2021

Novel Dishwasher with Thermal Storage and Thermoelectric Heat Recovery

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ABSTRACT

Residential dishwashers typically consume domestic hot water, heat it further with electric resistance heating elements, and drain the soiled heated water before each subsequent water fill. During the final rinse, the water is heated to a temperature of approximately 54.5–57.2°C (130–135°F) to heat the load and promote passive drying after the final drain event. In this work, the energy consumption, water consumption, and drying performance of a conventional dishwasher were measured under test conditions similar to U.S. energy efficiency test standards but with an unsoiled load. These measurements were considered baseline performance metrics. The dishwasher was then experimentally modified to recover heat from the drain water utilizing thermoelectric (TE) heat pump modules and a thermal storage component. The TEs were also used during the drying phase to improve the drying of the load. The novel dishwasher was operated in the laboratory under the same conditions as the baseline unit, and its energy consumption, water consumption, and drying performance were measured. The results demonstrated a 14.5% reduction in energy consumption, with the same amount of water consumption, and improved drying by 60% compared to the baseline.

1. INTRODUCTION

The residential sector represents around 20% of global energy consumption and 18% of U.S. energy consumption (International Energy Agency, 2019). Among all residential energy consumption units (cooking, lighting, space cooling, space heating, water heating, and appliances), residential appliances consume 27% of the overall residential energy. Growing energy demand worldwide urges researchers and scientists to improve the energy efficiency of home appliances. Today in the U.S., 65% of U.S. households, representing approximately 85.8 million households, (Consortium for Energy Efficiency, 2018) "use dishwashers that account for 3.2% of the 2005 residential primary energy use" (Bansal *et al.*, 2011). At present, the energy efficiency of dishwashers could be promoted by applying advanced control units that senses load size or soil level, improving food filters, reducing overall water consumption, using high-efficiency motors, increasing cabinet insulation, or improving the dry cycle (Bansal *et al.*, 2011). However, most of the dishwashers in the U.S. use an electric element to heat the water. Approximately 80% to 90% of electricity during a dishwasher cycle is consumed during the heating in the washing and rinsing steps (Bengtsson *et al.*, 2015). Despite the efforts to improve the energy performance of household dishwashers, new technologies that lead to the lowest possible amount of energy consumption while maintaining or improving cleaning performance are still necessary. Therefore, in this study, our goal is to reduce the energy consumption for water heating using an innovative

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thermoelectric (TE) heat pump system with thermal storage. Thermoelectric devices are semiconductor materials connected electrically in a series where the temperature gradient across hot and cold sides generates electricity (Morelli, 2017; Shittu *et al.*, 2020). If a DC current is applied at low voltage to a TE device, heat is transferred from one side of TE to the other side, resulting in one face of the TE device being cooled, and the opposite face being heated (Enescu & Virjoghe, 2014). Therefore, TE devices can be used as heat pumps. Here, we replaced the electric heater in the commercially available dishwasher with TE elements to heat the recirculated water in a dishwasher cycle, leading to an improved dishwasher efficiency.

2. EXPERIMENTAL SETUP

A commercially available residential dishwasher (DW) unit was modified to be heated and cooled by a thermoelectric heat pump with heat recovery. A rectanglular tube in tube heat exchanger was constructured for increasing the area for condensation. The internal inter tube was a mini-channel and the outer tube was aluminumn wrapped around the microchannel. The outer wrap was exended to increase the surface area of condensation, as illustrated in Figure 1. Two IHXs were mounted on the back wall of the DW tub to exchange heat between the tub and TEHP. During heating, the water in the tub flows through the mini-channels in the IHX, exchanging heat with the TEHP working fluid on the outer tube (Figure 1, right image). In the cooling cycle during drying, the external fins act as a condensing surface and are cooled by the TEHP working fluid on the outer tube.

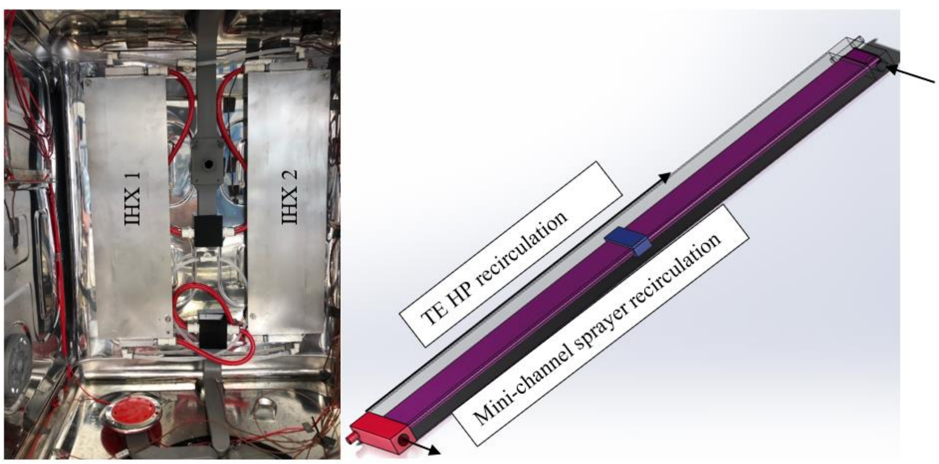

Figure 1. Two internal heat exchangers as installed on the back of the tub (left), CAD visualization of internal heat exchangers (right)

The thermoelectric heat pump (TEHP) unit assembly was constructed by sandwiching five thermoelectric modules between aluminum spacer blocks and two mini channel heat exchangers, as illustrated in Figure 2. The heat was pumped between the storage, thermoelectric, and the tub through the two mini channel heat exchangers with two external positive displacement pumps. The heat transfer fluid (water) flowed through the mini channels at a constant flow rate of 0.05 kg/s.

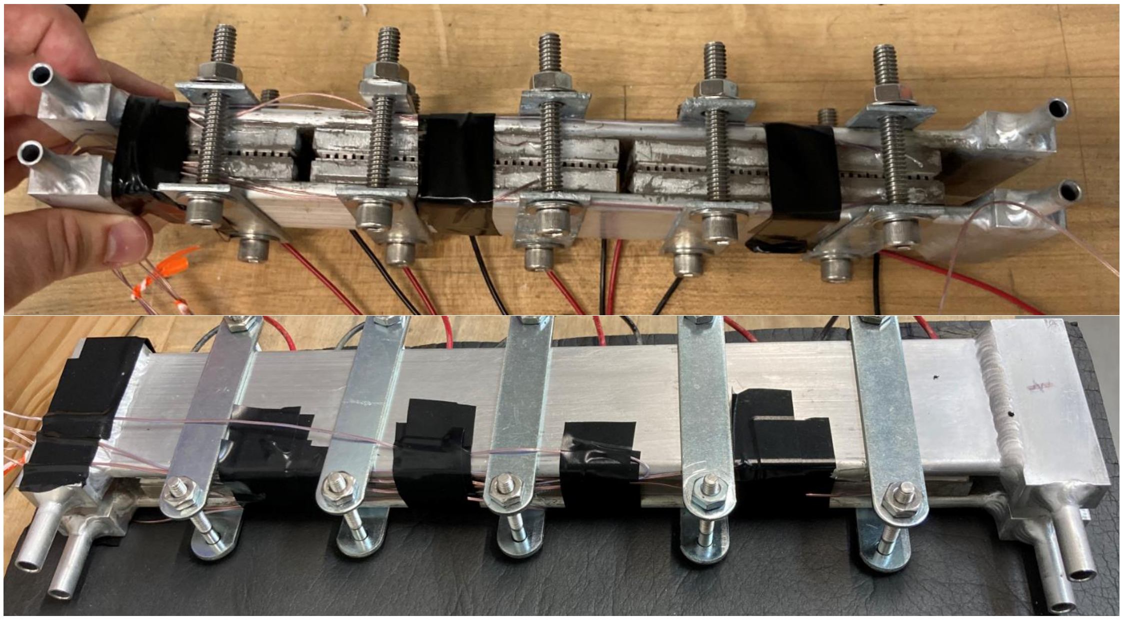

Figure 2: The sandwiched construction of TEHP with thermoelectric, spacer block, and two mini channel heat exchangers.

The piping and instrumentation diagram (P&ID) of the TEHP DW unit is shown in Figure 3, and was designed according to Gluesenkamp (Gluesenkamp, 2018). The instruments used for measuring various quantities and their uncertainties are summarized in Table 1. The tub water was circulated through the thermal energy storage (TES) tank for heat recovery before drainage in the recovery cycle. In the heating cycle, the heat was recovered from the TES tank through the cold side of the TEHP. The mini channel on the hot side of the TEHP pumps heat to the DW tub for water heating during the wash and rinse cycle. In the cooling cycle, the electrical polarity was reversed to provide cooling to the DW tub; the heat was pumped into the TES tank. Both heating and drying were accomplished with the same set of TEs by reversing polarity to the TEs. This study experimentally measured TEHP DW's performance using two voltage (35 and 40 VDC) conditions under an adaption of the DOE standard test conditions (US Department of Energy, 2019) without soiling or detergent.

The drying performance of DW was evaluated by measuring the remaining water content on the bottom and top rack *in-situ*. The dishwasher unit was modified to balance the top and bottom racks on four load-cells each.

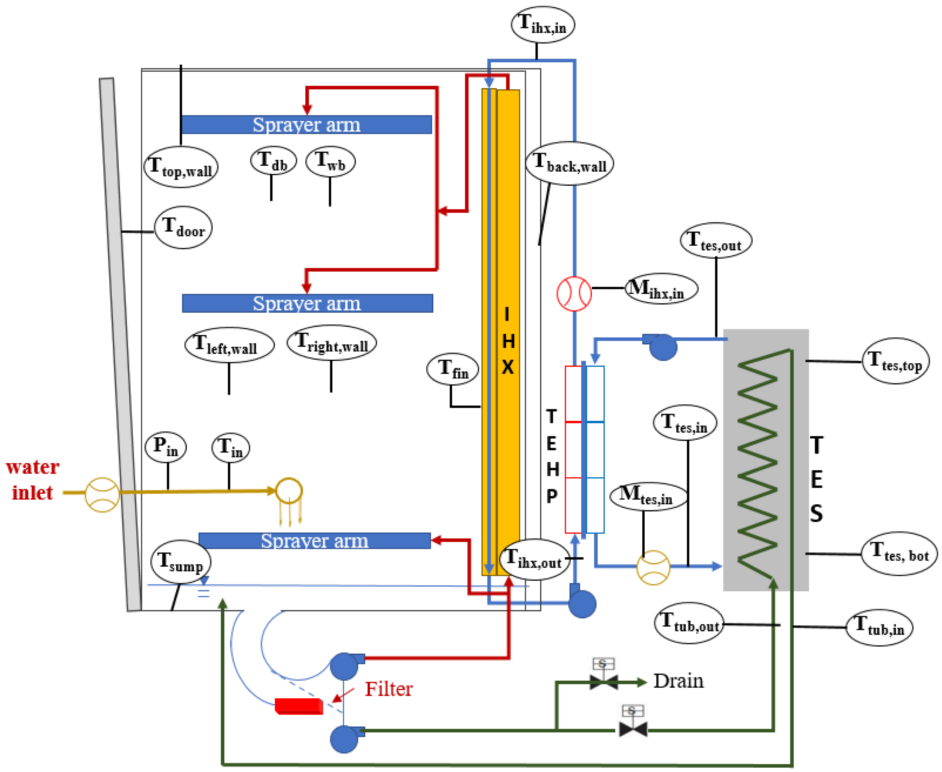

Figure 3: The P&ID diagram for the TEHP dishwasher unit with energy recovery. T is a temperature sensor. M is the mass flowmeter sensor. P is a pressure sensor.

Table 1: Instruments and their uncertainties.

Parameter	Instrument	Instrument Uncertainty
Temperature	T-Type thermocouple	0.5°C
TEHP temperature	RTD 1/10 DIN PT 100 ohms	0.1°C
Mass flow rate (TEHP)	Bronkhorst M-15 Coriolis flowmeter	± 0.5 %
Air relative humidity	Vaisala HMT330	± 1.0 %RH (0 – 40 %RH) ± 1.7 %RH (40 – 95 %RH)
Air dry bulb temperature	RTD built into Vaisala HMT330	0.1°C
Domestic water flow rate	Omega FTB-101 turbine flow meter with FLSC-C3-LIQ	±0.5% of flow reading
Power consumption	OSI AGW-001D Watt transducer with metering class current transformer (150:5) with nine turns of primary wire	±0.24% of power reading
Water pressure	Omega PX409-100GI pressure transducer	±0.08% best straight line
Weight	Futek LSB 210 IP67 load cell	±0.25% Full Scale

The TEHP dishwasher's COP was computed by measuring the electric power and internal heat exchanger's inlet water mass flow rate ($M_{ihx,in}$) and inlet water temperature ($T_{ihx,in}$), and outlet water temperature ($T_{ihx,out}$) over the heating period, as shown in Eqn. 1.

$$COP = \frac{\sum M_{ihx,in} * C_{p,water} * (T_{ihx,in} - T_{ihx,out})}{\sum P_{electric}} \quad (1)$$

The drying performance was also measured for the prototype and baseline operation. The weight was measured *in situ* by four load cells on the top and bottom racks.

3. RESULTS

The machine energy use performance of the dishwasher is summarized in Figure 4. The energy use of the DW is segregated into the heated wash, heated rinse, and others (pumps and fans). The total machine energy use of the unit was 511 Wh/cycle under a normal load test. The heated wash cycle phase consumed 191 Wh/cycle of energy to heat the water from 30.9°C (87.6 °F) to 45.6°C (114°F). The heated rinse cycle phase consumed 203 Wh/cycle of the energy to heat the water from 43.3°C (110°F) to 55°C (131 °F). The energy consumed by others was 117 Wh/cycle.

Water heating energy use represents the energy associated with supplying hot water to the dishwasher. Water was provided to the DW at 48.9°C (120°F). Therefore, it is assumed that the water delivered to the unit was heated from 10-48.9°C (50 to 120 °F). This energy use is directly proportional to the amount of water consumed. The baseline and the TEHP unit consumed 11.1L (2.94 gals) of water (Figure 5). The unit consumed a total of 495 Wh for water heating.

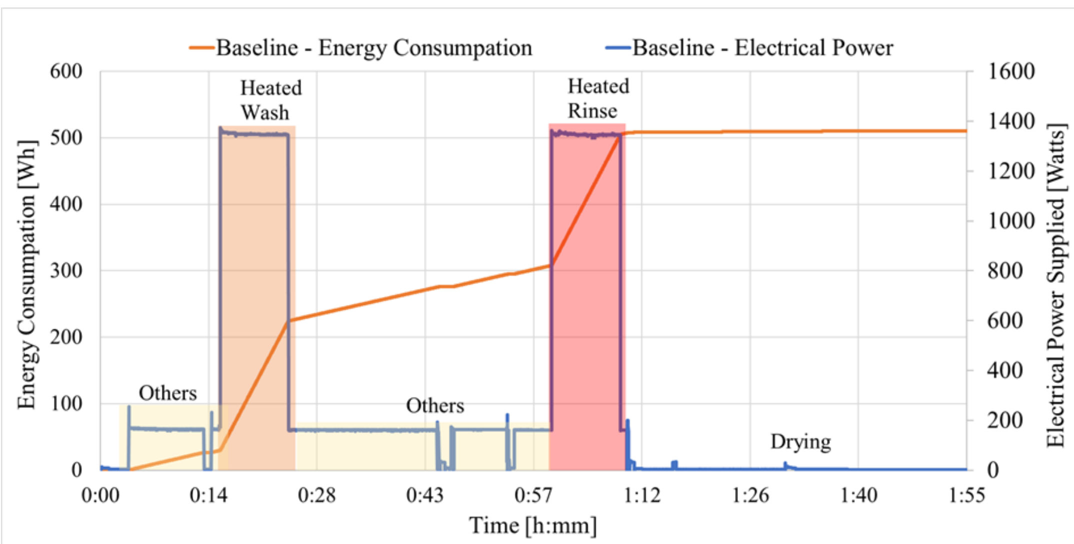

Figure 4: The DW unit's baseline energy consumption (accumulated energy consumption) under D.O.E.'s normal load cycle. The normal load cycle constitutes of heated wash at 45.6°C (114°F), heated rinse at 55°C (131°F), and unheated drying.

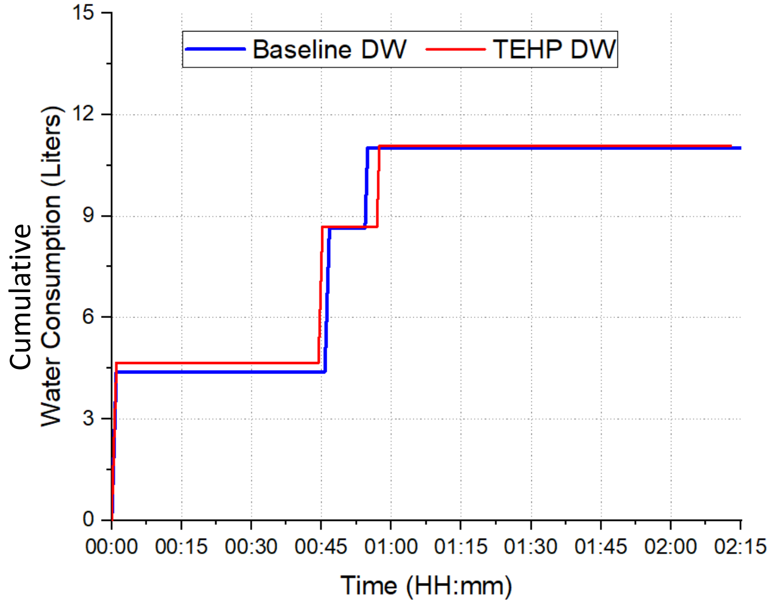

Figure 5: The baseline and TEHP unit water consumption.

The electrical power consumed by the TEHP unit is as summarized in Figure 6. The energy consumption of the TEHP unit was evaluated at voltage conditions of 40 and 35 VDC. When the TEHP was operated at 40 VDC, the unit consumed a total of 388.5 Wh/cycle, of which 187 Wh/cycle was used for the heated wash, 173.5 Wh/cycle for the heated rinse, and 28 Wh/cycle by other operations. When the TEHP was operated at 35 VDC, the unit consumed 369.5 Wh/cycle, of which 172 Wh/cycle was used for the heated wash, 169 Wh/cycle for the heated rinse, and 28.5 Wh/cycle by other operations. Reducing the TEHP operating voltage from 40 VDC to 35 VDC increased the DW cycle time by 18 minutes compared to the baseline unit.

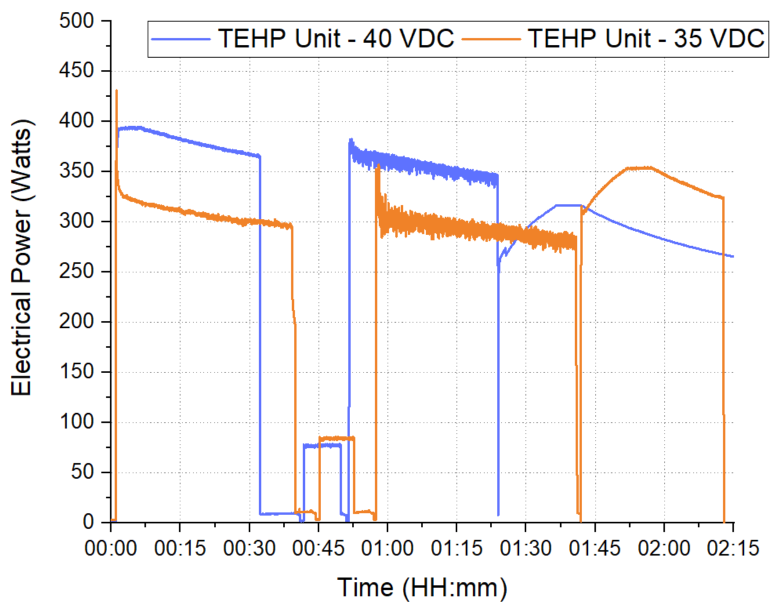

Figure 6: The TEHP unit's energy consumption under a normal load cycle. The TEHP runs at lower power and for a longer time than baseline shown in Figure 4.

The comparison of the energy performance of the TEHP unit and the baseline are summarized in Table 2. The maximum energy savings of 14.5% was achieved when the TEHP unit was operated at 35 VDC with a system-level heating C.O.P. of 1.17. During the recovery phase, 257 kJ of heat was recovered and raised the TES tank temperature to 90.2°F.

Table 2: Summary of performance of the TEHP unit and the baseline

	Heating Energy [Wh]	Drying Energy [Wh]	Heating COP	Heating Energy Savings [%]	Water consumption [L] / [gal]	Remaining water Content at 20 minutes of elapsed drying time [wt% of water]
TEHP Unit 40 VDC	885	112	1.14	12.0	11.1 (2.93)	2.8
TEHP Unit 35 VDC	860	120	1.17	14.5	11.05 (2.92)	3.1
Baseline	1006	-	1.00	-	11.02 (2.91)	4.8

The drying performance of the baseline and TEHP unit is as shown in Figure 7. The weight of the load was measured *in situ* by placing the top rack on four waterproof load sensors, and the bottom rock on four waterproof load sensors. The liquid water on the dishes could therefore be computed as the *in situ* wet weight of the load minus the dry weight of the load. The remaining water content is expressed in Figure 7 as a percentage, by comparing the water weight to the dry weight of the load. The TEHP unit consumed 120 $Wh_{electric}$ for 20 minutes of drying. In contrast, the baseline unit consumed zero energy during the drying phase. The drying performance of the DW was evaluated under two different conditions: (1) door prop , and (2) no door prop (the door prop was a feature of the DW model in which the door automatically opened slightly during the drying phase of operation). The initial drop in the first two minutes in the experiment was because of a small vibration caused by the insertion of the RH probe into the dishwasher. In the door prop case, the door was released open at the end of the 20th minute. The drying performance of the TEHP unit was enhanced by more than 60% with the additional cooling provided by the TEHP compared to the baseline unit.

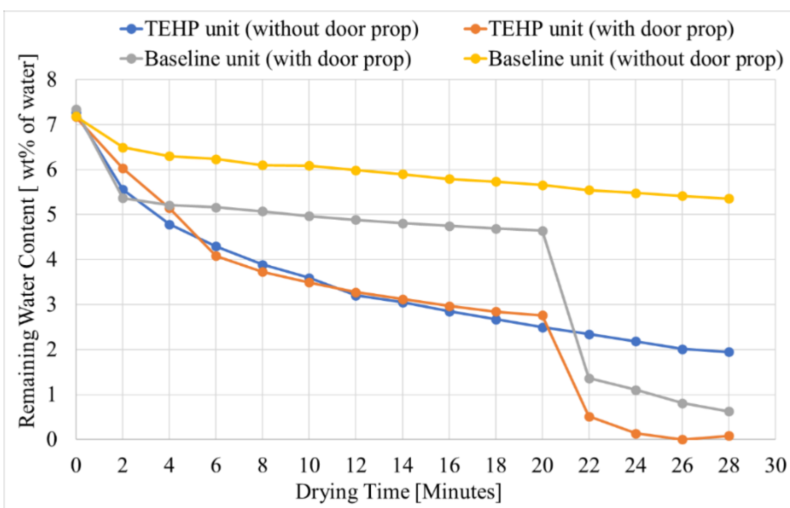

Figure 7: The drying performance of the baseline unit without cooling and the TEHP unit operated at 40 VDC with cooling.

4. CONCLUSION

In this work, the energy performance, water consumption, and drying performance of a conventional dishwasher were improved by modifying a dishwasher to recover heat utilizing a thermoelectric heat pump (TEHP) and a thermal energy storage tank. The results demonstrated a reduction in heating energy consumption and improved drying performance compared to the unmodified DW with the same amount of water consumption.

The TEHP with heat recovery reduced the heating energy consumption by 14.5 % and extended the cycle by 18 minutes. The heat recovery and the ability of the TEHP to be operated above a heating C.O.P. of 1 aided the reduction in heating energy consumption. On the other hand, in the baseline unit, the heating C.O.P. of a resistance unit is 1. During the drying phase, TEHP consumed 120 Wh of energy and improved the drying by more than 60 %. Overall, the TEHP unit with heat recovery consumed 2.5% less energy and provided a 60 % improvement in drying compared to the baseline unit. The system's energy consumption can be reduced further by improving heat recovery performance and changing the thermal energy storage configuration.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

COP	Coefficient of performance	
T	Temperature	(°F/°C)
M	Mass flow rate	(kg/s)
P	Pressure	(psi)
Subscript		
ihx	Inlet heat exchanger	
tes	Thermal energy storage	
in	inlet	
out	outlet	
tub	Dishwasher Tub	
fin	Inlet heat exchanger wall	
db	Dry Bulb	
wb	Wet bulb	

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ACKNOWLEDGEMENT

This work was sponsored by the U. S. Department of Energy's Building Technologies Office under Contract No: DE-AC05-00OR22725 with UT-Battelle, L.L.C. The authors would like to acknowledge Mr. Antonio Bouza, Technology Manager – HVAC&R, Water Heating, and Appliance, U.S. Department of Energy Building Technologies Office.