Thermoelectric heat pump clothes dryer design optimization

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Abstract

Clothes dryers based on thermoelectric (TE) heat pumps have the potential to save significant energy compared with the conventional electric resistance technology that is widespread today, without using any refrigerant fluid. In this work, guided by a validated system model, design and control improvements were implemented on an experimental prototype to optimize the dryer performance (duration to dry a load, and energy consumed per unit cloth mass). Starting from a fixed TE area, the physical design variables of interest were (1) the use of vented or ventless configuration, (2) the heat sink geometry, (3) the selection of blower and (4) the selection of motor used to drive drum rotation. The control variables of interest were (5) the average electrical current supplied to each bank of TEs and (6) the current profile for each bank during the drying time. By optimizing each of these choices in the model and applying the resulting design choices on the prototype, the experimentally measured efficiency of the TE prototype was improved to 2.96 kg/kWh (6.52 lb/kWh), 38% better than an Energy Star qualified electric resistance dryer, and within 14% of a vapor compression heat pump clothes dryer.

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1. Introduction

Conventional tumbling-type clothes dryers which are prevalent in the US market today rely on electric resistance (ER) heating of the air stream circulating through the dryer drum, to create drying potential for humidity transport. They generally use an open configuration, where the hot air stream passes through the drum once, before being vented to the outside. On the other hand, heat pump clothes dryers (HPCD) take a more efficient approach by using the low-temperature side of the heat pump to first remove moisture from the dryer outlet stream. The

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high-temperature side is then used to heat up the air, before reintroducing it into the drum. This configuration allows for considerable savings in energy compared to ER clothes dryers. It also results in a closed loop and so does not require a vent, which also makes installation simpler.

Most HPCDs use a vapor-compression cycle with a compressor, evaporator, condenser and expansion valve and have a secondary working fluid (such as refrigerant HFC-134a). Their performance and energy efficiency has been the subject of several previous works, such as that by Ganjehsarabi et al. [1], who conducted an exergy and exergoeconomic analysis of a HPCD using actual thermodynamic and cost data. Using this method, they were able to determine the effect of varying the main operating parameters and their effect on overall exergy efficiency and total exergy destruction of the cycle. They also identified the components in the system with highest exergy efficiency and highest exergoeconomic importance.

Denkenberger et al. [2] conducted a study which compared several North American conventional ER dryers with European HPCDs. The high-level conclusions of the study were that HPCDs used only 40-50% as much energy as ER dryers to dry the same amount of laundry, although they took twice as long to do so. They determined that HPCDs are a globally mature technology with substantial energy saving potential. More recent research on a two-stage prototype HPCD was conducted by Cao et al. [3]. They compared energy consumption and energy factor (EF) between a commercially available ER dryer (from the US market), hybrid heat pump clothes dryer (from the European market) and their prototype. The prototype utilized advanced technologies to improve performance, including a two-stage vapor-injected compressor. The results showed that the prototype dryer was able to achieve 59% energy savings and improved EF by 143% compared to the ER dryer. It was also able to achieve 25% energy savings and improved EF by 33% compared to the commercially available HPCD. Although HPCDs are relatively widespread and offer significant energy-savings, their use of HFC-based working fluids which have high global warming potential (GWP) is cause for concern; recent efforts in HPCD research have therefore considered other low-GWP working fluids such as CO_2 in transcritical cycles [4, 5, 6].

Although VC cycles are primarily used in HPCDs, thermoelectric (TE) elements can also be used as an alternative, solid-state, refrigerant-free heat pump technology. Thermoelectric-based heat pumps introduce fewer moving parts into the clothes dryer system and do not have any refrigerant as a working fluid. They are made up of two distinct semiconductors which are sandwiched together in a thin layer. When a DC current is applied, a temperature difference is created between the two sides of the element [7], and the TE can be used as a heat pump. The coefficient of performance (COP) for a TE element is a function of the hot and cold side temperatures and the figure of merit (referred to as the ZT value) of the TE material [8]. In particular, as ΔT between hot and cold sides increases, the COP decreases. To optimize a TE-based heat pump clothes dryer, the effect of different component efficiencies, TE current levels/profiles and flow configurations must be studied on the mass of fabric dried vs. energy consumed. The objective of this paper is to identify the optimum component designs and configurations that result in the highest mass of fabric dried for the least amount of energy and lowest drying time. The optimization is performed using a thermodynamic system model which is validated with experimental studies on two prototype TE clothes dryers (referred to as the Generation 1 and 2 TE prototypes).

2. Physics of the System

The previous development of the TE dryer in [9] involved thermodynamic system modeling and fabrication of an experimental prototype which had a TE module at its core. It had closed-loop air circulation and its overall energy consumption and efficiency were characterized. However, its design was not optimized and there remained many avenues to consider in this regard. For the current optimization study, both closed and open TE dryer systems were studied. Schematics of the two configurations are shown in Figure 1. The closed loop system circulates air continuously through the system, whereas the open system requires a vent.

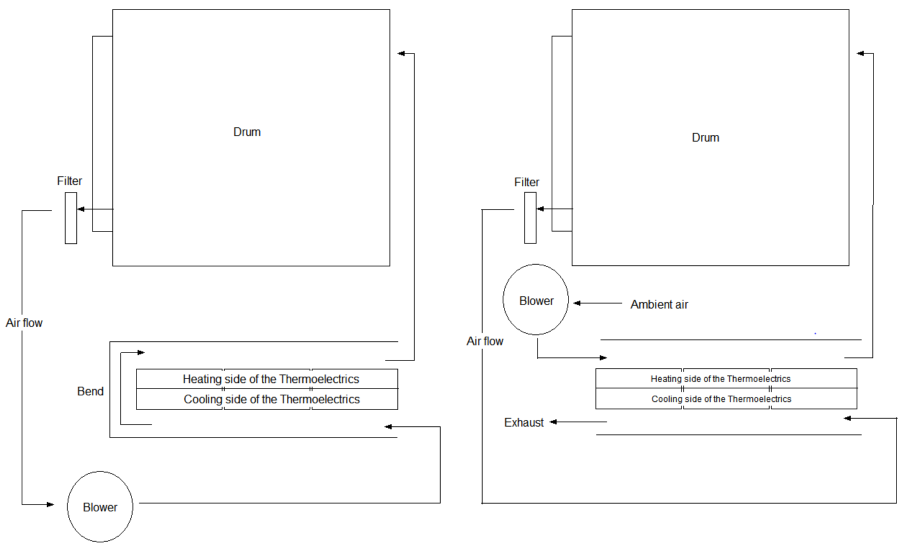

Figure 1: The closed (left) and open (right) TE clothes dryer systems

In the closed system, as air begins to flow through the system, it begins to pick up moisture in the drum from the wet cloth. The air leaving the drum now has a high relative humidity (RH) and is drawn through the blower and expelled towards the cold side of the TE heat sinks. The air here begins reducing in enthalpy. As energy is transferred, the air's temperature is reduced until it reaches its dewpoint temperature at which time condensation occurs. As moisture condenses out of the air, the ratio of mass of water to mass of dry air is reduced. The conditioned air then passes over the hot side TE heat sinks where heat is transferred to the air, thus raising its enthalpy without raising its moisture content, giving it a better ability to extract moisture from the cloth. This heated air re-enters the drum where it follows the same heat transfer process of moisture extraction discussed earlier. The air leaves the drum in a state near saturation and the process is repeated until moisture content of the cloth has reached the desired level.

In the open system, ambient air enters the blower and is directed directly to the heated TE heat sinks, increasing the air's enthalpy. The heated air enters the drum to extract moisture from the wet cloth. In the drum the air extracts moisture through the same process as the closed system. The air then passes through ducting to pass through the TE cold side heat sinks to transfer heat to the thermoelectrics. This keeps the cold side at a steady temperature; without this, the cold side temperature would keep decreasing and the COP of the TEs would suffer as a result. The air is then exhausted out of the system.

3. Thermodynamic System Model

3.1. Closed state

A key part of the system optimization process was creating a valid model of the system that can accurately predict any outcomes of system changes considered. As mentioned above, a steady-state, system level, coupled psychrometric and thermoelectric model for the closed system was created and its validation and calibration are detailed in [9]. The model inputs were the mass of the cloth, the clothes' moisture content (starting and final), the air flow rate and the current to the TE module independent variables. It utilizes psychometric functions to determine thermodynamic state points. With these, it is able to output the dry time and the dryer's efficiency. The model was created to fit the initial prototype, yet it can easily be modified to predict how system changes will effect experimental results. For example, to change the TEs in the system, only the thermophysical constants inside the code only have to be changed.

3.2. Switching to open state

A major system change considered that could not be modeled by the previously discussed model is the switch from a closed state to an open state system. To create the open system model, the flow through the state points were changed to mirror the actual experimental system. The ambient air experiences the same heat transfer that the conditioned air had experienced on the hot side heat sinks. The psychometrics of the air entering the drum are thus known and are subjected to the same heat transfer equations inside the drum. The only other model change is the fact that the air leaving the cold condensing side of the TEs is expelled out of the system after transferring heat to the cold side of the heat sinks in the same way it had done in the validated closed system. The variables that affect the model's accuracy are the RH and temperature of the ambient air. By carrying out the experiments in an environmental chamber**,** the open system model can very accurately predict the open state system.

4. Optimization of Energy Use

4.1. Heating capacity optimization

The experimental prototypes that were developed consisted of a TE module which had 3 banks of TEs. Each bank had a dedicated power supply, and all TEs within a bank were connected in series. One of the most important factors in the optimization of the system is the optimization of the heating capacities of the TEs, which is determined by the power supplied to them (i.e. the power level is changed by adjusting the current). However, the heating capacity does not vary linearly with power supplied to the TEs. The more power supplied to the TEs, the larger the temperature difference across them becomes, reducing their COP. In order to find the optimal power supplied to each bank, it is first necessary to characterize the Seebeck effect [8]. The model does this by changing the electrical resistance of a module using a linear regression dependent on the temperature difference across its associated bank. The linear regression is generated from experimental data. With this, a Pareto plot is created using a parametric table sweeping different combinations of currents to each bank. The Pareto front of this plot allows for the optimal current combination for a given dry time to be selected. Examples of the Pareto fronts can be found below.

4.2. Power profiles

In addition to variations in actual TE power levels described above, optimization of the power profiles was also studied. Constant current was typically applied, but due to the noticed lower drum efficiency at the end of the drying process, a power profile was implemented to make up for this. The idea behind the power profile was to increase the effect of drying in the drum at the end of the process by increasing the heat, to reduce the amount of time the blower and drum motor consumed power. However, the more efficient the drum motor and blower, the less of an impact this power profile has. The reason for this is that to increase heat, the power to the TEs must also be increased and as such, COP is reduced.

4.3. Open or closed state

Through the model, it was determined that an open system was more efficient than a closed system. The dry time of an open system is significantly shorter than the dry time of the closed system at the same heating capacity. This is primarily due to the difference in the removal of moisture from the system. Instead of condensing the moisture out (as in the closed system) the open system expels all of the moist air exiting the drum. The expulsion rate of moisture in the open system is simply greater than the condensing rate in the closed system. The shorter dry time means only a fraction of the energy used by the closed system is used by the open system, even if they have the same average power consumption.

4.4. Heat sinks

A key part of the system's optimization, was the optimization of the heat sinks in the TE modules between the Generation 1 and 2 prototypes. To have an efficient heat sink, it is necessary to have good heat transfer with minimal pressure drop across the sinks. This way the heat pumped by the TEs will raise the enthalpy of the air instead of raising the temperature of the heat sinks that would result in a higher ΔT across the TEs, thus lowering the COP of heating and cooling. The lower pressure drop created by a well-designed heat sink also allows for higher air flow and lower energy consumption for the blower. The optimization study resulted in changing the heat sinks from a pin-fin design in the Generation 1 prototype to a flat extruded-fin design in the Generation 2 prototype. A heat transfer and pressure drop model was developed to determine the ideal geometry for the heat sinks in the new TE module. It allowed for optimization of fan power consumption and TE heat transfer, and used heat transfer and pressure drop correlations available in the literature. The approach temperature and pressure drop were determined as functions of the fin geometry at a given air flow rate. The predicted pressure drop for the Generation 2 prototype heat sinks was significantly lower than that of the Generation 1 heat sinks, based on the correlations used from the literature.

4.5. Efficiency of the blower and drum motor

From the previous study [9], it was experimentally observed that the efficiency of the drum and blower motor can have a large effect on the overall system efficiency. For example, during a high-efficiency trial (where power consumption is minimized but dry time is long) the TEs are running at low power; this results in ~50% of power being consumed by the drum motor and blower. Therefore, improving the efficiency of these two mechanical devices results in large increases in the system's overall efficiency. For the selection of the blower, a careful analysis of the system pressure drop was conducted and an electrically commutated centrifugal fan was chosen to replace the Generation 1 blower. For the drum motor, measurement of the torque required to rotate the drum with a full test load was made to elucidate the expected power requirement, based on a rotation speed of 50 rpm. This allowed for precise sizing of an efficient DC motor and pulley assembly and reduced power consumption significantly.

5. Results of the Optimization

With all of the above considerations, the modeling and experimental optimizations were conducted. Figure 2 shows the Pareto plot with all of the above optimization cases for drying of an 8.45 lb (3.83 kg) load of clothes with a starting relative moisture content (water mass per mass of dry cloth) of 57.5%. The y-axes show the kg of dry cloth/kWh and lb of dry cloth/kWh (the latter of which corresponds to the Energy Factor in the US DOE standard test procedure [10]). Also shown are results from corresponding experiments for the respective Generation 1 and 2 prototypes. Experiments were performed for both open and closed systems for both prototypes at the air flow rates shown in Table 1. Table 1 compares some of the important measured quantities between the two prototypes. Compared to the Generation 1 prototype, the Generation 2 system had a lower pressure drop and higher corresponding air flow rate (due to improved heat sink design) and significantly lower blower and drum motor power consumption (due to selection of high-efficiency components). Experiments were performed to minimize dry time ("fast mode") and maximize energy factor ("eco mode"), among others. The lowest energy consumption (i.e. highest energy factor) was achieved with the Generation 2 prototype with an open system.

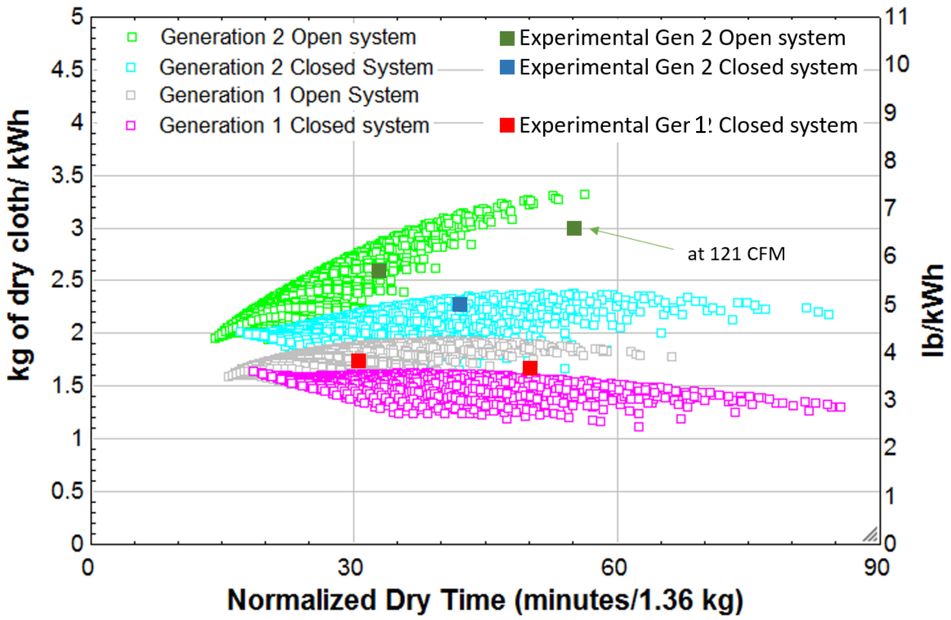

Figure 2: Pareto plot showing all optimization cases with experimental points overlaid

Table 1: Comparison of pertinent measured quantities between Generation 1 and 2 prototypes

Measured quantity	Generation 1	Generation 2
Max volumetric flow Rate	3.26 m^3/minute (115 CFM)	3.96 m^3/minute (140 CFM)
Pressure drop across heat sinks	822 Pa (3.30 in. H_2O)	286 Pa (1.15 in. H_2O)
Blower power	270 W	134 W
Drum motor power	240 W	100 W

6. Comparison of results to existing dryers

In addition to the optimization study, Figure 3 compares the overall energy consumption of the Generation 1 and 2 prototypes with energy consumption of an ERCD [11] and HPCDs [2].

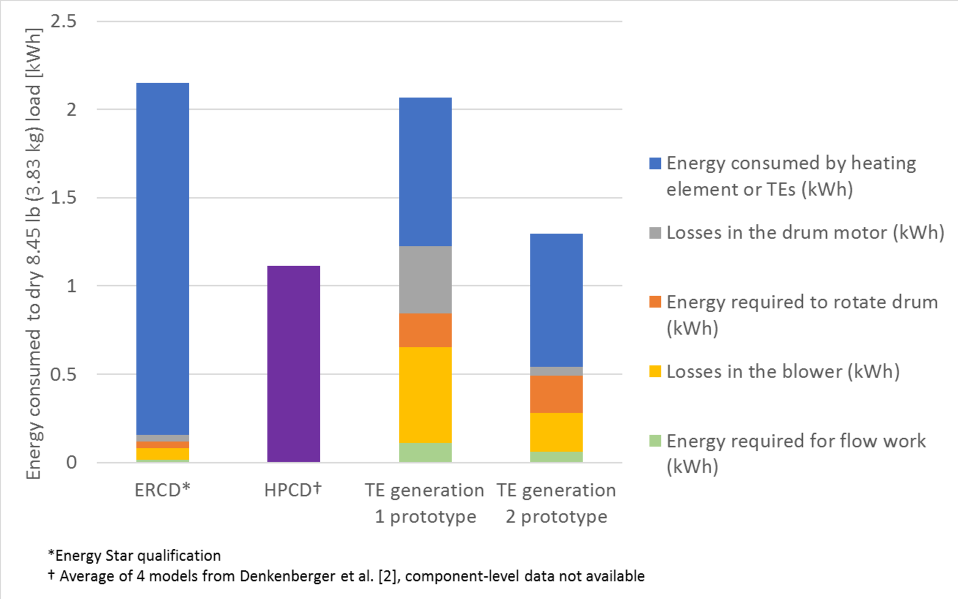

Figure 3: Comparison of energy consumption between commercially available ER and HPCDs with Generation 1 and 2 prototypes

Data for the ERCD are from the results published in [11]; and HPCD results from [2], [3], and [12]. The ERCD study was for a high-temperature, timed dry setting. For HPCDs, Denkenberger et al. [2] report on HPCD energy consumption of 4 commercially available HPCD models. These had EFs (under 2011 DOE test procedure with DOE standard cloth) ranging from 6.8 to 9.2, with an average of 7.6. Cao et al. [3] report on a commercially available model with EF up to 7.8, and a prototype two-stage vapor compression HPCD with EF of up to 10.4. Bengtsson et al. [12] reported specific moisture extraction rate for one commercially available model of up to 2.32 kg/kWh, which corresponds to an “EF” of 5.1 lb/kWh with starting and ending moisture contents of 69.5% and 5.6%. Since this number is in terms of mass of bone dry cloth, conversion is needed to make it directly comparable to the current DOE standard EF. It can be converted to an EF of 6.1 with 57.5% and 4% starting and ending moisture contents.

Although vapor compression-based HPCDs are generally performing at higher efficiency than the thermoelectric model developed in this work (with one exception identified above), this work is important for establishing the level of performance possible from a thermoelectric HPCD.

As shown above, the overall energy consumption of the Generation 2 prototype was comparable to that of the vapor-compression HPCDs tested in [2]. More importantly, the results of the optimization study are clearly illustrated when the Generation 1 and 2 prototypes are compared. The most dramatic reduction in energy consumption occurs due to the selection of the high-efficiency blower (which was also affected by the lower pressure drop heat sinks used in Generation 2) and drum motor. From all of the above results, the cost savings between a conventional ERCD and the Generation 2 prototype TE dryer can be determined, as a function of loads of laundry per year (assuming a load size of 3.83 kg or 8.45 lbs). Using retail electric rates from [12] and [13], the savings per year are as shown in Figure 4.

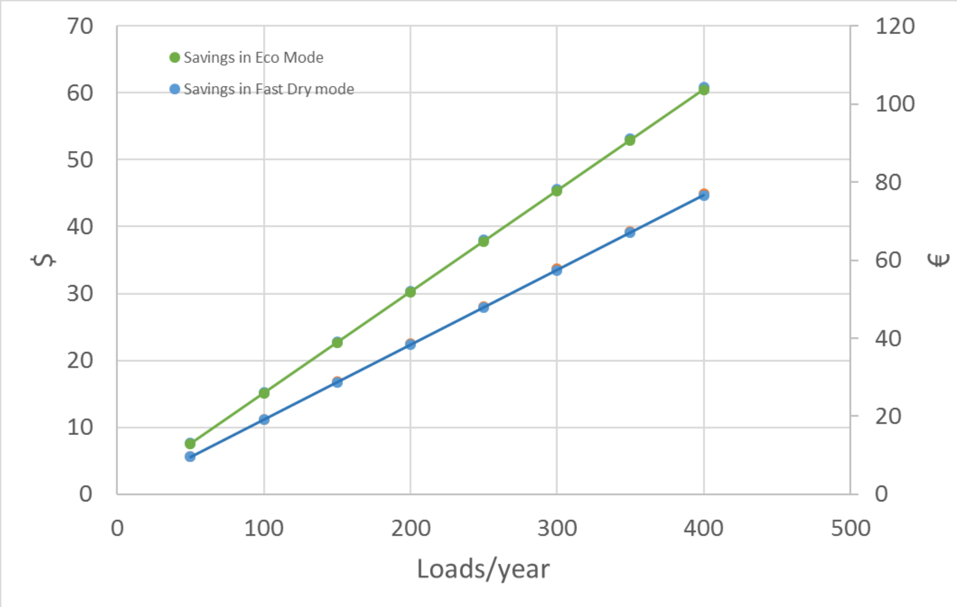

Figure 4: Electricity cost savings per year of Generation 2 TE dryer compared with conventional dryers

7. Conclusions

Modeling and experimental studies of design optimization for a thermoelectric heat pump clothes dryer were conducted. The results show that by selecting the appropriate high-efficiency components, applying appropriate thermoelectric power levels and profiles, selecting suitable heat sinks and running an open-state system, the energy consumption of the TE prototype dryer can be reduced by as much as 38% compared with conventional electric resistance dryers. They also indicate that significant yearly cost savings can be achieved with a TE clothes dryer compared to a conventional ER clothes dryer. Although the EF measured for the thermoelectric dryer was not as high as achieved in some vapor compressor dryers ([3], [2]), it is 38% higher than typical electric resistance units. It is also remarkable that ordinary off-the-shelf thermoelectric modules were able to outperform at least one vapor compression dryer (from [12], with a converted EF of 6.1), considering that TEs have lower COP at a given temperature lift than vapor compression systems. This counterintuitively-high system-level performance is due in part to the modularity of thermoelectric modules, which allows most of them to operate at lower lift than would be required of a single-stage vapor compression dryer.

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