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Experimental Investigation of Parameters Affecting Drying Time and Power Consumption of a Heat Pump Tumble Dryer

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Abstract

A heat pump clothes dryer comprises of two closed loops, namely, the heat pump cycle and the air cycle. Clothes dryers are among the most energy-intensive home appliance. This study experimentally investigated how the textile type, textile size, textile weight, fan speed, and compressor frequency influence the drying time and power consumption. A heat pump tumble dryer with a 9 kg rated capacity was selected for experimental investigations. The following values were selected for experiments: textile weight: 3, 6, 9 kg; textile type: sheet, pillowcase, towel; fan speed: 2850, 3150, 3450 rpm; and compressor frequency; 27, 35, 40 Hz. Results showed that the drying time and power consumption were increased by increasing the textile weight and the textile size. The drying time of 9 kg sheets was 42.2% and 22.5% higher than that of pillowcases and towels, respectively. Moreover, the drying time was decreased by increasing the fan speed and compressor frequency.

Keywords: Heat pump clothes dryer; drying time; experimental study; textile weight; textile size.

1. Introduction

Clothes dryers can be categorized as open-loop such as vented dryers or closed-loop such as heat pump dryers and condenser dryers depending on exhausting drum outlet air outdoors. Condenser clothes dryers and vented clothes dryers use an electric heater to heat up the air entering the drum while heat pump clothes dryers use condenser heat rejection to heat up the air. Shrinkage of clothes as a result of high air temperature and high energy consumption are disadvantages of clothes dryers that use an electric heater. Because energy consumption of heat pump clothes dryers is almost half of conventional dryers, their market share has grown rapidly [1]. It should be noted that drying time of heat pump clothes dryers is longer than conventional clothes dryers because of lower drying air temperature [2].

In 2019, the worldwide sale market of clothes dryers was $7.3 billion and it is expected to reach $10.8 billion by 2023 [3]. In 2015, the Energy Information Administration reported that total electricity consumption of clothes dryers were 57.4 billion kWh [4]. The number of clothes dryers in Northern Europe and North America is increasing because of small space requirement and dry clothes regardless of weather conditions [5]. It is expected to reach number of clothes dryers to 105.8 million by 2025 in the US [6]. Since the energy consumption of clothes dryers is considerable, energy efficiency enhancement of clothes dryers is crucial. Stawreberg and Nilsson [7] established a mathematical model for energy efficiency enhancement of drying small loads. Their results showed that by reducing the heat supply and the airflow rate, it is possible to improve the clothes dryer's specific moisture extraction rate by 6% when drying small loads. Braun et al. [8] experimentally compared performance of a heat pump tumble dryer with conventional electric dryers. They reported that energy consumption of a heat pump tumble dryer was 40% and 14% lower that an electric clothes dryer and a conventional electric dryer using heat recovery heat exchangers, respectively. Bengtsson et al. [9] reported that by increasing the cylinder volume of compressor by 50%, drying time of heat pump clothes dryer decreased by 14% without increasing in energy consumption. Erdem [10] developed a model to investigate effects of evaporator geometry on the energy consumption and drying time of heat pump clothes dryers. Their

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simulation results showed that energy consumption reduced by 12% and 8% by increasing number of evaporator rows and columns from 2 to 4, respectively. Moreover, energy consumption increased by 18% and 21% by increasing tube outer diameter from 6 to 10 mm and increasing the longitudinal tube pitch from 10 to 30 mm, respectively.

The purpose of this study was to investigate the effect of a wide range of textile type, textile weight, fan speed, and compressor frequency on the drying time and power consumption of heat pump tumble dryers.

2. Experimental study

A heat pump tumble dryer with 9 kg rated capacity was selected for experimental investigations. The heat pump tumble dryer was equipped with twenty-three thermocouples with the uncertainty of ±0.3 °C, and three "SHT85 model" relative humidity and temperature sensors with the uncertainties of ±1.5 %RH and ±0.1 °C. The schematic of heat pump tumble dryer is shown in Fig. 1.

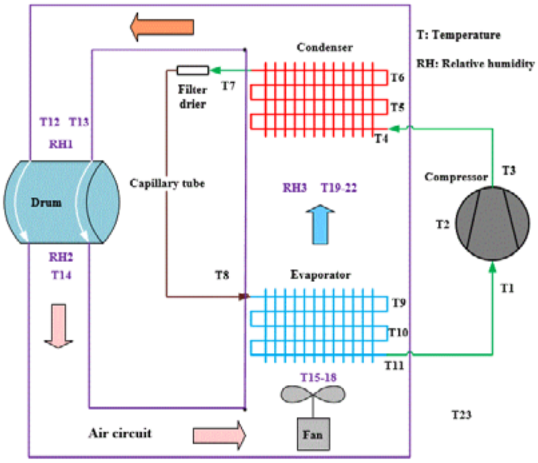

Fig. 1. Schematic of equipped heat pump tumble dryer

All experiments were conducted at the ambient temperature of 23±2 °C. According to IEC 60456 [11], the bone dry method was used for the conditioning of textiles to define the nominal mass of textiles at the start of experiments. The conditioned weight of textiles was defined as:

$$m_{cond,t} = m_{bd,t} \times F_{bd} \tag{1}$$

where $m_{cond,t}$ is the conditioned weight of textiles, $m_{bd,t}$ is the bone dry weight of textiles and the bone dry factor F_{bd} is bone dry factor which experimentally was found equal to 1.072. The difference between $m_{cond,t}$ and $m_{bd,t}$ is equal to the amount of moisture absorbed by textiles from surrounding for more than 15 hours at the ambient temperature of 20±2 °C and relative humidity of 65±5 %. All experiments started at the initial moisture content (IMC) of 60%. The initial moisture content "IMC" can be calculated as below:

$$IMC = \frac{m_{add,w}}{m_{cond,t}} \times 100\% \tag{2}$$

where $m_{add,w}$ is the weight of water added to the conditioned textile. In the present study, the effect of textile weight (3, 6, 9 kg), textile type (sheet, pillowcase, towel), fan speed (2850, 3150, 3450 rpm), and compressor frequency (27, 35, 43 Hz) on the drying time were experimentally investigated. To examine the effect of textile size on the drying time, three cotton base textiles were selected according to IEC 61121 [12]. Specifications of sheets, pillowcases, and towels are given in Table 1.

Table 1. Specifications of textiles used in the experiments.

Parameter		Unit	Sheets	Pillowcases	Towels
Length		mm	2400±150	800±50	1000±50
Width		mm	1600±40	800±20	500±30
Area		m^2	3.84±0.342	0.64±0.057	0.5±0.056
Weight per piece		g	725±15	240±5	110±3
Mass per unit area		g/m^2	185 ± 10	185 ± 10	220 ± 10
Substrate		---	Long staple pure cotton	Long staple pure cotton	Long staple pure cotton
Yarn		---	Ring spun	Ring spun	Ring spun
Weave			Plain weave linen 1/1	Plain weave linen 1/1	Huckaback
Water uptake in		%	138 ± 10	138 ± 10	250 ± 15
Yarn twist	Warp	T/m	600 ± 20	600 ± 20	610 ± 20
	Weft		500 ± 15	500 ± 15	490 ± 15
Yarn Count	Warp	tex	33 ± 1	33 ± 1	36 ± 1
	Weft		33 ± 1	33 ± 1	97 ± 1
Pick count	Warp	pick/cm	24 ± 1	24 ± 1	20 ± 1
	Weft		24 ± 1	24 ± 1	12 ± 1

A list of experiments is shown in Table 2. It should be noted that the heat pump tumble dryer was comprised of a fan-drum motor for rotating both the laundry drum and drying air fan. The drum rotation speed was 49.12 RPM when the fan rotational speed was 2850 RPM and it was 54.29 RPM for the fan rotational speed of 3150 and 3450 RPM.

Table 2. List of experiments used for the development of correlation.

Case	Conditioned weight of textile (kg)	Textile type	Fan speed (rpm)	Compressor frequency (Hz)
1	3	towel	3150	35
2	6	towel	3150	35
3	9	towel	3150	35
4	3	pillowcase	3150	35
5	6	pillowcase	3150	35
6	9	pillowcase	3150	35
7	3	sheet	3150	35
8	6	sheet	3150	35
9	9	sheet	3150	35
10	3	1 sheet/ 4 pillowcases/ 12 towels	3150	35
11	6	2 sheets/ 8 pillowcases / 24 towels	3150	35
12	9	3 sheets/ 12 pillowcases / 36 towels	3150	35
13	9	4 sheets/ 14 pillowcases / 26 towels	2850	27
14	9	4 sheets/ 14 pillowcases / 26 towels	3150	27
15	9	4 sheets/ 14 pillowcases / 26 towels	3450	27
16	9	4 sheets/ 14 pillowcases / 26 towels	2850	35
17	9	4 sheets/ 14 pillowcases / 26 towels	3150	35
18	9	4 sheets/ 14 pillowcases / 26 towels	3450	35
19	9	4 sheets/ 14 pillowcases / 26 towels	2850	43
20	9	4 sheets/ 14 pillowcases / 26 towels	3150	43
21	9	4 sheets/ 14 pillowcases / 26 towels	3450	43

3. Results and discussion

Drying time and total power consumption for cases 1 to 12 are presented in Figs. 2 and 3, respectively. It should be noted that the fan speed and compressor frequency were the same for cases 1 to 12 while the textile weight and textile composition were different. Results showed that the drying time and power consumption increased by increasing the weight of textiles. The shortest and longest drying time was related to towels and sheets because of the smallest size and largest size, respectively. Due to rolled up or rolled inside another, thus trapping moisture, the drying time of sheets was significantly more than towels and pillowcases. In other words, the stagnant core of sheets in the drum was bigger than pillowcases and towels. Therefore, the molecular diffusion which is slower than convection diffusion in the sheets was dominant. Results showed that the drying time of 3, 6, and 9 kg sheets was 7.2%, 28.4%, and 52.3% higher than that of a mix of textiles, respectively. Moreover, the total power consumption of 3, 6, and 9 kg sheets was 11.2%, 34.2%, and 56% higher than the total power consumption of a mix of textiles, respectively.

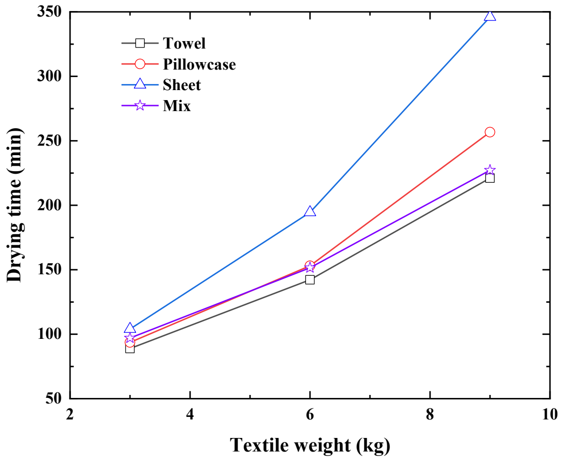

Fig. 2. Effect of textile weight and textile composition on the drying time

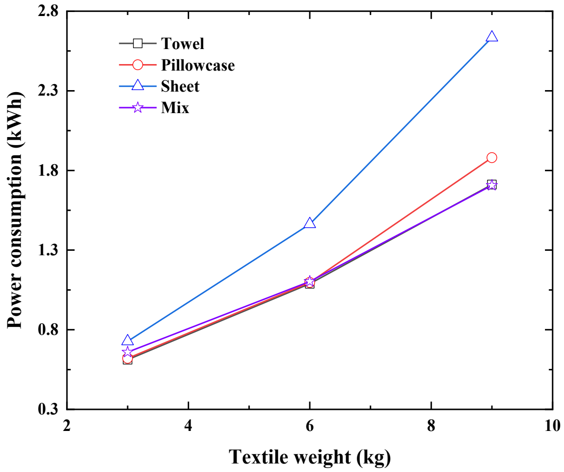

Fig. 3. Effect of textile weight and textile composition on total power consumption

Figs. 4 and 5 present the drying time and total power consumption for cases 13 to 21, respectively. The textile composition for 9 kg textile was selected according to the IEC 61121. The fan speed was changed from 2850 to 3450 rpm and the compressor frequency was changed from 27 to 43 Hz. Results showed that with increasing the compressor frequency from 27 to 43 Hz, the power consumption increased and the drying time decreased because of increasing the air temperature at the inlet of the drum. As shown in Fig. 4, the drying time decreased with increasing the airflow rate because of increasing the moisture evaporation rate in the drum. Manufacturers of clothes dryers are seeking to reduce the power consumption and the drying time. The results showed that although energy consumption decreased with decreasing the compressor frequency, the drying time increased. The power consumption was maximum while the heat pump dryer was working with the highest compressor frequency (43 Hz) and lowest fan speed (2850 rpm). Also, the power consumption was minimum while it was working with the lowest compressor frequency (27 Hz) and the highest fan speed (3450 rpm).

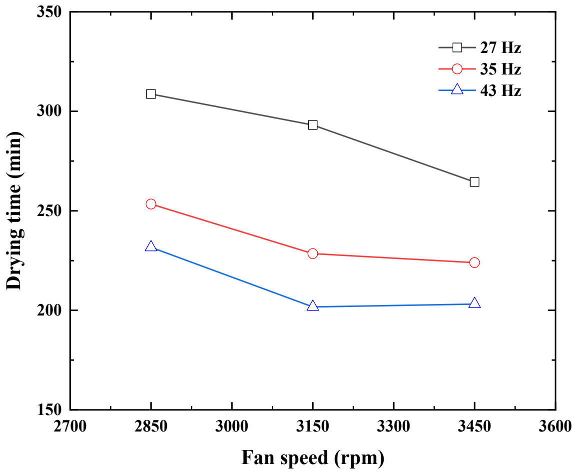

Fig. 4. Effect of fan speed and compressor frequency on drying time

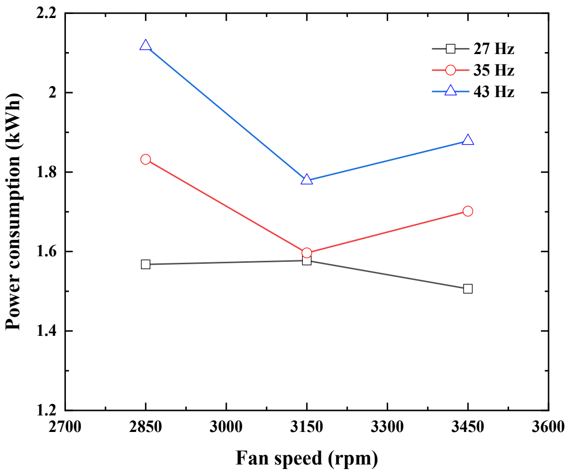

Fig. 5. Effect of fan speed and compressor frequency on total power consumption

The Energy Efficiency Index (EEI) was selected to determine the optimum condition and it was calculated according to the EU 392/2012 standard [13]. The energy efficiency of household tumble dryers is rated in terms of a set of energy labels from *A+++* to *D*, *A+++* being the most energy efficient, and *D* the least efficient as shown in Table 3.

Table 3. Energy efficiency classes.

Energy Efficiency Class (EEC)	Energy Efficiency Index (EEI)
A+++ (most efficient)	EEI < 24
A++	24 ≤ EEI < 32
A+	32 ≤ EEI < 42
A	42 ≤ EEI < 65
B	65 ≤ EEI < 76
C	76 ≤ EEI < 85
D (least efficient)	85 ≤ EEI

The EEI and EEC for 9 kg textiles are presented in Table 4. Results showed that case 15 (mix of textiles, fan speed: 3450 rpm, compressor frequency: 27 Hz) was the most energy efficient and case 9 (sheets, fan speed: 3150 rpm, compressor frequency: 35 Hz) was the least efficient. Moreover, the EEC was A+++ and A++ for all experiments while the heat pump dryer was working with the compressor frequency of 27 Hz and 43 Hz, respectively.

Table 4. Energy Efficiency Index of exeriments with 9 kg textile.

Case	weight of textile (kg)	Textile type	Fan speed (rpm)	Compressor frequency (Hz)	EEI	EEC
3	9	towel	3150	35	23.9	A+++
6	9	pillowcase	3150	35	26.3	A++
9	9	sheet	3150	35	35.9	A+
12	9	3 sheets/ 12 pillowcases / 36 towels	3150	35	23.5	A+++
13	9	4 sheets/ 14 pillowcases / 26 towels	2850	27	22.6	A+++
14	9	4 sheets/ 14 pillowcases / 26 towels	3150	27	22.7	A+++
15	9	4 sheets/ 14 pillowcases / 26 towels	3450	27	21.7	A+++
16	9	4 sheets/ 14 pillowcases / 26 towels	2850	35	26.4	A++
17	9	4 sheets/ 14 pillowcases / 26 towels	3150	35	23	A+++
18	9	4 sheets/ 14 pillowcases / 26 towels	3450	35	24.5	A++
19	9	4 sheets/ 14 pillowcases / 26 towels	2850	43	30.4	A++
20	9	4 sheets/ 14 pillowcases / 26 towels	3150	43	25.6	A++
21	9	4 sheets/ 14 pillowcases / 26 towels	3450	43	27	A++

4. Conclusion

This study presented effects of textile type (sheet, pillowcase, towel), conditioned weight of textiles (3, 6, 9 kg), fan speed (2850, 3150, 3450 rpm), and compressor frequency (27, 35, 43 Hz) on the drying time and power consumption of a heat pump tumble dryer. Twenty-one experiments were conducted on a heat pump tumble dryer with a 9 kg rated capacity. All experiments were conducted at the ambient temperature of 23±2 °C and initial moisture content of 60%. The results showed that the drying time and the power consumption increased by increasing the weight of textiles and the size of textiles. The drying time and power consumption of 9 kg sheets were 52.3% and 56% higher than that of a mix of textiles, respectively. Moreover, the drying time decreased and the power consumption increased by increasing the compressor frequency. The results showed that the lowest EEI was belonged to drying 9 kg of a mix of textiles while the heat pump dryer was working with the lowest compressor frequency (27 Hz) and highest fan speed (3450 RPM).

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