An Analysis Model for Domestic Hot Water Distribution Systems

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AN ANALYSIS MODEL FOR DOMESTIC HOT WATER DISTRIBUTION SYSTEMS

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ABSTRACT

A thermal model was developed to estimate the energy losses from prototypical domestic hot water (DHW) distribution systems for homes. The developed model, using the TRNSYS simulation software, allows researchers and designers to better evaluate the performance of hot water distribution systems in homes. Modeling results were compared with past experimental study results and showed good agreement. The model was also compared with existing domestic hot water distribution system modeling software HWSIM for verification. The developed model has several capabilities that are not available in HWSIM, including the ability to integrate any new or existing types of water heater systems, the ability to handle several simultaneous draws to different end uses, and the ability to handle unique annual draw profiles instead of weekly draw profiles. It also allows for draw profiles and ambient conditions to be considered using any time resolution. To demonstrate the abilities of this new model, a series of sensitivity analyses were performed using a benchmark domestic hot water distribution system. The effects of adding insulation to the domestic hot water distribution system of homes with a gas water heater and a solar water heater were also examined.

NOMENCLATURE

c_p: Specific Heat of Water
DHW: Domestic Hot Water
EF: Energy Factor
gpm: Gallons per Minute
lpm: Liters per Minute
PEX: Cross-linked Polyethylene
Q: Heat Loss
$R_{c,i}$: Inner Convection Thermal Resistance
$R_{c,o}$: Outer Convection Thermal Resistance
R_{cond}: Conduction Thermal Resistance
R_{net}: Net Thermal Resistance
R_{rad}: Radiation Thermal Resistance
SF: Solar Fraction
t: Time
T: Temperature
T_a: Ambient Temperature
T_f: Final Temperature
T_i: Initial Temperature
T_p: Pipe Temperature
UA: Overall Heat Transfer Coefficient
ε: Emissivity

INTRODUCTION

In any residence with hot water service, thermal losses occur in the pipes that connect the water heater to end use fixtures in the home. The magnitude of these losses depends on the location and layout of the distribution system, the homeowner's hot water use, and other factors. Thus, detailed models of domestic hot water (DHW) distribution systems are needed to make accurate predictions of the distribution losses.

Several models of residential DHW distribution systems are available. The National Association of Home Builders developed a plug flow model of a DHW distribution system and ran it for several cases [1]. However, this model was based on theoretically derived heat transfer coefficients for losses between distribution pipes and ambient air and was not compared to experimental data. Researchers at Oak Ridge National Laboratory also developed a DHW distribution system model and used it to evaluate several distribution system layouts [2]. However, they used draw profiles that represented the best and worst case scenarios of a highly clustered set of draws and only "cold start" draws where the pipe always starts at ambient temperature, respectively. This provides the extreme bounds for losses without necessarily estimating the actual losses. Their work also focused exclusively on homes in California. A third model was developed by Florida Solar Energy Center for use in whole home building energy simulation software [3]. This model has undergone only limited validation and cannot simulate complex distribution systems.

Based on a review of the existing models, the HWSIM program is the most detailed DHW distribution system modeling tool available. It was originally developed in 1990 for use in developing the California Title 24 Residential Building Standards [4]. The original model had several simplifications and could not accurately model thermal losses through a distribution system under typical operating conditions. The original HWSIM program has since been updated and can now model a full week of unique draws, several types of pipes, ambient temperatures that vary hourly and mains temperatures that vary monthly. The heat loss through pipes was validated by comparing the results to a study performed by Applied Energy Technology that specifically examined the heat loss in DHW distribution system pipes [5]. However, HWSIM cannot model multiple draws simultaneously and can use only one week of unique draws. Moreover, it is a standalone program that cannot be integrated with whole home energy models and features a limited number of water heaters. This modeling tool has been used to analyze the cost effectiveness of specific energy saving measures that could be used in DHW distribution systems for homes using a gas storage water heater [6].

Of all the discussed existing DHW distribution system models, only HWSIM is publicly available. The model developed here is also an in house model at the current stage due to the lack of a simple user interface and the complexity of changing distribution system layouts to model alternate distribution systems.

The goal of this paper is to present a new thermal model for a prototypical DHW distribution system that could easily be used with unique water heater models or whole house energy models. It was implemented in the TRNSYS environment [7], which can simulate entire buildings and is often used to model the performance of water heaters [8,9]. This model was verified against measured data and predictions from the HWSIM model using a prototypical distribution system. Parametric cases were then modeled with different pipe insulation, different climates and low, medium, and high hot water draw profiles. The distribution losses were also modeled for a gas and a solar water heater.

MODEL DESCRIPTION

The developed model uses a simplified "plug flow" model of fluid flow in pipes [7] that breaks the pipes into small discrete sections. Each has its own temperature and the size of each section is determined by the flow rate in the pipes and the time step size. This model neglects axial conduction in the pipe and any mixing between sections. The thermal mass of the pipes is also neglected in this model, although a modification was made to the overall heat transfer coefficient to account for this effect between draws when the water is still and cools to the ambient temperature. To minimize the size of individual sections and model realistic hot water use, a small time step size (6 seconds) was chosen for all simulations. The heat loss from each section to the environment while water is flowing through the pipes is determined by calculating the heat transfer coefficients for the pipe inner and outer surfaces and the thermal resistance of the pipe and any insulation as shown in Equations 1-2.

$$Q = UA\left(T_p - T_a\right) \qquad (1)$$

$$R_{net} = \frac{1}{UA} = R_{c,i} + R_{cond} + \frac{R_{c,o}R_{rad}}{R_{c,o}+R_{rad}} \qquad (2)$$

The overall heat transfer coefficient for pipes in the distribution system is determined analytically using a simple thermal resistance network [10]. For the inner heat transfer coefficient, an exact solution is used for laminar flow and the Dittus-Boelter correlation for turbulent flow [10]. For the outer heat transfer coefficient, radiation and natural convection are considered in parallel. The radiation heat transfer is calculated based on an emissivity (ε) of 0.9 for any insulating material and 0.6 for copper pipes. The emissivity of copper can vary significantly depending on the surface finish of the pipes and was not measured during testing. For this model, the emissivity of copper was determined by comparing the analytic model to test results and adjusting the emissivity to obtain good agreement (Table 1). For natural convection, a correlation developed by Churchill and Chu for horizontal pipes, valid under a wide range of Rayleigh numbers, was used [11]. Testing showed only a slight difference between heat losses for horizontal and vertical pipes [5], so this correlation was applied to pipes in both horizontal and vertical orientations. During periods of no flow when water in the pipes is still, the pipes and the water were assumed to be at equilibrium so the same temperature was applied to both and a lumped parameter model was used. The pipe temperature was calculated according to Equation 3.

$$\frac{T-T_f}{T_i-T_f} = \exp\left(-\frac{UAt}{mc_p}\right) \qquad (3)$$

To validate this assumption, the Biot number, defined as the ratio of conduction resistance inside the body to the thermal resistance at the surface of the body, was calculated. Cases with a Biot number less than 0.1 are generally considered to have a very small error associated with the lumped parameter assumption. For the worst case of uninsulated ¾ in. (19.05 mm) diameter pipes at 120°F (49°C) in air at 68°F (20°C), the Biot number was 0.106. Lower pipe temperatures, insulation, and ½ in. (38.1 mm) diameter pipe all reduce the Biot number below

TABLE 1: IMPACT OF COPPER EMISSIVITY ON OVERALL HEAT TRANSFER COEFFICIENT

ε	Root Mean Square Error Between Measured and Calculated UA	Average Error Between Measured and Calculated UA
0.5	0.146	5.77%
0.6	0.101	4.57%
0.7	0.167	7.69%

0.1. The thermal mass of the insulation was neglected because it is very small compared to the thermal mass of the water and pipe. Heat loss through fittings is also neglected because the surface area of all the fittings in the distribution system was calculated to be less than 1% of the pipes' surface area.

For each distribution system, a full year was modeled. This allows realistic annual draw profiles to be simulated.

BENCHMARK DISTRIBUTION SYSTEM

The prototypical distribution system modeled is based on the Building America program benchmark home [12], which reflects typical construction during the mid-1990s and serves as a baseline for model comparisons. The prototypical distribution system used in the benchmark home is based on a study of California homes that was performed to determine typical distribution system layouts for several homes of different sizes [13]. The layout considered in this analysis is designed for a one-story, slab-on-grade, 2010-ft^2 (187-m^2), three-bedroom two-bathroom home (see Figure 1). The distribution system is a trunk-and-branch configuration (see Figure 2) consisting of uninsulated copper piping where the water heater and the first 10 ft (3.05 m) of pipe are in an unconditioned garage. The Building America Benchmark calls for the water heater to be located in conditioned space, so scenarios of locating the water heater and part of the distribution system in both conditioned and unconditioned spaces were modeled.

While only one distribution system is considered in the analysis, many distribution system layouts are possible. Distribution system layouts vary significantly depending on the floor plan of the home and where the water heater. Additionally, in each home different distribution system layouts (such as a home run system), whether the distribution system is located in conditioned or unconditioned space, and the inclusion of a recirculation loop will change the energy use when compared to a trunk and branch configuration. While this layout used here is considered to be prototypical, the aforementioned factors mean the results of this study cannot be extrapolated to all homes.

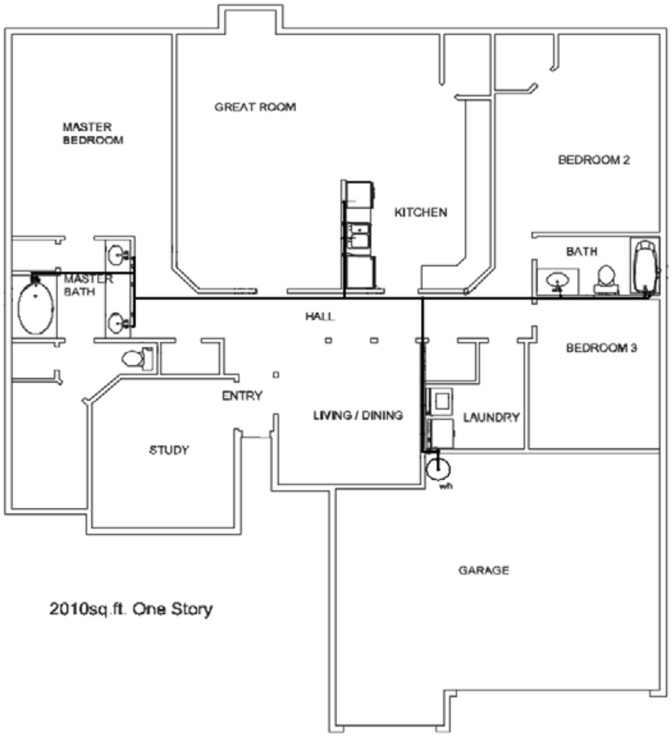

FIGURE 1: DISTRIBUTION SYSTEM OF THE BENCHMARK HOME

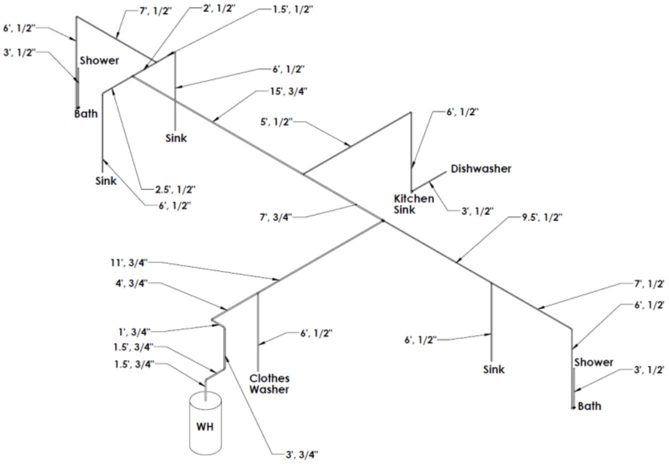

FIGURE 2: ISOMETRIC DRAWING OF THE DISTRIBUTION SYSTEM

Occupant behavior has a significant impact on the overall losses in a DHW distribution system: clustered events have less heat loss than spread-out events as the pipes have less time to cool to the ambient temperature. To capture the effects of occupant behavior on the distribution system, the Domestic Hot Water Event Schedule Generator was used [14]. This tool uses past surveys of homes to determine the probability of hot water events associated with various end uses (sinks, showers, baths, and appliances), then generates a full year of discrete events for each fixture based on the probability distribution (see Figure 3). Figure 4 shows the distribution of the duration of the hot water

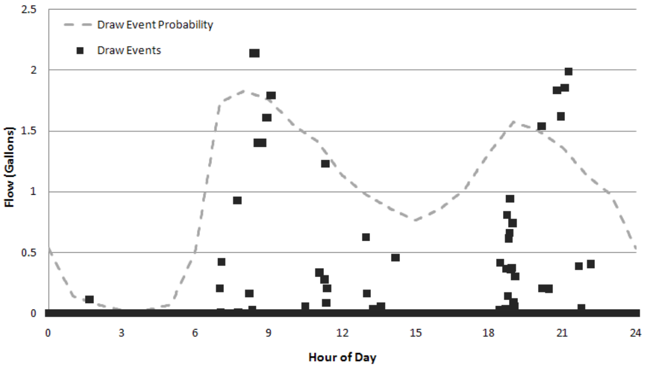

FIGURE 3: A SAMPLE DAY DRAW PROFILE AND ASSOCIATED PROBABILITY DISTRIBUTION

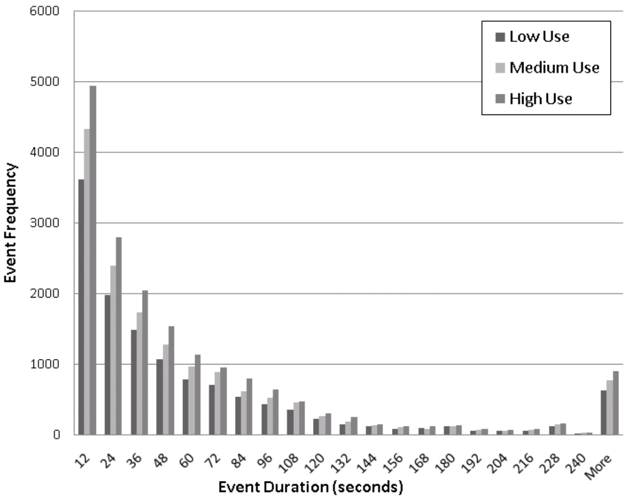

FIGURE 4: HISTOGRAM OF EVENT DURATION FOR ALL DRAW PROFILES

events, with the highest frequency of events having short durations and lower frequency as the duration increases. Figure 5 shows the distribution of event flow rates for all events, with an average flow rate of about 1 gpm (3.78 lpm). While Figure 5 shows the distribution of flow rates for all events, each end use has its own probability distribution.

Another feature of the DHW Event Schedule Generator is that the events are more realistic if a shorter minimum duration is specified. As an example, consider an occupant using a sink for 10 seconds. If a minimum duration of 1 minute is specified, the volume drawn during this 10 second event will be spread out over 1 minute, resulting in a flow rate that is one sixth the actual event flow rate. This has two impacts on the calculation of distribution losses: the lower flow rate yields a lower heat transfer coefficient calculated for the inner surface of the pipe and the flow is modeled to have ended 50 seconds later than the actual event. This results in higher temperatures of the pipe and its entrained water at the end of the 1 minute draw than it would be for the ten second event. For this study, draw profiles with a 6 second minimum duration were used to capture actual occupant sink use. These are small enough to capture realistic hot water use, especially during sink draws, while having a reasonable run time in the distribution system model. It was also found that 6 second draw profiles show good agreement

TABLE 2: DRAW VOLUMES FOR DIFFERENT SIX SECOND DRAW PROFILES IN GAL/DAY (L/DAY)

	Low Use	Medium Use	High Use
Bath 1	2.92 (11.1)	3.76 (14.2)	4.67 (17.7)
Bath 2	1.44 (5.45)	1.23 (4.66)	0.98 (3.71)
Clothes Washer	12.3 (46.6)	15.1 (57.2)	16.7 (63.2)
Dishwasher	4.12 (15.6)	4.98 (18.9)	5.71 (21.6)
Kitchen Sink	11.3 (42.8)	13.2 (50.5)	15.8 (59.8)
Sink 2	1.63 (6.17)	1.74 (6.59)	2.18 (8.25)
Sink 3	1.53 (5.79)	2.11 (7.99)	2.14 (8.10)
Sink 4	1.61 (6.09)	2.14 (8.10)	2.41 (9.12)
Shower 1	14.4 (54.5)	15.1 (57.2)	18.2 (68.9)
Shower 2	3.71 (14.0)	5.56 (21.0)	6.19 (23.4)
TOTAL	**55.0 (208)**	**64.9 (246)**	**75.0 (284)**

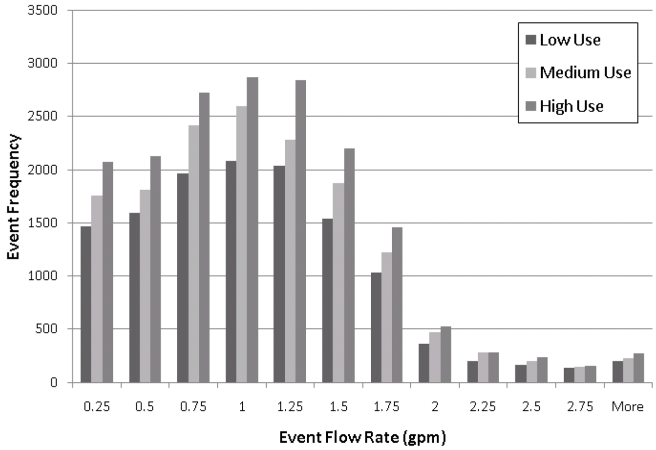

FIGURE 5: HISTOGRAM OF EVENT FLOW RATE FOR ALL DRAW PROFILES

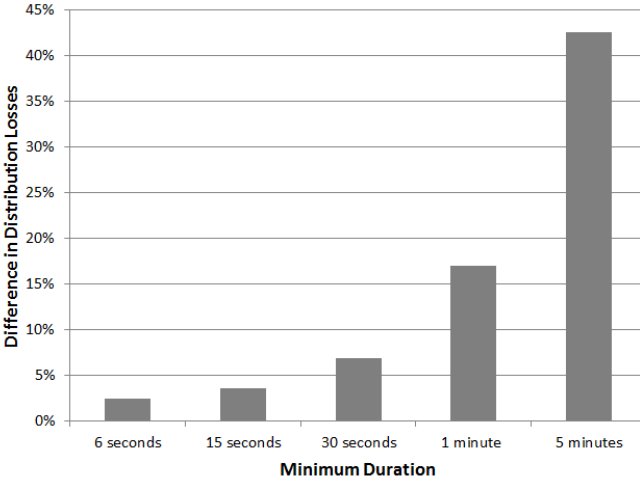

FIGURE 6: COMPARISON OF THE DISTRIBUTION LOSSES TO A ONE SECOND HIGH USE DRAW PROFILE

with 1 second draw profiles in terms of the distribution losses (see Figure 6).

This model also takes into account some event clustering for each water end use, as well as differences in weekday use vs. weekend use. It also includes two separate 1 week vacation periods. Any time step size can be used and multiple events going to different end uses can occur simultaneously. Three draw profiles representing low, medium, and high use households (Table 2) were modeled to determine the impact of DHW use on the thermal distribution losses.

Two types of hot water draws were considered for this model. For sinks, showers, and baths, most occupants will wait until a minimum "useful" temperature is reached before actually using any hot water. To model this, any water drawn below a minimum useful temperature of 105°F (40.6°C) was considered to be wasted. This wasted water is also a distribution system loss because the energy spent on heating the water from mains temperature to the water heater set point is completely lost during this "warm-up" period. For appliances (dishwashers and clothes washers), any temperature of water drawn was considered useful. A third potential use option, a so called "Btu draw" where the final temperature of all the water drawn must be above the useful temperature is possible for bath draws depending on occupant behavior, but was not modeled in this study. When analyzing the results, useful and wasted hot water draws are disaggregated and the energy associated with the wasted hot water is included in the overall distribution system losses.

VALIDATION ANALYSIS

The predictions of the TRNSYS model were compared against measured data. Past work had measured the heat loss for copper and PEX-AL-PEX piping (PEX-AL-PEX consists of a thin layer of aluminum sandwiched between two layers of PEX) [5], with and without insulation, under typical DHW distribution system conditions. Tests were performed on long segments (over 80 ft or 24.4 m) of ½ in. (12.7 mm) and ¾ in. (19.05 mm) pipe under controlled laboratory conditions for flow rates between 0 and 5 gpm (0 to 18.9 lpm). The overall heat transfer coefficient was calculated while hot water was being delivered and while the pipes cooled between draws. For the insulated pipes, tests were run with ½ in. (12.7 mm) and ¾ in. (19.05 mm) thick insulation for both ½ in. (12.7 mm) and ¾ in. (19.05 mm) diameter pipes using insulation with a rated R/in. value of 3.97 $ft^2 \cdot hr \cdot °F/Btu \cdot in.$ (0.275 $m^2 \cdot K/W \cdot cm$). Some unique flow phenomena, such as slip flow and stratified flow, were observed during this testing for flow rates in the transitional flow regime. These phenomena are not accounted for in the developed model.

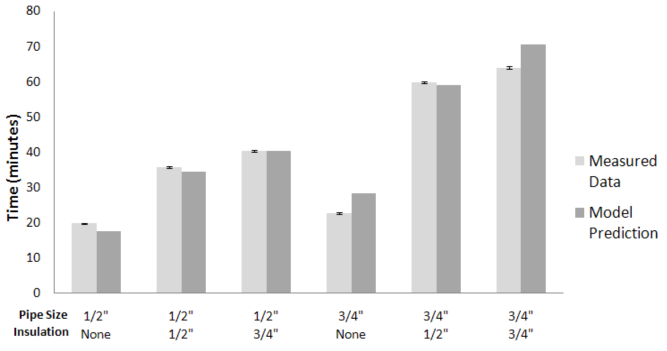

FIGURE 7: TIME FOR COPPER PIPES TO COOL FROM 135°F (57.2 °C) TO 105 °F (40.6 °C) IN 67.5°F AMBIENT AIR

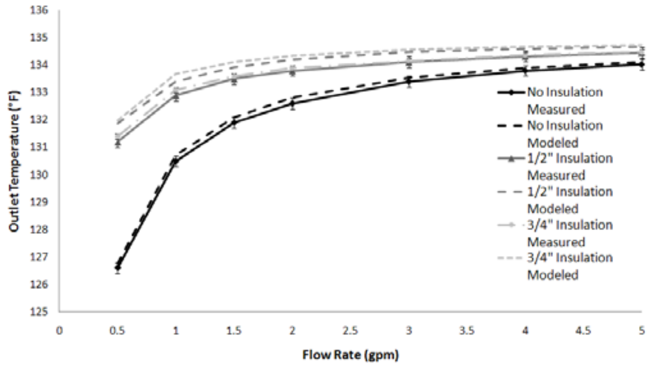

FIGURE 8: TEMPERATURE DROP IN 100 FT (30.5 m) OF ½ in (12.7 mm) DIAMETER COPPER PIPE WITH A 135°F (57.2°C) INLET TEMPERATURE AND 67.5°F (19.7°C) AMBIENT AIR

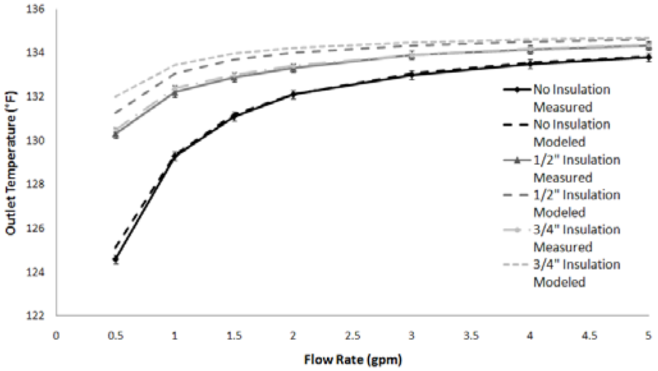

FIGURE 9: TEMPERATURE DROP IN 100 FT (30.5 m) OF ¾ in. (19.05 mm) DIAMETER COPPER PIPE WITH A 135°F (57.2°C) INLET TEMPERATURE AND 67.5°F (19.7°C) AMBIENT AIR

The results of comparing the model predictions against measured data are presented in Figures 7, 8, and 9. In general, the model more closely matches the test data at higher flow rates. At any flow rate, insulation causes a larger discrepancy than for the uninsulated case. This discrepancy increases as the thickness of the insulation increases. The larger discrepancies between the model and measured data at lower flow rates for any level of insulation occur because of the unique flow phenomena, which would be very difficult to capture in a model. The discrepancies caused by the addition of insulation

TABLE 3: COMPARISON OF DISTRIBUTION LOSSES PREDICTED BY THE TRNSYS MODEL AND HWSIM TOOL

	HWSIM	TRNSYS	Difference
Hot Water Use In Gal/Day (L/Day)	71.1 (269)	73.4 (228)	3.24%
Hot Water Waste in Gal/Day (L/Day)	10.1 (38.2)	10.7 (40.5)	5.55%
Distribution System Losses in kBtu/Day (kWh/day)	6.99 (2.05)	6.98 (2.04)	0.11%

could be related to nonuniform properties or underperformance of the insulation. Additionally, it is assumed that the surrounding air was still during testing and modeling, but airflow around the insulation during testing could cause a discrepancy between the measured data and the model predictions.

A comparative analysis was also performed to compare the performance of the model to the DHW distribution system modeling tool HWSIM. For this analysis, the benchmark distribution system was modeled using the HWSIM framework with a realistic week of draw profiles. However, the TRNSYS model and the HWSIM tool treat draw profiles somewhat differently: draw profiles in the TRNSYS model are assumed to include hot water waste for mixed events and those in the HWSIM tool do not. The TRNSYS draw profiles are therefore specified as the draw by the water heater, while the HWSIM draw profiles are specified as the draw of hot water at the end use. This complicates a direct comparison. In an attempt to compensate for this difference, additional distribution system losses and hot water use were added to the TRNSYS model results during post-processing based on the losses observed during the useful portion of minimum temperature events. This made the comparison more direct but led to an overprediction of the losses and hot water use. The results of this comparison and the difference between the HWSIM prediction and the postprocessed TRNSYS model are shown in Table 3. All other draw profiles used for modeling in TRNSYS included hot water waste, so no postprocessing of this nature was required for any other simulations. To minimize the differences between the two models on simulations of a full year of draw profiles (HWSIM models one week for each month of the year while the TRNSYS model considers every day of a full year), the ambient and mains temperature for both models were kept constant year round.

BENCHMARK DISTRIBUTION SYSTEM RESULTS

To examine the distribution losses in U.S. homes, the benchmark distribution system was modeled for homes located in various US climate zones. In particular, the benchmark home was simulated in five of the climate zones referenced in the Building America Program [15], which were chosen because they encompass the majority of the U.S. population. The five selected locations represent the cold (Chicago, Illinois), mixed-humid (Atlanta, Georgia), hot-humid (Houston, Texas), hot-dry (Phoenix, Arizona), and marine (Seattle, Washington) climates. Benchmark homes with the same floor plan as used for the prototypical distribution system were first simulated in a separate building modeling program, BEopt [16]. BEopt computed hourly indoor ambient air temperature, unconditioned garage temperature, and mains temperature, which were used as inputs to the TRNSYS model. Modeling the homes separately from the distribution system substantially reduces the simulation run time required to analyze the distribution system, although it would be possible to also model the homes in the TRNSYS environment with the distribution system to capture the interactive effects of the distribution system with the building thermal load (in warm climates, the distribution system would likely lead to an additional cooling load, while in cold climates it would lead to a reduction in the heating load). In all climates, the water heater was modeled as a 40-gal (151-L), 0.59 energy factor (EF) gas storage water heater set to 120°F (48.9°C). A multinode water heater model was used to capture any potential stratification in the tank.

Model parameters for this water heater were derived from the standard rating test results [17]. The hot water use was modeled using the previously described DHW event generator tool with a minimum event duration of 6 seconds and the draw characteristics shown in Table 2.

The benchmark homes show significant differences in the distribution loss for homes in different climates and with different DHW usage (Figures 10 and 11). The distribution losses in the most extreme case of a high use home in a cold climate are twice large as those in a low use home in a hot climate. In most climates, the average difference is 30% in the

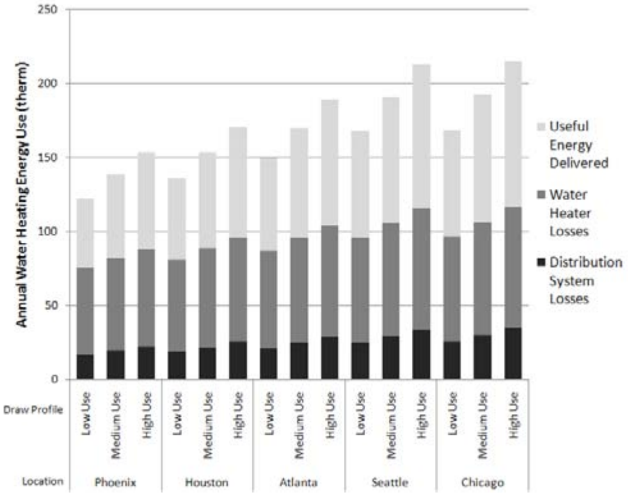

FIGURE 10: WATER HEATER ENERGY CONSUMPTION FOR THE BENCHMARK HOME DISAGGREGATED INTO USEFUL ENERGY AND WASTE

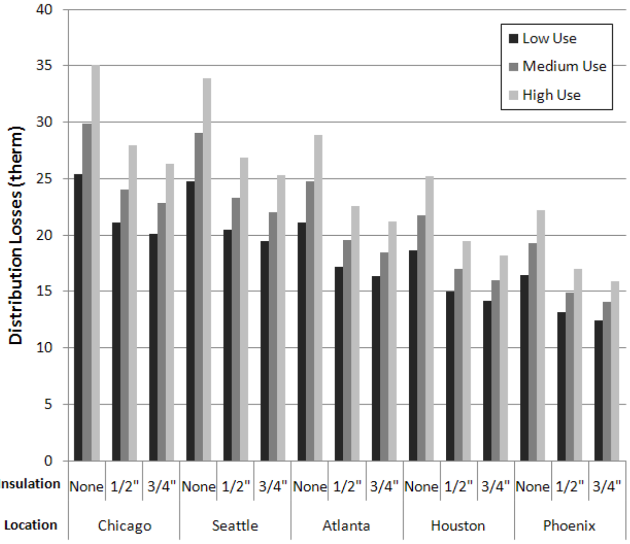

FIGURE 11: DISTRIBUTION THERMAL LOSSES FOR THE BENCHMARK HOME WITH A WATER HEATER LOCATED IN CONDITIONED SPACE

distribution losses for each home between the low use and high use cases.

To determine the impact of potential distribution system improvements, a full parametric study was carried out using different draw profiles, climate zones, water heater locations, and distribution system insulation levels to determine the site energy consumption for all cases. Due to the exhaustive nature of this parametric analysis, only selected results are presented here. The energy consumed by the water heater is significantly influenced by placing it in unconditioned space, but because only the first 10 ft (3.05 m) of the distribution system was located in unconditioned space, the difference between the distribution thermal losses for a water heater in conditioned space vs. unconditioned space was fairly modest: less than 3% or 1 therm (29.3 kWh) in the most extreme case. In hot climates (Phoenix and Houston), placing this piping in unconditioned space reduced the overall distribution system losses by as much as 0.5 therm (14.65 kWh) because of the high ambient air temperatures in the unconditioned space. Adding insulation to the distribution system can reduce the distribution losses by as much as 20%, but increasing the insulation thickness from ½ in. (12.7 mm) to ¾ in. (19.05 mm) only slightly further reduces the distribution losses. This 20% decrease reduces the whole house energy consumption by only 7.11 therms (208 kWh) if ½ in. (12.7 mm) insulation is used and by 8.68 therms (254 kWh) if ¾ in. (19.05 mm) insulation is used in a home in a cold climate, assuming none of the distribution losses affect the home's heating load. In reality, the actual reduction in energy consumption will likely be less.

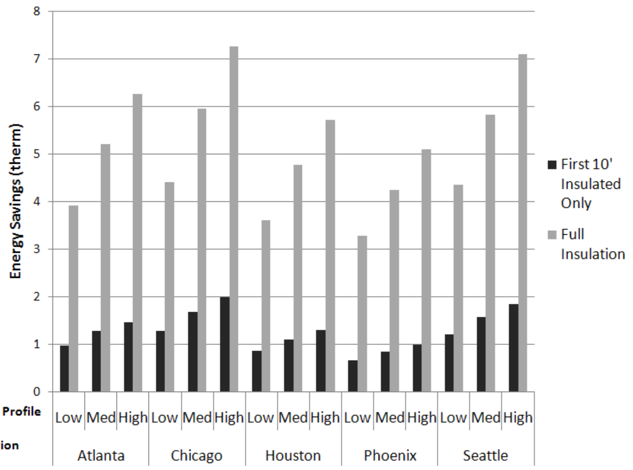

FIGURE 12: IMPACT OF INSULATING ONLY PIPES IN UNCONDITIONED SPACE

In addition to examining insulating the full distribution system, the impact of insulating just the portion in unconditioned space was examined. This should be the most important area to insulate because of the higher temperature difference between the pipe and the ambient air, especially in cold climates. This section also has all draws and the highest temperature water running through it. Insulating this section provides a large benefit, saving as much as 30% of the energy that could be saved from insulating the full distribution system for cold climate homes in the case of a low use home (see Figure 12). Even for homes in hot climates, at least 20% of the savings associated with insulating the distribution system could be achieved by insulating this section, which makes up just 8% of the distribution system. This is consistent with recommendations for commercial buildings [18] that the first 8 ft (2.44 m) of pipe always be insulated for any water heater. This recommendation is sometimes made for residential buildings [19], but it is not universally recommended [20].

To determine the cost effectiveness of adding insulation, the simple payback period was calculated for the benchmark homes. Cost estimates for pipe insulation [21] average about \$1.90/ft (\$6.23/m) for ½ in. (12.7 mm) insulation and \$3.30/ft (\$10.80/m) for ¾ in. (19.05 mm) insulation. For the payback calculation, the distribution system loss's impact on home heating and cooling load was not counted, so a more detailed analysis would be required to fully explore the payback associated with adding insulation. To determine the monetary value of the energy savings the most current statewide average for the cost of gas in each location was used (see Table 4) [22].

TABLE 4: ENERGY COSTS AT BENCHMARK HOME LOCATIONS IN \$/THERM (¢/kWh)

	Electricity	**Gas**
Atlanta	2.97 (10.14)	1.48 (5.04)
Chicago	3.57 (12.20)	0.86 (2.93)
Houston	3.41 (11.63)	0.95 (3.26)
Phoenix	3.21 (10.97)	1.55 (5.29)
Seattle	2.42 (8.26)	1.14 (3.91)

In the most cost effective case of adding ½ in. (12.7 mm) insulation to the distribution system of a high use home in Atlanta, the simple payback is estimated to be 26 years. Adding insulation to just the section of piping in unconditioned space appeared much more cost effective, with simple paybacks less than 10 years possible for homes in colder climates.

DISTRIBUTION LOSSES FOR SOLAR WATER HEATERS

The distribution losses for a home using a solar water heater were also evaluated using the developed model. With a solar water heater, the storage tank temperature varies as energy is gathered from the collector and stored in the tank, further increasing the distribution losses. Two solar water heating systems were modeled: a larger system for colder climates (Chicago and Seattle), and a smaller system for warmer cities (Houston, Phoenix, and Atlanta) as shown in Table 5. For all systems, an indirect, forced circulation system using a 50/50 mix of glycol and water was used and the collector was oriented due south with a slope equal to latitude. The piping between the collector and the storage tank was assumed to be 50 ft (15.24 m) long with ¾-in. (19.05-mm) insulation based on solar water heating system certification guidelines [8]. The storage tank temperature was set to 120°F (48.9°C) and the collector stopped circulating if the tank temperature exceeded 140°F (60°C) as specified by the manufacturer of this system. In both cases, a single tank with R-16 insulation and a backup electric heating element with a maximum output of 4.5 kW (15,355 Btu/h) was used. The model parameter for the insulation of this storage tank was derived from past work on a solar water heater with similar insulation [23]. Other model parameters, such as heat exchanger size, were derived from manufacturer specifications. A multinode tank model was also used for this case to capture stratification (which is much more important than for a gas storage water heater). The same six second high, medium and low draw profiles previously presented were used for this analysis. The impact of insulation on the distribution system losses was also examined.

TABLE 5: FEATURES OF SOLAR WATER HEATING SYSTEM FOR HOT AND COLD CLIMATES

	Cold Climates	Warm Climates
Collector Area	50.7 ft^2 (4.71 m^2)	39.8 ft^2 (3.70 m^2
Storage Tank Volume	80 gallons (303 L)	50 gallons (189 L)
Rated Solar Energy Factor	2.1	1.8

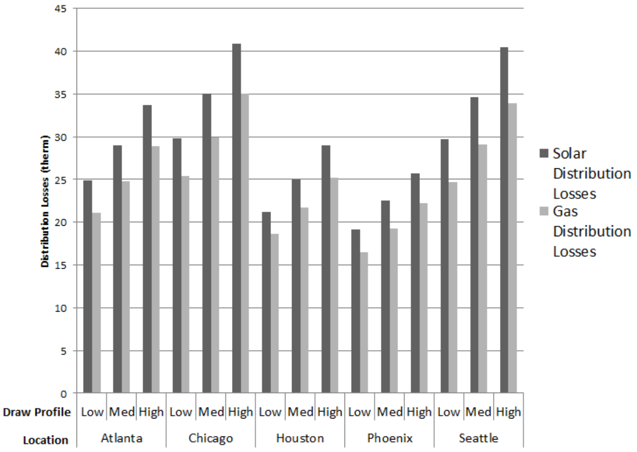

FIGURE 13: COMPARISON OF THE DISTRIBUTION SYSTEM LOSSES WITH GAS AND SOLAR WATER HEATERS IN CONDITIONED SPACE WITH NO INSULATION

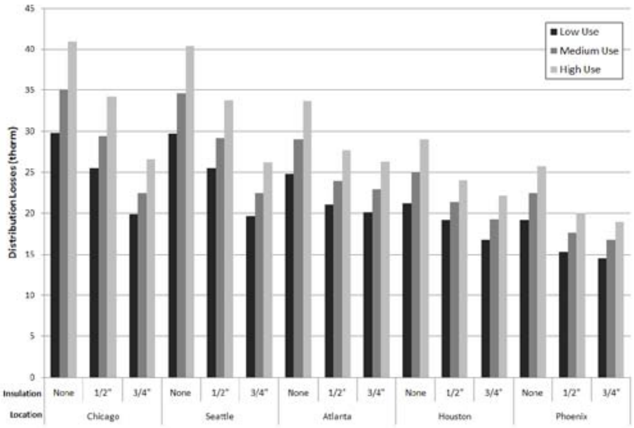

FIGURE 14: IMPACT OF INSULATION ON DISTRIBUTION SYSTEM LOSSES FOR HOMES WITH A SOLAR WATER HEATER IN CONDITIONED SPACE

The distribution system losses were found to be larger in all cases with a solar water heater (see Figure 13). In the most extreme case in of a high use home in Seattle, the losses were as much as 16% larger. The largest additional loss from the distribution system was 6.52 therms (191 kWh) more than the benchmark home for a high use home with uninsulated pipes in Seattle. The impact of adding insulation to the distribution system was similar to what was seen in the case of a gas water heater. There was an average 25% difference on the distribution losses between high and low use homes across the five climates (see Figure 14). There were also significant differences between the distribution losses, depending on climate. The distribution losses in Phoenix are about 35% lower than those in Chicago.

The impact of insulation on the piping between the solar collector and the water heater was also examined (see Figure 15). Standard practice is to include some insulation on this loop. For a solar water heating system to be certified in the United States, the collector loop must be insulated by insulation

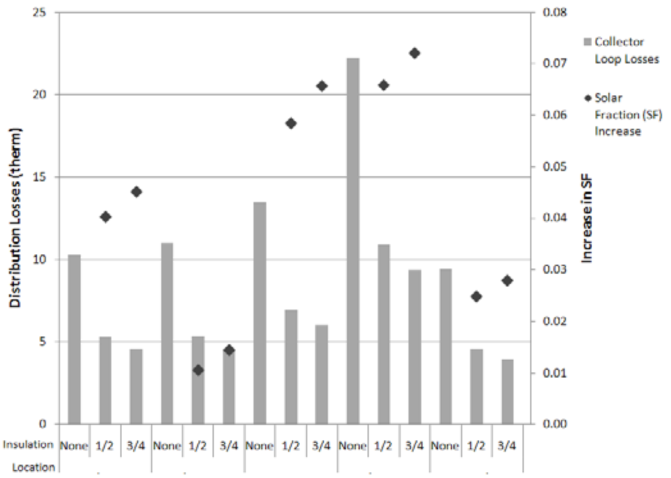

FIGURE 15: IMPACT OF COLLECTOR LOOP INSULATION FOR A MEDIUM USE HOME WITH THE WATER HEATER IN CONDITIONED SPACE

with a minimum R-value of 2.6 $ft^2 \cdot hr \cdot °F/Btu$ (0.46 $m^2 \cdot K/W$) [8]. Not insulating this loop seriously affects the performance of the solar water heater. A well-insulated loop can increase the solar fraction of the water heater by as much as 0.07, reducing the energy consumption of the water heater by 4.8 therms/yr (142 kWh/yr).

An economic analysis was also performed to determine the simple payback of adding insulation to the distribution system for a home with a solar water heater. In this case, the backup heat source is electric, so the most recent state average electricity prices were used for each home [24]. While the payback period is still always above 18 years, it is generally better than for homes using a gas water heater. This is due to both the increased temperature of water flowing through the distribution system and the higher cost of electricity. This can be generalized to other water heating options as well: insulating the DHW distribution system will be more attractive economically if the water heater is set to a higher temperature or if fuel costs increase. In this case, adding insulation to the DHW distribution system piping is more attractive than for homes with a gas water heater.

SUMMARY AND CONCLUSIONS

A modeling tool for analyzing DHW distribution systems was developed. The predictions of the model were found to reasonably match laboratory data for the losses in distribution systems as well as other distribution system models. Some discrepancies did occur between lab testing and the model, but can be attributed to flow phenomena too complex to properly model, possible underperformance of pipe insulation, and potentially moving air in the lab during testing. The TRNSYS model does not have the flexibility of other competing models in terms of quickly testing alternate distribution system layouts, but it does allow the distribution losses to be determined for a variety of water heater types This model also allows a full unique year of draws to be examined and uses a previously existing probabilistic draw profile generator to model realistic occupant behavior.

This model was applied to a benchmark distribution system for homes with a standard gas water heater and a solar water heater. For both cases the losses of the distribution system were examined under several possible sets of conditions that may be present in a home in several climates, including distribution systems with and without insulation, variable occupant behavior in terms of annual draw volume, and locating the water heater in conditioned or unconditioned space. The distribution losses varied significantly depending on all these parameters; the worst-performing system lost more than three times the energy as the best.

The impact of insulation was examined in detail and found to have a significant impact. Insulating the first few feet of the distribution system, particularly in homes with the water heater in unconditioned spaces, had significant energy savings, in some cases up to 30% of the savings that could be achieved by insulating the entire distribution system. Insulating the collector loops in the case of solar water heaters also significantly increased the performance of the solar water heater. The simple payback was examined for distribution system insulation and was found to be rather long for insulating the full distribution system, but more reasonable for just insulating the first few feet of the distribution system. Further modeling efforts combining the distribution losses with a whole home building model so that the interaction of the two systems could be fully explored would be required to verify the calculated payback periods.

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