Chemical flow rate control in injection-type sprayers

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Chi, L., Kushwaha, R. L. and Bigsby, F. W. 1988. **Chemical flow rate control in injection-type sprayers**. Can. Agric. Eng. **30**: 19–26. Direct injection of chemical into the sprayer system shows some advantages over the conventional sprayer. One of the problems in a injection-type sprayer is metering and controlling the concentrated chemical flow rate. In this paper a flow control system using electro-mechanical feedback was designed and tested. A positive displacement pump was used as a metering pump in the system. The feedback system kept the pressure drop across the metering pump at zero and controlled the metering pump speed according to the desired flow rate. The test results showed that the system worked well for fluids with viscosities from 90 to 300 mPa.s and flow rates from 3 to 20 mL/s. A linear relationship was achieved between the flow rate and pump speed. The response performance of the system also was tested. The results showed that the system would reach the steady state with a maximum of 5 s at start or when the travel speed was changed.

INTRODUCTION

Injection-type sprayers where water and the pesticide are kept separately have been developed in recent years. These sprayers show some advantages over a conventional sprayer system. In a conventional sprayer, a constant application rate at different travel speeds requires changes in the boom pressure in order to change the nozzle delivery. This change will usually cause changes in atomization quality i.e., distribution and drop spectrum (Bode et al. 1972). In an injection-type sprayer, a constant application rate can be obtained by controlling the flow rate of concentrated pesticide. The pressure in the boom can be maintained constant so that the atomization quality is not affected. Handling of chemical in an injection-type sprayer becomes easier than that in a conventional sprayer.

One of the major problems in an injection-type sprayer is metering and controlling the concentrated pesticide flow rate. This problem is caused by different properties of various pesticides and low flow rate requirement of the concentrated chemical (Gebhardt et al. 1984).

Many kinds of pesticides are in use at present. Gebhardt et al. (1984) studied some properties of five pesticides (Amiben, Treflan, Thuricide HPC, Aatrex 4L, and Dipel) and found that the viscosity was different for various pesticides at different temperatures, and ranged from 1.2 to 300 mPa.s. Some pesticides, such as Thuricide HPC, Dipel, and Aatrex 4L, behaved as non-Newtonian fluids. The difference of densities between pesticides and corresponding changes with the temperature was very small.

Most flow rate meters used today measure a secondary effect of the stream to measure the flow rate, rather than measuring the flow rate directly (Katz 1974). Thus, the properties of fluids, especially the viscosity, affect the result of measurement in these flowmeters. The viscosity effect becomes very significant when the flow rate is very small. As a result the measurement of flow rate of concentrated pesticides becomes very difficult.

Vidrine et al. (1975) designed a model of a constant-rate pesticide application sprayer with a piston pump for both pumping and metering the pesticide flow rate. A linear relationship was obtained between flow rate and pump speed from this system which utilized open loop control. However, any change in pumping characteristics due to wear would not be detected. There is always a leakage flow between the inlet and outlet of a positive displacement pump due to differential pressure between these points. This leakage flow cannot be detected in an open loop system.

Gebhardt et al. (1984) proposed a closed-loop system and a drag-body flowmeter was tested to measure the concentrated pesticide flow rate. The test showed that the characteristics of this drag-body flowmeter varied with different pesticides and temperature changes. The flowmeter had to be calibrated for each pesticide and that the temperature of pesticide had to be controlled around the calibration temperature during application.

The objectives of this study therefore, were to design and test a method to measure and control the low volume pesticide flow rate independent of viscosity.

BASIC CONCEPT

Most flow rate meters measure a secondary effect of the stream on a primary element with an exception of the positive displacement flowmeter. The positive displacement flowmeter directly measures a volumetric flow rate. For positive displacement flowmeters flow rate can be expressed by:

$$Q_a = Q_i \pm Q_l - Q_d \quad (1)$$

where:

Q_a = actual flow rate

Q_i = ideal flow rate, which is a direct function of the meter dimensions and shaft speed

Q_l = viscous leakage flow, that is a function of the meter dimensions, shaft speed, viscosity of the fluid, density of the fluid, and differential pressure between the inlet and outlet of the meter.

Q_d = delivery loss due to cavitation, or entraied gases or vapor.

When leakage flow and loss caused by cavitation are zero the rotary speed of the meter will be directly proportional to the flow rate.

For a properly designed system, the loss caused by cavitation can be reduced to a very small quantity. The main error in the

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positive displacement flowmeter is due to the leakage flow. Astro Dynamics Inc. (Katz 1974) found that when the differential pressure was held at nearly zero, the leakage flow could be reduced to a very low value.

In this study, an electro-mechanical feedback technique was used to keep the differential pressure at zero. The principle used was that when the fluid flow passed through a positive displacement flowmeter there was always some energy loss from friction and eddies. This energy loss showed a pressure drop between the inlet and outlet of the meter. This pressure drop caused a leakage flow across the flowmeter. In the proposed system an electro-servo motor was used to drive the flowmeter to make the pressure drop zero. The metering pump speed then could be controlled to a proper value according to the travel speed of the sprayer.

SYSTEM DESIGN

The complete control system comprised two subsystems, the flow rate control system and the pressure drop control system. The metering pump motor was used to measure the flow rate and to control the differential pressure across the metering pump. A needle valve was used to control the flow to the metering pump (Fig. 1). At a selected travel speed, the complete system would keep the pressure drop across the meter very low and would control the rotary speed of the meter at a proper value. A set point circuit was designed to simulate the travel speed. Figure 1 shows the block diagrams of the complete control system.

Flow rate measurement

A vane-type fuel pump (12-802 Holley) was used and its flow rate was determined at various speeds. In order to measure the rotary speed of this metering pump, a disc, in which 16 holes were drilled, was fixed on the shaft of the pump. The rotary speed signal of the disc was picked up by a optical switch (MAC81). A schmitt trigger (LM311) followed to condition the signal from the optical switch. And finally a frequency-to-voltage converter, which consists of a monostable multivibrator (555 timer) and an integrator (MC1458), changed the square wave signal into an analogue signal (Fig. 2). The output from circuit can be expressed by the following equation:

$$e_0 = Ks \times Vm \quad (2)$$

where:
e_0 = output voltage of the circuit.
Vm = metering pump speed.
Ks = gain of the circuit.
This signal was fed into the valve control circuit.

Measurement of differential pressure

The differential pressure between the inlet and outlet of the flowmeter was measured by a diaphragm-type differential pressure transducer (CD-15 Validyne). This pressure signal was fed into the pump motor control circuit.

Pump motor control circuit

The pump motor (102-802 Holley) was controlled by the differential pressure. The circuit consisted of a power amplifier (MC1458, 2N4239, and 2N3716) and a lowpass active filter (MC1458) as shown in Fig. 3. The lowpass active filter was used to eliminate oscillation in the pressure signal. The motor supply voltage was designed to be proportional to the differential pressure. When the pressure drop was high, the voltage supply to the metering pump motor would increase. This would put more energy into the metering pump to reduce the pressure drop across the pump, and vice versa. The gain of the amplifier was large so that the pressure drop across the pump was kept small. The circuit was capable of providing a maximum of 3A current to the motor.

Valve control circuit

A stepping servo-motor (20-2235D-28175 Sigma) and a SLO-SYN translator (Super Electro Inc.) were used to control the

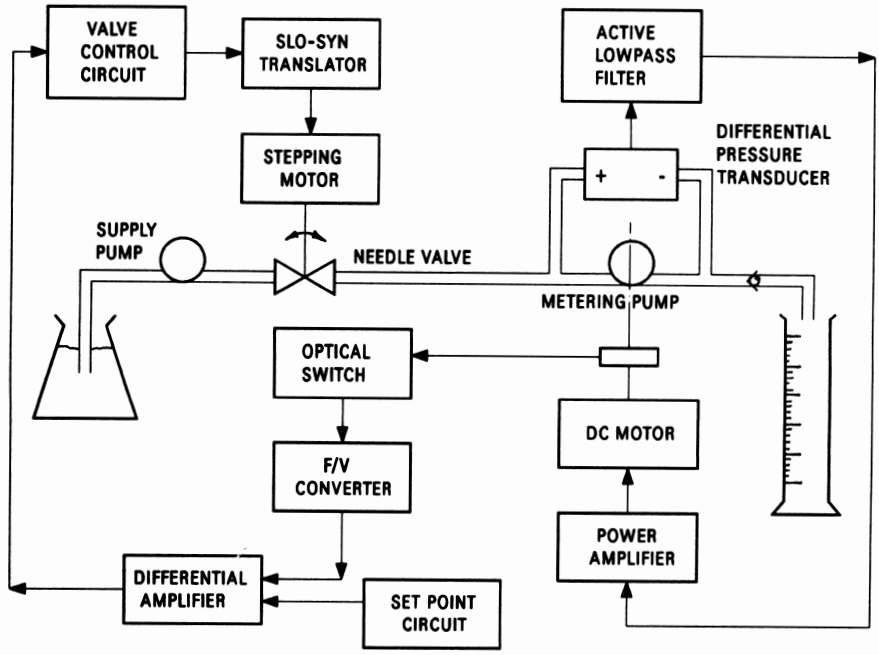

Figure 1. Block diagram of the flow rate control system.

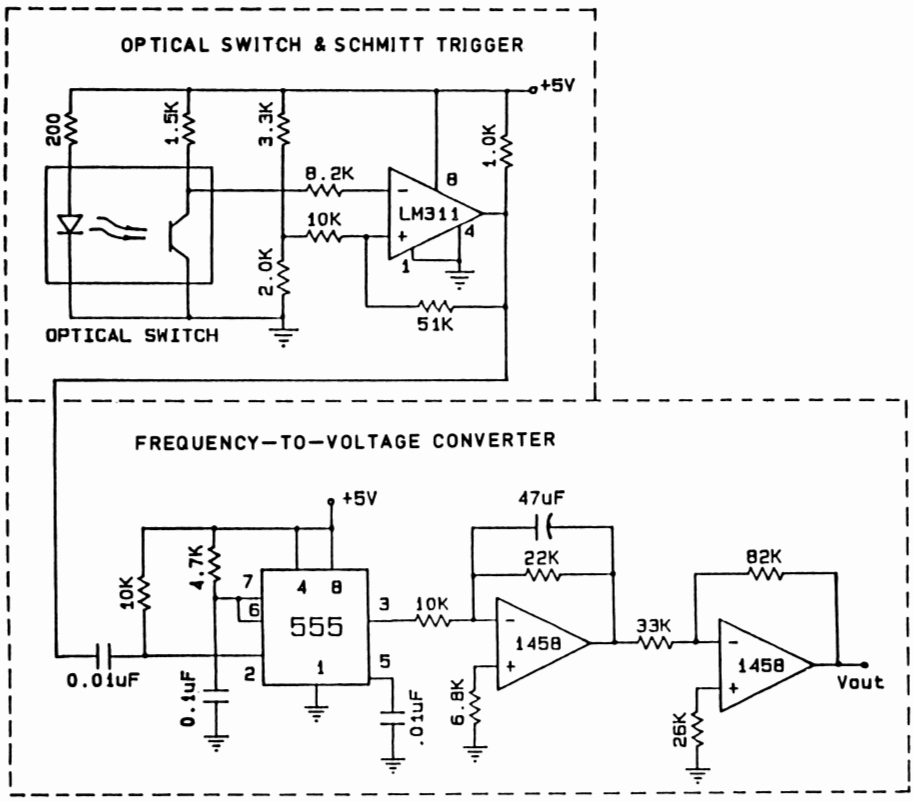

Figure 2. Circuit diagram for measuring metering pump speed.

needle valve (3212G4B Hoke). This stepping motor was controlled by the valve control circuit. A differential amplifier (TL074 and TL081) was inserted prior to the valve control circuit (Fig. 4). This amplifier compared the difference between the actual metering pump speed and the desired speed set by the set point circuit (Fig. 4). The function of the valve control circuit was that when the actual metering pump speed was higher than the required speed, a square wave signal was fed into the input terminal A (Fig. 4) of the SLO-SYN translator, which caused the stepping motor to move clockwise to close the valve. However, when the actual speed was lower than required speed, a square wave signal was fed into input terminal B (Fig. 4) of the SLO-SYN translator, which caused the stepping motor to move counter-clockwise to open the valve. Thus, the pump speed was controlled at a proper value. The two zener diodes were used to clip the signal within 0–5 V (Fig. 4). The two comparator (LM311s) compared the speed difference signal with the reference voltage set by the reference voltage circuit. An astable multivibrator (555 timer) was built to generate the square wave signal.

TESTS AND RESULTS

The characteristics of the pressure drop signal, the relationship between the set voltage and the flow rate, and response performance of the control system were tested. The fluids used in the test along with their properties are given in Table I. The viscosities of the fluids varied from 41.2 to 288.1 mPa.s.

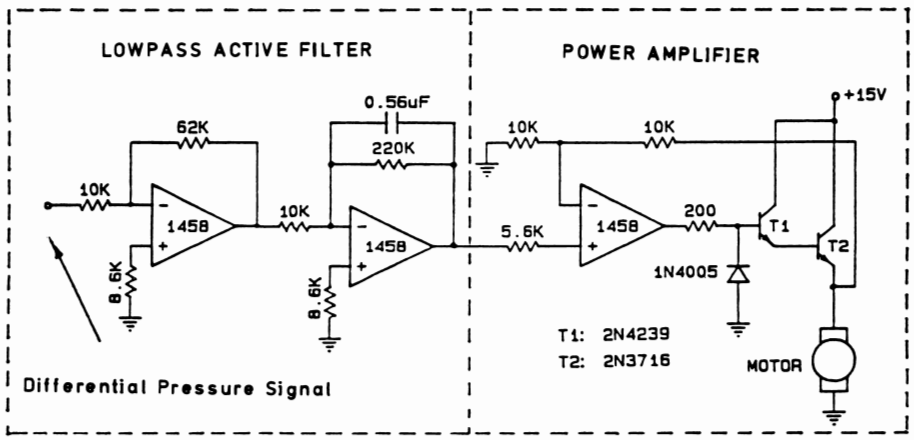

Figure 3. Circuit diagram for metering pump motor control.

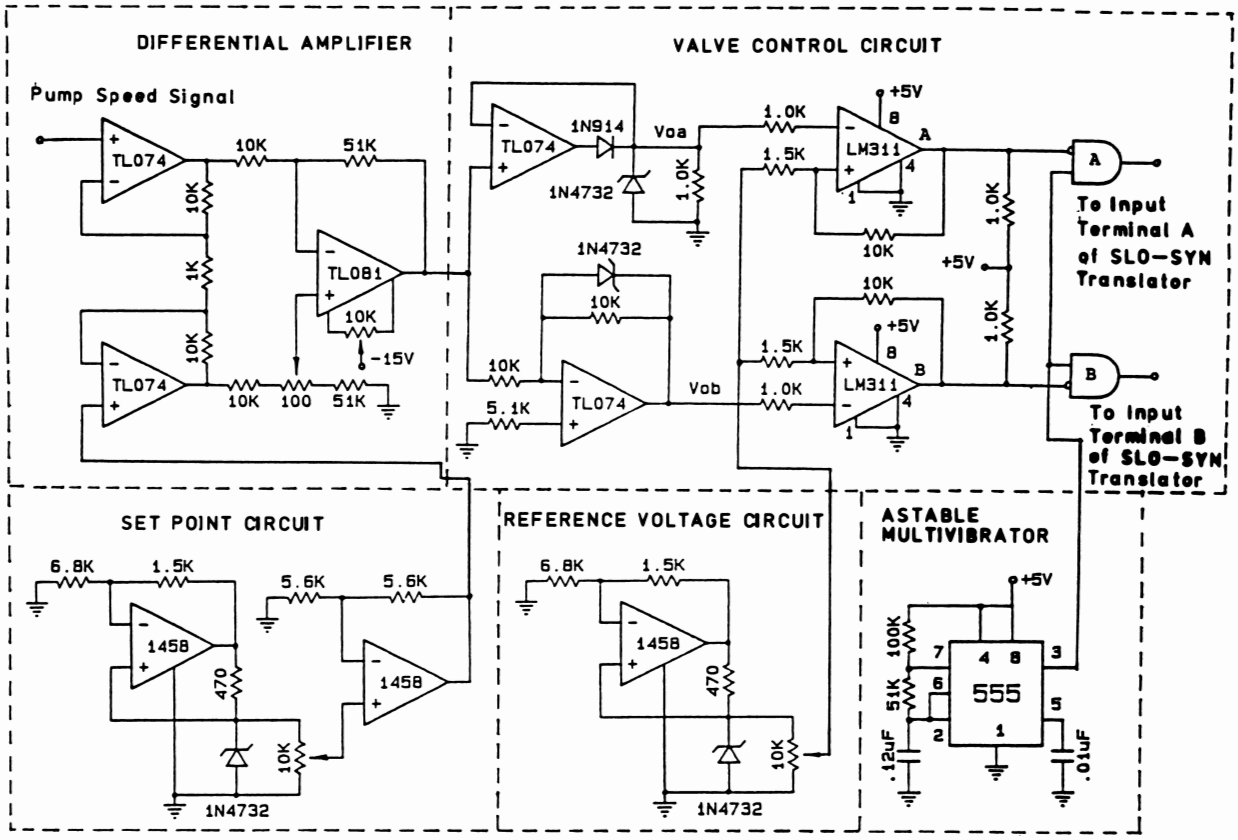

Figure 4. Circuit diagram associated with valve control.

Table I. Fluid properties (at temperature of 20 – 22°C)

Fluid	Saybolt universal viscosity (s)	Density (kg/m³)	Dynamic viscosity (mPa·s)
30 oil	1648.3	892	288.1
30 oil (+10)	1221.1	890	217.9
10w oil (+30)	497	882	89.6
10w oil plus diesel fuel	221	813	41.2

Characteristics of pressure drop signal

The relationship between flow rate and differential pressure was tested for each fluid at different meter speeds. The actual flow rate was measured by using a graduate cylinder and a stop watch. A linear equation was obtained from the test data between the actual flow rate and the differential pressure across the metering pump.

Table II lists the results of the regressions of flow rate measured and pressure drop across the metering pump. The leakage flow was always from the high pressure to the low pressure. Since the coefficient B is positive, the test data confirm the above hypothesis. When the differential pressure was positive the leakage flow was from inlet to outlet and when the differential pressure was negative the leakage flow was from outlet to inlet. Thus, the flow rate was larger when differential pressure was positive than when differential pressure was negative.

The differential pressure signal oscillated. Since this signal was used to control the metering pump motor, the oscillation could affect the system performance. The pressure signal was recorded on a tape recoder and digitized with an analogue-to-digital converter and ILS software (interactive laboratory system, Signal Technology, Inc.) using the VAX 11/780 computer. The FFT (fast fourier transformation) technique was used to study the frequency components in the pressure signal. The IMSL library (IMSL Inc.) on VAX 11/780 computer was used to perform the FFT analysis. The analysis was conducted for different fluids under different pump speeds. Figures 5 and 6 show the frequency spectra of differential pressure signals at two different pump speeds. The similar results were obtained for other pump speeds. There was a peak of the spectrum at the frequency four times as the pump speed. Since the metering pump had four vanes the oscillation under this frequency was produced by the metering pump. Also, the second peak of the frequency spectrum was around 10 Hz (Fig. 6). This effect was assumed to be produced in the hydraulic system. A lowpass active filter with cutoff frequency 1.2 Hz was built to eliminate oscillation as mentioned in the pump motor control circuit.

Relationship between the set voltage and flow rate

The relationship between the actual flow rate and the set voltage was tested with four different fluids. The set voltage was varied to make flow rate change from 3 to 20 mL/s. This was calculated by assuming an application rate from 3.5 to 14.0 L/ha, and travel speed from 4.8 to 8.0 km/h and a boom width 6.1 m. The results are shown in Fig. 7. The curves show that, for three high-viscosity fluids the flow rate varies linearly with the set voltage. However, for the least viscous fluid the relationship between the set voltage and flow rate was more like a quadratic.

A regression method was used to analyze the data from the test for each fluid and each model. The regression equation used for three high viscosity fluids is:

$$Q = B1 \times Vs \quad (3)$$

Table II. The results of linear regression for the equation $Q = A + B \times \Delta P$

Viscosity (mPa·s)	Pump speed (rpm)	SE†	R^2‡	A (mL/s)	B (mL/(s·Pa))
217.9	562.5	0.0601	0.9978	4.071	0.01244
	937.5	0.0374	0.9989	6.480	0.01260
	1312.5	0.0010	1.0000	8.881	0.01277
	1687.5	0.1171	0.9874	10.610	0.01060
	2062.5	0.1183	0.9939	13.160	0.01306
	2437.5	0.4347	0.9144	16.660	0.09755
89.6	562.5	0.1495	0.9950	4.055	0.01907
	937.5	0.0425	0.9178	6.780	0.01349
	1312.5	0.1140	0.9915	9.362	0.01354
	1687.5	0.0412	0.9988	11.810	0.01024
	2062.5	0.1144	0.9910	14.990	0.01095
	2437.5	0.1079	0.9931	18.500	0.01907
41.2	562.5	0.1181	0.9940	2.210	0.01639
	937.5	0.1173	0.9953	5.270	0.01690
	1312.5	0.0122	0.9999	8.461	0.01753
	1687.5	0.1485	0.9968	12.800	0.02659
	2062.5	0.1472	0.9978	17.370	0.02922
	2437.5	0.1281	0.9974	23.150	0.02514

†SE, standard error.
‡R^2, correlation coefficient.

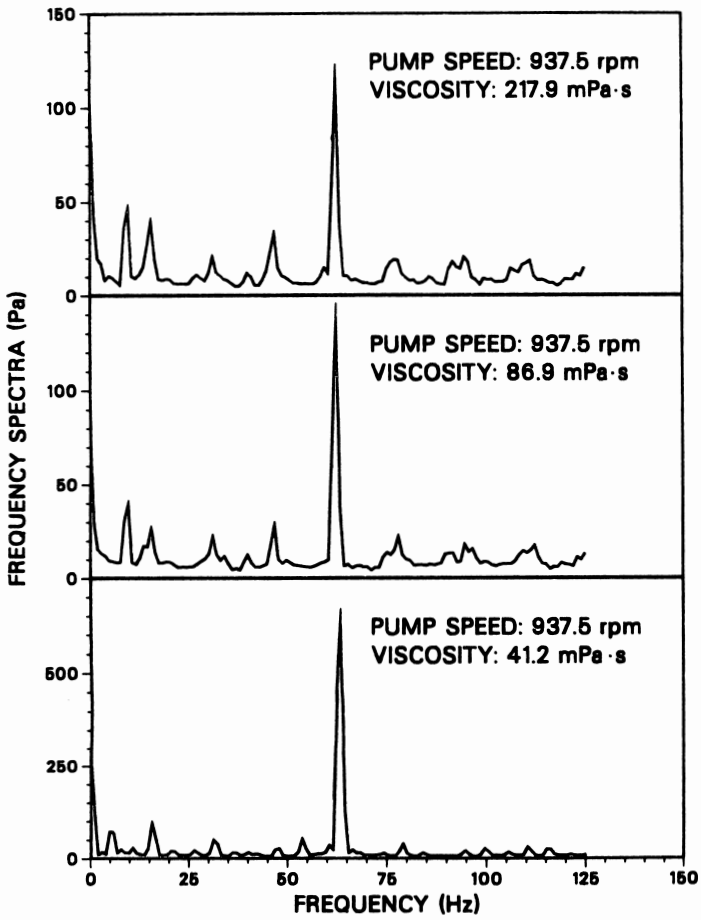

Figure 5. Frequency spectra of differential pressure signal at pump speed of 937.5 rpm.

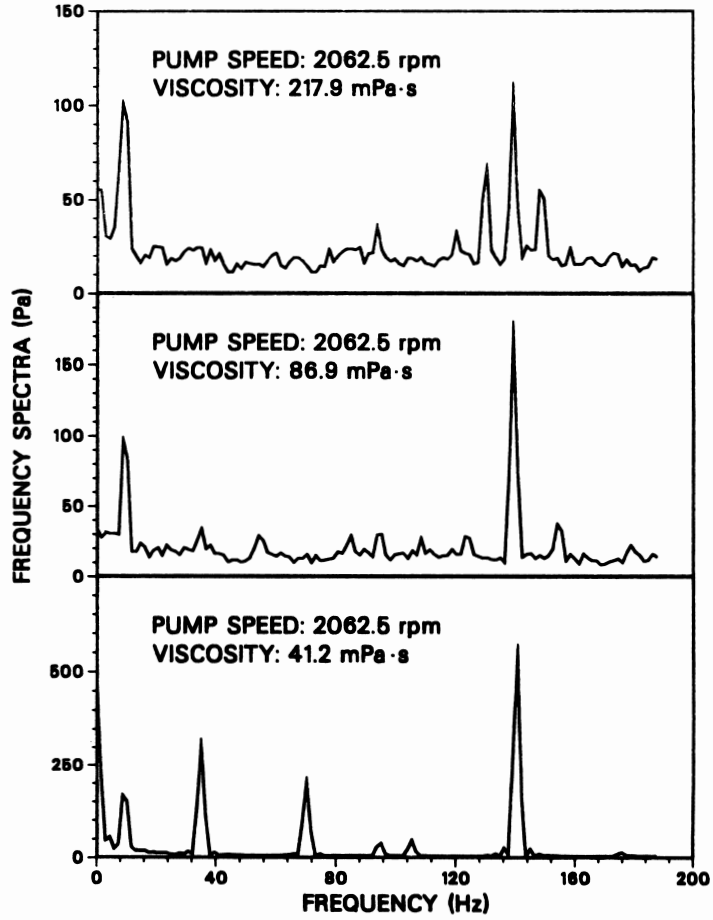

Figure 6. Frequency spectra of differential pressure signal at pump speed of 2062.5 rpm.

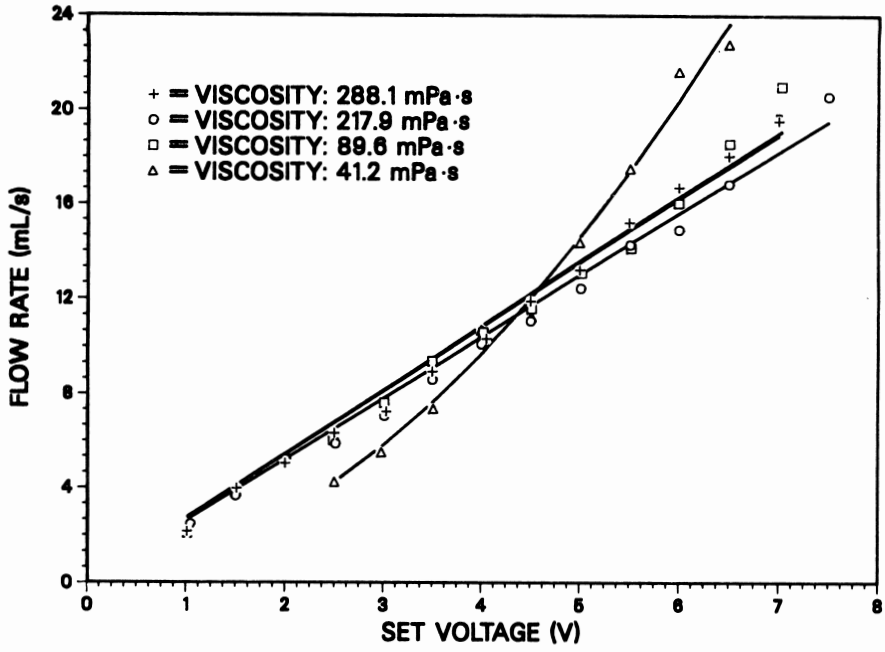

Figure 7. Relationship between the set voltage and flow rate.

For least viscous fluid the regression equation is:

$$Q = B1 \times Vs + B2 \times Vs^2 \quad (4)$$

where

Q = actual flow rate (mL/s).
Vs = set voltage (V).
$B1, B2$ = coefficients.

The results are given in Table III. The correlation coefficients for all the fluids and models are higher than 0.99. For three high-viscosity fluids one linear equation can express the relationship between the flow rate and set voltage.

Table III. Results from the regression for the relationship between the flow rate and the set voltage ($Q = B1 \times Vs + B2 \times Vs^2$)

Viscosity (mPa·s)	SE†	R^2‡	$B1$	$B2$
288.1–89.6	0.1371	0.9997	2.669	—
41.2	0.4694	0.9979	0.4694	0.4880

†SE, standard error.
‡R^2, correlation coefficient.

Performance of control system

Tests also were conducted to determine if the system would reach the desired steady state when started and when the set voltage was changed. The first test was made under a start-up condition to determine whether the system would reach the desired steady state and how long it would take to reach that state. The needle valve was set in the closed position and the set voltage was selected at 2.0, 4.0 and 6.0 V corresponding to flow rates of 5.3, 10.7 and 16.0 mL/s. The tests were conducted with two fluids of viscosity 41.2 and 288.1 mPa.s. The metering pump speed signal and differential pressure signal were recorded with a tape recorder. Figures 8 and 9 show some of the recorded signals. Similar results were obtained for other signals.

The settling time, which was defined as time interval from the system start up to the desired steady state, was measured from the metering pump speed signal (Figs. 8 and 9). The results (Table IV) show that the settling time for low-viscosity fluid was shorter than that for high-viscosity fluid. The settling time for a high set speed was longer than that for a low set speed, because the valve was set in the closed position at the start and a high set speed means that the valve must open wider than that for the low set speed.

The condition in the first test was an extreme case and would happen only at the system start up. The usual condition would be when the system was working at a certain steady state level and the travel speed was changed. Then the system would follow this change to reach another steady state. The second test was based on this situation.

In the second test the set voltage was set at 4.0 V prior to turn on the system. When the system reached a steady state, the set voltage was adjusted to approximately 5.0 V. The set voltage, pressure drop, and the pump motor speed were recorded. The results are shown in Fig. 10 and Fig. 11. The figures show that the system needed approximately 3.5 s to reach another steady state when the set voltage was changed approximately 1.0 V (corresponding to 2.67 mL/s flow rate change).

This delay was mainly produced by the hydraulic system (pump, valve, pipe, etc.). When the valve turns a certain angle,

Table IV. The settling time of the control system

Viscosity (mPa·s)	Set voltage (V)	Settling time (s)
41.2	2.00	2.542
41.2	4.00	2.740
41.2	6.00	4.976
288.1	2.00	4.705
288.1	4.00	3.245
288.1	6.00	4.327

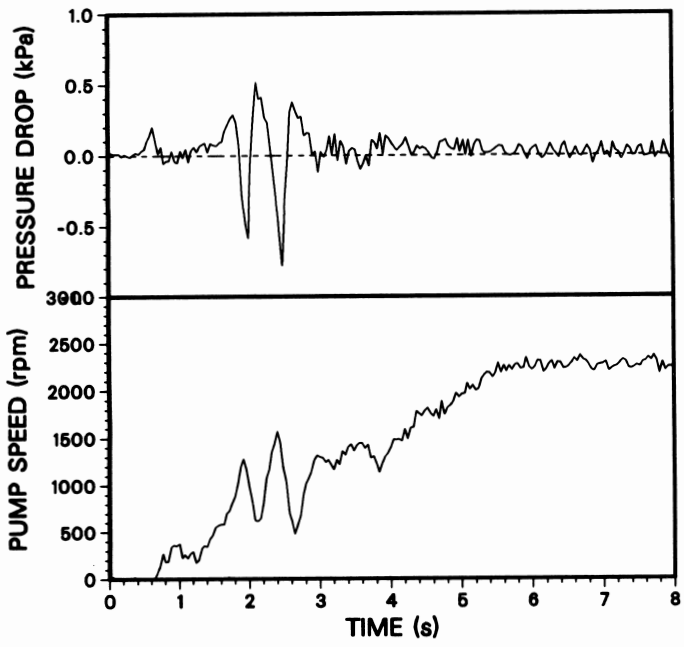

Figure 8. Response performance of the system at starting with viscosity of 41.2 mPa.s and set voltage of 6.0 V.

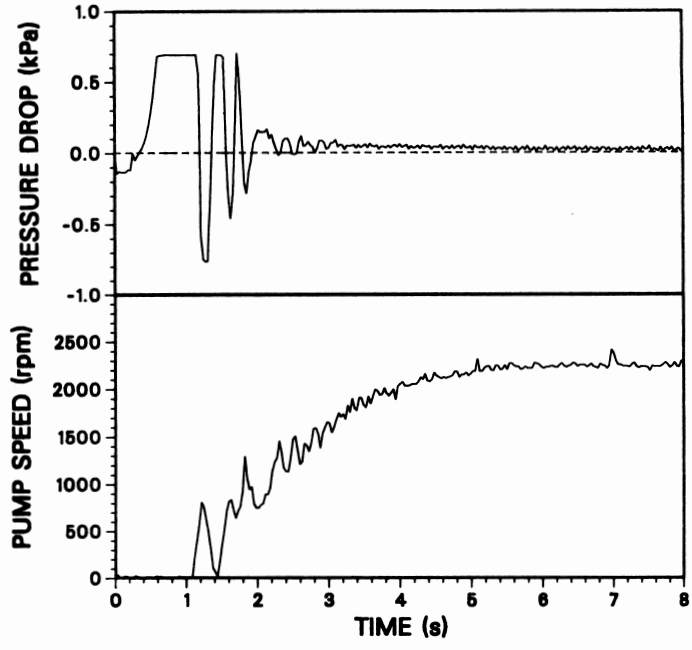

Figure 9. Response performance of the system at starting with viscosity of 288.1 mPa.s and set voltage of 6.0 V.

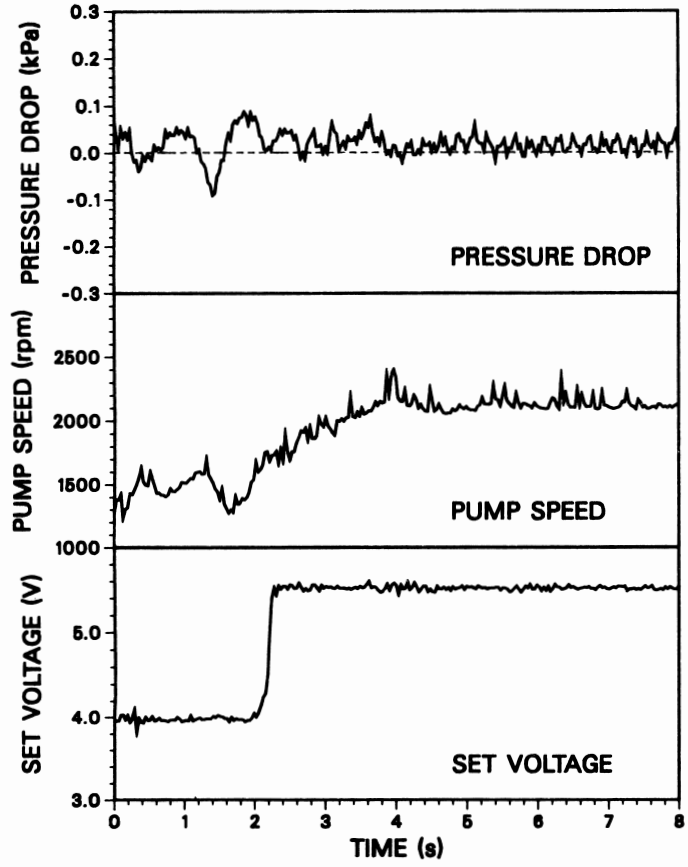

Figure 10. Response performance of the system when the set voltage was changed with viscosity of 288.1 mPa.s.

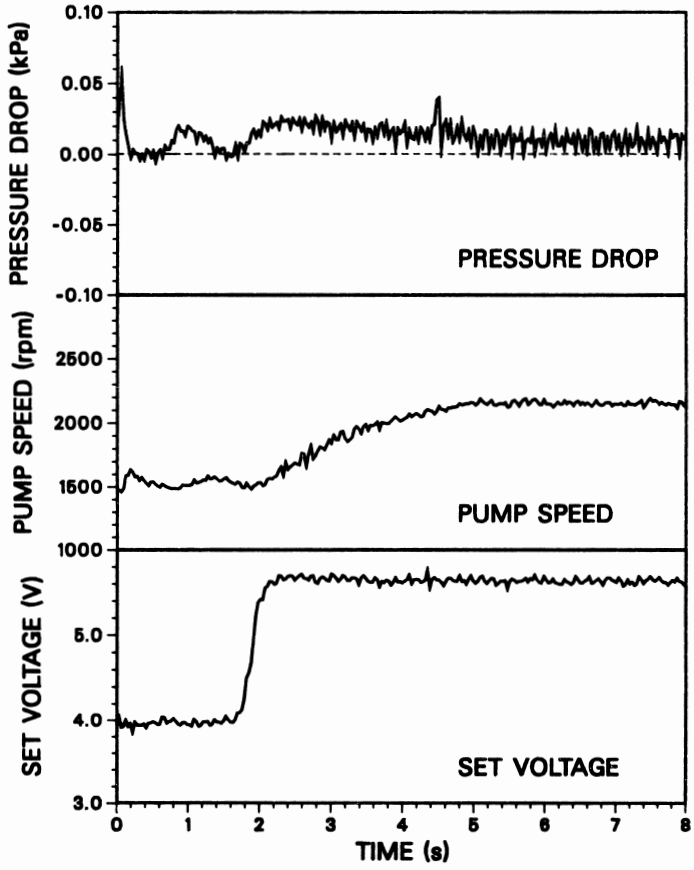

Figure 11. Response performance of the system when the set voltage was changed with viscosity of 41.2 mPa.s.

the hydraulic system needs some time to reach its steady state. This time interval was much longer than that in the electronic circuits and elements. Since the motor controlled the differential pressure across the metering pump, the pressure signals reached steady state very quickly. The pump motor speed controlled by the valve changed slowly to reach the steady state. The valve rotary speed could be increased by raising the frequency of the square wave signal in the valve control circuit. However an increase in this frequency will cause the system (valve and metering pump) to oscillate.

The energy consumption of the metering system was calculated from the motor voltage and current from the flow rate test (Fig. 12). The curves show that the higher the viscosity, the more energy was consumed in the metering pump. The electro-servo motor must be able to provide enough power for the highest viscosity fluid at highest flow rate. Otherwise the system would not keep the pressure drop near zero.

CONCLUSIONS

The control system, in which an electro-mechanical feedback volumetric flow rate measurement was used, worked well for fluids with viscosity from 90 to 300 mPa.s and with flow rate from 3 to 20 mL/s. The actual flow rate of the system was proportional to the set voltage and the pump speed for the above fluids. A single linear equation was used to express the relationship between the flow rate and set voltage. Thus, only a single calibration was needed for the above fluids. For fluids with viscosity lower than 90 mPa.s, the leakage flow became significant and the relationship between the flow rate and pump speed would then become a quadratic. This leakage flow would be mainly due to the structure of the metering pump.

An electronic circuit was designed to control the differential pressure and the metering pump speed. The results show that the control circuit works well. The differential pressure across the metering pump was less than 50 Pa for most conditions, and the pump speed varied linearly with the set voltage. There was a delay in the response of the control system which was mainly produced by the characteristics of the hydraulic system.

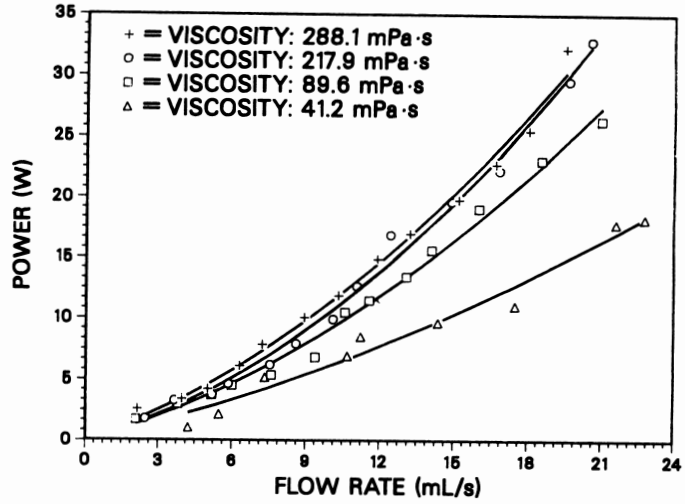

Figure 12. Power consumption in the metering system.

The electro-servo motor used was capable of providing enough power for the highest viscosity fluid at highest flow rate, in order to keep the pressure drop at near zero.

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