ACKNOWLEDGMENT

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Thermal Pulse Time-of-Flight Liquid Flow Meter

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A novel method uses no orifices or moving parts but rather dual glass-encapsulated thermistor probes to impart a heat pulse into the flowing liquid and to detect its arrival downstream. Detection triggers a subsequent upstream thermal pulse and the cycle repeats. The time of flight of the warmed zone is thus inversely related to liquid flow and the digital output is inherently computer compatible. A key to achieving dependable operation is electronic double time differentiation of sensor output to reject characteristically slower ambient thermal drift and to minimize response time in preparation for subsequent pulse detection. The meter is capable of measuring liquid flow rates between 0.1 and 10.0 cm^3/min with a precision of at least 0.1% (σ). The flow cell's glass and inert plastic composition makes it highly corrosion resistant. Besides its general utility in flow metering, this method is especially well suited to HPLC applications.

Although liquid flow metering is commonly practiced, approaches to measure flow in the cm^3/min range have been complex, inaccurate, or quite awkward to use. In liquid chromatography, inevitable flow vagaries in these lower ranges must be continuously monitored to ensure precise retention volume and time-integrated peak measurements (*1*). In size exclusion chromatography (SEC) and hydrodynamic chromatography, the very identification of sample molecular weight or particle size is predicated upon accurate knowledge of eluent flow history during a separation (*2, 3*). High precision "constant-flow" pumps are intended to permit elution volume measurements based on calibrated pump setting and time, but random and systematic flow fluctuations are nevertheless unavoidable in actual practice and interfere with volume determination. No pump can deliver absolutely constant flow under all operating conditions (*4*).

Flow rate may be measured automatically via a siphon counter wherein each "dump" of the siphon activates a photoelectric switch; but this technique suffers from poor day-to-day reproducibility (*5*), particularly as the siphon is miniaturized or employed with aqueous solvents. Direct weighing of eluent on an analytical balance is a flow metering alternative, but its size, cost, and periodic dump requirement together with elution behavior's common dependence on volume rather than mass all argue against its selection. Another current flow metering choice is a sensitive pressure transducer placed across a restriction in the flowing stream, although here the output varies with fluid composition and requires recalibration as the restrictor undergoes slight plugging or corrosion. Several additional methods based on bubble introduction or electromechanical manipulation commonly exhibit much greater than 0.1% variation as a consequence of fluid compressibility, mechanical hysteresis, or wear (*6*). Free drop counting methods are hindered by compositional effects on surface tension and wetting properties' great influence on final drop size.

Thermal methods have been applied to the measurement of liquid flow rate (*7, 8*). The "thermal dilution" principle exploits the proportionality between flow and the extent of cooling of an immersed, self-heating probe to detect flow rate (*9–11*). The principal obstacle to precise chromatographic flow metering on such a basis is the sizable influence of the fluid's specific heat on the result; compositional changes severely alter the measurement. A recent thermal pulse, time-of-flight aproach to chromatographic flow metering directly immerses steel wire filaments and thermocouples in a two-cell series arrangement (*12*). Direct immersion of uncoated wire and alternately operated dual detector cells are thus called for because of thermal recovery rate limitations. This technique is handicapped by its two-cell complexity and inevitable corrosion of the immersed wires impairing their operation.

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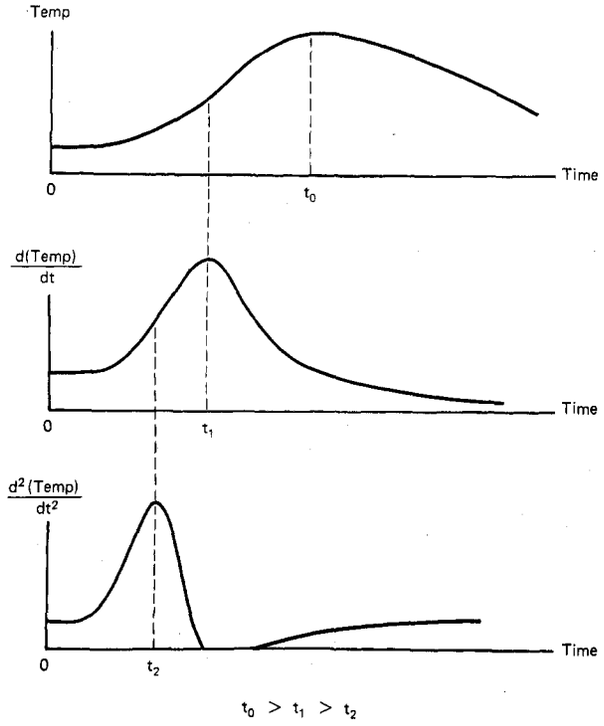

Figure 1. Thermal pulse wave form at the sensor.

The thermal pulse time-of-flight method reported here employs corrosion-resistant glass-coated thermal probes in a unique manner that overcomes the thermal recovery rate problem, opening the way to highly precise single-cell flow measurement with long-term stability.

EXPERIMENTAL SECTION

Principle of Operation. Triggered by thermal pulse detection downstream, a glass-encapsulated probe again generates a heat pulse so that instantaneous flow rate may be calculated from thermal pulse time of flight in the defined flow channel. Since encapsulation of heater and sensor ensures corrosion resistance and long-term stability, glass-coated thermistors are convenient selections for both, with the upstream thermistor employed in a pulsed, purely self-heating mode and the downstream thermistor engaged as a temperature sensor. Thermistors are attractive for both functions because of their wide variety of available sizes, low cost, large temperature coefficients compared to other element types, and well-documented and uniform electrical characteristics (*13*).

The challenge is to overcome the response time limitations imposed by the glass encapsulating mass. The downstream sensor is simply chosen to be extremely tiny (0.010 in. o.d.) to optimize response rate. The upstream heater, however, must be massive enough to produce a thermal pulse sensibly distinct above ambient temperature fluctuations downstream but sufficiently tiny to cool in time to generate a subsequent pulse.

As the heated zone is conveyed the length of the flow cell, heat transfer disperses the warmed zone axially so that the thermal pulse unavoidably encounters the sensor as a gradual rather than step temperature change, as portrayed in the upper section of Figure 1. Each temperature pulse is no more than 1 °C and may be superimposed upon a gradual temperature drift of ±5 °C. To reject this drift and lock reliably into step with the in situ pulse, the second time rate of change of temperature is derived and amplified electronically, as exemplified by the bottom wave form of Figure 1. In this way, not only is the method rendered insensitive to spurious temperature drift but also any delay in pulse detection is reduced, as shown by the improving response time trend: t_0, t_1, and t_2 in Figure 1.

The detected pulse is amplified and fed to a timing circuit that supplies about 100 mW of power to the upstream self-heated thermistor for a fixed duration, typically 0.8 s for a 0.5–5.0 cm^3/min flow rate. Figure 2 shows this feedback triggering process in block diagram form. Use of a negative temperature coefficient

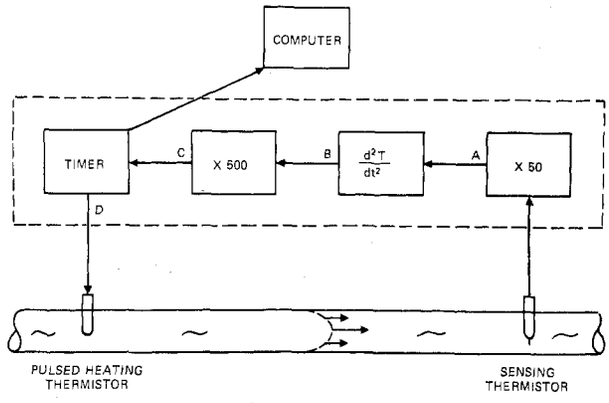

Figure 2. Flow meter operation.

thermistor as heater offers an added thermal pulse shaping advantage in that as the probe warms, it turns itself off due to power transfer to a series resistor. The geometry of the heater thermistor aids in the generation of sharp thermal pulses as well, since its active metal oxide semiconducting core is easily centered on the flow passage axis, minimizing wall effects and smearing while maximizing the exposed heat-exchanging surface area.

During the heat-triggering pulse, a timer circuit furnishes a signal to an external recording device or computer, each pulse representing the passage of about 50 μL of fluid.

When flow exists, an externally actuated first pulse awakens the metering system into continuous self-sustained operation.

Apparatus. *The Circuit.* As shown in Figure 2, the circuit must generate a heat pulse in response to downstream heat pulse detection. Sensor and heater appear in Figure 3 along with details of the electronics that accomplish this operation.

Fluid flow conveys a heated zone as shown by the arrow to the left of the figure. The sensor responds to warming by decreasing in resistance (−4%/°C) and feeding a positive-going signal to the input of the first amplifier, which in turn produces a 50-fold amplification at position A. By virtue of capacitively-coupled inputs, the subsequent two amplifiers extract the second time rate of change of this temperature signal and generate a zero-drift wave form at position B (*14*). The approximate shapes of the pulse wave form are depicted within the figure.

Additional signal gain and high-frequency filtering are afforded by a final amplifier whose output (C) is fed to a switching transistor that activates a timing circuit. By maintenance of a fixed duration of applied power, pulse characteristics have no feedback effect on the nature of the subsequent pulse, affording stable operation in spite of composition and flow rate changes.

Each cycle the timer circuit engages a relay that imparts a current pulse to the upstream self-heating thermistor along with a floating switch closure to communicate the event to external recording equipment.

Operating begins when the manual "start" pushbutton artificially activates the heat pulse timer circuit. The meter continues thereafter to self-trigger reliably as long as adequate flow is maintained in the flow cell.

The Flow Cell. In order to achieve resistance to solvent attack in flowing media ranging from corrosive aqueous solutions to powerful organic solvents, wetted surfaces of the flow cell are limited to Teflon and Kalrez plastic resins and glass. The flow channel is machined from a 1 in. square block of glass-filled Teflon as shown in Figure 4 in an exploded view. Thermistors are easily centered and sealed into the flow channel by means of tiny O-rings under compression around the circular thermistor glass bodies. Owing to their perfluoroelastomeric composition, the Kalrez O-rings are extremely resistant to chemical attack. Assembled finger-tight, the flow cell maintains up to 300 psig fluid pressures without leaking. The 1.5 in. thermistor spacing shown in Figure 4 creates a cell volume of about 75 μL, suited to metering flow accurately in a range of about 0.5–5.0 cm^3/min. Flow cells of 0.5 in. and 2.0 in. probe spacings extend the range of flow rates to 0.1–10.0 cm^3/min, respectively.

This flow cell design allows easy assembly and thermistor replacement, although no failures have occurred in thousands of hours of operation.

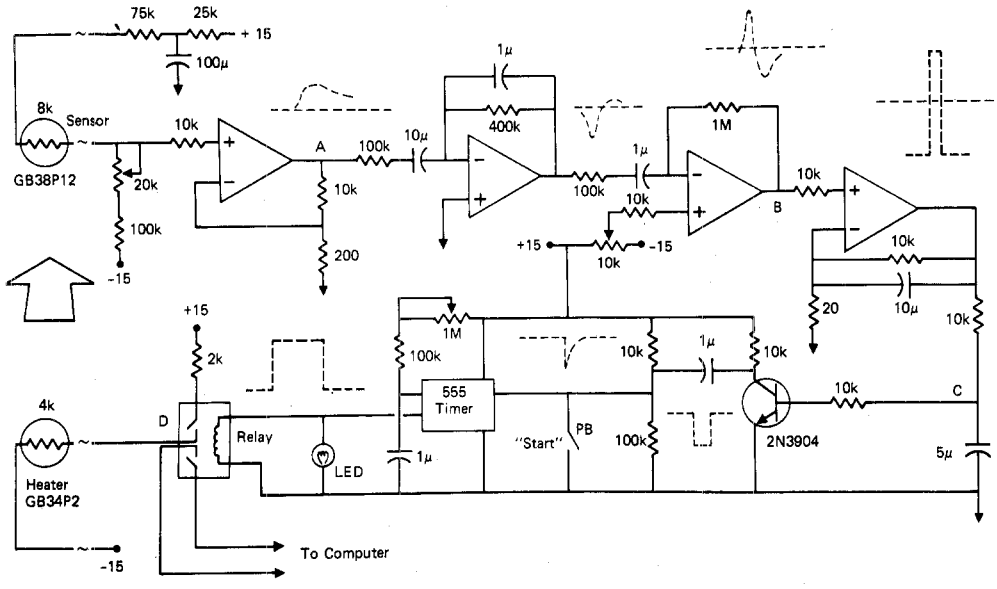

Figure 3. Electronic circuit detail. Dotted line wave forms show pulse conditioning.

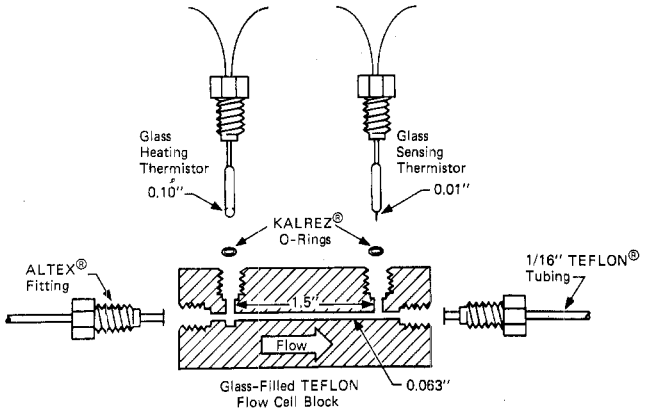

Figure 4. Flow cell, exploded view.

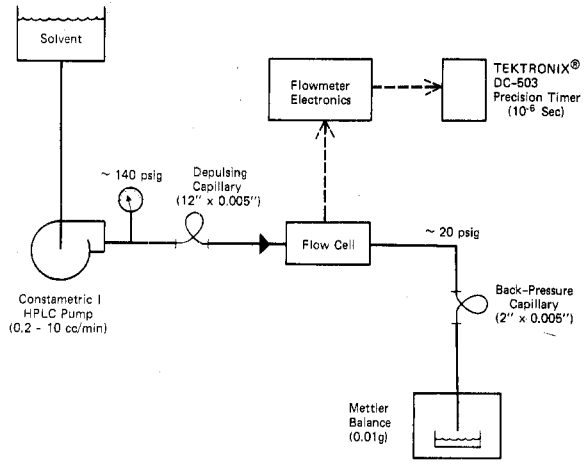

Figure 5. Flow meter calibration apparatus.

Calibration. The pulsing output from the flow meter relates to volumetric fluid flow according to the equation

$$T = V/f + K \quad (1)$$

where T is the pulse time period, V is the effective flow cell volume, f is flow rate, and K is a constant time. The time-of-flight contribution to total time is represented by the V/f term. The K term above arises from small delays in thermistor heating and in the time differentiation circuitry as indicated in Figure 1. Both V and K for a given metering system remain constant so that once they are determined via calibration, instantaneous flow is thereafter calculated from the measured time period between pulses, T, and eq 1. Note that the pulse time period, T, is the only externally monitored output and contains fluid time of flight (V/f) and constant time increment (K) components. The terms of t_0, t_1, and t_2 in Figure 1 illustrate how K has been minimized using time-differentiation circuitry.

To establish the calibration constants V and K, one must measure actual flow rates and corresponding pulse time periods.

The flow meter calibration apparatus in Figure 5 employs a pulseless 0–10 cm³/min HPLC pump with a gauge/capillary combination downstream to smooth the flow of solvent through the flow cell. Actual flow is determined for each pump setting by timing the accumulation of effluent on an analytical balance. The corresponding elapsed times between pulses, T, from the flow meter are measured with microsecond resolution by a Tektronix DC-503 precision digital timer, with at least 15 intervals recorded and averaged for each stabilized flow setting.

By use of deionized water as the eluent in the Figure 5 arrangement, the mean pulse period, T, relates to actual flow as shown in Table I. Linear regression analysis of these typical data yields an effective flow cell volume of 0.0480 cm³ and a constant

Table I. Example Calibration Results

nominal flow rate, f, cm³/min	actual flow rate, f, cm³/min	f^{-1}, s/cm³	av[a] pulse period, T, s
5.0	5.30	11.3	1.1826
4.5	4.78	12.6	1.2384
4.0	4.25	14.1	1.3078
3.5	3.74	16.0	1.3987
3.0	3.20	18.8	1.5240
2.5	2.64	22.7	1.7020
2.0	2.13	28.2	1.9729
1.5	1.61	37.3	2.4327
1.0	1.06	56.6	3.3449

[a] Each determined from at least 15 timings of microsecond resolution.

K value of 0.630 s for this example apparatus. The correlation coefficient result is 0.9999, indicative of excellent linearity. These calibration constants remain identical for a number of other solvents so far tested. These include acetone, chloroform, dimethylformamide (DMF), isopropyl alcohol, tetrahydrofuran (THF), and toluene.

In another laboratory, flow rate measurement precision has been examined in a ±0.01 °C temperature-controlled LC apparatus with more extensive pump pulse smoothing and high-speed computer data acquisition (*15*). In these experiments the standard deviation in pulse time period, T, is about 0.1% of its mean value

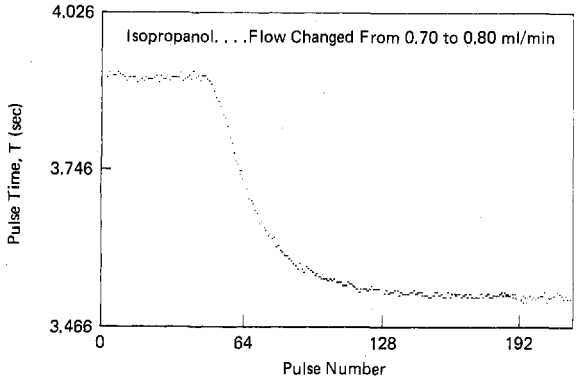

Figure 6. Pulse time reduction with 0.1 cm^3/min flow increase.

for 256 consecutive pulses when eluent flow is maintained as constant as possible. The standard deviation of the flow measurement technique itself may be less than this 0.1% since residual random variations in actual flow contribute to this value, quite possibly the greater part. Interestingly, the standard deviation in elapsed volume represented by a single flow meter pulse is thus less than 0.05 μL. Normal changes in laboratory ambient temperature (±5 °C) have no observable effect on measurement accuracy.

When pump setting is abruptly altered from 0.70 to 0.80 cm^3/min, timed pulses from the flow meter vary as shown in Figure 6. The observed exponential approach to a reduced pulse time period, T, is as expected for a 0.1 cm^3/min flow rate increase, with the time constant of the flow rate change characteristic of the volume and mechanical compliance of the system being monitored.

RESULTS AND DISCUSSION

The calibration linearity validates the assumption that effective flow cell volume, V, and the term K are constant and independent of flow rate itself. But the effective flow cell volume in the example (48.0 μL) differs substantially from its geometric, void value (76.7 μL). What then, is the physical meaning of "effective" flow cell volume in the laminar flow situation that prevails in this metering arrangement?

Assuming Newtonian fluid behavior and no-slip conditions at the cylindrical flow cell walls, fluid velocity, u, relates to radial position, r, as measured from the central axis according to

$$u(r) = \frac{\Delta P}{4\mu L}(R^2 - r^2) \tag{2}$$

where L is cylinder length and R its radius, ΔP is the pressure difference across L, and μ is fluid viscosity (*16*). Fluid velocity at the central axis ($r = 0$) is at a maximum

$$u_{max} = \frac{(\Delta P)R^2}{4\mu L} \tag{3}$$

but total volumetric flow depends upon average fluid velocity $\bar{u}$, which may be expressed as

$$\bar{u} = \frac{\int u(r)\, dA}{A} = \frac{(\Delta P)R^2}{8\mu L} \tag{4}$$

where A is the circular cross-sectional area of the flow passage. Thus a fixed ratio relates actual volumetric flow velocity to the velocity

$$\bar{u}/u_{max} = 50\% \tag{5}$$

observed by the approximately centered flow metering probes.

How does this velocity ratio account for the above inequality between effective (calibrated) and geometric (void) flow cell volume? If fluid velocity were radially uniform, it would equal the average value, $\bar{u}$, and time of flight in the passage would simply be geometric volume divided by flow rate. But since the centered probes observe velocity greater than the average, calibration yields a smaller cell volume, in proportion to the $\bar{u}/u_{max}$ ratio. Fortunately, since this velocity ratio is constant for Newtonian fluids, calibration using effective volume is capable of the excellent accuracy seen above.

The flow meter is now based on a single printed circuit board for reliability and ease of manufacture. A majority of the applications to date within The Dow Chemical Company have been to provide corrections for pumping imprecision in liquid chromatographic systems, but there are potential uses in medical, catalyst feed, and fuel conservation areas as well as in any automated production process requiring minute liquid volume handling.

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