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Experimental evaluation and thermodynamic system modeling of thermoelectric heat pump clothes dryer

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HIGHLIGHTS

- An experimental thermoelectric dryer with tumble-type drum is reported.
- A steady state model of a solid state heat pump dryer was proposed.
- Experimental results confirmed the model accuracy within 5%.
- An energy factor of 6.51 lb dry cloth per kWh was experimentally obtained.

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ABSTRACT

Electric clothes dryers consume about 6% of US residential electricity consumption. Using a solid-state technology without refrigerant, thermoelectric (TE) heat pump dryers have the potential to be more efficient than units based on electric resistance and less expensive than units based on vapor compression. This paper presents a steady state TE dryer model, and validates the model against results from an experimental prototype. The system model is composed of a TE heat pump element model coupled with a psychrometric dryer sub-model. Experimental results had energy factors (EFs) of up to 2.95 kg of dry cloth per kWh (6.51 lb_c/kWh), with a dry time of 159 min. A faster dry time of 96 min was also achieved at an EF of 2.54 kg_c/kWh (5.60 lb_c/kWh). The model was able to replicate the experimental results within 5% of EF and 5% of dry time values. The results are used to identify important parameters that affect dryer performance, such as relative humidity of air leaving the drum.

1. Introduction

Approximately 80% of households in the US have a clothes dryer, and 30% of these dryers are at least 10 years old [1]. Typical dryers use a tumble-type drum with air pushed through by a blower to dry clothes. The state of the art includes electric resistance (ER) dryers, vapor-compression heat pump clothes dryers (VC-HPCDs) and condensing dryers. ER dryers use a resistance-heating element to raise the temperature of ambient air, which is then passed through the dryer drum to collect moisture, before it is vented to the outside. In VC-HPCDs, the heat pump is a refrigeration cycle that includes a compressor, evaporator, condenser and expansion valve. Air circulates continuously in a closed loop; it is passed over the evaporator to condense moisture from the humid air leaving the dryer drum, and then over the condenser to heat up the dried air before it re-enters the drum. Condensing dryers typically use an air-to-air heat exchanger to dehumidify the air from the dryer. Since some models are ventless, installation is easier than conventional vented ER dryers. Of all the above, the VC-HPCDs are the most energy-efficient. Although they are based on mature technology and are used extensively in Australia and Europe, they have had poor market penetration in the US, with the major barriers being high cost and longer dry times [2]. There is therefore a significant potential for advanced clothes dryers to provide energy savings over standard ER models [3].

A review of recent research on advances in clothes drying is given here. It includes: modeling and experimental work on the fabric drying process itself [4,5], improving the performance of existing ER dryers using advanced control and termination [6,7], performance

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Nomenclature

A	area [m^2] *or* TE bank A (name of TE bank that cools air just before the exhaust)
AT	approach temperature [K]
B	TE bank B (name of middle TE bank)
C	TE bank C (name of TE bank that heats the air just before the drum), correction factor
CFM	cubic feet per minute
DC	direct current
EF	energy factor [lb_c/kWh] or [kg_c/kWh]
ER	electric resistance
FMC	final moisture content of cloth, expressed as mass ratio, $y_f = m_w/m_c$ [kg_w/kg_c]
h	specific enthalpy [kJ/kg]
I	DC current supplied to TE modules [A]
K	thermal conductance [W/K]
L	branch length [m]
m_c	dry mass of cloth [kg]
$\dot{m}$	mass flow rate [kg/s]
$\dot{m}_w$	mass flow rate of water vapor leaving dryer system (net of outflow vs inflow) [kg/s]
P	power [W]
q	heat transfer [W]
R	electrical resistance of TE modules [Ω]
RH	relative humidity [–]
SMC	starting moisture content of cloth, expressed as mass ratio, $y_0 = m_w/m_c$ [kg_w/kg_c]
SMER	specific moisture extraction rate [kg_w/kWh]
T	temperature [°C]
TE	thermoelectric
V	voltage [V]
$\dot{V}$	volume flow rate
VC	vapor compression
y	mass ratio of water to cloth, m_w/m_c

Greek

α	Seebeck coefficient [V/K]
ρ	electrical resistivity
λ	thermal conductivity [$W^1 m^{-1} K^{-1}$]
τ	dry time [min]
η_{PS}	power supply electrical efficiency (power conversion from AC to DC)
ω	humidity ratio [kg_w/kg_{da}]

Subscripts

0	initial
1–10	state points as defined in Fig. 1
c	cloth
C	cold side of TE module
da	dry air
e	electrical
f	final
H	hot side of TE module
n	n-type semiconductor
p	p-type semiconductor
w	water

characterization and analysis of VC-HPCDs [8,9], including VC-HPCDs that utilize alternative working fluids [10–12], optimization of components in condensing dryers [13,14], conceptual dryers that utilize hot-water heat exchangers [15,16], and early-stage research on the use of TE elements in a cabinet-type clothes dryer [17]. Based on this review, the literature is focused on improvements to existing technology, with limited research on the use of TEs for clothes drying applications.

The fundamental process of moisture removal from all kinds of materials has been studied for decades. For clothes dryers, moisture removal from fabric is of primary interest, as described by Yadav and Moon [4,5] for example, who developed a theoretical model that was validated with experimental data from a compact tumble-type dryer. The analytical model accounted for all the major components of the dryer. Some of the simplifying assumptions for the complex heat and mass transfer processes that occur during drying were: (1) uniform fabric material properties, (2) homogenous dispersion of moisture content within the fabric, (3) uniform instantaneous moisture distribution within working fluid and (4) wet-bulb temperature of working fluid equal to fabric temperature. These assumptions allowed the transport coefficients to be approximated and the process to be modeled successfully. Various model input parameters were used to compute the temperature and moisture levels of the air at the drum exit at each time level, along with the total drying time. These were then used to determine the total energy consumption. Experiments performed on the instrumented clothes dryer accounted for variation in load size/type, initial/final moisture content, and ranges for ambient conditions. The modeling and experimental results for variation of fabric moisture content with time were consistent with well-known trends from the literature. A common basis for comparison of dryer performance was the specific moisture extraction rate (SMER), which was defined as the amount of moisture removed from the fabric per unit of total energy consumed during the drying process. Overall, the experimental and numerical results for SMER were in fair agreement.

In addition to understanding fabric drying, modeling has also been used to investigate the effect of variation in control strategy on the overall performance of clothes dryers. Ng and Deng [6] developed a new control method by using a combination of mathematical modeling and experimental validation to determine the equilibrium moisture content relative to the ambient environment (rather than the drying environment, as is commonly used in traditional termination control methods). This was then used as the termination point for drying; by accurately predicting the termination point, the drying time was reduced (by avoiding over-drying) by 13%, resulting in energy savings during the clothes drying process. Similarly, Stawreberg and Nilsson [7] have shown that there is potential for energy savings by using a specific control strategy when tumble drying small loads of fabric. They developed a mathematical model validated by experimental data for various drying loads and reduced air flow, which was used to determine the drying time and SMER. The model was then used to test two control strategies with the smallest drying load. The first control strategy involved reducing the heat supply to the dryer (to lower temperature and reduce heat losses) and allowing for the same drying time as the reference test with the larger load. The second control strategy was to reduce the heat supply and lower the air flow by 20% (to increase the air residence time in the drum, leading to an increase in the moisture content at the drum outlet), with the same time constraint as the first strategy. Both strategies had a goal of increasing the SMER. The results from the model showed that the SMER for drying a small test load could be improved by 6% when the using a specific control strategy, but the drying time was equal to that of the larger load.

The performance and energy efficiency of VC-HPCDs have been the subject of many previous works, including that by Ganjehsarabi et al. [8], who conducted an exergy and exergoeconomic analysis of a VC-HPCD using actual thermodynamic and cost data. Using this method, they could determine the effect of varying the main operating parameters and their effect on overall exergy efficiency and total exergy