_2)/r \tag{21}$$

where $P(dyne/cm^2)$ is the pressure of the system and the pressure in the cavity is assumed to be the same as that of the outer shell. The mass of the hydrogen vapor is given by the equations:

$$\frac{dM_1}{dt} = (Q_1/\Delta\ H) - W_f \tag{22}$$

$$\frac{dM_2}{dt} = W_f - UA(T_2 - T_{He})/\Delta\ H \tag{23}$$

where we considered hereat only heat load due to nuclear heating which fluctuates, and $U(W/cm^2\cdot K)$ is an overall heat transfer coefficient of the condenser, $A(cm^2)$ the cryo-surface area of the condenser, and T_{He} the refrigerant temperature. The second term in the right hand side of Eq. (5.23) is written by

$$\begin{aligned} UA(T_2 - T_{He})/\Delta\ H &= (UART_{20}^2/(M_{20}\Delta\ H^2))M_2 + \quad (24) \\ \{UA(T_{20} - T_{He})/\Delta\ H - UART_{20}^2/\Delta\ H^2\} & \\ &= \zeta\ M_2 + \varepsilon \quad (25) \end{aligned}$$

where ζ expresses the coefficient of M_2 of the first term on the right side of Eq. (5.24) and ε the second term. Substituting Eq. (5.25) into Eq. (5.23) gives the following:

$$\frac{dM_2}{dt} = W_f - \zeta\ M_2 - \varepsilon \tag{26}$$

The dynamic equations describing the effect of the flow resistance of the moderator transfer tube are obtained with $m = M - M_0$, $q = Q - Q_0$ and $w_f = W_f - W_{f0}$ from Eqs. (5.21), (5.22), (5.26):

$$\frac{dm_1}{dt} = (q_1/\Delta\ H) - (K_1 m_1 - K_2 m_2)/r \tag{27}$$

$$\frac{dm_2}{dt} = (K_1 m_1 - K_2 m_2)/r - \zeta\ m_2 \tag{28}$$

where K, being now assumed to be constant, is the conversion factor from the pressure to the mass of the hydrogen vapor. When we eliminate m_2 from Eq. (5.27) and m_1 from Eq. (5.28), the dynamic equations expressing the change of the masses of the hydrogen vapor in the moderator cell and in the condenser against the nuclear heating fluctuation are given:

$$\frac{d^2m_1}{dt^2} + 2h(\frac{dm_1}{dt}) + k^2 m_1 = (1/\Delta\ H)(\frac{dq_1}{dt}) + (L_1/\Delta\ H)q \tag{29}$$

$$\frac{d^2m_2}{dt^2} + 2h(\frac{dm_2}{dt}) + k^2 m_2 = (L_2/\Delta\ H)q \tag{30}$$

where, $2h = (K_1 + K_2)/r + \zeta$, $k^2 = K_1\zeta/r$, $L_1 = K_2/r + \zeta$, $L_2 = K_1/r$. For simplicity, we assume that the heat load changes sinusoidally as $q_1 = q_1^0 \sin\omega\ t$. In this case, it is easy to obtain the particular solutions $m_1\prime$, $m_2\prime$ for equations Eqs. (5.29), (5.30) as:

$$m_1\prime = (q_1\prime/\sqrt{(k^2-\omega^2)^2 + 4h^2\omega^2})\sin\{\omega\ t + \arctan(\omega/L_1) - \arctan(2h\omega/(k^2-\omega^2))\} \tag{31}$$

$$m_2\prime = (q_2\prime/\sqrt{(k^2-\omega^2)^2 + 4h^2\omega^2})\sin\{\omega\ t - \arctan(2h\omega/(k^2-\omega^2))\} \tag{32}$$

where, $q_1\prime = (q_1^0/\Delta\ H)\sqrt{L_1^2 + \omega^2}$, $q_2\prime = (q_1^0/\Delta\ H)L_2$.

On the other hand, the general solution of Eq. (5.29) can be expressed in three different forms according to the conditions imposed to the constant factors as follows: (1) for $h^2 - k^2 < 0$, the general solution m_1^g is obtained by setting $-\xi^2 = h^2 - k^2$:

$$m_1^g = \exp(-ht)(C_1 \cos\ \xi\ t + C_2 \sin\ \xi\ t) \tag{33}$$

where, C_1, C_2 are arbitrary constants determined from initial conditions. This solution exhibits the damped oscillation. (2)for $h^2 - k^2 > 0$, the solution is given using $\nu = h^2 - k^2$ in the following form:

$$m_1^g = C_1\prime \exp\{(\nu - h)t\} + C_2\prime \exp\{-(\nu + h)t\} \tag{34}$$

This solution tends to zero for $t \to \infty$. (3)for $h^2 - k^2 = 0$, the solution is:

$$m_1^g = \exp(-ht)(C_1" + C_2"t) \tag{35}$$

The general solution m_2^g for Eq. (5.30) is written similar to m_1^g.

The response of the hydrogen vapor mass in the moderator cell and the condenser to the sinusoidal heat load applied to the system can be expressed by the particular solutions Eqs. (5.31), (5.32) excluding the transient period. The followings are clear from these solutions: (1)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 to their maximum value, that is, the resonance phenomenon appears. In this case, the phase lag at the condenser is $\pi/2$ and larger than that of moderator cell by $\arctan\{\sqrt{K_1\zeta/r}/(K_2/r+\zeta)\}$. (2)In case of the low flow resistance in the moderator transfer tube and $\omega < k$, the maximum quantity of hydrogen vapor becomes small and the phase lag at the condenser is approximately $\arctan\{(K_1+K_2)\omega/(K_1\zeta)\}$ and nearly equal to that of the moderator cell. Thus the system shows characteristics like the case in which the effects of the moderator transfer tube is negligible. (3)The vapor quantities and phases are generally different between the moderator cell and the condenser. Therefore, the self-regulating characteristics disappear when the effect of the mass transfer through the moderator transfer tube is not negligible.

A mockup test facility of the full-scale hydrogen loop will be built at INER for designing the TRR-II CNS in order to (1) investigate self-regulating characteristics of the cylindrical annulus moderator cell, in which the inner shell has hole in the bottom and has no hole in the top and vice versa, (2) demonstrate no onset of flooding in case of a single moderator transfer tube under CNS operating conditions [14] and validate the operating stability and good performance under the normal and faulted conditions. The design features of TRR-II CNS mockup test facility are to use a full-scale hydrogen loop and R-11 ($CFCl_3$) as a working fluid for reducing a cost of the experiments [15]. The results of the mockup tests will be published [16].

6 Concluding remarks

In case of the cylindrical annulus moderator cell like ORPHEE type of CNS, the result of thermodynamic considerations shows that three parameters must be optimized and adjusted with a good balance to maintain the state in which the inner shell contains only hydrogen vapor and the outer shell liquid hydrogen. It is not so easy to optimize three parameters in a good balance from view point of engineering. So, we recommend CNS with a cylindrical cavity moderator cell which has no hole in the bottom but has an opening for the hydrogen vapor inlet at the uppermost part of the inner shell. In this case the self-regulation is easily establised and liquid level in the moderator cell is maintained almost stably against heat load fluctuations. Therefore it is enough to control one parameter, that is, the reservoir tank pressure corresponding to the liquefaction capacity of the condenser given by the refrigeration power of the helium refrigerator. One parameter control is very easy in the closed thermosiphon. In practice, the temperature of the helium refrigerant at the exit of the refrigerator corresponding to the liquefaction capacity of the condenser is modified or controlled by the difference between set and process values of the reservoir tank pressure using simple feedback control system.

It is also shown that the self-regulating characteristics disappear when the flow resistance through the moderator transfer tube is large. Because a resonance phenomenon and a large phase lag in the mass transfer between the moderator cell and the condenser occur.

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