EVALUATION OF THE METHODS OF MEASURING STEAM QUALITY FOR HEAVY OIL-FIELD APPLICATIONS

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الخلاصـــة :

إنّ عمليات انتاج الزيت الثقيل بمساعدة بخار الماء - تتطلب معرفة جودة البخار الذي يتـمّ حقنه في مكامن الزيت بدرجة دقيقة .

ويقـدِّم هذا البحث تقييماً شاملا للطرق التقليدية والحديثة المستخدمة في قياس جودة بخار الماء . وقد تبيَّـنَ أنَّ معظم طرق القياس التقليدية لا تصلح للاستخدام في عمليات انتاج الزيت الثقيل . كذلك تبيَّنَ أنَّه من بين الطرق الحديثة فإنَّ طرق القياس التي تعتمد على استخدام الاشعاعات النووية تُعتبر أفضل الطرق تحت ظروف تشغيل حقول الزيت الثقيل .

ABSTRACT

Experience with steam-assisted *in-situ* heavy oil recovery operations has demonstrated the need for accurate measurement of the quality of the steam injected into the oil formation. This paper presents a comprehensive evaluation of the conventional and newly developed methods of measuring steam quality. It is shown that most of the conventional methods have shortcomings which limit their applications in heavy oil field operations. Newly developed methods employing nuclear radiation–interaction techniques provide non-intrusive on-line measurement of steam quality under most practical operating conditions. These methods are probably the best available methods for heavy oil field applications.

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1. INTRODUCTION

Most steam-assisted *in-situ* heavy oil recovery operations require the injection of high-pressure wet steam into the reservoir in order to heat up the oil-bearing formation. This reduces the viscosity of the oil, which can then be recovered.

Evaluation and prediction of reservoir and well performance for such operations depend largely on accurate knowledge of the amount of heat injected into the formation. This requires knowledge of the mass flow rate, pressure, and quality of the injected steam. Unfortunately, the steam quality at the individual injection wells is normally unknown. In such oil fields, steam is usually generated in a central plant and is fed into a network of distribution lines of different sizes leading to individual satellites. At each satellite, steam is further split and distributed to the various injection wells. Splitting of wet steam in such a manner results in uneven distribution of the water and vapor phases in the various branches of the distribution network. This uneven distribution of the phases, and the heat losses from the piping system, result in unknown quality at each injection well. A measurement of steam quality at each individual well is, therefore, required.

Several methods exist for measuring steam quality. The analytical and calorimetric methods have been in use in several applications for a long time. Other methods based on the characteristics of flow through restrictions, such as orifices, have been proposed but have seen limited application. All these methods were developed to provide a direct calculation of quality from the measured parameters. These methods are classified in this paper as "conventional methods". Still other methods based on measuring the two-phase flow void fraction and using a void fraction–quality correlation for quality calculation have also been developed. Such methods have been in use for some time in the nuclear industry and have recently been employed in the oil industry. These methods are classified here as "non-conventional methods".

In the following sections, the available conventional and non-conventional methods of measuring steam quality are described and evaluated with regard to their limitations and applicability to heavy oil-field operations.

2. CONVENTIONAL METHODS OF MEASURING STEAM QUALITY

2.1. Analytical Methods

Although the analytical methods are strictly useful for quality measurement at steam generators outlets, they are discussed here since such measurements are also required for heavy oil-field operations.

During the steam generation process, the dissolved solids in the feedwater are concentrated in the effluent water (the water in the discharged wet steam) due to the evaporation process in the generator. The most commonly used methods involve measurements of either the conductivity, or alkalinity, or a special ion (normally Na^+ or Cl^-) concentration of samples of the feedwater and the effluent water. The steam quality X is calculated from the relation:

$$X = 1 - (C_f/C_e) \qquad (1)$$

where C is the measured conductivity, or alkalinity, or ion concentration of the water sample; and f and e refer to the feedwater and effluent water respectively.

Analytical methods are used in most steam generation plants because they yield fairly accurate results. However, there are several problems associated with them which are discussed below:

1. A general, and quite serious, problem associated with all analytical methods is the obtaining of a representative sample of the effluent water. To obtain a sample of the effluent water, a steam sample is taken off the generator discharge end and fed into a separator or a trap to separate the water phase from the vapor phase. The separated water is then drawn through a condenser to avoid flashing. It is quite difficult to obtain a representative sample of a wet steam especially if the flow is not homogeneous. Certain standards exist for sampling wet steam; these, however, require the installation of a flow homogenizer upstream of the sampling point causing unfavorable pressure drops.

   Drawing the water sample through the condenser represents another problem and requires extreme care and experience. Drawing the sample off too quickly may result in drawing and condensing some of the vapor which subsequently dilutes the

water and results in lower than actual quality measurements.

2. The analytical methods assume that the dissolved solids in the feedwater are concentrated only by evaporation of the water as it passes through the generator. This, however, is not normally the case. The effluent water phase would usually contain carbonate and hydroxyl ions which are produced by the thermal decomposition of bicarbonate ions in the feedwater. The hydroxyl ions in the effluent water would then yield a conductivity that is out of proportion to the concentration of dissolved solids resulting in higher than actual quality measurements. This, however, can be avoided by neutralizing both the feed and effluent samples to a pH of seven with a weak acid.
3. Another problem with analytical methods results from the deposition of some of the dissolved solids in the feedwater as it flows through the generator. The reduction in the dissolved solid concentration results in a calculated quality that is lower than the actual. This problem, however, can be avoided by dealing with a special ion that does not precipitate under the existing operating conditions.
4. The fact that conductivity is a strong function of temperature presents another problem in using these methods for measuring quality. This problem, however, can be avoided if the conductivity of both the feed and effluent samples is measured at the same temperature. Most conductivity measuring devices utilize some temperature-correction factors to correct conductivity measurements to a common temperature base; these factors, however, have proven to be far from accurate especially with high-salinity water, which is the case for most heavy oil-field applications.
5. Finally, analytical methods are generally slow and require complicated chemical analyses.

The analytical methods are only applicable for quality measurements at steam generators outlets and cannot be used to measure steam quality in distribution and injection lines. It is believed that, among the various analytical methods, the most accurate results can be achieved by comparing the Na or Cl ion concentrations in the feed and effluent waters, provided that the effluent water sample is collected properly.

2.2. Calorimetric Methods

Unlike analytical methods, calorimetric methods are not restricted to quality measurements at steam generator outlets. The throttling and condensing calorimeters have been in use for many years; a separating–throttling calorimeter has recently been developed by Hodgkinson and Hugli [1]. These methods are discussed and evaluated below:

2.2.1. The Throttling Calorimeter Method

The throttling process is simply an adiabatic expansion of a fluid with no work done by the fluid. The throttling calorimeter utilizes this process. A sample of the wet steam is adiabatically expanded down to a low pressure (normally atmospheric pressure) to bring it to the superheated state where only pressure and temperature measurements are required to determine the enthalpy of the steam. This, together with the knowledge of the wet steam pressure (or temperature) allows the steam quality to be calculated as follows:

$$X = (h - h_f)/h_g \qquad (2)$$

where, h is the steam enthalpy as determined from the pressure and temperature of the expanded superheated steam, and h_f and h_g are respectively the enthalpy of saturated water and the latent heat of vaporization corresponding to the wet steam pressure.

As for analytical methods, the throttling calorimeter method has the same problem of obtaining a representative sample of the wet steam. However, this method is much faster and more convenient than the analytical methods since it only involves pressure and temperature measurements. In addition to the sampling problem, two other problems exist which make the method inapplicable under most oil-field operating conditions:

1. As the steam used in oil fields is typically of high pressure and relatively low quality (about 80%), it will not reach the superheated state after the throttling process. The final steam enthalpy h remains, therefore, unknown and Equation (2) cannot be used to determine the steam quality.
2. In most oil-field operations, steam is generated from a high salinity water; the dissolved solids in the feedwater will vary in concentration from time to time and so would the values of h_f and h_g which will make it impractical to employ the method even if the steam pressure and quality are of the right order to produce superheated steam upon throttling.

2.2.2. The Condensing Calorimeter Method

In this method, a sample of the steam is drawn off the steam line and is condensed in a properly equipped and insulated condenser. Measurements of the flow rate of the condensing medium (normally cold water), its initial and final temperatures, and the flow rate of the steam sample and the state of the condensate allow calculation of the enthalpy of the wet steam which in turn allows the calculation of steam quality. Although the method is simple in principle, it is a very slow process and requires a fair amount of measurement and careful calculations of heat losses. It has the same sampling problem as with the previous methods and its accuracy is questionable when used with steam produced from a varying high-salinity water.

2.2.3. The Separation–Throttling Method

Hodgkinson and Hugli [1] proposed a method for measuring steam quality under oil-field operating conditions. The method is basically an improvement over the throttling method. It consists of passing the wet steam sample first through a separator where a large amount of its water content is removed and measured. The dryer (higher quality) steam is throttled to atmospheric pressure to reach the superheated state where its pressure and temperature are measured. This allows the calculation of the quality of the steam at the outlet of the separator which, together with the measurement of the amount of water collected from the separator, can be used to calculate the quality of the original wet steam. The method has been tested in the field for a steam pressure of 600 psi and steam quality of 20% to 80%. The authors claim that the maximum absolute error associated with this method were 7% when compared to the titration measurements (analytical method). The results reported by the authors, however, show errors of up to 28%.

The method, though simple, involves a number of pressure, temperature, and flow rate measurements, and somewhat lengthy calculations. This makes the method very time consuming and limits its practical applications, especially when a large number of quality measurements is required at various locations throughout the field.

In addition to the previously discussed problems associated with sampling and steam produced from water of varying high salinity, this method is pressure limited. For pressures of 1600 psi or more, the method is not applicable as the steam would never reach the superheated state upon throttling even if all the water content were separated.

2.3. Methods Employing Flow Through Nozzles or Orifices

A method that is independent of the feedwater salinity, can be used at generator outlets or anywhere in the distribution network, and is not limited by steam pressure has been proposed by Wilson [2]. The method consists of forcing the steam (or a sample of the steam) to flow through a nozzle or an orifice. Measurements of the absolute steam pressure and the pressure drop across the nozzle (or orifice) together with an independent measurement of the steam flow rate allow the calculation of steam quality from the relation:

$$X = \left[\left(\frac{CH_w}{m^2} - V_f\right)/(V_g - V_f)^{2/3}\right]$$

where

C = the nozzle or orifice flow coefficient
H_w = the pressure drop across the orifice or nozzle in inches of water
m = steam mass flow rate in $\mathrm{lb\,h^{-1}}$.
V_g = specific volume of the vapour phase, $\mathrm{ft^3\,lb^{-1}}$.
V_f = specific volume of the saturated water phase, $\mathrm{ft^3\,lb^{-1}}$.

Wilson has field-tested this method and reported an accuracy of ±5% when compared to the analytical methods. The above method, though superior to all previously discussed methods as far as heavy oil-field applications are concerned is subject to the following limitations:

1. The method depends on measuring the total mass flow rate of the steam. This can be obtained accurately for once-through steam generator applications by measuring the feedwater mass flow rate which is the same as that of the effluent steam. For quality determination in distribution and injection lines, however, an independent measurement of the mass flow rate of the wet steam that flows through the nozzle (or orifice) is required. This presents a major problem as the existing flow meters are far from being accurate; they require frequent calibration under different operating conditions, and their outputs are largely affected by the two-phase flow pattern and quality.
2. The second limitation arises from the fact that when wet steam flows through an orifice or nozzle

meter, the recorded differential pressure exhibits short term fluctuations which are often a large percentage of the full-scale deflections.

3. Unless a sample of the steam is drawn off the main steam line for the measurements (which again brings the sampling problem), forcing the whole steam to flow through the meter would result in unfavorable pressure drops.

Another method that has been under consideration utilizes the fact that when a mixture of steam and water (*i.e.* wet steam) is expanded in a sonic nozzle it has a critical velocity which is a function of its quality. The calculations, however, show that this critical velocity is not a strong function of quality and, therefore, is relatively insensitive to small changes in quality. This method is not, therefore, discussed any further.

In 1980, a meter was developed by Rhodes and Scott [3] for measuring steam quality and flowrate. The meter consists of a twisted tape swirl generator immediately upstream of a Herschel-type venturi meter. The meter is placed horizontally along the steam line. The swirl generator redistributes the water phase to form annular flow to enhance the accuracy of the venturi meter. The method involves measurements of the frictional pressure drop across the swirl generator, the accelerational pressure drop across the venturi and the total line pressure downstream of the venturi. The mass flowrate and quality are then calculated through an iterative program.

Although this method appears to be simple and suitable for measurements in distribution lines, it may introduce undesired pressure drops throughout the system.

2.4. Summary: Conventional Methods

The above-discussed methods appear to be either not applicable to, or have limited application under heavy oil-fields operating conditions. These methods possess one or more of the following shortcomings:

1. The method is not applicable for the whole system (generators and distribution lines).
2. The method is not applicable to all practical ranges of steam pressure and quality.
3. The method requires sampling of steam off the main line.
4. The method is intrusive and disturbs the flow of steam.
5. The method requires analytical analysis or iterative calculations.
6. The device is not portable.
7. The method is sensitive to changes in water salinity.

3. NON-CONVENTIONAL METHODS OF MEASURING STEAM QUALITY

Several investigators proposed new non-intrusive methods for measuring steam quality. All of the methods developed relied on measuring the void fraction and calculating the quality using a void fraction–quality correlation. The void fraction is defined as the volume fraction of the gas phase in a two-phase mixture.

Several methods exist for measuring void fraction. However, only the non-intrusive methods applicable to steam–water mixture will be discussed.

3.1. The Conductivity Method

For two-phase mixtures with only one of the two phases being electrically conductive (such as water–steam and water–air mixtures), a method has been developed for determining the void fraction by measuring the conductivity of the mixture. A variety of conductivity probes have been developed for such measurements; the most recent one is an electrodeless conductivity monitor which has the advantage, over other probes, of eliminating direct contact between the conducting fluid and the sensor.

The electrodeless conductivity measurement utilizes the ability of an electric current to induce a magnetic field, and the complementary ability of a changing magnetic field to induce a current. A monitor manufactured by Auburn International, Inc. (Model 1084) is typical of such a device. It consists, as shown in Figure 1, of two toroidally-wound coils which are placed around the flow pipe. The two coils are shielded from each other such that the only coupling between them is provided by the conductive fluid flowing through the pipe. An AC current is applied to the drive coil to induce a magnetic field which causes a current to flow through the flowing fluid. This current is directly proportional to the conductivity of the flowing mixture. The magnetic field associated with this current induces a voltage in the windings of the pick-up coil, which is also directly proportional to the conductivity of the two-phase mixture. As the conductivity of the mixture is directly related to the

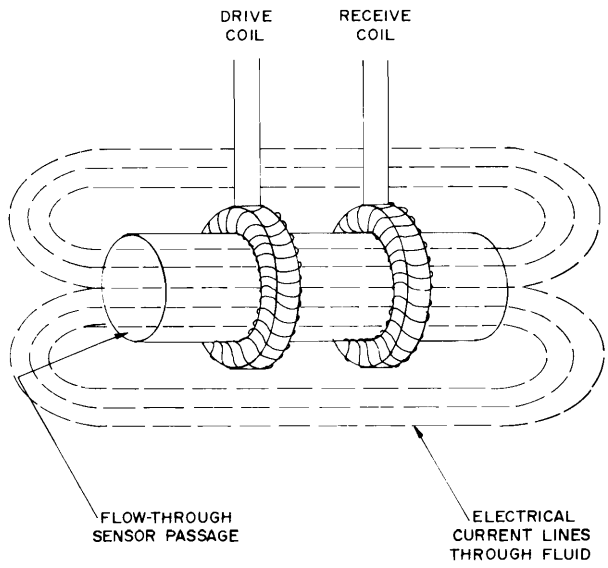

Figure 1. Basic Electrodeless Conductivity Sensor Design.

volume fraction of the conductive phase, the picked up voltage signal is used as a measure of this volume fraction.

The existing device is rated for pressures and temperatures lower than those experienced in heavy oil-field operations. A proper change in the design of the device, however, can probably make such applications possible. Another limitation is that the method utilizes the conductivity of the two-phase mixture as a measure of its water (conductive phase) volume fraction. This implies that the conductivity of the water in the mixture is constant. This, however, is not the case under normal operating conditions. Water conductivity is a function of temperature and salinity. Correction factors could be used to compensate for temperature dependence; such factors, however, have proven to be inaccurate especially for high-salinity water. The salinity dependence represents a real problem in applying this method in the field. Experience with heavy oil-field operations has shown changes in water salinity by as much as four orders of magnitude. These large changes in water salinity will result in totally meaningless measurements. Of course, the method will work if a reference water sample that is representative of the water in the mixture at the time of the measurement (same salinity and, perhaps, temperature) were available. This is obviously very difficult if not completely impractical to obtain. Furthermore, the method requires the installation of static flow mixers upstream of the measuring device. This, in addition to the extra costs involved, produces unfavorable pressure drops and might change the void fraction downstream of the mixers.

3.2. The Capacitance Method

Another method for measuring void fraction is based on measuring the capacitance across the flow pipe. The method has been shown to be dependent on the phase distribution in the pipe, and hence requires flow mixing prior to taking the measurements. The method has all of the limitations associated with the conductivity method; therefore, it is not considered any further here.

3.3. Radiation Attenuation Methods

Over the past two decades, experimental techniques for studying two-phase void fraction and void distribution, based upon the use of nuclear radiation, have been developed and extensively used in laboratory experiments.

The extensive research work has led to the development of new void fraction (or quality) meters based on photon-beam attenuation and neutron interaction. These are briefly described and evaluated below.

3.3.1. Photon-Beam Attenuation Method

Photon-beam attenuation is, in principle, a very simple technique for measuring void fraction. A source of radiation is collimated to produce a unidirectional photon flux which is made incident normal upon a section of the flow pipe. The beam is attenuated first by the pipe wall, then by the two-phase mixture, and finally by the opposite pipe wall. The emergent beam passes through additional collimators and is then measured by an appropriate detector. The monoenergetic collimated beam of photons is exponentially attenuated when it passes through a homogeneous material; therefore, the intensity of the beam at the detector is related to the intensity of the incident beam, and the composition of the two-phase mixture in the pipe. The void fraction can be determined from the measured photon-beam intensities.

Measurement of the void fraction by this method is, in general, affected by several factors such as the void distribution, the photon-beam collimation, the photon energy, the detector system, and the type and

characteristics of the photon source. Detailed discussions of the effect of these factors can be found in references [4–9].

Several types of meters based on this technique and using gamma radiation have been developed and extensively used in various applications specifically those related to nuclear safety. The most common of these meters is the three-beam gamma densitometer developed at the Atomic Energy of Canada Limited (AECL). As illustrated in Figure 2, the device consists of a 25-curie cesium-137 source from which three collimated beams of gamma rays are made incident at a section of the flow pipe. The transmitted beams are collimated and their intensities are measured by three detectors as shown in the Figure. Since the attenuation of the beams depends on the phase distribution, the intensities of the three transmitted beams are used to predict the flow pattern as well as the cross sectional average density (in other words, the void fraction).

This densitometer has been tested only on relatively small pipes and for steam qualities less than 50%. To examine the feasibility of employing this meter in the higher range of quality, experiments were conducted by the author and the results showed that the method is insensitive to changes in quality of up to 5% in the high quality range (50% or more). This is basically because gamma-rays are more attenuated by the pipe material than by the fluid within the pipe. While the use of a very strong source might help in improving the sensitivity, shielding and safety problems become unaffordable. The conclusion was that the gamma densitometer, a successful means of measuring void fraction in the low quality range and for small pipes, is not suitable for heavy oil-field applications. Another important conclusion was that the key to obtaining good sensitivity for the measurements is to use radiations which are less affected by the pipe wall materials than by the fluid within the pipe. This has led to the consideration of neutron attenuation and the development of a new meter.

3.3.2. Neutron Attenuation Methods

Neutron beams are fundamentally more attractive than gamma or beta beams for void fraction measurements in flows containing hydrogenous materials, *e.g.* steam-water flows. This is because neutrons are

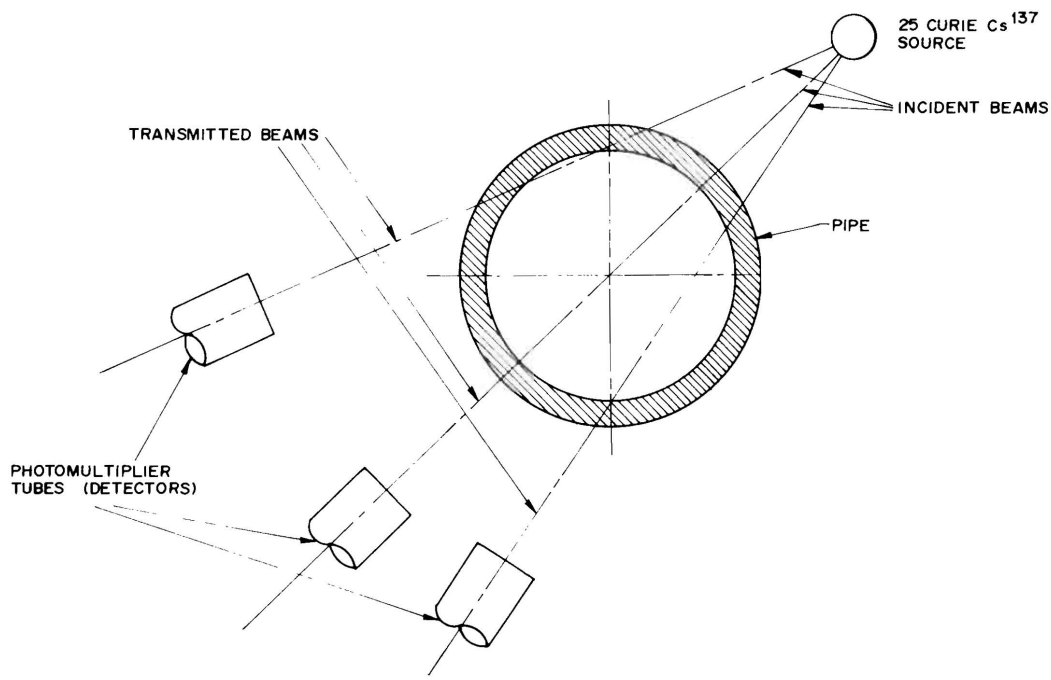

Figure 2. Gamma Densitometer.

less affected than gamma and beta rays by the metal walls containing the flow and more affected by the hydrogenous materials comprising the flow. Neutron beams, however, have not been used successfully till recently for measuring void fraction in systems of practical sizes and shapes. Thermal (slow) neutrons have been generally used but they are absorbed strongly by the hydrogenous materials resulting in poor counting statistics. Recently, preliminary investigations using fast neutron beams have been conducted by several investigators [10–15]. Two neutron attenuation techniques have been investigated and led to the development of two new meters as discussed below.

3.3.2.1. Method Based on Neutron Scattering Technique [16]. The process of slowing down (thermalization) of fast or epithermal neutrons occurs primarily due to the elastic scattering of the neutrons by the various nuclei in the scattering medium. The hydrogen nucleus is exceptional, in two ways, with regard to scattering neutrons. Hydrogen is the most effective element for slowing down fast and epithermal neutrons as it causes the incident neutron to suffer the largest energy loss per collision compared to any other element. In addition, the scattering angle cannot exceed 90°, *i.e.*, no back scattering of neutrons occurs from hydrogen nuclei. Several collisions are required to downscatter the neutrons into the thermal region. Therefore, when a fast/epithermal neutron beam of uniform intensity is made incident at a section of a pipe containing a two-phase mixture of hydrogenous material, the scattered thermal neutrons would not convey information regarding the position of the hydrogenous material. Thus the scattered thermal flux would, to a first approximation, depend on the mass of the hydrogenous material and not on its distribution.

Because neutron thermalization theory involves complex interactions, the mathematical treatment of this technique is difficult. Thus, the adopted approach was to develop standard calibration curves by passing fast neutron beams through samples of known hydrogenous material content.

Aggour and Banerjee [16] developed a new meter based on this fast neutron-scattering technique. Laboratory experiments were performed on simulated two-phase mixtures using lucite and air. Lucite was used because it has the same neutron thermalization properties of water. The experiments aimed at determining the type and strength of the neutron source, and the type and geometry of the thermal neutron detector to provide linear relationships between the void fraction and thermal neutron counts for various pipe sizes.

A full scale test facility was then built in the field to further test and develop the method. The tests covered pipe sizes ranging from 2 in, to 8 in, steam pressure up to 16 MPa and steam qualities up to 92%. Steam quality was measured using titration methods and correlations were obtained between quality and neutron count rate. Further, a correlation was developed between quality and void fraction.

The research and development work led to the construction of a prototype steam quality meter. Figure 3 shows schematic of the measurement set-up. It

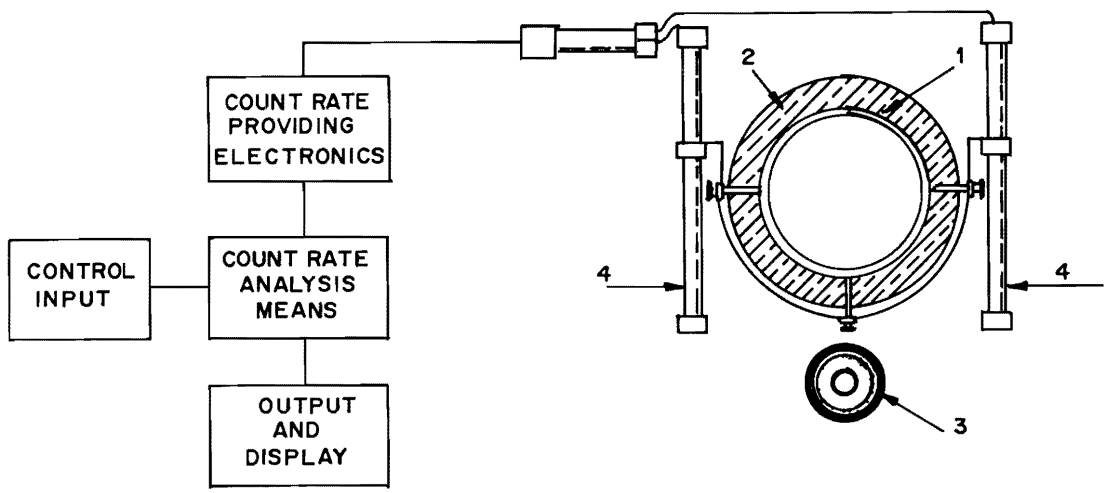

Figure 3. Schematic of the Measurement Set-up Developed by Aggour et al. *[16]. (1) Steam Pipe; (2) Thermal Insulation; (3) Moderated Neutron Source; (4) Thermal-Neutron Detectors.*

consists mainly of a moderated ^{252}Cf neutron source, two ^{3}He detectors and associated electronics for measurement and processing. The ^{3}He detectors are used to measure the scattered thermal neutrons which could be used to determine either the void fraction, or the quality. In addition to the thermal neutron measurement, the method requires only the knowledge of the steam pressure and pipe size. The instrument has built in correlations and calibration curves to provide direct reading of quality within a few minutes. Three meters have been used in field operations for over five years, providing quality measurements with errors of ±3%. The cost of these first prototype meters was relatively high. However, it is believed that a typical meter may cost about US$10 000. This new instrument does not have any of the shortcomings discussed in Section 2.4, and has the following advantages:

1. It provides non-intrusive on-line measurement of quality and void fraction.
2. It is portable so one unit could be used for measurement at several locations in the field.
3. It can be used anywhere in the steam generation and distribution system.
4. It works for all practical ranges of steam pressure and quality, and of pipe sizes.
5. It is independent to a large extent of the water salinity.
6. It could operate unattended thus reducing field manpower requirements.
7. The instrument uses a small well-shielded neutron source which makes it safe to operate.

3.3.2.2. Method Based on Neutron Transmission Technique [17]. In this technique, a collimated fast/epithermal neutron beam is made incident on one side of the pipe carrying the two-phase flow, and the transmitted flux is counted by a detector placed at the opposite side of the detector's collimation zone.

A method has been developed by Yuen *et al.* [17] based on thermal/epithermal neutron transmission. A collimated beam of the neutron is transmitted through the pipe carrying the wet steam, and a detector on the opposite side of the pipe measures the transmitted thermal/epithermal neutrons and generates a signal indicative of the wet steam density. The void fraction is calculated from the measured density and the quality is then calculated using a quality-void fraction correlation based on the slip-flow model using a proper value for the slip velocity.

This method has not been tested as extensively as the method of Aggour *et al.* However, it is expected that it would work satisfactorily. While this method has most of the advantages associated with the first method, it is limited to application in pipe sizes with diameter less than 5 cm, and most probably to only high qualities. For larger pipes or lower qualities the absorption of thermal neutrons by the water would be very high, reducing the transmitted neutron flux and, thus, affecting the accuracy of the measurements.

CONCLUSIONS

1. For steam-assisted *in-situ* heavy oil recovery operations, measurement of the steam quality at injection wells is essential for the evaluation of well and reservoir performance.
2. All available conventional methods of measuring steam quality have shortcomings which make them either of limited application or inapplicable to heavy oil-field operating conditions.
3. The method proposed by Yuen *et al.* [17] provides non-intrusive on-line measurement of steam quality, but it is limited in application to small pipe sizes and high steam quality.
4. The method developed by Aggour and Banerjee [16] which is based on neutron scattering provides portable, non-intrusive on-line measurement of steam quality under all practical field operating conditions. The method has been successfully tested in the field and is, therefore, recommended for field operations.

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