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The Dielectric Steam Quality Sensor, Laboratory Development and Field Evaluation

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Abstract

The newly developed Dielectric Steam Quality Sensor (DSQS) utilizes a unique approach to measuring steam quality. The DSQS actually measures the electrical impedance of the wet steam in an annular cross section between the sensor's electrode and housing. Based on the sensor's dimensions, geometrical cell constants relate the measured impedance of the steam to the dielectric constant and resistivity of the two phase medium. The documented electrical properties of water and vapor, established mixing laws, and the measured impedance are correlated with the liquid volume fraction. The more common "Steam Quality" expression is then computed using specific volumes of the phases at saturation conditions.

The DSQS was developed specifically for use in oil industry thermal recovery steam distribution systems. Application points include steam generator discharge, injector wellhead, steam headers, and other selected locations in the piping network. Direct use of the DSQS technology is also anticipated in geothermal industry steam collection systems.

This paper presents the theory of operation, the mechanical design, associated instrumentation and results of extensive testing. Laboratory testing conducted in Texaco's Steamflow Research Facility, provided guidance on the optimal mechanical design and demonstrated the concept of relating measured impedance to steam quality. Early field testing was accomplished in the Kern River Field to verify performance in oil field operating conditions. These tests showed the effect of saline field water on the DSQS system and provided the data necessary to development the methodology to incorporate various water resistivities into the impedance measurement. A further evaluation the DSQS system with a broader and more extensive test program was conducted where results were compared to concurrent measurements obtained using portable separator test units. The tests, conducted in various San Joaquin Valley oilfields, document the performance of the DSQS over a broad range of stable and unstable operating conditions.

Introduction

Enhanced Oil Recovery (EOR) operations are increasing the use of steam flooding to improve production rates and overall recovery in heavy oil reservoirs. Although the injection of "dry" or super-heated steam would transfer more heat into the reservoir, operating costs and practical limitations result in the injection of lower quality steam, usually 80% and below. To optimize the effectiveness of the steam flood and to model the steam flood movement, it is important to accurately know the mass rate and quality of the steam being supplied to each injector well.

One can calculate steam quality at the exit of a generator based on consumed fuel, feedwater rate, and associated generator factors. However, as the steam flows through long pipelines and becomes divided into multiple lines, the steam quality at any given point becomes unknown and varies throughout the distribution system. This is due primarily to the fact that "wet" steam is made of two phases, steam vapor and hot water. As the two-phase steam divides at tees or manifolds the proportional mass of the liquid to vapor is not maintained in the outlets. This phenomenon is known as phase splitting and has been the subject of many research studies.

Field personnel will often connect a trailer mounted apparatus to the steam line feeding an injector to measure the steam quality at the well-head. The apparatus on the trailer separates the two phases using settling tanks and demisters. Single phase vapor and liquid measurements are then used to calculate steam quality. While this method is accurate, it is time consuming to produce the final measurement and requires the service of skilled personnel. In addition, a trailer-mounted device is quite expensive and alone could not provide a "snapshot" of all the wells in the entire field.

A less expensive approach of monitoring each injector is the Orifice-Choke Steam Flow Measurement System[6] which simultaneously solves the two-phase orifice and choke equations for both mass rate and quality. While this approach is very attractive and practical for fields already using chokes at the well-head for rate control, applications without existing chokes usually can not accept the substantial pressure drop associated with the addition of such a device. Also, to measure the quality upstream in the distribution system which may be feeding several injectors, installation of a choke would not be feasible.

Texaco developed the Dielectric Steam Quality Sensor (DSQS) to economically measure steam quality in distribution lines without any substantial pressure loss. The device which senses the electrical impedance of the flow stream is designed to measure steam qualities ranging from 20-80% while producing only a minimum pressure drop. This sensor also has the advantage of providing measurements in the low quality range where other devices typically become less accurate. By tailoring the electrode configuration and with effective flow mixing, both the upper and lower limits can be expanded for specific applications.

Sensor Description

Mechanical Design. During the development of the DSQS, several designs of the sensor were constructed and tested. Figure 1 shows a schematic of the sensor design used in the joint evaluation with California Steam Service (CSS). Although there have been several variations, this schematic represents the general configuration of all the models. The sensing region of the device consists of two electrodes arranged in a coaxial configuration with the steam flowing through the annular cross-section between the electrodes. As shown in the figure, the sensor housing serves as the outer electrode in addition to confining the steam at the high operating pressures. The ceramic pieces support and electrically isolate the inner electrode from the case and distribution line. The two small diameter rods provide the electrical connection from the inner electrode to the electrical bulkhead. A coaxial cable connects the sensor body to the instrumentation which is contained in a separate enclosure mounted directly on the outside of the housing. The 1000 psig pressure rating of the sensor and the two inch ANSI 600# flanges on the inlet and outlet provide easy installation into most distribution lines for a full-stream measurement.

The design variations of the DSQS have addressed two primary concerns of the sensor, its mechanical integrity and the sensitivity of the impedance response to variations in steam qualities. Mechanical enhancements were related to improvements in the seals, survivability of the ceramic spacers and the dynamics of the flow through the sensor. Optimization of the sensor response was accomplished by adjusting the electrode length and the annular gap between the electrode and the housing.

Instrumentation. The DSQS instrumentation consists of an impedance measurement board and a microcontroller with additional inputs for line pressure and differential pressure flow sensors. The impedance board drives the DSQS probe at 6 MHz while measuring the resulting current and voltage along with the phase angle between them. The ratio of the measured voltage and current multiplied by a scaling factor gives the impedance magnitude of the steam filled sensor. The associated phase angle of the impedance is obtained by multiplying the measured phase signal times a scaling factor and subtracting a known offset. All three measurements are presented as a 0-5 volt signals to a Brute-52 microcontroller for continuous monitoring and real time calculation of steam quality.

The Brute-52 microcontroller, configured in a 3.5"x3.5" single board, is based on a CMOS version of Intel 80C52 microprocessor with an internal BASIC interpreter. The Brute 52 has eight 12-bit analog to digital inputs and two 12-bit digital to analog outputs. This microcontroller acquires the raw data, performs data averaging and stores the averages based on user selected times intervals. When configured for 15 minute averaging, the system can store 21 days of measurements before the oldest values are overwritten. This time period can easily be extended by increasing the data averaging interval. After completion of the monitoring period, an operator uses a portable or laptop PC to upload the stored data through an RS-232 communication port. The uploaded data file can then be imported into any standard spreadsheet for further analysis and documentation.

In addition to the storage capability, the Brute 52 through user programmed equations also provides calculations of steam quality for real-time display and analog output. One pressure or temperature measurement of the flow is required to determine the steam properties for use in the impedance interpretation equations. If available, one differential pressure across an orifice can be recorded and used with the calculated quality to also provide mass flow rate.

Theory of Operation

Impedance Measurements. As the "wet" steam flows through the annular cross-section between the electrodes, the DSQS measures the electrical impedance of the steam which varies as the percent water changes. The measured impedance, Z, is a mathematically complex quantity consisting of a magnitude, $\overline{Z}$, and a phase angle, θ, which can be expressed as:

$$Z = \overline{Z}\,(\cos\theta + j\sin\theta) \qquad (1)$$

In rectangular coordinates Equation 1 can be written as:

$$Z = R - \frac{j}{2\pi f C} \qquad (2)$$

where j is the imaginary unit, f is the measurement frequency, and R and C are the resistance and capacitance between the electrodes.

If the flow sensing area were a physically small capacitor or resistor connected to the electronics with a lossless cable, minimal consideration would have to be given to calibration or sensor corrections. However, the impedance of the cable and the residual impedances in the sensor make compensation necessary. These undesired effects can be modeled with the "T" network shown in Figure 2 where Z represents the measured impedance and S the actual sample impedance. The combined effect of the cable and residual impedances, represented by A, B and C, in the "T" section can be eliminated through the application of circuit theory and the measurement of three known samples. The samples or calibration standards which have been used to compensate the DSQS units are a saturated brine solution, air and toluene. These samples were selected based on their availability and known electrical properties.

The resistance and capacitance obtained from the measured impedance are related directly to the two electrical properties of the flowing mixture, the resistivity and dielectric constant, through geometrical cell constants. The cell constants are functions of the electrode configuration and spacing but will remain constant for a specific cell design. The relationship between the resistivity, ρ, and resistance, R, and between the dielectric constant, K, and capacitance, C, are given below:

$$\rho = g_r R \qquad (3)$$

$$K = g_c C \qquad (4)$$

where g_r and g_c are the geometrical constant related to the cell design or electrode configuration.

Electrical Properties of Saturated Water and Vapor. The resistivity of vapor is infinite but the resistivity of water is a function of both its temperature and salinity. For a given water salinity, the resistivity, ρ, can be determined or measured at a standard temperature, T_1 , and then corrected to an operating temperature, T_2, through the Arps Equation[1] which is given below for sodium chloride solutions:

$$\rho_2 = \rho_1 \left(\frac{T_1 + 6.77}{T_2 + 6.77} \right) \qquad (5)$$

The dielectric constant of the vapor is approximately 1 but does increase slightly with temperature. At room temperature the dielectric constant of water is 78 but decreases to around 30 at 450 °F. Both the dielectric constant of vapor and water can be calculated at saturated steam temperatures and pressures by using the equations developed and presented in SPE 20319[3]. For saturated steam, the dielectric constant of water, K_w, is given by:

$$K_w = \sum_0^i a_i \left(\ln \frac{P}{P_c} \right)^i \qquad (6)$$

and the dielectric constant of saturated vapor, K_v, is given by:

$$K_v = 1 + Exp\left[\sum_0^i a_i \left(\ln \frac{P}{P_c} \right)^i \right] \qquad (7)$$

where P is the absolute pressure, P_c is the critical pressure (3198.807 psia) and the a_i's are correlation coefficients. The correlation coefficients for each equation are listed in Table 1 and 2 for two distinct pressure ranges.

Relationship between Impedance and the Volume Fraction of Water. For the steam flowing through the DSQS, the measured impedance with the "T" transform correction and known geometrical constants provides the electrical properties, ρ_m and k_m, of the combined mixture of water and vapor. Electrical mixing laws or equations relate the overall electrical response of the mixture to the electrical properties of the individual constituents and the percent volume of these constituents. Several such mixing equations have been developed with various degrees of success. The Lichtenecker-Rother Equation[5] and the Hanai-Bruggeman Equation[4] have shown the most promising results based on the latest literature and our past experience. Although some preliminary analysis used the Hanai-Bruggeman Equation, the DSQS development has focused on the Lichtenecker-Rother Equation.

The Lichtenecker-Rother Equation states that for a mixture of water and vapor, the measured complex dielectric permittivity, ε_m, is given by:

$$\varepsilon_m^e = \lambda \varepsilon_w^e + (1 - \lambda) \varepsilon_v^e \qquad (8)$$

where λ is the fractional volume of water, e is a mixing exponent and the subscripts v and w denote the permittivity of the vapor and water respectively. Solving Equation 8 for λ gives:

$$\lambda = \left(\frac{\varepsilon_m^e - \varepsilon_v^e}{\varepsilon_w^e - \varepsilon_v^e} \right) \qquad (9)$$

In general, ε is complex and can be expressed by:

$$\varepsilon = K + \frac{j}{2\pi f \, \varepsilon_o \rho} \qquad (10)$$

where K is the dielectric constant, ρ is the resistivity, ε_o is the dielectric permittivity of a vacuum, f is the frequency and j is the imaginary unit. Defining B as the imaginary term,

$$B = \frac{1}{2\pi f \, \varepsilon_o \rho}$$

and substituting into Equation 10 gives the following expressions:

$$\varepsilon_m = K_m + j\,B_m, \qquad (11)$$

$$\varepsilon_w = K_w + j\,B_w \quad \text{and} \qquad (12)$$

$$\varepsilon_v = K_v \qquad (\rho \text{ is infinite}). \qquad (13)$$

Substituting Equations 11, 12 and 13 into the mixing equation, Equation 9, yields:

$$\lambda = \left(\frac{(K_m + jB_m)^e - (K_v + jB_v)^e}{(K_w + jB_w)^e - (K_v + jB_v)^e} \right) \qquad (14)$$

If the water is very fresh, the water resistivity approaches infinity and the imaginary terms of Equation 14 becomes insignificant and reduces Equation 14 to:

$$\lambda = \left(\frac{K_m^e - K_v^e}{K_w^e - K_v^e} \right) \qquad (15)$$

However, for most field applications the water resistivity is significant and the resistivity terms can not be neglected. The fractional power of the complex quantities complicates the mathematical solution of Equation 14, but it can be solved for its primary root. Expanding Equation 14 into its real and imaginary parts and solving the real part for the volume faction of water yields:

$$\lambda = \frac{\left(K^2 + B^2\right)^{e/2} \cos\left[e \tan^{-1}\left(\frac{B}{K}\right)\right] - K_v^e}{\left(K_w^2 + B_w^2\right)^{e/2} \cos\left[e \tan^{-1}\left(\frac{B_w}{K_w}\right)\right] - K_v^e} \qquad (16)$$

In an effort to simplify the application of these equations and reduce the number of parameters required, an empirical equation was also developed and has produced excellent results. This new empirical equation relating the impedance response to the volume fraction of water is:

$$\lambda = b\sqrt{P} \cdot \log\left(\frac{\overline{Z}_v}{\overline{Z}_m}\right) \qquad (17)$$

where λ is the volume fraction of water, P is steam pressure, $\overline{Z}_v$ is the impedance magnitude of 100% steam vapor, $\overline{Z}_m$ is the measured impedance magnitude of the steam mixture and b is an empirical constant. The empirical or calibration constant b is to some degree affected by the water salinity or resistivity but can be assumed constant for a given field or range of resistivities.

Relationship between the Water Volume Fraction and Steam Quality. To determine the steam quality from the volume fraction of water, one starts with the basic definition of steam quality:

$$X = \frac{M_v}{M_v + M_w} \qquad (18)$$

where M_v and M_w are the mass rates of the vapor and water respectively. Rewriting Equation 18 yields:

$$X = \left(1 + \frac{M_w}{M_v}\right)^{-1} \qquad (19)$$

If the velocity of the vapor and the water through the sensor are equal, the mass rate values of the water and vapor can be replaced by their respective ratios of volumes to specific volumes, V/v which gives:

$$X = \left(1 + \frac{V_w / v_w}{V_v / v_v}\right)^{-1} \qquad (20)$$

Expressing V_w and V_v as fractions of the total volume V_t where λ is the volume fraction of water gives:

$$V_w = \lambda V_t \qquad (21)$$

$$V_v = (1 - \lambda)V_t \qquad (22)$$

Substituting these values in Equation 20 and simplifying yields:

$$X = \left[1 + \left(\frac{v_v}{v_w}\right)\left(\frac{\lambda}{1-\lambda}\right)\right]^{-1} \qquad (23)$$

From this equation the desired value of steam quality can be obtained from the volume fraction of water calculated from either Equation 15, 16 and 17. In the derivation of Equation 23, the velocity of the two phases were assume equal, if this is not true a slip velocity factor must be included. For the DSQS units, the inlet mixing and the reduced annular cross-section promotes more uniform velocities of the phases and no slip velocity has been investigated. However, this concern is addressed in the design of the units where the cross-sectional area of the flow is minimized as much as possible without generating a substantial pressure drop.

DSQS Performance and Evaluation

Steamflow Research Facility Testing. The concept of the DSQS was first successfully demonstrated through a series of tests in Texaco's Steam Flow Research Facility. This facility is designed to conduct research at test conditions ranging from pressures of 300 to 800 psig, steam qualities of 20-100%, and vapor mass rates of 1000 to 7500 lb./hr, in two, three or four inch pipes. A more detailed description of the Steam Flow Research Facility and its operation are presented in SPE paper 24832[2].

One aspect of the Steamflow Facility which is significant for the DSQS testing or any electrical measurement of steam is that the facility uses deionized water for the generator feedwater and for the water used in mixing with the 100% steam vapor to obtain the desired steam quality. Since the water is deionized and has essentially zero conductivity or infinite resistivity, only Equation 15 was used for the analysis of the DSQS measurements.

Figure 3 shows the comparison of the steam qualities measured with the DSQS unit to the actual or reference qualities from the laboratory facility. As indicated by the multiple symbols on the graph, steam quality tests were conducted for a range of pressures (400-800 psig) and vapor mass flow rates (4000-6000 lbm/hr). During the tests the pressure drop across the sensor varied from a maximum of 27 psi at the lowest steam quality condition to less than 5 psi at the higher qualities.

Early Field Testing. The first successful field tests of the DSQS units were conducted in the Kern River Field, California with the assistance of Texaco's Bakersfield Division personnel. Two units were installed to monitor steam quality at the well head of two injectors which were operating in the 90-100% and 40-60% quality ranges. The data acquisition system was configured to average measurements over a 15 minute period so four points per hour were recorded and downloaded every two weeks. Since the injectors were already configured with a choke and an orifice meter run, the upstream pressure and differential pressure across the orifice plate were also recorded. These additional measurements were used in the same manner as in the Orifice-Choke Steam Flow Measurement System to obtain an independent measurement of steam quality for comparison with the DSQS quality.

Even though the water in the Kern River Field is fresh, its resistivity did influence the sensor's response and the resulting quality calculated by Equation 15. Equation 15 which neglects the resistivity terms of the Lichtenecker-Rother Equation yielded values that appeared to be a constant 10-15 quality units lower than the orifice-choke values. Since these tests were some of the earliest in the DSQS development, the empirical Equation 17 and the expanded Lichtenecker-Rother Equation 16 had not been fully developed. However, an earlier empirical correction was introduced into Equation 15 which produced excellent results. The correction was based solely on the resistivity part of the measured impedance and was sufficient for the Kern River applications where the water resistivity is high and varies little from well to well.

Figure 4 shows a typical result for the Kern River Field testing of the DSQS. The figure contains two graphs with the horizontal axis in both representing the same time scale and duration. The lower graph shows the magnitude and variation of the impedance response, line pressure and the differential pressure across the orifice plate. The scale of the impedance is indicated on the right and the scale for the pressure and differential pressure are combined on the left. The upper graph shows the excellent agreement obtained between the steam quality calculated by the Orifice-Choke Steam Flow Measurement System and the DSQS unit.

Expanded Field Testing. Based on the successful results in the Kern River Field, Texaco and California Steam Service (CSS) decided to jointly conduct a broader and more extensive evaluation of the DSQS technology. Texaco provided DSQS units for CSS to incorporate in their separator trailers. These trailer units with their separation capability provided a means of measuring the vapor and water as single phase components to give an accurate determination of steam quality for comparison to the DSQS results. The portability of the trailers also offered the capability to extend the testing of the DSQS over a wider range of operating conditions including variations in water resistivities and field sites.

For these tests, the DSQS data acquisition electronics was used only for display purposes with the trailer's acquisition system recording the three raw impedance voltages in addition to their normal measurements. Using the single acquisition system made data analysis and comparison easier and more accurate. In addition to the real-time data acquisition, a water sample from the liquid leg of the separator was collected during the test. The water resistivity of this sample was later measured at room conditions for use in the DSQS analysis.

During this joint evaluation program over 100 tests were conducted at various steam injectors within oil fields in the San Joaquin Valley. Numerous examples showing exact comparisons between the DSQS and separator could be presented, but to better document the DSQS performance eight tests are present which include a variety of stable and unstable operating conditions. Figures 5-12 display these results in a similar format with only a variation in the pressure and flow rate scales to reflect the different operating conditions. All the test figures contain two graphs with their horizontal axis representing the same time scale and duration. The time scale is shown as sample points with each point representing a ten second interval. The lower graph shows the magnitude and variation of the line pressure and the total mass rate calculated from the sum of the liquid and vapor rates measured by the separator. The overall test results shown by the upper graph is a direct comparison of the steam quality calculated by the separator trailer and the DSQS unit. The DSQS steam quality values shown in the figures are based on the empirical Equation 17. The constant b used in Equation 17 was varied based on the water resistivity but held constant over the range of water resistivities which are listed in Table 3.

Figure 5 shows a very stable operating test with a flow rate of 300 BPD CWE at a pressure of 230 psia. For this test, the DSQS and separator measurements showed a consistent 70% steam quality. The next test, Figure 6, also shows steam qualities close to 70% with slightly more variation in the DSQS values. The most significant difference between this test and the previous is the lower pressure and flow rate.

Figures 7 and 8 display tests with more dynamic conditions. The injector shown by Figure 7 has a pressure of 300 psia with a flow rate of 380 BPD CWE and test results indicate a 40-80% variation in steam quality. Similar variations in quality of 60-95% are displayed in Figure 8 for an injector with a slightly lower pressure and over a 150 BPD CWE lower flow rate. In both cases, the DSQS and separator steam qualities agreed closely but even more impressive is the how the qualities tracked during these variations.

In the remaining figures, except for Figure 10, the pressure and flow rate scales have been increased by 200 to display conditions with either higher pressures, higher flow rates or both. These cases display more unstable conditions with wide fluctuations in the injection rates. The steam qualities curves shown in Figure 9 indicate both low and high frequency dynamics over a range of 30-60% with the DSQS and separator values comparing very closely. Figure 10, with the lower pressure and flow rate scale, also shows a wide variation in the steam qualities with the DSQS indicating a lower quality but still tracking the separator value. The injector, whose conditions are displayed in Figure 11, appears to have cyclic surges which can be seen in the pressure, flow rate and both quality curves. However, the qualities which range from 30-95% are remarkably close even through these drastic variations.

The final example shown in Figure 12 was of particular interest in that during the test a generator upstream in the distribution system went down. The figure shows the associated drop in steam quality and then a rise in quality as the generator was brought back on stream. During these changing conditions, the DSQS steam quality values tracked remarkably well with the separator results.

From reviewing these figures and the results of all the other tests, the authors conclude that even over a wide range of operating conditions, the DSQS unit was in excellent agreement with the separator method. While most of the steam quality plots were fairly constant, some showed significant fluctuation caused by the flow conditions at the injector. In these cases, the dielectric steam qualities typically showed a larger variation but still basically tracked the quality values from the separator.

Based on the sucessful results of the DSQS evaluation and the potential application of this technology, Texaco has licence the DSQS technology to CSS for commerialization. Currently, DSQS units are available, being deployed and receiving wider industry acceptance. Application points include steam generator discharge, injector wellhead, steam headers, and other selected locations in the piping network. Direct use of this technology is also anticipated in geothermal industry steam collection systems.

Conclusions

1. Steam Flow Research Facility testing provided guidance on the proper design and demonstrated the basic concept of relating impedance to steam quality.
2. The water resistivity influences the impedance measurement and must be incorporated into the analysis.
3. If all parameters and conditions are known, results agree with theoretical analysis, however, an empirical approach is easier, more practical and provides better results for field operations.
4. Extensive testing showed excellent performance of the DSQS over a wide range of operating conditions, field locations and salinity variations.
5. DSQS provides the required steam quality measurements for thermal operations without a significant pressure drop in the distribution system.
6. Design and application of DSQS units should be expanded to larger diameter distribution lines to achieve full potential of this technology.

Nomenclature

a_i's = various sets of correlation coefficients for calculating saturated steam properties
b = an empirical constant
C = capacitance (farads)
e = mixing exponent
f = frequency (hertz)
g = the cell geometrical constant
j = the imaginary unit (square root of -1)
K = dielectric constant (unitless)
P = absolute pressure (psia)
P_c = critical pressure (3198.807 psia)
R = resistance (ohms)
T = temperature (°F)
M = mass rate (lbm/hr)
V = volume (ft^3)
X = steam quality
Z = complex impedance (ohms)
$\overline{Z}$ = impedance magnitude (ohms)
θ = impedance phase angle (degrees)
ρ = resistivity (ohm-meters)
ε = complex dielectric permittivity
λ = fractional volume of water
ν = specific volume (lbm/ft^3)

Subscripts

t = total
v = vapor
w = water
m = measured
o = vacuum
r = resistance factor
c = capacitance factor

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SI Metric Conversion Factors

Btu x 1.055056 E+00 = kJ
bbl x 1.589873 E-01 = m^3
ft x 3.048* E-01 = m
in. x 2.54* E+00 = cm
lbm x 4.535924 E-01 = kg
psia x 6.894757 E-03 = Mpa

Table 1 - Correlation Coefficients For Calculating the Dielectric Constant of Water.

Pressure Range	1.8 - 680 psia	680 - 2253 psia
a_0	1.2455263 E+01	9.1673450 E+00
a_1	-8.7906887 E+00	-1.5169608 E+01
a_2	-1.5104396 E-01	-4.6892058 E+00
a_3	0	-1.1529337 E+00

Table 2 - Correlation Coefficients For Calculating the Dielectric Constant of Vapor.

Pressure Range	6.8 - 1078.8 psia	1078.8 - 2116.7 psia
a_0	3.4299129 E-01	5.9650922 E-01
a_1	2.1733980 E+00	3.0604029 E+00
a_2	5.3285676 E-01	1.5010138 E+00
a_3	9.9768162 E-02	4.3431473 E-01
a_4	7.0968904 E-03	0

Table 3 - Relationship of the Empirical Constant "b" (Equation 10) to Water Resistivity.

Water Resistivity Range (Ohm-Meters @ 75 °F)	Value of "b"
$R_w < 0.2$	.0007
$0.2 \geq R_w < 0.4$	.0009
$0.4 \geq R_w < 0.7$	.0020
$0.7 \geq R_w < 1.0$	.0036
$R_w \geq 1.0$	.0073

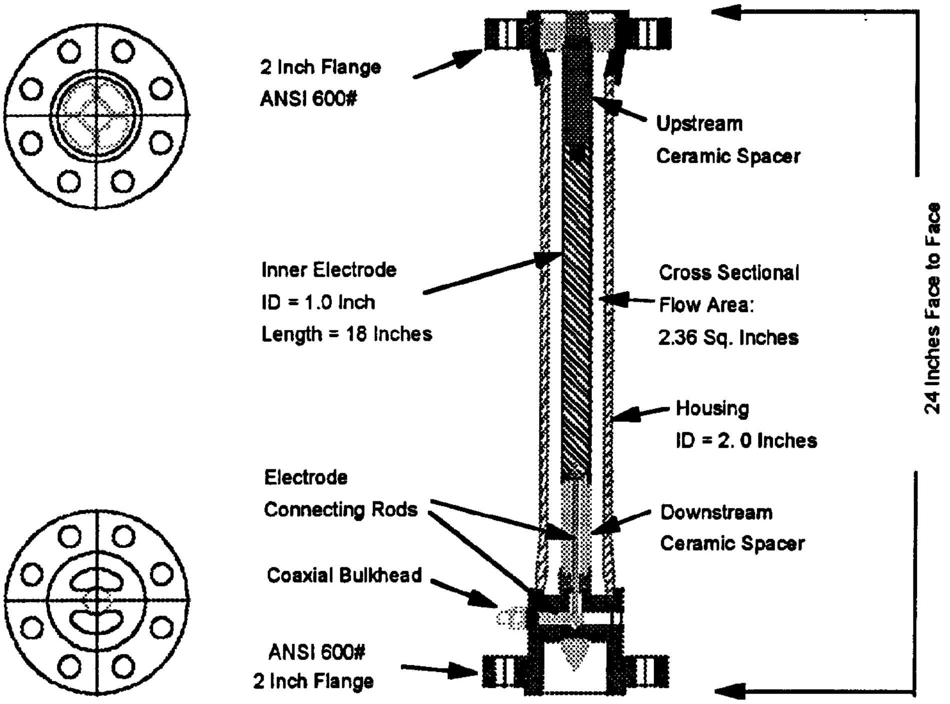
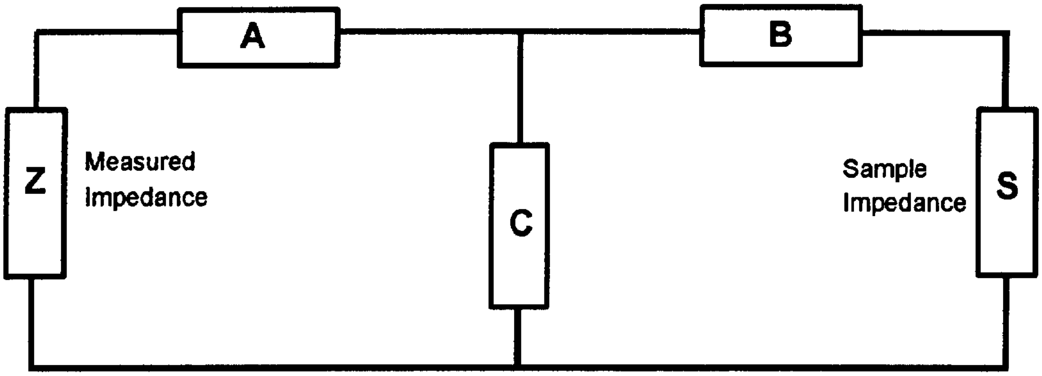


Figure 1: Mechanical Schematic Of The Dielectric Steam Quality Sensor



A, B & C = Residual Impedances

Figure 2: Diagram of the "T" Network

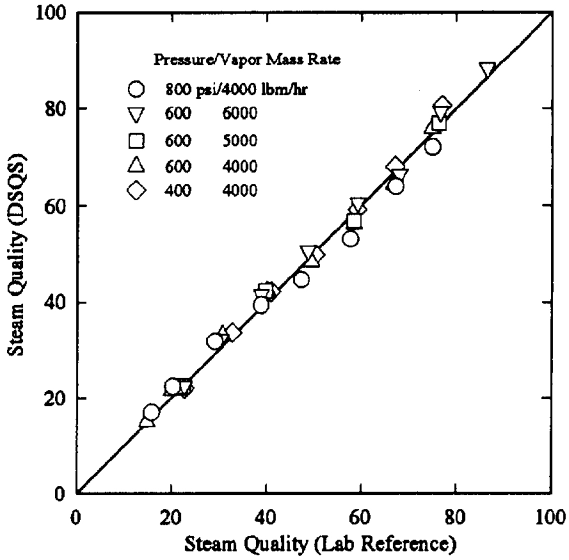


Figure 3: DSQS Test Results from the Steam Flow Research Facility

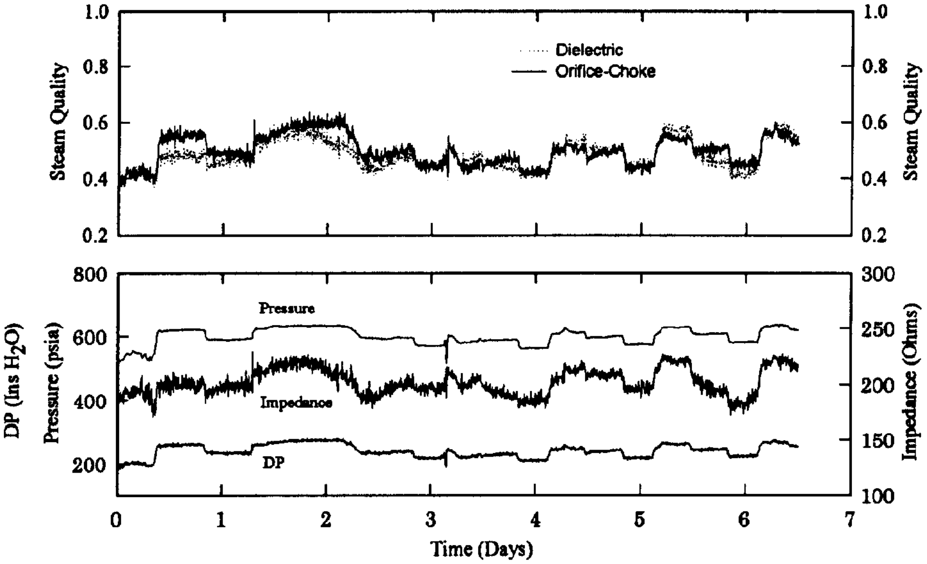


Figure 4: Kern River Field Test Comparing DSQS to Orifice-Choke Method

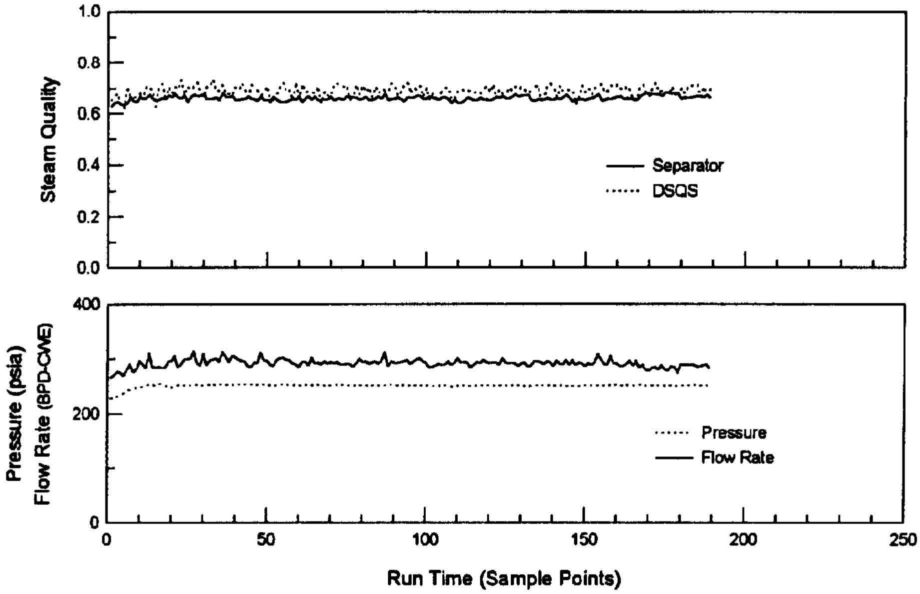


Figure 5 - Joint Field Test #1: Comparing DSQS to Portable Separator

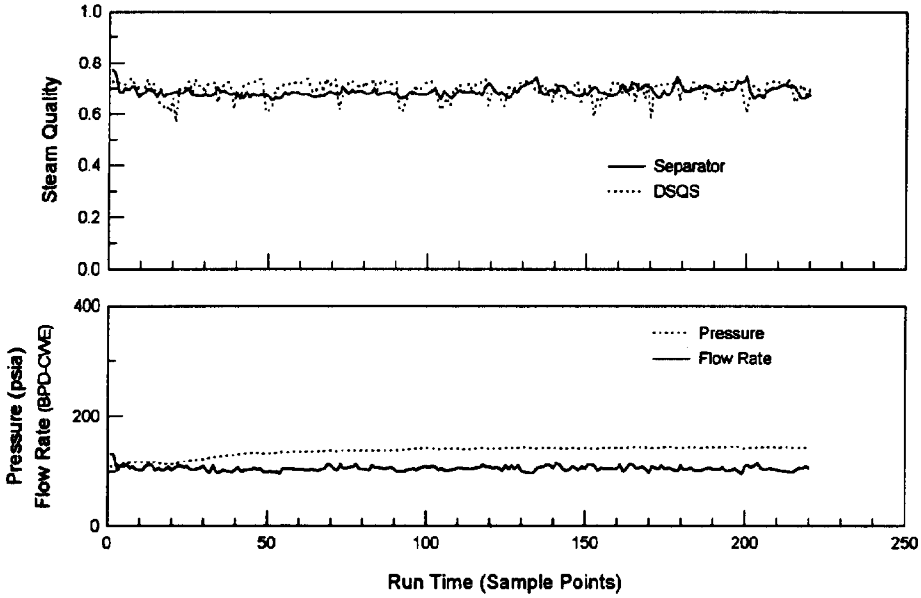


Figure 6 - Joint Field Test #2: Comparing DSQS to Portable Separator

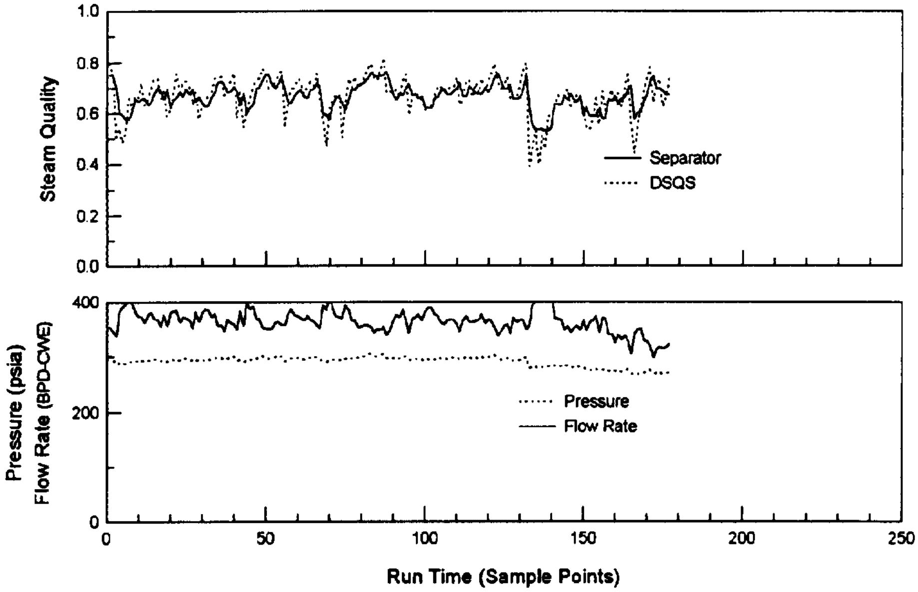


Figure 7 - Joint Field Test #3: Comparing DSQS to Portable Separator

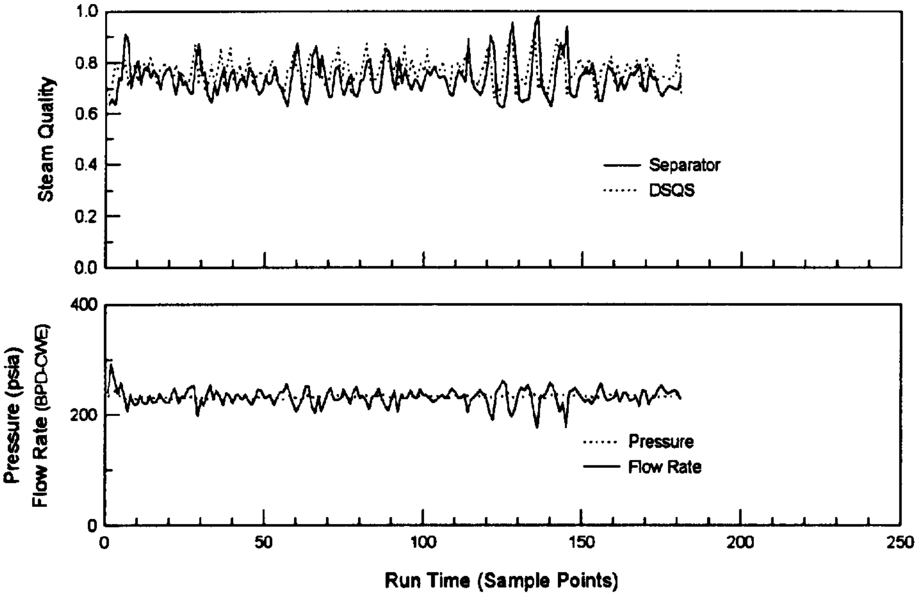


Figure 8 - Joint Field Test #4: Comparing DSQS to Portable Separator

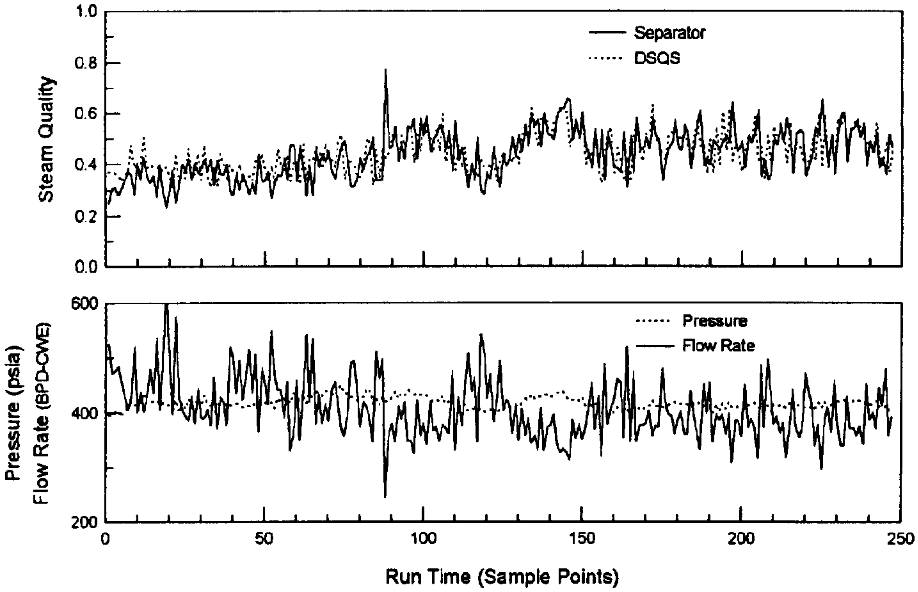


Figure 9 - Joint Field Test #5: Comparing DSQS to Portable Separator

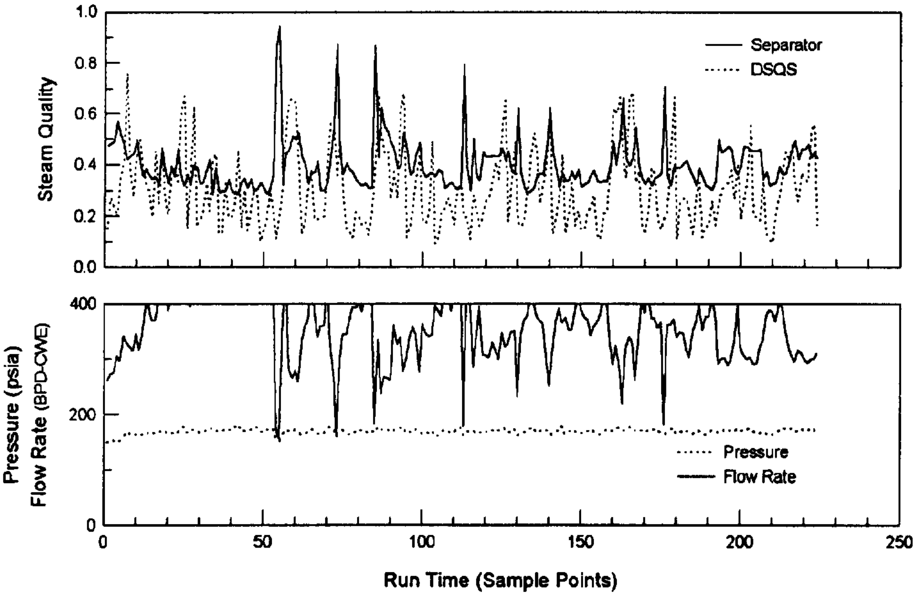


Figure 10 - Joint Field Test #6: Comparing DSQS to Portable Separator

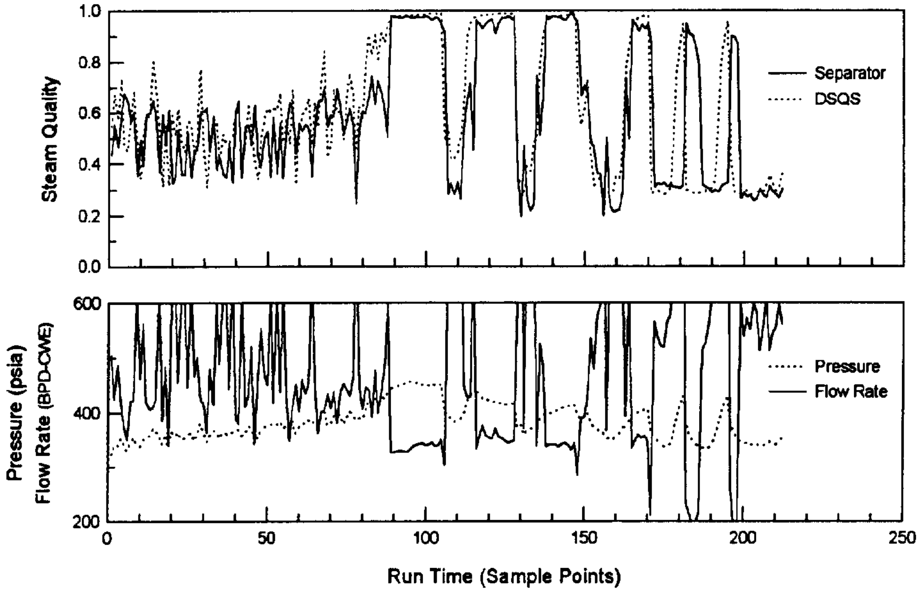


Figure 11 - Joint Field Test #7: Comparing DSQS to Portable Separator

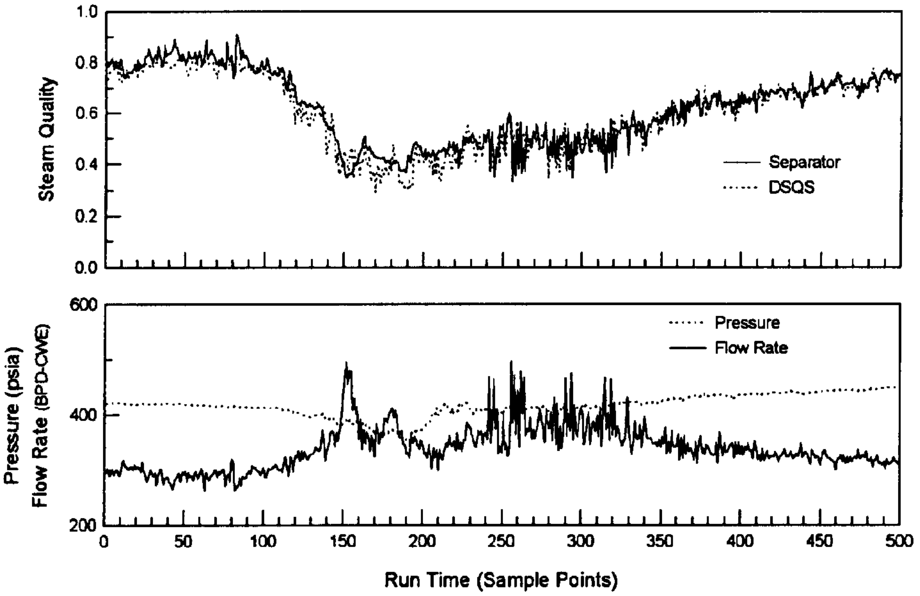


Figure 12 - Joint Field Test #8: Comparing DSQS to Portable Separator