Estimating the Fuel Consumption of Boilers and Furnaces through Burner Cycle Timing

Yshape Inc, 20A Northwest Blvd #263, Nashua, NH 03063
Prepared by: Radu Gogoana | email: radu.gogoana@yshape.com

The purpose of this document is to compare the accuracies of two methods for calculating fuel consumption, in residential central heating equipment. The first method is through the use of a smart thermostat that controls the HVAC equipment. The second method is through the use of an acoustic+vibration sensor that measures the timing of the combustion process.

The smart thermostat in this analysis is assumed to be a generic internet-connected thermostat. The vibration sensor used in this analysis is the Yshape HeetMeter. Mainstream combustion-based central heating systems are considered in this analysis; electrically heated systems are not covered.

Type of Central Heating Unit	# of HVAC units in US homes	Smart Thermostat Measurement Accuracy	HeetMeter Measurement Accuracy
Furnace (natural gas/propane/oil)	52.1 million [1]	± 10.2%	± 2.6%
Boiler (natural gas/propane/oil)	11.7 million [1]	> 50% [2]	± 3.1%

[1]source: http://www.eia.gov/consumption/residential/data/2009/#undefined (HC6.7 Space Heating by Census Region)
[2]we hesitate to report this number, as it is difficult to estimate and actual errors can be much larger. See further explanation below

The rest of this document describes how these accuracy numbers were calculated. In all cases, fuel consumption is calculated with the method below:

Knowing the fuel consumption rate → **Timing how long the burner is on** → **Calculating fuel consumption**

By knowing the BTU/h rating of the HVAC unit, its fuel burn rate per second of operation is determined.

For oil-burning systems, this information is determined by knowing the oil nozzle size and fuel pressure.

Smart thermostats can estimate burner on-time by knowing how long the "heat demand" command was sent to the HVAC unit, and by measuring the corresponding increase in room temperature.

The HeetMeter detects burner timing with a furnace-mounted vibration sensor.

The amount of fuel burned over a period of time is calculated by knowing the burner on-time and the fuel consumption rate.

Furnaces: causes of measurement error and impacts on accuracy

Note: in order to estimate relative error, we used 470 seconds as the average on-time of a furnace heating cycle. This average cycle time is characteristic of furnaces that we measured during our HeetMeter trials in 2011-2012.

Cause of Measurement Error	Description	Impact on Smart Thermostat Measurement Accuracy	Impact on HeetMeter Measurement Accuracy
Actual furnace fuel consumption rate differs from its rating	Furnaces are tuned to within 2% of their nameplate rating when new, and this value is periodically checked during regular maintenance tune-ups.	± 2 %	± 2 %
The moment that the burner turns on is controlled by the furnace's internal logic board, not by the room thermostat	When the thermostat sends a heat-demand signal to the furnace, the furnace will activate the burner after a pre-programmed sequence of events (draft inducer motor turns on, pressure switch is activated, igniter turns on, gas valve opens, flame is checked, room air circulation blower turns on, etc.) The delay timing between these events varies from furnace to furnace. The amount of time it takes for a furnace to begin blowing warm air into rooms, from the instant that it receives a heat-demand command from the thermostat, is between 44 and 150 seconds on the furnaces that we measured (sample size of 15 furnaces). We found that the best way to estimate burner timing is by assuming that the burner turned on at a time halfway between when the heat-demand command was sent to the furnace, and when the room air circulation blower turned on. On our sample of 15 furnaces, this got us an error of ± 28.5 seconds, or ± 6.1% relative error on the 470 second average furnace cycle.	± 6.1%	N/A – senses flame directly
Estimating the moment that the room air circulation blower turns on, by measuring room temperature rise, is error-prone	The location where the thermostat is mounted in the home determines when it begins to sense the rise in ambient air temperature. This varies from home to home, depending on how far away the thermostat is located from nearby vents. Lesser factors include the thermal capacity of the temperature sensor and its measurement resolution. Assuming that a 0.1 °F rise in temperature is necessary to confirm that the furnace blower turned on, and that a 2	± 2.1%	N/A

	degree temperature swing is covered by the average furnace in 470 seconds, it takes 23.5 seconds for the room temperature to initially rise 0.1 °F. In theory, a workaround for increased precision could be to backtrack the starting time of the blower by applying the “time to temperature” concept. In this case, the positioning of the thermostat relative to room vents is important, adding to the error in measurement. Only by testing a significant number of homes could we reach a clear conclusion on how accurate the “time-to-temperature” concept can backtrack the starting time of the blower. For the time being, we can only estimate. If we can backtrack the starting of the blower to within ± 10 seconds, that adds a 2.1% relative measurement error over a typical 470 second furnace on-cycle.		
Accuracy in determining the timing of the burner flame	The HeetMeter can determine the on-timing of the flame within ±1.5 seconds, as well as the off-timing. This adds a 0.6% relative error to a typical 470 second furnace on-cycle.	N/A	± 0.6%

Boilers: causes of measurement error and impacts on accuracy

Note: in order to estimate relative error, we used 270 seconds as the average on-time of a boiler cycle. This is characteristic of boilers that we measured during our HeetMeter trials in 2011-2012. The average on-cycle time of steam boilers was higher, leading to lower relative errors for those systems.

Cause of Measurement Error	Description	Impact on Smart Thermostat Measurement Accuracy	Impact on HeetMeter Measurement Accuracy
Actual boiler fuel consumption rate differs from its rating	Boilers are tuned to within 2% of their nameplate rating when installed, and this value is periodically checked during regular maintenance tune-ups. Another indicator of fuel flow rate is the nozzle size and pump pressure on oil-fired systems.	± 2 %	± 2 %
The firing of the burner is controlled by the boiler's aquastat (water-temperature thermostat), independently of the room thermostat's commands	When the thermostat sends a heat-demand signal to the boiler, the boiler will begin heating the water that is circulated through radiators. It will keep the water in the radiators hot, within a set temperature range (e.g. 165 °F - 180 °F). The burner will fire periodically to keep the water within this temperature range. When the room temperature has risen enough to satisfy the room thermostat, the boiler will no longer continue its firing cycles to keep the radiator water hot. The room thermostat has no way of knowing how long the burner was actually on for, during this heating period. We instrumented a home with a typical hydronic boiler system to log the thermostat commands as well as the burner on-times (see exhibit 2 in the appendix). Over a 24 hour period, the cumulative on-time of the heat demand signal from the thermostat was 24,760 seconds, while the burner was actually firing for a total of 10,564 seconds. Relative error = 134% We hesitate to report these errors with any degree of accuracy, as it is very difficult to estimate because the thermostat's commands are only loosely correlated to the boiler's burner operation. A thermostat may get within an order of magnitude for estimating the burner on-time, but we believe that these error margins are large for applications in fuel consumption monitoring.	> 50%	N/A – senses flame directly

Accuracy in determining the timing of the burner flame	The HeetMeter can determine the on-timing of the flame within ±1.5 seconds, as well as the off-timing. This adds a 1.1% relative error to a typical 270 second boiler on-cycle.	N/A	± 1.1%

Appendices:

Exhibit 1: Furnace sequence of operation

The sequence of operation of a typical non-condensing furnace is shown below. Ignition timing and draft inducer fan sequences are not shown, but it serves as a guide for illustrating the timing of furnace events that are difficult to detect from a smart thermostat.

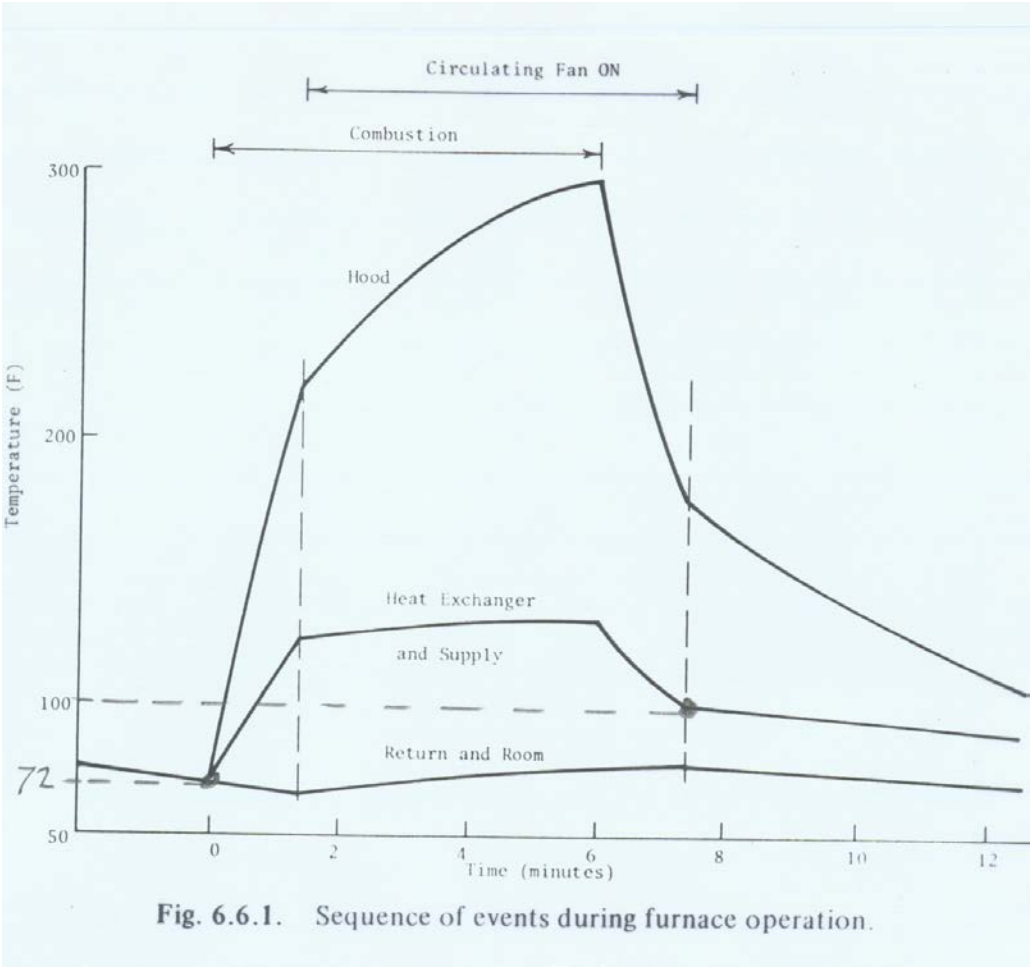


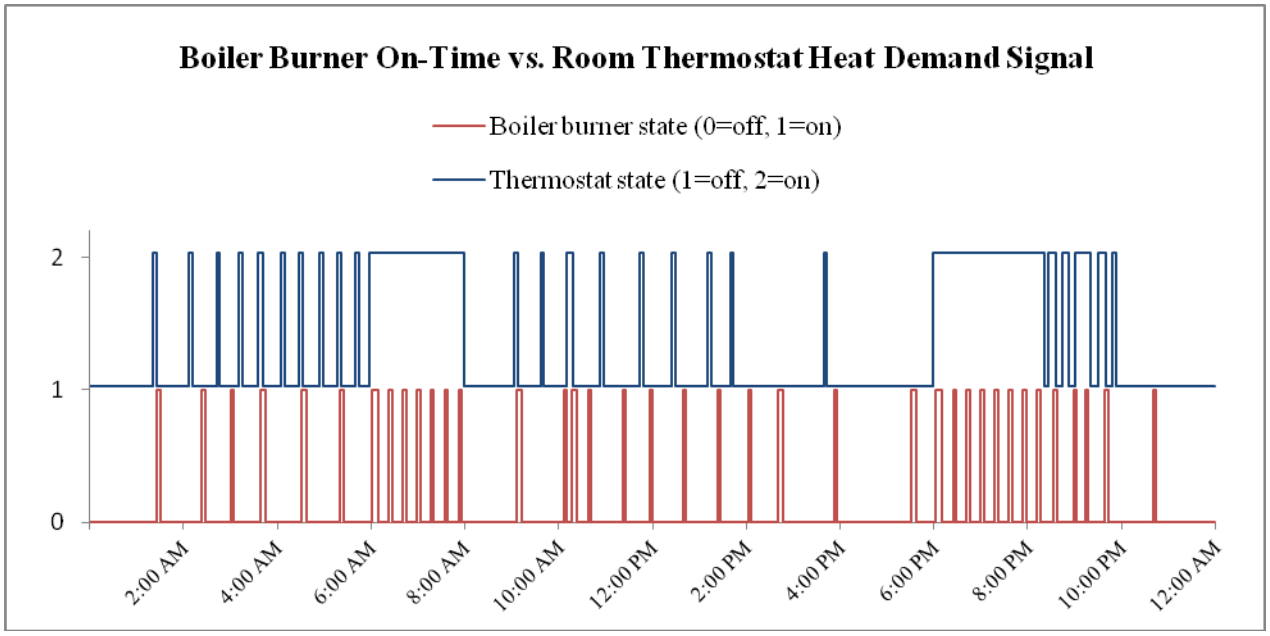
Fig. 6.6.1. Sequence of events during furnace operation.

Source: Energy Engineering, John Mitchell, Wiley Interscience, 1983.

Exhibit 2: Boiler flame on-time compared to room thermostat heat demand signal

The graph below shows the cycling of a boiler's burner, in response to the heat-demand signal from the room thermostat. On this home, schedule of the room thermostat was set to:

Period	Time	Temperature setpoint
Sleep	12am – 6am	18 °C (64.4 °F)
Wake	6am – 8am	22 °C (71.6 °F)
Leave	8am – 6pm	18 °C (64.4 °F)
Return	6pm – 12am	22 °C (71.6 °F)



Over this 24 hour period, the outdoor temperature averaged 32 °F, with a minimum of 22 °F, max 47 °F

The boiler's burner was on for a total of 10,564 seconds, while the total time that the thermostat commanded heat from the boiler was 24,670 seconds.