Mockup tests for developing the CARR-CNS with a two-phase thermo-siphon loop

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Abstract The cold neutron source (CNS) is a facility to increase cold neutrons by scattering thermal neutrons in liquid hydrogen or deuterium around 20 K. For extracting a stable cold neutron flux from the CNS, the liquid quantity in the moderator cell should be maintained stably against disturbance of nuclear heating. The China Institute of Atomic Energy (CIAE) is now constructing the China Advanced Research Reactor (CARR: 60 MW), and designing the CARR-CNS with a two-phase thermo-siphon loop consisting of a condenser, two moderator transfer tubes and an annular cylindrical moderator cell. The mock-up tests were carried out using a full-scale loop with Freon-113, for validating the self-regulating characteristics of the loop, the void fraction less than 20% in the liquid hydrogen of the moderator cell, and the requirements for establishing the condition under which the inner shell has only vapor. The density ratio of liquid to vapor and the volumetric evaporation rate due to heat load are kept the same as those in normal operation of the CARR-CNS. The results show that the loop has the self-regulating characteristics and the inner shell contains only vapor, while the outer shell liquid. The local void fraction in the liquid increases with increasing of the loop pressure.

Keywords CARR, CNS, Two-phase thermo-siphon, Annular cylindrical moderator cell, Self-regulation, Void fraction
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1 Introduction

The China Advanced Research Reactor (CARR) is a high-flux and multipurpose research reactor of 60 MW with light water as coolant and heavy water as moderator.[1,2] One of its main functions is to provide high intense cold neutron flux to the neutron scattering instruments for investigating structures and dynamics of nano-scale materials and hydrogen dynamics of proteins. The cold neutrons are commonly referred to those with a wavelength longer than 4Å. The longer the wavelength of neutrons is, the more neutrons become suitable probes for investigating structure and dynamics of larger size molecules (like proteins) and lower energy excitations. The facility providing cold neutrons with a high gain by scattering and slowing down thermal neutrons in the liquid hydrogen or liquid deuterium around 20K is called CNS (cold neutron source).[2] Thus the construction of CNS is important for the research reactor, especially for the high flux reactor.

A two-phase thermo-siphon loop was designed as a candidate for the hydrogen circulating loop of the CARR-CNS because it has self-regulating characteristics against disturbance of nuclear heating. In the case of the CARR-CNS, the refrigerating capacity of the helium refrigerator is designed to be at least 30% larger than the total heat load. The ratio of heat load among the outer shell wall, the liquid in the outer shell, the inner shell wall, and the liquid in the inner shell is so designed as to establish a state in which the inner shell has only vapor under the normal operation of the CNS. The pressure in the inner shell is a little bit higher than that in the outer shell due to its heat load and thus the liquid in the inner shell is pushed out under the normal operation. When the extra heat load is

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applied to the moderator cell, the liquid hydrogen is evaporated and pressure of the hydrogen circulation loop consisting of a condenser, moderator transfer tubes and a moderator cell is rising up. The loop pressure corresponds to the vapor pressure and the boiling point of hydrogen, and thus the liquefaction capacity of the condenser is also increased due to the increase of refrigerating capacity of the helium refrigerator. Therefore the increase of heat load is compensated. And the liquid quantity or liquid level is kept stable against the heat load disturbance. When certain requirements are satisfied, the thermo-siphon loop has such a characteristic, which is usually called "self-regulation". A series of analytical work for self-regulating characteristics is performed in the case of Kyoto University Reactor (KUR)-CNS and TRR-II CNS.[3,4] They proved that the ORPHEE-type CNS has also self-regulating characteristics when some requirements are satisfied.

Since no computer program can predict the requirements to establish self-regulating features for the hydrogen circulating loop, it is necessary to carry out mock-up tests to validate the self-regulating characteristics of the loop. Another problem for extracting a stable cold neutron flux from the CNS is how to maintain the void fraction smaller than 20%.

An annular cylindrical moderator cell is adopted in order to use liquid hydrogen as a moderator. The scattering and absorption cross sections of hydrogen are both large and thus the inner shell should contain only hydrogen vapor under the normal operation of the CARR-CNS.

This paper reports the results of the mock-up tests on the self-regulating characteristics of the loop against thermal disturbances, void fraction in the liquid of the moderator cell, and the confirmation of the state in which the inner shell has no liquid under the condition corresponding to the normal operation of the CARR-CNS.

2 Mock up test loop and test procedures

A full-scale mock-up loop as shown in Fig.1 was used, and it consists of the condenser, the moderator transfer tube and the moderator cell.[4] The moderator transfer tube is composed of two separate tubes, one of them for vapor up-flow and the other for liquid down-flow. Freon-113 (R113) is used as a working fluid. The scaling criteria[4] applied to the mock-up tests are described as follows. The geometry of the annular cylindrical moderator cell is the same as those of CARR CNS. The density ratio of liquid to vapor and the volumetric evaporation rate of the R113 were kept the same as the case of hydrogen in the normal operation of the CARR-CNS.

The annular cylindrical moderator cell shown in Fig.1 is an ORPHEE-type moderator cell. The inner shell is open at the bottom. The outer shell is a cylinder of Φ219mm×6mm in size. The moderator cell could maintain a state in which the inner shell contains only vapor and the outer shell only liquid when a liquefaction capacity of the condenser is large enough in comparison with the heat load, and the ratio of heat load of the outer shell wall, the inner shell wall and the moderator.[3]

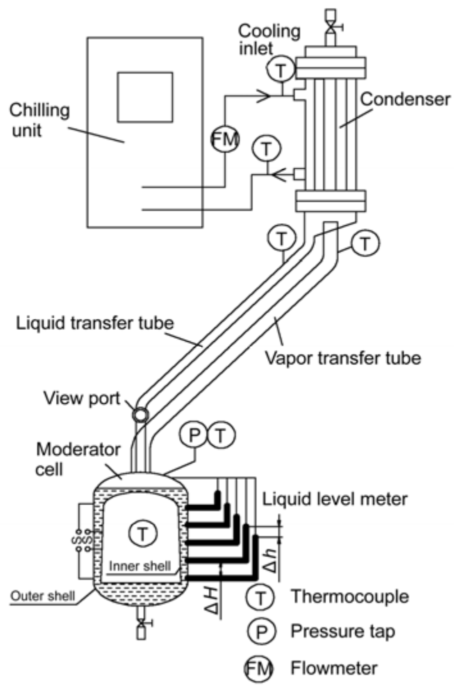

Fig.1 Schematic diagram of the mockup test loop.

To simulate heat load of the moderator cell, two electrical heaters are used in the mockup test. One is a chromel wire wound and mounted on the outer surface of the inner shell, the other is a stainless steel film heater (1.2 mm in thickness and 8 mm in width) mounted on the outer surface of the outer shell. The film heater is insulated from the outer shell with natural mica flakes. For establishing the adiabatic condition of the loop, the test vessel assembly, the two transfer tubes and the condenser are insulated from the environment by glass wool. The total heating efficiency is determined by heat balance test.

The condenser is a shell and tube-type heat exchanger connected to the moderator transfer tube and the cooling water system. The cooling water system is composed of a water chilling unit, a preheater, a turbine flow-meter and adjusting valves.

The K-type sheathed thermocouples were used to measure the working fluid temperature and the cooling water temperature. Accuracy of the thermocouples is ±0.5 K. The system pressure and local pressure drops were measured with Rosemount™ 3051 intelligent pressure and differential pressure transducers. Accuracy of the transducers is 0.075% of the full scale. In addition, a pressure gauge of 0.4% in accuracy was used to monitor system pressure on the spot. A voltage transducer and a current transducer with an accuracy of 0.5% and 0.02% of the full scale respectively were used to measure heating power. Two turbine-type flow-meters, LWGY-15 and LWGY-25, are used to measure the flow rate of cooling water. Accuracy of the turbine flow-meters is 0.5% of their full scale. All data were acquired, monitored and recorded by means of the measuring system comprising a computer and a Solartran™ IMP 3595 A/D system. The liquid level in the transparent tubes was monitored and recorded with a level measuring system, which consists of a CCD video camera, a video frame grabber card and a computer. In the present mockup test, we have obtained the local void fraction by measuring the collapsed liquid levels and the pressure differences in the moderator cell. The calculation of void fraction in the lower region of the moderator cell is presented below as an example to illustrate how the mean void fraction is calculated in local regions of the moderator cell. According to the hydrostatic principle, the mean two-phase density of the lower region is:

$$\rho_{\text{lower}} = \rho_{\text{L}}(1 - \frac{\Delta h}{\Delta H}) \tag{1}$$

where Δh is the liquid level difference between the two adjacent transparent tubes in lower region of the moderator cell and ΔH is the distance between the two pressure taps in lower region (see Fig.1), ρ_{L} is the density of liquid. Moreover, the mean density of the two-phase mixture is:

$$\rho_{\text{lower}} = \alpha_{\text{lower}}\rho_{\text{G}} + (1 - \alpha_{\text{lower}})\rho_{\text{L}} \tag{2}$$

where ρ_{G} is the density of gas. We then obtained the mean void fraction in lower region:

$$\alpha_{\text{lower}} = \frac{\rho_{\text{L}} - \rho_{\text{lower}}}{\rho_{\text{L}} - \rho_{\text{G}}} = (\frac{\Delta h}{\Delta H}) \Big/ (1 - \frac{\rho_{\text{G}}}{\rho_{\text{L}}}) \tag{3}$$

The first step of the experiment was to evacuate the air from the test loop using a vacuum pump. Then, a certain quantity of R113 was filled into the test loop up to a fixed level in the moderator cell. Finally, the inner heating power and the outer heating power (the ratio of inner heating power to the outer heating power being kept 1:1) were increased step by step to boil R113 and increase the system pressure. The parameters were recorded after the system pressure was maintained at a pre-set pressure by regulating the flow rate and temperature of cooling water for about 30 min. Then, the heater power was increasing gradually, and changes of the parameters were recorded again. This procedure was repeated until reaching the maximum heating power.

3 Results and discussions

The mockup test was carried out in a full-scale model under a range of pressures, heating loads and initial R113 inventory. In order to evaluate the CNS loop circulation characteristics, the void fraction of the moderator and liquid level in the moderator cell, the same density ratio ($\rho_{\text{L}}/\rho_{\text{G}}$), the same vapor volume flow rate and a relative heat load shown in Table 1 were applied to the test.

Fig.2 shows how the collapsed liquid level and the self-regulating characteristics are established in the moderator cell. Point *a* to point *f* in Fig.2 show fluctuation of the liquid level during start-up. Point *a* is the liquid level at cold state. As R113 is heated and its temperature increases, the specific volume increases, too. So, the liquid level slowly goes up to point *b*. At this point, the R113 begins to boil. As the R113 is evaporated, the pressure at the top of the inner shell increases quickly. Consequently, the liquid R113 is expelled from the inner shell into the outer shell. The liquid level of the moderator cell is raised abruptly to point *c*. As the pressure at the inner shell increases intensively, the liquid in the inner shell is further pressed out from the inner shell into the outer shell. So, the liquid level of the moderator cell further rise rapidly from point *d* to point *e* as shown in Fig.2. The quick swell of the moderator, on one hand, raises the liquid level of the outer shell; and on the other hand, decreases the pressure of the inner shell. Hence, the liquid level decreases from point *e* to point *f* before it reaches an equilibrium state. At point *f*, the equilibrium liquid level has been established in the moderator cell. This equilibrium liquid level, which is higher than the normal level in normal operating condition, is established partly by the swelling of the two phase mixture and partly by the push of the vapor in the inner shell. The variation process before point *f* indirectly illustrates that the moderator cell can easily accomplish such an expected state that the inner shell contains vapor and the outer shell maintains a certain level of liquid. From point *f* to point *j*, the liquid level fluctuates around the equilibrium liquid level (about 350 mm) as the heat power increases, which demonstrates the self-regulating characteristics of the loop.

Table 1 Comparison of operation conditions between CARR CNS and the mockup test

Parameters	H_2			Mockup test (R113)		
Operating pressure (kPa)	108.4	137.5	168.4	404.3	501.2	601.7
Operating temperature (K)	20.56	21.36	22.16	369.7	379.0	387.3
Density ratio ($\rho_L \cdot \rho_G^{-1}$)	49.56	39.35	32.23	49.56	39.35	32.23
Heat load (kW)	0.5195	0.5245	0.5394	7.919	7.857	7.998
Mass flow ($g \cdot s^{-1}$)	1.169	1.193	1.241	22.55	22.89	23.75
Vapor volume flow ($L \cdot s^{-1}$)	0.8214	0.6751	0.5834	0.8214	0.6751	0.5834

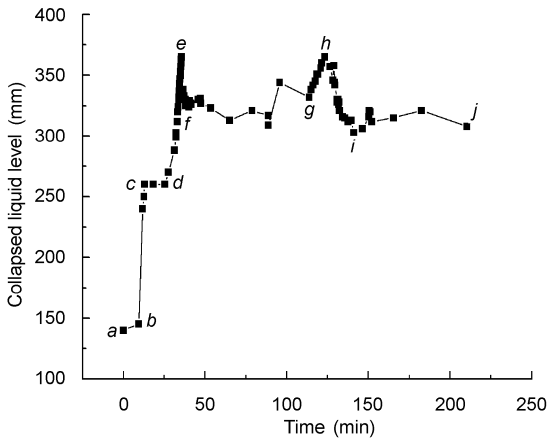

Fig.2 Variation of collapsed liquid level in moderator cell during the start-up.

Fig.3 and 4 show some experimental results under a pressure of 4.0 bar. Fig.3 demonstrates the effect of heat power on the local void fraction in the lower, lower middle, upper middle and upper regions of the outer shell at the same initial inventory. The void fraction is from 13% to 28% in the lower region, about 20% to 31% in the lower middle region, from 23% to 36% in the upper middle region, and from 28% to 43% in the upper region.

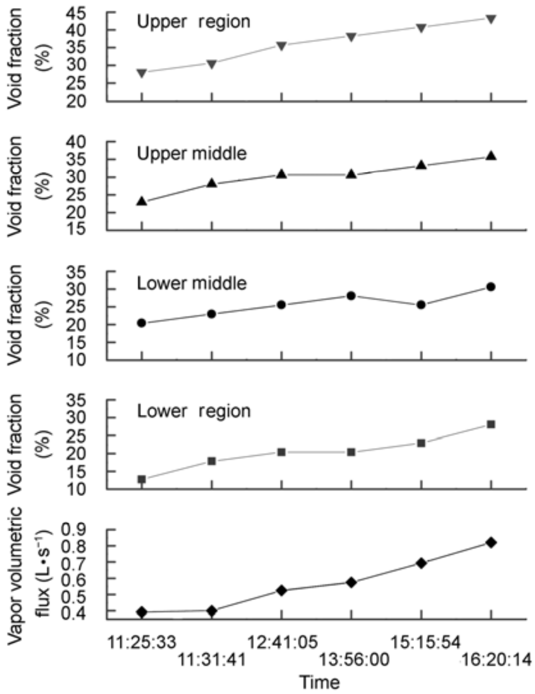

Fig.3 Effect of heat power on void fraction at different elevations in moderator cell (4.0 bar).

Fig.4 shows the effect of heat power on the collapsed liquid level in the moderator cell. The system pressure is kept stable at 4.0 bar. The collapsed liquid level in the moderator cell is stable at about 350mm as the heat power increases. We found the same tendency when the pressure is kept at 5.0 bar as shown in Fig.5. The collapsed liquid level in the moderator cell is stable at about 360 mm as the heat power increases from 5.05 kW to 7.85 kW under the pressure of 5.0 bar. These results prove that the mockup test loop has self-regulating characteristics. We can keep the moderator cell liquid level stable only by means of controlling the system pressure. The same conclusion can be obtained at the pressure of 6.0 bar.

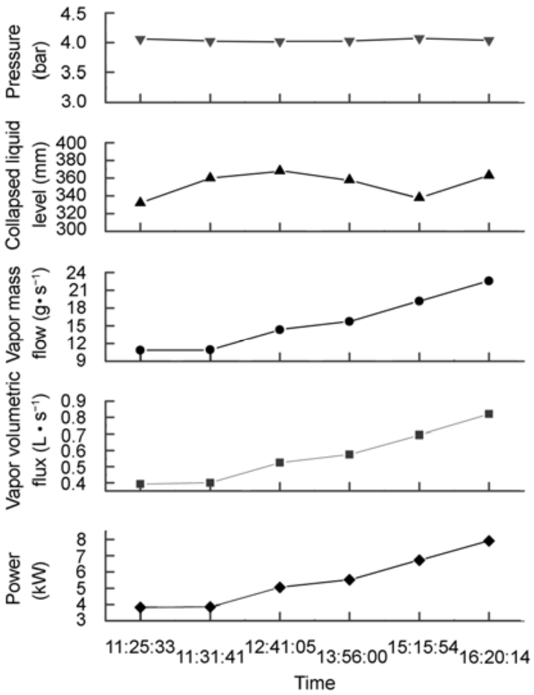

Fig.4 Effect of heat power on collapsed liquid level in moderator cell (4.0 bar).

Fig.6 shows the measuring results of local void fractions in the moderator cell. The local void fraction increases as the increase of vapor volumetric flow rate. The system pressure has considerable effects on the void fraction in the moderator cell. At the same vapor volumetric flow rate, the local void fraction increases along with the pressure.

According to a previous study,[5] the local void fraction of pool boiling is related to vapor volumetric flow rate and the bubble terminal velocity. The local void fraction increases as the decreasing of the bubble terminal velocity. The bubble terminal velocity can be expressed as[6]

$$V_\infty = 1.18\left[\frac{\sigma g(\rho_L - \rho_G)}{\rho_L^2}\right]^{1/4} = 1.18\left[\frac{\sigma}{\rho_L}\times g(1-\frac{\rho_G}{\rho_L})\right]^{1/4} \quad (4)$$

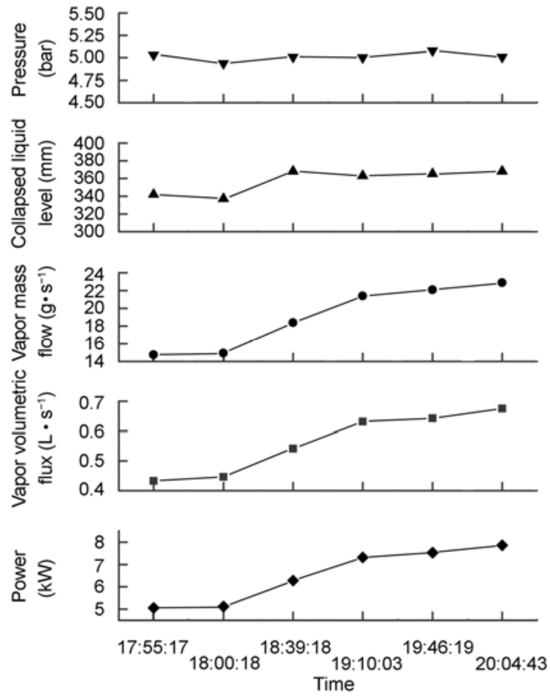

Fig.5 Effect of heat power on collapsed liquid level in moderator cell (5.0 bar).

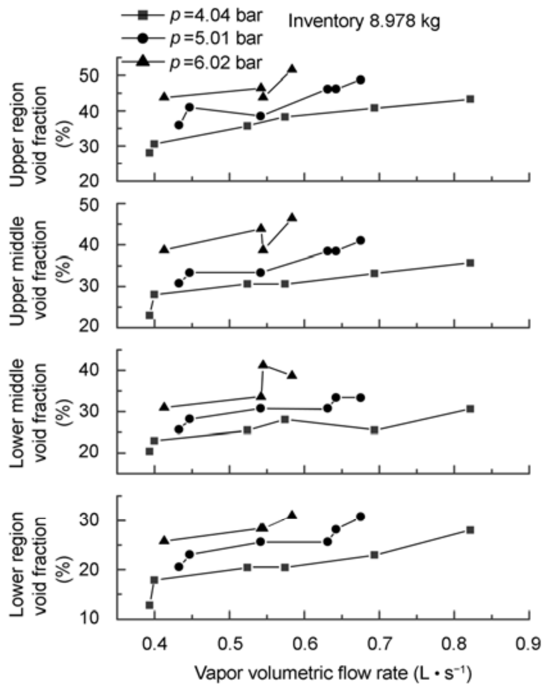

Fig.6 Effect of pressure on void fraction at different elevations in moderator cell.

where σ is the surface tension of liquid, ρ_G and ρ_L are density of gas and liquid respectively, g is the acceleration due to gravity. As the pressure increases, σ/ρ_L decreases (as shown in Table 2), so the bubble terminal velocity decreases as well, and the local void fraction increases. In addition, because of the difference between the physical properties of hydrogen and R113, the bubble terminal velocity is also different. For the same geometric size and density ratio, the bubble terminal velocity of R113 is less than that of hydrogen in the corresponding working condition of hydrogen loop because the σ/ρ_L of R113, the working fluid of the mockup test loop, is less than that of hydrogen. At the same vapor volumetric flow rate, the local void fraction in the moderator cell of the mockup test loop is therefore greater than that of the hydrogen loop. Further experimental studies on the bubble terminal velocity have been carried out to evaluate the local void fraction in the moderator cell of CNS on the basis of data from the present work, and the result will be reported in another paper.

Table 2 Physical properties of R113 in saturated condition

p (bar)	t_{sat} (℃)	ρ_L (kg·m^{-3})	ρ_G (kg·m^{-3})	σ (N·m^{-1})	σ/ρ_L
3	84.75	1412	20.75	0.01075	7.61331×10^{-6}
4	96.31	1379	27.41	0.00957	6.93981×10^{-6}
5	105.9	1351	34.12	0.00861	6.37306×10^{-6}
6	114.1	1327	40.91	0.00781	5.88546×10^{-6}
7	121.3	1304	47.81	0.00711	5.45245×10^{-6}

4 Conclusion

This paper reported a full-scale mockup test for the development of the CNS in CARR. Circulation and self-regulating characteristics of the CNS have been investigated. All the experimental runs under three system pressures and a series of heat load illustrate that the mockup test loop can establish a stable circulation. The collapsed liquid levels in moderator cell during startup of the test loop indirectly show that the moderator cell in the mockup test is able to establish a state in which the inner shell is only filled with vapor and the outer shell with liquid under the operating conditions. As the heat load is increased, local void fraction in the moderator cell is increased as well, but the collapsed liquid level is stable. Therefore, the mockup test loop has the self-regulating characteristics under the test conditions. What we need to do is to control the system pressure to maintain the liquid level in the moderator cell almost constant against thermal disturbances. The system pressure has considerable effect on the void fraction. With increasing of the system pressure, local void fraction in the moderator cell increases. But further research is needed to measure directly the liquid level of the inner shell to uncover the state of the moderator cell.

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