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TWO-PART-LIQUID-MIXTURE PERCENTAGE MEASUREMENT
USING A FLOW-THROUGH CAPACITANCE SENSOR

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SUMMARY

A flow-through capacitance sensor with application-specific electronics that includes auto-calibration and fail-safe circuitry has been built and tested to measure the percentage of TBP in n-dodecane. The circuitry uses two phase-referenced demodulators operating at 20 kHz. The mixture-percentage signal originates from the demodulator with 90 degree reference shift while the demodulator with 0 degree reference shift provides a the liquid conductivity. The system has been tested with the flow-through sensor at 100 feet from the electronics and shows no sensitivity to cable movement. The calibration data fits the given second degree polynomial well.

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I. Introduction

N-dodecane and tributyl phosphate (TBP) have significantly different relative dielectric constants (2 and 8 respectively). When these liquids are mixed, the resultant dielectric constant varies monotonically from 2 to 8 as more-and-more TBP is added to a fixed amount of dodecane. Since TBP is used in the Purex nuclear fuel reprocessing process as an extractant for uranium nitrate while dodecane is simply a diluent, it is necessary to regularly assure the TBP mixture percentage is proper. The sensor being reported here allows this measurement to be made continually without the need for daily sampling and analysis by analytical chemistry.

II. Discussion

The Schematic of Figure 1 illustrates the principle.

Figure 1 Simplified Percentage-Mixture Measurement Circuit

An a.c. signal varies the potential of the metallic vessel (relative to ground potential). The metal rod at the center of the vessel is capacitively linked to the outer vessel by the liquid or by air if the system is empty. Assuming the liquid level is always the same when measurements are made and also assuming and that the liquid is non-conductive, the a.c. current input to the operational amplifier input of Figure 1 is 90 degrees out of phase with the phase of the driver voltage. This input current varies directly with cell capacitance between the central rod and the vessel wall and is proportional to the liquid dielectric constant.

In actuality, things are not as simple as depicted in Figure 1. Oscillators typically do not generate a sine wave free of harmonics. The high impedance of the cell (typical cell capacitance is 17 to 50 pfd

which at 20 kHz corresponds to 4.7×10^5 to 1.6×10^5 ohms) acts as a differentiator of the drive voltage accentuating the presence of harmonics. So, without special techniques, the above problems as well as changes in coaxial cable capacitance versus temperature, position etc., would mask the desired signal.

Figure 2 shows the actual electronics used to make the measurement successfully with 100 feet each of drive and sense cable. On the drive side of the electronics, the Burr-Brown OPA-37A operational amplifier increases the oscillator amplitude to about 20V peak to peak. The Frequency Devices 728P2Q5 band pass filter removes harmonics and drives the triaxial cable. Photos, Figures 3 and 4, show the actual flow-through capacitance cell. The capacitance cell has a pipe within a pipe and a central 0.5 inch diameter rod within the inner pipe. The inner pipe and central rod are insulated from one-another and from the outer pipe. The central wire of the drive triaxial cable sinusoidally varies the potential of the inner pipe relative to the outer pipe which is assumed to be connected to plant ground. The sensor central rod is stimulated capacitively by the surrounding, driven, pipe and drives the output cable. Since the cell impedance of about 1×10^5 ohms is much larger than the 100 ohm input to the virtual ground of the input OPA-37A operational amplifier, the signal passes to the sense electronics as a current and essentially no voltage is developed in the central lead of the triaxial sense cable. Therefore, changes in cable capacitance, etc, do not affect the magnitude of signal reaching the sensing electronics.¹

The first OPA-37A of the sense electronics acts as a current-to-voltage converter while the second amplifies the voltage to the "few volt" range appropriate for the 728P2Q5 filter and the two AD-630K demodulators. A demodulator's action is to alternatively change its gain from +1 to -1 in phase with the waveform applied at its reference input. For an input signal of the same frequency and phase as applied to the reference input, the demodulator full-wave rectifies the input signal. After filtering this gives a net d.c. output. With the demodulator reference-connected sine wave shifted 90 degrees relative to the input signal, the output is chopped into + and - halves of waveforms resulting in zero output after filtering. Since the capacitance portion of the current output from the cell is shifted 90 degrees from the cell drive voltage, a 90-degree-shifted reference to one of the demodulators gives the cell capacitance signal while an unshifted reference to the other demodulator yields the cell conductance signal. Because of a -3 degree shift occurring in the reference-isolation-transformer, the required demodulator reference phases are actually +93 and 3 degrees rather than 90 and 0.

¹Note: 100 feet of cable with cable-insulation relative dielectric constant of 2 is equivalent (for signal passage) to $2 \times 100 \times 12/39.3 = 61$ meters. At 3×10^8 meter/second, signal passage through 61 meters of cable requires 2×10^{-7} second. At 20 kHz, 2×10^{-7} seconds amounts to a 4×10^{-3} fractional portion of a cycle. Thus, the line length is short and the phase shifts, reflections, etc in the cable can be ignored.

Octagon computer actuated calibration check.
The parts below are located at the side
of the sensing cell.

To center
rod of
sensing
cell

To 1" dia.
tube of
sensing
cell

The normal "cell-sensing" condition
has all relays non-actuated and
is the configuration shown below.

- ⊞ Components
powered ± 15 v
by one Dated
BPM 15/150 D3
and
- ⬇ Components
powered by
another
BPM 15/150 D3
- ⬆ Ground
at sensing
cell

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Figure 2 Actual Percentage-Mixture Measurement Circuit

Figure 3 Components of the Flow-Through Measurement Sensor

Figure 4 Assembled, End-View of the Measurement Sensor

III. Computer and Information Display

An Octagon Systems Corp² single board computer takes analog to digital readings every five seconds of the two demodulator filtered outputs and converts the pfd reading of volts to percentage of TBP per the calibration equation given later and displays it on a vacuum fluorescence display and also outputs it in RS-232 format. Every few minutes to a few hours, depending on the computer program, the computer operates the auto-calibrate relays discussed below to self-test the system. These results are also routed to the fluorescence display.

IV. Auto Calibrate

The upper portion of Figure 2 shows the relays, capacitances and a conductance of the auto-calibrate circuitry. These relays are located in two small boxes connected respectively to the feed-throughs to the inner-pipe and to the central sense rod. One of the relay coils in each box is driven as "coil #1". The coils of the other two relays in the drive-side box are driven separately as coils #2 and #3. When all the relay coils are non-activated, the circuit connected as shown in the main portion of Figure 2. The function of relay activation per Table 1 is to replace the flow-through sense cell with one or the other of the three reference admittances:

10 pfd,
20 pfd in parallel with 200K ohm or
40 pfd

which lie in the capacitive range the sense cell could have. The 200K resistor creates a nonzero output from the "conductance" demodulator. The left-hand portion of Figure 5 shows the way the relay coils are driven.

Table 1

Self Calibrate and Test Relay Activation

Coil #	1	2	3	"Capacitance" Selected
0	X	X		sense cell
1	0	0		10 pfd
1	0	1		20 pfd & 200 K
1	1	X		40 pfd

²Octagon Systems Corp, 6510W 91st Ave. Westminster Colorado, 80030

V. Fail Safe Alarm

The Fail Safe Alarm circuit of the right-hand portion of Figure 5 must have its retriggerable monostable input toggled at least once every 7 or 8 seconds to prevent the output relay coil from becoming unactivated and its contacts closing [which would signify a computer failure].

Circuit toggling is accomplished by placing one line of computer code in the five second loop to momentarily depress one of the single board computer's digital I/O lines. The fail safe circuit has its own battery and charger so that a power failure will not inactivate it.

VI. Results

Figure 6 shows the calibration data as well as the fit to the data. The system computer converts the electronics voltage output to the equivalent sensor cell pico-farads of capacitance which is used for the ordinate of the figure. The largest variation of the fit from the data is 0.47% of value. The fit polynomial used is:

$$\% \text{ TBP} = -0.015 [\text{pfd reading}]^2 + 2.828 [\text{pfd reading}] - 80.08$$

The above plotted data was taken with no flow of the TBP/dodecane mixture. Since the cell will be operated with up to about 1 liter/minute of flow, test were run on the change of system output to 1 liter/minute of flow. Typical output change to this flow was 0.1 pfd. At roughly 5 liter/minute of flow, the output change was more significant, about -1.6 pfd, and is thought to be caused by froth generated in the pump that passes through the cell lowering the equivalent dielectric constant of the liquid.

VII. Conclusions

The flow-through sense cell (with electronics specifically designed for the situation) allows the percentage mixture measurement to be made accurately. Use of low impedance amplifier input on the sense cable output causes the cell signal to flow to the sense electronics as a current. Since no appreciable voltage is developed on the sense cable, changes in line capacitance etc (as are caused by cable movement, temperature, etc.) cannot affect the registered signal. Phase referenced demodulators allow the low level signal to be amplified and recovered with no notable noise. The single board computer converts the pfd voltage reading to percentage TBP. If the liquid becomes somewhat conductive the "conductance" signal will become non-zero. A low enough drive frequency is used so that the drive and sense cables present no "wavelength" effects.

Relay Coil Drive Circuit

n-channel FET Buz 71

p-channel FETS IRFD 9120

Computer Output J2 pin 15 etc normally are pulled high; if a "1" is output, the output goes low turning on the p-FET.

Fail Safe Alarm Circuit

This line pulled to ground by computer every 5 seconds

Contacts close if relay becomes de-energized

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Figure 5 Relay Drive Circuitry and Fail Safe Alarm Circuit

Pfd Indicated & Fit vs %TBP

Line is Fit, Squares are Data

Figure 6 Calibration Data and Fit of Sensor Capacitance vs Mixture Percentage

END

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