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Stephen L. Caskey
Purdue University, School of Mechanical Engineering, Ray W. Herrick Laboratories, West Lafayette, IN 47907, USA,
stephen.l.caskey@gmail.com

Eckhard A. Groll
Purdue University, School of Mechanical Engineering, Ray W. Herrick Laboratories, West Lafayette, IN 47907, USA,
groll@purdue.edu

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Stephen L. CASKEY*, Eckhard A. GROLL

Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University
West Lafayette, IN, USA
scaskey@purdue.edu, groll@purdue.edu

* Corresponding Author

ABSTRACT

As the second largest consumer of global primary energy, research to reduce significant energy consumption in the United States can generate meaningful impacts. Household appliances account for the second largest site residential energy consumption at 27%.

Thermally integrating most or all of the residential appliances by leveraging waste heat recovery is currently not covered by U.S. federal standards and has not been adequately explored in the literature. Limited studies exist focused only on single appliances connected to waste heat recovery or being thermally integrated.

A Modelica model is presented capturing the operation of four major household appliances, namely the refrigerator-freezer (RF), dishwasher (DW), clothes dryer (CD), and clothes washer (CW), as well as their thermal connection to a simple storage tank model to simulate appliances thermally connected. For a fixed schedule, the simulation predicts the amount of energy recovered from the integrated system and explores the impact from varying the storage size or the heat recovery strategy.

1. INTRODUCTION

The U.S. used 103.2 EJ (97.8 quads) of primary energy in 2010 or 19% of global consumption (Kelso, 2012). Reducing consumption in the U.S. provides one effective mechanism to achieve significant reductions of global energy consumption. The U.S. building sector, both commercial and residential, is the largest consumer at 41% and accounts for 7% of global primary energy consumption (Kelso, 2012). A further look into the building sector identifies an energy loss of 49% where 21 EJ (20 quads) of site energy required 41 EJ (39 quads) of primary energy. Site electricity usage is the large source of these losses. Exploring methods to reduce site electricity will magnify impacts on annual building energy consumption by demanding less primary energy for electricity generation. A complete breakdown of each end use percentage of total site energy consumption is presented in Figure 1. The second significant percentage of combined usage is from household appliances at 27%; water heater, RF, wet cleaning (DW, CW, and CD) and cooking equipment (Table 2.1.5, Kelso, 2012).

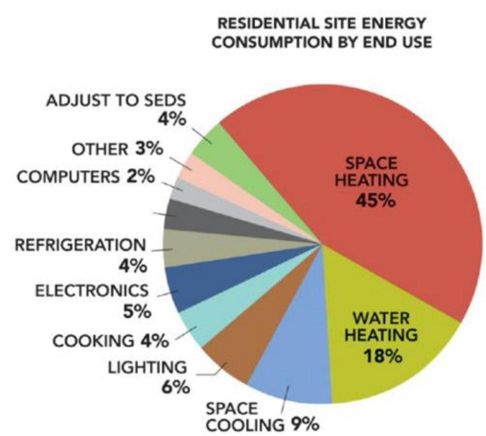

Figure 1: End-Use Residential Site Energy Consumption (Kelso, 2012)

Federal standards have resulted in significant reductions in appliance energy consumption. After a new standard, annual energy usage of RFs or CWs for example can be seen quickly decreasing by forcing the industry to explore and adopt new technology. The energy reductions also level off requiring standards to be updated and force new, energy efficient technology to be adopted. While regulation provides benefits, they can create tunnel vision for manufacturers by limiting their scope to the standard. 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. Most research has been focused on the appliance itself with some studies on benefits from resources available outside the appliance.

RF research has considered load shifting methods by introducing microprocessors or PCMs (Bansal et al., 2011). A review on prior studies have explored; the refrigerant used, methods to improve the cycle efficiency (charge optimization, new compressors, Lorenz-Meutzner), lowering the cabinet heat gain (vacuum insulated panels), reducing parasitic electrical loads (high-efficiency fan motors), and reducing on/off cycling losses (preventing refrigerant migration, defrost) are summarized (Radermacher et al., 1996).

Two approaches to reduce DW electricity consumption were applied to offset heating by the internal resistor (Persson, 2007). Increasing the DHW supply from 49C (120F) to 65C (149F), reduced electricity used by 19%, 0.8 kWh to 0.65 kWh. The entire cycle still used ~1.2 kWh of energy in total. A custom built HX connected a water loop as an external heat source for the DW. Above loop temperatures of 70C (158F), electricity usage plateaus to ~0.1 kWh while around temperatures of 50C (122F), about 0.6 kWh of electricity is predicted. Both cases use similar amounts of total energy, combined electrical and thermal, for the entire cycle.

The improvement in the energy efficiency of CWs is primarily focused on water consumption, both in volume and temperature. Advancements have improved load detection and wash performance to clean with less water volume. Detergents rated at colder water temperatures and external heat sources have reduced CW hot water consumption. One easy and cheap approach is a HX that extracts heat from ambient air by preheating cold water to the appliance. The highest predicted energy savings of approximately6% of the total baseline energy usage were achieved at the highest water and air flow rates. (Park, J.S. et al. 2009). Other advancements considered were heat from the outside of the appliance, a heat pump for internal heating, and even the combination of several appliances.

A study compared four different CD types; air vented, closed-cycle condensing, open-cycle condensing, and closed-cycle with heat recovery (Bansal et al., 2011). An energy savings of 14% and 7% over an air vented CD were reported for the open-cycle condensing and the closed-cycle with heat recovery respectively. The use of an air-cycle heat pump for a CD resulted in up to 40% reduced energy consumption compared to a conventional CD and does not require any venting to the outside (Bansal et al., 2011). A vapor compression heat pump cycle for a CD offers a 50% energy savings over conventional CDs (Bansal et al., 2011).

1.3 Waste Heat Recovery

Investigations on residential waste heat availability are not a new topic. A basic hot water preheating system was designed and tested by collecting drain water from the bath, washing machine and dishwasher and achieved a 10% savings of total energy consumption (Smith, 1975). Following a low exergy design explores waste heat recovery by capturing low quality energy (Schmidt, 2009). One study expands on vertical methods to recover waste heat from drain water by designing a horizontal orientation and reports HX effectiveness values around 50% (McNabola et al., 2013). Another study looked at waste heat recovery of waste water from showers, the dishwasher and the clothes washer using the same HX as well as recovering heat from the CD using a prototype HX (Tomlinson et al. 2012). More advanced methods use recovered heat from waste water for heat pumps to improve their efficiencies (Culha et al., 2015).

Early work on waste heat recovery of residential appliances used an RF condenser to preheat supply water to the water heater (Bansal et al., 2011). One study looked at DWs for waste heat recovery but reported a 13 year payback period (Bansal et al., 2011). Water recycling of the CW is one potential means of waste heat recovery. COs vent hot air with the potential for heat recovery (Bansal et al., 2011). One example is the CD exhaust has been used to preheat incoming cold air. Another study compared the effectiveness of using waste heat from a window air conditioner for drying clothes in a small room to indoor or outdoor drying (Mahlia et al., 2010).

Energy storage is required for waste heat recovery due to the intermittent nature of each appliance operation. This would need to be optimized for a range of temperatures; cooling, preheating, and reheating (Bansal et al., 2011). While projections on energy savings utilizing waste heat recovery are up to 25%, more research is needed: an energy storage system supporting a range of temperatures across all appliances, and investigating the physical approach to extract or deliver heat to each appliance; a combination of HXs, piping, pumps and sensors interfacing with the energy storage system (Bansal et al., 2011). Energy storage is also listed as an area of additional research needed to improve grid stability of net-zero energy buildings (Crawley et al., 2009). In another study, a life cycle analysis was performed on a seasonal thermal storage system connected to solar collectors to store summer heat during winter domestic hot water and space heating needs (Colclough et al., 2015). One author presents the combination of a water-to-water heat pump, two vertical ground loops, solar thermal collectors, and floor heating modeled with an exergetic analysis (Hepbasli, 2007). The exergy efficiency of the solar collector is calculated to be 10.8% with the authors recommending restricting solar energy for high temperature needs. A similar system (floor and fan-coil heating) is modeled in TRNSYS and various control strategies are explored (Xi et al., 2011).

1.4 Thermally Connected Appliances

The development of a physical model in Modelica representing four appliances connected to central thermal storage is a useful tool to evaluate the energy savings potential. The combination of different systems in an energy efficient home can be explored. A solar water heater, a heat pump domestic hot water heater, or a hydronic ground-source heat pump, are some example connections that would be worth pursuing. In supporting future net-zero energy buildings, indications are made on the benefits of thermal simulation models with accurate predictions of the dynamic responses (Kolokotsa et al., 2011).

To develop an understanding of the waste energy profile of household appliances, their standard operation and typical usage characteristics had to be captured. First, the total number appliances installed in the U.S. are identified. Next, the energy usage per appliance is reported as an annual or per cycle energy consumption. In addition, published or manufacturer data provides typical operational parameters of the appliance. This includes data on volume and temperature of the water being drained by the CW and DW, temperature and humidity of the exhaust air of the CD, and operating parameters of the vapor compression cycle of a household RF.

2. APPLIANCE BACKGROUND

The major residential appliances considered in this study are identified as the clothes washer and dryer, cooking oven, dishwasher, and domestic refrigerator/freezer. From this list, each appliance is investigated thoroughly to identify a number of characteristics or features that define the scope of the appliance; the total number of units installed in the U.S., the frequency of use, and the different technologies driving the appliance function.

2.1 Refrigerator-Freezers

Out of 113.6 million American homes, 113.4 are listed as using a refrigerator with 87 million having only one while 26 million have two or more (Table HC3.1 RECS, 2009). The majority of RFs are still driven by the fundamental technology of a vapor compression cycle maintaining a cavity temperature by rejecting heat to the ambient air.

In 2008, the annual electricity consumption for the top-mount freezer and side-by-side were 454 kWh and 580 kWh respectively (Refrigerator Market Profile, 2009). A higher annual consumption of 660 kWh is projected using the test conditions specified by the Department of Energy, DOE, (Table 2.1.16 Buildings Energy Data Book, 2011). The refrigerator size for this larger value is not mentioned and the test standard version is unknown, both of which would impact this estimated annual energy consumption. The current EPA Energy Star program requires a 10% reduction from the 2014 federal minimum standards (ENERGY STAR V.5, 2013).

Experimental data from the manufacturer was obtained of a DOE test run for a side-by-side refrigerator with ice maker. Referencing an older Energy Star version, the refrigerator was certified with a 552 kWh annual energy usage falling under the federal standard of 737 kWh. The data was processed using EES to determine the heat transfer rates and COP of the refrigeration cycle (Klein et al., 2002). The temperature difference across the evaporator was 3.9°C (7°F) providing about 148 Watts of cooling. For the condenser, the temperature difference was 5.6°C (10°F) requiring 256 Watts of heat rejection to the ambient. The measured power consumption of the entire refrigerator was 103 Watts and the rated compressor displacement was 5.56 cm^3 (0.34 in^3). Cooling and heating COPs were calculated to be 1.44 and 2.49 respectively. A refrigerator with the performance characteristics from the experimental data, 552 kWh per year, is referenced for the waste heat analysis. The number of units in the U.S is roughly 38.6 million from 34% of all refrigerators are side-by-side. Therefore, the total annual energy consumption for all side-by-side refrigerators is 0.077 EJ (0.073 quads).

2.2 Dishwasher
The market penetration of dishwashers in U.S. households is not as high as other appliances. Approximately 59% or 67.4 million households use a dishwasher (Table HC3.1 RECS, 2009). One source reported 65% of U.S. households use DWs, accounting for 3.2% of the 2005 residential primary energy consumption (Bansal et al., 2011). The use of DWs reduce the demand of hot water for cleaning dishware versus traditional hand washing by circulating a fixed volume of water to remove soils. While hot water provides some heat to raise the dishware temperature for ideal cleaning, an internal calrod heater is still required to further heat the dishware and cabinet to the design water temperature. One study reported 88% of total energy input of 1.05 kWh into one DW cycle is used for heating the inlet water, the dishes and cookware, and the physical cabinet of the appliance (Persson, 2007). The energy usage of a DW is heavily weighted by the heating demands for maintaining a high water temperature around 50°C (122°F). The frequency of DW use also impacts its energy consumption.

The largest number of dishwashing cycles per year is listed at 365 or one per day (Table 2.1.16 Buildings Energy Data Book, 2011). From the housing survey, 104 cycles per year covers 67% of all households using dishwashers while higher usage rates, 208 cycles per year only covers 35% (Table HC3.1 RECS, 2009). The current Energy Star rating for dishwashers reduced the average, annual number of cycles from 264 to 215 (ENERGY STAR V.6, 2015).

For a conservative estimate, 215 cycles per year is selected for dishwasher usage covering 35% or 23.7 million households. 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). A standard size, Energy Star dishwasher with 215 cycles a year, is selected by referencing an annual energy consumption of 270 kWh. With 23.7 million households, the total annual energy consumption of a standard, Energy Star dishwasher is 0.023 EJ (0.022 quad). 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).

2.3 Clothes Washer
More than 80% of U.S. households have clothes washers, consuming 3.7% of total residential primary energy (Bansal et al., 2011).The total number of U.S. households having a clothes washer is 93.2 million homes, slightly higher than the number of households with clothes dryers (Table HC3.1 RECS, 2009). In general CWs are first broken down into two designs dependent on the orientation of the drum, vertical axis, VA, top loading, or horizontal axis, HA, front loading (Bansal et al., 2011).

A breakdown of the number homes for a range of loads per week is used to understand the impact of the assumption on the annual number of cycles (Table HC3.1 RECS, 2009). Converting the weekly total to a yearly value, 43.9 million households use the washing machine at least 260 to 468 cycles per year versus 84.9 million homes using it at least 104 to 208 cycles per year. To be conservative on estimating the waste energy source, assuming an annual number of 289 wash cycles covers at least 43.9 million households and is larger than the annual number of drying cycles assumed. If the water heating energy is included, a top loader had an average, measured energy consumption of 2.26 kWh per cycle and a front loader had 0.96 kWh per cycle (Tomlinson et al., 1998). Following the same procedure with 289 cycles per year, the annual energy consumption is 653 kWh for top loading washers and 277 kWh for front loading.

Considering only top loading washers covering 76 million households, the total annual energy usage when including water heating energy (653 kWh/yr) is 0.18 EJ (0.17 quad) or excluding water heating energy (110 kWh/yr) is 0.03 EJ (0.028 quad).

To accurately determine the amount of energy available, the volume of water drained and the associated temperature is required. Top loading washers require larger volumes of water to achieve the desirable cleaning performance compared to front loading machines. With a significant number of CW in the U.S. being top loaders, a value of 144 liter (38 gal) per cycle is provided from one study (Pakula et al., 2010). A water usage of 155 liter (41 gal) per cycle from top load washers is assumed due to the large percentage, 81%, of all U.S. washing machines used.

Two separate steps occur during the entire washing machine cycle, a wash and then a rinse step. 48% of households report selecting warm water, wash cycle and 46% select a cold water wash (Table HC3.1 RECS, 2009). For rinsing, a large majority, 80% of households, report selecting cold water rinse. Similar trends are presented in another study with 58% to 67% of all washing machine cycles using a warm water wash, cold water rinse (Tomlinson et al., 1998).

To associate the relative terms: cold, warm, and hot water with temperatures, typical housing water supply temperatures and experimental data from the manufacturer were referenced. Cold water typically is close to ground temperatures and is assumed to be 12.8°C (55°F). Hot water supply temperature depends on the water heater set-point used by the homeowner and is assumed to be 49°C (120°F). Appliance testing data from the manufacturer identified warm water used during the wash step at a temperature of 36°C (97°F).

2.4 Clothes Dryer

Over 80% of U.S. households have CDs that account for 4.2% of the total, residential primary energy consumption (Bansal et al., 2011). Most CDs in the U.S. are vented by which removed moisture from wet clothes is ducted out of the appliance and blown outside the home. Vented CDs can use the two available heating technologies, electric or combustion driven (Eastment et al., 2006). The number of U.S. households that use a dryer at home is 90.2 million, out of 114 million households, with 80% (71.8 million) having electrically heated ones versus 20% using natural gas (17.5 million) or propane/LPG (1.0 million) (Table HC3.1 RECS, 2009). Only electrically heated clothes dryers are considered due to the small percentage of combustion heated dryers.

74.4 million households report that their dryer are used every time clothes are washed which provides some insight to the correlation between clothes dryer and washer usage (Table HC3.1 RECS, 2009). Other considerations such as clothes type or time of year can reduce dryer usage when air drying is desired. Until the DOE test procedure was adjusted in 2011, the number of drying cycles a year was assumed to be 416 (ENERGY STAR, 2011). With new data on usage characteristics from housing surveys, the number of cycles a year was adjusted to 283, or 32% less (Table HC3.1 RECS, 2009). This number is also lower than the assumed 359 cycles per year by the DOE, (Table 2.1.16 Buildings Energy Data Book, 2011).

The electrical consumption of clothes dryers depends on a number of inputs; some are specified by user settings on the interface of the appliance and the others depend on the moisture content of the clothes. Different drying cycles can be run: permanent press, delicates, or auto-termination using moisture detection. Low, medium or high temperature heat settings can be selected. The moisture content of the clothes being loaded directly correlates with the required heating energy to evaporate and remove all the stored water. The type of clothing, the amount of clothes or load size, and the water extraction efficiency of the washing machine all determine the clothing moisture content. One source reports an annual electric consumption of 1000 kWh for electric dryers (Table 2.1.16 Buildings Energy Data Book, 2011). Referencing the previously mentioned 359 cycles per year by the Buildings Energy Data Book, the average power consumption is estimated at 2.78 kWh per cycle. Experimental data with CD exhaust air conditions presents an example CD cycle for the waste heat analysis. An electric clothes dryer is first monitored and recorded with no modifications to develop a baseline operation before running different failure mode tests as a safety evaluation (Butturini et al., 2004). The parameters of interest here are the exhaust air temperature and relative humidity leaving the appliance. A load of wet towels weighing 10.1 kg (22.2 lbs) is loaded into an electric dryer where 4.5 kg (10 lbs) is removed during the drying process. The average exhaust velocity was measured to be approximately 6.8 m/s (1337 ft/min). Assuming a 10 cm (4 in) diameter, round exhaust duct, the volumetric air flow rate is 200 m^3/hr (117 CFM). The heating element draws an average of 22.8 amps while the electric motor draws an average of 4.35 amps. The power supply for electric dryers uses typically higher voltages, such as 220 volts, resulting in a lower amp draw. The baseline test lasted 1 hour. With the known power consumption, 5.97 kWh of energy is consumed over the entire CD cycle.

If 283 cycles per year are run with a power consumption of 5.97 kWh per cycle, an annual power consumption of 1,690 kWh is predicted. Applying the number of homes with an electric dryer, the total annual energy consumption with this example drying profile is 0.44 EJ (0.416 quads).

2.5 Appliance Schedule

Significant effort has been made by the DOE on developing a benchmark American home for modeling purposes to support and prove the benefit of using advanced systems in the home (Wilson et al., 2014). The study provides very specific usage characteristics for all systems in the home, including appliances. In one study, a weekly appliance schedule is generated from the 2008 version of the Building America Research Benchmark by Hendron, R., (Boudreaux et al., 2012). From the number of bedrooms and the appliance capacity in the study, an assumed number of cycles per year are calculated for each appliance. With an annual cycle count, the average number of cycles in a week is assumed for each appliance when spreading the annual usage evenly over the 52 weeks in a year. The authors selected six CW cycles, five CD cycles, and 6 DW cycles in a week. The DW is specified to be run every day at 7:30 pm except Saturdays. The CW and CD are used twice on Saturday and Sunday mornings, and two CW cycles to one CD cycle on Wednesdays.

3. MODELING APPROACH IN MODELICA

The modeling approach used prebuilt Modelica component models to capture four residential appliances connected to a water storage tank for heat recovery or delivery during each operation. A licensed Modelica thermal library provided well-built sub-models representing pumps, heat exchangers, storage vessels, and libraries with liquid properties for calculations. While many different open-source simulation engines exist for Modelica, a licensed version was needed for compatibility with the selected thermal library.

3.1 TLK-TIL Modelica Thermal Library

The desire to use Modelica as an object-orientated programming language was based on having easily built and modified models from quick development times and good simulation convergence. Many open-source platforms exist within the Modelica community having pre-built models for common equipment, dependent on the purpose of the platform. Often any support on these packages for a specific application is limited and thus, can be challenging to implement. Some companies have started developing advanced libraries with detailed component models, a wide variety of fluid properties, and a structured modeling approach to be adapted to your specific application. Additionally the licensed libraries are often experimentally verified for further accuracy. A licensed Modelica library TIL from TLK is a well-developed thermal systems library with component models and fluid property function (TIL Suite, 2016). The library covers all the common equipment applied in thermal systems; commercial or residential refrigeration, power generation, and building or transportation HVAC. From being a licensed product, the libraries are under constant updates and new components that capture emerging technologies in the field can be added.

3.2 Simulation Interface

A schematic of the simulation interface can be seen in Figure 2, where appliances are identified with the components representing their operation while connected to a storage tank.

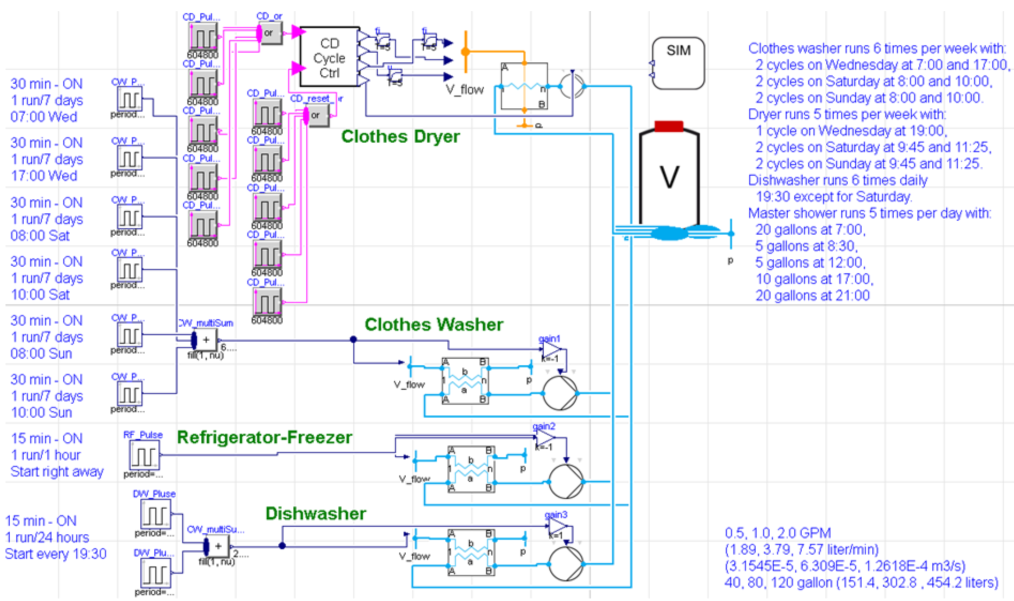

Figure 2: Modelica components representing 4 appliances connected to a central storage tank for heat recovery

3.3 Single-Node Storage Tank

The Modelica model of the storage tank represents a fixed volume of water all at uniform temperature. The model supports multiple fluid connections through ports that are added with each added connection. The port assignment is done automatically but can be adjusted after making the physical connection.

3.4 Flat Plate Heat Exchanger – Refrigerant Condenser

For the water cooled condenser of the RF, a flat-plate HX Modelica model is programmed with the physical dimensions of the installed HX used during preliminary experimental evaluation (Small, S. 2017). The exact values are shown in Figure 3. The model also requires a HTC. A correlation or constant value can be entered. For the initial phase to reduce model complexity, literature is referenced for a reasonable constant value capturing the condensation of R-134a in a brazed plate HX (Longo, G.A. 2008). Refrigerant fluxes in the span of 10 to 40 kg/m^{2}s start in the range of 1,800-2,000 W/m^{2}K and increase up to 2,200-2,600 W/m^{2}K. To cover most fluxes conservatively, a constant 2,000 W/m^{2}K will be assumed. This value can be adjusted depending on the simulation results or replaced with a physical model to calculate a HTC. During an testing phase to evaluate the Modelica model, a cooling stream of water is maintained at a fixed inlet temperature of 15°C (59°F) and flow rate of 0.25 L/min (0.066 GPM). The HX model also supports discretizing into cells to separate the analysis into several segments along the HX area.

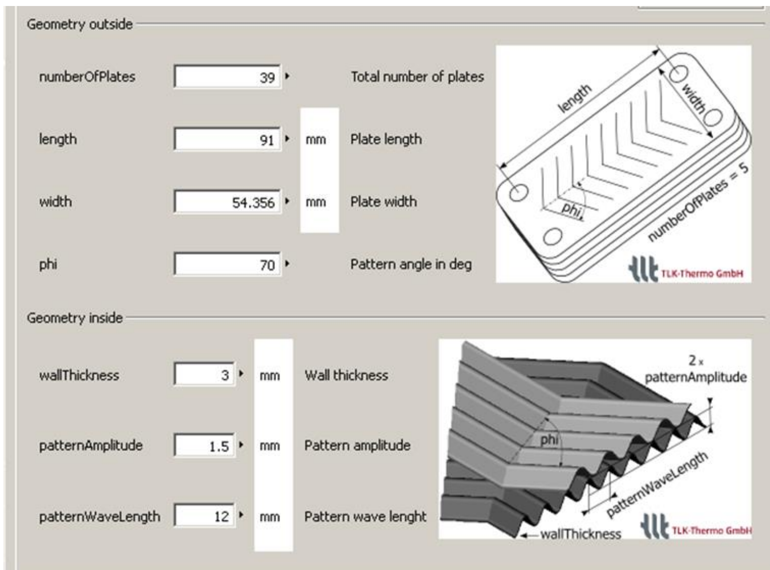

Figure 3: RF Water-cooled Condenser – Modelica Flat-Plate Model Geometric Inputs

3.5 Flat Plate Heat Exchanger – Water-to-water

A 14 plate water-to-water heat exchanger is loaded into the Modelica model to represent another HX available on-hand.

3.6 Fin-and-Tube Heat Exchanger

A basic, single circuit finned tube HX is used for the CD exhaust duct. A piping diameter of 10.21 mm (½ in) and a fin density of 13 FPI are used.

3.7 Simulation Assumptions

The various fixed temperature levels loaded into the model are collected using representative values of the operation of each appliance. Due to many appliances having a variable temperature source, a conservative estimate of a constant temperature is used where any high temperatures of the cycle are not collected. The RF is assumed providing 40°C, the CW provides 35°C, and the DW demands at 40°C.

4. SIMULATION RESULTS

4.1 Volume Impact on Tank Temperature

The water tank temperature as a function of time for varying tank volumes of 114 liters (30 gallons), 225 liters (60 gallons), and 454 liters (120 gallons) are shown in Figure 4. The collection flow rate was fixed for all appliances at 7.6 liter/min (2 GPM). The rate of temperature rise is higher as expected with the lower volume tank but by the sixth day, the largest tank starts to reach the temperature level of the smallest tank.

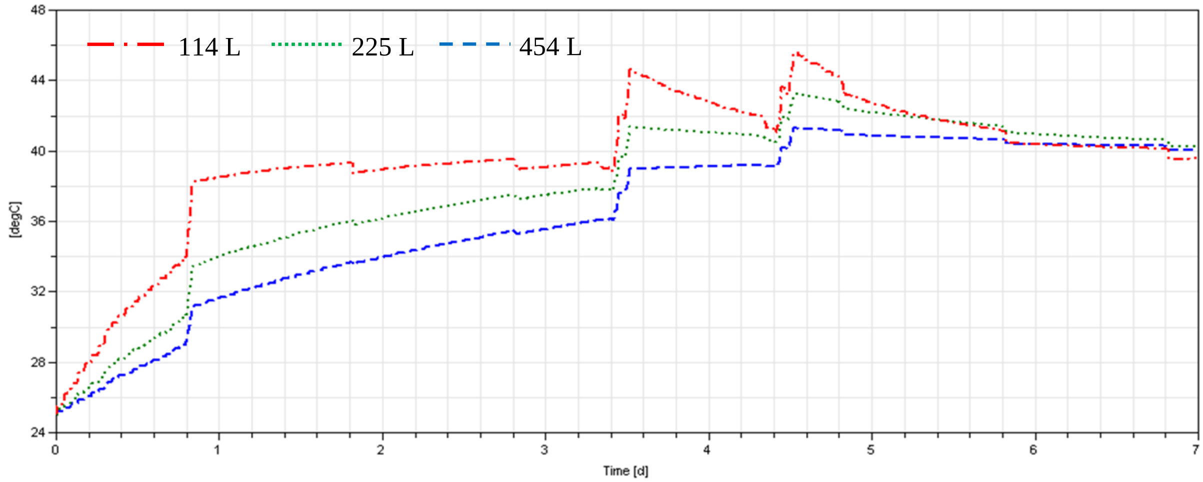

Figure 4: Storage Tank Temperature over Time

4.2 Impact on Heat Recovery Rate

As the tank heats up, the temperature rise impacts the amount of heat possible to extract from each appliance. The trends can be seen in Figure 5 for a tank volume of 454 liters (120 gal.).

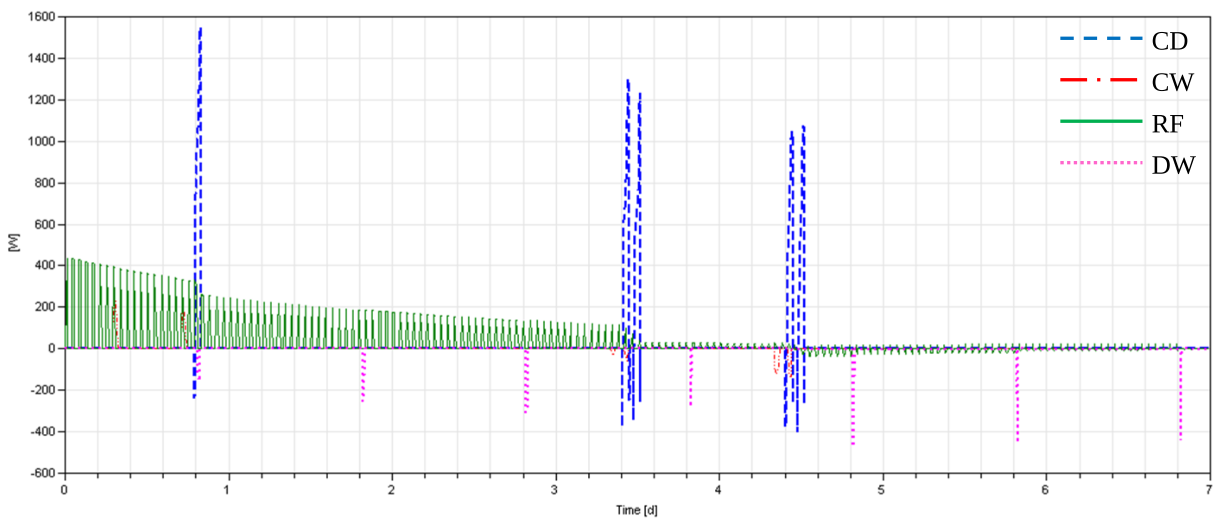

Figure 5: Rate of Heat Transfer between each Appliance and 454 L (120 gal.) Storage Tank

4.3 Energy Recovered

The amount of energy delivered or removed by each appliance by the storage tank is shown in Figure 6.

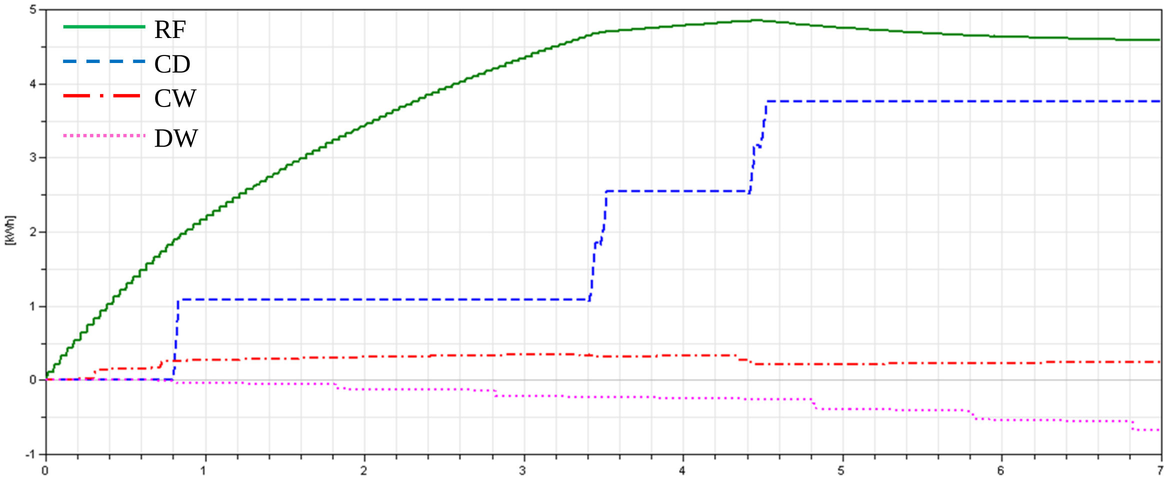

Figure 6: Amount of Energy Collected by Each Appliance with 454 L (120 gal.) Storage Tank

5. DISCUSSION

Different interactions between appliances result in a rate of heat input to the central storage tank. After the initial start-up at a lower tank temperature, the amount of heat transfer declines as the tank temperature starts to approach the fixed source temperatures of the individual appliances. The heat being utilized by the appliances is normally wasted. The ability to find a second use with this heat is significant. By implementing the approach of thermally integrating appliances under a conservative market penetration of 25%, and extending the amount of heat recovered on a weekly basis, the U.S. energy consumption could be reduced by 0.011 EJ (0.01 Quads) annually.

The actual system will experience heat loss between heat gain periods. Accounting for standby heat losses from the ambient on the storage tank can be done by adding a fixed temperature boundary and applying a layer of insulation to the tank. Additional considerations of the transient behavior can be done by modeling the piping material between each appliance and storage tank. Here the piping when cooled to room temperature can add to the losses experienced by the real system from the cycling behavior. Other improvements to the model includes variable flow rates, capturing thermal stratification in the storage tank with the ability to charge to different temperature volumes, and time-varying heat inputs representing the source from the appliance instead of basic fixed temperature inputs. Appliances thermally connected to a storage tank create a progression to combine with other residential systems using water as thermal storage. A basic and quick integration with the domestic hot water system is the first logical choice. In addition, integration to a solar warm or hot water system or to an HVAC system can be considered. One barrier to the adoption of new, highly efficient appliances is third-party decision makers. Typically, ther are developers, who purchase the equipment but do not pay the utility bills (Bansal et al., 2011). Creating a packaged, integrated appliance system for installation in new construction could appeal to developers with lower labor costs for installation and smaller dead volume in the building layout. Having all appliances connect to a single, cold water supply, the installation is easier and thus, becomes attractive to the installer. Additionally, the standard expectation of homes providing access to all five major appliances makes an integrated approach intuitive. The development of new appliances should be within a connected system instead of individual components operating independently.Due to safety regulations limiting the charge of hydrocarbons used in domestic systems, water cooled condensers used in domestic RFs could enable larger capacity RFs to use low GWP, natural, hydrocarbon refrigerants.

The next steps for the work are to take the simulation prediction and compare to experimental data collected from a benchtop test stand that captures the integration approach proposed.

6. CONCLUSIONS

The approach of thermally integrating appliances provides energy saving benefits that can aid in the improvement of energy usage in U.S. residences. A Modelica simulation takes in the operation characteristics of four major appliances and interfaces them with a storage tank to provide a mechanism of sharing heat. The amount of energy recovered or delivered is impacted by the temperature level of the storage tank. If 25% of homes deployed this technology, the U.S. energy consumption could be reduced by 0.011 EJ (0.01 Quads) per year using realistic assumptions of home appliance usage. Improvements of the tank model and the four approaches for each appliance would provide improved confidence in the predicted energy consumption reduction.

NOMENCLATURE

CD	clothes dryer	GPM	gallons per minute
CW	clothes washer	GWP	global warming potential
DHW	domestic hot water	HX	heat exchanger
DW	dishwasher	RF	refrigerator freezer

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