Final Technical Report
Extended Range Tankless Water Heater
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Introduction

This is the Final Report for a project sponsored in part by the DOE Energy-Related Inventions Program, Contract Number DE-FG01-89CE15407. The goal of the project was to undertake the engineering, construction, and testing of an innovative gas-fired tankless water heater, taking it from the concept stage to the prototype stage.

A tankless water heater incorporates a gas burner, a heat exchanger, and a control system. When a flow of water through the unit is sensed by the controller, the burner is fired. The controller modulates the heat input to the burner so as to maintain the outlet water temperature at the setpoint. The best units incorporate a burner and control system that can modulate the input over a fairly high turndown ratio; typically a four to five-to-one ratio. A tankless water heater is generally a natural draft appliance, and therefore its efficiency cannot exceed about 80%. However, since it does not store any hot water, there is no standby heat loss. Therefore, a tankless water heater can be a very energy-efficient means of heating water. It is also much more compact than a tank-type water heater, and can be easily moved about and installed by one person. The maximum input to the appliance is related to the rate at which it can produce hot water. A rule of thumb is that for each 50,000 btu/hr (15 kW) of heat input, a hot water flow of 1 gallon per minute (gpm) (3.8 liter/min) can be maintained. This assumes an appliance efficiency of 80% and a water temperature rise of 80 F (44 C).

There are some disadvantages inherent in a tankless heater. Since no hot water is stored, the hot water flowrate that can be provided is limited by the size of the appliance-- the maximum heat input rate and size of the heat exchanger. There is also a problem meeting low-flow demands, since the unit is limited to a given turndown ratio and will not light unless the design minimum flow of water is passing through the appliance. Also, even when the water flowrate is maintained between the design minimum and maximum values, there is often substantial variation in the discharge hot water temperature, particularly when the appliance is subjected to a change in flowrate. The automatic control system must change the firing rate to meet load changes with a minimum deviation in discharge temperature, and this is a very challenging control problem. Another disadvantage of the tankless water heater is high initial cost compared to tank-type water heaters. The retail price of a tank-type heater is in the \$150-400 range, while a tankless water heater is more likely to be in the range of \$400-800. The engineering challenge is to design a

tankless water heater that can be produced at a reasonable price while minimizing the inherent performance shortcomings of this approach.

In summary, the advantages and disadvantages of a tankless water heater are

Advantages:

1. Energy efficiency
2. Compact size
3. Endless hot water

Disadvantages

1. Limited flow capacity
2. No low-flow heating
3. Instability of outlet temperature
4. High initial cost

In this research program, a laboratory test facility was built for the purpose of testing a gas-fired water heating appliance. This test facility can be used to examine the important performance characteristics of efficiency, dynamic response, and quality of combustion. An innovative design for a tankless water heater was built and then tested to determine its performance characteristics. This unit was tested over a 5:1 range in input (20,000 to 100,000 btuh heat input). The unit was then configured as a circulating hot water boiler, and a specially designed heat exchanger was used with it to generate domestic hot water. This unit was also tested, and was found to offer performance advantages with regard to low flow and temperature stability.

This research and development effort has illuminated some of the fundamental difficulties inherent in a tankless water heater. These difficulties are in the area of dynamic response and control. Configuring the unit as a circulating boiler can largely eliminate these problems. It can be argued that the boiler configuration offers more commercialization potential, since it can be used for both space and water heating in a compact, energy-efficient, and economical package.

Laboratory Test Facility

In order to evaluate the performance of prototype units, a test facility was assembled. For a tankless water heater or modulating boiler, the following performance measures are pertinent:

1. Appliance efficiency and combustion efficiency at different inputs over the range
2. Maximim and minimum inputs consistent with acceptable performance
3. Concentration of pollutants in fluegas at different inputs over the range
4. Dynamic response of the appliance to a change in load.

Appliance efficiency is based on the amount of heat that is added to the water flowing through the appliance relative to the heat released by fuel combustion. Combustion efficiency is based on the amount of heat content in the fluegas exiting the appliance relative to the heat content it would have if no heat were removed after combustion. Put another way, these two measures of efficiency are:

$$\text{Appliance efficiency} = \frac{\text{rate of heat transfer into water flowing through appliance}}{(\text{rate of gas flow into appliance}) \times (\text{heat content of gas})}$$

$$\text{Combustion efficiency} = \frac{\text{heat removed from fluegas before it exits the appliance}}{\text{heat in the fluegas before any heat is removed in the appliance}}$$

These two efficiencies are measured independently of one another, so that there is some check on the accuracy of the measurements taken. Generally, combustion efficiency is a few percentage points above appliance efficiency because not all of the heat removed from the fluegas before it exits the appliance goes into heating water. There is some heat loss from the appliance itself, since it is running at a higher temperature than the surroundings. For a natural draft appliance, combustion efficiency is limited to about 85%. If the fluegas is cooled too much in the appliance, there are two negative results:

1. Condensation can form on heat exchange surfaces, resulting in accelerated corrosion. Flue gas condensate is highly corrosive to most metals, since nitric acid is produced from the presence of NO_x in the fluegas.

2. Natural draft out the fluepipe is impeded if the fluegas is cooled too much (i.e. it loses the buoyancy required for good draft).

It is important to design the appliance for minimal heat loss, so that appliance efficiency can be kept as close as possible to combustion efficiency.

For a modulating appliance, the range of acceptable inputs must be determined. The physical size of the appliance and the burner comes into play as input is increased above the maximum, resulting in

1. a decrease in efficiency

2. an increase in pollutant levels in the fluegas as the burner and combustion chamber capacities are exceeded.

The minimum input to the appliance is generally determined by acceptable combustion factors. A well designed atmospheric burner can achieve a turndown ratio in the neighborhood of 5:1. The problems that can occur if the input is decreased below the minimum include increased concentrations of carbon monoxide (airfree basis) in the fluegas. Also, efficiency can degrade in a natural draft appliance at low inputs because the level of excess combustion air increases as the input is lowered. Too much excess air lowers combustion temperature to the point where significantly less heat is removed by the heat exchanger, resulting in lowered efficiency.

The pollutants that are of concern in natural and LP gas appliances are carbon monoxide (CO), oxides of nitrogen (NO_x), and unburned hydrocarbons. The ANSI standard for water heaters limits carbon monoxide to 200 parts per million (ppm) in the fluegas on an airfree basis. In addition, the state of California limits the quantity of NO_x in the fluegas, and a similar standard may be adopted nationally in the future. A well designed gas burner will not emit detectable amounts of unburned hydrocarbons, so the presence of this pollutant indicates a fundamental design problem with the burner.

Perhaps the most challenging operational problem relating to a tankless water heater is outlet water temperature stability following a change in load (i.e. a change in water flowrate through the unit). Therefore, a way to chart outlet temperature with time is mandatory in a system that evaluates the performance of these units.

The test facility is shown schematically in Figure 1. A brief description of the components in the test facility follows.

Water Loop. Whether the system is configured as an open-loop tankless water heater or as a closed-loop circulating boiler with a hot water generator, water from the cold main is passed through the system. The fundamental measurements which must be taken are the water flowrate and the temperature of the water into and out of the appliance. With this information, the amount of heat transferred to the water can be determined, giving the numerator in the appliance efficiency calculation. Also, the dynamic response characteristics can be charted.

The components in the water loop are

1. Turbine flowmeters. These are highly accurate flow measuring transducers utilizing a rotating turbine wheel. The rotational speed of the turbine is converted to a pulse rate which is counted by interface electronics in the data acquisition system.

2. Thermocouple and thermistor probes. Various probes are placed in fittings to measure water temperature at points in the loop. The signals from these probes are processed by the data acquisition system.

3. Mercury-in-glass thermometers. The most accurate and reliable temperature transducer is still the old-fashioned mercury thermometer. For the purpose of determining the heat transferred to the flowing water, thermometers are placed into wells at the inlet and outlet to the appliance, and these readings are taken visually and input manually to the computer for calculational purposes in determining the appliance efficiency. The heat transferred to the water can be calculated by

$$q_{\text{out}} = \dot{m} c_p \Delta T$$

where

q_{out} is the heat added to the water, btu/hour

(numerator in appliance efficiency equation)

$\dot{m}$ is the mass flowrate of water, lbm/hour

c_p is the specific heat of water, 1.0 btu/lbm-F

ΔT is the the temperature rise of the water through the appliance, $(T_{\text{out}} - T_{\text{in}})$, deg. F

4. Tubing, valves, and pressure gages. These components finish off the water loop.

Gas Loop. The gas loop measures the gas flowrate into the appliance, exhausts the fluegas, and samples the fluegas to determine its composition. The components in the gas loop are

1. Natural gas supply line and LP gas supply. An appliance can be tested on either of these fuels.

2. Positive displacement gas meter. A high precision gas meter is used to determine the gas flowrate. Visual readings are taken and input to the computer manually for computational purposes; this option was chosen because it allows accurate flow to be measured over a wide range of flowrates, and several turbine flowmeters would have been required to cover the same range, with a substantial increase in cost. The meter includes fittings into which pressure and temperature gauges are placed, so that the volumetric flowrate can be corrected to standard conditions. The heat content of the gas was obtained from an associate at another company that has a calorimeter in its lab; little error was introduced into the heat input calculations, since the heat content of the gas varied very little from day to day. The heat released by combustion of the gas is determined by

$$q_{in} = Q \Delta H_r$$

where

Q is the volumetric flowrate of gas, corrected to standard conditions of
14.7 psia, 60 F

ΔH_r is the standard heat of reaction for the fuel being used. By convention, the high heat of reaction is used for computing gas appliance efficiency, where the base state has water in the liquid state rather than the vapor state in the products of combustion. Typical values for ΔH_r for natural gas and LP are

natural gas: $\Delta H_r = 1000 \text{ btu/SCF}$

LP gas: $\Delta H_r = 2500 \text{ btu/SCF}$

(SCF = one cubic foot of gas at standard conditions)

3. Fluegas analyzer. A fluegas analyzer was used to sample fluegas for its composition. The analyzer measures oxygen (percent), carbon monoxide (CO, ppm), nitrogen oxides (NO_x, ppm), unburned hydrocarbons (ppm), and fluegas temperature. From these measurements, the following can be inferred: excess combustion air (percent), airfree concentrations of CO and NO_x, and combustion efficiency.

4. Exhaust hood. The appliance is located beneath an exhaust hood so that fluegas is removed from the lab space. The appliance can also be connected directly to a natural draft flue. If the draft diverter in the appliance is properly designed, the combustion characteristics won't change if the appliance vent is connected to the flue; i.e. stack action in the flue should not be a factor that influences the natural draft through the appliance. Allowing the appliance to discharge to the room, and then drawing the fluegas out through the hood, allows testing to be conducted where there is assurance that there is no stack action influence from the flue.

Data Acquisition and Appliance Control. The data acquisition system is the interface between the transducers in the water loop and gas loop and the computer system which processes the data and displays the results. All the electronic hardware in the data acquisition system was fit into a single desktop-sized enclosure.

Another set of electronic hardware was built to allow computer control of the appliance. This computer control activates the gas supply and ignition devices and the gas input modulating control valve.

The data acquisition and control system communicated with the computer through a single multiconductor cable. The one other connection between the computer and the lab system is an RS-232 connection between the computer and the fluegas analyzer.

Computer Processing and Control. An AT computer was used to process and display the data gathered by the various transducers in the system. Software was written to perform these functions in various ways. Two outputs that can be generated by the system are shown in Figures 2 and 3. Figure 2 displays steady-state appliance performance at a given heat input. Figure 3 shows a temperature vs. time plot for a dynamic response test.

Figure 1. Laboratory test facility.

Figure 1 Legend

1. Cold water supply
2. Turbine flowmeter
3. Pressure gauge
4. Mercury thermometer, inlet water temperature
5. Mercury thermometer, outlet water temperature
6. Thermocouple temperature sensor
7. Pressure gauge
8. Hot water discharge to drain
9. LP gas supply
10. Natural gas supply
11. Positive displacement gas meter
12. Exhaust hood
13. Exhaust vent (optional venting means)
14. Sensor interface electronics
15. Controls interface electronics
16. Laboratory AT computer
17. Fluegas analyzer
18. Appliance controls enclosure
19. Tankless water heating appliance

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HARMONY THERMAL Data Inputs 02-06-1991 15:46:11
Tcols, deg F function keys fluegas (conc. are on dry gas basis)
TC 1 75 F 1 ON Flue Pump FUEL NATURAL GAS:21870 BTU/LB
TC 2 75 F 2 OFF Graphics COMBUSTION EFFICIENCY: 80.4 %
TC 3 75 F 3 OFF AMBIENT TEMPERATURE: 81 _F
TC 4 75 F 4 OFF STACK TEMPERATURE: 412 _F
TC 5 75 F 5 OFF OXYGEN: 007.1 %
TC 6 75 F 6 OFF CARBON MONOXIDE: 8 PPM
TC 7 75 F 7 OFF Stepper CARBON DIOXIDE: 07.8 %
TC 8 75 F 8 OFF Control COMBUSTIBLE GASES: 0.00 %
TC 9 75 F 9 OFF Reset STACK DRAFT (INCHES H2O): + 00.0
TC 10 75 F 10 OFF End Program EXCESS AIR: 44 %
TC 11 217 OXIDES of NITROGEN: 59 PPM
TC 12 665 CO ALARM: 50 PPM

thermistors
Water IN 49.2 F Water OUT 128.5 F Water DEL-T 79.3 F Water FLOW 1.81 gpm
Flow Timer 171.8 sec Control Temp OUT 129.3 F

thermometers
Water IN 49.1 F Water OUT 128.5 F Water DEL-T 79.4 F
Nat. gas. heating value 980 btu/scf Cu ft in elapsed time = 4.5
Heat rate to appliance = 89420 btu/hr Manometer press.= 4.1 in. water
Thermal efficiency = .79

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Figure 2. Computer output for steady-state performance.

Figure 3. Computer display showing dynamic temperature response.

Tankless Water Heater

I. Design

The tankless water heater prototype that was built and tested in this program incorporated several features which distinguishes it from most appliances of this type. The external view of the appliance is shown in Figure 4. The cylindrical portion contains the burner, heat exchanger, and draft diverter. The box attached to the side contains control components to sense water flow, measure outlet water temperature, turn on and modulate the gas flow, and perform the ignition function.

The features of the appliance are described in some detail below.

1. The heat exchanger was made from a single piece of finned soft copper tube which was wound into a spiral. The heat exchanger also incorporated a cylindrical skirt of thin copper sheet with unfinned tube wound in a helix and bonded to the inside surface of the skirt. The skirt extended below the spiral of finned tube, thereby creating a combustion zone. The burner is positioned in the bottom center of the cylindrical space. The heat exchanger assembly is shown in Figure 5.

2. An atmospheric burner, shown in Figure 6, was designed for the appliance. This burner was designed for high turndown (about 5:1) and relative economy of manufacture. It incorporates a single mixing tube, in contrast to the burners used in other tankless water heaters. The flame pattern produced by the burner is compatible with the geometry of the heat exchanger.

3. The controls were designed to interface with a digital electronic system. The choice of such a control system allows for maximum flexibility in evaluating different control strategies. It also aims at the eventual development of a production control based around a digital microcontroller. For development and evaluation purposes, the appliance controls communicated through the interface hardware with the laboratory AT computer, as shown schematically in Figure 1. Specifically, the components enclosed in the side box on the appliance were

- a. A water flow sensor. This sensor was designed to turn "on" at a flowrate of 0.35 gpm (gallons per minute) and "off" at a flowrate of 0.25 gpm. A hysteresis on/off characteristic is necessary to prevent a chattering on/off signal at the turn-on flowrate. The flow sensor is basically an inverted rotometer; i.e. a plastic ball is in a transparent tube having

a tapered bore, but in this case, the bore tapers from a larger diameter at the bottom to a smaller diameter at the top. At the threshold "on" flowrate, the ball floats off the bottom stop and "snaps" to the top stop. Since the bore is smaller at the top, the ball won't fall from the top stop until the flowrate decreases to a magnitude less than the "on" flowrate. An optical sensor is located at the bottom of the tube, so that the ball blocks the light path when it is on the bottom stop and opens the light path when it floats off the bottom stop. The signal from the optical sensor is processed so give a binary input to the computer, indicating water flow as on or off. The flow sensor is shown in Figure 7.

b. Ignition system. A standard off-the-shelf spark ignition system was used in the appliance. The lab computer was used to activate the ignitor. The ignitor incorporated a flame rectification sensor to verify ignition, and this signal was also transmitted to the computer. Thus, the main gas valve could be closed in the event that flame was not proved.

c. Gas train. The gas train incorporated two valves. The first was a standard off-the-shelf combination control valve, which performs the functions of gas shutoff/turnon and pressure regulation. The second valve was a modulating valve which discharged a gas jet directly into the mixing tube of the burner. The modulating valve incorporated a motor-driven actuator which could be controlled by the lab computer. Therefore, the computer could be used to turn the gas flow on and off to the appliance, and modulate the gas input to the appliance in response to load requirements. The gas train is shown in Figure 8.

d. Temperature sensor. A thermistor temperature sensor was located in a well on the hot water discharge from the heat exchanger. This sensor provided a signal to the computer for the purpose of automatic feedback control.

Figure 4. Tankless water heater.

Figure 5. Heat exchanger.

Figure 6. High-turndown atmospheric burner.

Figure 7. Water flow sensor.

1. Water inlet
2. Water outlet
3. Transparent tube with reverse taper bore
4. Ball position, "off" signal
5. Ball position, "on" signal
6. Optical path sensor

Figure 8. Gas train.

1. Gas supply
2. Combination control valve
3. Modulating valve
4. Gas jet entering burner mixing tube
5. High turndown burner
6. Spark ignition electrode
7. Spark ignition module
8. To controls interface electronics

II. Performance

The performance of the appliance was measured in several areas, as described in the section on the laboratory test facility. The results of these tests are described in this section.

The appliance performs acceptably over a range in excess of 5:1 (19,000 to 103,000 btu/hr input). Performance at various inputs over this range is plotted in Figures 9-11. These data were taken while running water through the appliance at a rate which gave a temperature rise of 80 F. The lowest flow was 0.33 gpm (at 19,000 btu/hr) and the highest rate was 2.0 gpm (at 103,000 btu/hr).

Figure 9 shows combustion and appliance efficiency over the range of inputs. The appliance is near the limit for natural draft appliances, particularly at the higher inputs. The reason for the dropoff in efficiency at lower input is due to the increasing percentage of excess air being drafted through the appliance (plotted in Figure 10). The excess air lowers the temperature of the fluegas passing through the heat exchanger, thereby lowering the rate of heat transfer. This effect is partially offset by the lower fluegas velocity through the heat exchanger at the lower input. The efficiency could be brought up by using a finned tube with higher fin density. The prototype appliance was built with tube having seven fins per inch; there is also available a tube having nine fins per inch, but otherwise the same. Using the nine-fin tube would bring the appliance efficiency up a few points, and would probably bring it very close to the limit for natural draft appliances.

Pollutants in the fluegas are plotted in Figure 11. Carbon monoxide (CO) and nitrogen oxides (NO_x) are given in parts per million (ppm) on an airfree basis. The performance here is creditable, particularly with respect to CO. The ANSI standard for water heaters is 200 ppm CO (airfree) in the fluegas, with a concentration up to 400 ppm airfree permissible at the minimum input. There is no national standard for NO_x, but the California standard calculated for an 80% appliance efficiency is about 69 ppm airfree. Therefore, the appliance is seen to exceed this standard over most of its range. However, there is a good possibility that the atmospheric burner used in the appliance can be optimized to reduce NO_x emissions. Some testing was conducted on burners having the same design except that the flame retention fins were increased in height (refer to the drawing of the burner in Figure 6, showing short angled fins.) These burners showed significantly lower NO_x emissions, perhaps due to a lowered peak combustion temperature, although the reasons are not totally clear. In any case, it appears that it may be possible to effect slight design modifications to lower the NO_x emissions.

The major performance shortcoming for the tankless water heating appliance is dynamic control. The objective of the control system is to maintain outlet temperature stability following load changes, i.e. after the water flowrate through the appliance suddenly changes. Maintaining perfect stability is impossible because of the thermal capacitance of the heat exchanger. A sudden decrease in water flowrate is followed by an outlet water temperature increase even if the burner is completely shut down immediately, due to the heat stored in the hot metal of the finned tube. Therefore, the best that can be hoped for is to minimize temperature overshoot following a decrease in flow, and temperature undershoot following an increase in flow.

The first approach that was taken to implement control utilized the outlet water temperature only as a feedback control variable. A proportional-integral-derivative (PID) algorithm was implemented on the laboratory AT to modulate gas input in response to the temperature input. This approach proved to be unsatisfactory. After a decrease in water flowrate, there was a delay of a few seconds before the thermistor sensor in the water outlet responded to the change in discharge water temperature. During this delay, a heat input exceeding the load requirement continued, storing up heat in the heat exchanger and causing a subsequent severe temperature overshoot in the outlet. This overshoot could be as high as 30 degrees F. Such an overshoot in a water heater can cause scalding.

Next, an investigation was conducted into the concept of control based not only on the outlet water temperature, but also on the water flowrate. This was straightforward to implement in the lab, because the input from the turbine flowmeter is available to the lab AT. Clearly, this approach would be a major challenge for a production water heater, since a conventional electronic flow transducer having even a modest level of accuracy would be prohibitively expensive. Nevertheless, it is instructive to investigate this control method, since the information available to the controller in this case represents the ceiling. If control difficulties arise even with this much information, then we can conclude that we will have fundamental control problems.

Based on this investigation, there are fundamental control problems with a tankless water heater. Implementing a control strategy in which a change in water flowrate was followed immediately by a proportional change in heat input, outlet temperature instabilities still resulted. This occurred even when the proportional change in heat input exceeded the proportional change in flowrate. This comes back to the effect of thermal capacitance in the heat exchanger, which has already been discussed. The dynamic response to load change shown in Figure 3 is representative of the best control that was achieved for the tankless water heater.

This problem with dynamic control can be addressed by placing some thermal capacitance between the outlet of the tankless heater and the hot water tap. One approach to implement this strategy is to configure the tankless heating appliance as a circulating boiler and use a semi-instantaneous water heater to generate hot water. This was done, and the system and its performance are described in the next section.

Efficiency Vs. Input Tankless Water Heater

Figure 9. Efficiency vs. input, tankless water heater.

Excess Air vs. Input Tankless Water Heater

Figure 10. Excess air vs. input, tankless water heater.

Fluegas Concentration vs. Input Tankless Water Heater

Figure 11. Fluegas concentration vs. input, tankless water heater.

Combination System

I. Design

A combination system is shown schematically in Figure 12. In this system, a modulating circulating boiler is used for both space heat and hot water. The tankless water heater described in the previous section was configured as the circulating boiler, using water as the circulating fluid. A semi-instantaneous water heater was designed and constructed. It was placed into the system, and various tests were run to evaluate performance. (Space heating convectors were not added. They are shown in Figure 12 to indicate how a combination system could be configured.)

The design of the semi-instantaneous water heater is shown in Figure 13. The objectives of the design are

1. Retain the advantage of compact size
2. Eliminate the dynamic control problem.

The dynamic control problem can be eliminated with a large hot water tank, which is the principle behind hot water storage tanks used with either direct or indirect fired systems. If a tank with a volume of say 40 gallons is used, there is no particular advantage to a modulating control system on the boiler; since the thermal capacitance is so large, an on/off control system can be used to add heat to the tank without effecting large swings in the outlet water temperature. If the tank volume is made small, however, a modulated heat input must be used. In a combination system with several space heating zones, there are advantages to using a modulating boiler, so it makes sense to utilize the modulating capability to advantage on the hot water side. The result is that a compact size can be used for the hot water tank, saving on space, materials, and standby heat loss. The tank in this case becomes a sort of hybrid between a conventional heat exchanger and a conventional hot water storage tank. These units have come to be known as semi-instantaneous water heaters.

The semi-instantaneous water heater built and tested is shown in Figure 13. A heat exchanger is immersed in a small tank. The tank volume in the unit built and tested was about 1.8 gallons. The heat exchanger can transfer heat at a rate of 80,000 btu/hr, which is the peak output of the boiler. This will occur when a hot water tap is open and water is flowing through the unit at about 2 gpm. The heat exchanger can also transfer heat at a rate of 20,000 btu/hr to quiescent water in the tank. This will occur during periods of temperature maintenance or very low flow through the unit.

The control scheme for this system is a modified PID algorithm which uses two temperature inputs: a thermistor located in the semi-instantaneous water heater, near the bottom of the tank, and a thermistor located in the hot water discharge of the boiler. The control has two setpoint temperatures: the desired hot water temperature (say 130 F) and the maximum permissible boiler outlet temperature (say 210 F). The control normally modulates to maintain the hot water setpoint, but there is an override mode if the boiler discharge gets too close to the upper limit, in which case the boiler is modulated to not exceed this limit.

In this control system, the water flow sensor is eliminated. The control will act to maintain the water temperature at the setpoint whether there is flow through the unit or not. Thus, the system maintains a small volume of hot water. This is a great advantage in meeting low flow demands and demand spikes (a tap is opened for a short period and then closed). These are modes which are not accommodated by the tankless water heater. The thermal capacitance in the small volume of stored hot water also dampens the temperature fluctuations associated with sudden changes in hot water flowrate.

II. Performance

The steady-state performance of the tankless water heater has already been described in the previous section. Configured as a circulating boiler, the efficiency and fluegas pollutants are unchanged, so this section will discuss only the dynamic response characteristics of the boiler/semi-instantaneous water heating system.

Three dynamic response tests are shown in Figures 14-16. These show a cold start test, a low flow test, and a step input test.

The cold start test shows one problem that needs to be addressed as the system design is refined; this is the problem of temperature stratification in the water tank. After the cold start, the water temperature in the top of the tank is about 30 degrees higher than the temperature in the bottom of the tank, where the sensor is located. This issue can be addressed orienting the tank on its side or by changing the sensor location. It is also appropriate to note that tank stratification appears to be much less pronounced after the tank has been at temperature for awhile, as indicated in Figures 15 and 16.

The low flow test shows the system response when the average heating demand is lower than the lowest heating rate that can be delivered by the boiler. In this situation, the boiler will cycle on

and off at low input to meet the average demand. It can be seen in Figure 15 that the outlet water temperature stays within a few degrees of the setpoint in this test. The deadband for turning the boiler on and off was set at ± 3 degrees F (on at 3 degrees below setpoint; off at 3 degrees above setpoint). The resulting on/off cycle time for the boiler is seen to be about 200 seconds. It may be desirable from the standpoint of control valve life to lengthen the cycle time to about 400 seconds when the system is in this mode. This could be accomplished by increasing the deadband. It appears that this could be done while maintaining outlet water temperature variation within an acceptable range. Also, increasing the tank volume somewhat will permit an increase in the deadband while further dampening the outlet temperature fluctuations.

The step-input response is shown in Figure 16. In this test, the tank was at temperature and the boiler was off when the hot water tap was opened to a flow of about 1.3 gpm. After about 10 seconds, the boiler came on in response to the decreasing tank temperature. The outlet temperature dropped about 10 degrees below setpoint before coming back up and stabilizing.

The dynamic response seen in Figures 15 and 16 would be acceptable in a domestic hot water system. The temperature overshoot seen in the cold-start test in Figure 14 is not acceptable, but as already discussed, this probably can be eliminated with minor design changes.

Overall, it appears that the system comprising the modulating boiler and the semi-instantaneous water heater can deliver hot water over the full range of flows normally encountered in a domestic application, while holding the hot water temperature within an acceptable range.

Figure 12. Schematic of combination system.

1. Modulating boiler
2. Semi-instantaneous water heater
3. Space heating convectors
4. Circulating pumps
5. Temperature sensors
6. Electronic control
7. Gas flow and ignition controls
8. Gas supply
9. Water supply
10. Hot water tap

Figure 13. Semi-instantaneous water heater.

1. Cold water
2. Hot water
3. Boiler supply
4. Boiler return
5. Temperature sensor

Figure 14. Dynamic response after cold start.

Figure 15. Dynamic response in low flow mode.

Figure 16. Dynamic response to a step change in flow.

Conclusions and Recommendations

This project proved the feasibility of a tankless water heater having an unconventional heat exchanger and burner design. The turndown characteristics of the modulating burner system are excellent. Electronic control of the system is seen to be feasible. However, the fundamental dynamic control problem of tankless water heaters in general is present in this design.

Adding a small amount of stored hot water in the system between the modulating appliance and the hot water tap is seen to simplify the control system, improve dynamic response, and permit low flows of hot water to be maintained. This concept was implemented in the project by configuring the tankless water heater as a modulating boiler and adding a semi-instantaneous water heater to the system to generate domestic hot water. Such an approach permits the utilization of the boiler for a zoned space heating system as well as for provision of domestic hot water.

Of the two systems evaluated in this project, the modulating boiler is likely to have more marketing potential. The boiler and semi-instantaneous water heater could easily be integrated into a single enclosure about the size of a small forced-air furnace. This appliance could meet all the space and water heating needs of a typical residence. The compact size of the system is particularly appealing for apartments, townhomes, and small commercial facilities. It has been demonstrated that this heating system can achieve an appliance efficiency of about 80% over a 5:1 range of input, which approaches the efficiency limit for a natural draft appliance.

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