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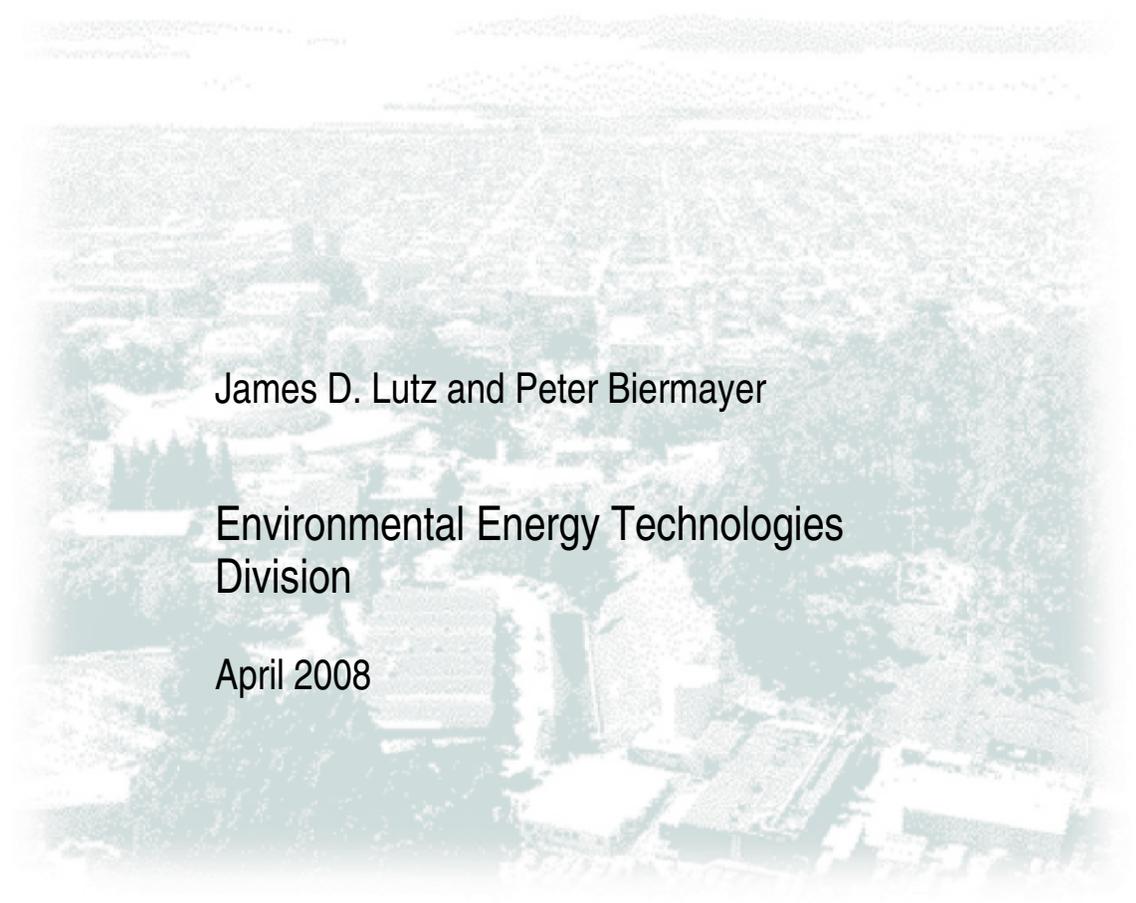
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## **Feasibility of Using Measurements of Internal Components of Tankless Water Heaters for Field Monitoring of Energy and Water Use**

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## **ABSTRACT**

The objective of this study was to determine if it was feasible to collect information regarding energy use and hot water delivery from tankless gas water heaters using the sensors and controls built into the water heaters. This could then be used to determine the water heater efficiency – the ratio of energy out (hot water delivered) to energy in (energy in the gas) in actual residential installations. The goal was to be as unobtrusive as possible, and to avoid invalidating warranties or exposing researchers to liability issues. If feasible this approach would reduce the costs of instrumentation.

This paper describes the limited field and laboratory investigations to determine if using the sensors and controls built into tankless water heaters is feasible for field monitoring.

It was more complicated to use the existing gas flow, water and temperature sensors than was anticipated. To get the signals from the existing sensors and controls is difficult and may involve making changes that would invalidate manufacturer warranties. The procedures and methods for using signals from the existing gas valves, water flow meters and temperature sensors will vary by model. To be able to monitor different models and brands would require detailed information about each model and brand.

Based on these findings, we believe that for field monitoring projects it would be easier, quicker and safer to connect external meters to measure the same parameters rather than using the sensors and controls built into tankless water heaters.

## **BACKGROUND**

Tankless water heaters heat water only as it is being drawn for use. There is no storage tank that hot water is kept in, and thus no standby losses from keeping water hot. Tankless water heaters have become more common in North America in the past several years, with annual sales of about 200,000. It is claimed that tankless water heaters are more efficient than tank-type water heaters. These claims are made on the efficiency of tankless water heaters based on Department of Energy (DOE) test procedures.[1]

However, as far as we know, no one has measured the field efficiency of tankless water heaters. It would be beneficial to measure the actual efficiency in real life applications. Actual water heater efficiency varies with the frequency, duration and flow of hot water draws.[2]. The number, duration, and flow rate of hot water draws vary from household to household, so it would be useful to monitor many households over time. In addition, tankless water heaters are designed to provide a continuous level of hot water. This may influence behavior and the amount of hot water used. For example, individuals may take longer showers if they know they will not run out of hot water.

Because of the way tankless water heaters operate, there are some other reasons to expect consumers with tankless water heaters may use hot water differently than consumers with

tank-type water heaters. There is a pre-purge time at the beginning of every draw with tankless water heaters. This is a 10 to 15 second period after water starts flowing before the burner is turned on. Since there is no stored hot water in a tankless water heater, cold water flows through the water heater for this period. The initial flow of water from a tank-type water heater is at the temperature of the stored hot water. The heat left in the water and the heat exchanger in the tankless water heater after a draw dissipates and is lost. This loss means shorter draws will be less efficient than longer draws.

A quick, easy and inexpensive way to monitor the energy and water use of tankless water heaters would be very helpful. The tankless water heaters sold in the U.S. in the past several years have sophisticated controls and sensors to provide constant temperature hot water. If the sensors and controls built into the tankless water heaters could easily be used in a monitoring project, then conducting studies to answer questions about the field efficiency of tankless water heaters might be easier to conduct.

## **INTRODUCTION**

This project examined the feasibility of using the sensors and controls built into modern tankless water heaters for field monitoring projects.

There were two main parts to this project:

1. field observations and investigations, and
2. laboratory testing of proposed measurement methods.

In the first phase of this project, we looked at two tankless installations at residential single family houses, one in Berkeley and one in El Cerrito, California. Both water heaters were installed outdoors. The two heaters were models of major manufacturers of tankless water heaters, Takagi and Rinnai. The purpose of these site visits was to investigate possible methods of collecting data from the sensors and controls in the water heaters in the field. This phase also included researching existing literature and reading water heater operating and installation manuals.

The second phase of this project was to supplement what we learned from the field observations by running various tests on a tankless water heater in a laboratory where all parameters could be accurately monitored and compared to measurement methods we were considering using in a field study. We tried various instrumentation approaches with laboratory type instrument monitoring the same parameter, and comparing them. A Rinnai tankless water heater was tested in the laboratory

### ***Determination of tankless water heater efficiency***

Efficiency is defined as the ratio of output energy to input energy. The output is the heat energy in the supplied hot water. The input energy is the heat content of the natural gas supplied to the water heater and the electricity used by the water heater.

To determine efficiency we would need to monitor water temperatures and flows, gas use and electricity use. Modern tankless water heaters have sensors that measure water flow rate, and outlet temperature. The Takagi model, but not the Rinnai model, also measured inlet temperature.

These three parameters can be used determine the energy output of the water heater. In order to measure efficiency, additional measurements must be taken to determine the energy input. This means measuring the gas consumed by the water heater, and the electrical energy input. To measure the energy, the gas flow rate, gas pressure, gas temperature and the heat content (higher heating value) of the gas needs measured.,

Tankless water heaters use electricity for the combustion air fan and to power controls when the unit is running. When the unit is not heating water some electricity is consumed as standby power. Also some models use electricity for freeze protection.

### **Factors effecting efficiency**

Field efficiency can vary from the efficiency measured in a laboratory under the DOE test procedure due to differences in the:

- number, duration, frequency, and flow rate of hot water draws,
- ambient temperature surrounding the water heater,
- temperature of the water supplied by the water heater,
- temperature of the water supplied to the water heater, and
- use of resistance heating for freeze protection.

### ***Department of Energy Test Procedure***

The DOE test procedure to measure the efficiency of water heaters is a 24 hour simulated use test.[1] The 24-hour simulated use test determines the amount of fuel and electricity used during a 24-hour period to heat 64.3 gallons (243 L) of water. The water is heated from 58 °F (14.4 °C ) to 135 °F (57.2 °C). It is drawn in six equal draws of 10.7 gallons (40.5 L) at one-hour intervals at the beginning of the test. After the draws, the water heater is left in standby mode for the remainder of the 24 hour test. If the water heater has a variable input rate, as nearly all modern tankless water heaters do, the first three draws are at maximum flow rate and the second three draws are at the minimum flow rate. There are additional requirements if 135 °F (57.2 °C) outlet water temperature cannot be reached at the minimum flow rate.

### ***Plumbing system effects***

Plumbing systems vary by the distance of the end-use from the water heater. Differences exist for the diameter of the pipe and the pipe material. The efficiency of the entire domestic hot water system and how the water interacts with the system can have important impacts on hot water use. Some of the factors that may impact how consumers use hot water are the structure of the plumbing system, including any long, un-insulated

pipes, and if a hot water recirculation system is present. Field monitoring of hot water use at large numbers of houses may be able to give insight into plumbing system effects. We did not consider plumbing system issues in this project.

## **FIELD INVESTIGATIONS AND TESTING**

We investigated a Tagaki TK-2[3] and a Rinnai Continuum Model 2532 in the field. Initial observations from the site visits and from reading installation manuals are discussed below. These provided suggestions of what could be further investigated in the laboratory.

### ***Initial observations and identification of monitoring options***

Both the Tagaki and the Rinnai models have a monitor and controller that displays temperatures and water flow rates via a two-wire connection to the water heater. The controller can be used by the consumer to set the hot water temperature. There is the option of having more than one monitor and temperature controller per water heater. These can be placed in separate locations within the house. Typically, a master controller is placed in a bathroom and this controller can override any other controllers. The Tagaki remote monitor is used to set the water temperature leaving the water heater. It has the capability to display the inlet and outlet water temperature as well as the hot water flow rate from the water heater. The Rinnai monitor only shows the outlet water temperature.

Sensors for water flow and temperature feed into a printed circuit board. The monitor has one display and the user can toggle between the available outputs. The water heater sends this information as a digital signal. The digital signal sent by the circuit board in the water heater could be deciphered and sent to a continuously recording data logger. This would be difficult to do without the help of the manufacturer or would require specialized knowledge to decipher the digital signal with a logic analyzer.

Without using the sensors on the water heater, the inlet and outlet water temperatures could be determined more conventionally by thermocouple probes in the water lines or with surface mounted temperature sensors on the inlet and outlet pipes.

The gas flow is harder to measure without installing a gas meter. The water heaters we investigated don't appear to measure gas flow rate. Because combustion air flow is proportional (within limits) to the gas input, combustion air flow or combustion blower speed could serve as a proxy for gas consumption. The fan speed could be measured by a Hall effect device or a tachometer. While a typical diaphragm type gas meter can be used to accurately measure and record gas flow, this would require breaking into the gas supply line. Gas flow, as well as other parameters could be determined for the most popular tankless water heaters in a laboratory and then correlated to a simpler parameter to measure in the field as a proxy. It is very important to understand details of tankless water heater operation for this approach. Another approach would be to monitor the house gas meter, try and account for any other gas use and subtract that amount from the total gas use.

The gas heat content (also referred to as the higher heating value or HHV in BTU/cu.ft. (J/m<sup>3</sup>)) can be obtained from the local gas utility for the service area of the residence.

The electrical energy input could be measured with a watt-hour meter or less accurately with a clamp-on current sensor. This assumes the voltage and power factor stays constant. The line voltage will not vary by much but power factor would need to be measured. With variable speed blowers and sophisticated electronics – assuming the power factor is constant may not be a good assumption.

We wanted to become more familiar with the operation of tankless water heaters in field installations. We also checked how the flow meter from the water heater remote monitor compared to the water flow recorded by the house utility meter. This would be useful if we could record the flow from the remote monitor or from the water heater flow meter. We also wanted to see if a parameter that might be easier to measure such as blower speed (RPM) or blower current (amperes) could be used to monitor gas input.

### ***Takagi Site***

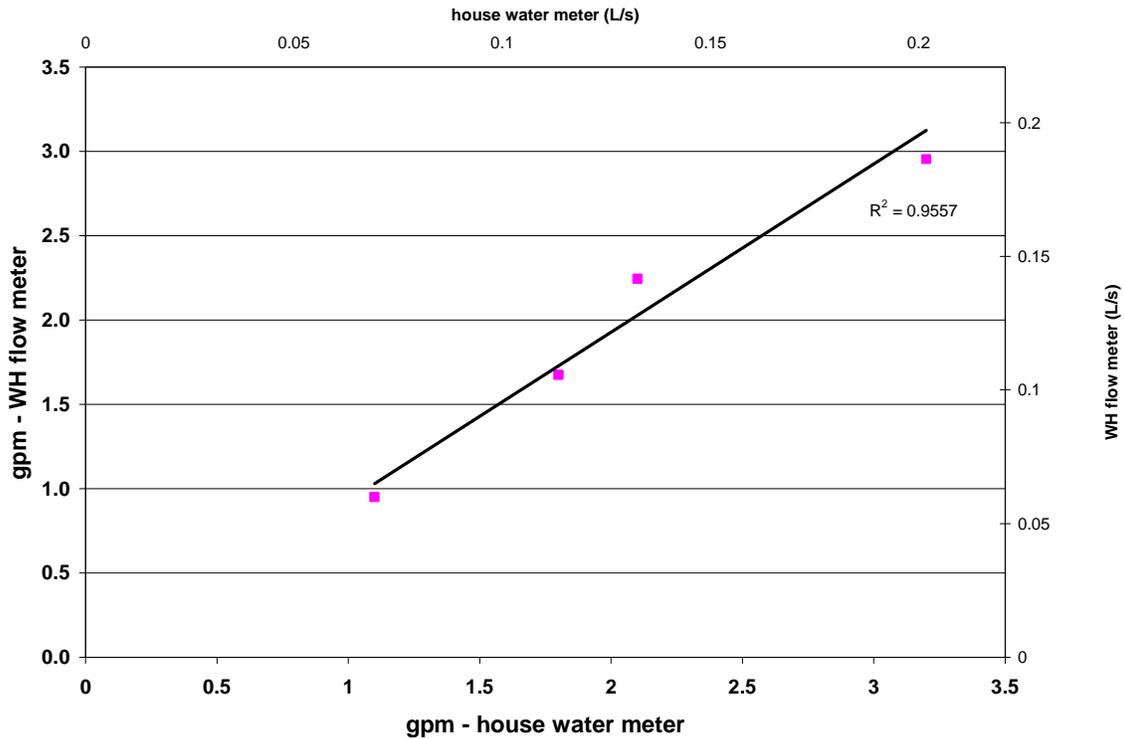
A photo of the Takagi water heater with the front cover removed is shown in Figure 1. Although the water heater is installed on an exterior wall, a vent system was attached to exhaust combustion products above the roof level. At this location we investigated water flow rates and gas consumption rates. The remote control panel for water heater displayed inlet and outlet water temperatures.



**Figure 1 Takagi tankless water heater with front cover removed.**

To check the accuracy of the flow reported by the water heater display, we compared it to the flow reported by the water utility meter for the whole house. A water faucet was

opened to produce various hot water flow rates. Water volume was measured for a few minutes at the street meter. Flow was calculated by dividing volume by time. The water flow at the street meter was plotted against flow on the water heater monitor and display. Results are shown in Figure 2. The results show that the flow meter in the water heater is quite accurate compared to the utility meter.

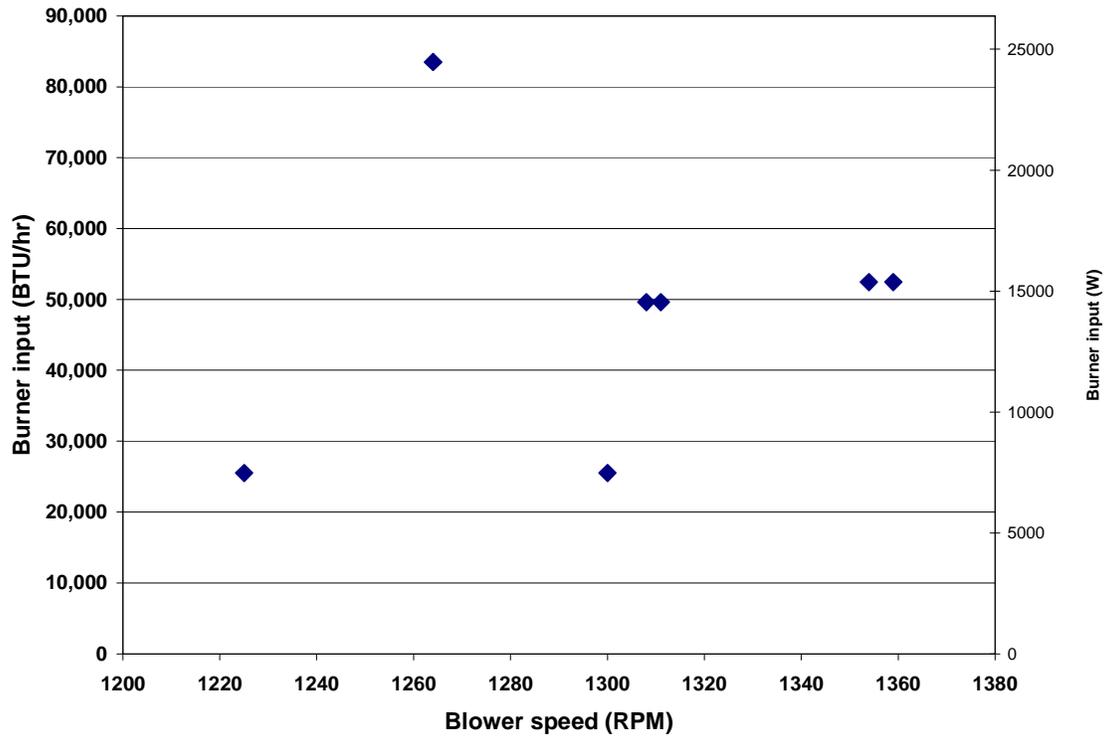


**Figure 2: Water flow Takagi versus house meter**

Attempts at measuring gas use were not as successful. The water heater display does not report gas use. As far as we could tell, the water heater does not measure gas consumption. We investigated using the combustion air blower speed and electricity consumption as proxies for gas consumption.

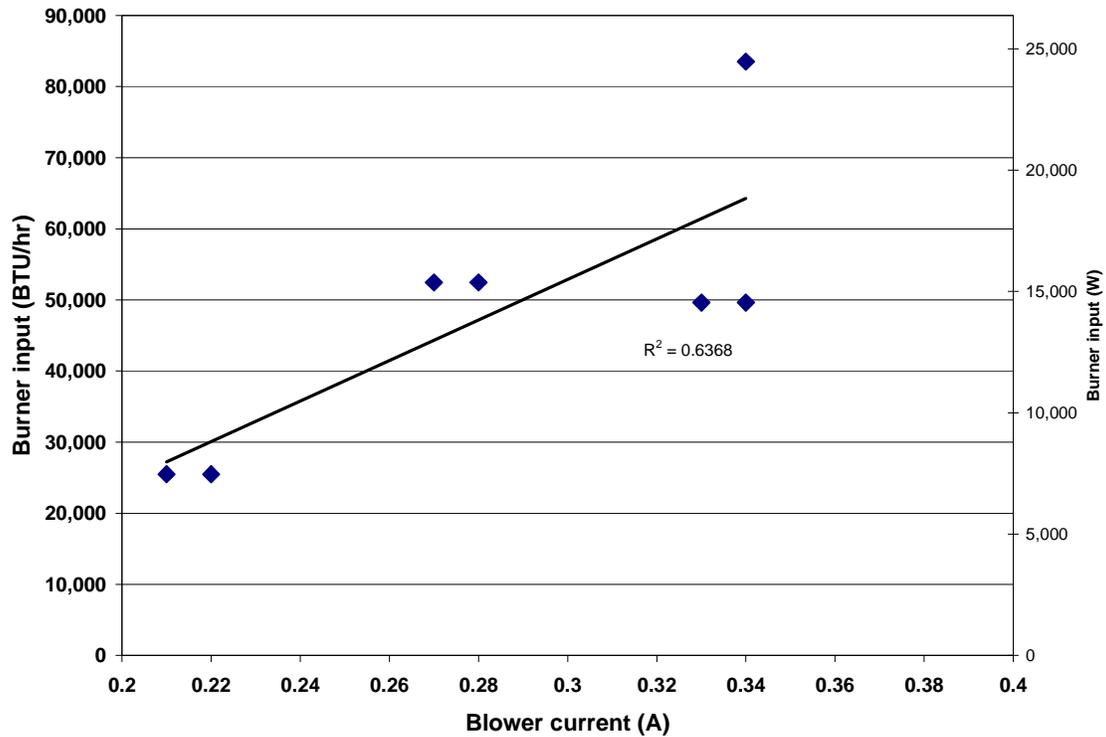
A stop watch was used to determine the gas flow rate measured at the house gas meter and compared to the rotation speed of the combustion blower. The combustion blower speed was measured with a tachometer. This approach was inconclusive because it was difficult to set the tachometer properly. We did notice considerable hunting for the combustion blower (as it got feedback from sensors in the water heater), especially when there was a change in flow rate. These could average out if the blower revolutions were determined over a longer time period (rather than the instantaneous measurements of a tachometer). Our field data was inconclusive and possibly incorrect. (See Figure 3: Takagi - blower rotation speed versus gas supplied) This measurement could be repeated in a laboratory setting. If a good correlation exists between the blower speed and gas

flow, then a small tachometer or a Hall effect or optical sensor could be used to count the revolutions of the blower vanes and thus determine gas consumption.



**Figure 3: Takagi - blower RPM versus gas consumption**

We also measured current to the blower and compared that to gas flow (from the house gas meter with only the gas water heater on). Because the blower is variable speed, probably an electrically commutated motor with non-sinusoidal current draw, this approach was not promising either. (See Figure 4: Current versus Gas Consumption – Takagi)



**Figure 4: Gas Consumption versus Blower current - Takagi**

We investigated the relationship between the blower speed and blower current. The blower RPM might correlate with the gas usage but it might be easier to measure the current to the blower than to measure the blower speed. Theoretically, power consumption is proportional to the cube of the blower speed. We also looked at this correlation to determine if we could see a correlation between the speed cubed and the current to the motor. We did not find a good correlation. (See Figure 5: Takagi - RPM cubed versus amps)

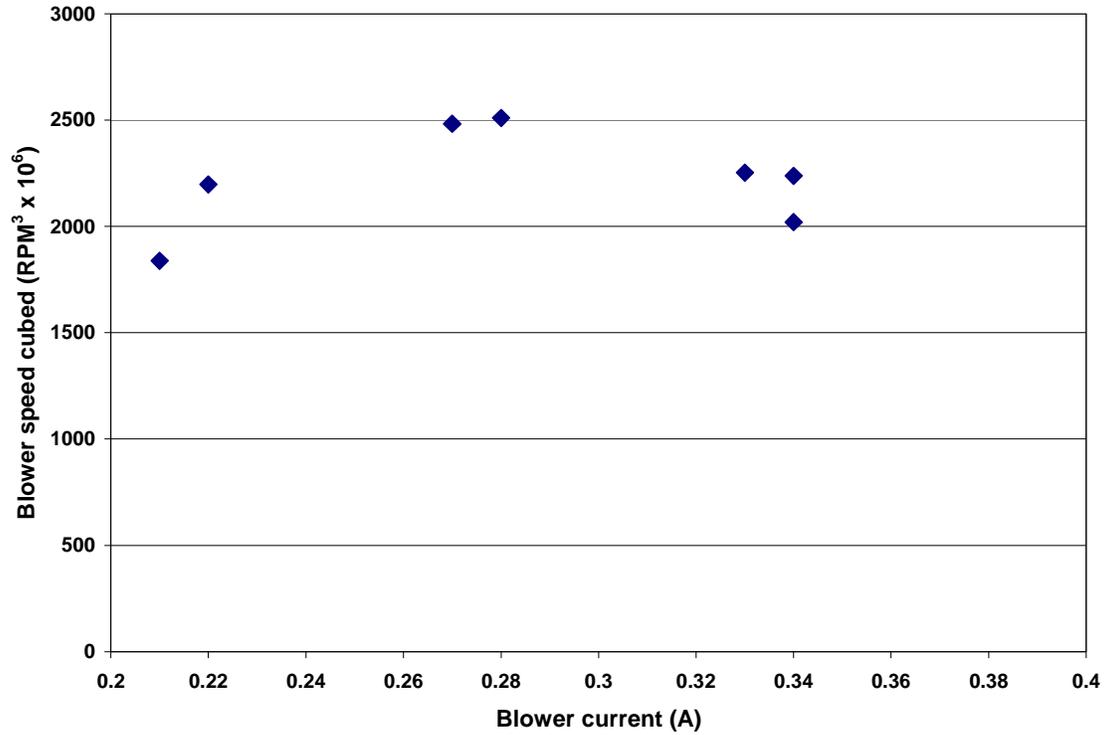


Figure 5: Takagi - Blower speed cubed versus current

### ***Rinnai Site***

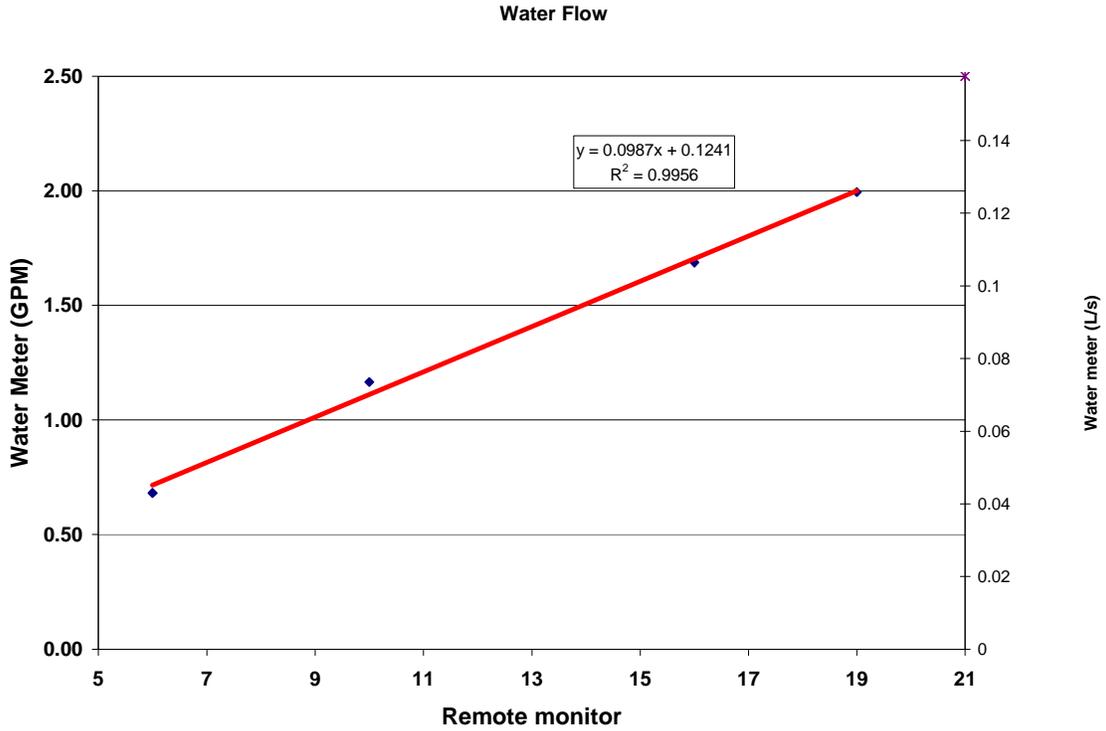
The other field installed water heater we investigated was a Rinnai Continuum 2532. At this site the water heater was also mounted on an exterior wall. It was a direct vent model, and did not use a vent system. The installation is shown in Figure 6.



**Figure 6: Rinnai tankless water heater with front cover removed**

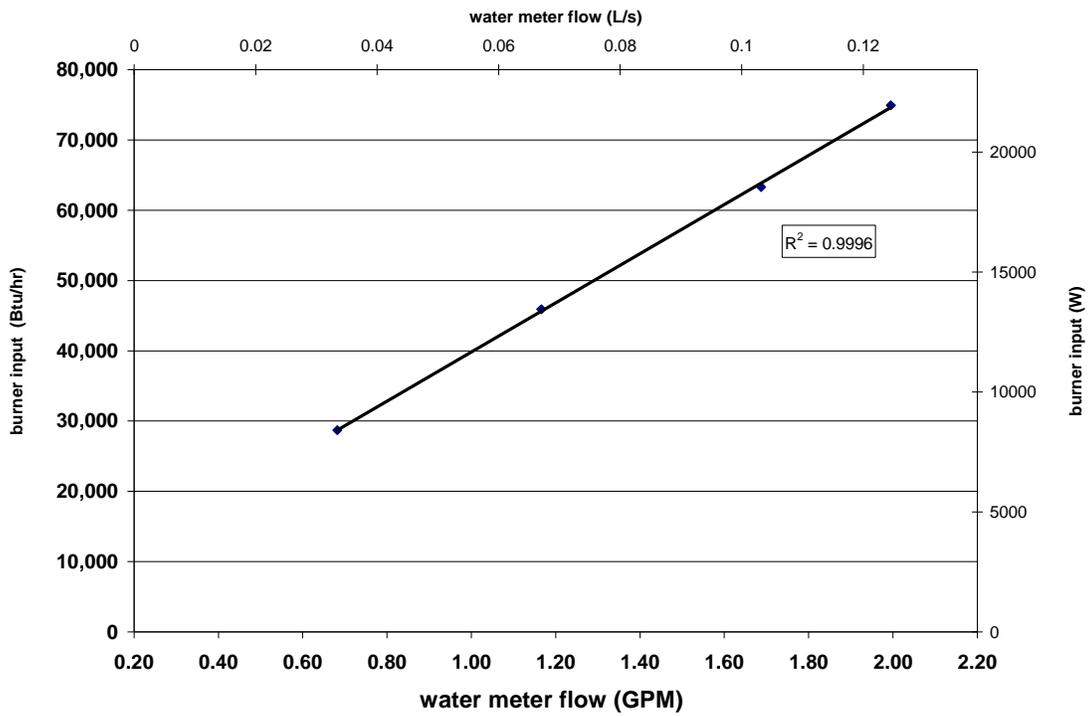
We investigated the water flow rates and gas consumption. At this location we also measured water flow with the utility water meter for the whole house when no other

water was being used. At various water flows, the flow display of the meter was compared to the reading of the city flow meter. The city flow meter was fairly new and considered accurate. Again for this water heater the flow rate reported by the monitor showed good correlation with the utility meter although the units of flow on the remote monitor were not obvious. (See Figure 7: Rinnai remote monitor versus water meter)



**Figure 7: Rinnai remote monitor versus water meter**

We did compare gas consumption with water flow rates at this site. (See Figure 8: Water flow versus gas input) However since the inlet and outlet temperatures were not changed, all this shows is that the burner modulating controls in the water heater were very good at regulating gas consumption to maintain a constant outlet temperature.



**Figure 8: Water flow versus gas input**

At this site we also compared gas consumption to blower motor current. For this model, blower motor current did not seem to be a good proxy for gas consumption. (See Figure 9: Gas input versus motor amps)

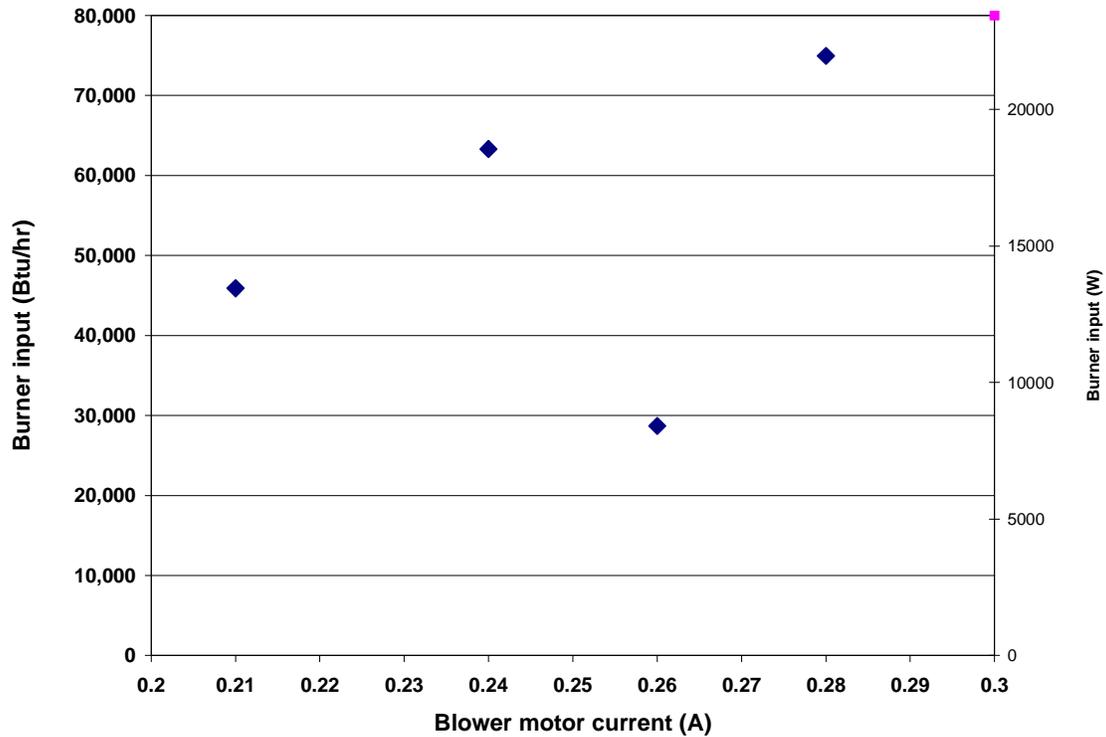


Figure 9: Gas input versus motor amps

### ***Energy Efficiency versus gas input for both water heaters***

For both sites we calculated efficiency during different flow rates. (See Figure 10: Efficiency versus gas input) Efficiency was calculated as the heat added to the water divided by the heat content of the gas consumed using the following equation:

$$\eta = \frac{flow_{water} \times \rho \times Cp \times (T_{out} - T_{in})}{flow_{gas} \times HHV}$$

Note that the efficiency varies significantly at different flow rates. This indicates the importance of field monitoring, as the assumptions from laboratory testing may not apply in actual field use.

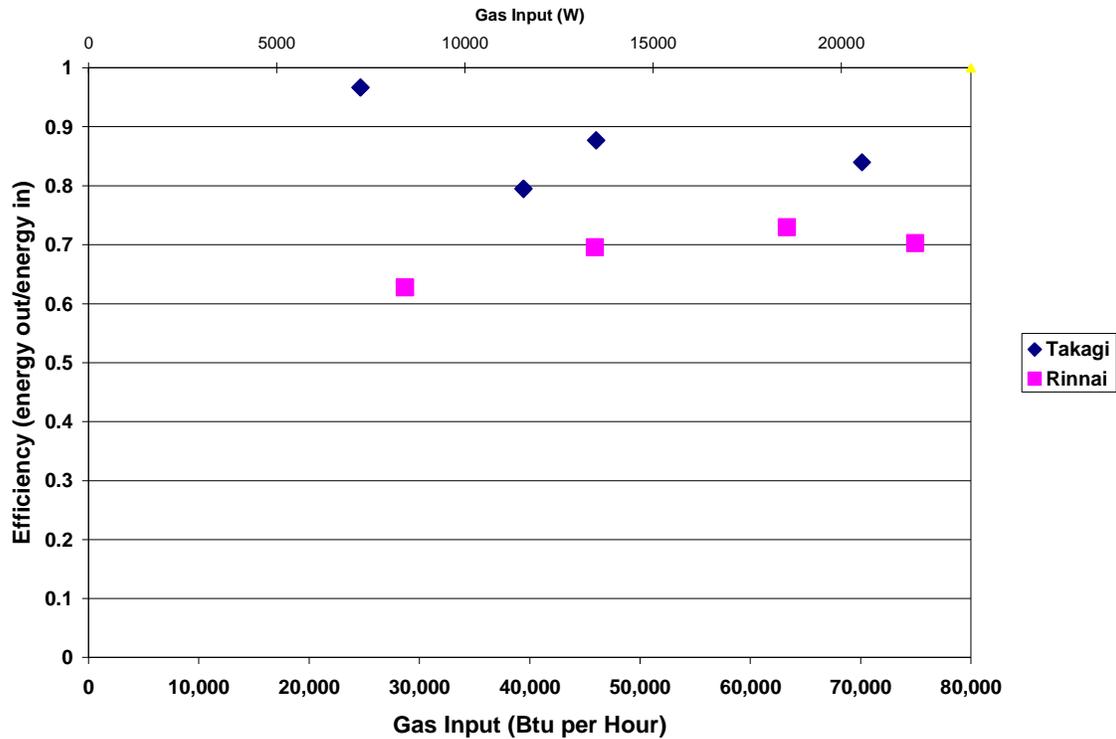


Figure 10: Efficiency versus gas input

## Conclusions from Site Visits

At this point we can not recommend using the sensors and controls in tankless water heaters for field monitoring purposes. The two models we investigated seemed to report water flow accurately. One of the water heaters reported both inlet and outlet water temperatures. These data would be sufficient to monitor energy output. However the other water heater did not report inlet water temperature. Neither model reported gas consumption or electricity use. Field investigations of using blower motor speed or electricity consumption as a proxy for gas use were not encouraging.

## LABORATORY TESTING

### Purpose

We conducted laboratory tests to investigate other potential methods of monitoring tankless water heaters in the field. A Rinnai model 2424 tankless water heater was set up and instrumented in a laboratory. We tried different methods of measuring the

temperatures, water flow and gas consumption. The emphasis was on trying to use existing sensors to obtain data without making any changes to the water heater.

In addition, we installed instrumentation that would not be installed in the field, to assess whether alternate methods would work. These included thermocouples, water flow meters, a gas meter and a power meter. Thermocouples were used to measure the water inlet and outlet temperatures, a water flow meter measured water flow into the water heater, a gas meter was connected, as well as a power meter to measure gas and electricity use respectively. In addition, other temperatures including ambient air and flue gas temperatures were measured. A photo of the test setup is shown in Figure 11 Laboratory test of Rinnai water heater.



Figure 11 Laboratory test of Rinnai water heater

## *Investigations*

## **Measuring inlet and outlet water temperatures**

The manufacturer uses a thermistor to measure inlet and outlet water temperatures. The thermistors are clamped on to a fitting that is brazed to the copper pipes in the water heater. We compared two options to collect inlet and outlet water temperatures.

### *Option 1- Tap into existing thermistors.*

One method of collecting data is to tap into the signal from the existing thermistors and send that to a small data acquisition system. Wires were soldered to the thermistor wires. In the field connectors would be used to do the same. The electrical connectors are not standard connectors, and we would need to obtain the non-standard connectors that the Rinnai uses for field application of this technique. In a field application we would not want to remove the insulation from the thermistor wires and solder to them the way we did in the laboratory. Because, most data loggers have a high impedance, tapping into the thermistors with parallel wires should not effect the output voltage of the thermistors. We would need to know what type of thermistors they are to convert the voltage into a temperature. Alternately, this could be determined empirically.

### *Option 2- Tape temperature sensors to the pipes entering and leaving the water heater.*

Another way to measure inlet and outlet water temperatures is with stick-on surface temperature thermocouples mounted directly on the water pipes and then insulated. These would need to be attached under insulation around the pipe. For greater accuracy the pipe surface measurements would have to be adjusted to give the same temperature as probes mounted inside the pipe and this correction factor would have to be determined in a test laboratory. High time resolution data is not possible with this method because of the thermal mass of the pipes.

## **Temperature measurement conclusions**

It would be easier to tape surface mount thermocouples or thermistors to the copper pipes leading into and out of the water heater than to insert additional connectors into the wires leading to the thermistors that come installed on the water heater.

## **Measuring Gas Consumption**

The water heater had modulating gas burner. The gas burner would vary the heat output and thereby gas consumption according to what was needed to meet the outlet water setpoint. The gas first flows through a main on-off gas valve before entering a modulating gas valve. From here the gas piping splits off to feed two burners, one on each side of the water heater. Each burner has its own solenoid valve. The ribbon type burners are fed gas through gas ports from the manifold. Air is supplied from a blower that blows air to a chamber beneath the ribbon burners and also flows around the ribbon burners.

In the lab we can easily set up a gas meter, but we wanted to see if we could avoid this in a field monitoring situation. Knowing which gas valves are open and by how much if they have variable openings could be used to determine the gas input.

To investigate whether this might be possible we determined the input signals to the solenoids. Wires were connected in parallel with the gas valve solenoids to read the input signal. Since the gas valves are connected to 90V DC power, for safety and to reduce the voltage, the tap-off wires were run through opto-isolators.

The gas valves are controlled by pulse width modulation. This is a square wave signal, with constant frequency but varying pulse widths. Only one valve seemed to modulate. The input frequency was 500 Hertz and didn't change. Since the frequency is always the same the input to the gas modulating valve cannot just be connected to a pulse counter. The data acquisition device would have to measure the width of a pulse and not just the number of pulses. This is too complicated for a simple data acquisition system to measure.

A way around this problem is to convert the varying pulse width, constant frequency signal to a voltage. The gas valve control could be determined by the average voltage which would change with the pulse width.

### **Conclusions from investigating modulating gas valves**

Measuring gas flow by recording the input to the modulating gas valves will be difficult to use in field monitoring. The electrical input to the gas valves is hard to get to and the voltage is too high to measure safely. The gas valves are controlled with pulse width modulation which is hard to measure directly with standard data acquisition systems. All this means using the signal to the gas valve is not likely to work well for field monitoring projects.

### ***Measuring Water Flow***

The tankless water heater has a built in flow meter which sends a signal to the PC board in the water heater housing. This signal is converted to a flow by the water heater circuitry.

The built-in flow meter has a pulse output signal. We measured the frequency of the pulsed output compared to laboratory measured flow. The data for a range of flow rates are shown in Table 1

**Table 1: Water flow versus pulse frequency from tankless water heater flow meter**

<b>Flow in GPM (l/s)</b>	<b>Frequency (Hertz)</b>
1 (0.06)	50
2 (0.13)	89
3 (0.19)	140
4 (0.25)	191
5 (0.32)	242

## **Conclusions for water flow measurement**

The signal from the flow meter built into the tankless water heater is very easy to use. However getting to the signal would require either cutting and/or reconnecting wires.

## ***Electricity Consumption***

Because it has a variable speed motor that modulates the blower speed, this water heater does not have a constant power input. This is typical of tankless water heaters sold today. Even when the no hot water is being generated, there is a standby power consumption. Other items requiring power on a tankless water heater include freeze protection resistors if the ambient temperature gets close to freezing, and power for the gas valves.

To accurately measure the power, a true RMS power meter would be needed to measure voltage and current. Because of electronic controls the power curve may not be sinusoidal. The load on the blower could also have an effect on the power factor and a constant power factor can not be assumed.

We measured power consumption for the entire unit by plugging the power cord of the water heater into a true watt meter. This method would not be possible if the water heater electrical connections were hard-wired.

## **CONCLUSIONS**

It is more complicated to use the existing gas flow, water and temperature sensors than was anticipated. To get the signals from the existing sensors and controls is difficult and may involve making changes that would invalidate manufacturer warranties. The procedures and methods for using signals from the existing gas valves, water flow meters and temperature sensors will vary by model. To be able to monitor different models and brands would require detailed information about each model and brand.

Based on these findings, we believe that for field monitoring projects it would be easier, quicker and safer to connect external meters to measure the same parameters.

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