HWSIM: Development and Validation of a Residential Hot Water Distribution System Model

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ABSTRACT

The performance characteristics of storage water heaters (the predominant water heater type in the U.S.) are well documented. The performance of the distribution system is not well understood as once the hot water leaves the water heater a wide range of factors come into play. Hot water usage patterns and quantities, piping materials and pipe locations, environmental temperatures surrounding the piping, and presence of insulation are just a few of these factors. A detailed event-based simulation model (HWSIM) was developed to better evaluate hot water distribution system performance. The program tracks the flow and heat transfer of a volume element of hot water as it flows from the water heater to the end use point. The program is based on engineering first principles and allows the user to input the hot water distribution layout (pipe material, location, diameter, surrounding environment), temperature conditions of the surrounding environments (varying monthly and hourly, if desired), cold water inlet temperatures by month, hot water draw characterization (time of day, day of week, duration, flow rate, end use fixture, minimum useful temperature), and water heater performance parameters. Model output includes energy tabulations, hot and cold water wasted and used, and overall distribution efficiencies.

The paper describes model development, validation against laboratory data, and presents results from a set of runs evaluating the effect of insulation and hot water usage pattern on overall energy and water use.

Introduction

HWSIM is a hot water distribution simulation program that models the heat losses through a piping network from the water heater to each hot water use point in a home. The HWSIM hot water distribution model was originally developed in 1990 by Davis Energy Group as part of a California Energy Commission project[1] to develop a comprehensive water heating methodology for the Title 24 Residential Building Standards. Due to budget constraints at the time, the 1990 HWSIM program implemented some simplifying assumptions and had limited input flexibility in certain areas. In 2004 Davis Energy Group received additional funding from the Department of Energy's Building America program to develop an enhanced version of HWSIM with improved capabilities and a graphical interface. Funding was augmented in 2006 with support from the California Energy Commission's Public Interest Energy Research (PIER) program. An enhanced HWSIM simulation has now been developed in the Microsoft .NET environment.

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[1] The March 31, 1991 final report to the California Energy Commission under contract 400-88-003 documents the development of the original HWSIM.

Program inputs in the new HWSIM program allow for definition of hot water distribution piping that passes through various environments with user-defined temperatures that can vary monthly or hourly. A hot water draw schedule is built up for a full week by specifying the hot water use point, draw start time, volume, flow rate, and desired use temperature. HWSIM models an entire domestic distribution system by segmenting the pipe network into small user-specified “delta volumes”, which are typically set at 0.01 gallons. Heat transfer from water to pipe and pipe to environment is modeled as each delta volume moves through the piping system in response to individual hot water draws. A representative week of draws is modeled for each month, extrapolated to a full month, and summed to calculate annual values.

HWSIM uses a graphical user interface separated into two sections: the distribution system and the draw characteristics. The distribution system defines the materials, dimensions, and surrounding environment characteristics of the piping network that delivers water to each use point. The draw characteristics define how and when water is drawn from each use point.

Distribution System

- Most varieties of main and branch, home run, and recirculation distribution systems can be modeled (recirculation models are not yet fully implemented).
- The user builds up the distribution system by defining lengths, diameters, materials, insulation, and environment temperatures surrounding pipe sections.
- Recirculation control capability will include continuous, timed, and demand.
- Pipe materials include Type L and M Copper, PEX, PAX, and CPVC. Additional materials can be added to the library.
- Environments have monthly temperature profiles with hourly variation, if desired.
- Cold water inlet temperatures can be varied monthly.

Draw Characteristics

- Each draw is assigned to a use point and is characterized by draw type, volume, flow rate, desired temperature, hot water ratio, and start time. Each draw can be assigned to occur on one or more days of the week.
- Three types of draws can be defined:
  - Appliance: A fixed volume of water from the hot water line.
  - Mixed (e.g. tub draw): A mixed volume of water at a final use temperature.
  - MinTemp: (e.g. shower or sink): Requires a minimum water temperature before the water is deemed useful.
- Hot Water Ratio, used for Mixed and MinTemp draws, specifies an initial mix of hot and cold water. This provides the ability to assess how the user influences draws based on fixture operation (in terms of hot water usage and water waste).

HWSIM produces five output reports that can be exported in various formats. The five reports are described below:

1. Annual Summary:
   - Hot and cold water use and water wasted
   - Hot water energy delivered to fixtures

- Water heater recovery load and energy use
- Water use, distribution, water heater, and overall system efficiencies

2. Energy Flow Monthly Summary
   - Hot water use, delivered energy, water heater load, & use point distribution efficiency

3. Water Use Monthly Summary
   - Hot & cold water use, waste volumes, and water use efficiency by use point

4. Heat Flow Monthly Summary
   - Monthly pipe heat loss (and loss per foot) for each environment specified

5. Water Heater Monthly Summary
   - Water heater load, energy delivered, fuel used, and efficiency

Model Validation

The primary objective of the initial model validation efforts presented here was to compare HWSIM results to detailed laboratory test data collected by Applied Energy Technology (AET). AET has completed extensive testing for both copper and PAX (cross linked polyethylene with an aluminum oxygen barrier) piping in air, as well as buried copper piping. These validation efforts will continue as more data becomes available. Several comments should be presented prior to presenting the validation results. First, the AET test reports indicate flow phenomena under certain conditions that indicate unusual flow characteristics that will be challenging for the as-configured HWSIM to mimic. Secondly, maintaining 100% consistency in a test environment is a challenging prospect.

The validation effort presented here focuses on in-air test results in three areas:

- Comparison of hot water outlet temperatures for ½" copper, ¾" copper, and ¾" PAX piping "in air" at different hot water flow rates.
- "AF/PV" ratios (***A***ctual hot water ***F***low divided by ***P***ipe ***V***olume) for the model vs. the laboratory data. The AF/PV ratio reflects flow phenomena that occur and characterizes the additional hot water usage that is needed at a distant use point before a minimum hot water use temperature (e.g. 105ºF) is achieved[2].
- Temperature decay characteristics for different pipe material types.

The validation effort focused on determining proper adjustment factors for "h_o, h_i" heat transfer coefficients, and the "qmix" term. The "h_o, h_i " adjustment factors simply represent direct multipliers on the HWSIM calculated pipe outside ("o") and inside ("i") heat transfer coefficients to better match the detailed laboratory testing results. Likewise the "qmix" term was added in an effort to mimic the slip flow phenomena observed in the laboratory testing. The "qmix" term represents an axial U-value between the adjacent volume elements within the pipe.

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[2] For example, an AF/PV of 2.0 would indicate that twice the volume of water contained in a pipe must be wasted before a minimum use temperature (e.g. 105°F) is achieved at the pipe outlet.

The greater the "qmix" term, the greater the heat transfer down the pipe in advance of the flowing plug of hot water.

Figure 1 plots outlet hot water temperature data for 100 feet of ½" copper in 67.5ºF air at varying flow rates. The graph plots AET lab data and HWSIM results for h_o, h_i, and qmix values of "1.0, 1.0, 1.0" (unadjusted) and "1.3, 1.0, 1.0". The latter case was found to match nearly exactly for this case and also matched well for ¾" copper.

Figure 1: Pipe Heat Transfer Coefficient Impact

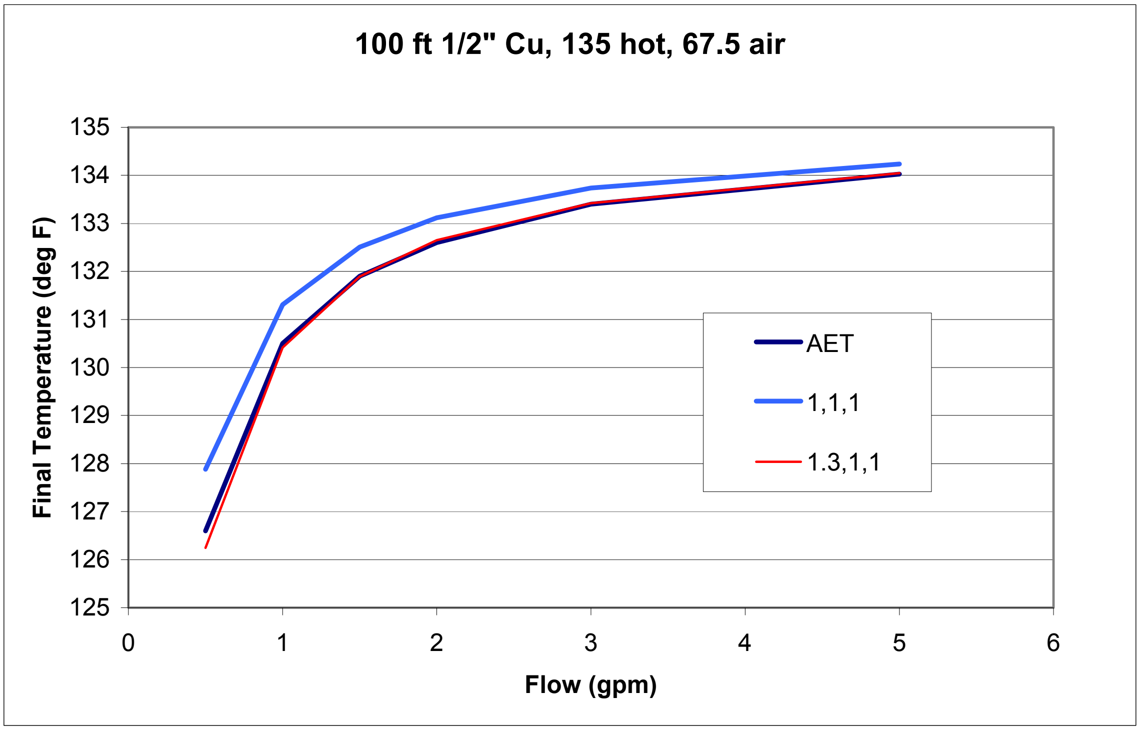


Figure 2 plots outlet temperature vs. flow rate for ½" and ¾" copper in air, and ½" copper with ½" insulation in air. These plots use the "1.3,1.0,1.0" set of factors. The two uninsulated cases show very good agreement over the full flow rate range. The insulated case shows a small divergence, particularly at the very low 0.5 gpm flow rate. Since the uninsulated case provides a good match, the small deviation is likely due to the conductivity specification or the model assumption of perfect insulation performance vs. the small anomalies that cannot be avoided in the laboratory. Figure 3 shows a similar plot for ¾" PAX, in air and insulated. Again the uninsulated case shows very good alignment, with a greater divergence in the insulated case.

Figures 4-7 provide a comparison of AF/PV lab results to model predictions. In general the lab data shows a trend of decreasing AF/PV with both increasing flow rate and increasing pipe length. Simultaneously, the lab data shows variations that can be expected in doing experimental work; in other words trends are evident but not all data points follow these trends.

Figure 4 plots AF/PV data as a function of pipe length at a hot water flow rate of 0.49 gpm. HWSIM model results are shown for a range of h_i and qmix values, with h_o fixed at 1.3. The HWSIM "1.3,1.0,1.0" and "1.3,1.0,0.0" lines sit directly on top of each on either in this example. Given the small sensitivity to variations in the h_i and qmix values, the recommended specification of "1.3,1.0,0.0" is proposed.

Figure 2: Model vs Lab Outlet Temperature Data (½" Cu, ¾" Cu, ½" Insulated Cu)

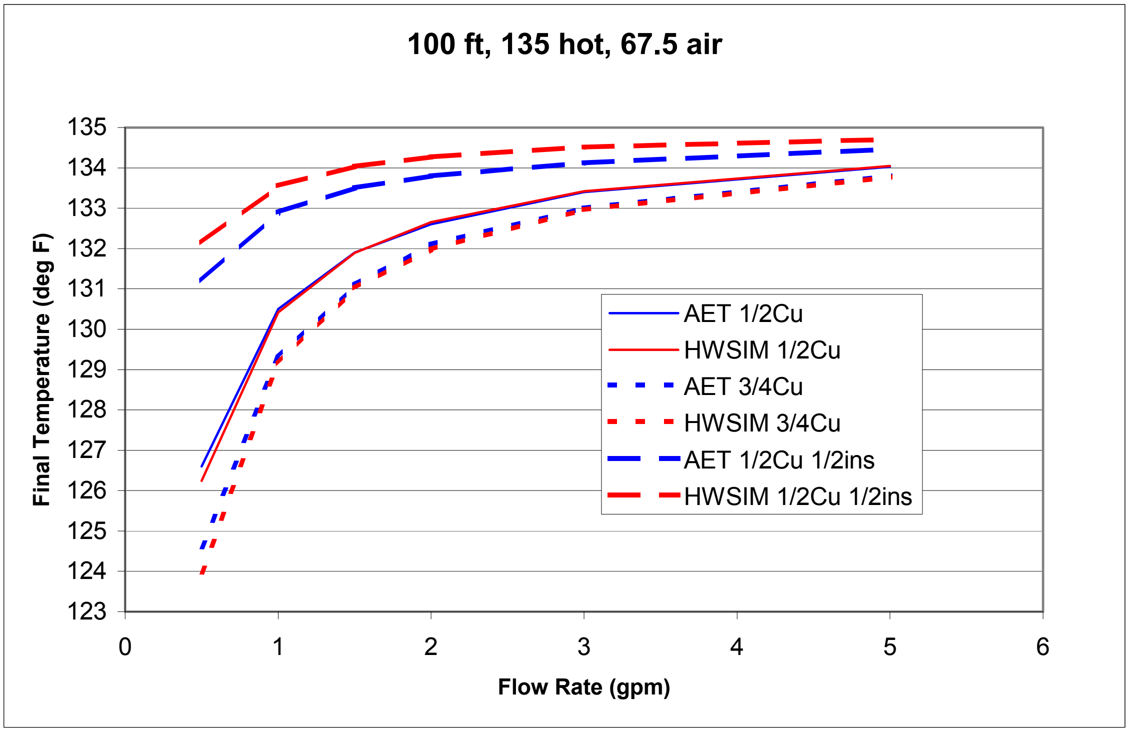


Figure 3: Model vs Lab Outlet Temperature Data (¾" PAX, ¾" Insulated PAX)

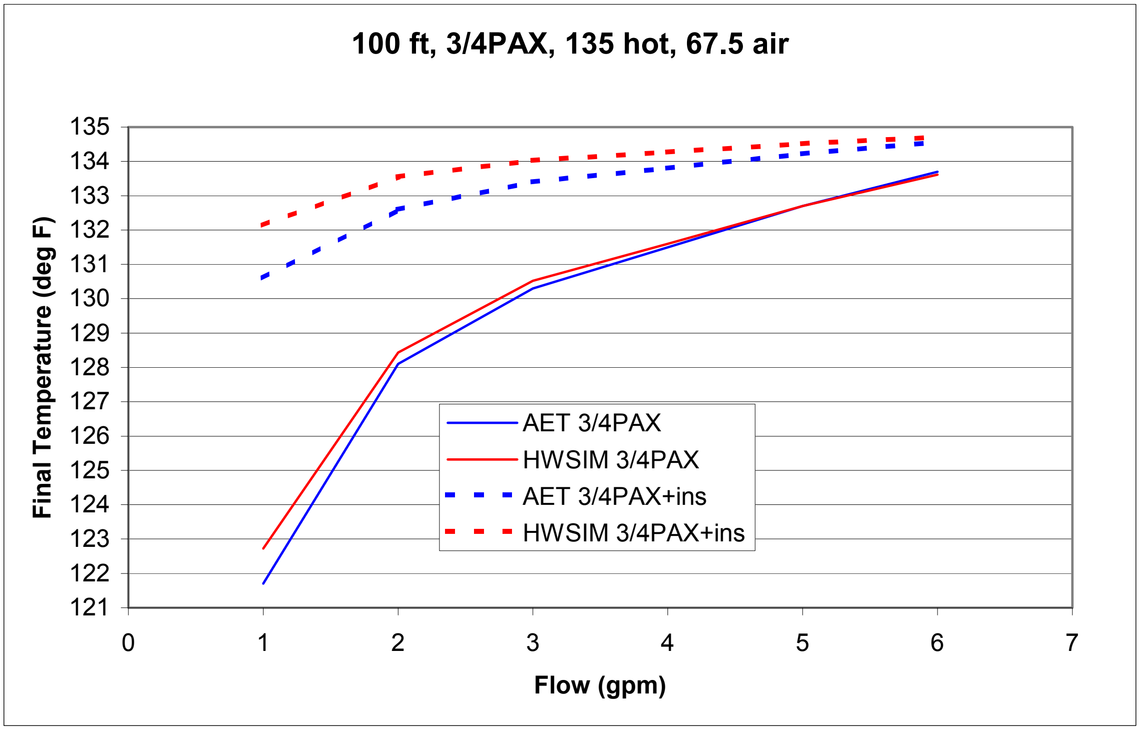


Figure 4: Model vs. Lab AF/PV Validation as a Function of Pipe Length (½" Cu)

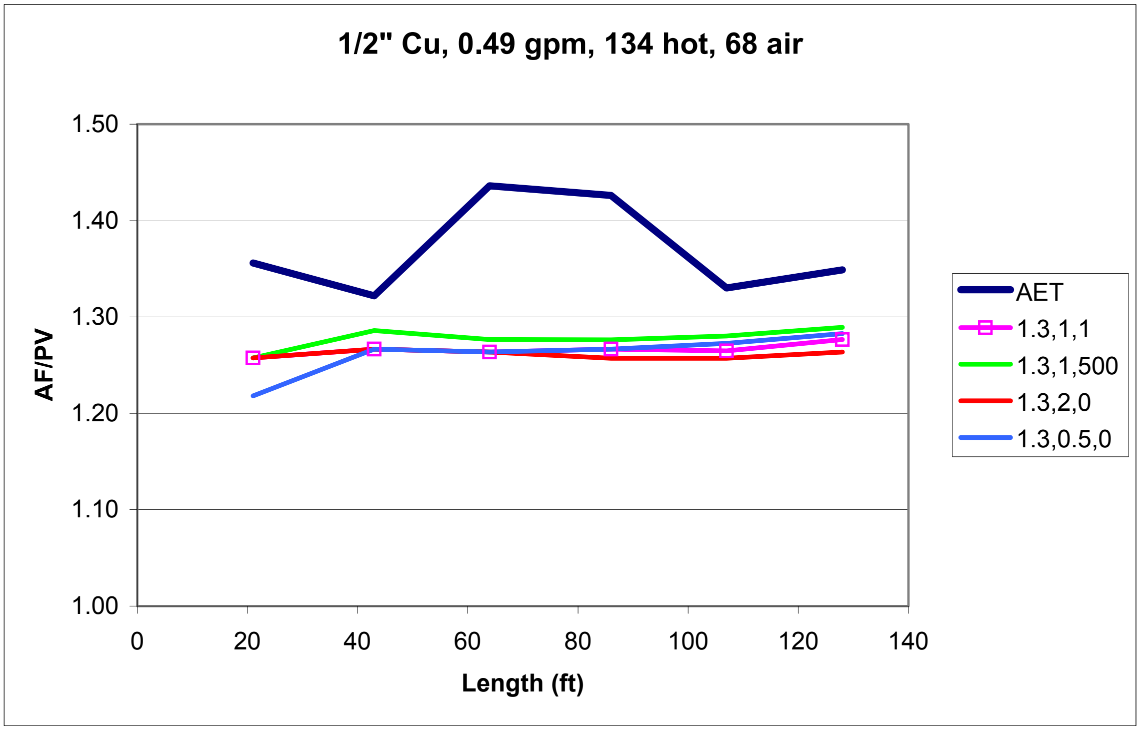


Figure 5 takes the "1.3,1.0,1.0" validation assumption and applies it to 135ºF inlet hot water in ½" copper pipe in 65ºF air. Four lab cases ("AET") are compared to four HWSIM projections at hot water flow rates of 0.49, 0.94, 1.6, and 3.02 gpm. Although the lab data shows a much greater AF/PV sensitivity to flow rate than the model, most residential hot water flow rates will occur in the 0.9 to 2.0 gpm range where the model matches the lab data quite well.

Figure 6 plots results for 120ºF inlet hot water in ½" copper pipe in 70ºF air. The lab data shows a stronger downward trend in AF/PV with increasing pipe length than HWSIM indicates. Similar to the Figure 5 data, outside of the low 0.49 gpm case, the model predictions are reasonably close to the AET lab results.

Figure 7 plots results for 135ºF inlet hot water in ¾" copper pipe in 58ºF air. The lab data shows a similar trend to Figure 6, with generally higher AF/PV's for short lengths and a trend towards lower values for longer pipe lengths. HWSIM shows minimal variation with length, but on average matches well with the lab data at flow rates of 1.98 gpm and above.

In summary, HWSIM does not the same degree of variation in AF/PV as demonstrated the lab data. Root mean square deviations range from 0.03 to 0.12 with larger variations generally occurring at higher or lower than normal hot water flow rates. The 0.12 RMS error amounts to ~10% deviation from typical AF/PV values.

Figure 5: Model vs Lab AF/PV as a Function of Pipe Length & Flow Rate (½” Cu)

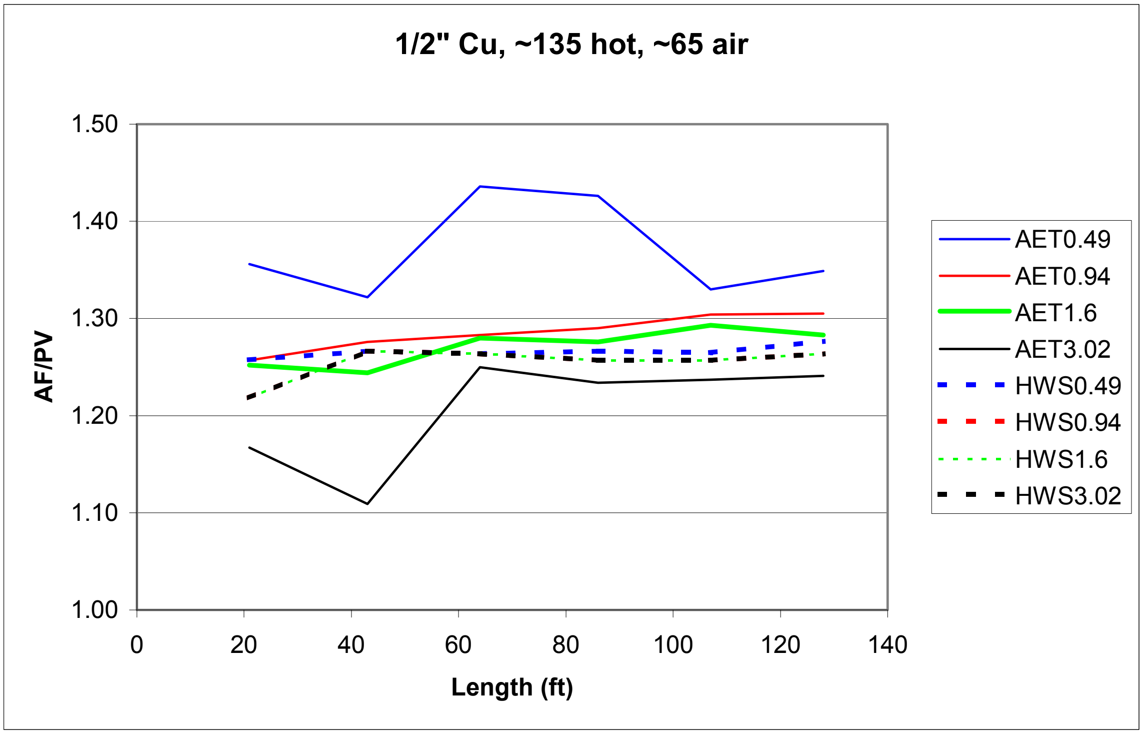


Figure 6: Model vs Lab AF/PV as a Function of Pipe Length & Flow Rate (½” Cu)

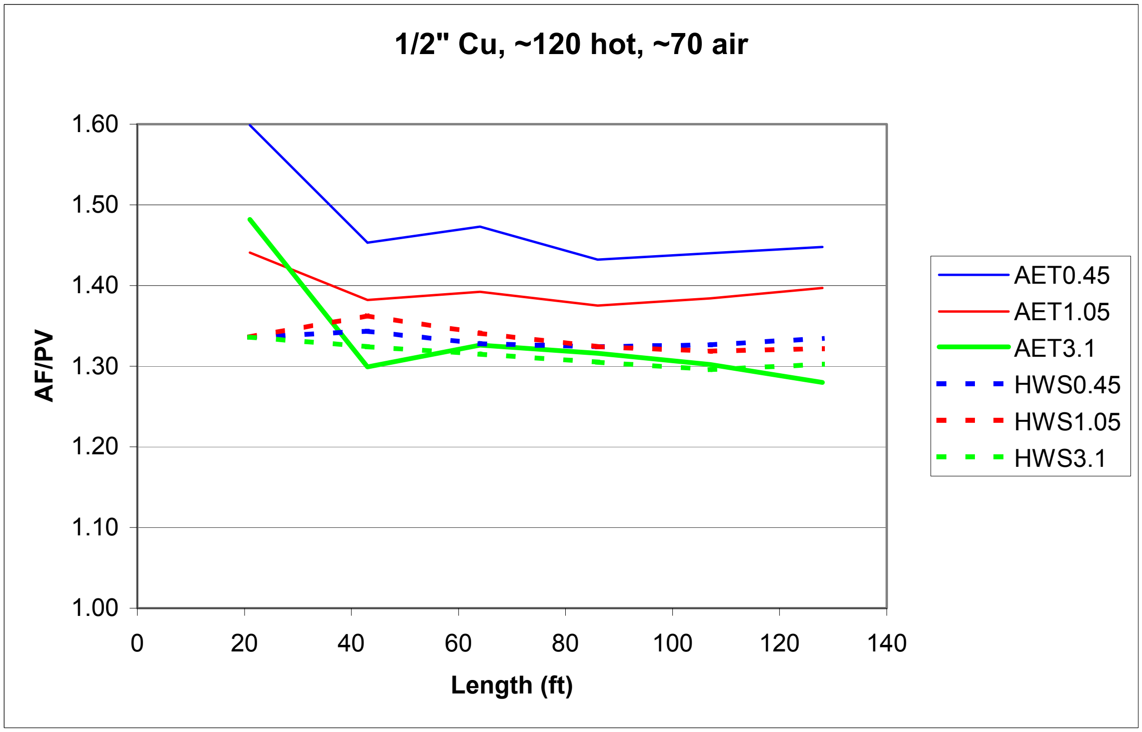
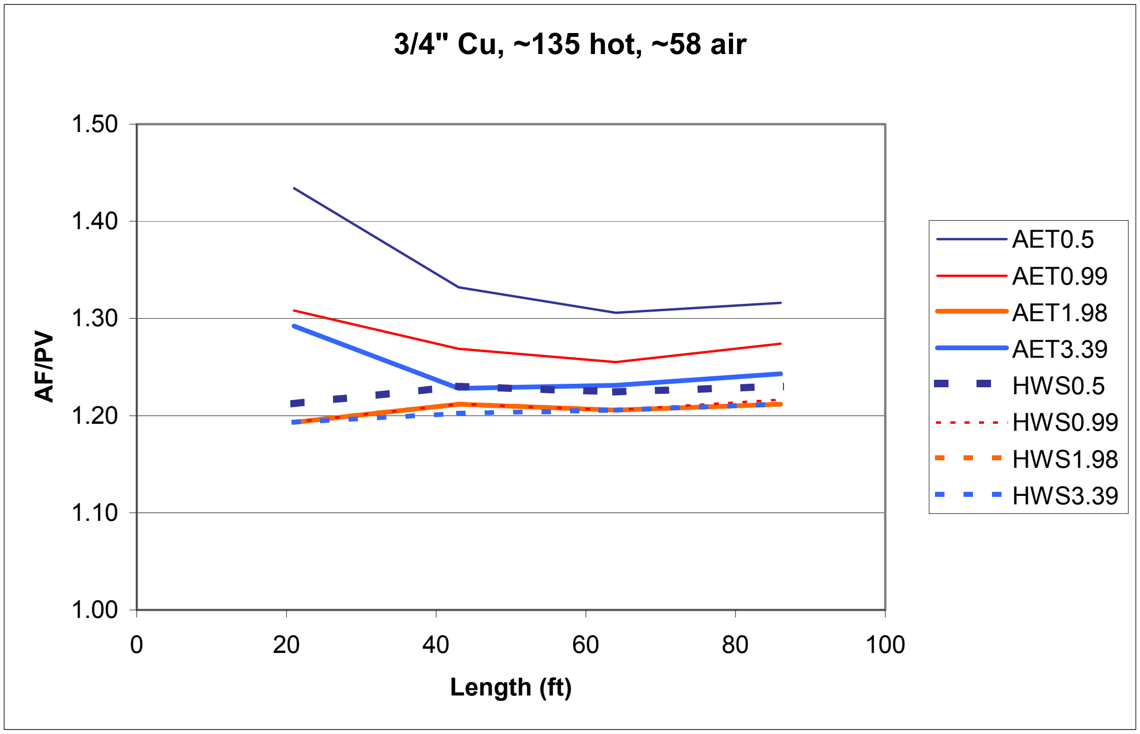


Figure 7: Model vs Lab AF/PV as a Function of Pipe Length & Flow Rate (¾" Cu)



The final step in this initial validation process is to evaluate how the model predicts pipe cool down between hot water draws. AET completed lab testing on various pipe configurations and determined an average effective pipe UA during non-flow situations. These loss coefficients were used to determine pipe cool down times. Table 1 summarizes these cool down times for various cases. An HWSIM model was set up for each of the pipe cases shown in Table 1. A short two-foot pipe section from the water heater was modeled to insure that the outlet water temperature would be very close to the tank outlet temperature. A five-minute draw was imposed, at the end of which a time delay was imposed (e.g. 19.8 minutes for the "½" Rigid Cu, no insl" case). A second draw then ensued, and the initial outlet water temperature was recorded for comparison to the lab result.

Figure 8 plots this initial water temperature for each of the cases in Table 1. The x-axis label characterizes the insulation (none, ½", or ¾") as well as the pipe material. For complete consistency with the lab data, all cases should converge to 105ºF. On average for the 125ºF and 135ºF starting temperatures, HWSIM over-predicts the lab results by 2.6ºF and 3.5ºF, respectively[3]. Curiously the trend is not consistent with uninsulated ½" Cu showing a faster predicted decay, and all other cases showing a slower decay. Three potential factors could be affecting the decay results:

1. The decay calculations are based on a lumped capacitance assumption that combines energy contained in the pipe and water into a single temperature.

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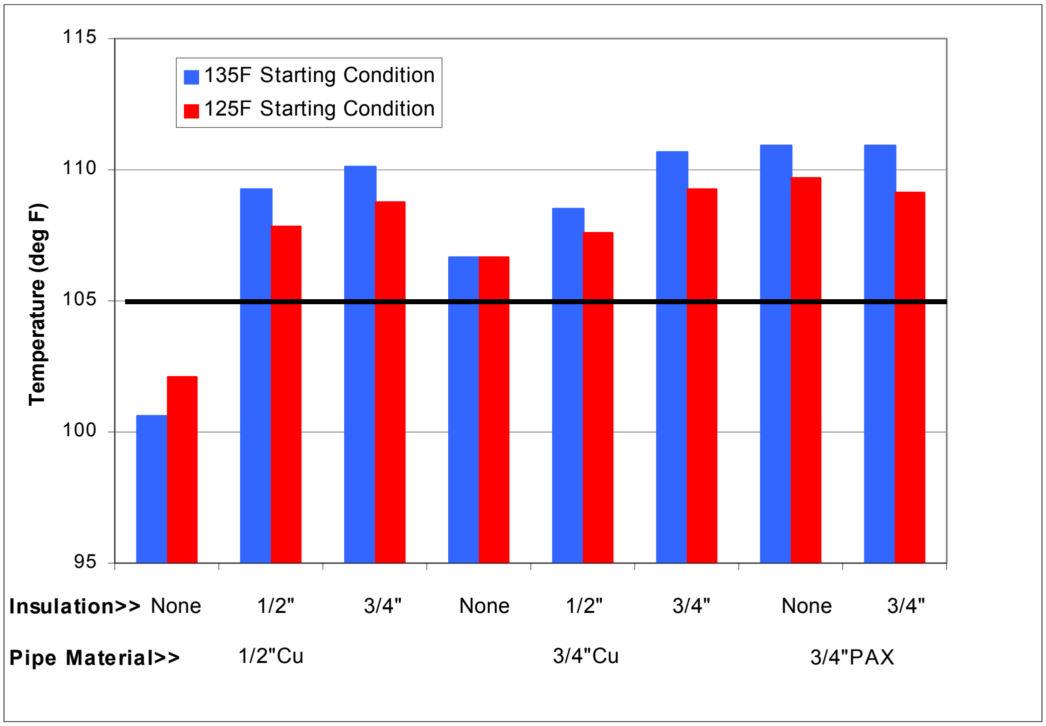
[3] Keep in mind that the Figure 8 reported temperatures represent projections at 14 to 64 minutes after the end of the hot water draw.

2. The assumption of a “still air” pipe exterior convection coefficient may not fully represent conditions in the lab. Small environment effects or radiant heat transfer can have a sizable impact on pipe heat loss, especially for uninsulated pipes.
3. HWSIM assumes perfect insulation performance at an R-value of 3.97 per inch. Although pipe insulation tested and rated, discrepancies in product specifications raise uncertainties as to actual performance characteristics of individual products.

Table 1: Lab Pipe Cool-down Time (minutes to reach 105ºF in 67.5ºF still air)

Pipe Description	135ºF Starting Temperature	125ºF Starting Temperature
½” Rigid Cu, no insl	19.8	14.4
½” Rigid Cu, ½” insl	35.8	26.0
½” Rigid Cu, ¾” insl	40.4	29.4
¾” Rigid Cu, no insl	22.7	16.5
¾” Rigid Cu, ½” insl	59.8	43.5
¾” Rigid Cu, ¾” insl	64.0	46.5
¾” PAX, no insl	18.1	13.2
¾”PAX, ¾” insl	56.3	47.1

Figure 8: Initial Draw Temperatures After Cool-Down Period



To demonstrate the capabilities of HWSIM, a series of runs are presented illustrating the impact of pipe insulation and hot water usage schedule on both energy and water consumption. The runs are a subset of a broader study being completed for the National Renewable Energy Laboratory as part of their development of water heating benchmark data for typical homes. The home modeled was a 2,010 ft^2 home located in St. Louis. For this case, the gas storage water heater and most of the hot water piping (conventional trunk and branch design with copper piping) are located in the basement.

The data shown in Table 2 includes hot water used from the fixtures, as well hot water wasted before an acceptable temperature is reached at the use point. Cold water use, representing the cold water consumed in conjunction with the hot water draw, varies with the temperature of the hot water supplied to the fixtures. Hot water recovery load and delivered (kBtu) represents the energy leaving the water heater and fixtures, respectively. Efficiencies are reported in terms of water use (used water divided by used + wasted water), distribution system efficiency (Btu's delivered divided by Btu's leaving the water heater), water heater efficiency (a function of the recovery load), and overall efficiency (water heater efficiency times distribution system efficiency).

Results are shown for the base uninsulated system with a hot water usage pattern of about 70 gallons per day (use + waste). The addition of R-4 pipe insulation reduces hot water use and waste, resulting in an 8 therm per year projected savings. The last two cases look at extreme scenarios where the hot water draws are either uniformly spaced in time, or clustered one after the other. The uniform draw pattern results in roughly triple the hot water waste and an annual hot water gas usage 17% higher than the base scenario. Conversely, the clustered draw pattern demonstrates hot water waste half that of the base case, with a resulting annual gas usage 5% less than the base case. Interestingly, the clustering of draws is projected to have a bigger energy and water savings impact than the addition of insulation, documenting impact of behavioral factors on energy use.

Table 2: HWSIM Comparative Results Summary

	Base		**Insulated**		**Base (uniform)**		**Base (clustered)**	
	Annual Total	Daily Average	Annual Total	Daily Average	Annual Total	Daily Average	Annual Total	Daily Average
Hot water use (gal)	21799	59.7	21394	58.6	21548	59.0	21748	59.6
Hot water waste (gal)	3715	10.2	2972	8.1	10921	29.9	1812	5.0
Tempering (cold) water use (gal)	4079	11.2	4485	12.3	4331	11.9	4128	11.3
Hot water recovery load (kBtu)	13906		13286		17680		12844	
Hot water delivered to fixtures (kBtu)	11259		11320		11281		11292	
Water heater fuel energy (therms)	256		248		300		243	
Water use efficiency (%)	87%		90%		70%		93%	
Distribution efficiency (%)	81%		85%		64%		88%	
Water heater efficiency (%)	54%		54%		59%		53%	
Overall efficiency (%)	44%		46%		38%		47%	

Conclusions

This paper describes the development and preliminary validation of a residential hot water distribution model. The HWSIM model allows the user to precisely define hot water piping system configuration, hot water usage patterns, environmental conditions surrounding the piping, and some level of behavioral influences. The model tracks and reports energy flows as well as water usage and waste. HWSIM model flexibility makes it a powerful tool for assessing the performance of alternative distribution systems in different climates, under different usage patterns. Ongoing validation efforts and improved data on real hot water usage profiles are needed to enhance the ability of HWSIM to predict real world performance of hot water distribution systems.

Acknowledgements

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References

Hiller, C., 2006. "Hot Water Distribution System Piping Heat Loss Factors – Phase I Test Results." ASHRAE Transactions, vol. 112, pt.1: 415-425.

Hiller, C., 2006. "Hot Water Distribution System Piping Time, Water, and Energy Waste – Phase I Test Results." ASHRAE Transactions, vol. 112, pt.1: 436-446.