Influences of physical properties of two-phase mixture on void fraction in an annular vessel

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Abstract To keep the void fraction of two-phase hydrogen in the moderator cell of the cold neutron source (CNS) of China Advanced Research Reactor (CARR) to a specified range, an annular vessel with the same size as the actual moderator cell was used as test section. Deionized water and alcohol, sucrose, and sodium chloride solutions with different concentrations were used as working fluid to find out influences of physical properties, such as density, viscosity and surface tension, of the two–phase mixture on void fraction. The tests proved that the ratio of surface tension to density of liquid phase has great influence on void fraction: the larger the ratio, the smaller the void fraction. Since the ratio of surface tension to density of Freon 113 is lower than that of liquid hydrogen, Freon 113 can be used as a working fluid to study the void fraction in the two-phase hydrogen thermosiphon loop in the CNS of CARR and the results will be conservative.

Keywords Void fraction, Bubble, Surface tension, Density

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1 Introduction

A great deal of heat will be generated when neutron beam passes through liquid hydrogen and cell metal in a cylindrical-annulus moderator cell of the cold neutron source (CNS) in China Advanced Research Reactor (CARR). As a result, a lot of hydrogen gas appears inside. If hydrogen gas could not overflow from liquid hydrogen in time, the hot neutron could not meet liquid hydrogen, cooling effect will be decreased, and cold neutron could not be obtained. Thus, it is a critical problem to control void fraction in a moderator cell to a specified range. Many experimental studies have to be carried out to get a proper design of the moderator cell of CNS.

It is impossible to use hydrogen as a test fluid, for it needs a great cost to keep the system operation, and it involves safety problem of hydrogen. Freon-11 has been used to perform a mockup test of void fraction in the neutron moderator cell.[1] But Freon-11 has different physical properties from liquid hydrogen, for example, the latter has smaller density, viscosity, and surface tension. To apply the modeling results to a real moderator cell that uses hydrogen as working fluid, additional experimental studies have to be carried out to understand the influences of physical properties, such as density, viscosity, and surface tension, on void fraction. Investigation on the issue seems to be seldom reported in the literature.

One of the most important objectives is how to measure void fraction. Hewitt reviewed the main methods.[2] One of the simplest techniques for determining void fraction is quick-closing valve method. The other methods used for void fraction measurements include resistance (or conductance) probe, capacitance,[3] nuclear attenuation techniques (beta, gamma, neutron, or X-rays),[4-6] ultrasonic,[7] fibre optical probes,[8] hot-wire and hot-film anemometry, microthermocouples, isokinetic sampling, and electrical conductivity probes.[9] But employing any of these methods is difficult in our application. Therefore we have chosen a simple method to measure the differential pressure at different heights, then to calculate void fraction.

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2 Experimental apparatus and operating procedure

The test facility is shown in Fig.1. The test section is made of Lucite and has the same size as the actual moderator cell. There are five pressure ports with a space of 50 mm along the height of the moderator cell. The inner shell is wrapped by iron sheet, with a lot of uniformly drilled small holes, which diameter is 1 mm on the side and bottom surface. Compressed air supplied by an air compressor is introduced into the inner shell and expel the liquid into the annular vessel from those small holes. This process is to simulate the formation of bubbles in the cold neutron moderator and the expelling of air contained in the inner shell. Then those bubbles will rise up inside the liquid between the inner shell and the moderator cell. Because the gas holds some space of liquid, liquid will overflow from the moderator cell. When the overflow has stopped, a balance will be reached for a given gas flow rate. Then local void fraction can be obtained by measuring the differential pressure by closing and opening corresponding valves shown in Fig.1. The liquid temperature is measured by a thermocouple and adjusted by thermostatically controlled warmer. Deionized water, sodium chloride solution, sucrose solution, and alcoholic solution with different concentrations are respectively used as working fluid, so that the void fraction at different density, viscosity and surface tension can be found out. The physical properties of different liquids used in the experiments are given in Table 1.

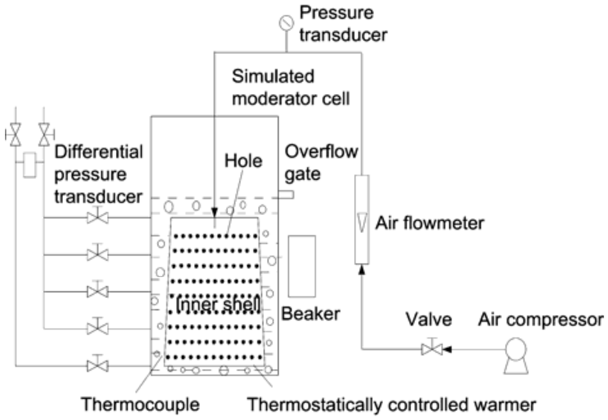

Fig.1 Schematic diagram of the test facility.

Table 1 Physical properties of different liquids used in the experiments

Liquid	Density (kg/m^3)	Viscosity (×10^{-3} Pa·s)	Surface tension (×10^{-3} N/m)	Surface tension/density (×10^{-3} m^3/s^2)
Deionized water	997	0.9663	73.05	0.073270
5% sodium chloride solution	1032	1.0930	73.8	0.071512
10% sodium chloride solution	1065	1.1500	75.2	0.070610
15% sodium chloride solution	1106	1.2740	76	0.068716
23% sodium chloride solution	1168	1.5140	77	0.065925
5% sucrose solution	1016	1.1210	73.19	0.072037
10% sucrose solution	1034	1.3240	73.11	0.070706
20% sucrose solution	1077	1.9670	73.97	0.068682
5% alcoholic solution	983	1.1700	56.3	0.057274
10% alcoholic solution	976	1.5380	49.6	0.050820
Freon-113 (25 °C)	1566	0.719	17.0	0.010856
Liquid hydrogen (20.86 K)	70.119	0.0127	1.87	0.026669

The measuring instruments include K-type thermocouples, differential pressure transducer, pressure transducer and air flowmeter. The layout of the instruments and the moderator cell is also shown in Fig.1. The accuracy of thermocouple is 2.0 K or 0.75% of the full scale. A differential pressure transducer is used to measure the local pressure difference at different elevations. Note that two pressure guide tubes are empty technically when measuring pressure difference, therefore the pressure difference obtained is “pure”, i.e. it does not include manometer offset due to the altitude difference of two pressure taps. A pressure transducer is used to measure the pressure of compressor air so that air flow rate is calculated correctly. The accuracies of both differential pressure transducer and pressure transducer are 0.75% of the full range. The accuracy of air flowmeter is 2.5%.

The operating procedures are illustrated as follows: (1) Fill a liquid into the moderator cell to a given level. (2) Keep the liquid to a specified temperature using the thermostatically controlled warmer. (3) Blow in a given amount of compressed air to the inner shell by using an air compressor. A beaker is used to contain the overflowed liquid. (4) Record the gas flow rate. (5) Measure the differential pressures by opening or closing the valves after a balance was established. (6) Calculate the average void fraction from the differential pressure, and calibrate it with the void fraction obtained from the measuring of overflowed liquid.

3 Thoery of void fraction measurement

The void fraction is defined as

$$\alpha = A_\mathrm{g} / A = A_\mathrm{g} / \left(A_\mathrm{g} + A_\mathrm{l} \right) \tag{1}$$

where α is void fraction, A (m^2) is total area of the cross-section of the annular channel between the inner cell and the moderator cell, A_g (m^2) and A_l (m^2) express the sectional areas occupied by gas phase and liquid phase respectively. The quantities of these two variables are difficult to measure. However, we can calculate void fraction in moderator cell from the density of two-phase mixture, density of gas phase, and density of liquid phase according to the relation between density and void fraction given by

$$\rho_\mathrm{m} = \alpha \rho_\mathrm{g} + (1-\alpha)\rho_\mathrm{l} \tag{2}$$

Then α can be solved as

$$\alpha = (\rho_\mathrm{m} - \rho_\mathrm{l}) / (\rho_\mathrm{g} - \rho_\mathrm{l}) \tag{3}$$

where ρ_m (kg/m^3) represents average density of the gas-liquid mixture, ρ_g (kg/m^3) and ρ_l (kg/m^3) represent densities of gas phase and liquid phase, respectively.

If we can measure density of the two-phase mixture, void fraction can be obtained from Eq.(3). In fact, we can obtain density of the two-phase mixture from differential pressure measured. That is, we can calculate density of the two-phase mixture from the differential pressure at a given altitude and get void fraction from Eq.(3).

The correlation between differential pressure Δp and density of the two-phase mixture ρ_m is:

$$\rho_\mathrm{m} = \Delta p / (gh) \tag{4}$$

Where Δp (kg/m^3) represents differential pressure, h =0.05m is altitude difference between two pressure taps, g (m/s^2) is acceleration of gravity.

Finally, void fraction can be expressed

$$\alpha = \frac{\Delta p / (gh) - \rho_\mathrm{l}}{\rho_\mathrm{g} - \rho_\mathrm{l}} \tag{5}$$

Here, $g, h, \rho_\mathrm{l}, \rho_\mathrm{g}, \Delta p$ are known quantities, and then α can be calculated easily.

4 Results and discussion

According to the analysis of the neutron moderator cell in CARR, the production rate of hydrogen gas is about 3 L/s. To model the different amount of gas generated at different operating conditions, air flow rates ranging from 1 to 5 L/s are used in the tests. The data of void fraction measured in the tests for various solutions with different concentrations are shown in Fig.2~4. Fig.2 shows the void fraction curves of sodium chloride solutions with different concentrations, the corresponding data for deionized water is also shown on the figure for comparison. It is noted that there was little changes on void fraction for various concentrations. Similar results can be found in Fig.3 for sucrose solution with different concentrations. Fig.4 shows a completely different result, the void fraction for alcohol solutions is much higher than that of deionized water, and a greater difference is also found for various concentrations. Fig.5 collects all of void fraction data of our tests except that of 10% (wt), 15% (wt) sodium chloride solution and 10% (wt) sucrose solution, which are removed for a clear view. It is also worthwhile to note that the void fraction curves for alcohol solutions are in the highest, sodium chloride solutions and sucrose solutions are in the middle, and the water is the lowest.

The void fraction is related with the rising velocity of bubbles, i.e. the greater the rising velocity, the lower the void fraction. Although there are many physical properties which affect the rising velocity of bubbles, the most important properties are surface tension, viscosity and density. Surface tension affects the shape of bubbles. Larger surface tension makes resistance decreasing due to bubbles approaching spheres, so the rising becomes quicker. Viscosity is a main factor of resistance on bubble rising velocity. Smaller viscosity conduces to the rising of bubbles. Density of liquid affects buoyancy and drag force of liquid on bubbles, and the difference between buoyancy and drag force determines the rising velocity of bubbles. It can be seen from Table 1 that viscosity increases by about 100% when the concentration of sucrose solutions increases from 0% to 20%, but the void fraction in Fig.3 does not increase significantly as compared with that of sodium chloride solutions, so the influence of viscosity on void fraction can be ignored. Thus, surface tension and density of liquid become dominant, but they have contrary contribution to the rising velocity of bubbles: high surface tension promotes the rising of bubbles, but higher density makes the drag coefficient increasing significantly under experimental conditions, which leads to the increment of drag force larger than that of buoyancy, and then the rising of bubbles will become slower. So we consider the ratio of surface tension to density as a governing factor. A larger ratio makes the rising of bubbles quicker, and the void fraction lower.

Fig.6 shows curves of surface tension to density of sodium chloride solutions, sucrose solutions and alcohol solutions used in the experiments. It is found that all the three curves descend as the concentration is increased. But the curves of sodium chloride solutions and sucrose solutions are higher than that of alcohol solutions and the descend tendencies are relatively flat. The alcohol solutions demonstrate quite different results, its curve goes down significantly with the increasing of concentration in the experiments. So, in Figs.2 and 3, the curves for sodium chloride solutions and sucrose solutions have smaller changes for various concentrations, but those for alcohol solutions have larger changes (see Fig.4). In Fig.5, the curves of sodium chloride solutions and sucrose solutions are very close because of little difference in ratios of surface tension to density of solutions. But void fractions of alcohol solutions with various concentrations are quite different, this may result from the fact that the ratio of surface tension to density of alcohol solutions has a significant decrease as the concentration increases (see Fig.6).

The experiments confirmed that the ratio of surface tension to density is the dominant factor of void fraction, so we can select a working fluid with lower ratio of surface tension to density than that of liquid hydrogen to simulate the void fraction produced in practical moderator cell, and the results will be conservative. It is seen from Table 1 that Freon 113 is a good choice, so we can use Freon 113 as working fluid to model void fraction in the hydrogen two-phase thermosiphon loop.

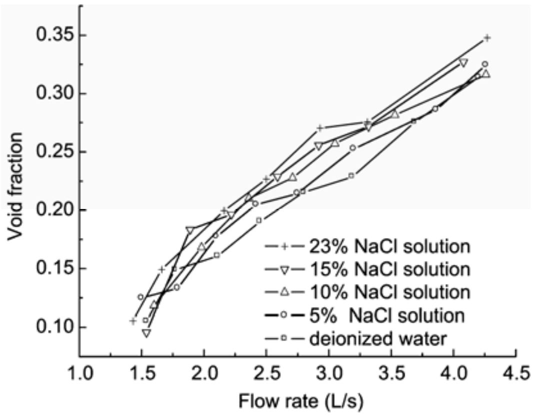

Fig.2 Void fractions for sodium chloride solutions with various concentrations.

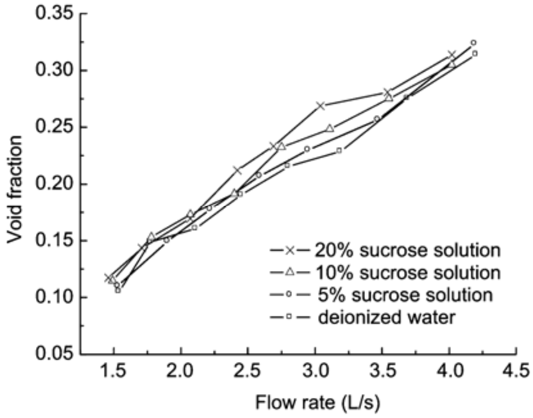

Fig.3 Void fractions for sucrose solutions with various concentrations.

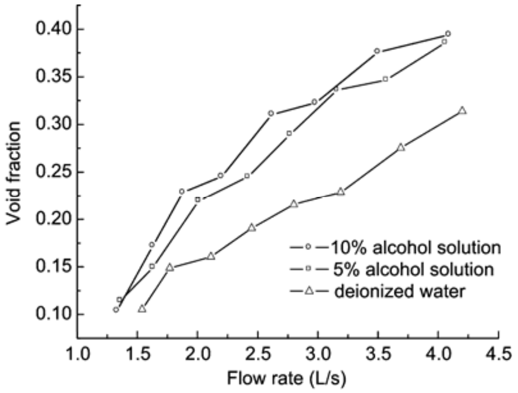

Fig.4 Void fractions for alcohol solutions with various concentrations.

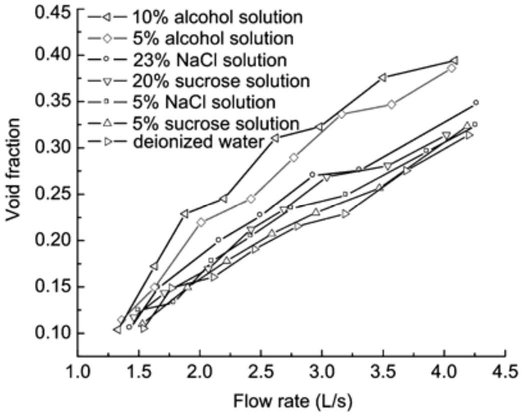

Fig.5 Void fraction for different solutions.

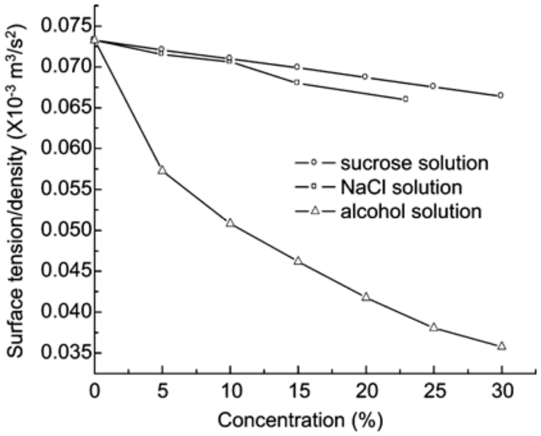

Fig.6 The ratio of surface tension to density as a function of concentrations for different solutions.

5 Conclusions

Experimental researches on void fraction in an annular channel were carried out for a wide range of the ratio of surface tension to density for several solutions. The results have verified that the ratio is the governing factor of void fraction: the larger the ratio, the smaller the void fraction.

The ratio of surface tension to density of Freon 113 is lower than that of liquid hydrogen, so Freon 113 can be used as working fluid to mockup void fraction in the hydrogen two-phase thermosiphon loop, and the results are a little conservative. Further researches are necessary to ensure the proper design of the CNS in the CARR.

References

1 Lee C H, Kawai T, Chan Y K. Physica **B**, 2002, **311**: 173-181

2 Hewitt G F. Measurement of two-phase flow parameters, London: Academic Press, 1978

3 Kendoush A A, Sakis Z A. Exp Thermal Fluid Sci, 1995, **11**(4): 321-326

4 Jones O C, Zuber N. Int J Multiphase Flow, 1975, **18**: 847-860

5 Kendoush A A. Nucl Eng Des, 1992, **137**: 249-257

6 Vince M A, Lahey R T. Int J Multiphase Flow, 1982, **8**: 93-124

7 Atkinson C M, Kytomaa H K. J Fluids Eng, 1993, **115**: 665-675

8 Van Hout R, Shemer L, Barnea D. Int J Multiphase Flow, 1992, **18**: 831-845

9 Hsu Y Y, Graham R W. Transport processes in boiling and two-phase systems, Washington DC, Hemisphere Publishing, 1976