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ABSTRACT

With the United States being the world's second largest consumer of primary energy, research into areas of significant consumption can provide large impacts in terms of the global energy consumption. Buildings account for 41% of US total energy consumption with the residential sector making up a majority. Household appliances account for the second largest site energy consumption at 27%, after the HVAC system for the U.S. residential sector. By quantifying the expected energy available in the waste stream for five major appliances; household refrigerator, clothes dryer and washer, dishwasher, and cooking oven, a potential energy source is presented. A cold water cooling stream is applied to the waste stream of each appliance and an estimated amount of energy can be recovered. The household refrigerator is modeled having an increase in cooling capacity of about 12% and a reduction on compressor power consumption of about 26%. A sample operation of the clothes dryer has the exhaust air stream being cooled down to 30.5°C (86.9°F) or on the other side, is able to heat 19 liter (5 gal) of water up to about 54.5°C (130.1°F). Large volumes of water are available by the clothes washer, but due to typical operation characteristics, low wash and rinse temperatures, the waste stream was not high in temperature. While the dishwasher provided higher heat source temperatures, 40°C (104°F), than the clothes washer, 36°C (97°F), the opposite was true. The volume of waste water drained is very low compared to the clothes washer 11.7 liter (3.1 gal) to 155 liter (41 gal). Thus water temperatures in the storage tank did not reach above 30°C (86°F) even with low storage volumes. The cooking oven can generate very high water temperatures depending how small of a storage tank is connected. Further work in this area is recommended due to the potential of high water temperatures generated from residential waste energy streams not currently being captured, and thus can offset some site-energy usage.

1. INTRODUCTION

The United States has fallen to second place behind China as the largest consumer of energy in the world with less than a quarter of the population. The US consumed 103.2 EJ (97.8) quads of primary energy in 2010 (Buildings Energy Data Book, 2011). Reducing the energy consumption of the US provides an effective mechanism to achieve significant reductions to the world total energy consumption. The U.S. DOE breaks down the energy picture across four sectors: transportation, commercial, residential and industrial. The building sector which combines both the commercial and residential sectors accounts for the largest consumer at 41% of the US total compared to 29% from the transportation sector and 30% from the industrial sector. A further look into the energy consumption of the building sector shows 41 EJ (39 quads) of primary energy provided only 21 EJ (20 quads) of site energy at an energy loss of 49%. A large source of these losses occurs from on-site electricity usage. From the production at the power plant to the transmission and distribution of electricity through the grid, many conversion and resistive losses occur. Exploring methods to reduce the on-site electrical usage will expand the impact of the local energy savings. Due to the residential sector having a slightly larger consumption over the commercial sector, 22% versus 19%, the focus will be on addressing the residential energy picture.

The largest percentage of residential, site energy usage is from the heating, air conditioning, and ventilation (HVAC) system, 54%. The next significant percentage 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). Countless studies have been conducted to reduce building HVAC energy by exploring various improvements on the HVAC equipment to upgrading building materials obtaining reductions in the thermal demand of the home. For household appliances, the research has been focused only on the appliance itself and less on the external factors to the appliance. The use of federal standards propels exploration and adoption of new technologies by appliance manufacturers. One example for household refrigerators is the average, annual electricity use in 1980 of about 1300 kWh drops to about 950 kWh in 1990 and then is under 700 kWh by 1992 due to the introduction of new energy efficiency standards in 1990 and 1993 (Meyers *et al.*, 2003). While the use of federal standards can create reductions in the individual appliance energy usage, they force appliance manufacturers to only consider improvements within the scope of one appliance. New savings exist when one considers the waste streams available from each appliance that is not covered by the standards. The refrigerator rejects heat to air behind or beneath the unit. Clothes washers and dishwashers drain hot or warm water after each wash and rinse cycle. Clothes dryers exhaust hot, moist air to the exterior of the building. Cooking ovens have thermal mass with very high temperatures at the end of a baking cycle. The goal is to identify the amount of heat and the associated temperatures available from these waste streams and to explore the amount of reuse possible through heat recovery.

2. U.S. APPLIANCE CHARACTERISTICS

To develop an understanding of the waste energy profile of household appliances, their standard operation and typical usage characteristics had to be understood. The total number appliances installed in the United States are identified. If available, a distinction is made between the different technologies available driving the appliance. For example, clothes dryers heated by gas combustion or electric resistors. The energy usage per appliance is reported as an annual or per cycle energy consumption. Usage characteristics are applied for appliances with cycle energy consumption to estimate annual energy consumption. Published or manufacturer data provides typical operational parameters of the appliance; volume and temperature of water being drained by the clothes washer and dishwasher, temperature and humidity of exhaust air by the clothes dryer, vapor compression cycle of a household refrigerator, and the metal cavity mass of the cooking oven.

2.1 Household refrigerator

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). Two configurations are the most common: top-mount freezer accounts for 49% of all refrigerators while the side-by-side accounts for 34%. In 2008 the median volume and annual electricity consumption for the top-mount freezer and side-by-side were 510 liter (18 ft^3), 454 kWh and 710 liter (25ft^3), 580 kWh respectively (Refrigerator Market Profile, 2009). A higher annual consumption of 660 kWh is projected when under certain test conditions specified by the Department of Energy (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). As an example, the maximum annual energy consumption under the current standards; a top-mount freezer with no icemaker and a rated capacity of 510 liter (18 ft^3), can use 403 kWh for the federal standard and 363 kWh for Energy Star. For the other common configuration, a side-by-side with an icemaker and a rated capacity of about 710 liter (25 ft^3), must have a maximum annual consumption of 705 kWh for the federal standard and 634 kWh for Energy Star. Comparing the median values from 2008 to the 2014 federal standard, a reduction of 11% is reported for the top-mount freezer, while for the side-by-side, an increase of almost 10% is found. One potential reason for the allowable increase for the side-by-side is having an icemaker puts the refrigerator into a different category for the federal standard, and thus provides a higher annual consumption to handle ice making.

Experimental data collected by the manufacturer during a standard DOE test run was obtained for a 750 liter (26.5 ft^3) rated volume, 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). Many cycles of the compressor turning on and off are captured during the 48 hour test. The ambient and refrigerated cavity conditions are relatively constant during the testing span and only one cycle is needed to understand the operation of the refrigerator. The ambient and freezer compartment (location of the evaporator) temperatures measured were 32.2°C (90°F) and -16.6°C (2.1°F) respectively. Air flow rates of 85 m^3/hr (50 CFM) and 68 m^3/hr (40 CFM) were assumed for the evaporator and condenser. Air side measurements were used to obtain an estimated heat transfer rate for each heat exchanger. 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. Using the ambient and freezer compartment temperatures for heat sink and source reservoir temperatures, a Carnot COP provides the ideal cycle efficiency for cooling and heating. Dividing the measured cooling and heating COPs by the Carnot COP generates a 2nd law efficiency temperature. The data shows a cooling second law efficiency of 27% and a heating second law efficiency of 40%. 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. The total annual energy consumption is therefore 0.077 EJ (0.073 quads) for all side-by-side refrigerators.

2.2 Clothes dryer

The number of U.S. households that use a dryer at home is 90.2 million with 80% having electrically heated ones versus 20% using natural gas or propane/LPG (Table HC3.1 RECS, 2009). Only electrically heated clothes dryers will be considered due to the small percentage of combustion heated dryers. 74.4 million households report the dryer is used every time clothes are washed which provides some insight to the correlation between clothes dryer and washer usage. 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. While all these factors directly impact the amount of heating energy delivered by the electric resistor, the motor electricity consumption will be relatively constant regardless of dryer inputs. 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.

Due to the large number of different inputs available and the associated number of different combinations for the dryer operation, experimental data from a published study presents exhaust air conditions used for 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). Two plots identify the baseline operation for measured temperatures at various locations throughout the dryer starting from the ambient air intake to the exhaust air, and relative humidities of the ambient, interior cabinet, and exhaust. The parameters of interest here are the exhaust air temperature and relative humidity leaving the appliance. Curve-fits are generated off the two plots in the study by picking points evenly along the curves of interest and applying a polynomial fit to the points found using a spreadsheet software. 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 about 6.8 m/s (1337 ft/min) and assuming a 10 cm (4 in) diameter exhaust duct, the exhaust volumetric air flow rate is 200 m^3/hr (117 CFM). The heating element drew an average of 22.8 amps while the electric motor drew an average 4.35 amps. The power supply for electric dryers is typically higher voltages, 220 volts, for a lower amp draw. The baseline test lasted 1 hour and with the known power consumption would result in 5.97 kWh consumed over the entire cycle. Clothes dryers are often rated by their moisture extraction rate, MER, a ratio of the drying energy used divided by the wet clothing weight at the start of the drying cycle. For the data shown here, a MER value of 0.5914 kWh/kg is calculated. If 283 cycles per year are run with a power consumption of 5.97 kWh per cycle, an annual power consumption of 1690 kWh is determined. Including the total number of homes with an electric dryer, the total annual energy consumption with this drying profile is 0.44 EJ (0.416 quads).

2.3 Clothes washer

The total number of U.S. households having a clothes washer is 93.2 million homes, slightly more than the number of households with clothes dryers (Table HC3.1 RECS, 2009). While there are two different clothes washers to consider, top loading, vertical axis machines versus front loading, horizontal axis ones, the predominate type is the top loading washer at 81% of all clothes washers used. Many sources were found for the number of wash cycles per year. The smallest value reported was 289 for North American in a worldwide study of washing machine usage which is close to the number of dying cycles assumed (Pakula *et al.*, 2010). The largest value mentioned, 1.21 loads per day or 442 cycles per year, was obtained from a two-month, field demonstration in Bern, Kansas comparing vertical and horizontal washing machines (Tomlinson *et al.*, 1998). One value was found in two reports, 392 cycles per year, from the Texas Water Development Board and the DOE (7.2 Residential Clothes Washer, 2013) (Table 2.1.16 Buildings Energy Data Book, 2011). A final source provided a breakdown of the number homes for a range of loads per week (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.

The energy consumption per cycle of clothes washers is sometimes reported with the energy required for generating the hot water used during the wash cycle in spite of the energy being spent externally to the appliance. Low average wash temperatures for North American result in low energy consumption levels due to reduced energy required for heating water, 0.43 kWh per cycle (Pakula *et al.*, 2010). Annual energy consumption at this level with 289 cycles is 124 kWh. On the same magnitude, 110 kWh is reported when excluding energy required to heat water used by the appliance (Table 2.1.16 Buildings Energy Data Book, 2011). 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).

The waste stream of clothes washers is the elevated temperature water at the drain of the appliance. To accurately determine the amount of energy available, the volume of water drained and the associated temperature is required. The type of washing machine greatly impacts the volume of waste water leaving due to the different methods employed to agitate the clothing. Top loading washers require larger volumes of water to achieve the desirable cleaning performance compared to front loading machines. With a significant number of clothes washers 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). The extensive field demonstration is able to identify average water usage per cycle for top loaders at 157 liter (41.5 gal) covering a range of 68 liter (18 gal) to 227 liter (60 gal), and for front loaders at 98 liter (26 gal) covering a range of 64 liter (17 gal) to 140 liter (37 gal) (Tomlinson *et al.*, 1998). One report lists top loaders at 155 liter (41 gal) per cycle and high-efficient clothes washers between 42 liter (11 gal) and 95 liter (25 gal) per cycle (7.2 Residential Clothes Washer, 2013). 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. The remaining moisture content, RMC, of the clothes at the end of a wash cycle reduces the amount of water supplied to the appliance from making it down the drain. The type of clothes, load size, and maximum spin speed of the washer all impact the RMC. Front load washers operate at much higher spin speeds and result in lower RMC values than their top load counterparts. Comparing the total volume of water remaining in the clothes to the total volume of water used during the entire cycle results in a small percentage, 2-5%, of total volume left in the clothes. Thus the impact of the RMC on the energy available in the waste stream will not be accounted for.

The other piece of information needed on the waste stream is the temperature of the water being drained. Two separate processes occur during the entire washing machine cycle, a wash and then a rinse step. 48% of households report selecting a 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 a 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). While for a hot water wash, and cold water rinse, the same study showed higher percentages of all washing machine cycles, 17% to 25%. 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 around 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 Dishwasher

The market penetration of dishwashers in U.S. households is not as high as the other appliances covered so far. About 59% or 67.4 million households use a dishwasher (Table HC3.1 RECS, 2009). 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). The current Energy Star rating for dishwashers reduced the average, annual number of cycles from 264 to 215 (ENERGY STAR V.6, 2015). 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). For a conservative estimate, 215 cycles per year is selected for dishwasher usage covering 35% or 23.7 million households.

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). And for a compact dishwasher (less than 8 place settings) the annual energy usage must be less than 203 kWh or 0.94 kWh per cycle. 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 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 limits water usage to 13.2 liter (3.5 gal) per cycle and for a compact dishwasher, limits usage to 11.7 liter (3.1 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. The water usage of a standard, Energy Star dishwasher is used for the volume of waste water available. With a working water temperature around 50°C (122°F) being maintained by the internal electric heater, assuming some but minimal losses, result in an estimated drain temperature of 40°C (104°F).

2.5 Cooking oven

The number of U.S. households that have a stove is 102.3 million where 60% are heated by electricity and the remaining 40% are heating by direct combustion (Table HC3.1 RECS, 2009). The number of cooking cycles a year depends on the usage per day. Only 3.5% of all households are using an oven 3 or more times a day, while 31% are using the oven at least once a day. The largest jump in percentage of households occurs when the oven is only used 2-3 times a week or 104-156 cycles a year. To capture a large number of ovens, 104 cycles a year is assumed to capture 72.1 million households. In the U.S. electric ovens annually consumed an average of 444 kWh (Hager *et al.*, 2013). An annual usage of combustion driven ovens could not be found in the literature. Therefore only electrically driven ovens will be considered. With the 104 cycle and 444 kWh per year assumption, the oven is estimated to use 4.27 kWh per cooking cycle. To determine the mass of metal creating the oven cavity, a cavity size must be determined. Referencing the local, building supply retailers identifies the most common oven size at about 150 liters (5.3 ft^3) for a free-standing range having a self-cleaning feature. The waste heat recovery of the cooking oven will utilize only the energy from an elevated temperature, metal cavity. Self-cleaning ovens offer the consumer a convenience and for waste heat, a bonus with a higher temperature heat source at the end of the cooking process. The rough cabinet dimensions for the oven cavity selected are 71 cm by 66 cm by 33 cm (28 inches by 26 inches by 13 inches). Assuming a wall thickness of 0.635 cm (1/4 inch) and using the calculated surface area of the oven, not including the door, of 1.6 m^2 (17.3 ft^2), the total estimated volume of the metal oven cavity is 0.0102 m^3 (0.36 ft^3). Assuming the oven cavity is made from steel with a density of 7,900 kg/m^3 (493.5 lbs/ft^3); the resultant mass of the cavity is about 80 kg (178 lbs). A cooking temperature of 204°C (400°F) is assumed as the initial temperature of the oven cavity at the end of a cooking cycle.

3. METHODS AND PROCEDURES

3.1 Transient Analysis

Both the household refrigerator and the clothes dryer generate a waste heat steam that is occurring over time. When the refrigerator compressor turns on, it rejects heat either to the ambient air as in a normal application or is rejected to a cooling water loop with a water to refrigerant heat exchanger. For the clothes dryer, the exhaust air is typically sent outside the home, but for heat recovery, a fin and tube heat exchanger is placed in this exhaust stream and a cooling water loop provides an ability to recover the sensible and latent heat leaving the dryer.

To simplify the analysis, a lumped parameter, heat transfer effectiveness of 80% is assumed for all heat exchangers, waste heat and the vapor compression cycle heat exchangers. The maximum heat transfer is determined by cooling or heating the refrigerant to the inlet conditions of the air or water streams. The experimental data from the manufacturer for the refrigerator is used to provide the compressor displacement and the cycle improvements implemented in a standard household refrigerator. Modeling the suction line heat exchanger attached to the capillary tube was captured by further cooling the subcooled liquid leaving the condenser with the leaving refrigerant vapor of the evaporator. The expansion process then was assumed to be isenthalpic. The subcooling leaving the condenser and the superheat leaving the evaporator were both assumed to be 5°C (9°F). Due to the suction line heat exchanger, this means additional subcooling is created for a larger evaporator capacity while sacrificing some of the compressor efficiency with higher suction superheat. Additional properties of the compressor were assumed to roughly model the compression process. A volumetric efficiency of 95%, an isentropic efficiency of 80%, and 20% of the input power into the compressor is lost as waste heat to the ambient. The evaporation and condensing conditions are free to move depending on the heat sink and source temperatures being exposed to the respective heat exchangers. For the clothes dryer, the exhaust air stream dew point temperature is checked with the incoming cooling water temperature to determine if the coil is wet or dry. If the inlet water temperature is below the exhaust air dew point, then the exit air temperature of the waste heat exchanger is at saturated conditions. Otherwise when the cooling water temperature is above the dew point, the humidity ratio is kept constant across the waste heat exchanger.

The strategy for measuring the available heat recovery during the transient process is to explore different volume sizes of water storage tanks and cooling water flow rates. The storage tank supplies the waste heat exchanger with cool water where it picks up heat and returns to the storage tank. Over time the tank temperature should rise in temperature depending on amount of heat being rejected to the water stream. Smaller water volume tanks and flow rates should obtain higher temperature at the end of the transient process. While this higher temperature water has more potential to offset energy usage in another location of the home, less total energy is recovered from the waste stream due to the higher sink temperatures for cooling.

3.2 Bulk Analysis

Due to the infrequent available heat source from the clothes washer, dishwasher, and cooking oven, all the available thermal energy is considered as a bulk source. A fixed volume of cooling water is brought into contact with the fixed volume of waste water or thermal mass as in the case of the cooking oven, to reach thermal equilibrium. Decreasing the volume of cooling water used causes the final temperature to approach the original temperature of the heat source. Maximizing the temperature of cooling water provides a higher availability energy input to another heat demand, and thus reducing the amount of external energy required. A trade-off exists between maximizing the heat recovery from the waste stream of the appliance with larger volumes of cooling water, and maximizing the supplemental heat provided to another process from smaller cooling water volumes providing higher temperatures.

4. MODELING RESULTS

4.1 Transient Heat Generation

Four different tank volumes were run for the refrigerator model covering a typical cycle time of 50 minutes and a cooling water flow rate of 1.9 liter/min (0.5 gal/min). A summary of the water tank temperature at the end of the cycle run for each tank volume is shown in Table 1. The tank volume sizes were selected based off a desirable water temperature.

Table 1: Summary of household refrigerator performance with water cooling and air cooling condenser

Cooling Stream	Tank Volume [liter/gal]		Maximum Tank Temperature [C/F]		Total Evaporator Energy [kJ]	Total Compressor Energy [kJ]	Avg. Cooling COP [-]
Water	19	5	28.58	83	753.6	198.4	2.71
Water	15	4	32.5	90	745.8	205.3	2.62
Water	11	3	39	103	730.8	217.8	2.47
Water	7.6	2	55.9	132	694.2	246.8	2.17
Air	-		-		669.6	267.6	2.20

To see the transient analysis of the tank temperature for the same tank sizes, Figure 1 shows 4 curves with the same conditions shown in Table 1.

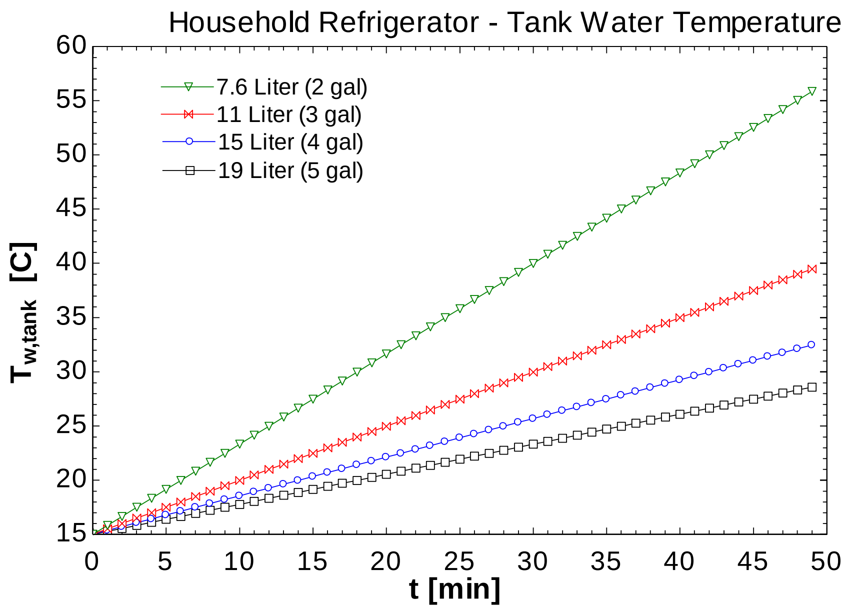

Figure 1: Storage tank temperature for water cooled condenser of household refrigerator

A summary of the clothes dryer simulation runs is shown in Table 2. As the tank size increases the percent of energy recovered increases but the maximum tank temperature decreases. Also the air outlet temperature of the heat recovery process decreases, providing a better possibility of allowing the dryer exhaust to be vented indoors instead of outdoors.

Table 2: Summary of clothes dryer heat recovery

Tank Size [liter/gal]		Start Tank Temperature [C/F]		End Tank Temperature [C/F]		Max Air Outlet Temperature [C/F]		Total Heat Recovered [kJ]	Total Energy Input [kJ]	Percent Energy Recovered
378	100			22.2	72.0	30.5	86.9	11408		51.8%
113	30			33.0	91.4	39.1	102.5	8369		38.0%
76	20	15	59	37.7	99.8	42.9	109.2	6937	22041	31.5%
38	10			45.4	113.7	49.1	120.3	4471		20.3%
19	5			54.5	130.1	56.3	133.4	2668		12.1%

To understand the impact of the storage tank size for the same water flow rate as the refrigerator, 1.9 liter/min (0.5 gal/min), Figure 2 shows the tank temperature as a function of time. As the volume decreases from 113 liter (30 gal) to 19 liter (5 gal), the final tank temperature at the end of the drying cycle goes from 33°C (91.4°F) to 54.5°C (130°F).

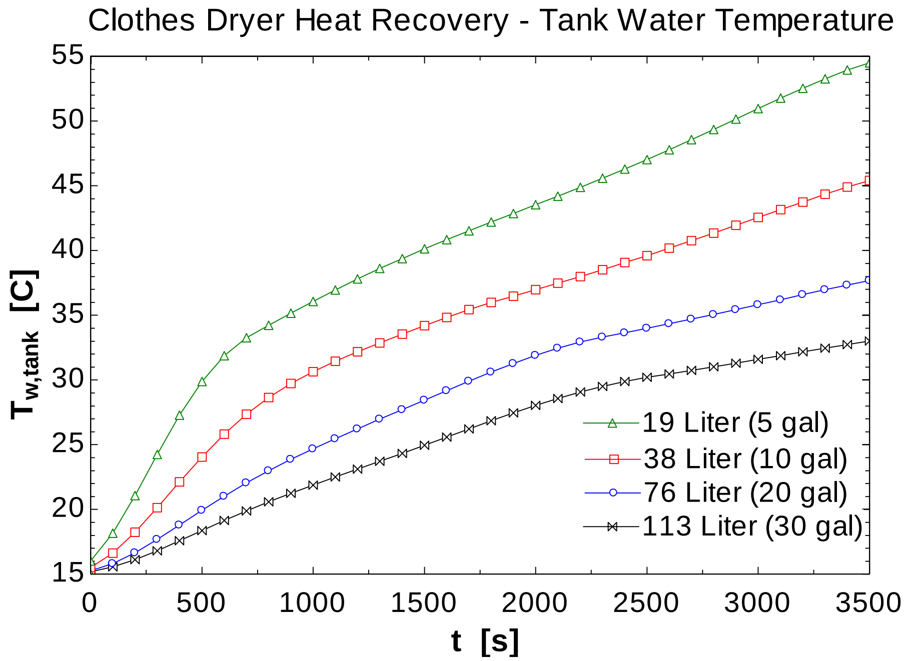

Figure 2: Impact of the storage tank volume size on the water temperature stored in the tank

A secondary benefit of having heat recovery at the exhaust of the dryer is the reduction of the dryer air exhaust temperature and the removal of moisture from the exhaust stream. Figure 3 provides an indication of the exhaust air stream leaving the heat exchanger changes as the storage tank increases in temperature over time.

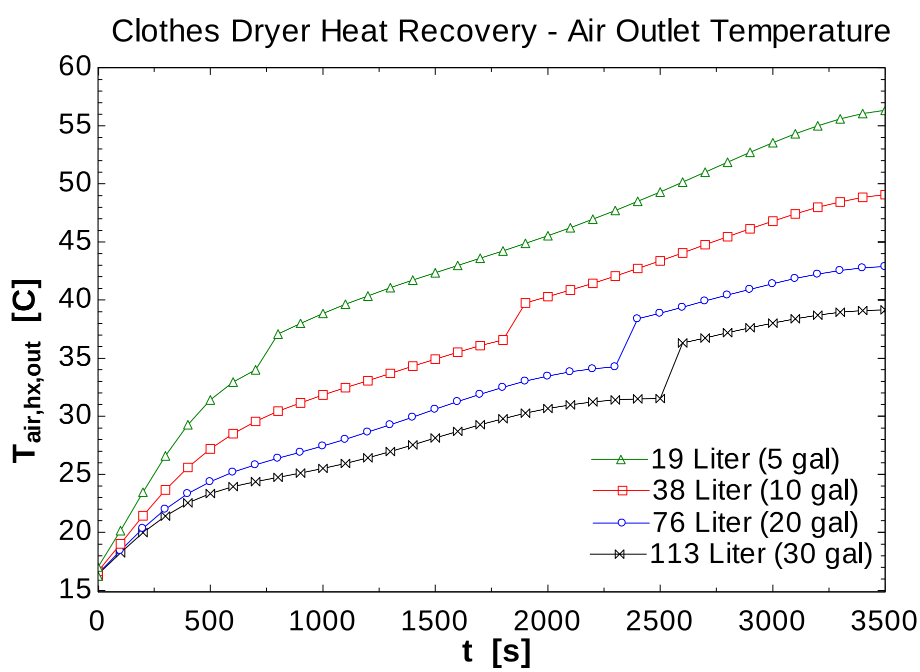

Figure 3: Cooled dryer exhaust air leaving the waste heat exchanger as a function of the storage tank volume

4.2 Bulk Heat Generation

Using the assumed cycle parameters for each appliance providing a bulk energy source, the amount of heat recovered by the cooling water source is calculated for a number of tank volumes. A summary of all the results is listed in Table 3. The assumed cycle energy per cycle presented in section 2 is converted from kWh to kJ to calculate a percent of energy input recovered by the cooling water source.

Table 3: Summary of bulk energy recovery from the clothes washer, dishwasher and cooking oven

Tank Volume [liter/gal]		Clothes Washer [8136 kJ/cycle] Final Tank Temperature [C/F]		Clothes Washer Heat Recovered [kJ]	Clothes Washer % Recovery [-]	Dishwasher [4536 kJ/cycle] Final Tank Temperature [C/F]		Dishwasher Heat Recovered [kJ]	Dishwasher % Recovery [-]	Cooking Oven [15372 kJ/cycle] Final Tank Temperature [C/F]		Cooking Oven Heat Recovered [kJ]	Cooking Oven % Recovery [-]
7.6	2	34.9	94.8	700.7	8.6%	30.0	86.1	546.2	12.0%	123.9	255.0	3530	23.0%
15.1	4	33.9	93.1	1339	16.5%	25.4	77.7	799.6	17.6%	90.5	194.9	4923	32.0%
22.7	6	33.0	91.4	1922	23.6%	22.7	72.9	945.8	20.9%	72.3	162.1	5652	36.8%
30.3	8	32.2	89.9	2457	30.2%	21.0	69.8	1041	23.0%	60.9	141.7	6096	39.7%
37.9	10	31.4	88.6	2951	36.3%	19.8	67.6	1108	24.4%	53.2	127.8	6398	41.6%
45.4	12	30.7	87.3	3407	41.9%	18.9	66.0	1158	25.5%	47.6	117.7	6615	43.0%
53.0	14	30.1	86.1	3829	47.1%	18.2	64.7	1196	26.4%	43.4	110.1	6776	44.1%
60.6	16	29.5	85.0	4222	51.9%	17.6	63.7	1226	27.0%	40.0	104.1	6902	44.9%
68.1	18	28.9	84.0	4588	56.4%	17.2	62.9	1251	27.6%	37.4	99.3	7004	45.6%
75.7	20	28.4	83.0	4929	60.6%	16.8	62.2	1271	28.0%	35.2	95.3	7086	46.1%

5. DISCUSSION

There exists a strong trade-off between the tank volume of water used to circulate for heat recovery and the final temperature at the end of the appliance cycle. While smaller tank volumes provide higher water storage temperatures which are useful as a direct input to another appliance cycle, smaller percentages of the energy recovery result due to the higher water temperatures being delivered to the appliance. An improved analysis would be to calculate the availability or exergy of the heat recovered by the water cooled heat exchanger. Most of the input energy for all appliances is pure exergy in the form of electricity since it can be used to perform any task. Once it is converted by the appliance into useful work through refrigeration, cooking or wet cleaning, much of this potential energy is destroyed. The leaving waste stream is now low in availability due to the low temperature and its close to a dead state where no more useful work can be extracted.

An improvement of the work presented here would be to have one fixed volume tank and conduct a large transient analysis where different appliances would come on and off. This approach would explore potential benefits or pitfalls when larger storage tanks are used to combine all the waste heat into one location. Additionally, the ability to offset some of the household domestic hot water would be introduced by adding in a hot water schedule relative to the appliance schedule.

While the experimental data referenced for the clothes dryer was very detailed and provided an easy way to calculate the available energy from the waste stream, the drying conditions seen might not be fully representative of a typical cycle. The clothing load was large and the heat setting was on high. Obtaining exhaust air data for different dryer conditions would properly identify an optimal tank size for circulating the cooling water.

6. CONCLUSIONS

Household appliances account for the second largest site energy consumption, 27%, after the HVAC system for the U.S. residential sector. Many approaches explored in the past to address this area were mainly focused on only the appliance itself. If the scope for improvement also considers factors external to the appliance, there is the potential for greater energy savings. By quantifying the expected energy available in the waste stream for five major appliances; household refrigerator, clothes dryer and washer, dishwasher, and cooking oven, a potential energy source is presented. A cold water cooling stream is applied to the waste stream of each appliance and an estimated amount of energy can be recovered. The household refrigerator is modeled having an increase in cooling capacity of about 12% and a reduction on compressor power consumption of about 26%. A sample operation of the clothes dryer has the exhaust air stream being cooled down to 30.5°C (86.9°F) or on the other side, is able to heat 19 liter (5 gal) of water up to about 54.5°C (130.1°F). A different modeling approach is used for the bulk energy sources. A large volume of water was available by the clothes washer, but due to typical operation characteristics, low wash and rinse temperatures, the waste stream was not high in temperature. The highest temperature of water generated was at 35°C (95°F). While the dishwasher provided higher heat source temperatures, 40°C (104°F), than the clothes washer, 36°C (97°F), the opposite was true in that the volume of waste water drained is very low compared to the clothes washer 11.7 liter (3.1 gal) to 155 liter (41 gal). Thus storage tank water temperatures did not reach above 30°C (86°F) even with low storage volumes. The cooking oven can generate very high water temperature depending how small of a storage tank is connected. There exists a controls risk when preventing the cooling water stream from reaching the boiling point and creating steam. Further work in this area is recommended due to the potential of high water temperatures generated from waste energy streams not currently being captured.

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