CHAPTER III
SIMULATION AND EXPERIMENTS

This chapter has four sections. It begins with the Monte Carlo simulation using MCNP program version 4C. Then, three different experiments, which were a static air-Lucite experiment, a dynamic nitrogen-water experiment and a dynamic steam-water experiment, were performed. The specific details of each section, such as the system arrangement and materials, were introduced. The basic principles necessary to understand each experiment were also reviewed.

3.1 Monte Carlo Simulation

Since scatterometry was a sophisticated physical process, the main purpose of the Monte Carlo simulation was first used to confirm the adequacy of the fast neutron scattering techniques with different system geometries of the scatterometer before proceeding experimental work. For this present work, the MCNP program version 4C (MCNP4C) was used for the Monte Carlo simulation. It was developed and released in 2000.

3.1.1 Scatterometer Geometry Setups

The MCNP analysis simulated the geometry of the scatterometer, which was basically composed of a 0.5-inch outside diameter stainless steel 316 pipe with 0.049-inch wall thickness as a test section with ^{252}Cf as an wasotopic fast neutron source and a detector. Since the test section can be placed on the x-, y- or z-axis, the simulations were divided into three different scatterometer geometries corresponding to the test section arrangements as shown in Table 3.1.

Table 3.1 System arrangements of three different scatterometer geometries.

Case	Test section	Neutron source	Detector
1	Parallel to x-axis	On z-axis at (0, 0, 1)	On y-axis (0, -1, 0)
2	Parallel to y-axis	On x-axis at (1, 0, 0)	On z-axis (0, 0, -1)
3	Parallel to z-axis	On y-axis at (0, -1, 0)	On x-axis (1, 0, 0)

The example was shown as in Figure 3.1. However, all cases were based on the same principle that the test section was typically located perpendicular to both the incident beams from the fast neutron source and the neutron detector.

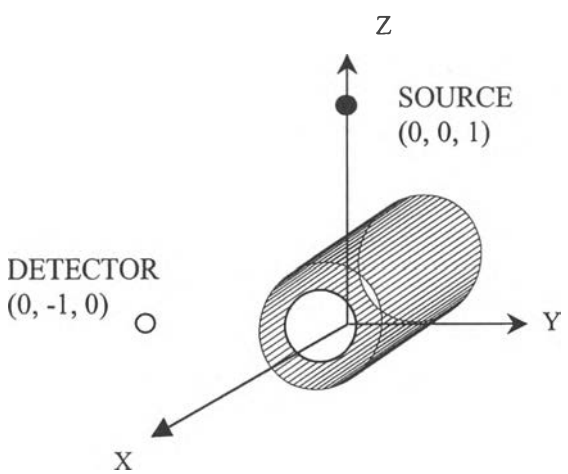

Figure 3.1 Scatterometer geometry setup for case 1.

3.1.2 MCNP4C Simulation Procedures

The input files (INP file) were created and divided into three main cards, which contained the input information about the simulation. The example of an input file can be found in Appendix A.

(1) A cell card

The geometries of scatterometer were defined in a right-handed Cartesian coordinate system. There were two materials for this simulation. One was

the steam-water mixture and the other was the stainless steel pipe. The condition was set at 260°C for the temperature of the steam-water mixture inside the test section and the pressure at the saturated value, the density of the mixture can be varied by changing the value of void fraction in the range from 0 to 1 as expressed in the Equation 3.1).

$$\rho = \rho_L - \alpha(\rho_L - \rho_g) \quad (3.1)$$

where ρ, ρ_L and ρ_g were the density of the mixture, the liquid phase and the vapor phase respectively and α was the void fraction. However, the density of the stainless steel pipe was assumed to remain at a constant at 8.02 g/cm^3 for all temperatures.

(2) A surface card

The surface mnemonics CX, CY, and CZ were used to determine the cylinder on the x-, y-, and z-axis, respectively. Table 3.2 shows the equations of these mnemonics.

Table 3.2 MCNP surface cards.

Mnemonic	Description	Equation	Card Entries
CX	On X–axis	$Y^2 + Z^2 - R^2=0$	R
CY	On Y–axis	$X^2 + Z^2 - R^2=0$	R
CZ	On Z–axis	$X^2 + Y^2 - R^2=0$	R

Since the dimension of the pipe must be changed into centimetre units, the inside radius of 0.501 cm and the outside radius of 0.625 cm were used as the numerical coefficients for the surface equations.

(3) A data card

The simulations were considered as a neutron-transport-only problem. ^{252}Cf was specified as the spontaneous fission source using the Watt fission energy spectrum probability to approximate the energy of the fission neutron in source specification card. For simplification, the detector was designated as a point detector in this simulation in order to estimate the scattered neutron flux. However, it can be expected to provide results similar to those of a volume detector at least for

comparative purpose. For terminating the Monte Carlo calculation, history cutoff card was used after 10000000 particle histories had been followed, unless the calculation was terminated earlier for some other reason such as computer time cutoff. In addition, the numbers of source particles simulated were sufficient to generate detector tallies with less than 5% relative error.

3.2 Static Air-Lucite Experiment

The static air-Lucite experiment was an experiment employing a solid material to simulate the water fraction. The purpose of this experiment was to check linearity between the detector response, which was defined as the number of neutrons that hit the detector per total counting time (neutron count rate), and the actual Lucite fraction. It was composed of a test section, the ^{252}Cf source, a ^{3}He detector as thermal neutron detector and cadmium sheets as arranged in Figure 3.2. Paraffin wax was used guard against neutrons emitted from the source.

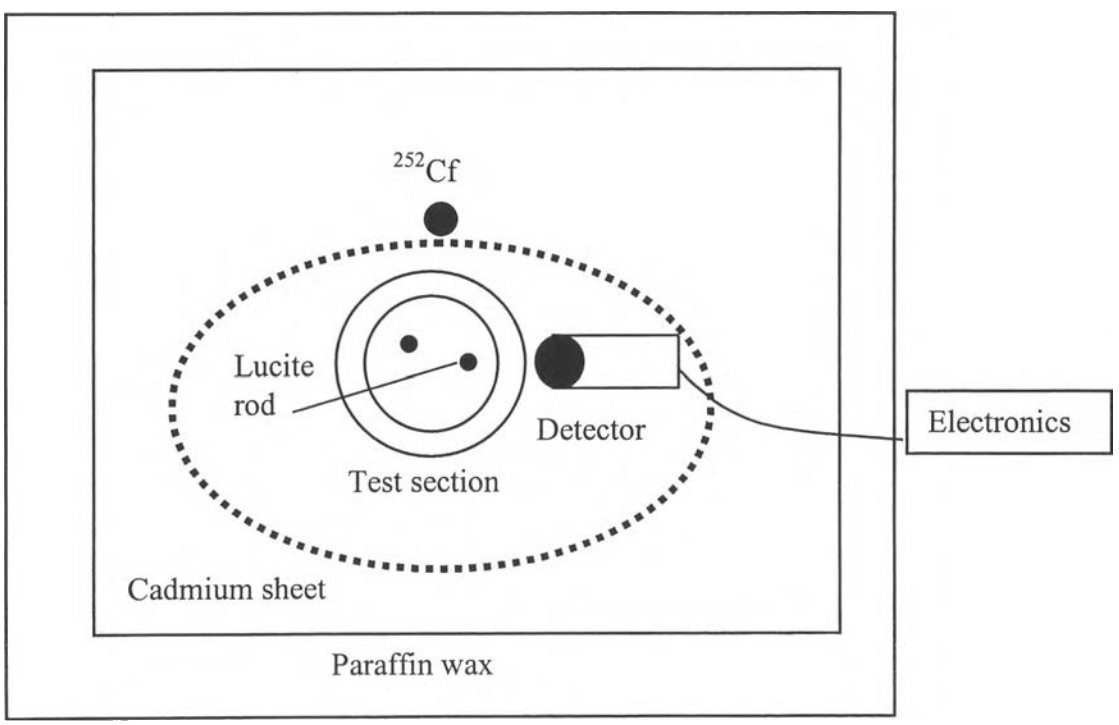

Figure 3.2 Static air-Lucite experimental arrangement.

3.2.1 Test Section

The test section consisted of two main components, the stainless steel type-316 pipe with 1.27cm outside diameter and 0.12cm wall thickness and :Lucite rods.

Lucite ($C_5H_8O_2$) rods were physically suitable to simulate the water fraction because of their high hydrogen content and its density close to water (about 1.18 g/cm^3). In order to obtain different Lucite fractions, there were two sizes of Lucite rods inserted into the test section randomly. One was 3 mm diameter, which gave 0.1 volume Lucite fraction, and the other was 9 mm diameter, which filled a full test section (zero void fraction). Therefore, the range of simulated water fraction from 0-1 Lucite fraction was investigated. However, a Lucite fraction above 0.6 could not be achieved because there was not enough space available for inserting enough Lucite rods into the pipe.

3.2.2 Neutron Source

Two micrograms of ^{252}Cf were employed as the wasotopic fast neutron source. This source undergoes spontaneous fission of 3% of the total decays to release a neutron; it has a half-life of 85.5 years. On a unit mass basic, 2.3×10^6 n/s were produced per microgram of ^{252}Cf. In addition, the other important decay mechanism was alpha decay with a half-life of 2.73 years. The gamma dose rate was about 1.6×10^2 mR/hr/mg at 1 meter from source. Therefore, when the activities of alpha and spontaneous fission decay rate were combined, the neutron yield of this source was 0.116 n/s per Bq. The average neutron energy of the ^{252}Cf was 2.14 MeV. The shape of a typical fission spectrum was approximated as follows;

$$\frac{dN}{dE} = E^{\frac{1}{2}} \exp\left(\frac{-E}{T}\right) \tag{3.2}$$

where N is the number of radioactive nuclei, E is the neutron energy in eV and T is a constant value of 1.3 MeV (Knoll, 1989). The effective half-life is 2.65 years, which is long enough to be convenient. Moreover, ^{252}Cf involved very small amounts of active material (normally of the order of micrograms) and can therefore be made in very small sizes dictated only by the encapsulation requirements.

3.2.3 Detector

A ^{3}He detector was used as the thermal neutron detector and configured as a standard proportional counter that had the physical dimensions of 5.08cm diameter and 16.5cm length with a gas filling pressure of 4 atmospheres. The operating voltage was between 1600 to 1700 volts.

Thermal neutrons that entered the detector can be captured into curtained element, which was helium. Then positively charged nucleus, a triton ($^{3}H^{+}$) and a proton, were produced. Therefore, the sum of the accumulated charges was proportional to the number of incident neutrons. However, it was necessary to eliminate the thermal component in the background signal because this detector was most efficient for measuring the thermal neutrons. Therefore, cadmium sheets were used to surround the detector and the test section in order to exclude any thermal neutrons produced outside the system and to allow just fast neutrons to enter the system (cadmium cut-off energy ~0.5eV). Therefore, the detector measured only thermal neutrons scattering from the test sections. This led to a lower background signal.

3.2.4 Electronics

The counting system used in this experiment was a pulse-type consisting of a high-voltage power supply, a preamplifier, an amplifier and a multi-channel pulse height analyzer, as shown in Figure 3.3. All of these commercially available electronic instruments conform to the standards of Nuclear Instrument Modules (NIM). Specifications of the above equipment were reviewed in the related operating and service manual and were not repeated here. In order for detector to function smoothly, the positive high voltage from the high voltage power supply should be adjusted to the operating point of the detector; that was, 1600 kV for this experiment.

Since the output signals of the detector were generally weak and would be lost due to the accompanying electronic noise, before being recorded they must be preamplified by transmitting through the preamplier, which was placed between the detector and the amplifier. The signals were shaped by the preamplifier in order to provide an optimized electronic coupling between the impedance of the

output signals and that of the amplifier. This helped to minimize the attenuation from any source of noise. In the case of a weak signal, it was recommended that the preamplifier be placed as close to the detector as possible in order to minimize the electronic noise.

After the signals passed through the preamplifier, they were safely delivered to the amplifier, located a distance away with only a small loss of amplitude. At the preamplifier output, the amplifier, which was the main unit for amplification, increases signals by as many as 1000 times or more and converts them into a suitable form for measurement. Therefore, the Coarse and Fine gain on the amplifier were the important parameters for setting the counting system. An oscilloscope connected to the output of the amplifier was used to set the counting system. It can check the quality of signals as well as the level and type of the electronic noise since it was the equipment used to study rapidly changing phenomena, such as a sinusoidal or the pulse of a counter.

The multi-channel pulse-height analyzer recorded and stored the signals according to their pulse height in the storage unit called a channel. Each signal was stored in a particular channel corresponding to certain energy. The distribution of signals in the channels was an image of the distribution of the energies of the particles. The electronic noise can be eliminated because the channel that produced the electronic noise can be omitted. At the end of the counting period, the total number of pulses recorded was displayed. A TC 6000 multi-channel pulse-height analyzer was used in this experiment.

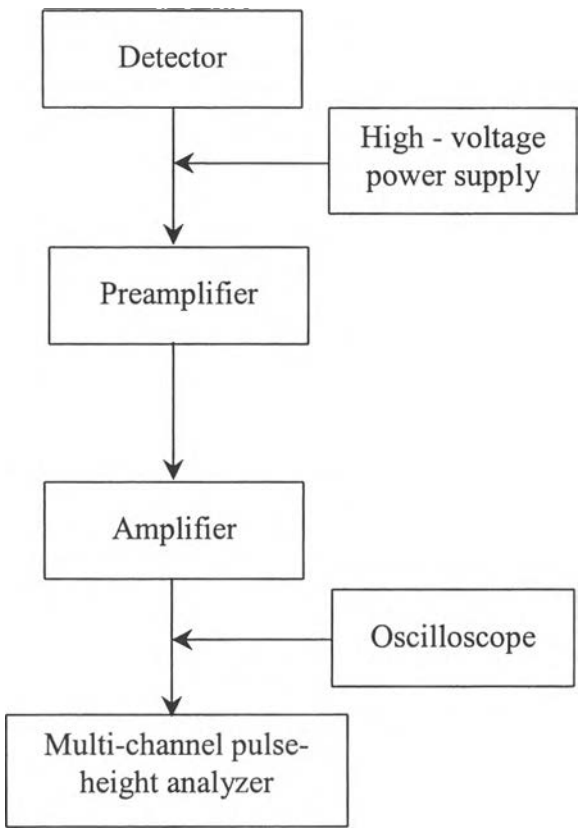

Figure 3.3 Diagram of electronic instrument used for the static air-Lucite experiment.

3.2.5 Calibration Method

As in the simulation results, the linearity between estimated Lucite and actual Lucite fraction was expected from the experiment. To simplify the calibration process of the device, the neutron count rate at zero and at one known fraction of Lucite were taken as two calibration points before the other Lucite fractions were measured. The Lucite fraction can be calculated from the relationship:

$$\hat{\rho} = \frac{R(\rho) - R(0)}{R(1) - R(0)} \tag{3.3}$$

where $\hat{\rho}$ is the Lucite fraction, $R(\rho)$, $R(1)$ and $R(0)$ is the neutron count rate corresponding to a known Lucite fraction, a full-of-water and an empty test section, respectively. This calibration process can be used only for atmospheric conditions because the effect of temperature and pressure may affect the probability of neutron interactions (the macroscopic cross-section).

3.2.6 Static Air-Lucite Experimental Procedures

(1) Electronic instruments were warmed up for 45 minutes before starting the experiment and the operating conditions were set as follows:

- The high voltage power supply at 1600 kV.
- The amplification levels of the amplifier at 200 for Coarse gain and at 2.5 for Fine gain.
- The timer at 2 minutes.

(2). The empty test section was first measured ten times to check the stability of electronics. The standard error was calculated by following equation (B.4). The acceptable standard error should be less than one percent. If not, there might be unstable equipment, external signal problem or insufficient time to warn-up the equipment. The proper counting period should produce at least 1000 counts.

(3). For calibration process, the full test section using the 9mm Lucite rod was measured. Different Lucite fractions were obtained by inserting 3mm Lucite rods randomly into the test section. The measurements were taken after the output signals were stable and repeated ten times for each point.

3.3 Dynamic Nitrogen-Water Experiment

One of the two-phase experiments was the dynamic nitrogen-water experiment. The objective of this experiment was to test the feasibility of the fast neutron scattering technique before applying it to the real two-phase systems. It was also used to study the effect of the bubble size on the relationship between neutron count rate and void fraction. The possibility of using the fast neutron transmission technique for measuring void fraction in this system was also investigated.

3.3.1 Experimental Arrangement

The top view and diagram of the dynamic nitrogen-water experiment were composed of a test section, a ^{252}Cf source, a ^{3}He detector, cadmium sheets and a paraffin wax shield as shown in Figures 3.4 and 3.5. In order to create different void fractions, nitrogen was bubbled through the test section at different flow rates by adjusting the regulator connected to the nitrogen tank. The test section was a 3.8

cm outside diameter plexiglas tube with a 3 mm-thick wall and 120 cm length. The neutron source and the detector were placed around the middle of the test section. The level of the water in the test section have to be above both the neutron source and the detector in order to avoid the effect of the entrance on the count rate. In order to investigate the effect of bubble size on the neutron count rate, the screen and the filters were attached at the bottom of the test section to create the different diameters. The diameter of the screen was 0.6 cm and two sizes of filter pores were used - 15 μ m and 60 μm.

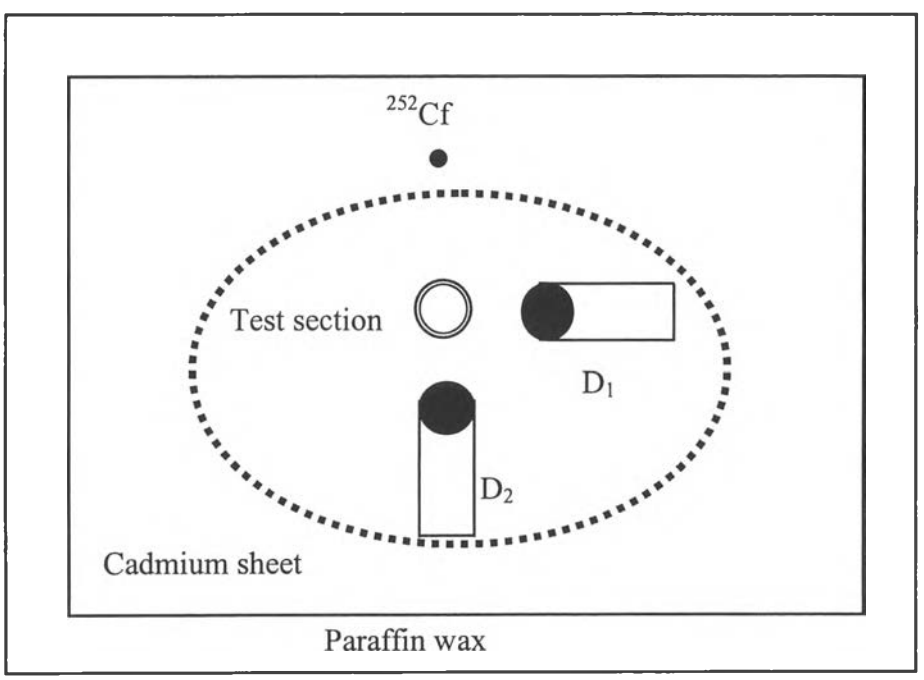

Figure 3.4 Top view of the dynamic nitrogen-water experimental arrangement.

As mentioned before, this experiment was operated in both scattering and transmission modes. There were two different positions of detectors, D_1 for the scattering technique and D_2 for the transmission technique.

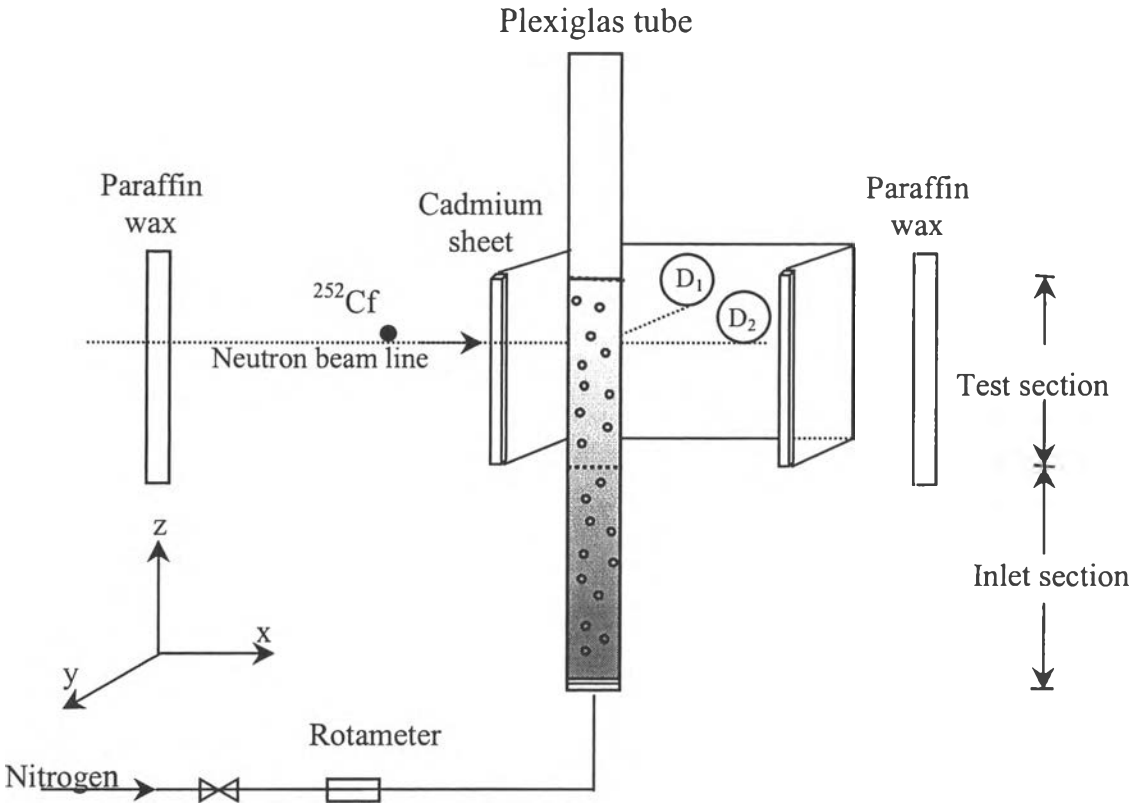

Figure 3.5 Diagram of the dynamic nitrogen-water experiment.

3.3.2 Calibration Method

The purpose of the calibration for the nitrogen-water experiment was to check the linearity between the estimated void fraction from the detector response and the void fraction from the experiment. Two calibration points, at empty and full test section, were first done. The estimated void fraction was predicted by using equation (2.1). As the nitrogen flow rate was changed, the water height varied from the normal level and was measured in order to calculate the void fraction.

This calibration method was appropriate only for room temperature and atmospheric pressure. For high pressures and temperatures condition the effect of probability of neutron interactions (the macroscopic cross-section) may affect the calibration.

3.3.3 Electronics

The electronics consisted of a high voltage power supply, a charge-sensitive preamplifier, an amplifier, a Single Channel Analyzer (SCA) and a

timer/counter as shown in Figure 3.6. This system was similar to the one used in the static air-water experiment, except that, a SCA and a timer/counter were added.

The ORTEC 556 high voltage power supply supplies the positive high voltage to the detector operating point, which was 1650 kV for this experiment. The signals from the detector were transmitted through the amplification system composed of an ORTEC 142 PC charge-sensitive preamplifier and an ORTEC 590A amplifier. When the signals were amplified, the electronic noise presented in a circuit was also amplified. Therefore, the SCA was used to eliminate the electronic noise and to reject unwanted signals. The noise should not be counted. The ORTEC 590A SCA was used in this system. The ORTEC 871 timer/counter was connected to the SCA in order to start and stop the SCA at desired counting time intervals.

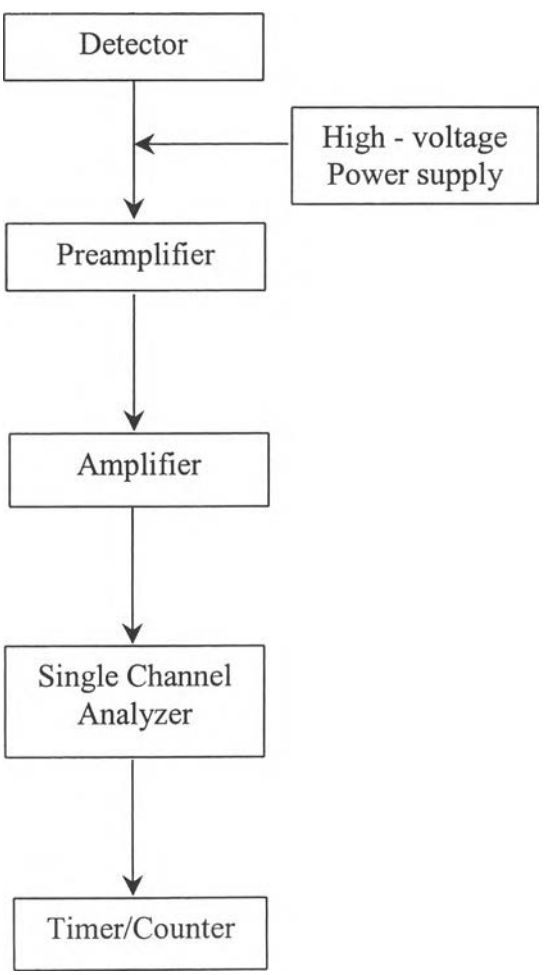

Figure 3.6 Diagram of electronic instrument used for the dynamic nitrogen-water experiment.

3.3.4 Dynamic Nitrogen-Water Experimental Procedures

(1) Electronic instruments were warmed up for 30 minutes before starting the experiment and the operating conditions were set as follows:

- The high voltage power supply at 1650 kV.
- The amplification levels of the amplifier at 100 for Coarse gain and at 1.5 for Fine gain.
- The timer at 50 seconds.

(2) The detector was placed at either D_1 or D_2 for the scattering or transmission method.

(3) There were three different sizes of filter to vary the size of the bubble as follows:

- Case 1: with 0.6 cm screen.
- Case 2: with 60 μm filter.
- Case 3: with 15 μm filter.

The filter was attached at the bottom of the test section. These three cases were done in sequence.

(4) The empty test section was first measured to check the stability of electronics twenty times. The measurements were taken after the output signals were stable.

(5) The standard error was calculated by following equation (B.4). The acceptable standard error should less than one percent. The proper counting period should produce at least 1000 counts.

(6) For the calibration, the test section was filled to 66.5 cm with purified water in order to measure the full test section.

(7) The flow rate of nitrogen was varied at 56.6, 90.6, 127.4, 198.2, 260.5, 396.4 and 504.0 cm^3/h for different void fractions. At each point, the increased height of purified water was measured for calculating void fraction. The number of count rate was repeated twenty times after the output signals were stable.

3.4 Dynamic Steam-Water Experiment

The objectives were to study the feasibility of the neutron scatterometer to provide on-line measurement of steam quality and to investigate the effect of temperature on the scatterometer response. This experiment was separated into two parts, the study of the temperature effect and that of steam quality.

3.4.1 Experimental Loop

The experimental loop consisted of a 60-liter reservoir, a pump, a pulsation dampener, a heat exchanger, a pre-heater, a heater, an autoclave, a cooler and a rotameter as depicted in Figure 3.7. The backpressure valve was used to pressurize the system. Water from the reservoir was pumped through the heat exchanger into an electric pre-heater that heats the water up to the set temperature before it enters the autoclave. The heater controlled by the power controller was installed inside the autoclave in order to reduce heat loss to surrounding and to generate steam. The mixture of steam and water passes through the heat exchanger before going through a cooler and then back to the reservoir. The rotameter was placed between the cooler and the reservoir for metering the volumetric flow rate of the water. In order to allow the scatterometer to detect the signals, the valve on the test pipe was opened and the steam-water mixture passes through the test section. The test pipe was 1.27cm stainless steel 316 pipe with the thickness of 0.12cm that was the same as the static air-Lucite experiment. A pulsation dampener was employed to reduce the pressure pulse produced by the diaphragm pump. Safety features such as a pressure-relief valve and an autoclave by-pass line were also included in the system. The electronic equipment that controled the scatterometer in this experiment was the same as that in the dynamic nitrogen-water experiment.

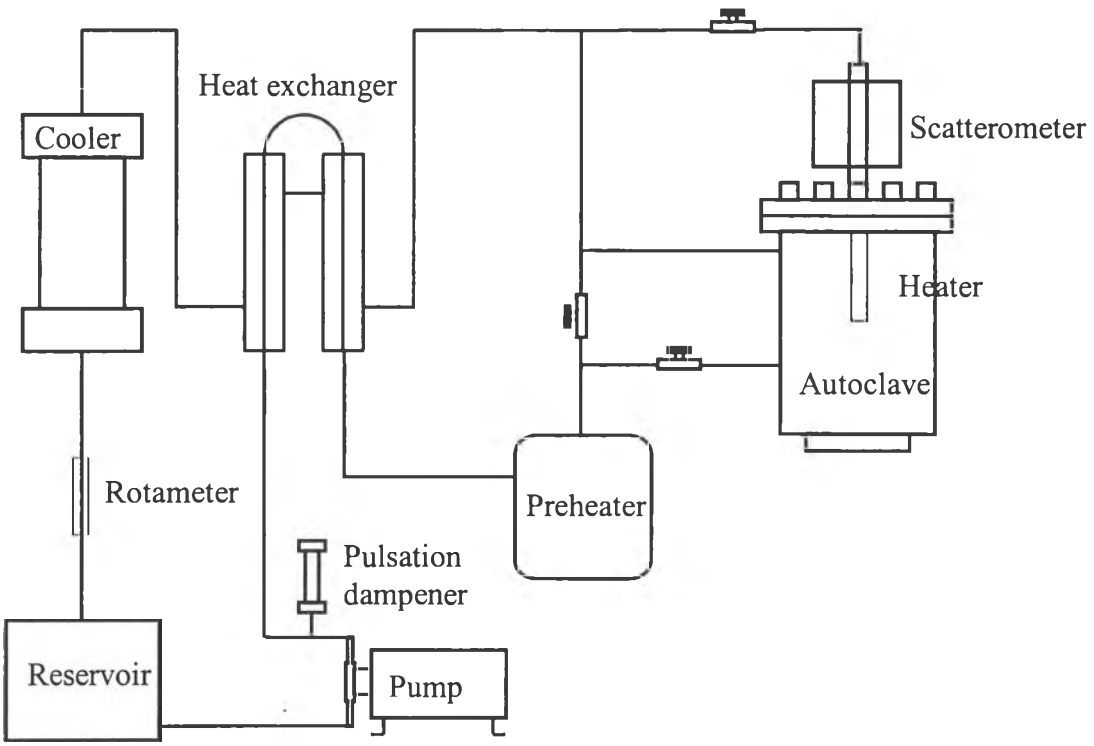

Figure 3.7 Flow diagram of dynamic steam-water experimental loop.

3.4.2 Study of Temperature Effects

The effect of temperature was investigated in this work by keeping the pressure of the autoclave constant at 5 MPa and varying the temperature of heated water entering the autoclave. The heater must be turned off in order to have only pressurized water passing through the scatterometer while the pump was operated at 80% maximum capacity. The procedures were shown as follows:

(1) Electronic instruments were warmed up for 30 minutes before starting the experiment and the operating conditions set as follows:

- The high voltage power supply at 1650 kV.
- The amplification levels of the amplifier at 500 for Coarse gain and at 1.5 for Fine gain.
- The timer at 10 seconds.

(2) At constant pressure 5 MPa, temperature was set at 50°C, 80°C, 100°C, 150°C and 200°C in order to vary the density of water. For each point, twenty measurements were taken after the output signals were stable. The acceptable

standard error should less than one percent. The proper counting period should produce at least 1000 counts.

3.4.3 Steam Quality Measurements

In order to measure steam quality, the experimental loop must be operated at saturated conditions. From Figure 3.8, the heated water was assumed saturated before entering by the autoclave at point 1. It received some heat while passing though the heater and vaporizes into steam before moving out to the scatterometer at point 2. The maximum capacity of the heater was 500W. In order to generate different steam qualities, the power of the heater was varied at different percentage of maximum capacity from zero to full capacity at 25% intervals. The pump was operating at 50% maximum capacity. There were three different saturated conditions investigated, which were at temperature of 150°C, 200°C and 250°C.

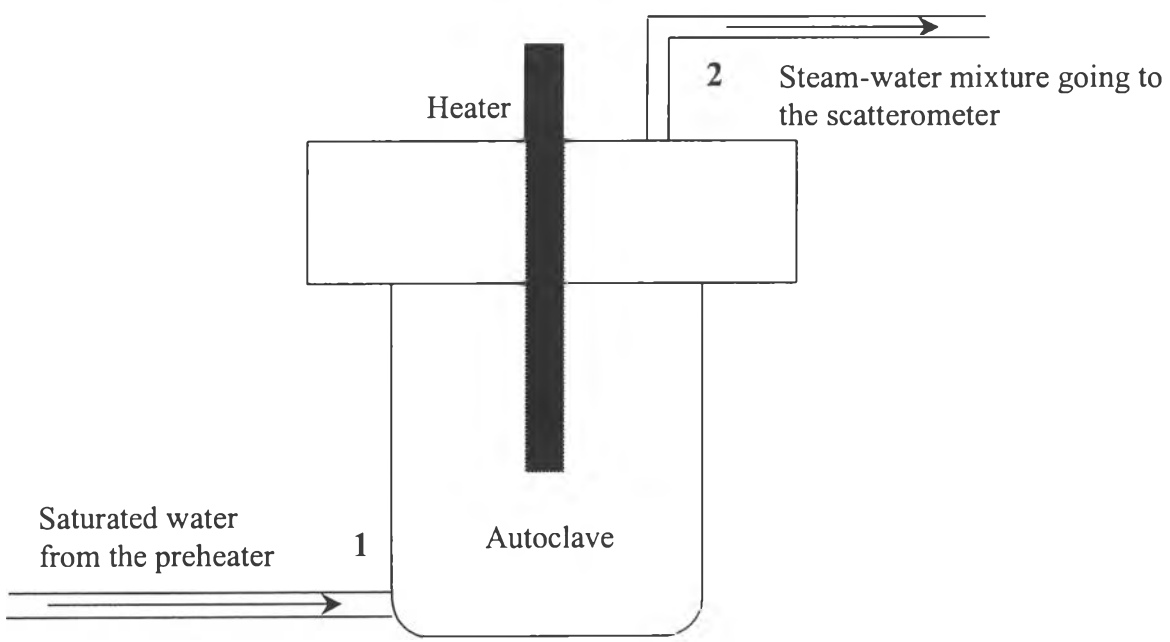

Figure 3.8 Diagram of the autoclave for steam quality calculations.

The electronic instrument was set up the same as in the previous experiment. The procedures were as follows:

(1) At each temperature and corresponding saturated pressure, the power of the heater was changed to give 100%, 75%, 50%, 25% and 0% maximum capacity in order to obtain different steam qualities.

(2) For each point, twenty measurements were taken after the output signals were stable. The acceptable standard error was less than one percent. The proper counting period should produce at least 1000 counts.