CHAPTER II
LITERATURE SURVEY

Steam quality or, equivalently, void-fraction is the parameter to indicate the proportions of vapor present in a mixture. Quality depends on the mass fraction while void fraction is the volume fraction of vapor in the liquid. The measurement of steam quality or void fraction in a pipe enables a complete analysis of the heat balance of the system to be made. This, in turn, helps in determining the efficiency and leads to economical benefits. Especially, both fossil and nuclear power plants need accurate and reliable steam quality measurements to establish the thermal performance of steam systems. Also, in oil fields, large amount of steam is injected into reservoirs to enhance heavy oil recovery. If the quality and mass flow rate of wet steam in the distribution system are known, the amount of heat injected into the reservoirs could be better monitored and controlled.

2.1 Steam Quality Measurement Techniques

Several steam quality measurement techniques have been proposed, depending upon specific needs. Hart *et al.* (1989) described four devices for measuring steam quality in power plants. There are a densitometer, a separating/accumulating calorimeter, a choke and a throttling calorimeter.

Ma (1998) reported that a combination of thermocouples and sensors can be used for simultaneous measurements of temperature, pressure, flow rate and steam quality. The pressure and temperature, measured respectively by the pressure sensors and the thermocouples, were transmitted to a data acquisition system, and they were converted to flow rate and steam with a correlation.

Shen (1999) presented a new concept for steam quality measurement that uses a transit-time ultrasonic meter. This method is based on a rigorous consideration of steam thermodynamic properties. It is shown that the speed of sound in steam depends on the steam quality at a given saturated temperature. As a result, the quality of the wet steam can be determined if the speed of sound is measured. This method is capable of achieving an accuracy of better than ±3% of the steam quality under conditions of a typical oil field steam injection. Neutron techniques are also established for measuring steam quality. They have been developed since 1965 (Sha and Bonilla, 1965) until 1995 (Hussein and Han, 1995).

2.2 Development of Neutron Technique

Transmitted thermal neutrons have been previously used to measure void fractions in steam-water flows (Sha and Bonilla, 1965). The beam of neutrons can be extracted from either a nuclear reactor or a bulky thermalization assembly containing an isotopic source. The problem is that it is difficult to have a compact or portable device. However, since fast neutrons can be produced from an inexpensive neutron source, efforts have been made to develop a fast neutron technique for void fraction measurements. The method is based on the fact that the liquid phase in a steam-water flow is a more effective neutron slowing-down material in the mixture. By utilizing a fast neutron source and measuring the thermal neutrons scattered by the mixture, an estimate of the amount of liquid present can be obtained, and, in turn, the void fraction can be deduced. (Rousseau *et al.*, 1976; Banerjee *et al.*, 1976; and Frazzoli *et al.*, 1978).

Neutron scatterometers have been studied so far both experimentally and theoretically. Hussein (1987) developed a nine-step design method by employing a simple analytical model to optimize the performance of the scatterometer. A collision probability model (CP model) is one of the analytical models, based on the theory of collision probability that is used to provide a preliminary design of scatterometer. The simplicity of this model enables designers to scan quickly energy range of the source. The other model is Monte Carlo simulation that can be used to verify the results of the CP model for different flow regimes. Also, an isotropic source of energy is evaluated as closely as possible to optimize the chosen energy. The center of mass in the Monte Carlo simulation can be employed to check the adequacy of the choice. The results from the nine-step design method agree with other work and experimental tests.

The design and testing aspects of a neutron scattering device for measuring steam quality in a large pipe (127 mm outside diameter) in a circulating fluidized bed plant were presented by Hussein and Waller (1990a-b). This device employs a californium-252 source and a thermal neutron detector that measures the flux of neutrons scattered from the pipe. The scatterometer was designed for a small diameter pipe (22 mm inside diameter) in the Thermo-Hydraulics Test Facility of Ecole Polytechnique de Montreal, which is a scaled down model of a typical heat-transport loop in a CANDU reactor. The performance of the device was determined by a Monte Carlo simulation. A ^{241}Am/Be source was selected and a ^{3}He detector was used to count the scattered thermal neutrons. The test section was enclosed within a cadmium sleeve in order to increase signal-to-background ratios. Cadmium sheets can minimize the number of thermal neutrons within the detection cavity. Results obtained in static experiments using lucite rods and in a dynamic air-water flow system showed good correspondence between the predicted liquid fraction and the reference liquid fraction (Waller and Hussein, 1990b).

A portable fast-neutron scattering device was developed for monitoring the void fraction in boiling water flowing through a metallic rod-bundle channel. Neutrons lose a significant amount of energy as they react with the hydrogen of water yet hardly lose any energy upon collision with the nuclei of the metals. However, the slowed-down neutrons can be absorbed by metal in significant proportions, as a result, the signal-to-background ratio is small. Thus, the system configuration has been designed to minimize the background signal and increase the scatterometer's contrast. The overall system configuration was designed by using a Monte Carlo simulation. The scatterometer performance was optimized by selecting a neutron energy source that results in a linear response and minimizes the flow regime dependence. The response of three independent methods; scatterometer, gamma-ray densitometer and flow meter, had the same trend (Hussein and Han, 1995). Also, these workers suggested a parameter, the contrast ratio, in order to improve the performance of the designed scatterometer. The contrast ratio (CR) is defined as:

$$CR = \frac{N(1)-N(0)}{N(0)} \tag{2.1}$$

where N(1) is the scatterometer count rate corresponding to a test section full of liquid and N(0) is the count rate for a test section void of liquid. If the contrast ratio is low, the count rate for the empty section or background count rate is large. This is because neutrons tend to bounce off the shielding walls, which are typically made of a hydrogenous material.

Recently, Hussein and Han (1995) measured void fractions in oil-water-gas flows. The transmission and scattering of fast neutrons are required to measure volume fractions of gases and ratios of oil to water, respectively. The discrimination between oil and water in scattering measurements was achieved by adding salt to water. Although oil and water have about the same ability to slow neutrons down, salt-carrying water is a stronger neutron absorber of slow neutrons than oil.

2.3 Neutron Scatterometer

A scatterometer consists of three components; a fast neutron source, a test section and a neutron detector; the detector is typically located perpendicular to both the incident beam and the test section. Two neutron detectors are recommended in order to minimize the flow-regime dependence, Banerjee (1976). A schematic diagram of a neutron scatterometer is shown in Figure 2.1.

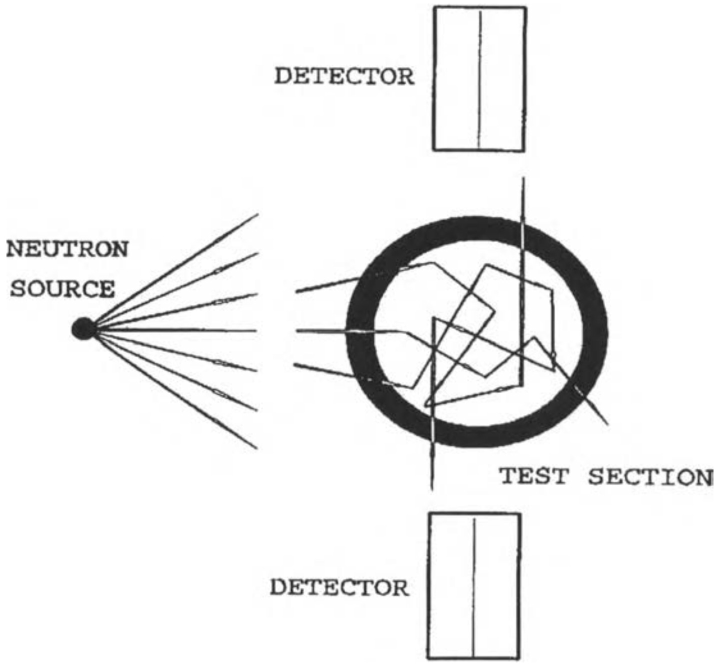

Figure 2.1 A schematic diagram of neutron scattering device with two detectors (Waller, 1990).

When a neutron collides with a proton (i.e., a hydrogen nucleus), the resulting elastic scattering can be treated as a "billiard ball" collision because the proton and the neutron have approximately the same mass. In this collision, the neutron loses, on average, half of its energy. After a sufficient number of collisions, the speed of the neutron is reduced to such an extent that it has approximately the same average kinetic energy as the atom of the scattering medium and reaches a thermal equilibrium state.

After colliding with a target nucleus of large mass, the neutron hardly loses any energy. Therefore, by measuring the amount of neutron slowing-down (thermalization), one can obtain an indication of the hydrogen content in the scattering medium. In boiling water, most slowing down neutrons would be caused by hydrogen in the liquid phase. The hydrogen content in the vapor phase is too small to cause significant slowing down and elastic scattering by the metallic container hardly affects the slowing-down process. Therefore, the technique of utilizing neutron scattering for void fraction measurements in water-vapor flow relies on measuring the slowing down of neutrons by the liquid phase.

The liquid fraction can be evaluated by the relationship:

$$\hat{\rho} = \frac{N(\rho)-N(0)}{N(1)-N(0)} \qquad (2.2)$$

where $\hat{\rho}$ is the estimated liquid fraction. $N(\rho)$, $N(1)$ and $N(0)$ are the scatterometer responses corresponding to respectively the test section with the actual liquid fraction, the test section full of liquid and test section full of vapor (Hussein, 1987). This relationship can be applied to test the linearity between the scatterometer response and the liquid fraction and to facilitate the calibration process. Also, as the void fraction increases the neutron count rate decreases, due to the diminishing liquid fraction. Best linearity can be achieved by matching a neutron source energy range to the pipe size (Hussein, 1987).

2.3.1 Neutron Source

Neutrons can be classified into four energy ranges: cold (10^{-4}-10^{-3}eV), thermal (0.025 eV at room temperature), epithermal (0.5eV to keV) and fast neutron (MeV). Neutrons can be generated in a nuclear reactor by spontaneous fission, (α, n) reactions, photo-neutron reactions and spallation by accelerated charged particles. Neutrons were previously extracted from research reactors because of their high neutron intensity; however, practical applications require a proper portable source. Some of the commercially available isotropic sources are shown in Table 2.1.

Table 2.1 Summary of commercial isotropic sources (Hussein, 1987)

	^{252}Cf	^{241}Am/Be	^{247}Am /Li	^{241}Am/B	^{239}Ra/Be
Neutron emission (neutrons per second)	$2.3\text{x}10^{6}$ /µg*	60/MBq	1/MBq	14/MBq	37/MBq
Half-life (year)	2.65	433	433	433	24000
Fractionof neutrons below 1.5 MeV	0.46	0.23	1.0	0.06	0.33
Mean energy of A)low energy component	-	400 keV	400 keV	-	375 keV
B)high energy component	2.3 Mev	4.5 MeV	-	3 MeV	5 MeV
Neutron dose rate at 1 m (per 10^{6} neutrons/second)	10	10	-	-	-
Gamma exposure rate at 1m (per 10^{6} neutrons/s, µG/h)	1	10	625	50	-

* Specific activity of ^{252}Cf: ~20 MBq/µg.

There are two procedures to determine a suitable neutron energy range. The first one was suggested by Yuen and Menely (1988), which employs the Monte Carlo model. However, this Monte Carlo code was expensive and time-consuming to execute. The second one was proposed by Hussein (1987), who developed a simple method to determine the source energy range. The method relied on Collision Probability (CP) theory, which was used to search the entire energy range by setting up an objective function which is the function for calculating the deviation of scatterometer's response from linearity. A pipe size and detector placement were considered. The source energy range was determined when the best value of objective function was obtained. Hussein and Waller (1990a) applied Center-Of-Mass (COM) Monte Carlo code that enabled to verify the results of the CP model in different flow regimes. The COM program can be employed to check the adequacy of the choice.

For the design example of 125-mm pipe, a 2 MeV source is required. As shown in Table 2.1, the isotropic source of average energy that matches the 2 MeV energy is the Californium-252. Despite its low half-life, this source has a low gamma-ray yield per neutron produced. This reduces the amount of material required for gamma ray shielding.

Modifying the source spectrum is a possibility for providing the required source energy. The basic concept of an energy filter is to use a hydrogenous material around the source to change its energy spectrum (Figure 2.2). This is by moderation of high-energy components, which gives greater weighting to low energy components. Also, the shape of a moderator is important in changing detector's responses (Knoll, 1989).

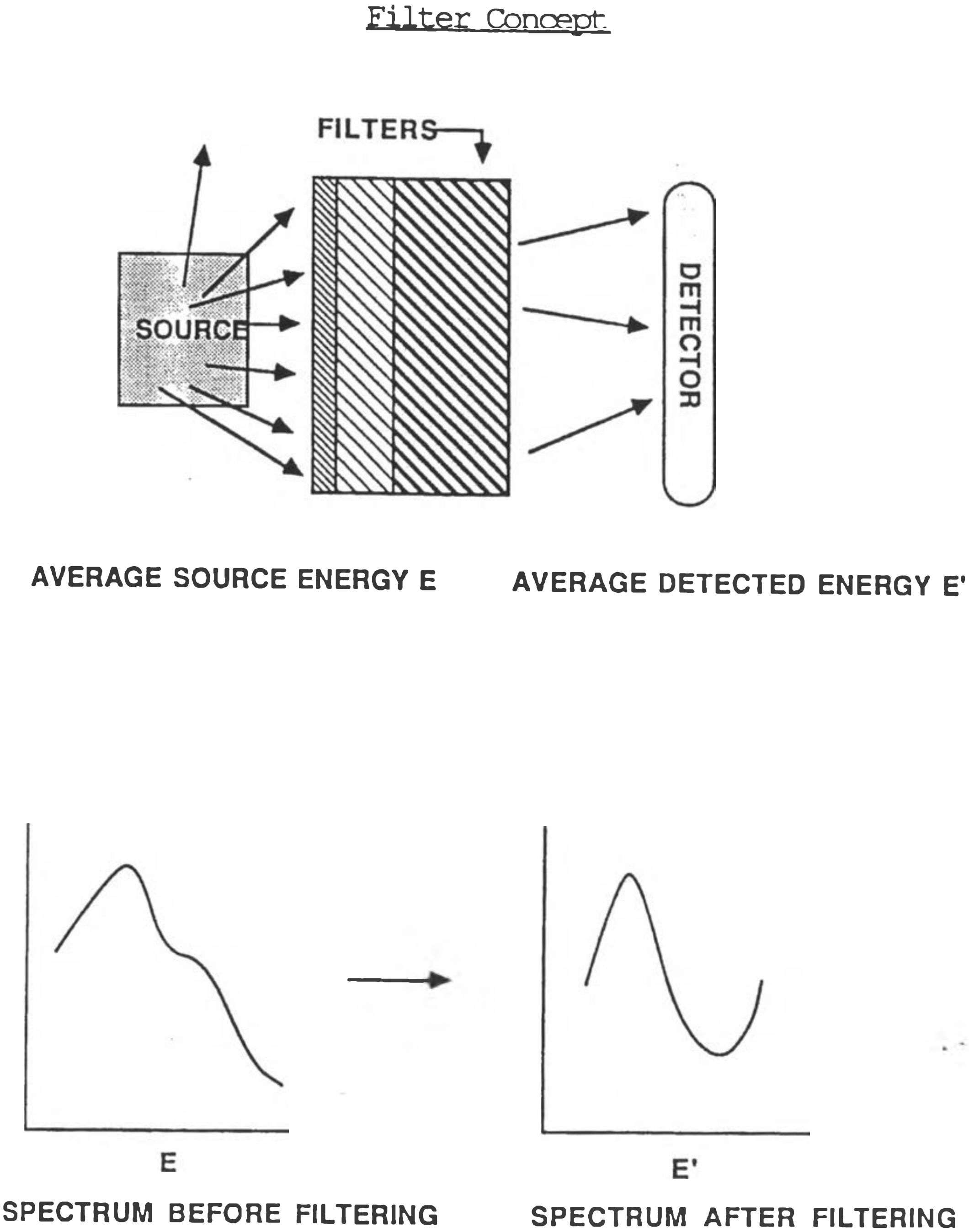

Figure 2.2 The filter concept (Waller, 1990).

2.3.2 Test Section

The geometry and size of the test section are also important factors in the design of a scatterometer. The larger the size, the higher is the source energy required for good linearity and minimum flow regime independent (Hussein, 1987). For a large test section, a low source energy will lead to a high concentration of neutron interactions in an area close to the source and most of the test section will not be involved in providing the signal. On the other hand, high-energy neutrons will pass through a small test section with minimal interaction resulting in a low slowing-down probability. Most previous work showed test sections with metallic walls. There is a significant probability of neutron interaction with metal in comparison with water at lower energy, which means that metals are not entirely transparent to neutrons.

Thick metallic wall absorption reduces intensities of both the incident neutrons and the out-going scattered neutrons. Yuen and Meneley (1988) found that, because of this effect, the void fraction tended to be overestimated when a thick iron wall replaced an aluminum wall.

2.3.3 Detector

There are two main types of detector for slow neutrons; helium (^{3}He) filled detectors and boron trifluoride (BF_3) detectors.

A ^{3}He detector has a higher thermal neutron cross section (5330 barns) for the ^{3}He (n, p) reaction when both thermal and epithermal neutrons are to be measured and when the count rate is an important factor (Knoll, 1989). Yuen and Meneley (1988) employed a ^{3}He detector to measure sub-cadmium neutrons (neutrons below the cadmium cut-off energy of 0.5 eV) by subtracting the measurements made with a detector wrapped with cadmium foil from detector measurements without cadmium.

BF_3 detectors were widely used in previous work for thermal neutron detection, based on the B (n, α) reaction for neutron detection (boron has a cross section of 3480 barns at thermal energy). The position of the detector in a scatterometer was considered not to be important because the thermal neutrons are isotropically scattered out of the test section. However, in the situation where there is much metal but little hydrogenous fluid, the location of the detector (detecting forward-side-or back-scattered neutrons) can affect the performance of the scatterometer (Hussein and Han, 1995). For small diameters, the effect of detector location is quite small (Waller, 1990).

The distances between a source and a test section and between a detector and a test section were found not to be important for a scatterometer (Yuen and Meneley, 1988 and Hussein, 1987). However, the distance can affect the count rate, but cannot affect strongly on variation in void fraction. Besides, it was found that the closer the detector to the test section, the lower the average energy of neutron needed to be incident upon the test section (Waller, 1990).

2.4 Thermodynamic Effect

Temperature and pressure may affect the performance of a scatterometer. An increase in temperature of the flow medium affects the flow density and then decreases the number of water nuclei per unit volume. This can reduce the probability of the slow-down neutrons. Also, temperature is defined for thermal energy of neutron as shown in equation (2.3):

$$E_{th} = kT \tag{2.3}$$

E_{th} is thermal energy of neutron, i.e., the energy at which neutrons reach equilibrium with the medium. T is the medium temperature and k is the Boltzmann's constant. As temperature increases, the thermal energy of neutron increases. Therefore, probability of neutron interaction with a nucleus or microscopic cross section decreases because microscopic cross section is inversely proportional to square root of the energy. Some experimental work reported that a counting rate decreased when temperature increased for the same void fraction (Yuen and Meneley, 1988). Waller (1990) indicated that there is an underestimated water fraction as temperature increased.

The pressure directly affects the fluid density and consequently the number of nuclei presents per unit volume. Roussean *et al.* (1976) indicated that pressure can affect slightly and can be ignored for pressure less than 5 MPa due to the vary small change on the density of liquid phase when pressure change.

2.5 Monte Carlo Method

The Monte Carlo method is a method of approximately solving mathematical and physical problems by the simulation of random quantities. In general, the simulation is performed on a digital computer because the number of trials necessary to describe the phenomenon adequately is usually quite large.

In particle transport, the Monte Carlo technique is a theoretical experiment. Each particle history involves the generation of a source particle, its random walk as its moves through and collides with the transporting medium and finally its termination by a given criterion. Probability distributions are randomly sampled using transport data to determine the outcome at each step of its life. Figure 2.8 represents the random history of a neutron incident on a slab of material that can undergo fission.

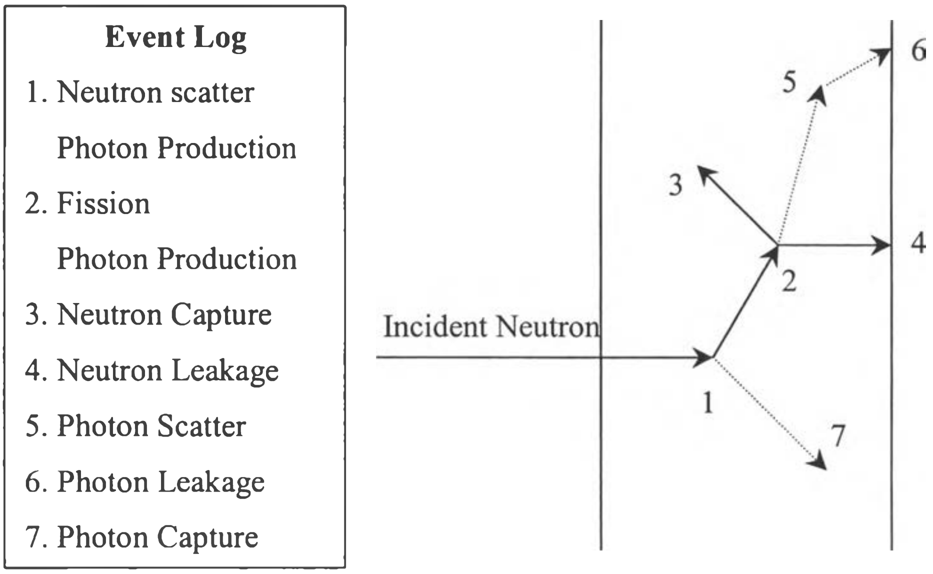

Figure 2.3 The history of neutron incident on a slab (Los Alamos National Laboratory, 2000).

In this particular example, a neutron collision occurs at event 1. The neutron is scattered in the direction shown, which is selected randomly from the physical scattering distribution. A photon is also produced and is temporarily stored, or banked, for later analysis. At event 2, fission occurs, resulting in the termination of the incoming neutron and the birth of two outgoing neutrons and one photon. One neutron and the photon are banked for later analysis. The first fission neutron is captured at event 3 and terminated. The banked neutron is now retrieved and, by random sampling, leaks out of the slab at event 4. The fission-produced photon has a collision at event 5 and leaks out at event 6. The remaining photon generated at event 1 is now followed with a capture at event 7. This neutron history is now complete. As more and more such histories are followed, the neutron and photon distributions become better known.

The quantities of interest, such as the response of designed detectors, are evaluated by employing suitable estimators to particle histories. All components, which are its source, test section, detector as well as shielding and configuration, can be defined in the simulation (Los Alamos National Laboratory, 2000).