NON-INTRUSIVE PIPE FLOW MEASUREMENT BY CROSS CORRELATION OF TEMPERATURE VARIATIONS

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ABSTRACT

The flow of water in pipes has been measured by placing thermistors at two points along a pipe's surface and measuring the temperature variations (on the order of 30 sec duration) as the fluid passes. Cross correlation of the two sets of temperature versus time data is used to determine the time delay from the upstream to the downstream sensor. The distance between the two sensors is then used to calculate an estimate of the bulk fluid velocity.

This technique was first used in the laboratory on a half-inch copper pipe. The temperature variations were introduced with a propane torch applied to the pipe upstream from the sensors and data were taken using a microcomputer with an analog input module. The flow rate calculated using cross correlation was lower than that obtained by timing the flow into a graduated cylinder, especially at the higher rates tested. Significantly better agreement was obtained in tests where the temperature variations were introduced using valves to vary the mix of cold and hot water. For these tests, flow rates calculated were less than 20% below the actual values. The observed consistent underestimation was hypothesized to be an effect of either the boundary layer or the heat capacities of the fluid and the pipe. A simple plug flow simulation of the thermal interaction between the fluid and the pipe gave accurate flow rates thus indicating that the consistent underestimation was caused by the fluid boundary layer.

The technique was tested on a two-inch copper pipe of the domestic hot water system in the boiler room of a 62 unit apartment building which had also been instrumented with in-line flow meters. This test showed that sufficient temperature variations exist in the normal operation of the system to deduce flow rates with an uncertainty of less than 20%.

The method appears to be a useful diagnostic tool. More experimentation and testing is suggested in order for this technique to be used with confidence on pipes of various sizes and compositions and in various flow regimes.

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INTRODUCTION

The measurement of fluid flow through pipes in building mechanical systems or industrial processes is usually done using flow meters of some sort placed directly in the fluid stream. In an existing system, the installation of a flow meter is often unreasonably disruptive or costly, involving a complete draining of the system, several hours of down time, and a significant expense for labor and equipment. Thus for short term measurements such as those required by energy audits or building diagnostics, the ability to measure flow in a "non-intrusive" manner[1] is a great asset.

Large buildings often use pipe loops for circulation of hot water for space heating and domestic purposes, and these distribution systems can be a major source of heat loss. The ability to quantify this loss as a part of a routine energy audit procedure would lend greater confidence to the selection of energy conservation measures and better precision to the prediction and measurement of energy savings. The measurement of the flow of oil into a burner during its operation would be another important application, determining more directly its energy input.

There currently exist a number of commercially available devices which are used for non-intrusive flow measurement. However, each of these has disadvantages which are serious enough to make it undesirable for many applications. Existing non-intrusive techniques fall into three categories: ultrasonic transit time, ultrasonic doppler, and hot-wire anemometry. A review of "non-intrusive flow meters (Krigman, 1982) surveys available devices using these techniques and others such as the commonly used magnetic flow meters which usually must be inserted into the pipe and thus are not non-intrusive in the sense used here.

The ultrasonic devices (see Krigman, 1982 for manufacturers) are most successfully used for measuring the flow of slurries and wastes, especially in large diameter pipes. Transit time devices inject continuous ultrasonic signals both upstream and downstream into the pipe, then compare the transmission speeds of each. The measurements are rigidly dependent on the geometry and composition of the pipe and therefore a unique sensor arrangement is required for each pipe size and material. Small diameter pipes (less than one inch) do not lend themselves to this technique. Due to the short circuiting of the ultrasonic signal through the pipe wall, inadequate signal passes through the fluid.

Doppler techniques require that there be either particulates or bubbles suspended in the fluid, as sensors detect the ultrasonic signal reflected from such inhomogeneities, and fluids in field situations, especially potable water, are often too "clean" to enable use of this method.

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[1] "Non-Intrusive in this paper means that no intrusion into the pipe is necessary to install the flow meter. The use of this term should not be confused with other authors' broader use to include devices which do not disturb the flow once installed.

Hot-wire anemometry (ADEC, 1987) does not depend on pipe size or impurities, and is being used for submetering in some existing buildings. However, this method must be considered "semi-intrusive," as it uses at least a "hot-tap" method to insert a sensor directly into the flow.

The technique presented here utilizes frequent measurements of pipe surface temperature made at two locations some distance apart along the pipe. Flow velocity is determined using the time delay calculated between related temperature variations measured at the two locations. The delay time is calculated by maximizing the cross correlation of the responses of upstream and downstream sensors as a function of the delay time. This method has previously been explored (van Meulenbroek & Wakker, 1985) for the measurement of flow in the cooling pipes of a nuclear reactor, an application where non-intrusive techniques are commonly employed. A number of authors have discussed the general cross correlation method using signals of any type, not necessarily temperature (Gurevich & Kirshten, 1981; Coulthard, 1983; Koppermann, 1983; Medlock, 1984; Hargitai et al., 1984). Others have investigated the statistical error of the cross correlation analysis (Lassahn & Baker, 1982; Kebadze, 1984). This paper describes an application of the simplest cross correlation analysis to signals from temperature sensors for the measurement of water flow in the 1 to 3 inch diameter pipes commonly found in boiler rooms.

As an energy audit tool, the desired accuracy of the technique discussed here is better than 20%, similar to that of other instrumented energy audit procedures. Instrumentation configured to use this technique could be used to take instantaneous measurements of flow rate or could be left running for an hour or a day to get a more representative sample of the flow.

Correlation signal processing hardware exists (Coulthard, 1983; Medlock, 1984) but was not available for this project and was easily and inexpensively implemented using a personal computer. The equipment in this study consists of two thermistors attached to the surface of a pipe and a microcomputer outfitted with a data acquisition board. It is relatively inexpensive ($2000) and flexible enough to be used on a wide range of pipe sizes, types and flow rates. The software developed for this project displays the temperature variations graphically and in real-time and calculates the flow rates.

METHOD

The velocity of the fluid in the pipe is determined by measuring the time delay for temperature variations to travel between two points along the pipe. Two temperature sensors are mounted a measured distance apart on the surface of the pipe (see Figure 1). The flow rate is determined by computation of the time lag between the response of the upstream sensor and the downstream sensor.

Temperature variations occur naturally in all residential usage of hot water due to the on-off operation of the heater, introduction of cold (makeup) water, thermostat set-back, etc. The time lag, τ, is determined from the cross correlation between the signal outputs, $T_1(i)$ and $T_2(i+\tau)$, of the two sensors using the relationship:

$$r(\tau) = \frac{\Sigma\{[T_1(i) - \overline{T}_1(i)]\cdot[T_2(i+\tau) - \overline{T}_2(i+\tau)]\}}{\{\Sigma[T_1(i) - \overline{T}_1(i)]^2\cdot\Sigma[T_2(i+\tau) - \overline{T}_2(i+\tau)]^2\}^{1/2}} \qquad (1)$$

here $T_1(i)$, $T_2(i)$ are the sensor outputs and
$\overline{T}_1(i)$, $\overline{T}_2(i)$ are their means, e.g. $\overline{T}_1(i) = \Sigma^n_{i=1}T_1(i)/n$,

τ is the time lag and n is the number of points (temperature measurements).

The cross correlation is computed for each possible delay (up to half the time span in the whole data set). τ is the delay which gives the largest correlation coefficient, r. If L is the distance between the two sensors, then the flow velocity is simply:

$$v = L/\tau \tag{2}$$

From a handbook of standard pipe sizes, the inside diameter can be determined from the type, material, and outside diameter of the pipe to be examined. For typical hot water applications, standard pipes are used according to the plumbing codes established state or nationwide. If the inside diameter is unknown, it must be estimated based on the application involved. With inside diameter, D, and distance between the sensors, L, the volumetric flow rate is calculated as

$$f = \pi\ (D^2/4)\ L/\tau \tag{3}$$

The major assumptions in this method are: (a) that the thermal path between the fluid and the sensors introduces equal time delays at the two locations and (b) that the temperature variations in the fluid travel downstream at the fluid bulk velocity. It is important that the time dependence of the temperature variations be similar. The variation amplitudes at the two sensors may differ so long as they are both large enough to be detected. In terms of control theory, the above assumptions can be stated as: (1) the transfer function is the same between the fluid and each of the sensors, and (2) that the input function is the same at the two sensors.

EXPERIMENTAL SETUP

Two temperature sensors are brought in good thermal contact with the pipe surface (using heat sink grease) at a known distance from each other (Figure 1). The sensors could be thermocouples, thermistors or any other fast responding temperature-sensitive device[2]. In order to achieve resolution adequate for calculating τ, a pair of temperature measurements need to be made in a time which is no more than one tenth of the shortest delay time expected. The area of the pipes around and between the sensors is insulated to reduce heat transfer between the pipe and its surroundings. A bridge circuit (Figure 2) is used to transform signals from the sensors to a form suitable for recording by a data acquisition system (DAS). The DAS has two analog input channels with appropriate range. (A PC Mate Lab-Master analog/digital I/O board and an IBM-PC compatible microcomputer were used in these laboratory experiments.) The signals are sampled and digitized at a constant rate and are stored as two time series. Both sensors are read simultaneously. Typically, temperature variations appear with periods much longer than the delay time. For the cross correlation to produce useful results it is necessary to collect data for a period of time at least long enough to record an extremum (maximum or minimum) at each sensor. A cross correlation is then performed on the microcomputer, shifting the downstream

[2] The response time of the sensor/pipe system is determined by the pipe because its thermal mass is much greater than that of the sensors.

temperatures back one step at a time until the maximum correlation coefficient is found. This defines the time delay. With this information, the inside pipe diameter and distance between the sensors, the volume rate of flow is computed. In the lab, this is compared to the volume rate of flow measured using a graduated cylinder and a stop-watch. The accuracy of this calibration measurement is estimated to be better then 3%.

LABORATORY EXPERIMENTS AND RESULTS

Testing in the laboratory was carried out using several successive setups and the results are described in a working paper which includes the source code for the programs developed. (Feuermann et al. 1988) The program developed included a real time graphic display of the data which proved valuable in determining when temperature extrema had been measured. Temperature variations that are too small result in uncertain measurements and temperature variations that are too large saturate the analog to digital converter. Experimentation with different methods of introducing the temperature variations showed the importance of having the fluid well mixed. Adequate temperature variations were found in a building's domestic hot water (DHW) distribution loop (due to varying hot water draw causing cold makeup water to enter the loop). These large temperature variations appear to have cross-sectional temperature profiles more uniform than those created by heating the pipe externally. Figure 3 shows a sample data set and Figure 4 shows the cross correlations obtained. A summary comparing measured vs actual flow rates for 10 test runs is presented in Figure 5. A small but consistent under-estimation is evident. The Reynolds number for water in the ½ inch pipe is about 100 times the flow rate in cm^3/s so all the tests are in the region of turbulent flow.

FIELD TEST AND RESULTS

The thermistor/PC system was tested in the boiler room at Beechwood Apartments (a 62 unit building) in February 1987 (NJECL 1986). A diagram of the DHW heating system in use at the time is shown in Figure 6. The system consists of a large gas fired boiler with a circulation loop that supplies hot water to the 60 apartments. Flow meters are installed in the cold water makeup line[3] and in the circulation loop return[4] as part of the ongoing research on energy in multifamily buildings being conducted at the Center for Energy and Environmental Studies (see NJECL 1986). The thermistors for the non-intrusive flow measurements were located one foot apart on the supply side of the DHW circulation loop as indicated in Figure 6. The whole section of pipe around and between the sensors was insulated. At this point the flow should be the sum of the makeup water flow and the circulation loop return flow. The makeup cold water flowmeter was read visually at the beginning and

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[3] Positive displacement meter by Badger Mfg. Co., installed on 2" pipe. Installed cost: $1765 in addition to the cost of the DAS. Range: 8 to 160 gpm; accuracy: ± 2% of full scale (manufacturer's data).

[4] Magnetic paddle wheel flow meter by Signet Mfg. Co., installed on 3/4" pipe. Installed cost: $1205 in addition to the cost of the DAS. Range: 4 to 30 gpm; accuracy: ± 1% of full scale (manufacturer's data; tests by CEES staff indicate that paddle wheel cuts in at 3 gpm and drops out at 1.5 gpm when installed on 3/4" pipe).

end of each test and the return flowmeter data were recorded by the data acquisition system (DAS) every two minutes.

Since the cold makeup water enters the loop upstream from the thermistors, temperature variations were expected to occur as a result of hot water use. In order to create such variations some hot water was drawn into laundry tubs nearby as the temperature data were being recorded. Two thousand of the first 4000 data points are shown in Figure 7. Figure 8 shows the correlation coefficients plotted as a function of the time delay calculated for the 2000 point set and for each of its 500 point segments. The first segment did not include sufficient temperature variations to give an accurate delay (note the negative correlation coefficients) and the third segment included only a monotonically rising temperature which also did not yield a good measure of the time delay. The second and fourth segments, however, both included temperature extrema and hence the time delays obtained are expected to be meaningful.

Similar results were obtained from the four other data sets taken. In each run cross correlations were performed on the entire 4000 point data set. The results of these non-intrusive flow measurements are compared with flow meter data in Table I.

Table I. Field test results, 2/26/87, 1pm.

Non-Intrusive Method					Mechanical Flow Meter				Comparison		
Trial	Duration	Delay	Velocity*	Calc. flow	Makeup		Return	Meas. flow	Leakage	Const. (0.14)	
	min	sec	*cm/s*	*l/s*†	*l*	*l/s*	*l/s*	*l/s*	*l/s*	*l/s*	Ratio
1	3.927	2.53	12.0	0.233	41.6	0.177	0.157	0.334	0.100	0.194	1.20
2	3.927	2.77	11.0	0.215	51.1	0.217	0.156	0.373	0.159	0.233	0.92
3	3.927	3.77	8.1	0.158	45.4	0.193	0.146	0.339	0.182	0.199	0.79
4	3.927	3.53	8.6	0.170	68.1	0.289	0.095	0.384	0.216	0.244	0.69
5	1.907	2.37	12.8	0.252	37.9	0.331	0.095	0.426	0.176	0.286	0.88
Averages		3.00	10.5	0.205	48.8	0.241	0.130	0.371	0.167	0.231	0.90

*Distance between sensors: 30.5 cm (1.0 ft.)

†Inside diameter: 4.98 cm (1.96 in.)

Each row of the table represents a different experimental run. "Duration" is the total time for 4000 pairs of temperature measurements. "Delay is the time lag (τ) which yields the maximum correlation coefficient. The next four columns refer to the cross correlation measurement of the flow. "Velocity" is obtained using Equation 2 with L = one foot (30.5 cm). "Calc. flow" is the product of "Velocity" and the cross sectional area of the two inch pipe (19.4 cm^2).

The first column under "Makeup" is the volume (liters) of cold makeup water recorded by a Badger flow meter previously installed in the DHW system. This meter is read visually at the beginning and at the end of each run. The second column under "Makeup" gives this value divided by "Duration" to yield the makeup flow (l/s). "Return Flow" is the flow measured at the return end of the DHW circulation loop by another in-line flow meter connected to the DAS. The total flow into the circulation loop, "Meas. flow" (measured flow), should be the sum of "Makeup" and "Return Flow". Thus "Calc. flow" is to be compared to "Meas. flow".

Initially, the difference between the flow measured by the existing in-line flow meters and that calculated by the non-intrusive method was a surprise. Further thought suggested that the data could be explained by a leak into the boiler between the in-line flow meters and the non-intrusive one. Thus, the difference between "Meas. flow" and "Calc. flow" is titled

"Leakage." The next column, "Const. (0.14)" is the measured flow corrected using a long term average leakage of 0.14 l/s (see analysis below). The last column, "Ratio", shows the calculated flows divided by these "corrected" values.

All 5 runs showed more water flowing into the boiler than was flowing out into the DHW circulation loop. In fact, the excess averaged 0.167 l/s (2.6 gallons per minute) or 86% of the flow measured by the non-intrusive method. Laboratory tests had established that the errors in the non-intrusive flows were not more than 20% and the uncertainties in the makeup and return flow rates were of this order as well. Thus it is clear that the non-intrusive flow meter detected a leak in the DHW heating coils inside the boiler. Confirmation of this leakage rate was obtained from hourly DAS measurements of minimum DHW usage which usually occurs between the hours of 1 and 5 AM (Figure 9). (Feuermann et al. 1988) This minimum value rose monotonically from 40 to 530 liters per hour, (about 10 to 140 gallons per hour) between May 1986 and February 1987. After the boiler was replaced in March 1987, the minimum returned to its earlier value of 40 l/h (10 gal/h). The leakage into the boiler is thus measured to be 530 - 40 = 490 l/h or 0.14 l/s (2.2 gpm). Thus the flow measured using the mechanical flow meters is 0.37 - 0.14 = 0.23 l/s (3.6 gpm) is in reasonable agreement (13%) with the 0.20 l/s (3.2 gpm) value obtained by the cross correlation method.

DISCUSSION

The cross correlation of upstream and downstream temperature measurements has been shown to yield fluid flow rates to an accuracy of better than 20% when sufficient temperature variations are present in the fluid. The experiments show that the most reliable cross correlations occur when there is an extremum in the temperature time series used. Constant or monotonic temperature data frequently yield low values of the correlation coefficient and erroneous time delays (see Figure 8). In addition, care is required to assure equal thermal contact between each of the sensors and the pipe. Adequate insulation should be applied at and between the two sensors since heat transfer with the surroundings in this region can significantly alter the temperature data obtained. Even when care was taken and adequate temperature variations were present in the fluid, still, a consistent underestimation of the flow rate is observed.

This consistent underestimation was believed to be an effect of either the heat capacities of the pipe and the fluid or the more slowly travelling boundary layer next to the pipe. To test the heat capacity hypothesis, a computer simulation of the experimental setup was carried out (Feuermann et al. 1988). The simulation used plug flow to explore the exchange of heat between the fluid and the pipe. The simulation showed that the heat capacity of the pipe spreads the temperature variations and reduces their amplitude, but that the fluid velocity is still accurately determined by the cross correlation method.

Since heat capacity effects did not explain the consistent underestimation of flow, attention was turned to the details of the velocity profile in the pipe. The major source of error appears to be associated with a fluid velocity which varies across the pipe. The method used assumes temperature variations travel at the fluid bulk velocity, though it is known that there is a boundary layer at the pipe surface through which the actual velocity must drop to zero. It appears that the fluid boundary layer is responsible for the observed consistent underestimation of the fluid bulk velocity. This underestimation was larger for the tests done in which the necessary temperature variations were introduced by heating the pipe than when the variations were already present in the fluid. The larger discrepancy with the torch method might be anticipated since the heat externally applied with the torch has to travel first through the boundary layer before it later travels back out to the sensors some distance downstream.

Simple modifications of the analysis technique including cross correlation of the first derivative and direct measurement of the time delay between extrema or inflection points were attempted, but did not improve the results. The cross correlation of the first derivative gave less underestimation for high flow rates, but some over-estimation for low flow rates and no lower overall spread. More sophisticated cross correlation analyses are by Lassahn & Baker (1982), Kebadze (1984), Koppermann (1984) and van Meulenbroed & van de Wakker (1985), and might also lead to improved accuracy for the application discussed here.

The presence of extrema in the temperature data have been shown to be essential. When the temperature variations are due to a process which also causes changes in the flow rate, caution is needed in the evaluation of cross correlations (i.e. several separate sets of data, perhaps selected around the individual extrema, should be analyzed).

In the laboratory tests conducted with hot and cold water mixing, the errors ranged from -2% to -18% (Figure 5) with smaller errors at lower flow rates. The Reynolds numbers ranged from 2500 to 10000 in these tests. The underestimation for the ten laboratory trials and the one field test is plotted vs Reynolds number in Figure 10. This accuracy of better than 20% is sufficient for measurement of flow in pipes for purposes of energy conservation diagnostics.

The apparatus could be duplicated with new equipment for under $2000, of which about half is the cost of a microcomputer. This cost is relatively small for "house doctors" who spread the cost over many buildings. It is, perhaps, low enough to be a good investment in larger buildings such as the one reported on in this work.

CONCLUSIONS

A cross correlation method of measuring the flow in pipes non-intrusively was developed and tested both in the lab and in the field. A computer program was developed for rapid on-site determination of flow rates and computer simulations were carried out to explore the causes for the errors found. The preliminary experimentation reported here shows that flow of water in pipes can be measured without costly and time-consuming installation of flow meters. The method of cross correlating two temperature time series to find the time delay as the fluid passes two sensors along the pipe was tested satisfactorily on both ½ inch and 2 inch copper pipes carrying clean, potable water. The accuracy was better than 20%. The method is expected to work equally well for other pipe sizes, on pipes made of other materials and with pipes carrying other fluids. More tests should, however, be performed.

Additional theoretical work is needed to explain the low readings at high flow rates, thought to be due to a boundary layer moving more slowly than the bulk of the fluid. It is plausible that with a correction to account for the actual velocity profile, the accuracy could be improved.

Questions to be answered by further research include:

1.) How large must the temperature fluctuations be?
2.) Are adequate temperature variations usually present in buildings?

3.) What range of Reynolds numbers (velocities) can be accurately measured?
4.) How does pipe size and composition affect accuracy?
5.) How important are insulation around and between the sensors and the distance between sensors?

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Acknowledgement

We thank professors Enoch Durbin and Harvey Lam in Princeton's department of Mechanical and Aerospace engineering and others in the Center for Energy and Environmental Studies for their helpful comments after reading early drafts of our paper. The work has been supported by the U.S. Department of Energy under contract number DE-FG01-86CE23838 and also by the New Jersey Energy Conservation laboratory.

FIGURES

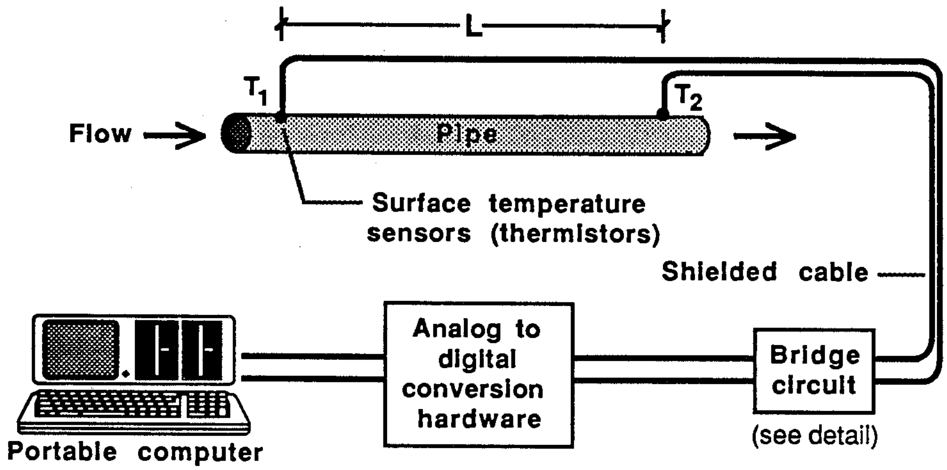

Figure 1. *Non-intrusive pipe-flow measurement system.*

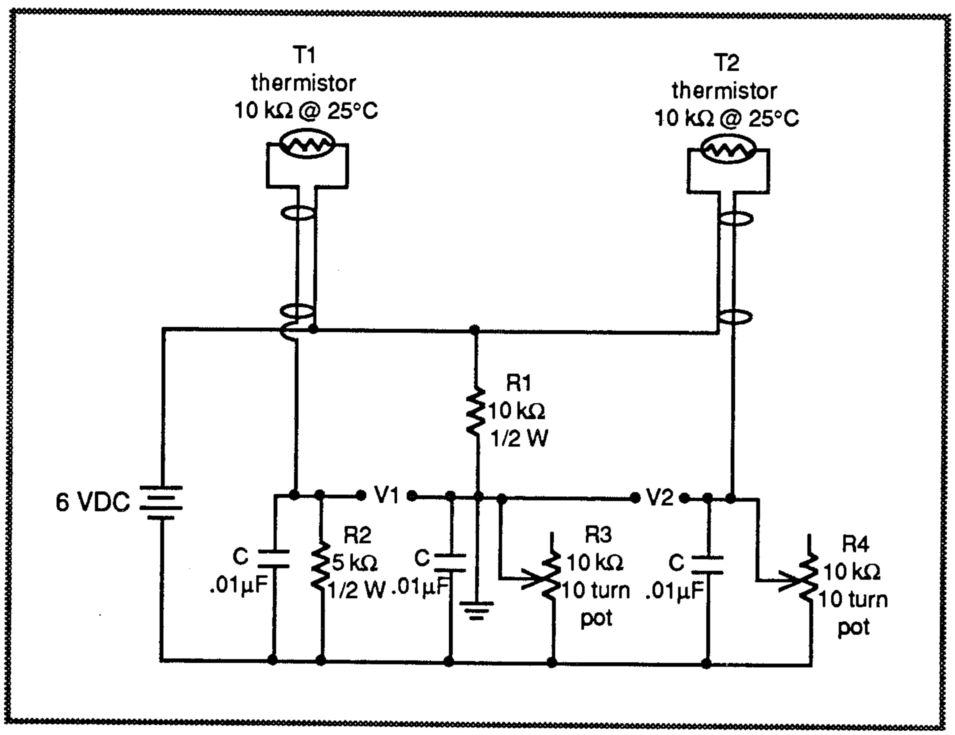

Figure 2. *Bridge circuit to transform thermistor outputs to voltages (V1 and V2) appropriate for input to the analog to digital converter. Capacitors reduce noise, R3 is adjusted to obtain a midrange reading from T1(V1), R4 is then adjusted to bring V2 close to V1.*

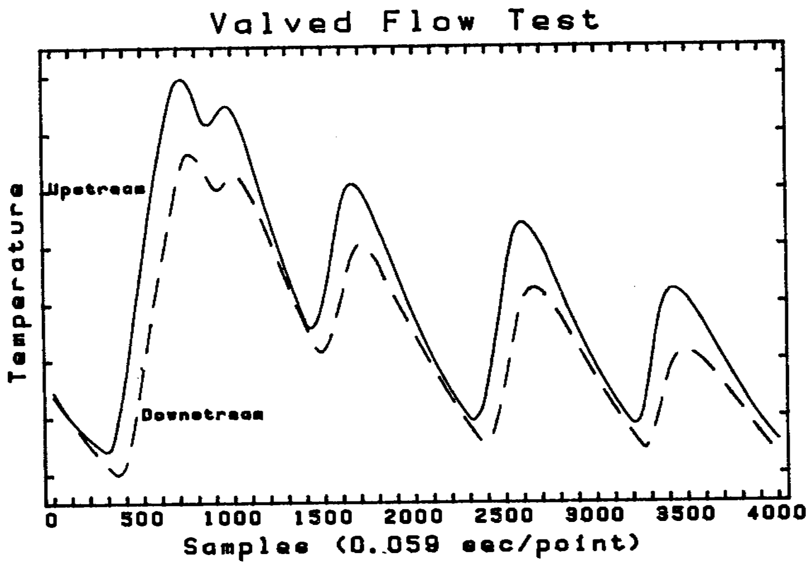

Figure 3. (above) Temperature time series data for valved hot and cold water laboratory test. Sensors are 1 ft. apart on half-inch copper pipe; actual flow rate is 29.4 cm^3/sec.

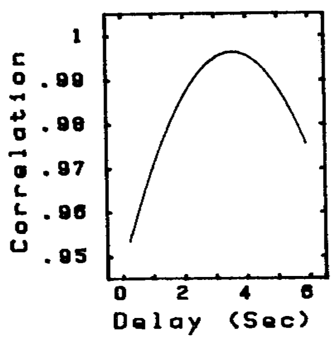

Figure 4. (right) Cross correlation coefficient plotted as a function of time for temperature data shown in Figure 6. Maximum occurs at 2.68 seconds, corresponding to a flow rate of 31.2 cm^3/sec. The actual flow was 29.4 cm^3/sec.

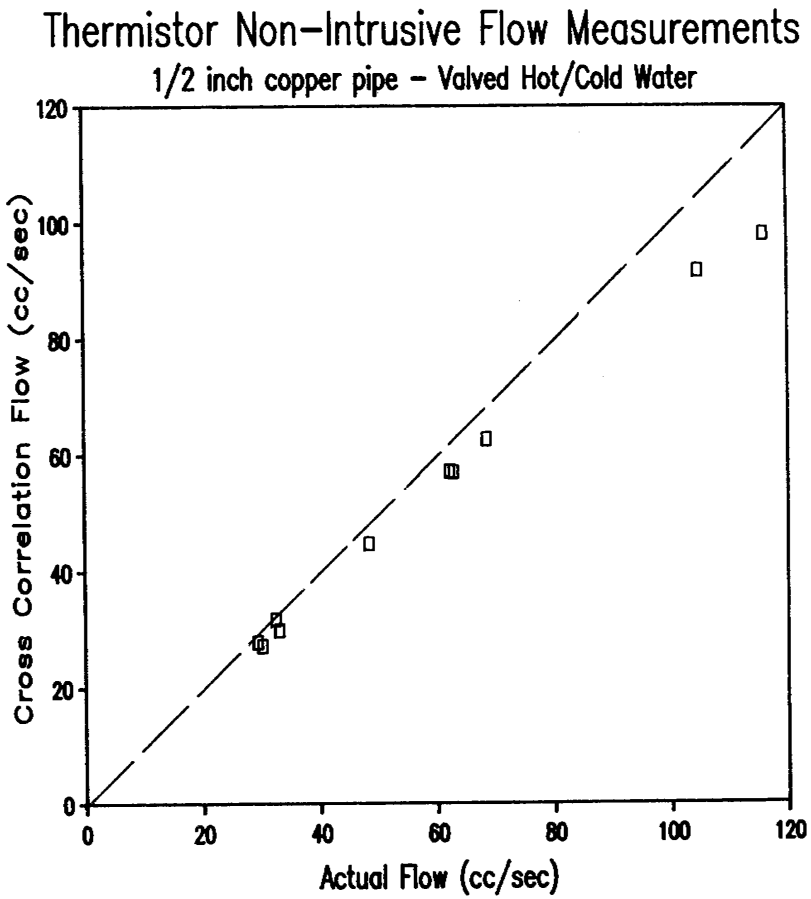

Figure 5. Comparison of flow rate determined with the cross correlation method to actual flow rate measured by timing the flow into a graduated cylinder. Temperature fluctuations were created using the valve setup shown in Figure 5. Reynolds numbers are about 100 times the indicated flow rates.

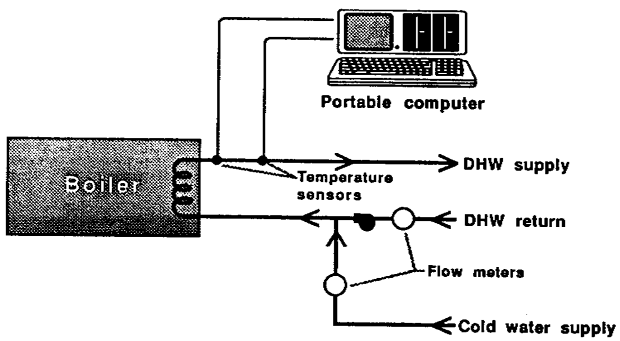

Figure 6 Setup for field test on the domestic hot water (DHW) system at Beechwood Apartments.

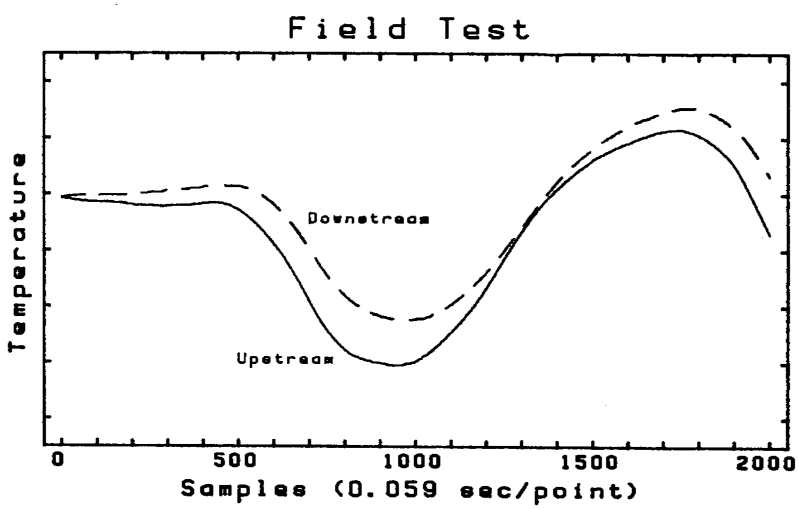

Figure 7. *Temperature time series data for field test. Sensors are 1 ft. apart on 2" copper pipe. Total duration was 118 seconds. The temperature variations are on the order of 1 °C.*

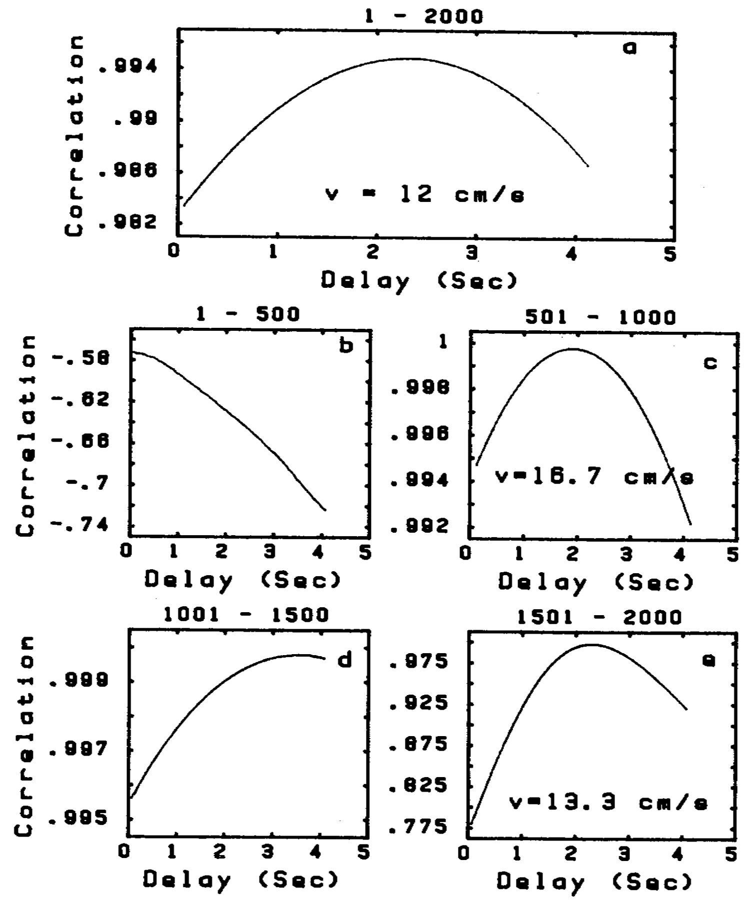

Figure 8. *Cross correlation plotted as a function of time for temperature data shown in Figure 10. Correlations were performed on the data set as a whole (a), and each 500-point segment (b through e). Graphs b and d show inconclusive results due to abscnce of temperature extrema in these segments. (Note different scales in correlation axes).*

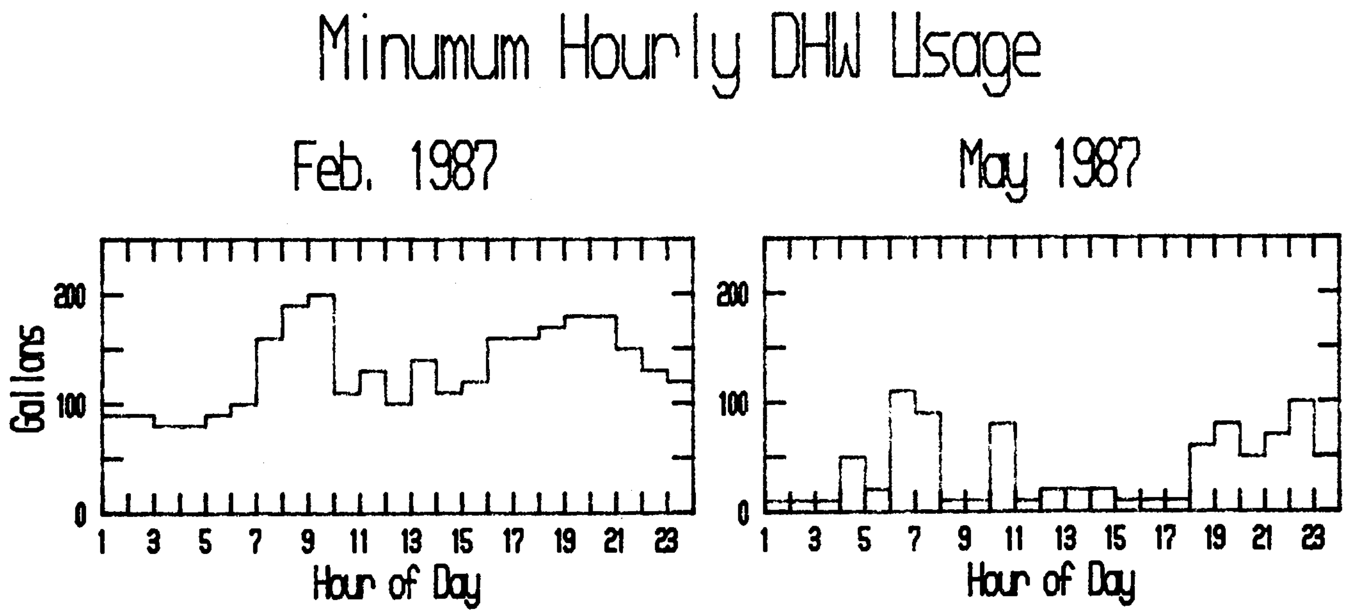

Figure 9. Minimum hourly DHW hourly usage for Beechwood Apartments, for all days of the month. Note the large minimums (80-90 gallons per hour) in February and the normal (10 gallons per hour) values in May after the boiler was replaced.

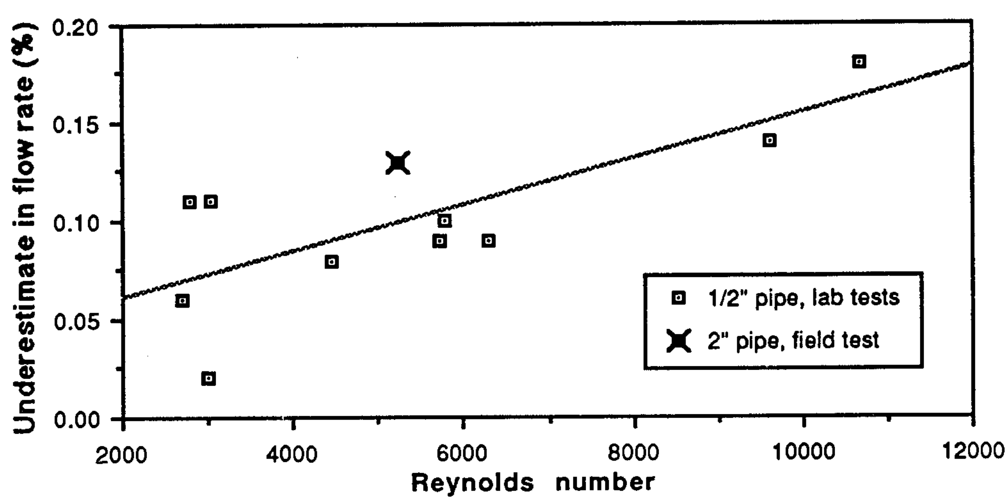

Figure 10. Underestimate in flow rates determined by the non-intrusive method as a function of Reynolds number. Data shown are for 10 laboratory trials using 1/2" copper pipe and one field test on 2" copper pipe.