Study on key-tech problems in development of a cold neutron source in China advanced research reactor

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This paper introduces main design schemes of the cold neutron source in CARR. Because of large reactor power, high nuclear heating and high heat flux in moderator cell, special solutions were proposed. Moderator cell is directly cooled by cryogenic helium. Higher saturation vapor pressure of moderator, hydrogen, is adopted. A composite condenser and a single-tube thermal-siphon loop for moderator are used. All these designs will provide the CNS with excellent operation performances.

INTRODUCTION

Cold neutrons have very wide-ranging applications in modern science and technology researches, and in performance improving of industrial and agricultural products. Specially, it has unique advantage in the detection of molecular structure of organic substances such as protein, nucleic acid etc. The development and application level of cold neutrons characterizes the level of modern science and technique to a country.

In the past 30 years, about 20 sets of cold neutron sources have been established in many research reactors in the world. Most of them belong to mini-type cold neutron sources and their heat loads generated by nuclear heating are mainly from 100 to 1000W. To get strong flux and high quality (high proportion of cold neutrons with long wavelength) of cold neutrons requires larger reactor power, bigger cell size, the more reasonable shape of liquid moderator zone and the lower void fraction in liquid moderator.

One of important difficulties in design of a large cold neutron source is how to remove the heat load of moderator cell out. Power of CARR is 60MW. It has been decided to use Liquid hydrogen as moderator and two-phase thermal-siphon loop as cycling apparatus to transport nuclear heat from the cell to the hydrogen condenser. All nuclear heating generated from cell material and liquid hydrogen should be transported by vaporized hydrogen in the case of conventional cold cell structure (Fig 1). As a result, high heat flux and small cross section area in the moderator cell will cause the void fraction in the moderator liquid hydrogen to exceed the limited amount (20~25%). Therefore, a special structure of moderator cell and thermal-siphon loop should be developed.

MAIN DEMANDS ON CNS DESIGN OF CARR

1) The cold neutron source designed for CARR should supply high flux and high profit factor of cold neutrons.

2) Material of the moderator cell should be as little as possible, and its construct should be as simple as possible.
3) The designed moderator cell should have excellent ability of moderating neutrons and bearing-pressure

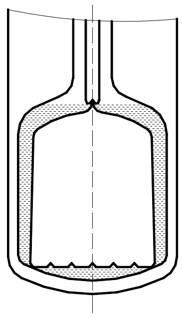

Figure 1 Conventional moderator cell structure

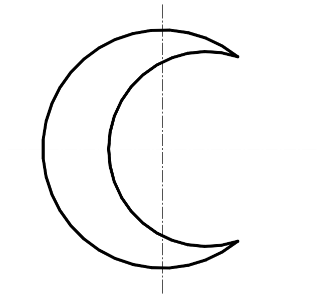

Figure 2 Moderator cell with crescent moon-shape

(inner and outer pressure). It should work well in different work conditions, specially referring to quite different temperature and pressure.
4) Void fraction of liquid hydrogen in the moderator cell should be controlled bellow 20%, had better bellow 15%.
5) Another common work conditions of the cold neutron source may occur like this: the reactor is running without operation of helium refrigerator. All nuclear heating load of cell material should be carried away easily by coolant fluid under room-temperature condition. This means that circulating helium should easily reach all the walls in the moderator cell.
6) Level of liquid hydrogen in the moderator cell should be maintained at constant height to assure the steady operation of the CNS.
7) Hydrogen facilities, specially, inner the reactor should have multi-layer safety barriers.

STRUCTURAL FEATURES OF THE CNS IN CARR

Design of the moderator cell

The Monte Carlo MCNP code of neutronics is used to calculate and analyze the structure of the moderator cell designed for CARR. The results show that, ideal moderator cell should have 30~35mm thickness of moderator in the square window(200×200mm) of neutron scattering and have thicker layer of moderator around the window's brim. It is well known that an annular-cylinder type of moderator cells used in the CNS of FRANCE ORPHEE is successful example of moderator cell structure, for it has annulus-ring of moderator zone and has advantages described above.

Furthermore, according to the principle of neutron moderation, it had better no moderator zone existing in the exit of cold neutron, shown as in a crescent moon-shape moderator cell (in Fig.2). For this shape of moderator cells has a function of gathering moderated neutrons, it is beneficial to increase cold neutron flux in scattering channel. So it has more remarkable advantages over annular-cylinder type of moderator cells in moderating neutrons. But it has a fatal disadvantage in structural stability when high pressure in moderator cavity acts on the thin inner-wall of the cell. This may be the main reason why crescent moon-shape moderator cells have been rarely used in different CNS in the world.

According to the analysis described above, a special structure of moderator cells is designed for CARR by authors. As shown in Fig.3, the inner cup of the moderator cell in Fig 1 is moved near to one side of the hydrogen cell, so that a crescent moon-shape moderator cell is constructed. Furthermore, an interlayer is constructed at outside of the moderator cell, in which cold helium is introduced to help cooling moderator and its cell material.

This kind of moderator cells has crescent moon-shape moderator zone and good inner-pressure-bearing character like annulus cylindrical-type moderator cells. Therefore, it may be an idea kind of moderator cells.

The function of the helium assistant-cooling system outside the moderator cell is so powerful that more than 2kW nuclear heating power in the moderator cell can be directly transported out by it. At first, all helium with temperature 17.5K from refrigerator is guided into the interlayer of the moderator cell. Then it flows into hydrogen-helium heat exchanger to condense hydrogen steam into liquid hydrogen. Nuclear heating power carried by vaporized hydrogen from the cell to the condenser is only 800~900W. In this way, void fraction of liquid hydrogen in the moderator cell will be reduced to a large extent.

Figure 3 New designed moderator cell for CARR

Flow rate of hydrogen stream in moderator cell is predicted as 0.70l/s according to hydrogen latent heat and the nuclear heating power for vaporized hydrogen to carry off. In order to exactly predict void fraction in liquid moderator, mock-up tests were conducted. Different kinds of Working fluids are used to simulate working cycles of two-phase hydrogen in thermal-siphon loop. They are water, Freon 113, alcohol and liquid nitrogen. The facility for mock-up test is shown in Fig 4.

From all the results of mock-up tests, quantitative relations were determined between void fraction in moderator and their main influencing factors such as bubble-rising velocity in liquid hydrogen, liquid hydrogen density, viscosity and surface tension. From all information, we can predict that the void

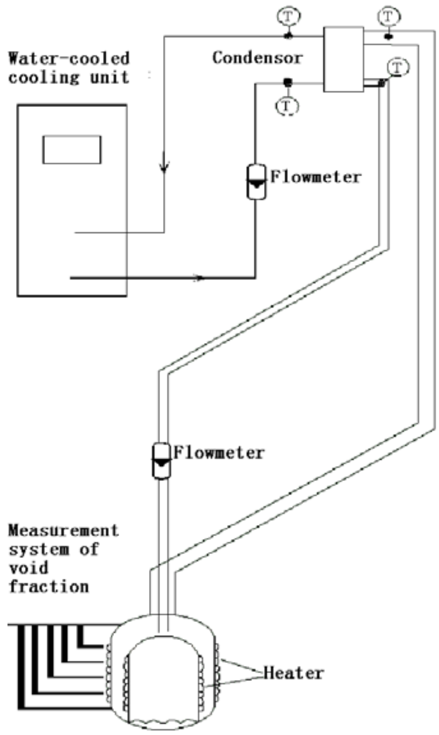

Figure 4 Facility for mock-up tests

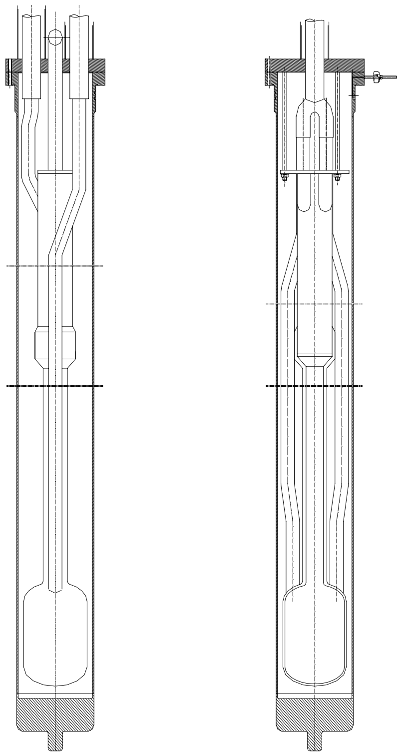

Fig 5 Structure of CNS facility in reactor pool of CARR

fraction in liquid hydrogen is about 10~15% when steam-generating rate is 0.70l/s for the moderator cell described above. This result can entirely satisfy the requirement of neutron moderation.

Considering complexity of the cell structure designed for CARR and performances of 6061 aluminum alloys, feasibility of fabrication process must be carefully considered, especially welding procedure.

Design of condenser and loop

In the CNS of CARR, all thermal-siphon loop including moderator cell, hydrogen-helium heat exchanger and their connecting pipe are placed in a six-meter long vertical channel, which is made of 6061 aluminum alloys and inserted in heavy water pool of the reactor. Inner-diameter of the vertical channel is 260mm. high vacuum is kept in channel to ensure excellent thermal-isolation between the CNS and wall of the channel.

After carefully analyzing various affecting factors and comparing different schemes, Layout of all in-pile components of the CNS in CARR is proposed as shown in Fig 5. Hydrogen steam going up to the condenser and liquid hydrogen falling down to the cell are completed in a single tube.

The cold helium from refrigerator is directly guided into the moderator cell from the upper end of the vertical channel. After surrounding-flowing outside of the moderator cell, helium goes up through a annular pipe to condenser. Then it flows out of the condenser and returns to refrigerator.

This arrangement shown in Fig.5 has another important advantage, that is, when reactor keeps operating and refrigerator stops working, the helium cycling system can still send room-temperature helium into the moderator cell by a fan to carry out nuclear heating of cell material and to keep temperature of all cell wall bellow 110℃.

CONCLUSIONS

Based on the research results described above, follow conclusions can be obtained:

1) The power of nuclear heating of the moderator cell in CARR is quite large and heat flux in moderator is very high. Conventional structures of moderator cell and thermal-siphon loop can't supply normal operation of the CNS for CARR.
2) There are many requests and limits in the design of CNS, so a reasonable design should harmonize the conflicts among these requests and limits.
3) In the CNS of CARR, the moderator cell is directly cooled by cold helium, higher working pressure is chosen for the hydrogen loop, and a moderator cell with crescent moon-shape moderator zone is used. All of these will effectively contribute to reduce void fraction of liquid hydrogen in moderator cell and to increase the cold neutron gain.

REFERENCES

1. Klause G, Present and future cold neutron sources in Garching, Germany, International Workshop on Cold Neutron Utilization, Korea (1997) 43-52
2. D.L.Selby, Scientific upgrades at the high flux isotope reactor at oak national laboratory, International Workshop on Cold Neutron Utilization, Korea (1997) 83-87
3. Shen Feng, Yuan LZ, Conceptual study of cold-neutron source in china advanced research reactor, Physica B311(1-2): Jan 2002, 152-157
4. B.Farnous, New cold neutron sources of the Orphee reactor [A]. Proceeding the 5th Asian Symposium on Research Reactor[C]. Taejon: Korea (1996) 599-609