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Modelica Household Dishwater Model with External Heat Loop

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Dishwasher Modelica Model Analysis with an External Heat Loop

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ABSTRACT

Research efforts addressing large U.S. consumers can generate impactful reductions on the global energy picture. 41% of U.S. energy consumption is from buildings, 22% residential versus 19% commercial. Household appliances combine to 27%, the second largest residential site energy usage. With many appliances converting electricity to heat and generating waste heat, the authors propose energy reduction through thermal integration of all major appliances. The novel approach will require adding equipment and modifications to existing appliances for thermal sharing. A Modelica model is built for each appliance and simulated to quantify energy savings. The dishwasher is the first appliance investigated by installing a heat exchanger to heat the process water via an external hot water loop instead of the electric calrod heater. The traditional function is first captured in the model and the predicted water sump temperature is compared to available experimental data from the manufacturer. After tuning, the same model is run with a fixed temperature heat loop and any electrical savings is reported. After tuning, the dishwasher model of the traditional system shows an agreement within ±5% for most water sump temperatures. 0.564 kWh of energy is consumed by the calrod heater during the traditional mode versus 0.434 kWh during the heat loop input, a 23% reduction in electrical energy.

1. INTRODUCTION

Global energy demands are outpacing the population growth as developing nations advance the standard of living to larger percentages of the population. The annual growth rate of global energy and population in 1990-2000 was 1.3% and 1.4%, respectively, while during the next 10 years, in 2000-2010, this increased to 2.8% and decreased to 1.0%, respectively (Buildings Energy Data Book, 2011). At this high rate of energy growth from the fastest growing population sectors, the U.S. has fallen to second place behind China as the largest consumer of energy in the world, with less than a quarter of the population. Reducing the energy consumption of the US provides an effective mechanism to achieve significant reductions to world energy consumption. The U.S. Department of Energy breaks down the energy picture across four sectors: transportation, commercial, residential and industrial. The building sector, which combines both commercial and residential, is the largest consumer of the U.S. total. In broader terms, U.S. buildings, on their own, account for 7% of global primary energy consumption. A further look into the energy consumption of the building sector indicates 41 EJ (39 quads) of primary energy provided only 21 EJ (20 quads) of site energy for an energy loss of 49%. Reducing site electricity will magnify reductions on annual building energy consumption by demanding less primary energy for electricity generation. Addressing residential energy consumption for the building sector is of greater relative importance due to residential buildings accounting for a slightly larger consumption than the commercial buildings, 22% versus 19%.

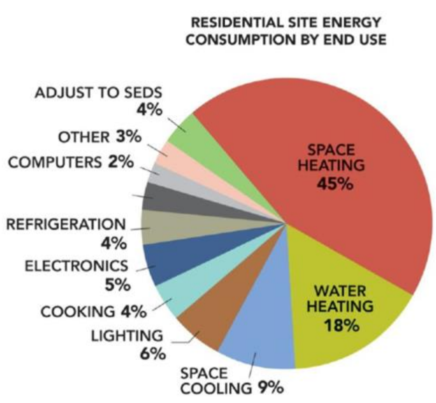

Figure 1: Residential Site Energy Consumption by End Use (Buildings Energy Data Book, 2011)

The second largest percentage of residential, site energy usage is from the household appliances; water heater, refrigerator, wet cleaning (dishwasher, clothes washer and dryer) and cooking equipment at 27% (Table 2.1.5 Buildings Energy Data Book, 2011). A complete breakdown of each end use percentage of total site energy consumption is presented in Figure 1.

Appliance research has mainly been focused only on the appliance itself with some studies on benefits from connection to resources available outside the appliance. Legislation is mentioned as a great mechanism to drive energy reductions in household appliances (Bansal et al., 2011). Federal standards have resulted in significant reductions in appliance energy consumption by forcing the industry to explore and adopt new technology. As one example, the average annual electricity use of U.S. household refrigerators in 1980 of about 1,300 kWh dropped to about 950 kWh in 1990 and then to under 700 kWh by 1992 due to the introduction of new energy efficiency standards in 1990 and 1993 (Meyers *et al.*, 2003). In spite of legislation demanding appliances to complete the same function with fewer resources, manufacturers have been able to increase the capacity of appliances in the same timeframe.

This perspective is referenced in literature, "appliances are optimized to meet standards and not actual use, especially when it comes to energy" (Bansal *et al.*, 2011). The authors point to three experimental studies where the best performance of the appliances tested was at the same conditions as their respective standard. New savings are realized when one considers waste heat streams available from each appliance that is not covered by the standards.

1.1 Energy Saving Methods

An energy savings of 20% over a residual heat drying system is reported from a dishwasher (DW) assisted by sorption (Bansal *et al.*, 2011). The Super Efficient Home Appliances Initiative promotes a DW using a maximum electricity consumption of 295 kWh/year and a maximum water consumption of 16 L/cycle (Bansal *et al.*, 2011). Recommended areas of improvement are adaptive control sensing the soil level, improving the food filter to reduce redepositing, using ECM motors, higher levels of cabinet insulation, and an improved dry cycle (Bansal *et al.*, 2011).

Sense Soil Level

Depending on the level of soil in the dishware, a soil sensor coupled with filtered recirculation can help reduce unnecessary purges of wash water. A prewash will circulate water to remove any locations with large soil levels and accumulate in the DW sump. Here an optical sensor checks the turbidity of the water and determines if a new batch of water is needed to reduce the rate of soil redepositing before proceeding to the main wash. The DW is able to reduce the volume of water used per cycle by adjusting to the type of load.

Reuse Waste Water

As explained previously, Federal standards on DWs regulate both the amount of energy used (including energy required to heat domestic hot water (DHW) volume) and the volume of water consumption. One approach investigated focuses on storing the previous cycle final rinse for the next cycle prewash. Here the DW can reduce the total volume of DHW needed per cycle and thus, reduce the associated energy and water penalty. The approach is effective when assuming that fairly clean water produced at the final rinse can provide useful cleaning water during the highest expected soiled wash step. The concern for redepositing of soils from the previous final rinse is not significant due to the already high expected presence of soils on the dishes. The estimated energy savings from this approach is not quantified.

Alternative Heating Sources

Two different approaches were applied to reduce the electricity consumption by offsetting some or all of the internal resistor heating energy (Persson, 2007). The first explored varying the hot water supply temperature. By increasing the DHW temperature from 49°C (120°F) to 65°C (149°F), the amount of electricity can be reduced by 19%, 0.8 kWh to 0.65 kWh with the entire cycle still using about 1.2 kWh of energy in total. The other approach applied an external water loop as a heat source to the internal water and dishware through a custom designed and built HX. Above loop temperatures of 70°C (158°F), the amount of electricity used plateaus to about 0.1 kWh while around a loop temperature of 50°C (122°F), about 0.6 kWh of electricity is predicted. Both conditions use similar amounts of total energy, combined electrical and thermal, for the entire cycle.

1.2 Approach

One study looked at DWs for waste heat recovery but reported a 13 year payback period (Bansal *et al.*, 2011). A review on technological status of five major residential appliances; RFs, DWs, CWs, CDs and COs identify overall energy use can be reduced by more than, 50%, 17%, 43%, 50%, and 45%, respectively, through several strategies including waste heat recovery and legislative improvements (Bansal *et al.*, 2011).

1.3 Objectives

To properly investigate thermally integrated appliances and provide useful recommendations, a theoretical and comprehensive analysis assessing the impact of thermal resource sharing between residential appliances through Modelica models has been conducted. Sub-models are created for each major appliance capturing its operation when running under the standard, standalone mode. The performance predictions of each appliance model are compared to readily available experimental data collected by the manufacturer for quick verification.

The work culminates in a parametric study on the validated, integrated model by exploring the impact on appliance energy savings with variation in the thermal network temperature and the storage tank. Considerations can be made from multi-family or single-family housing units having different usage levels that are dependent on the respective consumer trends or behaviors from those sectors. The level of energy and operating costs reduced is identified for the respective different input factors to further map the system capabilities.

2. BACKGROUND DISHWASHER CHARACTERISTICS

A quick review of the current state of DWs is provided in this section, which includes the number of units installed, the frequency of usage, the amount of electricity and water used per cycle, and the transient behavior within one sample DW cycle. The controller of the DW is understood by examining the experimental data from the sample cycle along with feedback from the manufacturer. After introducing characteristics that define DWs, research efforts to improve both the electrical and water usage efficiencies are listed to identify the alternative approaches previously investigated.

The market penetration of dishwashers in U.S. households is not as high as other appliances. About 59% or 67.4 million households use a dishwasher (Table HC3.1 RECS, 2009). 65% of U.S. households use DWs accounting for 3.2% of the residential primary energy consumption in 2005 (Bansal *et al.*, 2011). Water savings are obtained over traditional hand washing by recirculating same volume of water to remove soils. A calrod heater provides energy input to water to indirectly heat the dishware and cabinet.

2.1 Usage Frequency

The current Energy Star rating for dishwashers reduced the average, annual number of cycles from 264 to 215 (ENERGY STAR V.6, 2015). 215 cycles per year covers 35% or 23.7 million households (Table HC3.1 RECS, 2009).

2.2 Electrical Consumption

The energy usage of a dishwasher is heavily weighted by the required heating energy to maintain the water temperature at a high temperature of around 50°C (122°F). One study on dishwasher energy usage reports 88% of a dishwasher cycle energy input of 1.05 kWh is used for heating the inlet water, the dishes and cookware, and the physical cabinet of the appliance (Persson, 2007). Another source that does not include the energy required for water heating lists an annual energy consumption of 120 kWh or by including the associated 365 cycles per year, the energy usage per cycle is 0.33 kWh (Table 2.1.16 Buildings Energy Data Book, 2011). When considering Energy Star requirements, a standard size dishwasher cannot use more than 270 kWh per year or 1.26 kWh per cycle with 215 cycles per year (ENERGY STAR V.6, 2015). With 23.7 million households, the total annual energy consumption of a standard, Energy Star dishwasher is 0.023 EJ (0.022 quad).

2.3 Water Consumption

The amount of water used by the dishwasher per cycle is listed in one study at 10.2 liter (2.7 gal) per cycle (Persson, 2007). The current Energy Star requirements for a standard size limit water usage to 13.2 liter (3.5 gal) per cycle (ENERGY STAR V.6, 2015). Minor losses of water volume to the ambient through evaporation and being trapped in the dishwasher on cookware or in the sump for the pump are all neglected. A working water temperature of approximately 50°C (122°F) being maintained by the internal electric heater, and assuming some but minimal losses, result in an estimated drain temperature of 40°C (104°F).

2.4 Cycle Characteristics

A study was conducted on the DW electric heater by developing a mathematical model that captures the variation associated with power input, geometry, and operating strategy (McDonald *et al.*, 1989). During a DW drying cycle the calrod heater is exposed to air, becoming red-hot, reaching temperatures near 1300°F (980°C) (McDonald *et al.*, 1989). As a result, the resistance increases with temperature and the power output of the heater reduces as Equation (1) identifies. Parameters for heaters used by one U.S. DW manufacturer are, 0.135 in nominal diameter, power outputs of 600-800 Watts, and heat fluxes from 14-28 W/in^2 (W/m^2) (McDonald *et al.*, 1989). European DW versions have higher nominal power due to higher supply voltages but with longer lengths, the surface areas are also larger resulting in comparable heat fluxes, 19-39 W/in^2 (W/m^2) (McDonald *et al.*, 1989).

$$\dot{W}_{elec} = \frac{E^2}{R} = \frac{E^2}{R_O[1+\alpha(T-T_O)]} \qquad (1)$$

The water sump temperature and power consumption during a sample DW cycle with a soil sensor is shown in Figure 2. Two different power levels are easily recognized in the graph; one during the water heating periods of the cycle, at approximately 800 W, the second during the drying portion of the cycle when exposed to air, at approximately 500 W. The control of the electric element pulses the power supply to maintain a safe element temperature and prevent any localized temperature extremes, which could result in deformations or damages to the DW tub or cabinet.

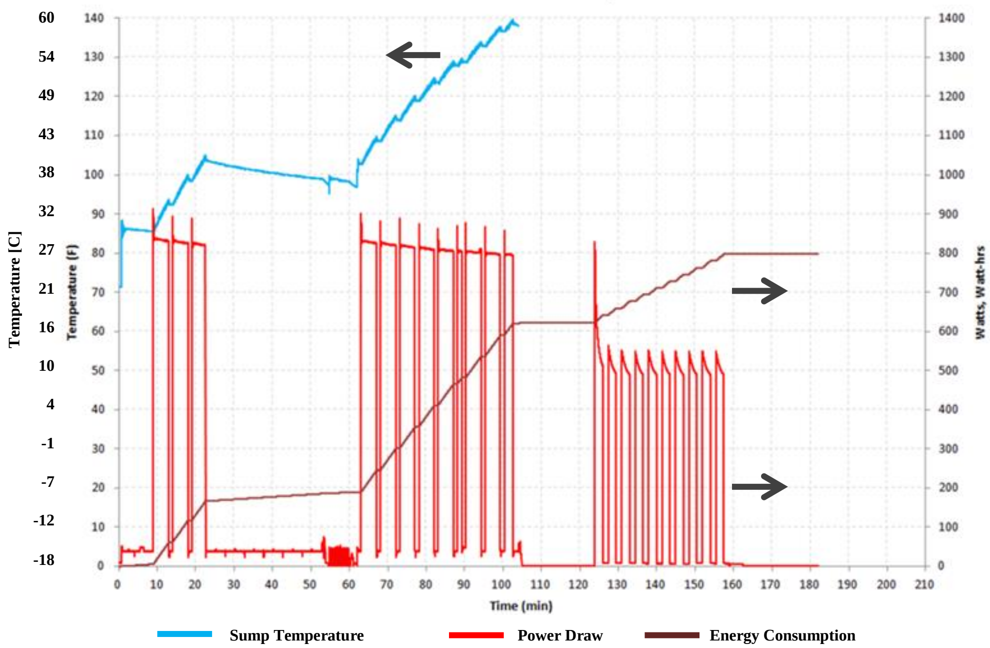

Figure 2: Example DW Sensing Wash Cycle with Sump Temperature, Power Consumption and Accumulated Energy (Whirlpool Corp., 2017)

The thermal capacity for one heater was obtained by closely matching experimental data of temperature versus time. In this study, the best match was found with 145 W-s/K (McDonald *et al.*, 1989). The authors report that for an 800 Watt heater, 619 Watts or 77% are transferred by radiation and the remaining 181 Watts or 23% by convection (McDonald *et al.*, 1989). Three curve-fits provide the heater temperature, convection heat flux, and fraction of heat flux transferred by radiation, all dependent on the surface heat flux (McDonald *et al.*, 1989). Within the sample cycle shown in Figure 2, 0.8 kWh of electricity is consumed, where approximately 0.17 kWh are used for heating the wash water volume from 85°F (29°C) to 105°F (40.5°C), approximately 0.43 kWh for heating the rinse water volume from 98°F (37°C) to 140°F (60°C), and approximately 0.18 kWh for drying the dishware (Whirlpool Corp., 2017). The DOE energy efficiency rating requires accounting for the energy delivered to the DW in the hot water volume, which is not included in the 0.8 kWh cycle total.

The temperature rise in the DW water during the wash and rinse steps can be used to estimate a lumped thermal capacity of the system including the dishware. By taking the total amount of energy delivered during a heating step and dividing by the change in the system or DW water sump temperature, a lumped thermal capacity is found. For a different set of experimental data, ten heating cycles are identified and ten values of thermal capacity are calculated. Figure 3 is a plot of the calculated thermal capacity versus the starting temperature of the water sump.

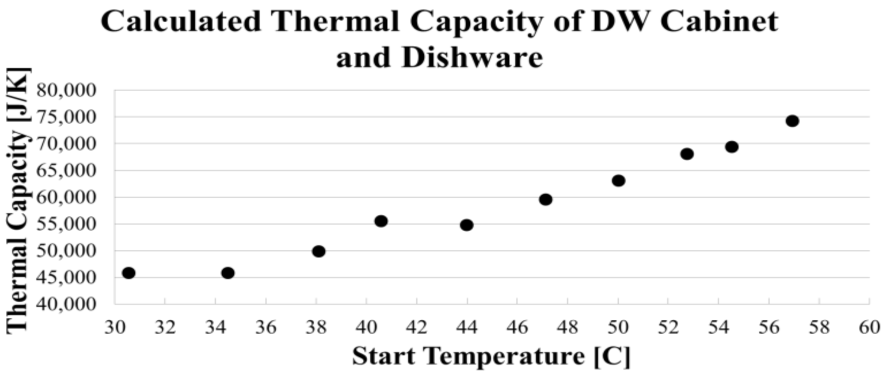

Figure 3: Calculated Thermal Capacity of Entire DW during Heating Cycles as Function of Starting Water Temperature

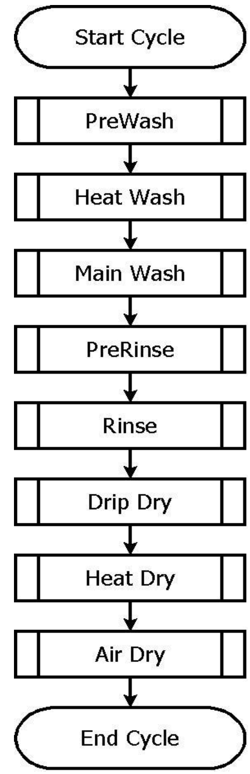

Figure 4: DW Control Sequence Flow Chart

2.5 Controls

The sample DW cycle shown in Figure 2 was referenced to build a sequence of operations that the appliance controller follows. A step was identified by having a unique function for a fixed duration within the cycle. The experimental cycle data obtained from the manufacturer was found to have 8 unique steps possible within one DW cycle, as shown in Figure 4. Depending on the region in the world where the DW is used, some of the steps listed are not used. For example, European DWs do not use a heated dry function and therefore, would skip this step in the cycle.

The prewash step draws the initial volume of DHW for the cycle, circulating around the appliance using one spray arm at a time. An optical sensor checks the turbidity of the water in the sump to decide if a new batch of water is needed before proceeding into the main wash. If the amount of soils removed during the prewash is high, the sump is drained to reduce the rate of soil redepositing on the dishware during the main wash. Next the electric element is energized to heat the water in the sump to the required wash temperature, 40.5°C (105°F). The wash performance is improved at higher temperatures. After reaching the set-point, the DW uses the mechanical action of the spray arms for the main wash by pumping the water. A diverter oscillates the pump outlet to operate one spray arm at a time on each rack. Water reductions required by federal standards have reduced the volume allowed over the whole cycle and not enough volume of water is available to run both spray arms at the same time. The main wash terminates after a timer expires and proceeds into a pre-rinse step. The main wash water is drained and a smaller volume of DHW is drawn to lightly rinse the dishware, removing any soils redeposited from the main wash. Depending on the DW technology for the specific model, this may occur more than once before the rinse step is entered. The electric element is again energized during the rinse step but this time a water sump temperature of 60°C (140°F) is the set-point. One purpose of the high rinse temperature is to raise all the dishware to a high temperature which improves the drying performance by starting the system at elevated temperatures. The rinse water is drained and the DW controller enters the drying steps after a short time delay to let any water drip off the dishes. The electric element is used one last time to accelerate the drying process and runs for a fixed time interval. The last step consists of drying with ambient air assisted by the residual heat remaining in the dishware at the end of rising.

3. TRANSIENT MODELICA MODEL

A model of the major physical components of a traditional DW was developed in Modelica. It captures all features of the water path from filling to washing to draining. A heat exchanger model was added to increase the water temperature with a hot water loop offsetting usage of the electric calrod heater. The model inputs consist of equipment specifications, manufacturer design settings, and cycle experimental data. Custom Modelica controllers were built and implemented in the model.

A DW Modelica model was developed by first identifying and capturing the function of unique steps within one complete dishwashing cycle. Separate, unique steps are defined by characterizing experimental data during one DW cycle over time. The sump water temperature and overall instantaneous power draw is predicted over time. The soil sensing DW cycle shown in Figure 2 is used to generate the flow chart for the DW controller shown in Figure 4. An overall controller is built to simulate all steps of the DW cycle. To properly represent the response of the DW to a cycle controller, the dynamics of the dishware and other components are captured as well. Major parts involved in the DW cycle are the recirculation and drain pumps, the volume of the recirculating water, the cabinet heat loss to the ambient, and the thermal capacity of the dishware.

3.1 Modelica Components

To capture all major parts that interact during a DW cycle, the Modelica model uses TIL prebuilt component models (TIL Suite 2016). The diagram view of the finalized DW Modelica model is shown in Figure 5. Three simple pump models represent the circulation pump, the drain pump, and the heat loop pump for external heating feature. Three tube models represent the DW water interacting with the electric element, the thermal capacity of the dishware, and ambient heat losses through the cabinet. A simple, single-node water volume model is connected to account for the mass of water circulating inside the DW during a cycle. Three different type of connections are made between the various component models; fluid, thermal or control. Fluid connections communicate mass flow rate and two fluid properties, usually pressure and enthalpy, for the working fluid selected. In this application, all fluid connections are water. Future iterations could explore fluid types other than water as the heat loop. Thermal connections communicate temperature and heat transfer rate. Control connections are custom made and can communicate numerical values as volumetric flow rate to pumps or heating level to electric elements, or Boolean variables for basic ON/OFF (1/0) control.

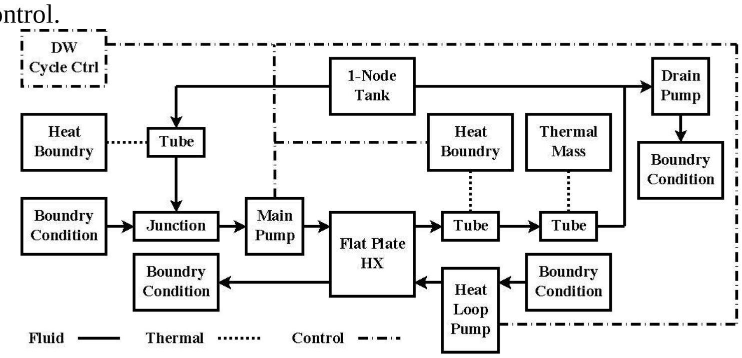

Figure 5: Dishwasher Modelica Model Diagram with Controller

3.2 External Connection

The boundary conditions used in the diagram shown in Figure 5, are replaced with the external port connections shown in Figure 6. The DW external model reduces the available inputs for the user to only the sump volume to be modified.

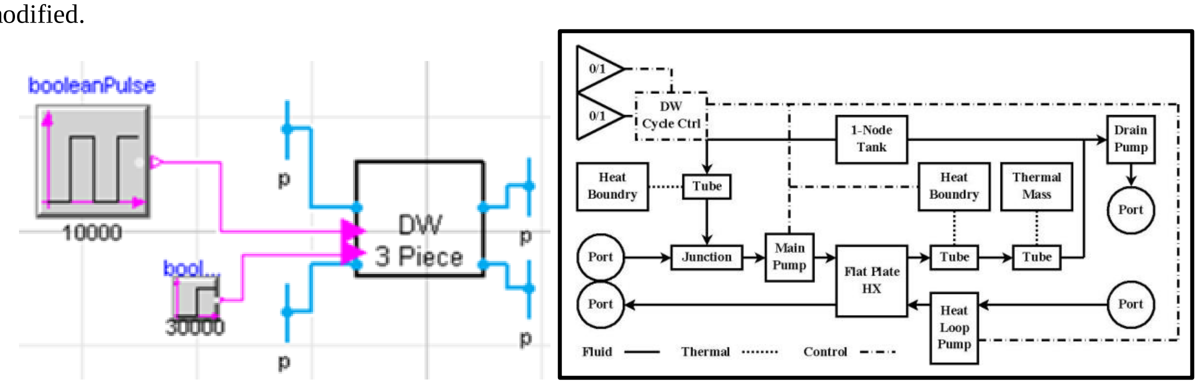

Figure 6: Boundary Conditions for DW Modelica Model

3.3 Step Controllers

The three identified major step controllers are the fill and drain, timer, and temperature. For compatibility with the DW Modelica components, the timer and temperature basic controllers are embedded into a wash step and a heating step controller.

Fill and Drain Control

The filling and draining steps of the DW are captured within the same controller. In the model, the drain pump results in a draw of DHW into the DW at an equal volume. The drain flow rate is set by quickly charging the assumed volume of water used for a step in the DW cycle. The first controller built was the drain/fill.

Timer Control

The subcomponent to control any timed steps during a cycle accepts two Boolean inputs, has an internally modifiable timer, and generates an output signals. The Modelica icon of the timer and the parameter window to enter the duration is shown in Figure 7. Of the two inputs, the first initiates the controller to start the output while the second input either resets the controller to an OFF state from the END state or overrides the controller by interrupting the timer and ending the controller output independently of the timer. Of the two outputs, the first provides a status value that corresponds to the state of the controller: 0 – controller is off and waiting for a start signal, 1 – the controller is active and waiting for the timer to lapse, and 2 – the controller timer has expired and the step has been completed.

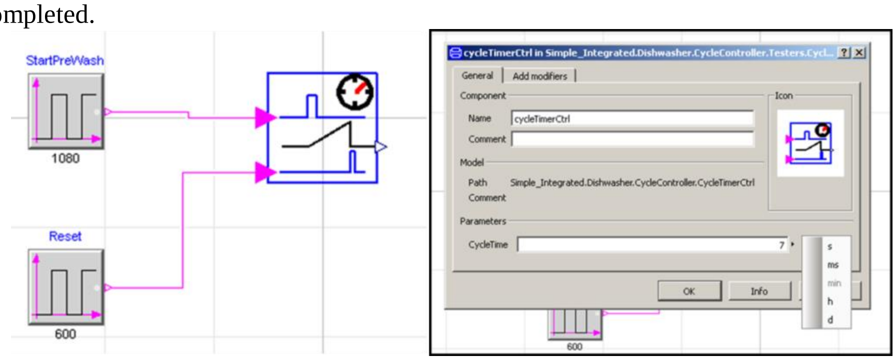

Figure 7: DW Modelica Diagram and Parameter Window for the Timer Controller

Wash Step Control

A wash step controller is built around the completed timer controller that generates an ON signal for the main pump in the appliance to simulate the water circulation from the sump to the spray arms. The controller is active until the input time is elapsed or a reset signal is received. The controller can applied for different steps in a DW cycle to capture the required durations of main pump operation during washing or rinsing. The wash step controller also passes out the timer status to monitor the wash step status externally.

Temperature Control

A second subcomponent controls any heating steps required during the overall dishwashing cycle. The overall structure is very similar to the timer step controller but instead of a timer setting, it has a temperature setting. Two parameters can be varied at the calling level of the subcomponent; a goal temperature and a delta T overshoot on the goal. The Modelica diagram and the input window can be seen in Figure 8.

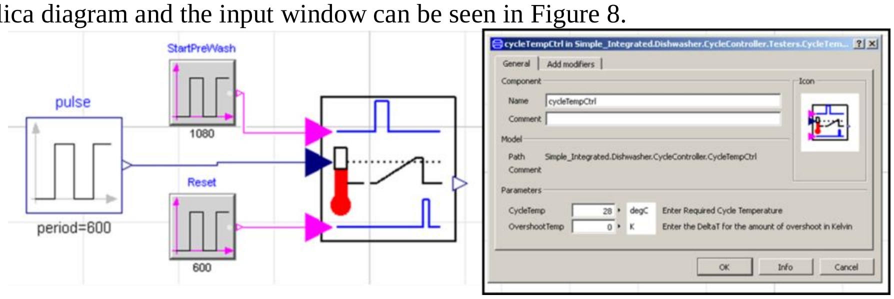

Figure 8: DW Modelica Diagram and Parameter Window for the Temperature Controller

Heat Step Control

A heating step controller is built around the completed temperature controller that generates an ON signal for the main pump and the electric heater until the temperature controller is satisfied. Two ON/OFF inputs start the heating controller and reset or override its outputs. An input temperature is also connected to be monitored until the goal temperature is exceeded plus the delta T overshoot.

3.4 Overall Cycle Controller

Of all the unique steps within one DW cycle, several are governed by the same controller but with different settings. For example, each cycle starts with a pre-wash that only recirculates water and provides no heating until a timer condition is satisfied. The same function is observed during the main wash but operates for a different amount of time. Here a controller for the prewash or main wash step dependent on a timer has the same function but requires different durations. The same similarity is found in the heated wash and rinse steps where the controller heats the water sump to a required temperature but to a different level for the respective steps. The draining and filling steps of the cycle are combined into the same controller due to how the Modelica components have a constant holding volume of water.

After a controller is built for each major function identified, an overall DW cycle controller is built. The sequence of stepping through each controller is established in this overall cycle controller. A cycle is started by an ON signal. The entered assumptions for various steps are read and the model marches through each step controller of the cycle. Since the model also receives an external heat input, the cycle controller reads an input whether to use the heat loop or not. A heat loop controller modifies the electric heater control by overriding the output if adequate temperature of water is available. Otherwise the electric element is energized following a pulsing controller and heat is delivered to the water sump. The controller accepts two 0/1 boolean signals, starting the DW cycle, and using the external heat loop. Two temperatures are monitored by the cycle controller, the water sump temperature and the source temperature for the heat loop. The controller follows the built-in sequence of operations, and converts 0/1 boolean, ON/OFF signals into volumetric flow rates for the three pumps, or a wattage level for the electric element.

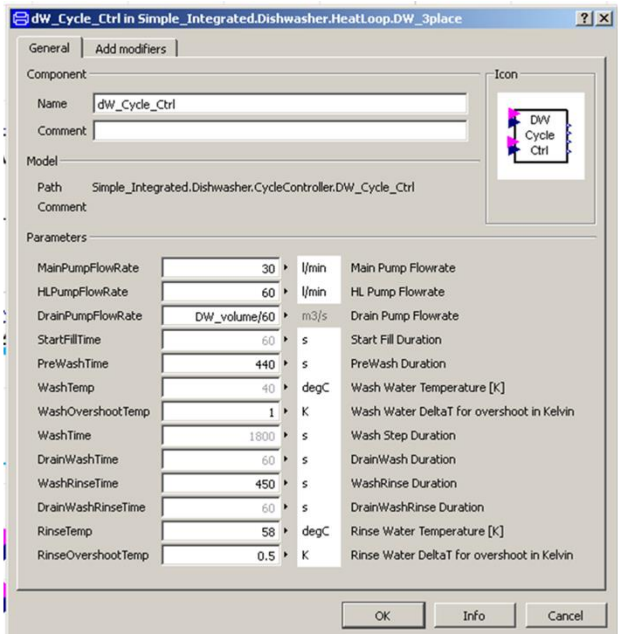

Figure 9: Parametric Inputs for DW Cycle Controller

Heat Loop Control
When the DW is to use the external heat loop, the source temperature must be higher than the sump temperature for any heating to occur. An input for the source temperature provides the controller feedback to accept a fluctuating temperature source. If the source is not more than 10C higher than the sump temperature, the heat loop pump does not turn on and the normal heating mode is used by energizing the electric element.

Overall Control Parameters
With all the controllers finalized to capture every step of the DW cycle, the overall cycle controller is built. Each controller occurs sequentially representing a step. The available parameters that can be adjusted on the controller to improve agreement with experimental data are shown in Figure 9.

4. SINGLE CYCLE SIMULATION RESULTS

4.1 Traditional DW Simulation Results
First the DW appliance model is run in the traditional mode and compared to the experimental data. After some adjustment of the cycle control parameter, better agreement with the data was achieved. The comparison between the experimental and measured water sump temperature and power consumption for the traditional DW are both shown in Figure 10. Good agreement is found on the time required to reach the wash and rinse temperatures. Also, the temperature decay during the main wash from recirculating water with no heat input is captured in the model. The pulsing controller for the electric element is also represented well. One improvement possible on the heater controller is to incorporate Equation 1 and modify the power output as a function of the element temperature.

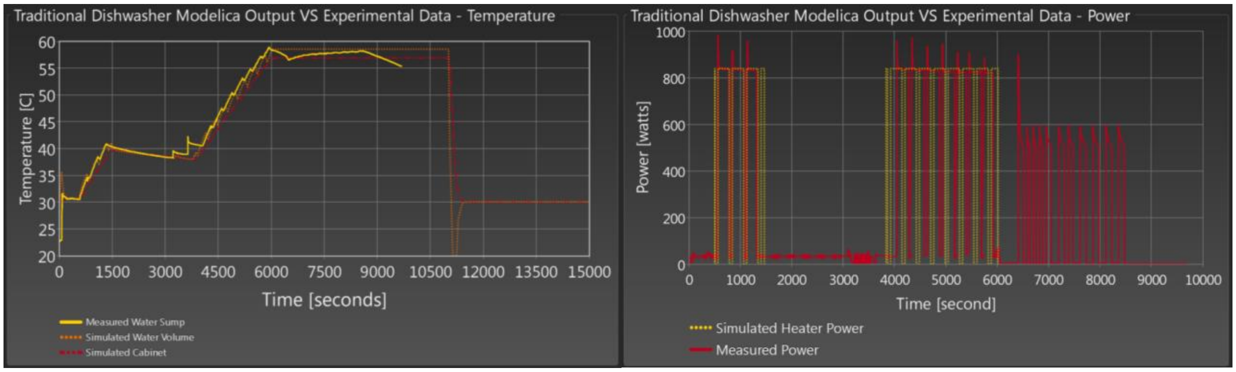

Figure 10: Traditional DW Operation Simulated Versus Experimental Data
(Left) Temperatures - (Right) Electric Element Power

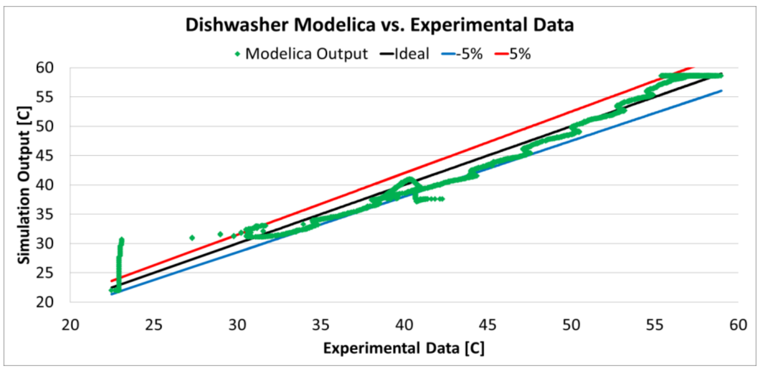

Figure 11: Water Sump Temperature – Simulated vs Experimental

Figure 11 presents a comparison of the predicted sump temperature versus the sump temperature from experimental results and identifies a 5% error band. Overall the model predictions show fairly good agreement. At lower temperatures the model tends to under predict while at higher temperatures the model starts to slightly over predict the sump temperature. For the purposes of the initial simulation, this agreement is suitable as a starting point to explore DW cycle impacts from thermal integration.

4.2 Heat Loop DW Simulation Results

The heat loop feature of the DW was simulated and compared to experimental data as shown in Figures 13 to 15. The heat loop is supplied with a fixed hot water temperature source representing the typical level used for domestic hot water of 120 °F (48.9 °C). Comparisons of the predicted and measured sump temperature and power consumption versus time are both shown in Figure 12. The heated wash step required more time than the traditional system due to the lower heating capacity of the hot water loop. The number of electric element cycles is reduced as desired by leveraging the external heating loop.

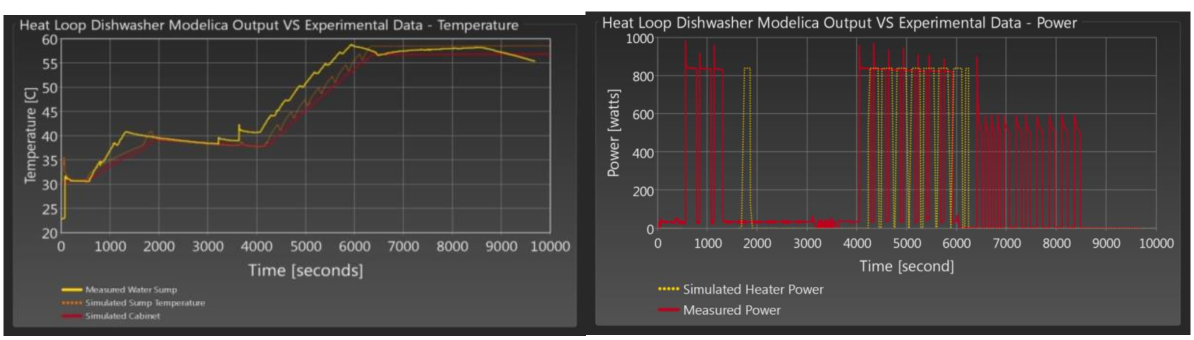

Figure 12: Heat Loop Driven DW Simulated Versus Experimental Data
(Left) Temperatures – (Right) Electric Element Power

The amount of energy required between the two operations is analyzed by focusing on the energy transferred by the heat loop HX and the energy delivered by the calrod heater. 0.564 kWh of energy is consumed by the calrod heater during the traditional mode versus 0.434 kWh during the heat loop input, a 23% reduction.

5. DISCUSSION

In typical dishwashers the water flow rate fluctuates between the two spray arms, upper and lower, during the wash and rinse steps. In the model presented here, the water flow rates are kept constant for simplicity. The duration for one cycle is increased when using an external heat source due to the lower heating rate when compared to the rated wattage of the calrod heater. Although this lower heating rate could come from various waste heat sources in the home compared to the calrod heater using electricity. While not analyzed here, there are expected second law benefits from heating with a lower temperature source at closer temperature to the heating control temperature.

6. CONCLUSION

A dishwasher (DW) was investigated by installing a heat exchanger to heat the process water via an external hot water loop instead of the electric calrod heater. It is expected the heat loop taps into waste heat from other home appliances. The traditional functions of the DW were captured in the model and the predicted water sump temperature was compared to available experimental data from the manufacturer. After tuning, the dishwasher model of the traditional system shows an agreement within ±5% for most water sump temperatures. The model was then run with a fixed temperature heat loop and the electrical savings were reported. Based on the simulation, 0.564 kWh of energy is consumed by the calrod heater during the traditional mode with no external heat input versus 0.434 kWh when leveraging an external heat loop, resulting in a 23% reduction in electrical energy.

REFERENCES

Bansal, P., Vineyard, E. and Abdelaziz, O. (2011). Advances in household appliances – A review. *Applied Thermal Engineering 31*, 3748-3760.

Buildings Energy Data Book. (2011). Pacific Northwest National Laboratory, Buildings Technologies Program, Energy Efficiency & Renewable Energy, U.S. Department of Energy. Retrieved from http://buildingsdatabook.eren.doe.gov/

Eastment, M., and Hendron, R. (2006). Method for Evaluating Energy Use of Dishwashers, Clothes Washers, and Clothes Dryers. *ACEEE Summer Study on Energy Efficiency in Buildings*.

ENERGY STAR Version 6.0 Specification for Residential Dishwasher. (2015). U.S. Environmental Protection Agency. Retrieved from: https://www.energystar.gov/products/spec/residential_dishwasher_specification_version_6_0_pd

Klein, S. A., & Alvarado, F. L. (2002). Engineering equation solver. F-Chart Software, Madison, WI.

McDonald, A.T., Friskney, S.H., and Ulrich, D.J. (1989). Thermal Model of the Dishwasher Heater in Air. *IEEE Transactions on Industry Applications*, 25, *No. 6.*

Meyers, S., McMahon, J.E., McNeil, M., & Liu, X. (2003). Impacts of US federal energy efficiency standards for residential appliances. *Energy 28*, 755-767.

Park, J.S., and Jacobi, A.M. (2009). A run-around heat exchanger system to improve the energy efficiency of a home appliance using hot water. *Applied Thermal Engineering 29*. 3110-3117

Pakula, C., & Stamminger, R. (2010). Electricity and water consumption for laundry washing by washing machine worldwide. *Energy Efficiency 3*, 365-382.

Persson, T. (2007). Dishwasher and washing machine heated by a hot water circulation loop. *Applied Thermal Engineering 27*, 120-128.

Residential Energy Consumption Survey (RECS). (2009). U.S. Energy Information Agency. Retrieved from http://www.eia.gov/consumption/residential/data/2009/

TIL Suite Modelica Thermal Library. (2016). TLK-Thermo GmbH, Braunschweig, Germany. https://www.tlk-thermo.com/index.php/en/software-products/overview

Whirlpool Corporation. (2017). Manufacturer experimental data of KitchenAid dishwasher following Department of Energy test procedure. *Personal communication*.

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