Development of a Real-Time High Resolution Gas Appliance Monitoring System

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Chang Gen Tan

We, the thesis committee for the above candidate for the

Master of Science degree, hereby recommend

acceptance of this thesis

Jon Longtin – Thesis Advisor

Professor – Mechanical Engineering

John Kincaid – Chairperson of Defense

Professor – Mechanical Engineering

Satya Sharma – Committee Member

Professor – Mechanical Engineering

This thesis is accepted by the Graduate School

Lawrence Martin

Dean of the Graduate School

Abstract of the Thesis

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Chang Gen Tan

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There has been considerable interest in monitoring gas appliance usage due the increasing price of natural gas. Ideally one would like to know how much gas each appliance consumes, as well the time of day it is used, while providing this information in real time. This work develops a real-time gas appliance monitoring system that uses gas consumption rates to determine when an appliance is on or off. Most major gas appliances consume gas a fixed rate, with each appliance having a unique consumption rate. The concept of the system is to convert the mechanical motion of the gas meter output shaft into actual flow rates. The experimental setup includes retrofitting an existing gas diaphragm meter with an optical encoder and microprocessor. The microprocessor converts the signals from the encoder into flow rates. The times and flow rates are output to a file on a personal computer. In this work the flow rates of the furnace, dryer and water boiler are simulated using compressed air and a custom-designed piping system. The appliance monitoring system has two forms of visual identification to notify which appliances are on. The first is through on-board LEDs that illuminate to notify when a given appliance is on. The second is the flow rates and total consumption versus time plots that identify when and how long each appliance has been on. The system provides very high resolution and is inexpensive, which makes it desirable for commercial usage. Suggestions for further improvements on the system are given.

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Chapter 1: Introduction

There has been a great amount of interest in the monitoring of appliances due to the increase cost of utilities. The price of utilities has gone up considerably over the last few years. In fact, the national average price of natural gas in the United States has increased by 35% from 2003 to 2007[1]. The Figure 1 shows the trend of gas prices over several decades. The cost of natural gas has increased by thirteen times over the last four decades. Energy has become a valuable commodity. There is greater desire to control and reduce consumption. One way of reducing utility usage is to develop better ways of monitoring the amount of energy that is consumed in households. In most areas, the monitoring of utility usage is accomplished with mechanical meters. These meters only show the total energy consumption and do not give any insight into where the energy is being used. In order to better quantify the energy usage, users should have the ability to know how much energy each appliance consumes. Advancements in technology allow better ways to monitor and control energy usage. For example, items such as optical encoders and microprocessors are readily available and inexpensive.

1.1 Background and Motivation

Most utility companies use methods for recording meter usage from technology developed over a hundred years ago [2]. The overwhelming majority of the meters are still read visually with readings recorded manually by a meter reader. This method of recording can be very inconvenient since most meters are located inside the premises and are hard to access. It usually requires the homeowner to be present during the readings.

Manual readings are labor intensive and require many people to service a large population area. In addition, meter readers face dangerous situations such as slips and falls, attack by dogs and irate customers [3]. Errors in recording have lead to customer disputes, which causes delays in payment. Most of the time, the bill is estimated when the meter reader is unable to gain access to the meters. The need for more frequent and accurate information has led to advances in metering techniques.

Another recording method commonly used is remote automatic meter reading (AMR). This recording method uses short radio frequency that requires meter readers to be within a certain distance of a meter. However, there is no need to directly access the customers premise. This includes a drive by or walk by meter reader equipped with a vehicle or a handheld device that transmits a signal to “wake up” the meter. The meter is normally at a standby state. The meter then responds by sending the meter’s serial number and the consumption data. These readings have better accuracy than manual readings but are infrequent since they take place once a month. This type of meter reading cannot support real time monitoring of data.

More advanced metering techniques includes fixed network AMR. These readings involve the transfer of information directly from the meters to a central location. These readings are fully automatic and do not require readers on the premise or in the approximate vicinity. The data typically transfers over telephone lines, electric power line carriers, satellite and wireless or broad band. Fixed network AMR supports real time metering that gives feedback to the customer on demand continuously. Hence, management of utilities and monitoring of appliances is improved. Customers get real time response of their appliance usage, which leads to benefits for the customers as well as for the utility companies.

The individual tracking of appliances has always been difficult and inconvenient. They usually involve placing sensors on each appliance or having a separate meter before each appliance to monitor individual activities [4]. This can be very impractical and costly when the number of appliances is large. It is also inconvenient for the user as it requires direct access to individual appliances, thereby invading on consumer property.

The first person to develop nonintrusive appliance load monitoring (NALM) was George Hart [5], [6]. The idea of analyzing power flows to determine the set of appliances and report their states of being on or off occurred to George Hart in 1982 at Massachusetts Institute of Technology Lincoln Laboratory while collecting and analyzing data as part of residential photovoltaic system study [5]. While analyzing the load data from neighborhood homes, Hart was able to see the events that were happening in their homes. He used sensors at a single point of entry between the existing electric socket and electric meter. Hart used complex algorithms that included variables such as current and voltage for the determination of the power entering the meter. NALM has been further developed by [7], [8], using different algorithms, while still relying on using the current and voltage. Baranski and Voss used optical sensors to detect the rotating disk of the electric meter [10], [11]. Using an optical sensor is a less expensive method than the ones mentioned above. Another study uses current sensors to measure major electric appliance usage from electric panel boards [9]. These works are applicable for electric appliance as they require current and voltage or are design for the mechanisms of an electric meter.

Most monitoring systems deal with appliances that consume electricity. There have been very few that track the usage of gas appliances. Since the meters convert the volume of gas into mechanical motion, there is no voltage or current to measure the consumption rate as in electric meters. The strictly mechanical nature of the gas meter movement has made it difficult for nonintrusive monitoring of appliances. A study conducted in Japan used gas appliance consumption rates to determine when an appliance was on [12]. The gas meter used converts the diaphragm movement into crank shaft rotations. The meter has a magnet attached to it that emits electronic pulse as the crank rotates. The minimum distinguishable unit in the system was one crank rotation. Another device detects the pulses and is attached to a microcomputer in the meter. Once the microcomputer in the meter receives the pulse, it transmits a timestamp and elapsed time between consecutive pulses to a data logger. The information on the data loggers are collected approximately four times per year. Once the timestamps are collected, it enters into a software program. The algorithm for the software consists of two steps: decomposition and identification. The times were decomposed into flow rates and the appliances were then identified. However, the work required the use of a special meter that is very sensitive. Each crank rotation on the meter is equivalent to 0.0318 ft^3, as oppose to the standard of 2 ft^3 in homes in the United States. The work also does not support real-time monitoring because it required all the data to be collected before the flow rates and appliances can be identified.

The three types of utilities are electric, gas, and water. This work focuses on retrofitting an existing gas meter. The labor cost for retrofitting an existing electric meter is approximately the same as replacing one. Water and gas meters on the other hand, both require significant efforts to replace. The cost to replace these meters is substantially more than to retrofit because replacing the plumbing is very labor intensive. This makes retrofitting water and gas meters a more practical approach. The cost of water is significantly lower than natural gas. Therefore, this work first focuses on gas meters and will deal with water and electric meters at a later time. This retrofit system can also be placed on new gas meters that are installed.

There are many states converting to AMR systems. Some of the biggest manufactures of AMR technology are Itron, Cellnet, Elster. These companies provide products to utilities companies that only monitor total consumption. They do not have the ability to monitor individual appliances. Therefore, they do not allow solutions for energy programs that will give deeper understanding of customer energy usage patterns. Currently, there is only one commercial supplier of Non-Intrusive Appliance Load Monitoring technology in the world [13]. However, this technology only works for electric appliance and can be quite expensive. This makes it impractical for widespread use into residential families.

There are some current products in the market that can retrofit to diaphragm gas meters for AMR. These products provide a higher resolution compared to products currently used by utilities companies for collection purposes. However, the resolutions provided by most of the products are still inefficient for individual appliance monitoring. They usually allow one or two pulses per revolution [14-16]. They make used of reed switches or piezo electric material to generate signals that can be processed. One product uses an optical encoder to achieve higher resolutions [17] but the application is mainly for the industrial meters. All the retrofits products mention above requires a separate device for recording and processing capabilities. This will add additional cost to the final system. They are also being used for AMR systems that only capture total consumption and not appliance identification.

This work deals with retrofitting an existing gas meter for real-time high resolution gas appliance monitoring. An optical encoder with the ability to monitor small amounts of gas consumption is used. The encoder converts the rotation of the diaphragm gas meter output shaft into useful digital signals. The microprocessor will process the signals into gas consumption rates, as well as total consumption. The processing is done by the microprocessor instantaneously. This is opposed to other methods that use software on a computer that first requires all the data to be collected. This constitutes as one component of an AMR solution. Professor Jon Longtin is working on creating a fixed network AMR system that will allow meters to communicate with each other and to a central location. The data from the microprocessor is downloaded to a computer at the present time, but has the ability to communicate wirelessly or through broadband access. There are two forms of visual feedback to allow users to identify the state of appliances. The first is through on board LEDs that illuminate to notify when an appliance is turn on. The second is through the flow rate and total consumption versus time graphs The Teaching Mode will collect the flow rates of various appliances to identify appliance characteristics. Teaching Mode takes less than 30 minutes to gather appliance information, which greatly reduces the setup times. This work provides a very inexpensive solution that combines AMR technology with non-intrusive monitoring of appliances. The technique used has the ability to work for all three utilities meter, utilizing rotating dials that are common to all the meters. To the best of my knowledge, this method has not been previously used.

1.2 Advantages of the System

Visual feedbacks of energy consumption information can lead to energy saving behavior [17-19]. Knowing how much energy each appliance uses can create awareness for homeowners and lead them to save on utilities usage. This may include taking shorter showers, or encourage people to turn the thermostat down one or two degrees, as it can make a great savings in energy. It can also lead to someone replacing old windows or insulating the house better. It may also lead people to buy energy saving appliances instead of settling for cheaper, less efficient ones.

With the ability to monitor historical usage, it allows defective detection of appliances. For example, if a dryer normally takes 30 minutes to dry a given load, but suddenly takes 60 minutes for a similar load, it is an indication that the appliance is not performing properly. The homeowner can then contact a service professional to perform an audit on the appliance and replace it if necessary.

This work contains a system that has the ability to detect very small levels of flow. Since leaks of natural gas can be potentially deadly as they are highly combustible and emit carbon monoxide, this system has a highly desirable safety characteristic. The system can detect the flows in real-time and give immediate warning. It can be used to notify the homeowner or a service center of the potential leaks and get the necessary help from the proper personnel.

The current residential meters only show total consumption with meter reading personnel that only come once per month. With the long time between readings, it is difficult to know if the meters have been tampered with. Depending on the season or conditions, the utility company can look for suspicious patterns of utilities theft based on the monitored data.

1.3 Outline of the Present Work

In chapter 2, the concept of the system will be discussed. It will talk about how mechanical motion is converted into actual consumption flow rates. It will give details of the mechanical motion of the gas meter. Some basics of the rotary optical encoder and microprocessor are also given. The algorithm of the software is discussed.

The experimental set-up and components of the system are described in chapter 3. The system is a custom built and inexpensive. It will simulate the actual flow rates of the furnace, dryer and water heater with having the actual appliances themselves. It will outline in detail the retrofitted system including rotary optical encoder mounting, microprocessor and development board.

Chapter 4 shows the results of the experiment. This includes finding the pulse widths for the reference flow rate. The accuracy of the LED detection system for the combination of appliances with different flow rates is analyzed. Finally two trials are run one giving a longer period and one that demonstrates the high resolution of the system.

Chapter 5 gives a summary of the present work. It will also discuss the improved that are needed for the current system and the direction of the future work.

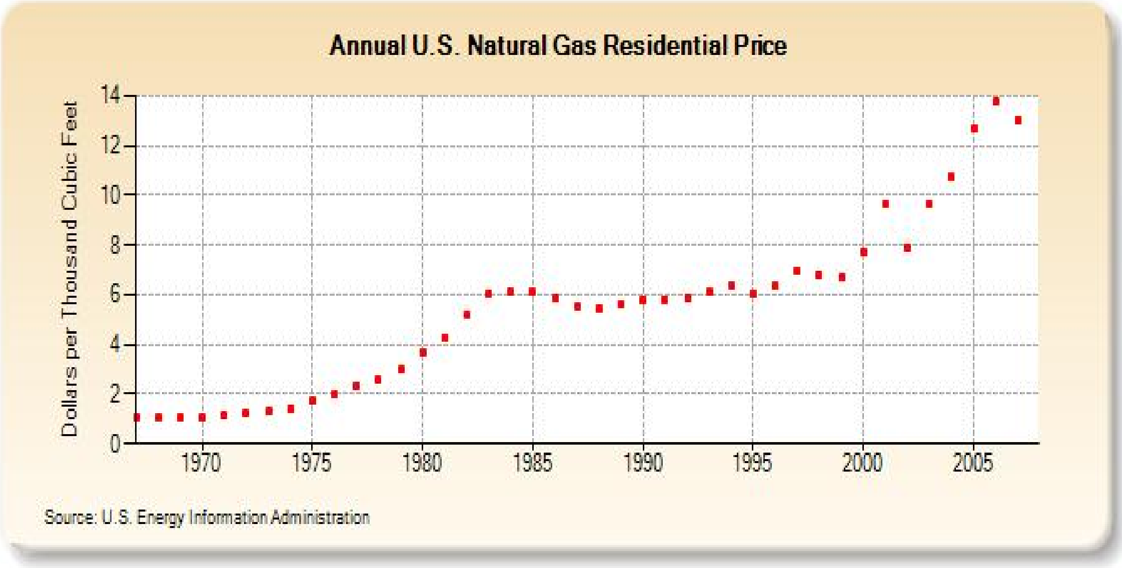

Figure 1. Annual price of natural gas in the U.S.

Chapter 2: System and Component Theory

Most appliances consume a fixed amount of gas and modulate their needs by cycling the gas on and off. Since the gas consumption rate is fixed and usually different for each appliance, it is possible to determine which devices are turned on at any given time provided that the meter can resolve small changes in gas consumption. By resolving small quantities of gas usages, the consumption flow rate versus time can be determined by the meter to determine the history of each major energy-consuming appliance in the house. High resolution appliance monitoring system requires the ability to resolve 0.05 ft^3 of gas. Present day meters do not have this capability. Most of the meters today resolve increments of $2ft^3$, which is far too high for the concept to work. The main feature of this work is retrofitting the existing meter to provide high resolution of gas consumption. The system concept is shown in Figure 2. The figure shows the cycling of the hot water heater and boiler versus time at the top, with the consumption flow rate plotted in the middle. The total consumption versus time is shown at the bottom. Each step increase or decrease in the consumption rate represents a change in the state of an appliance either switched on or off. The boiler and hot water heater each have their own consumption rate characteristics that are clearly visible in the figure. When two appliances are on, the consumption rate is usually the summation of the two individual flow rates. By considering how long the flow rate remains constant, it is possible to determine exactly how long the appliance has been running. As gas is billed by total consumption, it is possible to know the costs to operate each appliance. The lower right hand corner of Figure 2 shows two columns of points. The points on the left represents the superior resolution that this system will achieve compared to the standard meter. The present work has the ability to acquire 125 points, compared to two points by the standard meter. The points represent the number of readings acquired per revolution. The low resolution of the standard meter will not be able to capture the events shown in the figure.

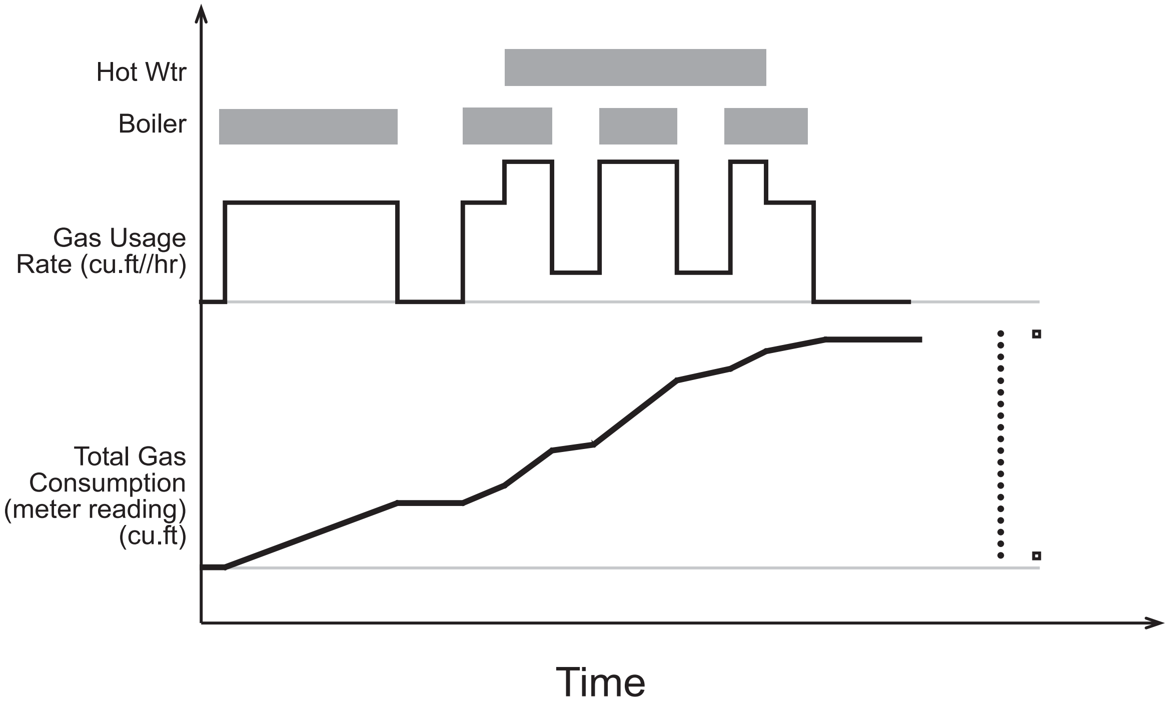

Figure 2. High resolution gas monitoring system concept. The cycling of a residential boiler and hot water heater versus time shown at the top, with gas usage rate plotted in middle. Total gas consumption is what meter records (bottom), and can be used to assess utility consumption of appliances.

2.1 Flow Rate

The volumetric flow rate of a system, Q, is a measure of how much volume, V, passes through a system in a given time, t. It is defined by $Q = \frac{V}{t}$. A diagraph gas meter measures the volume of gas that enters the meter and converts it into mechanical rotations. The flow rate is proportional to the angular velocity, ω, of the meter output shaft. The angular velocity is defined by $\omega = \frac{\theta}{t}$, where θ, is the angle of rotation of the output shaft. For gas meters, the volume of fluid that enters the gas meter and the angle of rotation of the output shaft are proportional. Typically, one revolution is equal to 2 cubic feet in gas meters. By measuring the time required for the shaft to complete one revolution, the flow rate can be determined. Table 1 shows the time required for the output shaft to make one rotation for the appliances with the given flow rates.

Table 1. Time required for one revolution for the given appliances

Appliance	Consumption Rate, Btu/hr	Flow Rate, ft^3/hr	Time for one revolution, seconds
Furnace	102,000	102	70.59
Dryer	25,000	25	288.00
Water Boiler	43,000	43	167.44

Natural gas contains an average of 1000 BTU of energy per cubic feet. Since, a resolution of 2 cubic feet is not adequate for the proposed system, a device that will capture N signals per revolution is needed. For this proposal, N has to be greater than or equal to 100. The total time for one revolution can be split into many discrete times. The time for one revolution is given as, $t_{rev} = \sum_{i=1}^{N} \mathrm{t_i}$. Where $\mathrm{t_i}$ is the time it takes for the shaft to rotate a certain degree at a certain position, i, and N is the resolution of the device. Due to the mechanical motion of the meter, the instantaneous angular velocity of the shaft is not constant for a constant flow. Since the angular velocity is not constant, the successive times are not equal (i.e., $t_{i-1} \neq t_i \neq t_{i+1}$). However, the mechanical motion of the meter, which is described later in the chapter, is observed to be repeatable. At a known position of the shaft rotation, the angular velocity is similar for each rotation at that position for a constant flow. Figure 3 shows sample pulse times for two rotations.

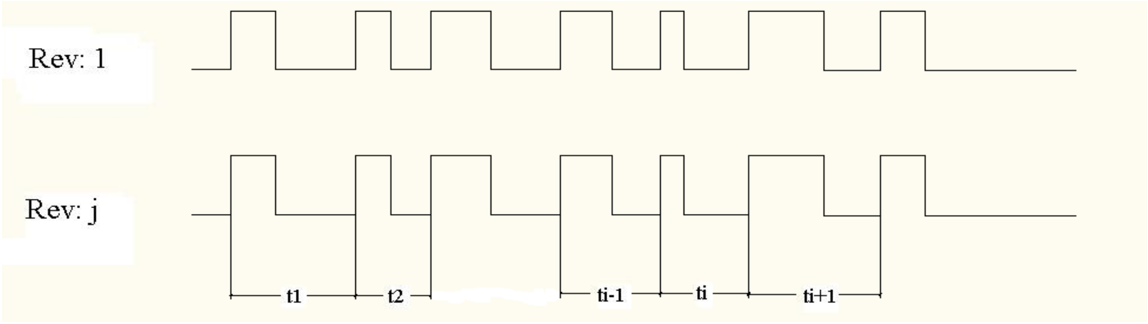

Figure 3. Sample pulse times for two revolutions

For a known flow rate, there will be distinct times at each position of the shaft rotation. Given a reference flow rate, other flow rates can be obtained by

$$Q(i) = \frac{V}{t(i)} = kQ_{ref} = k\,\frac{V}{t_{ref}(i)} \qquad (1)$$

solving for k,

$$Q(i) = \frac{t_{ref}(i)}{t(i)} Q_{ref}. \qquad (2)$$

2.2 System Components

The main components of the high resolution monitoring system are the rotary optical encoder, diaphragm gas meter and microprocessor. The operating principles of these components are discussed below.

2.2.1 Internal Mechanism of the Meter

The present system requires the motion of the output shaft to be repeatable once every rotation. The internal mechanism of the meter is analyzed to ensure that this characteristic is satisfied. The meter used for this procedure is a diaphragm type gas meter. The gas meter has an inlet and an outlet port. Figure 4 shows the inside of the meter with the top cap removed. The circular port on the right is the outlet port of the gas meter, with the rest of the figure showing the internal mechanisms of the inlet port. Gas enters the two inlet valves which alternately open and close. The gas enters the valves and causes linear translation of the diaphragm in the bottom of the meter. As the diaphragm moves back and forth, gas is simultaneously pushed into and out of the meter. The motion of the diaphragm will cause the two rods on the upper and lower left hand corners to oscillate at a certain angle. The two rods represent the ground link of a 5-bar linkage and is the driving force behind the motion of the linkage. The motion of the 5-bar linkage causes a vertical worn gear to rotate. The worm gear causes the horizontal gear and shaft to rotate in the counter-clock wise direction. The horizontal output shaft then interfaces with the dial meter index on the outside of the meter. The readings that are seen from gas meters are the result of to the rotation of this output shaft. The gear contained in the horizontal shaft has 18 teeth. It requires 18 complete cycles of the 5-bar linkage motion for one complete rotation of the horizontal shaft. It is determined that the motion of the 5-bar linkage drives the rotation of the output shaft. The variation in the angular velocity of the output shaft is due to different speeds at different positions of the 5-bar linkage. The motion of the 5 bar-linkage repeats itself 18 times per revolution and therefore also once per revolution. The output shaft has different angular velocity at each position, but for each subsequent revolution the angular velocity is similar at those corresponding positions. Therefore, equation (2) can be used to find the flow rates at each position when a reference flow rate and times are given.

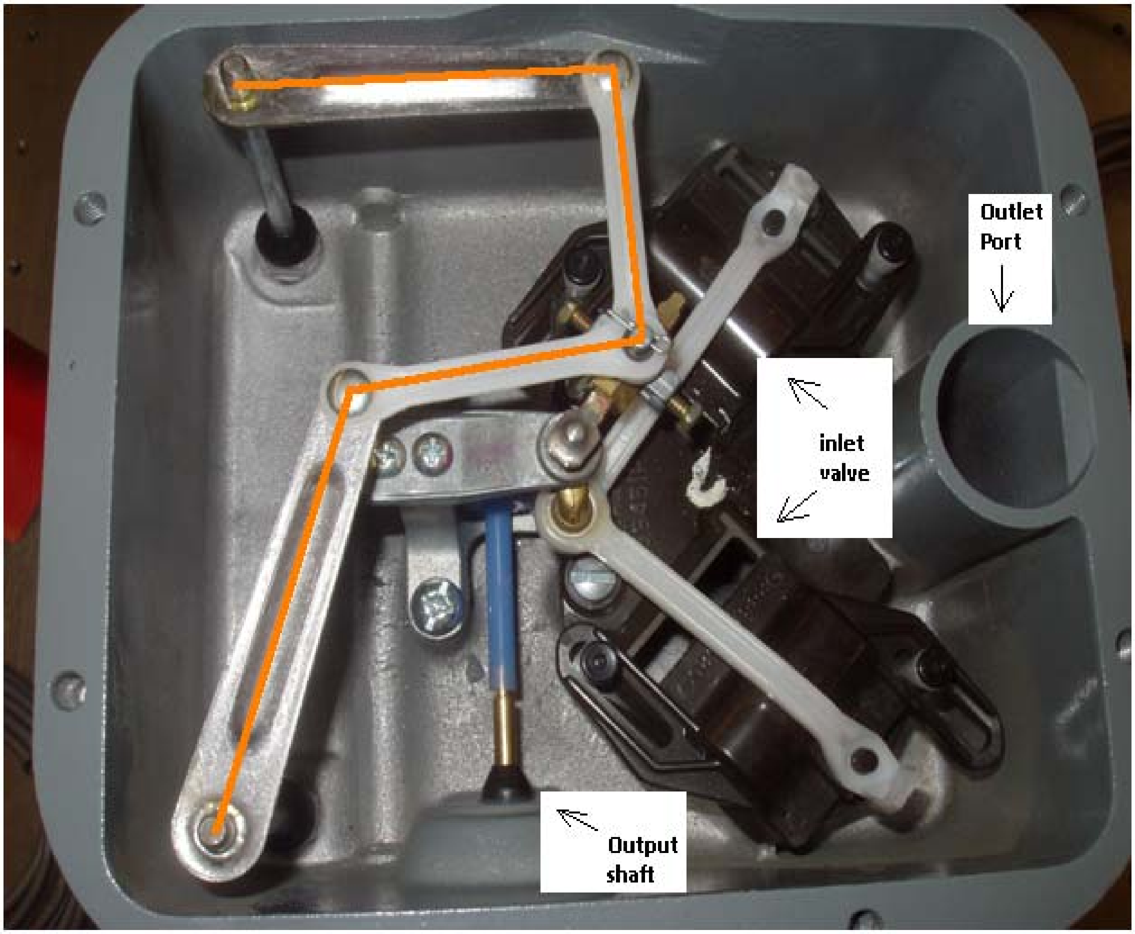

Figure 4. Internal mechanisms of meter inlet port

2.2.2 Optical Encoder

A rotary optical encoder is a device that converts mechanical motion into a sequence of electrical pulses [21]. The main components of an optical encoder are the light source, pulse disc, grid diaphragm, detector and connector. The light source consists of high quality infrared light-emitting diode (LED). The pulse disc is mounted on a hollow hub and has alternating clear and opaque sequence that the light source scans. The grid diaphragm, which also has clean and opaque patterns, splits the light into an additional signal by shifting the phase 90^o. The photodiode detector detects the light passing through the pulse disc and converts it into useful electrical signals. The connector transfers these signals into the control unit or processor.

The operating principle of an encoder is that the light source is emitted through convex lens. The lens focuses the rays into a parallel beam. The light then goes through the grid diaphragm. When the pulse disc rotates, the clear and opaque patterns of the disc will overlap with the clean and opaque patterns of the grid diaphragm. With the grid diaphragm and pulse disc overlapping, light or dark patterns are created. These patterns are detected by the photo detector. The detector will convert the light and dark patterns into a square wave. The high portion of the square wave corresponds to the light pattern, while the low portion corresponds to the dark patterns. The square wave signal generated by the detector is shown in Figure 5.

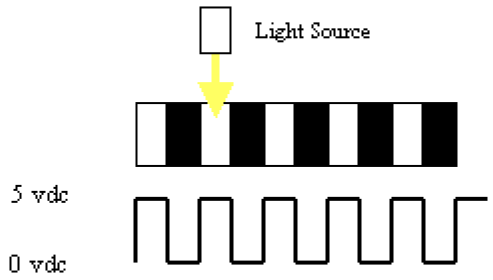

Figure 5. Square pulse generated by optical encoder based on light and dark patterns

While there are a few types of rotary encoders, this work concentrates on the incremental encoder. Incremental encoders consist of evenly spaced clear and opaque patterns on a single track. The resolution is defined by pulses per revolution. The number of clean and opaque patterns on the disc corresponds to the resolution. Some encoders have a zero reference pulse that occurs once per revolution. They are used when there is a need to keep track of the position. If direction of the rotation is needed, the 90^o phase shift tracking by the two detectors. Optical encoders offer a very liable and precise solution when it comes to position tracking and timing. They are also inexpensive and durable.

2.2.3 Microprocessor

A Microcontroller is a programmable device that read inputs from external devices, analyzes the input data, and output signals to other devices. It can send and receive data from systems like a personal computer, optical encoders, home automation systems, industrial control systems, etc. Many everyday devices have microprocessors imbedded in them such as TV, DVD/VCR, microwaves, cars, GPS systems, etc.

Microcontrollers can even communicate with other devices by serial lines, infrared, radio and satellite waves and even the internet.

Microcontrollers are highly integrated systems in which the processor, memory, and input/output functions are contained on a single chip as the central processor unit (CPU). This is unlike the microprocessors in computers that need separate devices for memory storage, input and output.

The microcontroller used for this project is the ZX-24a. It is a 24-pin module that adapts to the Parallax Development board. The heart of the ZX-24a is the Atmel AVR ATmega644 microcontroller running at 14.7MHz. It contains 3.5K user ram and has 32K byte EEPROM user program memory. It required a 5.5 regulated voltage power supply to operate. The execution speed is up to 175,000 instructions per second. Of the 24 pins, 16 can be used for digital input and output pins.

2.3 Algorithm

The program uses a very simple algorithm to allow it to determine the flow rates. The algorithm is shown in Figure 6. The program starts by reading in the 500 points of the reference pulses from a file. It then waits from an interrupt from the zero pulse. The zero pulse occurs once per revolution and is used to assure that the program starts at the same position every time. Once the zero pulse triggers a signal, the program enters a subtask and remains there in an infinite loop. The InputCapture function acquires the number of counts between successive pulses. It checks to see if the number of counts is less than 65535. If the number of counts is less than 65535, it converts the number of counts into actual time widths. The flow rate is calculated by comparing the current time with the reference time at a specific position using equation (2). The time of day and average flow rate of four points is printed to the output file. The system then searches the range of flow rates to see which appliance is turned on, while illuminating the LED. If the number is greater than 65535, the timeout period is exceeded, indicating that the output shaft has stopped. The flow rate in this case equals to zero. The time and flow rates are printed to a file. The program then waits for an interrupt of one of the fast pulses. When the system reads a signal, it resumes the InputCapture process.

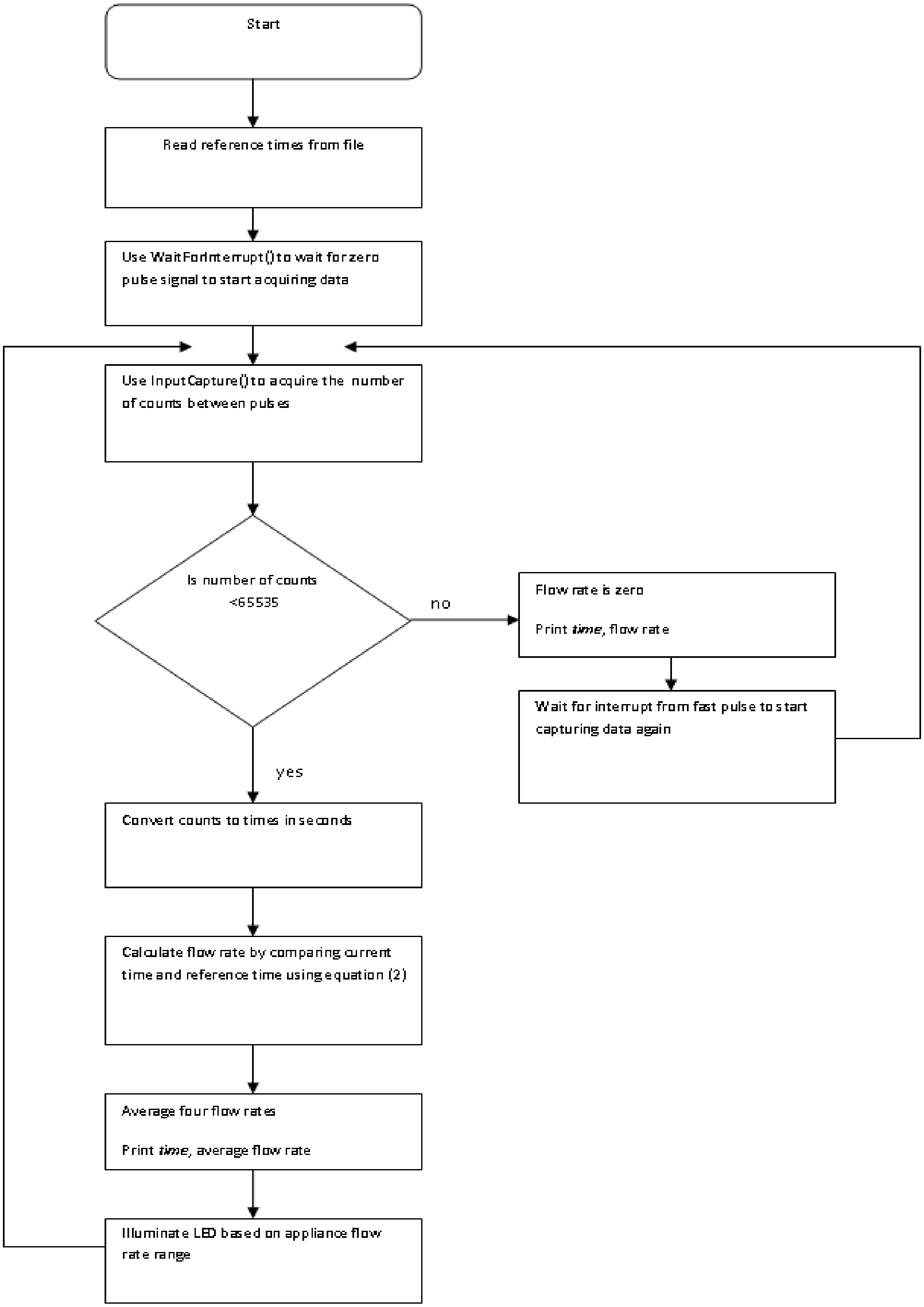

Figure 6. Flowchart of Algorithm

Chapter 3: Experimental Setup

The experimental setup for high resolution gas appliance monitoring system is shown in Figure 7. The setup is an inexpensive system that measures the flow rates of fixed consumption appliances. The main components include a rotary optical encoder, Parallax board for interfacing with the encoder, and microprocessor for processing the signals from the encoder. The data is analyzed using Microsoft Excel. The mass flow controller is used to measure the flow entering the gas meter. The experiment simulates the actual flow rates of the household appliances water heater, dryer and furnace. The flow rates for all seven possible combinations of the three appliances are to be measured.

Compressed air is used as a substitute for natural gas. The gas meter measures the total volume of fluid passing through it and operates effectively with compressed air. This saves money and eliminates the dangers of having combustible gas in the air. The compressed air used is at room temperature with an inlet pressure of 70 psi. The air from the inlet is connected to a pressure regulator using 3/8” inner diameter vinyl tubing. The regulator decreases the pressure to 45 psi. The regulator is used to control the amount of flow coming from the inlet of the air source.

The regulator is connected to the first filter using vinyl tubing with 1/4” inner diameter. The air coming from the building compressor is often wet and contains impurities. Although the pressure regulator contains a filter, it does not adequately eliminate the contaminants. There are a total of four filters connected together in series. They are for required for the filtering of particles, oil, coalescing and desiccant, respectively. They allow maximum flow rates of 5, 5, 10 and 5 cubic feet per minute, respectively. The filters are attached to each other in series using 4” nipples. The filters are mounted on the wall with pipe hangers through the nipples. The filters are used to protect the mass flow controller, which only accepts clean and dry air. Figure 8 shows a picture of the filters.

The OMEGA FMA5543 mass flow controller measures the flow rate of the compressed air before it enters the gas meter. It is used to verify that the amount of flow coming into the meter is the same as the flow recorded by the meter. Custom made brass compression tubing having outer diameter of 1/4” on one end and 3/8” on the other are inserted into the compression fittings of the flow meter. The flow meter requires a 12 VDC power supply and a minimum current rating of 800mA to operate. The power is supplied using a 15 pin type D connection located at the side of the transducer. The flow meter allows a maximum flow rate of 200 L/min (424 ft^3/hr). It is accurate within 2% for flows in the range of 25% to 100% of the maximum flow rate. The flow controller has a solenoid valve that can be adjusted to regulate the flow. The solenoid valve can be adjusted by changing the local set-point or supplying 0 to 5 VDC to two of the pins on the 15 pin adaptor. The measurements from the flow controller will be compared with the results found using the microprocessor. The flow controller has a LCD display panel that shows the instantaneous flow rates. Figure 9 shows a picture of the mass flow controller.

The setup uses a diaphragm gas meter model AC250 from Elster American Metering Company. The meter allows a maximum flow rate of 250 ft^3/hr. Before the compressed air from the mass flow controller can enter the gas meter, it must go through a set of regulators. Figure 10 shows the propane regulators that reduce the pressure from 45 to 0.5 psi. Each regulator allows a maximum flow rate of 76 ft^3/hr. The regulators are used because the meter has a maximum pressure rating of 5 psig. Three regulators are used since the maximum theoretical flow rate may reach as high as 170 cubic feet/hour. Adding more regulators also decreases the pressure drop of the system. It makes the flow rate of one appliance less dependent on the other. These regulators are arranged in parallel. The inner diameter of the regulator inlet tubing is 1/4”. The outlet of the regulator is 1/2” inner diameter piping before entering the gas meter. Current residential household gas meters also have inlet diameter of 1/2”. The regulators are used to duplicate the gas meter setup found in residential homes. Most homes have regulators at the inlet of the gas meter to regulate a constant pressure.

The system requires replacing the meter index with an encoder retrofit. The mounting plate for the encoder is made from 3.25 x 1.5 x 0.5 aluminum bar. The mounting plate consists of five holes. The two holes on the edge of the mounting plate attaches to the meter at the location the meter index use to be attached. The hole in the middle houses the adaptor shaft. One end of the shaft consists of a male adaptor pin that mates with the female portion of the output shaft from the meter. The adaptor shaft rotates in the middle hole of the mounting plate. This simulates the motion of the dial meter index. Figure 11 shows a picture of the retrofitted meter with encoder on the mounting plate.

The components for data acquisition are the Dynamic Research Corporation TK731 rotational optical encoder, ZX24a microprocessor, Parallax Board of Education development board and a personal computer. The encoder is attached to the mounting plate by the remaining two holes. The inner hub of the encoder is attached to the adaptor shaft using a set screw. The encoder records the pulse duration of each incremental rotation of the shaft. The encoder is powered by 5VDC. The development board is the interface between the microprocessor and the encoder. The Parallax board requires 6-9VDC power supply to operate. It also supplies an input the 5 volts needed to power the encoder. The orange, green and grey wires of the encoder are attached to pins P7, P11, and P13 on the board, respectively. The orange wire will output 500 pulses per revolution or one pulse every 0.72^o. The green wire is the inverse of the orange wire and will also output 500 pulses per revolution. The grey wire is the zero pulse and occurs once per revolution. Four LED's are also attached to the development board. The red LED is attached to pin P0 through a resistor. The green and yellow LEDs are attached to pins P1 and P2 through resistors, respectively. The ultraviolet LED is attached to pin P3 of the development board. The operation requirement for the each LED is 2.5 volts. The development broad provides a regulator power of 5 volts. The resistors are used to step the voltage down to 2.5 volts**.** The push button is attached to pin P5 and the ground. Pin P5 is set to a logical high state. When the program first starts, it detects the state of Pin P5. Once the push button is held down, the state is at a logical low, at which time it enters the Teaching Mode. The push button will be used in the Teaching Mode for further instructions. Figure 12 shows the development board, microprocessor and wiring of the system.

The development board is connected to a computer using a serial cable. The microprocessor has 24 male mating pin that plug directly into the female pins on the development board. The microprocessor runs on an Atmel AVR Atmega644 processor and has operating speed of 14.7MHz. The microprocessor is programmed using the Z Basic language. The pulse width acquired by the microprocessor is outputted to a text file.

The furnace, dryer and water heater are simulated using a custom built piping system. The system is shown in Figure 13. The outlet of the gas meter is connected to a 3/4” inner diameter vinyl tubing. Having a larger diameter reduces the pressure drop in the system. The vinyl tubing is eventually connected to a 3/4” inner diameter cross. The cross branches out to an elbow and T-junction joint that splits the flow into three parallel pipes. Ball valves are connected to each of the three pipes. These are similar to shutoff values connected to household appliances. Each ball valve is connected to a square head pipe plug. The plugs have different size areas drilled in the middle to allow for different flow rates. Larger drilled areas allow for greater flow. The sizes of the areas were increased incrementally until the proper flow rates were acquired using the microprocessor. Figure 14 shows a close-up view of the plugs. The appliances represented from left to right are the furnace, dryer and water heater.

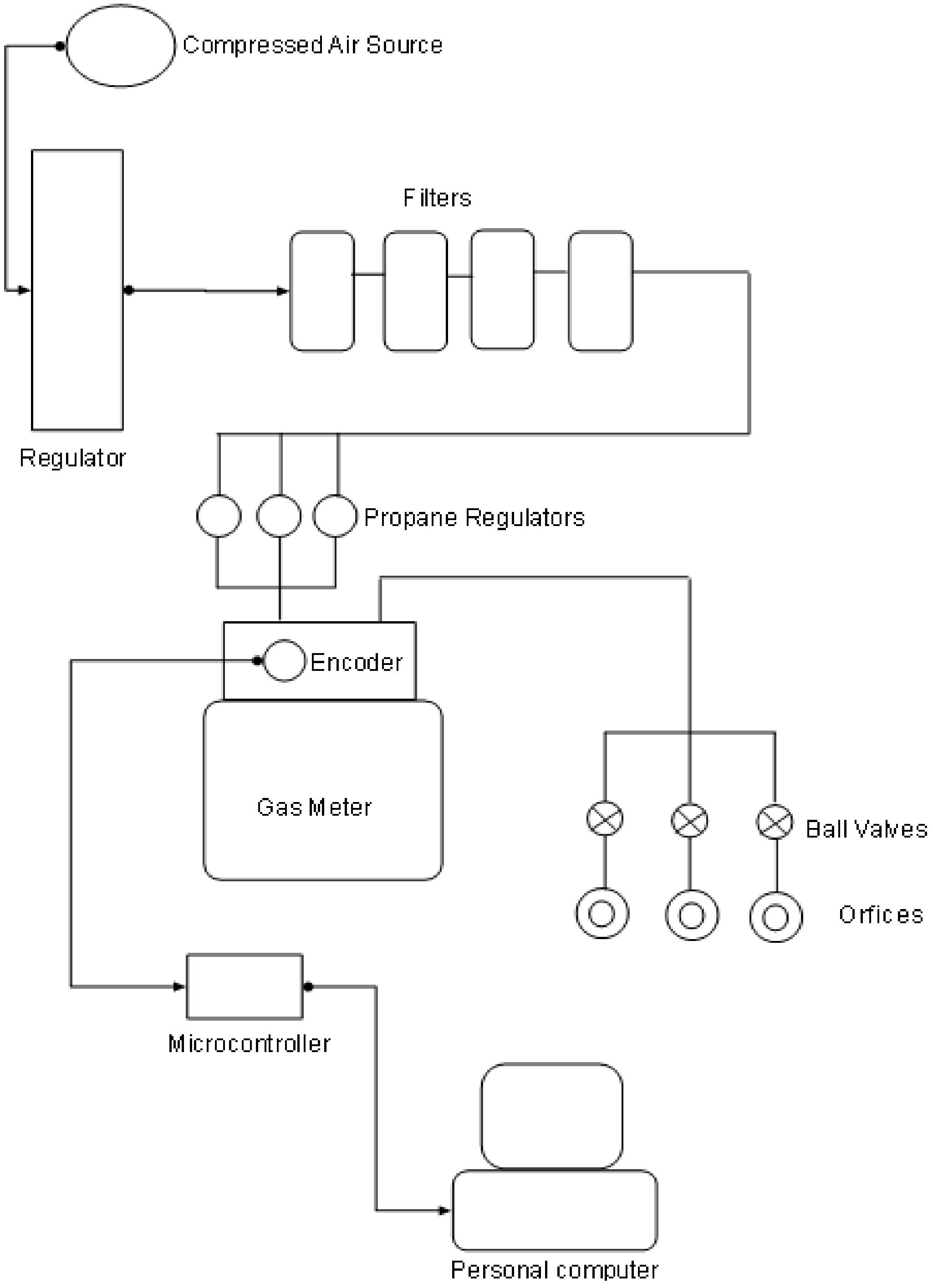

Figure 7. Experimental setup for high resolution gas appliance monitoring system

Figure 8. Filters - particle, oil, coalescing and desiccant

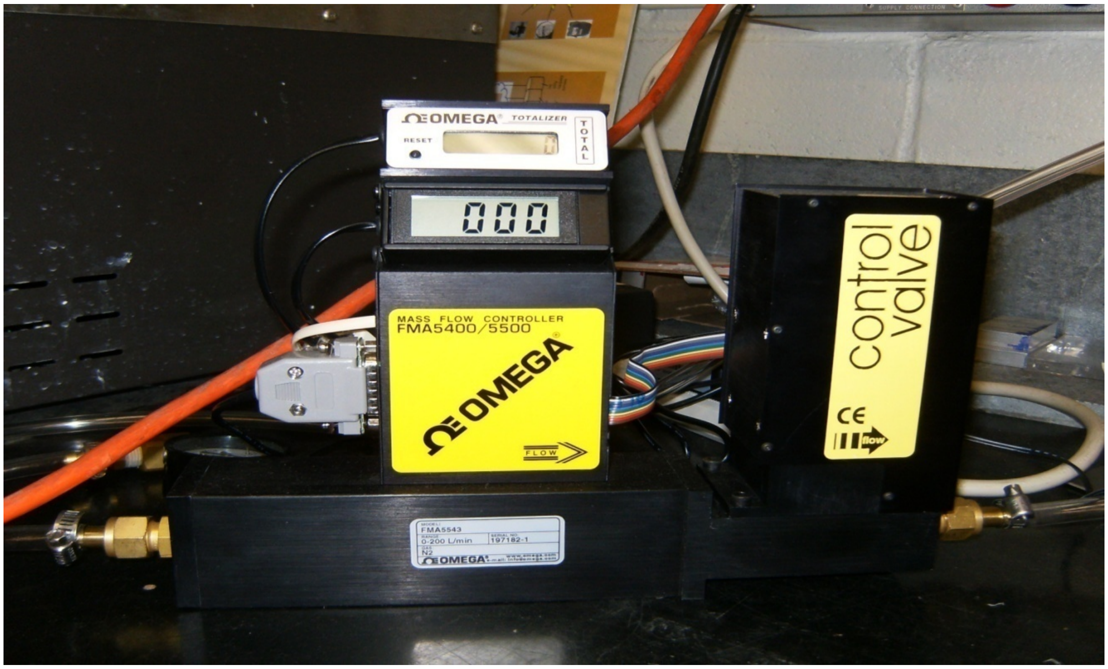

Figure 9. Mass Flow Controller

Figure 10. Three propane regulators at inlet of gas meter

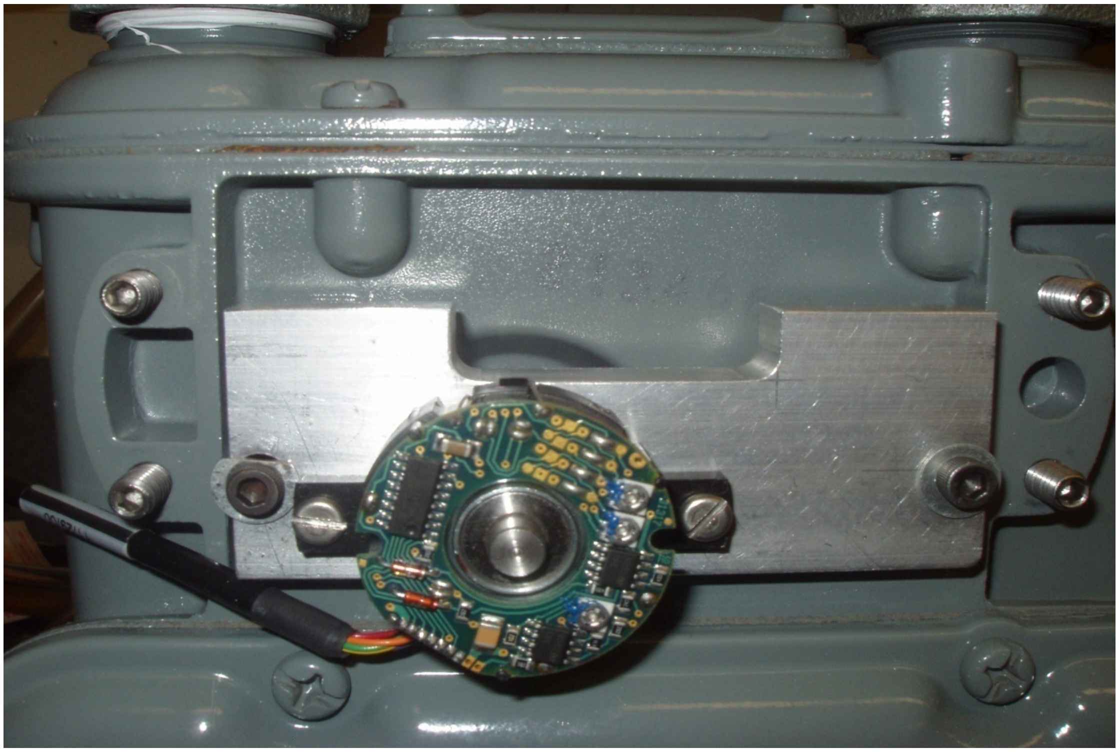

Figure 11. Retrofitted meter with encoder on mounting board

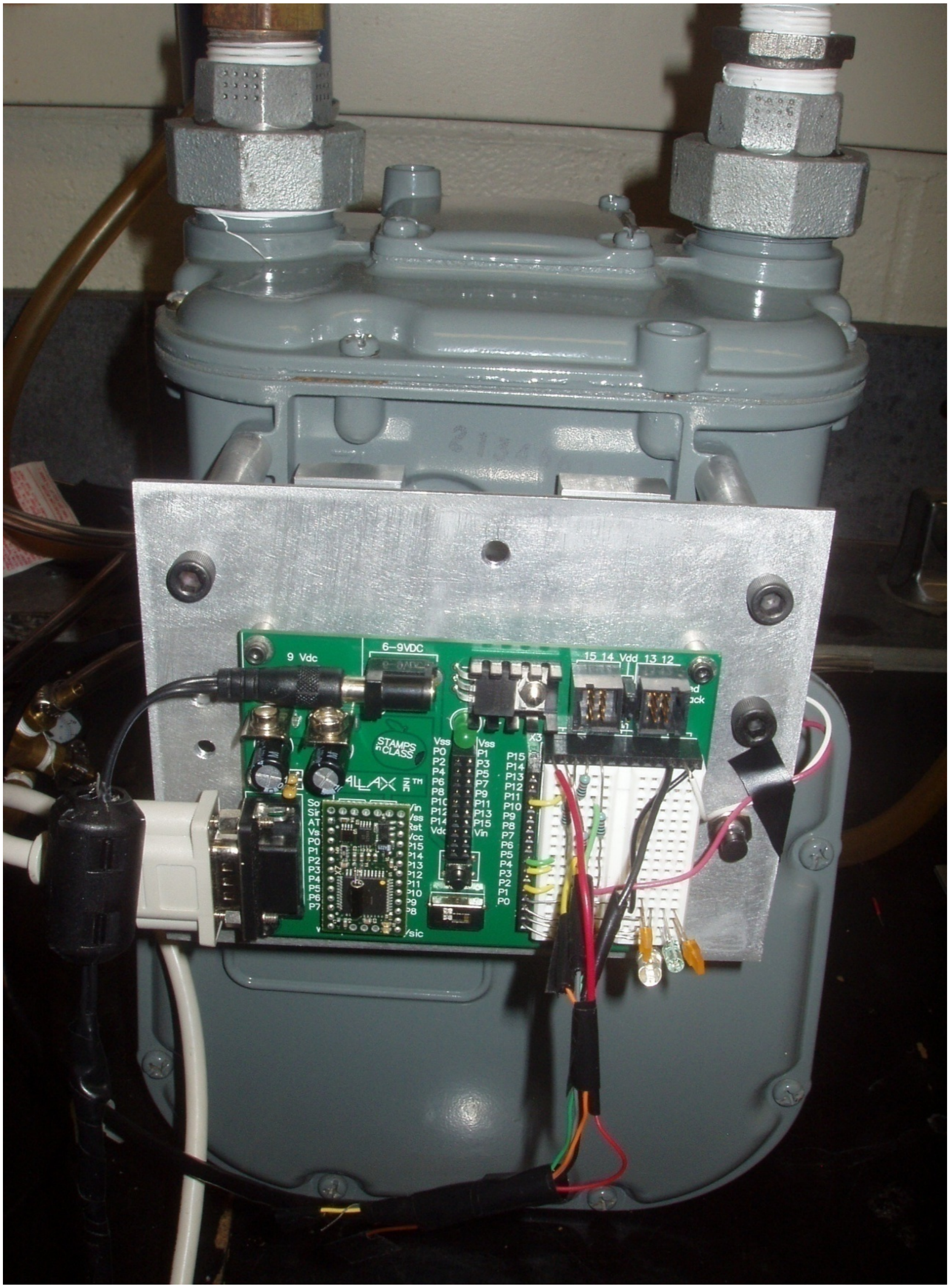

Figure 12. Parallax development and microprocessor system

Figure 13. Piping system representing appliances – furnace, boiler, water heater

Figure 14. Orifice areas for dryer, water heater and furnace

Chapter 4: Results and Discussion

After completing the experimental setup as described in chapter 3, the pulse widths and flow rates are collected. The values are downloaded to a text file from the microprocessor serial port. The data is then analyzed using Microsoft Excel spreadsheet. The flows for each appliance are acquired in the Teaching Mode. These values are compared in subsequent trials for accuracy of the LED detection. Finally two separate trials were ran, one for a longer duration and the other for a shorter duration to show the high resolution of the system.

4.1 Reference flow rate

The pulse times are taken for each of the 500 positions of one complete revolution of the rotating shaft. The values are taken using the InputCapture function which records the time that the system stays at the corresponding low and high portions of a pulse. The system records the number of counts that occur for one pulse. The counts are then converted to actual times. The reference flow rate is chosen to be 112 ft^3/hr. The full capacity of the meter is 250 ft^3/hr but is not expected to reach that amount during normal usage. The meter limit is generally about 80% of the full capacity. The reference was selected to be 50% of 224 ft^3/hr (90% of the full capacity). Choosing the flow at 50% allows for better accuracy when calibrating above and below those flows. The maximum theoretical value for this experiment was approximately 170 ft^3/hr. Therefore, the reference value chose was more than sufficient. Figure 15 plots the pulse widths of the 500 positions. The data represents the average of 10 trials at 112 ft^3/hr. A few corrections were made to points that showed extreme values when calibrated against other flow rates. The figure shows 18 cycles that includes a relative maximum and minimum for each cycle. These correspond to the 18 teeth in the gear connected to the output shaft. The fluctuations in the times are due to the varying velocity of the 5-bar linkage motion at different positions. The maximum and minimum values of the pulse width are 0.25 and 0.072 seconds, respectively. These correspond to the maximum and minimum response times of the system at this flow rate.

4.2 Teaching Mode

The system was put through the Teaching Mode after the reference pulses were collected. The system enters the Teaching Mode when the black button is held down and the system reset button is pushed. The system asks for all possible combinations of the appliances being on and off. The valves representing different appliances must either be fully opened or closed, no valves should be partially opened. The system waits for the zero pulse to trigger the high precision pulse for the collection of data. It takes the first 400 points for each of the 7 possible appliance combinations. The system then averages each 4 successive points to reduce the points from 400 to 100. Averaging 4 points together greatly reduces the fluctuations in the measurements. The average and standard deviation of the 100 points are calculated. Table 2 shows the values acquired from the Teaching Mode. The dryer was measured at 24.71 ft^3/hr with a standard deviation of 0.51. The flow for the furnace and water heater was 102.24 ft^3/hr and 43.00 ft^3/hr, respectively. They had a standard deviation of 1.68 and 0.82, respectively. The combination of dryer and water heater was 65.9 ft^3/hr with a standard deviation of 1.30. The furnace and dryer combined for 122.13 ft^3/hr with a standard deviation of 2.00. The dryer and water heater had a flow rate of 136.43 ft^3/hr with a standard deviation of 1.57. All the appliances being on simultaneously had a flow of 153.53 ft^3/hr with a standard deviation of 2.65. There is an increase in standard deviation with increase in flow, with the exception of the furnace and hot water heater combination. It had a lower standard deviation than the furnace, and the furnace and dryer combined, which had lower flows. It is expected that higher flow rates have higher standard deviations because they tend to fluctuate due to the increased speed of the meter movement.

Table 3 shows the actual and theoretical flow rates for the system. The theoretical flow rates are calculated by combining the flow rates of two or more appliances. The actual flow rates were acquired from the Teaching Mode. It also gives the errors calculated using the equation [(actual-theoretical)/theoretical] x 100%. The loss in flow of the actual flow rates are due to the pressure drop from two or more appliances opened at the same time. In an ideal system there would be no pressure drop but in a realistic system, there is usually some loss of flow due to pressure drop. The error for the dryer and furnace being on at the same time is 3%, which reduces the flow rate by 2.1 ft^3/hr. An increase in flow leads to an increase in error. When all three appliances are on simultaneously, there is an error of 10% or a reduction of 16.47 ft^3/hr. The loss of flow might be reduced by having better regulators upstream of the gas meter. The current experimental setup uses three propane regulators that step down the pressure from 45 psi to 0.5 psi. These regulators are inexpensive and allow a minimum flow rate of 56 ft^3/hr each. By adding a better regulator or increasing the number of propane regulators, the co-linearity of the system is reduced and so will the flow loss. The advantage of this system is that we do not have to worry about the pressure drop in the system. By putting the microprocessor through the Teaching Mode, the flow rate values are successfully acquired without having to worry about how much flow is loss.

The flow rates measured by the mass flow controller are also shown in Table 3. There is a large discrepancy between the readings from the mass flow controller compared to the values acquired from the Teaching Mode at low flow rates. The values acquired in the Teaching Mode are 23% higher than the readings of the flow controller for the dryer. The water heater shows a 16% higher value, while the combination of dryer and water heater show a 14% increase in flow rate when compared to the mass flow controller readings. The probable cause of error in the flow controller reading can be in the specification of the mass flow controller. The mass flow controller states that it is accurate to within 2% for 25% to 100% of the maximum flow rate. The maximum flow rate of the system is 200 L/min (424 ft^3/hr). This gives a 2% accuracy range of 106 to 424 ft^3/hr. The mass flow controller is not probably not sensitive enough to accurately measure flow rates significantly below 106 ft^3/hr.

4.3 Accuracy of LED system

The range that is used to verify the accuracy of the experiment is 2 standard deviations from the mean flow rate acquired in the Teaching Mode. Two standard deviations will give flow rates that fall within the mean 95 percent of the time in a normal distribution. Flow rates that fall within this range will trigger the LED's to illuminate by the system. Though the meter motion has some random fluctuation, a general repeatable motion is followed most of the time. By comparing the data for the various appliances to

2 standard deviations of the average flow rates that acquired in the Teaching Mode, it is possible get a general idea of the accuracy of the LED system.

Figure 16 shows the flow rate versus time for 2 revolutions at 24.71 ft^3/hr. The figure shows that the data follows a relatively repeatable pattern for each corresponding point of a revolution. The upper and lower limits are 25.73 and 23.69 ft^3/hr, respectively. There are 13 points outside the range of the two limits with and error of 5.2%. Figure 17 shows the total consumption versus time for the dryer. The figure shows that the consumption versus time is linear for a constant flow. It takes 587.6 seconds to complete two revolutions.

Figures 18-29 show the flow rate and total consumption versus time for 2 revolutions for the other appliance combinations. The errors in the LED detection system and total consumption times are summarized in Table 4. The water boiler, dryer and water boiler combination, and furnace have errors of 3.2, 7.6, and 8.4 percent, respectively. The total consumption times are 336.6, 219.6 and 140.8, respectively. The combinations of furnace and dryer, furnace and water boiler, and all appliances together have errors of 3.6, 11.2, and 8.2 percent, respectively.

Except for the combination of furnace and water heater, the accuracy of the LED system is under 10% for other appliances combinations. As discussed earlier, it was one of the values that had a lower standard deviation than expected. One of the ways to reduce the error is to take 500 points instead of 400 points in the Teaching Mode. Taking 500 points represents one complete rotation. If there were more fluctuations in the last 100 points of a rotation, it would lead to a higher standard deviation. If those points are missed, the range that would activate the LED would effectively be lower. Another way to reduce the error would be to increase the range to 2.5 or 3 times the standard deviation. By widening the range, the percentage error would be well under 10% for all the appliances. Another way to reduce the error would be to average more points together. For this system, the average of 4 points was taken, which reduced the 500 points to 125 for each rotation. If the number of points being averaged was increased to 5 or more, the errors will be reduced. The number should divide evenly in 500 to insure that the process is repeatable for each rotation. One of the drawbacks to increasing the number of points averaged is that there will be a reduction in response time of the system. Thus, both accuracy and response time should be considered when making the decision.

4.4 System Test Runs

As discussed above, one way to identify when an appliance is on is by the LED system. Another way of knowing which appliances are on is by the flow rate versus time data that is outputted to a text file. The data from the file is plotted in Microsoft Excel to give graphical representation of the state of the appliances. Figure 30 shows the values conducted for the first 70 minutes after the program was started. For the first 7 minutes the average flow rate is about 102 ft^3/hr. This indicates that the furnace was turned on at the time based on the values acquired from the Teaching Mode. After approximately 7 minutes, there is a jump in flow rate, with the range between 118 and 126 ft^3/hr. The flow rate indicates the dryer and furnace are on. At about the 14 minute mark, there is yet another jump in flow to about 155 ft^3/hr. This shows that all appliances are on simultaneously. Near 24.5 minutes, the flow rate reduces to 60 ft^3/hr. The furnace is then switched off, with the dryer and water heater remaining on. During 34.5 to 44 minutes, the flow rate decreases to 43 ft^3/hr, this indicates that the water heater is the only appliance that is on. At the 44 minute mark, the flow increases to a range of 133 to 140 ft^3/hr, indicating that the furnace and water boiler are running. At about the 50 minute mark, the water heater is the only appliance operating. By the 53.5 minute mark, all the appliances are turned off. Finally, the dryer is turned on from 59 to 70 minutes. Figure 31 shows the accompanying total consumption graph.

One of the advantages of the system is the high precision and fast response time. Figure 32 and 33 show the flow rate and total consumption of the system, respectively. In total, 11 events are captured in a matter of 12.5 minutes. For a low precision system that only gets one pulse per revolution, it would only be equivalent to getting two data points for a flow rate of 10 ft^3/hr. This system acquires a total of 642 data points, with an average response time of about 0.02 seconds. The different slopes of the total consumption are also an indication of the change in events. In figure 33, the flow is constant from 0 to approximately 50 seconds. The slope increases after 50 seconds to show an increase in flow rate and therefore a different event. The consumption slope is zero from 4.5 to 6.1 minutes, and between 7.4 to 10 minutes. This indicates that all the appliances are off.

The two trial runs show that it is possible to determine which appliances are on at any given time by the flow rates acquired by the retrofitted system. The trials also show how long each appliances are on and off in real-time. This allows the historical usage information to be extracted. Analysis can then be done on the performance of the appliances based on historical patterns.

4.5 Sources of Error and Improvements on the System

Some of the possible causes of fluctuation of the measurement is the mounting of the system. The dimensions of the mounting holes were only estimates as detail drawings of the meter were not readily available. At certain positions, the rotation shaft tends to slow down and not run as smoothly as in other positions. This is mainly due to the eccentricity of the shaft not being perfectly aligned to the mounting holes. With the proper dimensions of the meter, it is possible to remove some of the fluctuations in the readings, thereby increasing system accuracy.

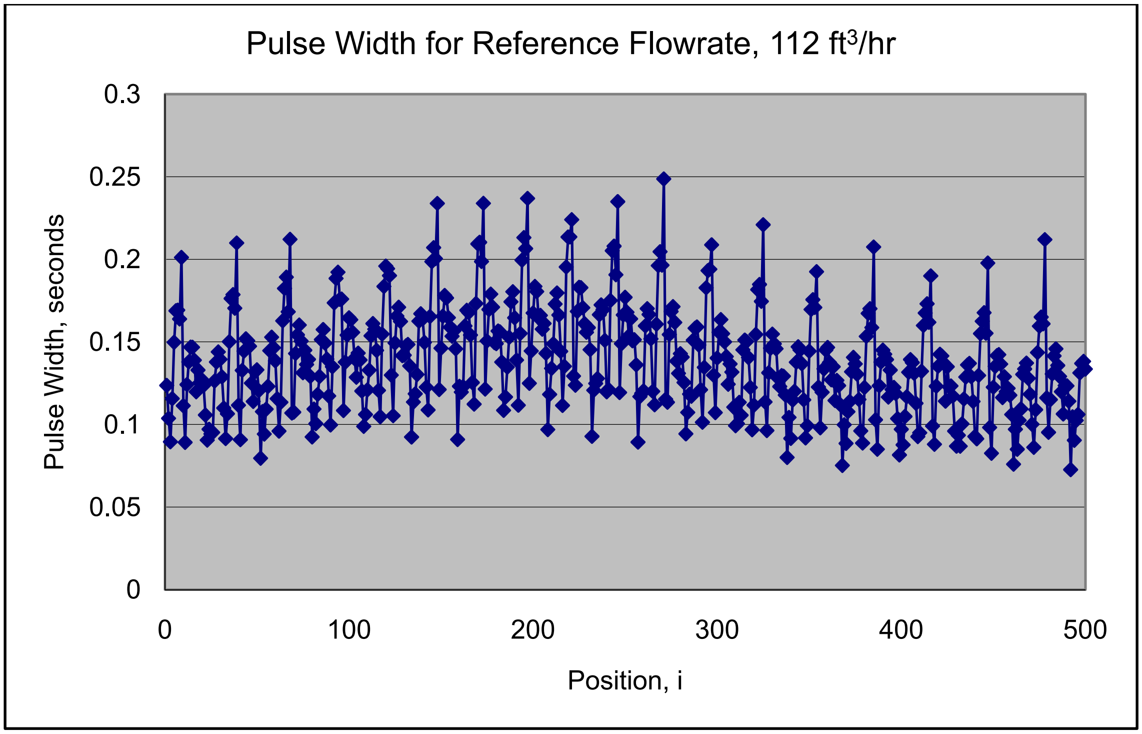

Figure 15. Pulse width for the 500 positions of the reference flow rate. The 18 relative maximums and minimums correspond to the 18 teeth in the gas meter output shaft gear.

Table 2. Flow rates and standard deviations for appliances acquired from Teaching Mode.

Appliance(s)	Flow Rates, ft^3/hr	Standard Deviation	2 Standard Deviations	Range for 2 standard Deviations
Dryer	24.71	0.51	1.02	23.69-25.73
Water boiler	43.00	0.82	1.64	41.36-44.64
Dryer, Water boiler	65.90	1.30	2.60	63.30-68.50
Furnace	102.24	1.68	3.36	98.88-105.60
Furnace, Dryer	122.13	2.00	4.00	118-126.13
Furnace, Water boiler	136.43	1.57	3.14	133.29-139.57
Furnace, Dryer, Water boiler	153.53	2.65	5.30	148.23-158.83

Table 3. Errors of actual flow rates(Teaching Mode) compared to theoretical flow rates and flow controller readings

Appliances	Actual Flow rate (Teaching Mode) ft^3/hr	Theoretical Flow rate ft^3/hr	Percentage error (Actual vs. Theoretical)	Flow Controller Readings ft^3/hr	Percentage Error (Actual vs. Flow controller)
Dryer	24.71	25	-1%	19	23%
Water boiler	43	43	0	36	16%
Dryer, Water boiler	65.9	68	-3%	57	14%
Furnace	102.24	102	0	102	0
Furnace, Dryer	122.13	127	-4%	121	1%
Furnace, Water boiler	136.43	145	-6%	136	0
Furnace, Dryer, Water boiler	153.53	170	-10%	153	0

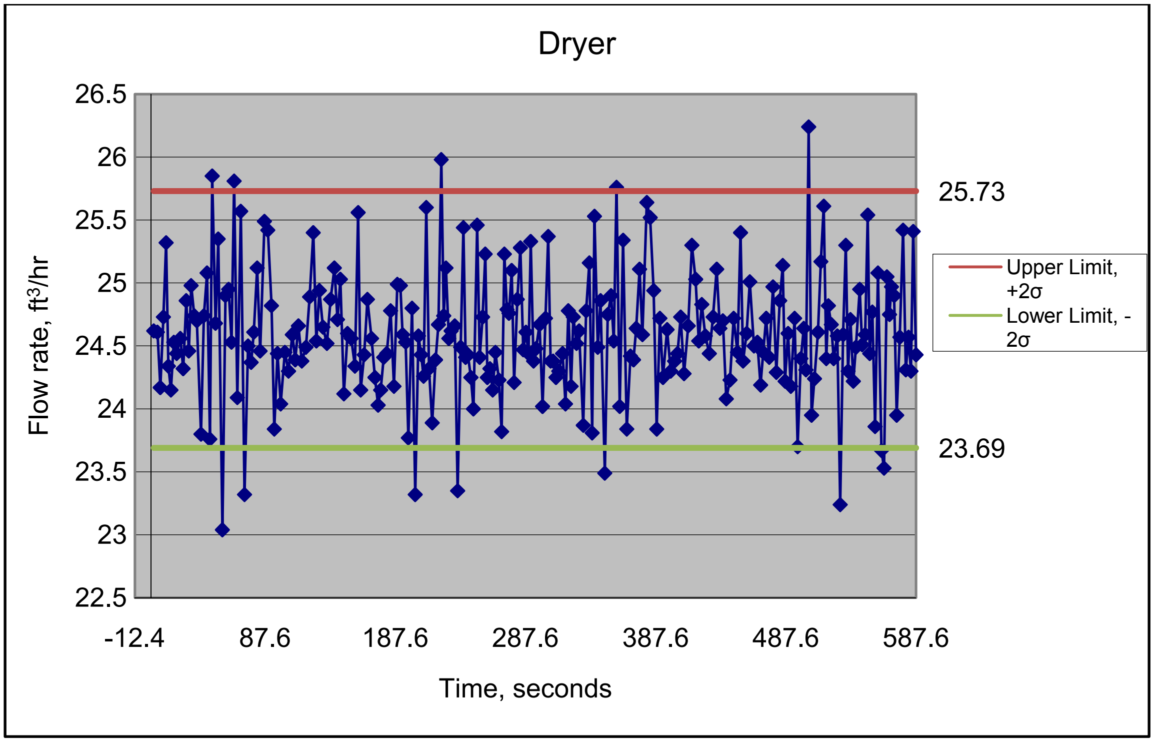

Figure 16. Flow rate versus time for two revolutions of output shaft for dryer

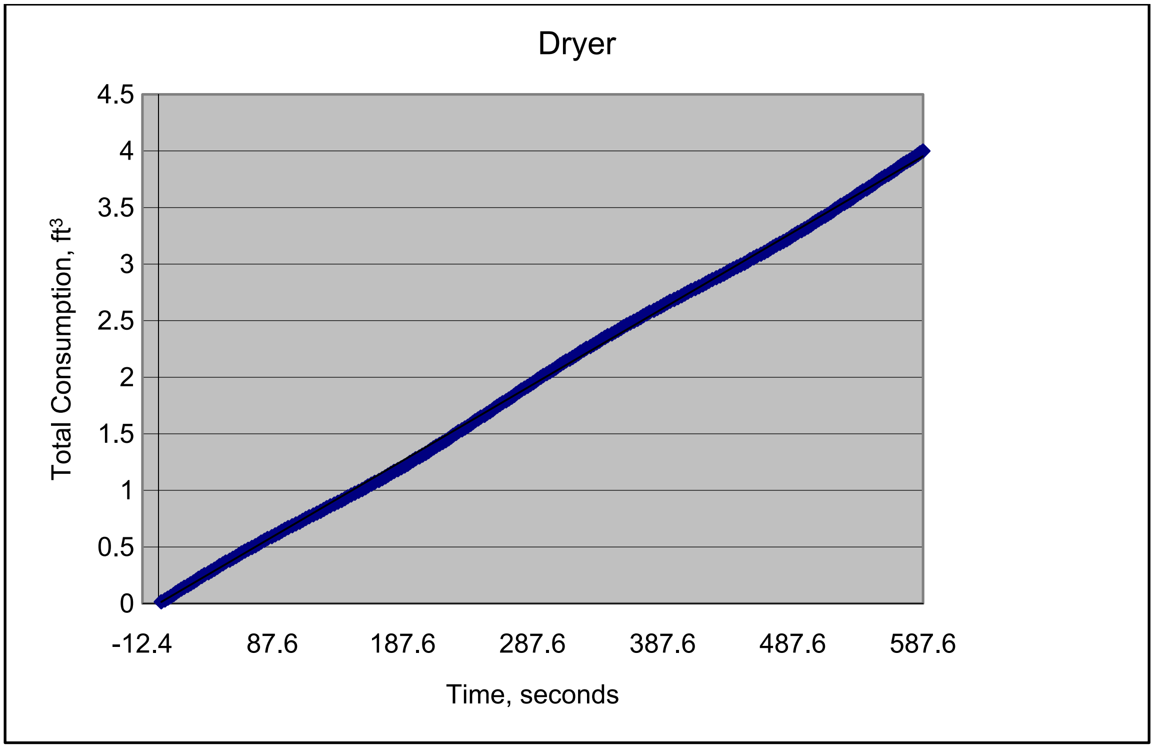

Figure 17. Total consumption versus time for two revolutions of output shaft for dryer

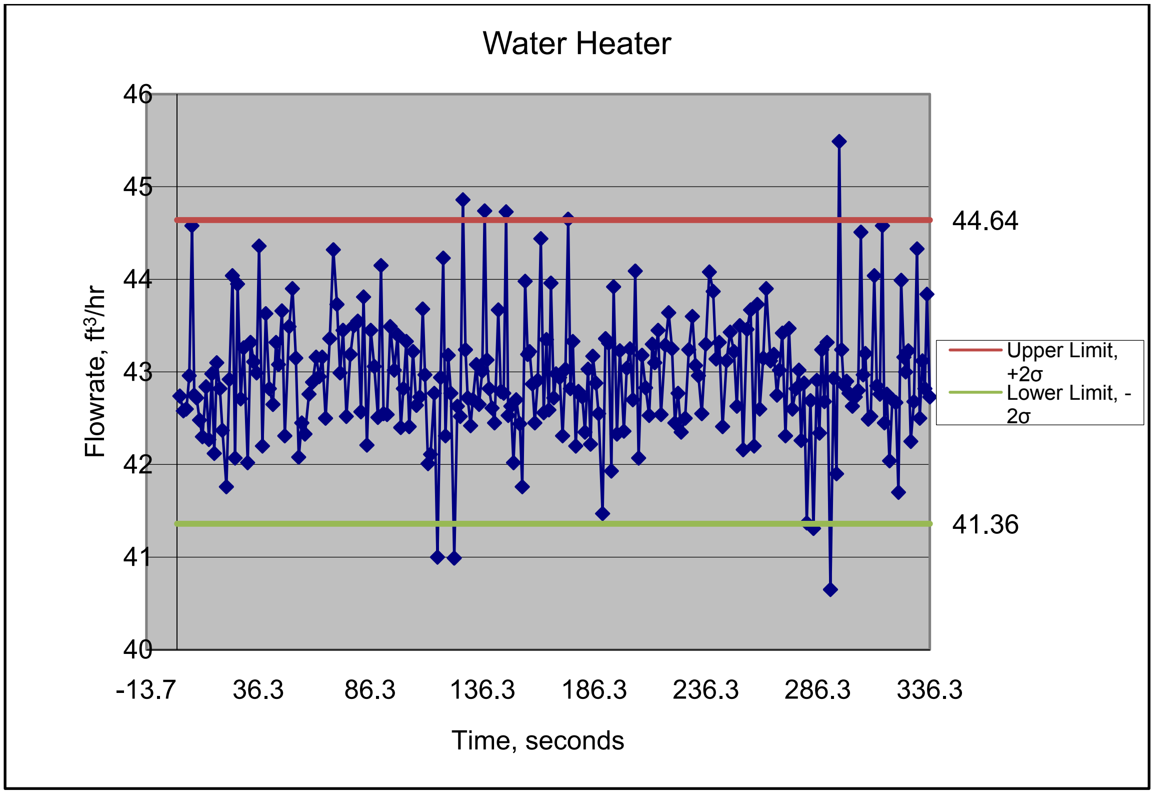

Figure 18. Flow rate versus time for two revolutions of output shaft for water heater

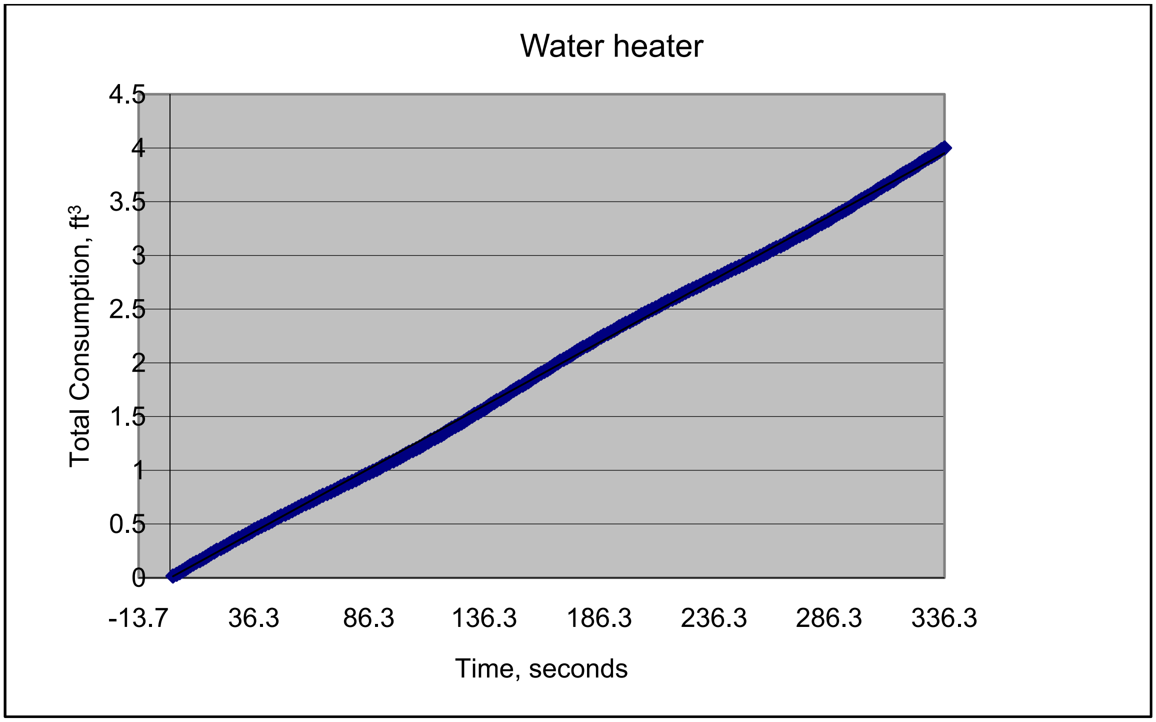

Figure 19. Total consumption versus time for two revolutions of output shaft for water heater

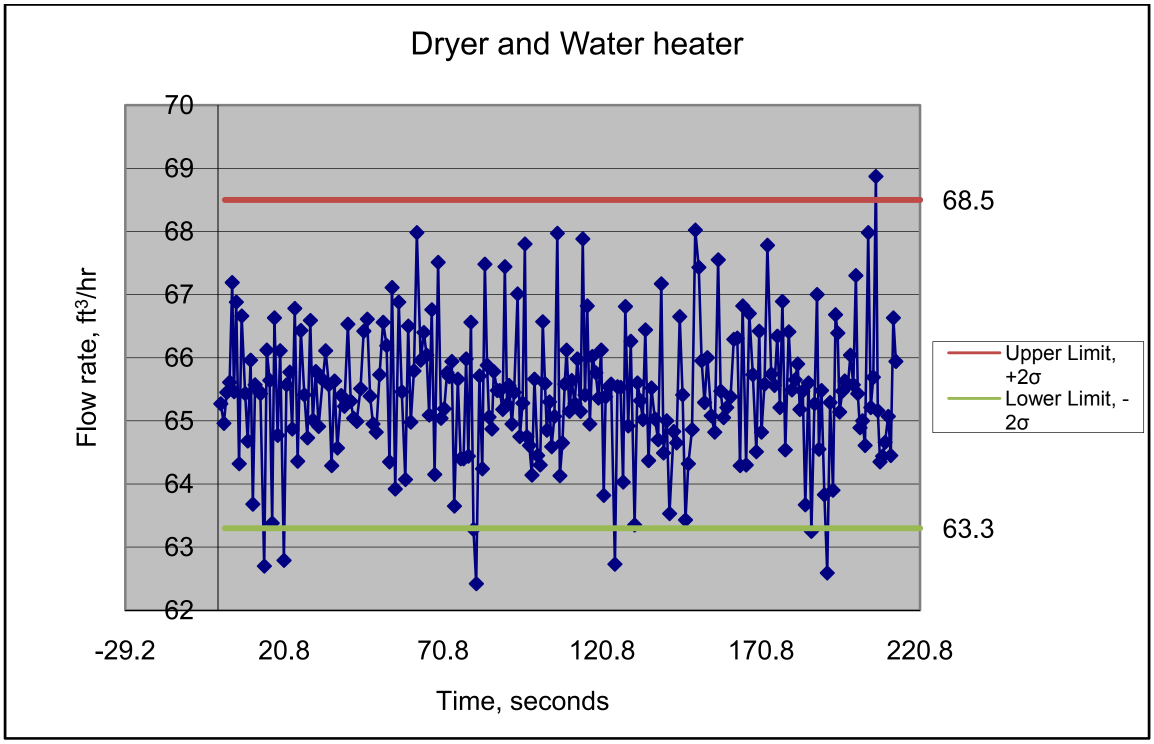

Figure 20. Flow rate versus time for two revolutions of output shaft for dryer and water heater

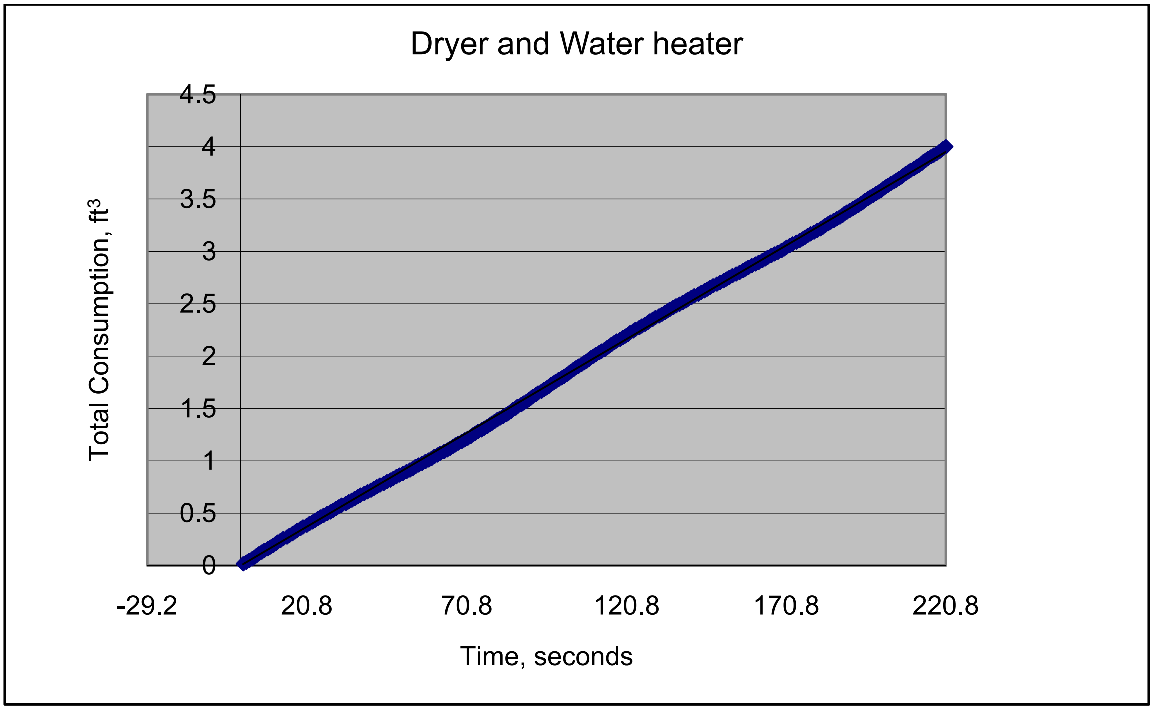

Figure 21. Total consumption versus time for two revolutions of output shaft for dryer and water heater

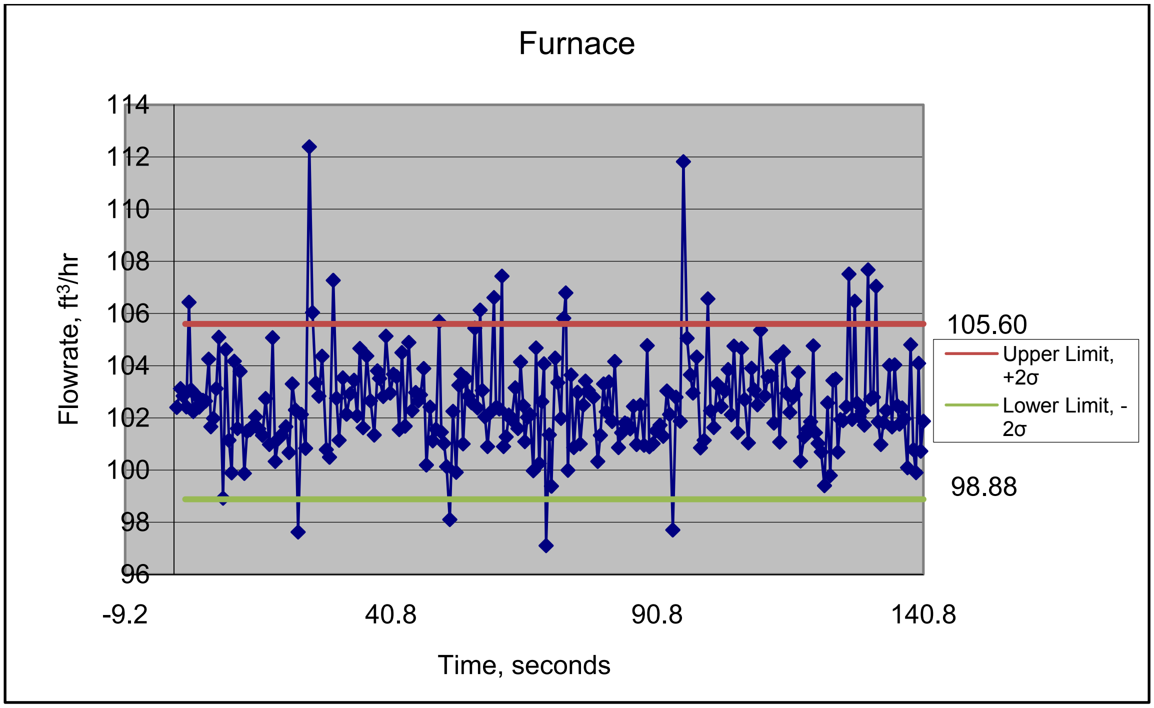

Figure 22. Flow rate versus time for two revolutions of output shaft for furnace

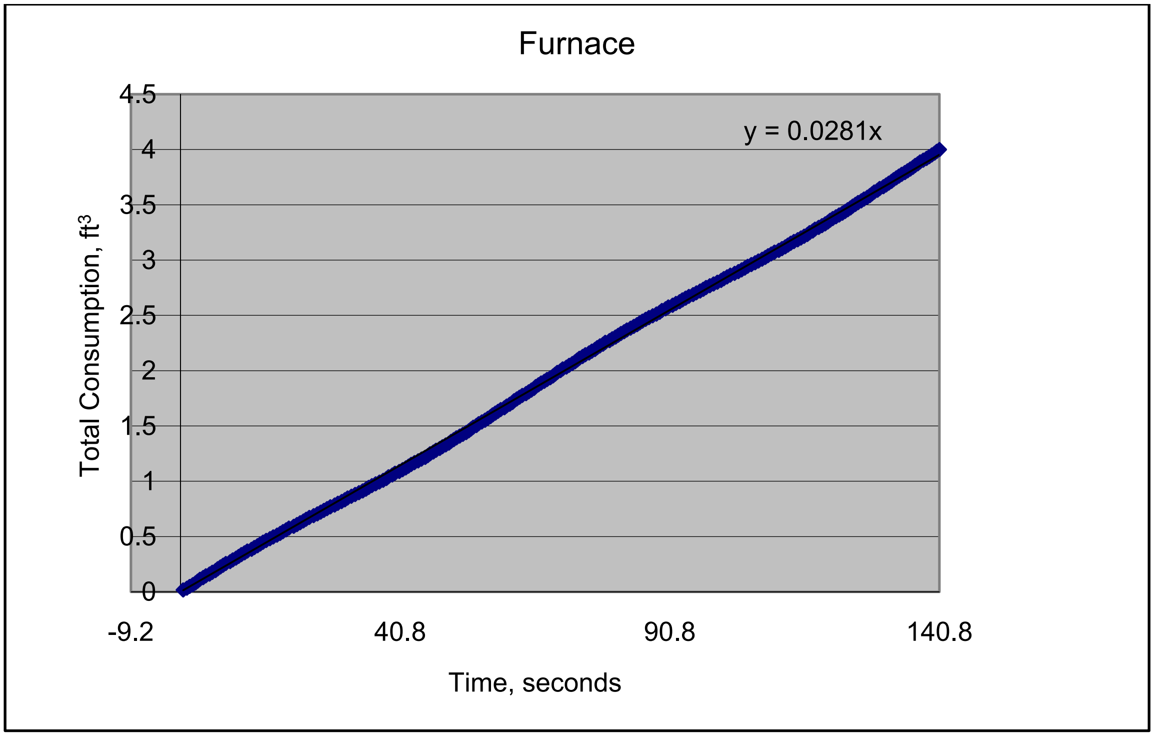

Figure 23. Total consumption versus time for two revolutions of output shaft for furnace

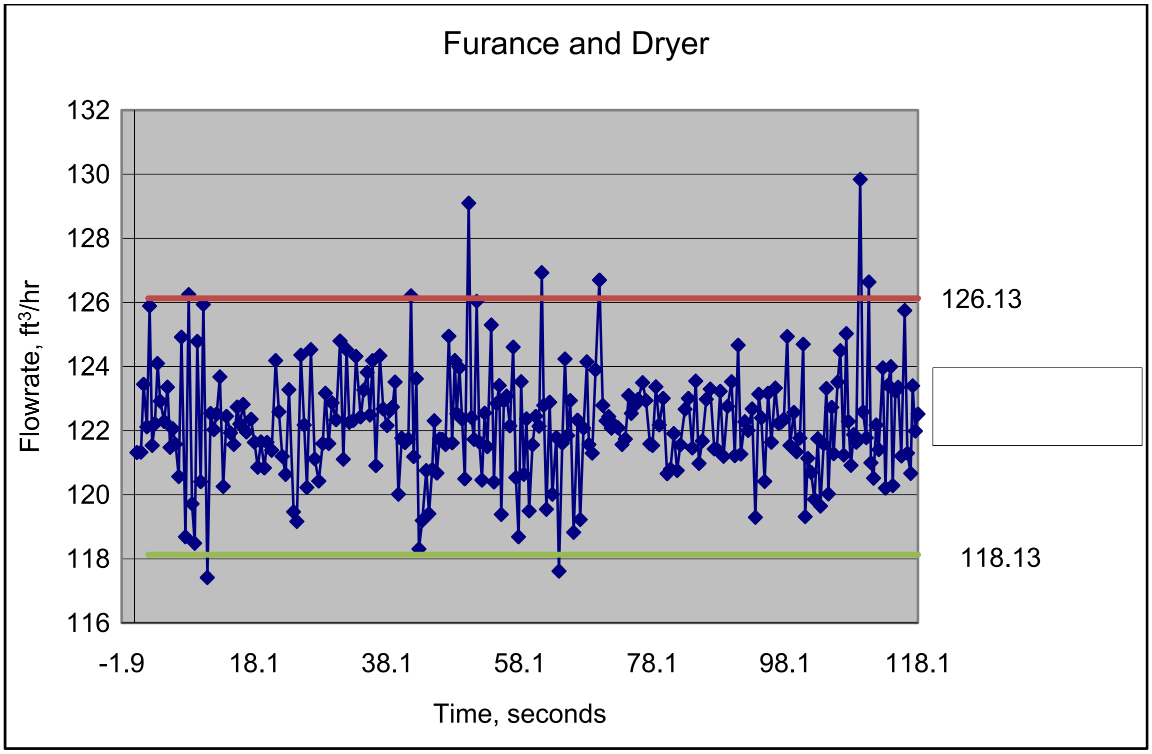

Figure 24. Flow rate versus time for two revolutions of output shaft for furnace and dryer

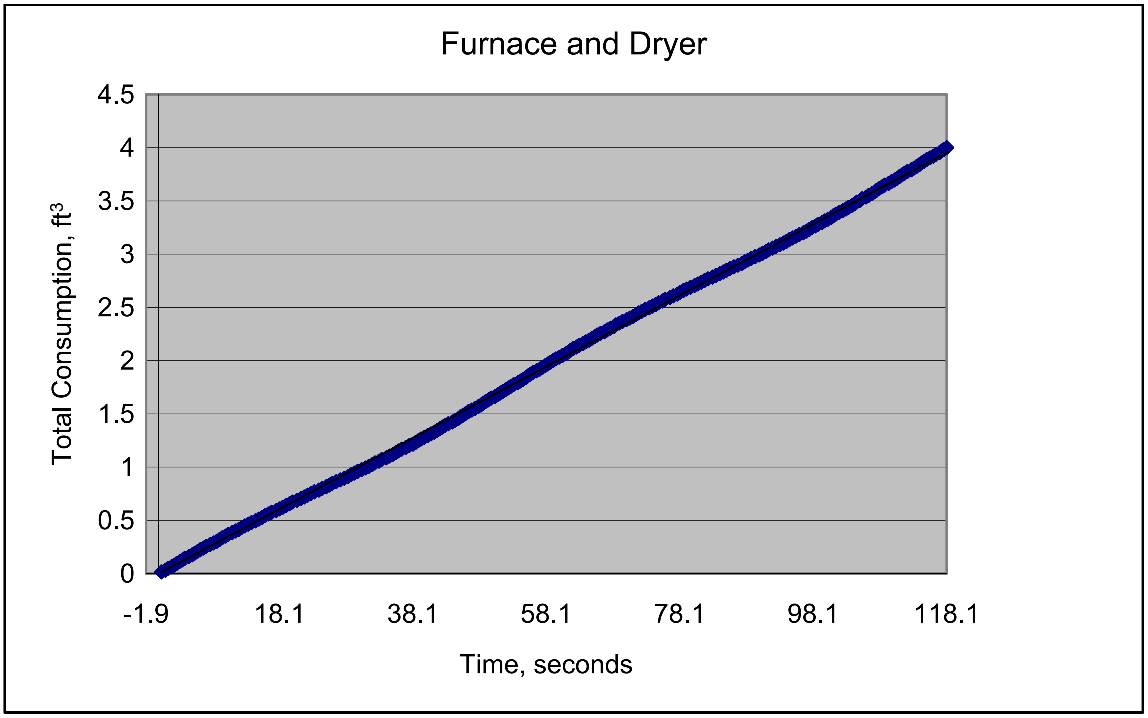

Figure 25. Total consumption versus time for two revolutions of output shaft for furnace and dryer

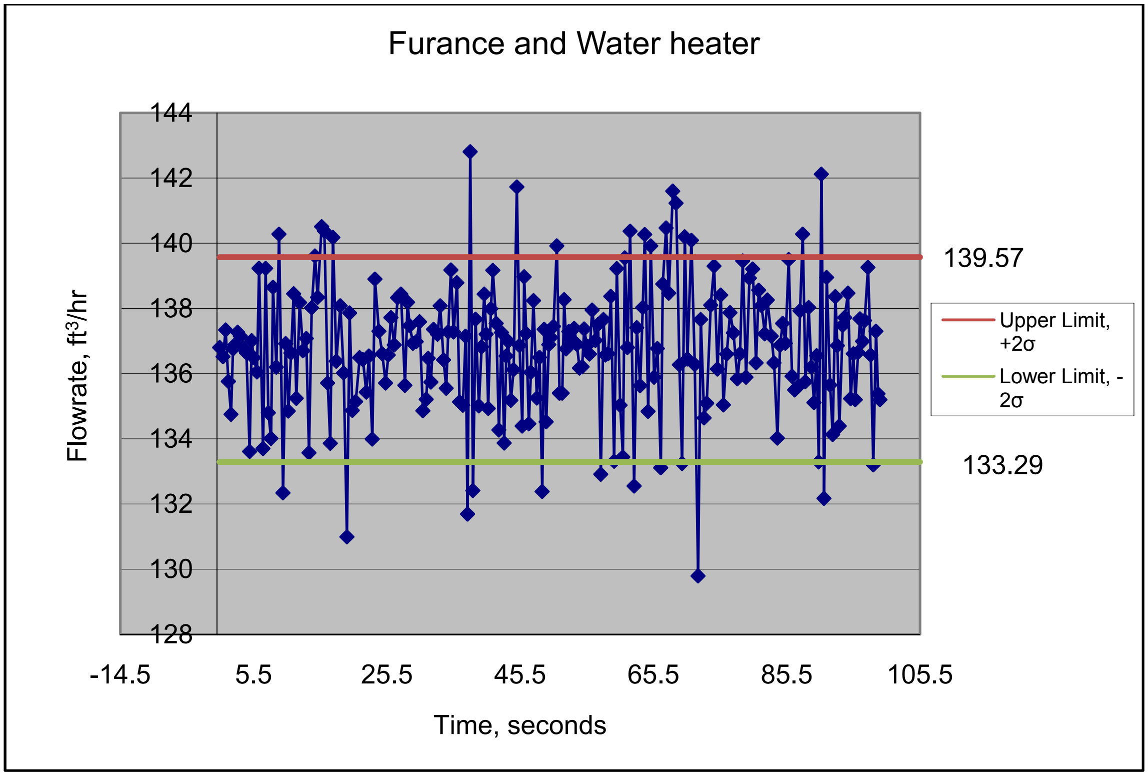

Figure 26. Flow rate versus time for two revolutions of output shaft for furnace and water heater

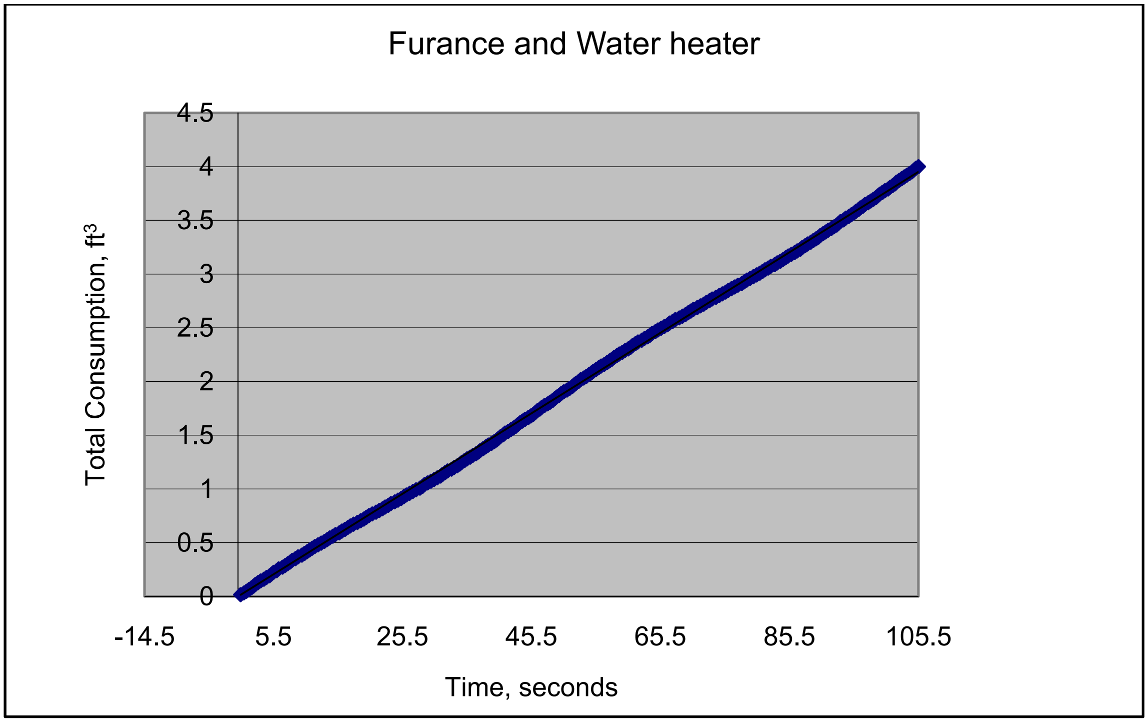

Figure 27. Total consumption versus time for two revolutions of output shaft for furnace and water heater

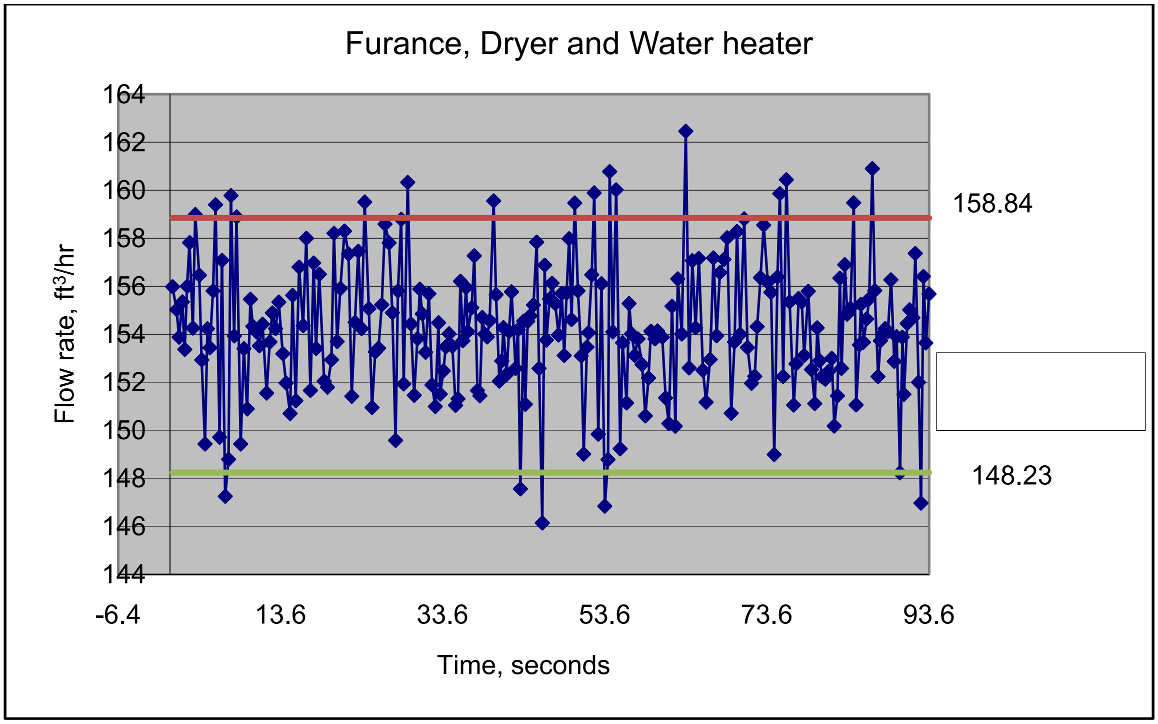

Figure 28. Flow rate versus time for two revolutions of output shaft for furnace, dryer and water heater

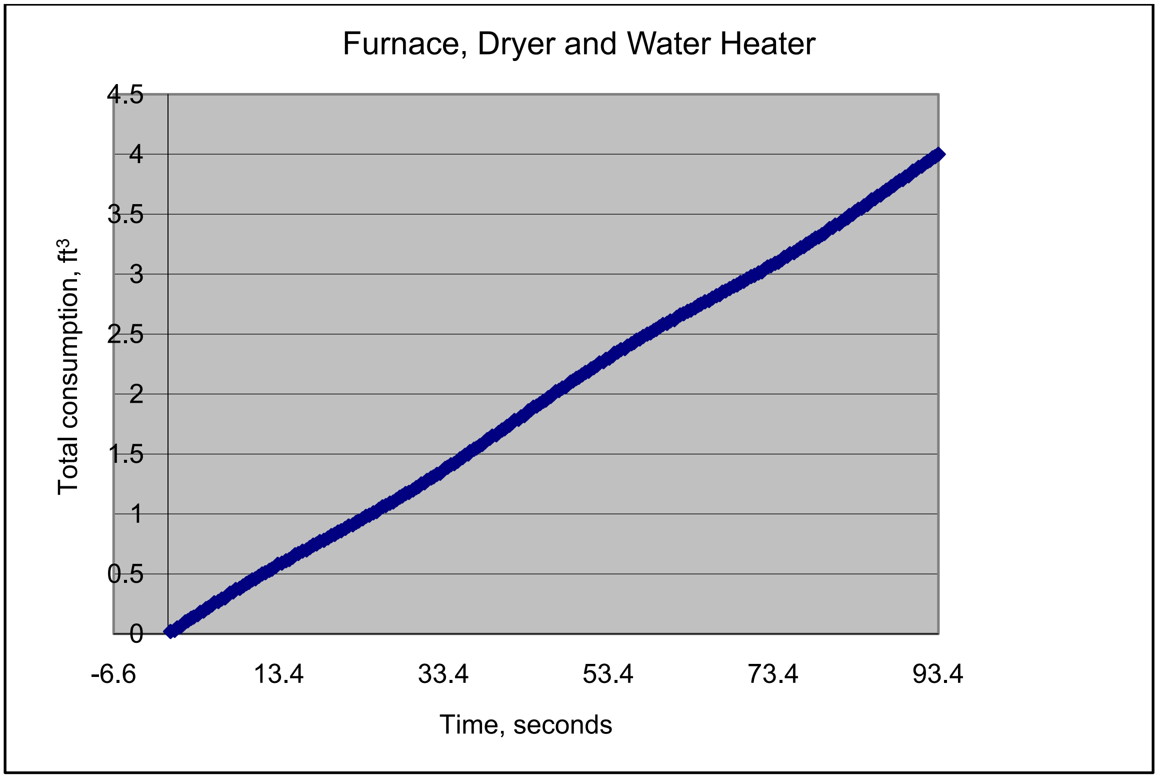

Figure 29. Total consumption versus time for two revolutions of output shaft for furnace, dryer and water heater

Table 4. Summary of errors in LED detection system and total consumption time for two revolutions

Appliances	Upper Limit	Lower Limit	Points outside the range	Error	Time of Total consumption for two revolutions
Dryer	25.73	23.69	13	5.2%	587.6
Water boiler	44.64	41.36	8	3.2%	336.3
Dryer, Water boiler	68.50	63.30	19	7.6%	219.6
Furnace	105.60	98.88	21	8.4%	140.8
Furnace, Dryer	126.13	118	9	3.6%	118.1
Furnace, Water boiler	139.57	133.29	29	11.2%	105.5
Furnace, Dryer, Water boiler	158.83	148.23	21	8.2%	93.4

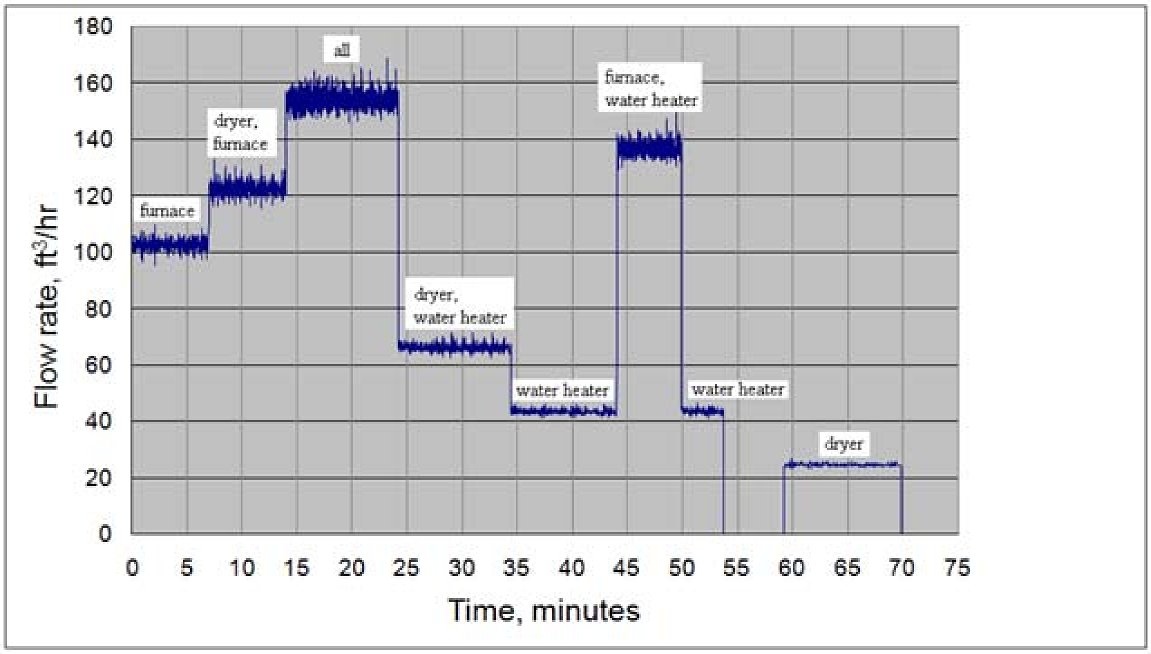

Figure 30. Flow rate versus time for long duration

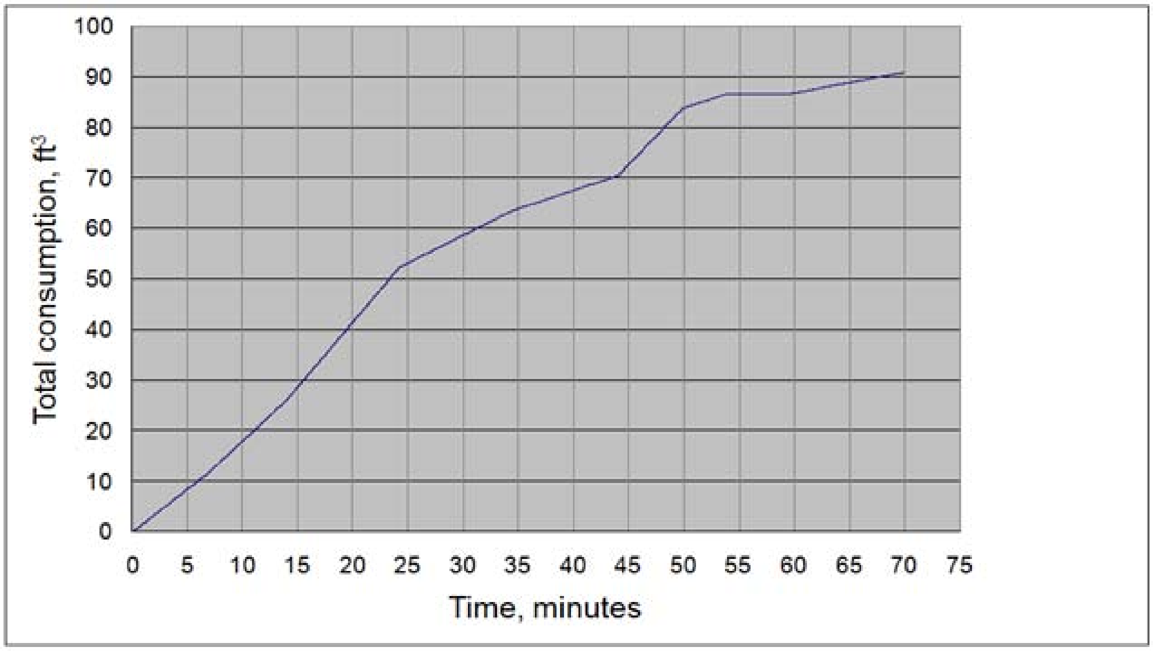

Figure 31. Total consumption versus time for long duration

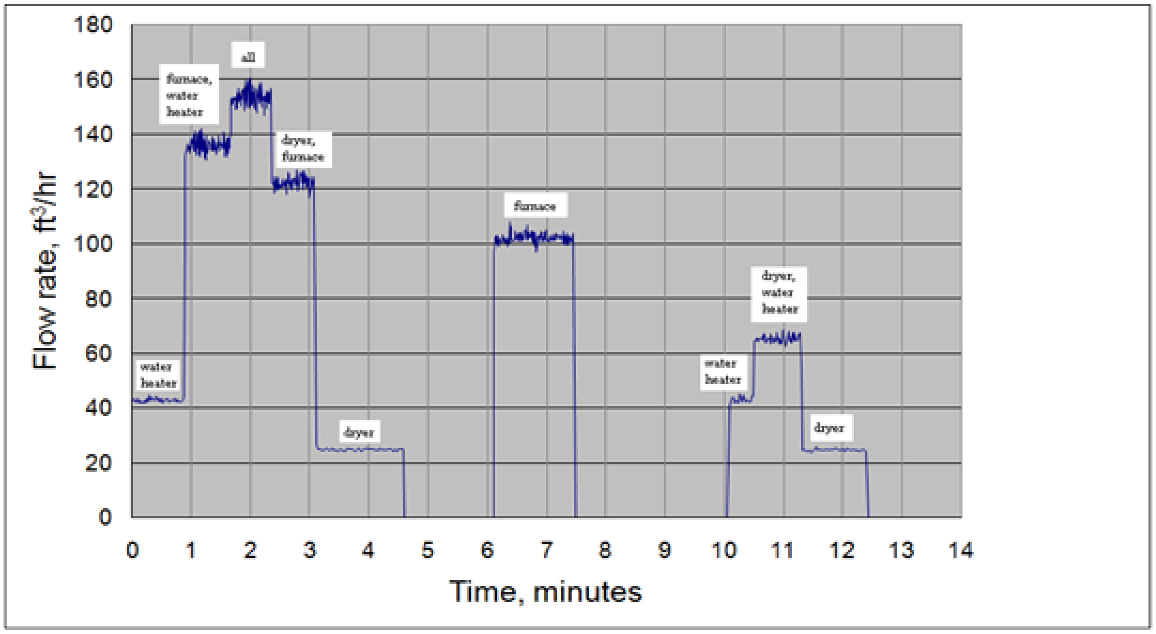

Figure 32. Flow rate versus time for short duration to show high resolution of system

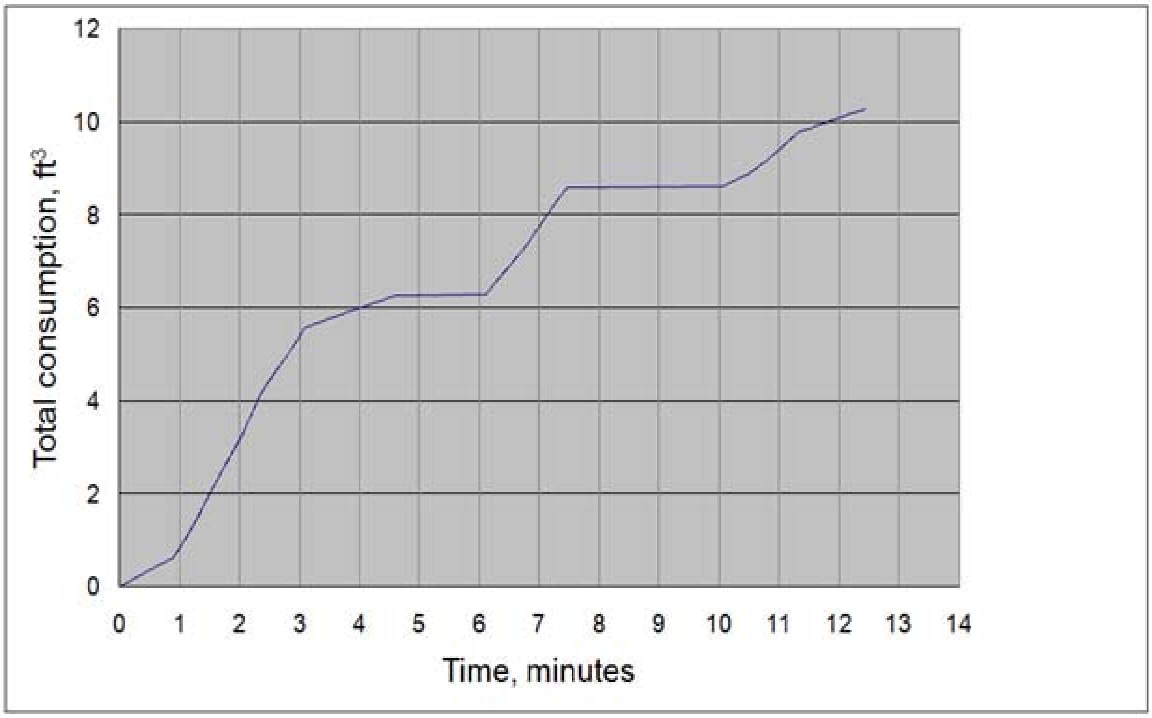

Figure 33. Total consumption versus time for short duration to show high resolution of system

Chapter 5: Conclusion

This work developed a real-time gas appliance monitoring system that uses gas consumption rates to determine when an appliance is on or off. The concept of the system is to convert the mechanical motion of the meter output shaft into actual flow rates. The experimental setup includes retrofitting an existing gas diaphragm meter with an encoder and microprocessor. The setup also simulates the flow rates of the furnace, dryer and water boiler using a custom-design piping system. The appliance monitoring system has two forms of visual identification to notify which appliances are on. The first is through on board LEDs that illuminate to notify when a given appliance is on. The second is the flow rates and total consumption versus time plots that identify when and how long each appliance has been on. The results discuss the typical accuracy of the LED system. The LED system is accurate to within 10% for all flow rates except one which had 11.5% error.

5.1 Conclusion of the Present Work

Chapter 2 presents the basic concept of the system. The internal mechanism of the diaphragm gas meter used is discussed. The basic theory of the optical encoder is also discussed. A outline of the microprocessor, along with the algorithm is also mentioned.

Chapter 3 presents the experimental setup for the monitoring system. The locations of the regulators, filters, mass flow controller, encoder, microprocessor custom-design piping systems are described in detailed. The flow rates of the furnace, dryer and water heater were made using different size orifices. These orifices were machined from pipe plugs with different diameter holes drilled in the middle to allow for the right amount of flow.

In chapter 4, the results for the different flow rates were discussed. The pulse width for the 500 different positions of the reference flow rate was acquired. In the Teaching Mode, the flow rates and standard deviations were acquired. The accuracy of the LED detection system was then compared with 2 standard deviations of the flow rates acquired in the Teaching Mode. Ways to improve the accuracy of the system was also mentioned. Two separate trials for the appliance monitoring system were shown. One trial was for a longer period, while the other was shorter to show the high resolutions of the system. Both trials show that the appliances are clearly identified based on the flow rates.

5.2 Direction of Future work

Possible suggestions for improving the system and future research possibilities are presented below.

5.2.1 Improvement to the system

The mounting of the encoder can be improved if detailed drawings of the meter are obtained. Locating the exact dimensions of the output shaft and mounting holes helps increase system reliability. When the output shaft rotates to a certain position, it tends to slow down. Imperfections in the alignment of the adaptor shaft and mounting plate with the meter output shaft cause fluctuations and errors in measurements. If the output shaft were able to move freely in all locations, it would give better measurements.

Having an encoder with lower resolution and a multiple of 18 would help reduce the fluctuations in the system. The resolution of the current encoder is 500 pulses per revolution and is reduced to 125 pulses per revolution by averaging 4 data points. The higher the resolution of the encoder, the shorter the pulse time is between each reading. Therefore, if there is a small fluctuation in the pressure of compressed air or the meter motion, it will cause a large change in the flow rates that are calibrated by the system. Reducing the resolution would make the pulse times longer, which thereby does not affect the system as much. Currently the resolution is being reduced manually by taking averages, using a new encoder would be more effective. A suggested resolution of the new encoder is 126 pulses per revolution. It is still high enough to detect about 0.016 ft^3 of gas but gives the desired characteristic of being divisible by 18. Since there are 18 cycles of the 5-bar linkage per revolution of the output shaft, exactly 7 readings per cycle will be recorded. There are 500 reference pulse widths for the current encoder. By using the suggested resolution, the number of reference pulse widths reduces to 7. As a result the sources of error due to some of the pulse widths possibly being off are reduced.

5.2.2 Future work

Further research includes adding more appliances to the present systems. Other appliances that used natural gas include fireplaces, ovens, stove and outdoor grills. The present system also does not include appliances that use variable flow rates. These types of appliances would be included in future works.

As this is one of the main parts of an AMR system, it is in our interest to complete the fixed network AMR system where it can communicate the present flow rates and data over the internet through wireless or broadband. Wireless infrastructure is to be set up where various meters can communicate their data to a central location.

The present system has only been tested in a laboratory environment. It would be desirable to use this technology to collect data from actual homes and test the accuracy and performance of the system.

The current method has the possibility to be incorporated into the other utilities. Some electric and water meters also have output shaft that are used to indicate the total energy consumption. It may be possible to study the characteristics of electric and water appliances by using consumption flow rates by the present proposed method.

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