Cold neutron source with self-regulation

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Abstract

A way to increase the cold neutron flux is to cool moderator from where cold neutrons are extracted. Although various kinds of cooling system are considered, the closed thermo-siphon cooling system is adopted in many institutes. The notable feature of this system is to be able to keep the liquid level stable in the moderator cell against thermal disturbances, by using self-regulation, which allows a stable supply of cold neutrons. The main part of the closed thermo-siphon consists of a condenser, a moderator transfer tube and moderator cell, which is called the hydrogen cold system. When an extra heat load is applied to the hydrogen cold system having no flow resistance in a moderator transfer tube, the system pressure rises by evaporation of liquid hydrogen. Then the boiling point of hydrogen rises. The liquefaction capacity of the condenser is increasing with a rise of temperature, because a refrigerating power of the helium refrigerator increases linearly with temperature rise of the system. Therefore, the effect of thermal heat load increase is compensated and cancelled out. The closed thermo-siphon has this feature generally, when the moderator transfer tube is designed to be no flow resistance. The report reviews the concept of self-regulation, and how to design and construct the cold neutron source with self-regulation.

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1. Introduction

The word of self-regulation is used also in the fields of dynamical study of physiological control systems. When the physiological control systems lose their self-regulating functions against the disturbances, pathological conditions result.

The self-regulating machine has an inherent function of returning the unstable state, resulted from the external disturbance, to the stable state. In thermodynamic terminology, the disorder or fluctuation is described by increase of entropy of the system. Therefore, self-regulating machine needs to have a function to compensate for its entropy increase and cancel it out. When the cold neutron source (CNS) has inherent characteristics of compensating the thermal heat load disturbance which leads to the instability of the liquid level in the moderator cell, and cancel it out, such a CNS is called a self regulating CNS. The main subject of this report is how to design the self regulating CNS [1, 2, 3, 4, 5, 6].

2. Cold Neutron Source

Using cold neutrons with wavelengths longer than thermal neutrons, the dynamics of hydrogen in the protein molecule could be investigated without disturbance by Bragg scattering from the molecular structure. The dynamics of hydrogen in the protein is deeply related to the function of that protein. These studies would lead to the creation of the new medicine. The ultra-cold neutrons (UCN) with wavelengths around 600 Å are used for a search of the neutron electric dipole moment, which verifies directly the break of the time symmetry, but UCN are also generated from cold neutrons.

However, the intensity of cold neutrons is about 1 or 2 % of the total neutron flux in the thermal distribution of 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 it was constructed at many institutes having a neutron source like a research reactor or a spallation neutron source, and still being constructing.

Although there are several choices of materials as a cold moderator in principle, only liquid hydrogen and liquid deuterium are used for a research reactor except for supercritical hydrogen [7] due to their suitable cross sections, negligible radiation damage compared with solid methane, and ease of control, and safer comparing with a supercritical hydrogen gas.

3. Design concept of self regulating CNS

For constructing CNS, we have to resolve many kinds of problems described below:

1) Choices of moderator material and its temperature, structure and size of a moderator cell, and an installation place of CNS for maximizing the cold neutron gain factor,
2) Calculation of cold neutron flux and nuclear heating estimation,
3) Removing method of nuclear heat load,
4) Safety problem on controlling the combustible material.

We thus need to optimize several important factors for getting the maximum gain factor and protecting the personnel and facility from the accidents.

Another point, but important, is how to generate stable cold neutron flux in the moderator cell, that is, how to control the liquid level in the moderator cell against thermal load disturbance. This problem could be resolved, if we could design the CNS so as to have self regulation against heat load disturbance.

Figure 1 shows us an example of a CNS facility with a closed thermo-siphon cooling system.

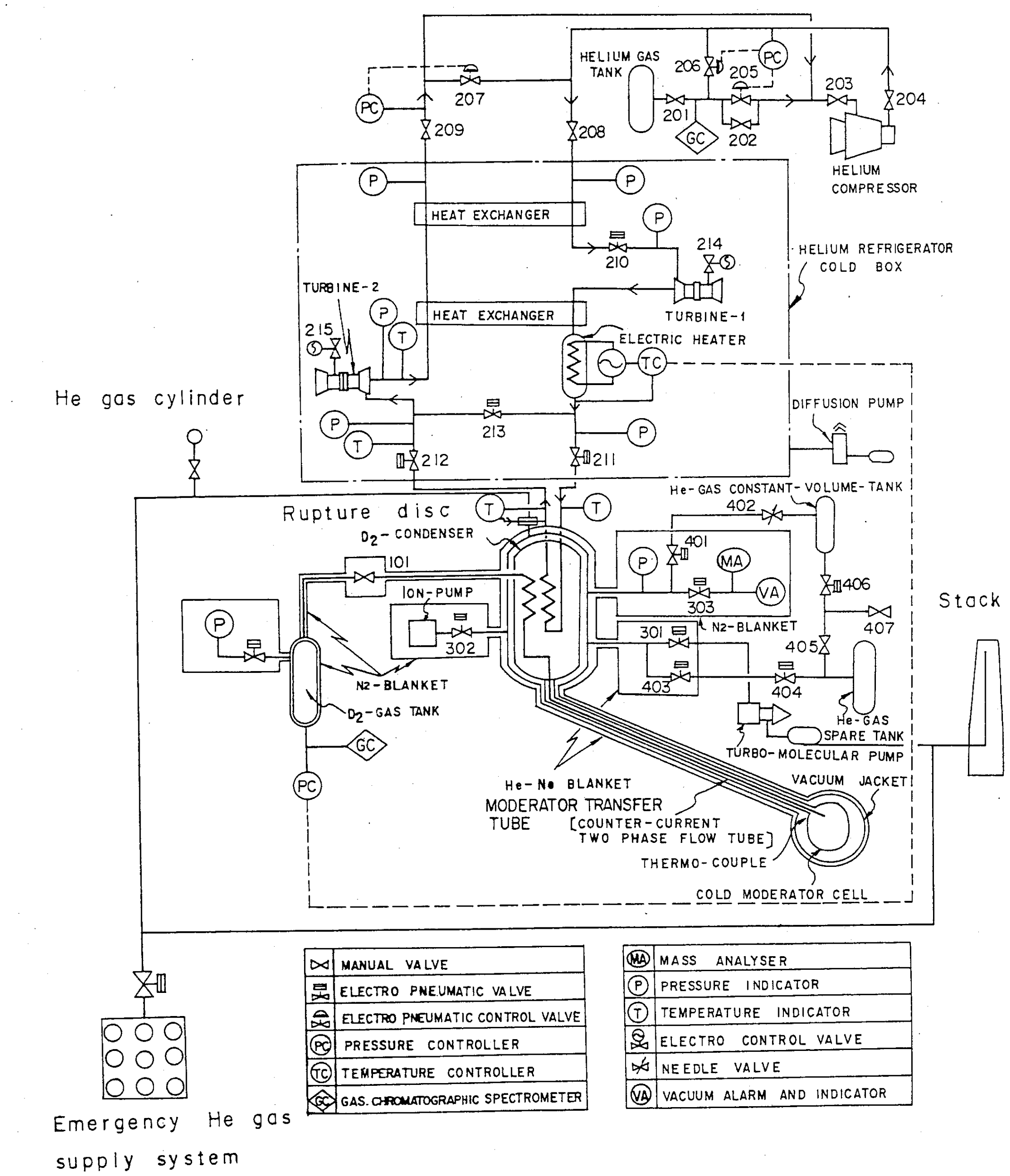
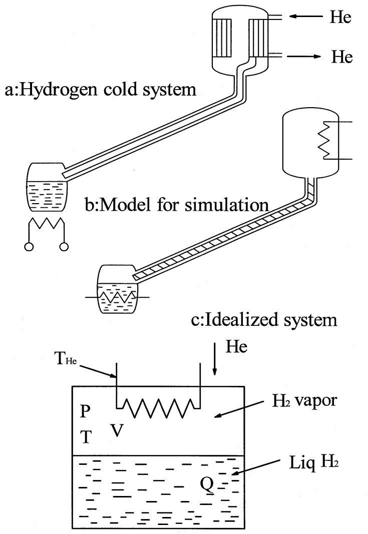


Fig. 1. Example of a CNS facility with a closed thermo-siphon cooling system.

The main part of the CNS, which is called hydrogen cold loop, consists of the condenser at which the hydrogen gas of ambient temperature is liquefied by heat exchange with cold helium gas, the moderator transfer tube through which the liquefied hydrogen is flowing down to the moderator cell and hydrogen vapor evaporated at the moderator cell is flowing up to the condenser, and the moderator cell in which liquid moderator is stored. The CNS of which the hydrogen cold loop has self-regulation is called the self regulating CNS, because the liquid level is kept stable under the thermal heat load fluctuation.

Figure 2a describes the hydrogen cold loop and Fig. 2b the model for simulation, and Fig. 2c the idealized system with no flow resistance in the moderator transfer tube.



The mechanism of the self regulation is as follows: when an extra heat load is applied to the moderator cell, the pressure in the hydrogen cold loop rises due to evaporation of liquid hydrogen and the boiling point of hydrogen also rises. The liquefaction capacity of the condenser increases with a rise of temperature, because the refrigerating power of the helium refrigerator increases linearly with temperature rise of the loop [3]. Therefore, the effect of thermal load increase is compensated and cancelled, and the liquid level in the moderator cell is kept stable. Such a CNS is told to have self-regulation against the thermal load disturbance [3, 5, 7]. However, if flow resistance in the moderator transfer tube is large, the pressure rise in the moderator cell cannot transfer to the condenser without a time lag, and thus self-regulation is not established. Therefore, if we could design and construct the moderator transfer tube with a negligible flow resistance, the hydrogen cold loop could have self-regulation as if a human body has an immune mechanism against a foreign invasion.

Fig. 2. Schematic diagram of hydrogen cold loop

In the next section, we discuss a little more how to reduce the flow resistance in the moderator transfer tube.

4. Design concept of the moderator transfer tube

Let us consider firstly what problem must be resolved to reduce a flow resistance. That is how to prevent “flooding” in the two-phase countercurrent flow tube, which is called the moderator transfer tube. When the flooding phenomena occur, liquid is prevented from flowing down to the moderator cell by the upward flow of vapor from the cell. In the two-phase countercurrent flow, flooding occurs when the upward flow rate of vapor reaches the critical velocity, which depends on the tube diameter, tube length, tube structure, and flow pattern. Also waves formed on the interface between vapor and liquid tend to trigger flooding, and the formation of waves is affected by the surface tension of liquid and the upward flow velocity of vapor. And thus we have to avoid flooding in the moderator transfer tube. The hydrogen cold loop is considered to be a sort of a wickless heat pipe, which absorbs the heat at the moderator cell and releases it in the condenser using hydrogen as a heat carrier. How much the

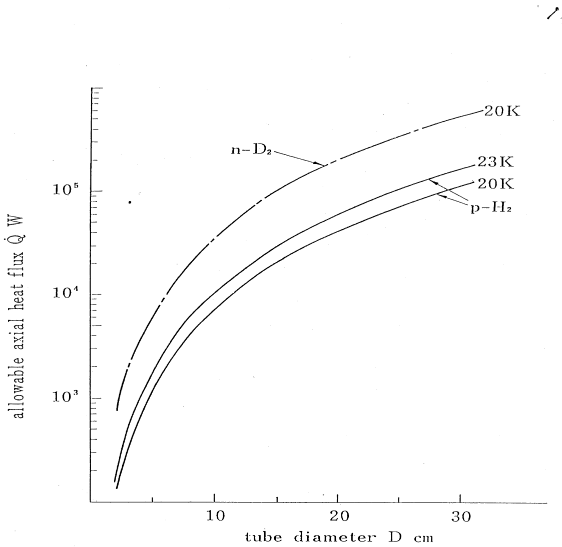


Fig. 3. The maximum allowable heat flux through the vapor/liquid countercurrent flow as a function of the tube diameter under the Wallis’s flooding constraints.

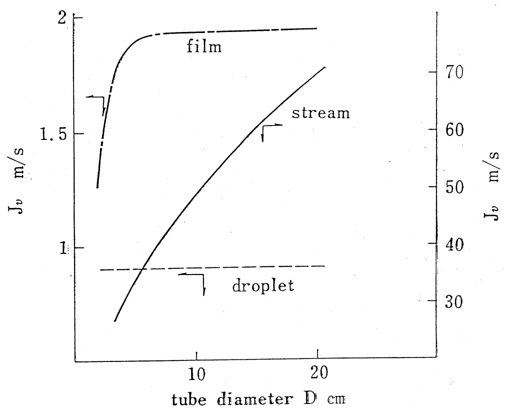


Fig. 4. Minimum flow velocity j_v to support various type of flows of liquid hydrogen at 23 K as a function of tube diameter

heat quantity is transferred by this heat pipe, we must answer. It is answered by the Wallis's flooding constraints. Figure 3 shows us the allowable heat quantity as a function of the tube diameter.

The larger the tube diameter, the more the heat is pumped out. However, the larger the diameter, the more the flow tends to be film type flow and this is apt to cause flooding. In case of a film flow, the liquid is blown up by the small upward flow rate of vapor, even if the tube diameter is suitable for preventing flooding.

As shown in Fig. 4, a stream type flow has potentiality against flooding than a film type flow. Therefore, in order to avoid flooding and maintain the steady countercurrent flow, a double-walled countercurrent flow tube is adopted in many CNS facilities to separate the liquid from the vapor and make liquid stream down in the inner tube.

5. Design concept of the moderator cell

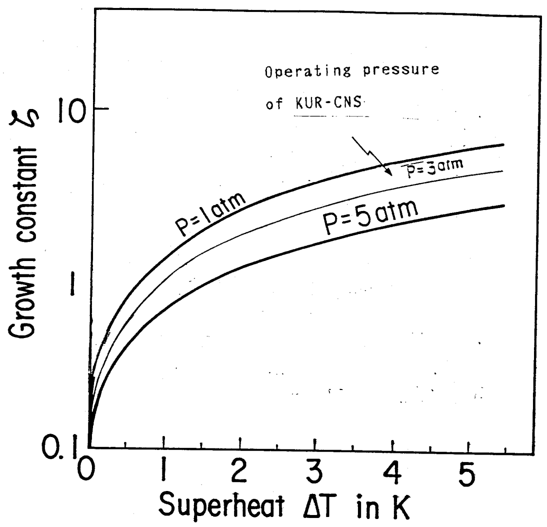
In order to raise utilization efficiency of a research reactor many neutron guide tubes or wide guide tubes are required to be installed, and thus a large volume of liquid deuterium was used as moderator because of its small absorption cross section. However, when liquid deuterium is used as moderator, several problems arise: (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 thus deuterium gas release through the reactor stack is limited even if air contamination occurs, (3) deuterium gas is expensive and the cost of maintaining its purity is also high. Hydrogen is also useful, except that the available volume is restricted because of its large absorption cross section. Recently a moderator cell with a cavity was constructed in the HFR at ILL, and a cylindrical annulus moderator cell at the ORPHEE reactor in 1993 and a spherical annulus cell at the NIST in 1995 were constructed using liquid hydrogen as a moderator to solve these problems. They have shown substantial gain factors of cold neutron fluxes using liquid hydrogen as a moderator.

In this case, the cross section or volume of the moderator cell is determined so that the solid angle looked from the entrance of cold neutron guide tubes becomes as large as possible for extracting longer wavelength neutrons similar to the case of a large volume of liquid deuterium. The peculiarity of this type of the cell is that the outer shell is required to include liquid hydrogen but the inner shell only hydrogen vapor or vacuum. Furthermore, the thickness of the liquid hydrogen is less than 2 cm.

The self regulation of this type of CNS is feasible by balancing the three parameters, that is, the liquefaction capacity of the condenser in proportion to a refrigerating capacity of the refrigerator, the liquefaction capacity of the inner shell through the pressure rise due to evaporation of liquid by the heat load increase and the liquefaction capacity given from the outer shell to the inner shell through the temperature rise of the inner shell [8, 9]. Among these parameters, last two parameters depend also on the material quantity of the inner shell through nuclear heating.

Another problem is how to reduce the void fraction in the liquid hydrogen of the outer shell, because the large void fraction in liquid thin layer affects the moderation efficiency through the reduction of the average hydrogen density. Sudden bubbling and boiling induce liquid level fluctuation and thus they should be prevented.

The rate determined process of the bubble growth is considered to be the heat diffusion in the liquid hydrogen. Bubble growth constant ? is shown in Fig. 5 as a function of super heat ?T and the operating pressure [10].



The growth rate becomes large with increase of super heat. The larger the nuclear heating of the moderator cell wall, the larger the super heat of liquid becomes. Thus the material and thickness of the wall should be designed reasonably. As bubbles are hard to grow so large under the higher pressure, the system pressure of 3 to 5 atm is recommended in practice. The departure diameter of the bubble is also depending on the system pressure as shown in Fig. 6 [11].

Under the same bubble frequency, the higher the system pressure, the smaller the departure diameter becomes.

Fig. 5. Bubble growth constant as a function of super heat.

The bubbling phenomena are also affected by the surface condition, and a non-treated surface is much better than the polished one for preventing sudden bubbling.

In practice, we need to do the mock-up tests on the flooding and bubbling phenomena, because we have no simulation code to estimate them correctly.

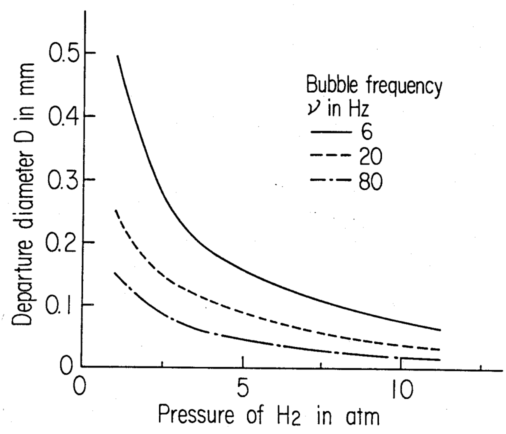


Fig. 6. Departure diameter as a function of system pressure.

6. Conclusion

How to design the CNS with self-regulation was discussed generally. The CNS with self-regulation property could keep the liquid level in the moderator cell stable and thus supply stable cold neutron fluxes. The design concept of the hydrogen cold loop was discussed too from a viewpoint of self-regulation.

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