Hybrid Optimized Tank/Tankless Water Heating: Breadboard Testing & Lessons Learned

Paul Glanville, Douglas Kosar, and David Kalensky, Gas Technology Institute

ABSTRACT

An efficiency gap exists between storage-based gas-fired water heaters, primarily ranging from the National Appliance Energy Conservation Act (NAECA) minimum and Energy Star® levels with Energy Factors (EF) of 0.58 to 0.62, and tankless water heaters, with EFs of 0.80 and above. In partnership with a major manufacturer, the Gas Technology Institute (GTI) performed analysis and laboratory testing to develop a hybrid optimized tank/tankless (HOT) water heater that lies within this EF gap. Such a hybrid water heater combines a lower firing rate tankless type component with smaller volume onboard storage, a buffer storage tank component without a center flue. The goal is to provide a low-cost, mid-efficiency gas-fired water heater which overcomes the intermittent performance and water wastage issues with whole-home tankless water heaters and avoids the expensive installation upgrades to gas lines and venting systems as well, making it especially attractive for EF upgrades in the dominant retrofit market

CFD modeling, analysis, and baseline testing of typical storage and tankless water heaters were performed to identify potential preferred configurations. Then laboratory parametric "breadboard" testing was performed on varied tank sizes, configurations, and firing rates to optimize designs. Active and passive control strategies were explored for stratification management and smart burner delay. Prototype design specifications were developed for the HOT water heater to meet the following requirements: (1) an EF between 0.7 and 0.75, (2) retrofit ability with ½ inch gas lines and Category I/Type B venting, (3) single firing rate burner and simplified controls, and (4) a lower installed cost than tankless water heaters.

Introduction

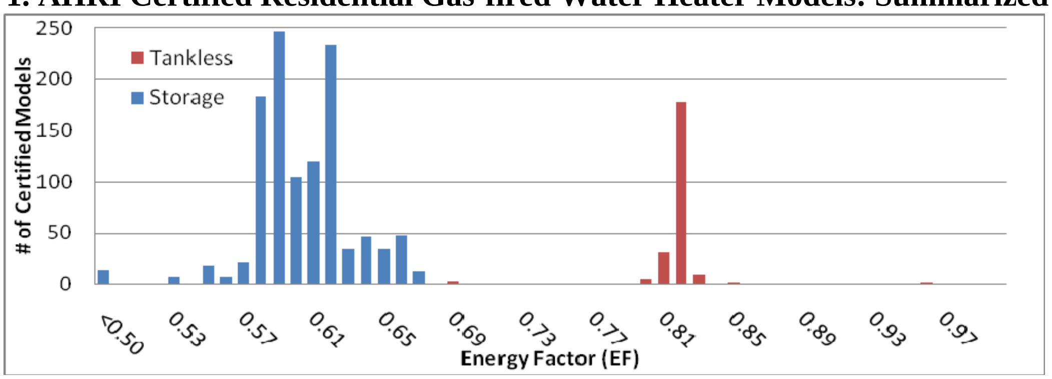
With respect to energy efficiency, it is often said that the residential water heating industry has seen more innovation in the last five years than the previous fifty, particularly in gas-fired water heating (Hunt 2008). This is due to a number of drivers including: the rising price of energy, influx of foreign tankless technology, aggressive government and utility incentive programs, and finally the inclusion of residential water heating in the Energy Star ® program. Following widespread gains in forced-air furnace efficiencies in the early 1990's and tightening of residential envelopes, water heating is becoming a larger portion of residential energy use. This is especially the case in California where gas-fired water heaters are used in more than 10 million households, constituting about 40% of residential natural gas consumption, second only to space heating at 44%, and 31% of residential end use CO_2 emissions (Hunt 2008). An increasingly significant energy-efficient product class is gas-fired tankless water heaters, which saw an increase in residential market share from 0.8% to 3.5% from 2004 to 2007 (DOE 2009). Typical non-condensing units have Energy Factors (EF) ranging from 0.8 to 0.82, compared to gas-fired storage water heaters at between 0.58 and 0.62 (Hunt 2008). This efficiency improvement comes at significant additional unit and installation costs, the latter due to often-required gas line and venting upgrades. These infrastructure upgrades are significant in the residential market, as 80% of residential water heaters installed are retrofits (CEE 2008). Additionally tankless water heaters have some unique performance drawbacks, such as minimum hot water draw requirements and burner ignition delay, which result in water wastage and the "cold water sandwich" effect during low or intermittent draws.

Another gas-fired product class is emerging which combines tankless water heating with onboard integrated buffer storage, providing incremental energy efficiency gains relative to conventional storage water heaters without the performance limitations of tankless water heaters. These "hybrid" products are currently available, which despite interest have limited penetration due to higher unit costs than tankless. To drive further penetration of energy-efficient hybrid gas-fired water heaters, the Gas Technology Institute (GTI) worked with a major manufacturer to develop prototype specifications for a "Hybrid Optimized Tank/Tankless" (HOT) water heater. The primary goals were to have (1) incremental efficiency gains at a commensurate cost, and (2) retrofit ability with low-efficiency storage water heater infrastructure.

Market Opportunity for Hybrid Water Heaters

Owing primarily to their low cost, the atmospheric center-flue design is still the majority of the gas-fired residential water heater market. This simple, pilot-lit, unpowered design is sized to a given application and can deliver hot water at small or large draw rates (albeit in finite quantities). This popularity is despite well-documented poor efficiencies, such as the estimation that over 24 hours, 17% of the heat input is lost up the stack during standby (Lutz, 2008). Incremental efficiency improvements have been made over time, primarily concerning insulation and flue baffles, however the EF limit has been estimated at 0.63 (DOE, 2009).

Figure 1. AHRI Certified Residential Gas-fired Water Heater Models: Summarized by EF



Source: AHRI, current as of 2/10

With up to five times the firing rate of typical storage units, tankless water heaters can sustain an indefinite demand with little standby heat loss (a measurable efficiency lag exists from heating the heat exchanger mass, however this has not been quantified). With good temperature control, compact size, and EFs between 0.8 and 0.82 (non-condensing), they are an increasingly popular high-efficiency water heater. However, the compact heat exchanger results in a large pressure drop and units have a minimum hot water draw rate to initiate burner firing.

The added controls, complexity, and copper result in unit costs typically three times that of low-efficiency storage water heaters. Additionally in retrofits, the higher firing rate and pressurized flue gases require gas line and venting upgrades, at equal to or greater than the unit cost.

Examining the distribution of certified residential gas-fired water heaters in Figure 1, there is an efficiency gap between storage and tankless water heaters. Storage has two peaks, at their NAECA minimum and Energy Star ® EFs, and tankless has a peak at its Energy Star ® level. Between the peaks is an area lightly populated with powered storage water heaters compliant with increased 2010 Energy Star ® levels and low-efficiency tankless water heaters. Manufacturers are aware of this efficiency gap and hybrid products can fill this product spectrum with onboard storage and firing rates bridging these established product classes.

The scope of this effort, through modeling and experimentation, is to develop prototype specifications for a "Hybrid Optimized Tank/Tankless" (HOT) water heater through (1) identification of an optimized combination of onboard storage and burner capacity and (2) examination of the effects of system integration and control strategies on thermal management. A key constraint is that the HOT water heaters have retrofit ability in homes with low-efficiency gas-fired storage water heaters with ½" gas lines, which limits firing rates to approximately 100,000 BTU/hr and below. Single stage combustion is considered to reduce cost and complexity and facilitate air-to-fuel ratio tuning in the development of low-NO_x prototypes.

Screening Simulation

In bridging the efficiency gap shown in Figure 1 with a hybrid tank/tankless water heater, an additional gap is bridged between large volume, low heat input passive water heating with no volume, high heat input active water heating. While these spectra are not coincident, the tradeoffs along this storage/heat input spectrum are intuitive, moving from transient to steady state performance. A larger tank can sustain longer hot water draws without a call for heat, however recovery times increase. Similarly, higher heat inputs provide rapid recovery times with small storage volumes, however the buffer for large or intermittent draw rates is small, requiring frequent firing. Across this spectrum, simulation tools including single and multi-nodal spreadsheet models, the TANK simulation program for residential gas-fired storage water heaters (Paul, 1993) and computational fluid dynamics (CFD), were used to screen potential system combinations for experimental evaluation and to examine the impact of system integration and control strategies on thermal management.

Primary System Components

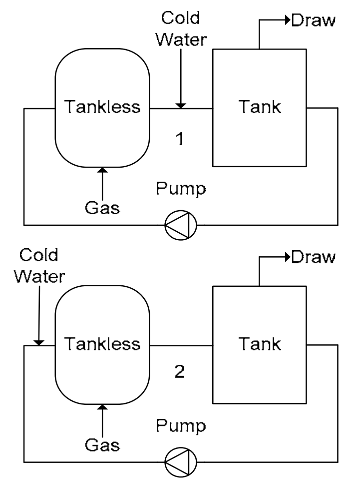
Typical baseline systems to frame this storage volume/heat input spectrum were a 40 gallon 36,000 BTU/hr storage water heater and a 199,900 BTU/hr modulating tankless water heater. In addition to gas line sizing constraints for retrofit ability, HOT water heater storage volumes considered were between 10 and 40 gallons and single stage heat inputs were between 40,000 and 100,000 BTU/hr. The storage volume and heat input are collectively referred to as "primary system components" to later distinguish from the diptube length (the submerged tube delivering cold makeup water to the tank bottom), thermostat location, and other "secondary system components". This frames HOT water heater performance as follows:

- An Energy Factor between 0.59 < EF < 0.8
- A First Hour Rating (FHR) greater than 66 gallons and sufficient capacity to meet peak loads
- The ability to support hot water draws at or below 0.66 gpm, the minimum required for operation of the tankless baseline, and minimized "cold water sandwich" effect

Using single and multi-nodal spreadsheet models for tankless and HOT water heaters and the TANK simulation program for baseline storage water heaters, simulation was validated with certified data for baseline systems for the above criteria. Relative performance of the HOT water heater range of storage volume and heat inputs were assessed.

Two hybrid system configurations were considered, integrating the storage volume with the "tankless" thermal engine in an open circulation loop, shown in Figure 2. It was assumed in the spreadsheet model that in configuration 2, the line pressure of the cold makeup water overwhelms the circulation loop during a hot water draw with a call for heat, which fixes the tankless component inlet temperature to that of the groundwater, later confirmed in laboratory testing. The participating manufacturer asserted that with a circulation rate of 3.0 gpm or more, the 40 gallon or less storage tank will rapidly become thermally well-mixed. This was confirmed using CFD modeling, thus a conservative assumption of uniform temperature was made for the spreadsheet model. This ignores the effect of stratification, which was examined in modeling and testing.

Figure 2. Configurations 1 and 2



Baseline water heaters and HOT storage and heat input combinations were put through a simulated test battery including a sustained low flow, peak draw, "cold water sandwich", and FHR tests. Despite the importance of the Energy Factor (EF) in measuring performance, the simulation of HOT water heater component combinations in a 24 Hour Simulated Use Test was not modeled for the purposes of screening out storage volume and heat input combinations due to the influence of variables beyond the simplifying assumptions in the spreadsheet models.

By virtue of sufficient onboard storage like the baseline storage water heater, the HOT water heater showed no problem sustaining hot water draws above 110 °F during the low flow and "cold water sandwich" draw simulations, which consist of sustained 0.5 gpm draws and 1.0 gpm draws interrupted by brief 0.5 gpm draws respectively. With the peak draw, two tests are considered, a sustained 3.5 and 4.5 gpm draw and a short duration 5.0 gpm draw for three minutes. With the exception of the 30 and 40 gallon storage volumes, the HOT water heater combinations are unable to sustain these peak draws longer than the baseline storage water heater, which is unsurprising. The peak draws are meant to determine the relative HOT water heater performance under these extreme loads. Lastly, the FHR, as defined by the Department of Energy (DOE) test procedure, determines the hourly hot water capacity (DOE, 1998). The results of the short duration peak draw and FHR simulations are summarized in Table 1. Each cell contains the simulated FHR, in gallons, of both configurations, and the shading indicates whether neither (white), configuration #1 only (light gray), or both configurations (dark gray) can deliver sustained hot water at 5.0 gpm for three minutes. Based upon screening simulations, HOT water heater component combinations with 40,000 BTU/hr are undersized, with 40 gallons storage are oversized, and with configuration #2 have reduced performance.

Table 1. HOT Water Heater Screening Model for Peak Draw and First Hour Ratings

Burner Firing Rate (BTU/hr)	10 gallon	15 gallon	20 gallon	30 gallon	40 gallon
40,000	105/55	108/57	110/60	110/63	132/63
50,000	131/70	137/71	143/71	152/69	143
75,000	180/106	180/107	180108	180/106	180
100,000	180/180	180/180	180/180	180/180	180/180

Note: Controls for HOT water heater are conservative such that a hot water draw initiates a call for heat.

Thermal Management and System Control

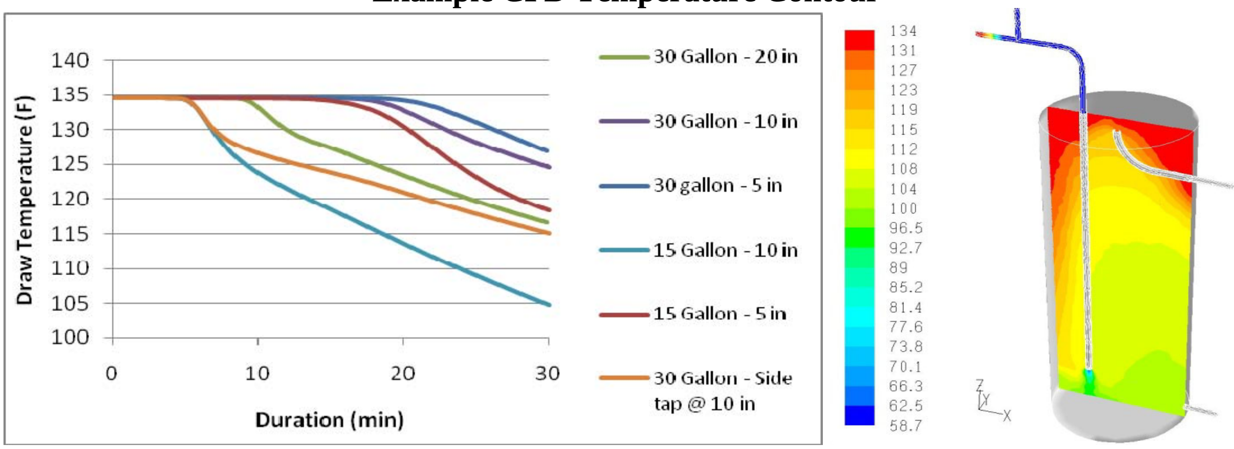
While ignored for the sake of simplifying conservative assumptions, stratification and thermal mixing dynamics play a big role in the efficiency and performance of the HOT water heater. The system integration (i.e. location of pipe connections) and control strategies will affect efficiency and HOT water heater resiliency under varied draw profiles. When maintaining stored hot water, managing stratification can prevent unnecessary firing, however only to the point that when the thermostat(s) calls for heat that the resulting temperature of the well-mixed tank is acceptable. Stratification and its importance to transient efficiency is well understood (Ji, 2007), thus its effect on HOT water heater performance was studied in greater detail.

Component integration. As the stratifying behavior of the storage tank, and thus the presence of well-mixed conditions, is a measure of the vertical temperature distribution, the influence of the storage tank tap type and location was expected to be great. Tap types considered are dip tubes of varying lengths, side taps, and J-tubes, which typically used for hot water outlets have side ports with internal "J" shaped extensions terminating perpendicular to the outlet.

Following validation with experimental baseline storage water heater testing, TANK and CFD simulation showed that stratification was primarily the result of plug flow from the use of diptubes, which is their design intent. The effect of non-uniform heat flux from the center flue was found to be negligible in relation to the flow of cold makeup water at the tank bottom, which was due to heat dissipation from the formation of convective circulation.

In the case of a cylindrical vessel, stratification is best managed during hot water draws as thermal plug flow, whereby the hot water at set point exits one end unmixed with cold makeup water entering the other end. Ideally, this is a one-dimensional process, with hot water exiting the top using buoyancy to an advantage (Hahne, 1998). At a slight cost of increased pressure, this is achieved with a large distance between the cold inlet and hot outlet, as shown in Figure 3. Here, CFD simulation of a 30 and 15 gallon tank under a 0.5 gpm draw beginning at a 135 °F set point, with diptubes terminating at various distances from the tank bottom, show the clear benefit of increased stratification. Simulation with a cold water inlet side tap showed markedly poorer stratification than diptubes of equal elevation. As the side tap injects cold water as a jet orthogonal to the mean flow, mixing is induced and plug flow does not develop. This is confirmed by observation of temperature profiles, indicating well-mixed conditions reached after approximately 7 minutes, which the diptube of similar elevation takes four times as long. This example highlights an extreme case, as hot water draw rates are generally larger than 0.5 gpm and inlet velocities have an effect on the development of stratification, however these observed trends remain at higher velocities typical of residential water heaters.

Figure 3. CFD Simulation Draw Temperatures at 0.5 gpm for 15 & 30 gallon Tanks with Example CFD Temperature Contour



Notes: All temperature profiles are for diptubes terminating with various distances from the tank bottom unless otherwise indicated. CFD performed with FLUENT Version 6.3, example is 30 gallon tank with diptube 5” off tank bottom, after 15 minutes of the 0.5 gpm draw.

Control strategy. As stratification management is key with reduced storage volumes, use of a simple single-stage thermal engine makes the control strategy is critical. Unlike baseline systems, which have either sized the hot water storage capacity or the heat input to meet a given hot water demand, the challenge with a HOT water heater is leveraging the combination of storage and heat input which individually are insufficient for the same demand. In managing stratification, the variables of interest are the thermostat(s) location and dead band (allowable temperature drop at a given thermostat from set point prior to a call for heat**)**.

With CFD modeling, extended draws were simulated on 30 gallon tanks with thermostat locations at various tank elevations. Tank temperatures were recorded during draw downs from set point at various draw rates, noting the impact of thermostat elevation for a given dead band. Especially during highly stratified flows, the selection of thermostat elevation had a great effect on burner activation. For example, starting at a 135 °F set point, a 0.5 gpm draw on a 30 gallon tank with a diptube 10” off the tank bottom, a thermostat placed 5” off the tank bottom versus a thermostat 5” off the tank top will call for heat 27 minutes apart. While important to the overall HOT water heater efficiency, such a control strategy is best optimized with a typical load profile in mind and controller algorithms can “learn” from the end user (PC, 2009). Therefore, the relative impact of thermostat locations & dead bands were examined but not optimized.

Experimental Breadboard Testing

Figure 4. Laboratory Breadboard Setup

The testing of the baseline water heaters and HOT water heater combinations of storage and heat input was performed in a fabricated "breadboard" of piping and electronic controls. To minimize experimental biases between systems, the storage components, including the baseline storage water heater, could be swapped in and out of the piping. The tankless component was fixed, as the baseline tankless water heater was modified by the partner manufacturer to switch between normal (modulating) and fixed firing rate modes, where the latter mode overrode internal controls and fired the burners at a user-defined rate regardless of the set point or draw rate. All piping was in compliance with current DOE test procedure requirements.

Baseline & Primary System Component Testing

Initially baseline testing was performed on storage and tankless water heaters to both validate previous simulation and to validate the experimental setup against the certified FHR and EF, which results were within acceptable limits (GAMA, 2006). Dynamics observed in modeling were largely confirmed during the non-DOE tests: the low flow draw, "cold water sandwich" draw, and peak draw. The storage water heater was able to sustain the 0.5 gpm low flow and "cold water sandwich" draw without issue and was able to deliver hot (< 110 °F) water at peak draws of 3.5 gpm, 4.5 gpm, and 5.0 gpm for 8.35, 7.05, and over 3 minutes respectively. The tankless water heater could not sustain hot water for low flow and "cold water sandwich" draws and it was able to satisfy each peak draw rate without issue.

Table 2. HOT Water Heater Breadboard Components Tested

Burner Firing Rate (BTU/hr)	10 gallon	15 gallon	20 gallon	30 gallon
50,000			x	x
75,000			x	x
100,000				

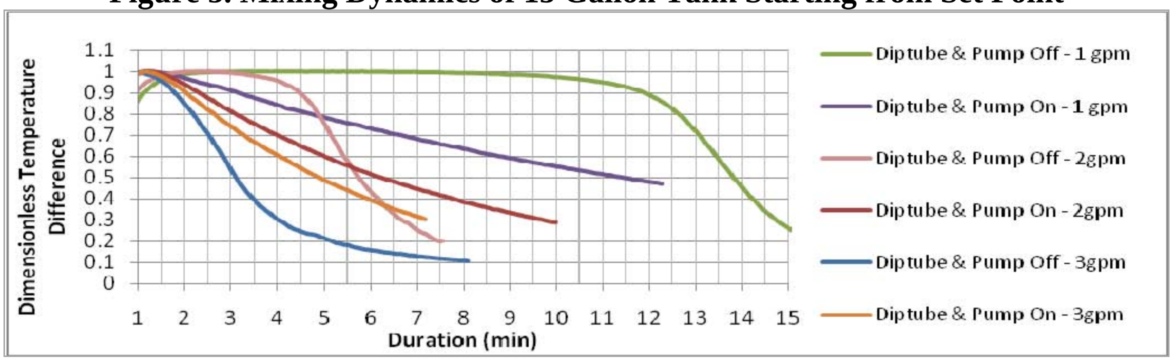
Note: Shading indicates likely undersized (white), optimum (light gray), and oversized (dark gray) and an "x" indicates component combinations that are defined as Residential Storage Water Heaters by DOE

Table 2 summarizes the range of primary components considered in the breadboard testing, as screened by previous simulation. Highlighted within the table with an "x" are component combinations that would be defined as a Residential Storage Water Heater by DOE. This is significant, as those cells with an "x" would be both (1) subject to the DOE test procedures and requirements for EF and FHR and (2) eligible for Energy Star ®, and those without an "x" would be uncategorized and would not.

Prior to applying the test battery to the matrix in Table 2, the individual HOT water heater components were examined experimentally. In the fixed-firing mode, the tankless water heater introduced a few biases to HOT water heater testing due to its design, which included (1) continuously running combustion blowers with or without hot water draws and (2) varying steady state efficiencies (SSE) at different fixed firing rates. As quantified in Figure 7, the former can be compensated for numerically, however the latter is dependent on both the hot water draw rate and the tankless component inlet temperature. As such, there is not a simple numerical adjustment for the varying SSE observed.

Experimental testing of storage tank mixing dynamics under different scenarios confirmed trends observed in simulation. With respect to component configuration, testing of configuration 1 versus 2 confirms that the cold water makeup should be downstream of the tankless component. Inlet pressures from the circulation pump and cold water inlet compete when upstream of the high pressure drop tankless unit, with the line pressure winning out. During a 3.0 gpm draw, configurations 1 and 2 had circulation loop rates of 3.0 gpm and 0.8 gpm respectively. For rapid recoveries and efficient pump operation, configuration 2 is not attractive. Concerning tap type and location, side taps for the storage tank cold inlet resulted in poorer stratification, delivering lower temperatures than diptubes of an equal height. A 15 gallon tank with a diptube delivered hot water at 3.0 gpm 40% longer than with a side tap of equal height.

Figure 5. Mixing Dynamics of 15 Gallon Tank Starting from Set Point



Concerning storage tank mixing dynamics, in Figure 5 a 15 gallon tank with a diptube 80% of the tank height at set point is drawn down at 1.0, 2.0, and 3.0 gpm with and without the circulation pump running (no burner firing). A dimensionless temperature difference is used to reduce experimental noise, defined as $(T_{hot} - T_{cold})/(T_{max,draw} - T_{cold})$. Interestingly, all draws with the pump off are stratified, displaying one-dimensional plug flow behavior. As the thermal plug, or "wave", travels up the tank with cold inlet water upstream and hot set point water downstream, unmixed hot water at set point leaves the tank relatively undisturbed. Once the thermal wave reaches and passes the outlet, the draw temperature rapidly declines. This decline is at almost identical rates for 1.0, 2.0, and 3.0 gpm draw rates. Based upon vertical tank temperature measurements, it seems that while this thermal wave has a velocity close to the average superficial velocity, its thickness is dependent on the draw rate. Higher draw rates increase the height of this mixing zone proportionally to the wave speed such that a fixed observer (e.g. thermostat) sees the same temperature decay. A second important phenomenon is that all draws with the pump on reach well-mixed conditions, as evidenced by the approximately first order temperature decay. These two phenomena, which are consistent for the range of draw rates, can lead towards draw rate prediction based upon a thermal wave height, as observed by one or two temperature measurements, and from that optimized timing of the call for heat.

Table 3. Secondary Parameters – Baseline and Variants

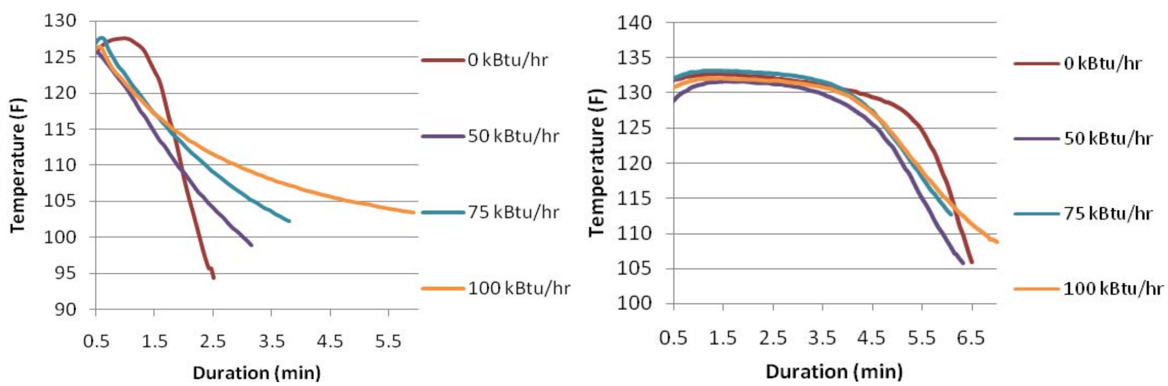
Parameter Selection	Baseline	Variants		
Dip Tube Length (% of tank height)	80%	90%	70%	50%
Thermostat location	TC 6	TC 5	TC 4	TC 3
Thermostat deadband	15 F	20 F	25 F	10 F

Note: "TC" refers to thermocouples 1 (top) though 6 (bottom) on tree as constructed per DOE requirements

HOT Water Heater Testing

With storage volumes and firing rates varied per Table 2, testing is performed with ambient and inlet conditions per the DOE test procedures. Temperature set points are 135 °F and circulation rates are between 3.0 and 3.3 gpm. The secondary parameters concerning control strategies are held at baseline values shown in Table 3, with the "variants" employed in later secondary HOT water heater testing.

Figure 6. 3.5 gpm Draw on 10 and 30 Gallon HOT Water Heaters at Varying Heat Inputs



Note: 10 and 30 gallon HOT water heaters are left and right respectively. "0 kBTU/hr" refers to a no fire/pump draw.

As simulated, all HOT water heater combinations were able to sustain hot water draws during the low flow and "cold water sandwich" draws. For peak draws, the benefit provided by a larger heat input depended on the corresponding storage volume, as shown in Figure 6. With a small 10 gallon volume (left) the depletion and recovery times are both rapid, as shown by a quick depletion without firing for "0 kBTU/hr" and tankless-like behavior at "100 kBTU/hr". With a larger volume of 30 gallons (right), the benefit of higher firing rates, or firing at all, is negligible. Thus for period of high demand, the performance is optimized with small storage and a high firing rate or vice versa, as highlighted in Table 2.

All FHR results shown in Table 4 show improvement upon the baseline storage water heater with 67 gallons certified. A dip in FHR is observed from 15 to 30 gallon storage which was not captured in modeling, in which thermal mixing becomes important. As a high FHR is achieved through either high onboard storage or a fast recovery time, a transition between the two occurs near 20 gallons. The FHR is improved through (1) having sufficient hot water storage or (2) having a high recovery rate, as the FHR shows significant dependency on firing rate. The transition in storage reflects the transition from one regime to the other, highlighting a reason why 20 gallons is the minimum cutoff for a "storage" water heater as defined by DOE.

Tables 4 & 5. First Hour Rating & 24 Hour Simulated Use HOT Water Heater Results

Burner Firing Rate (BTU/hr)	10 gallon	15 gallon	20 gallon	30 gallon
50,000		82/5	73/5	86/3
75,000	171/3	143/5	97/5	126/4
100,000	182+/0	175/1	165/2	163+/1

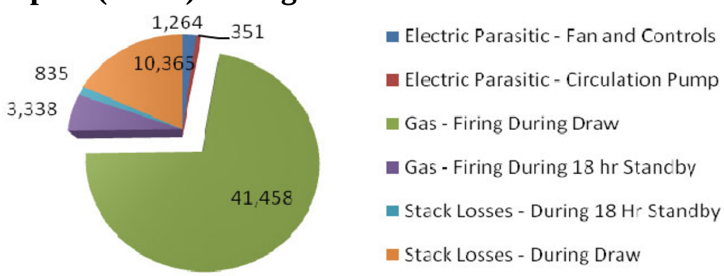
Note: Cell value is First Hours Rating (gal)/number of draw-recovery cycles. A "+" indicates asymptotic behavior

Burner Firing Rate (BTU/hr)	10 gallon	15 gallon	20 gallon	30 gallon
50,000			121.5 °F/0.67	128.3 °F/0.61
75,000	109.0 °F/0.66	113.4 °F/0.68	123.5 °F/0.68	128.7 °F/0.67
100,000	111.4 °F/0.63	114.2 °F/0.62	124.9 °F/0.65	129.0 °F/0.61

Note: Cell values are average delivered temperature in °F and the estimated EF, with standby recovery suppression

Results for the 24 Hour Simulated Use Test in Table 5 summarize the average delivered water temperatures and estimated EFs, which numerically employ a widely used control technique, standby recovery suppression (PC, 2009). This test consists of draws at 3.0 gallons per minute (gpm) at the start of the first six hours, totaling 64.3 gallons, followed by 18 hours of standby. The 20 to 30 gallons and 75,000 firing rate combination shows to be a relative optimum, balancing EF and quality of hot water delivered. Drawing 3.0 gpm, the benefit in increased output for a larger input is minimal, as observed in prior peak draws.

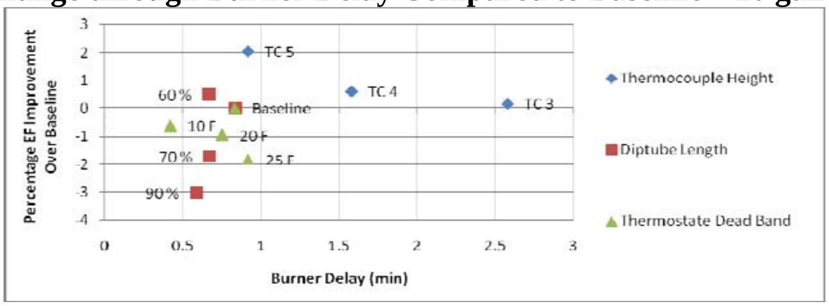
Figure 7. Energy Inputs (BTUs) during 24 Hour Simulated Use Test - 20 gal/75 kBTU/hr



Dissecting the energy inputs during a typical 24 Hour Simulated Use Test, as shown in Figure 7, highlights areas for efficiency improvements and experimental biases. With reductions in the largest component, end use, left to conservation and efficient distribution, the remainder can be tackled methodically. With an intended low-cost non-condensing design, the stack losses can be improved but not significantly as the thermal efficiency of the unit used was 80 – 82%. Through standby recovery suppression, 4,173 BTUs are saved (as reflected in Table 5), additionally suppression of the continuously running blower on the experimental unit saves 1,100 more BTUs. This leaves little left for input efficiency improvement, shifting the focus to improved delivered efficiency in the form of higher average hot water temperatures.

In an effort to improve delivered efficiency, accelerated testing was performed on the secondary parameters outlined in Table 3, which impacted control strategy and response, for the HOT water heater primary combination of 20 gallons and 75,000 BTU/hr and the four adjacent cells in Table 2. Testing consisted of holding two secondary variants constant while varying the other and comparing estimated EF results to the baseline results, as summarized in Table 5. With respect to delivered energy, the varied diptube lengths, thermostat heights, and dead bands have a primary impact through burner delay following draw initiation.

Figure 8. EF Change through Burner Delay Compared to Baseline – 20 gallon/75 kBTU/hr



The results for the 20 gallon and 75,000 BTU/hr HOT water heater are shown in Figure 8. The greatest improvement in this case comes from a slightly higher thermostat, which acts to call for heat at an optimum stratified state for the given draw. This testing was performed for other HOT water heater storage and heat input combinations, resulting in the development of a semi-empirical model which estimates the EF change resulting from burner delay for all HOT water heater combinations explored. On average, optimized burner delay could increase the EF by an additional 1%. Optimizing these parameters results in a prototype EF increase of up to 0.70, which when accounting for experimental biases resulting from use of an off-the-shelf tankless water heater, most notably a continuously running blower, results in a 0.71 EF.

Conclusions and Future Efforts

The development of the HOT water heater prototype specifications in this analytical and experimental work demonstrated that incremental efficiency improvements are feasible with a simple HOT water heater design that meets the initial mid-efficiency performance requirements. The remaining challenge is to realize the complementary incremental cost increase, in which the cost savings relative to tankless water heaters from the simplified single-stage burner and compact heat exchanger are not erased by hybrid system integration and controls.

The simulation and laboratory analysis of the component performance discussed highlights the importance of thermal management and the possibility for simple effective controls. When integrating the two components that individually cannot meet the thermal load, but together can, the design required stresses the individual strengths with flexible operation. In the case of the HOT water heater, the stratification management of the buffer storage facilitates the use of a single-stage tankless thermal engine, where normally a complex fully modulating unit would be required. Understanding and utilizing the thermal mixing dynamics replaces much of the dynamic feedback control. Further work will explore correlations between primary and secondary parameters beyond the testing discussed. Future efforts with the alpha prototype include: eliminating "breadboard" experimental biases, Category I/Type B venting evaluations, plastic tank integrations, low-NOx burner development, and integration of smart controls.

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