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Modeling of heat pump tumble dryer energy consumption and drying time

Abstract

The use of heat pump tumble dryers is nowadays more common because they offer huge energy savings compared to conventional tumble dryers. Earlier studies made on conventional tumble dryers have shown that parameters such as heater power, fan speed, drum speed, weight and initial moisture content of textiles and air leakage have a huge impact on the energy efficiency and drying time. In the present study, a modified commercial heat pump tumble dryer was evaluated for energy consumption and drying time by changing operating parameters including fan speed, drum speed and mass load. The total energy consumption and drying time were measured and corrected for the initial and final moisture content in the textiles. The experimental results based on 27 drying tests were evaluated to develop linear regression models for energy consumption and drying time, which show a good agreement with the experimental data. The results show that a large mass load, a high drum speed and a low fan speed give the highest energy efficiency, i.e. the lowest energy consumption per kg of drying load. Larger loads extend the length of the drying cycle while higher fan and drum speeds result in shorter drying time.

1. Introduction

The use of tumble dryers in households is becoming more and more popular. Tumble dryers require little space and provide a fast and convenient way of drying clothes independent of weather conditions. In 2015 more than 4 million tumble dryers were sold across the EU [1]. In general, conventional tumble dryers, equipped with electric heaters, are considered as energy-inefficient household appliances because they consume huge amounts of electricity. The high operational cost and the possibility of textiles shrinkage due to high drying temperature are main concerns, raised against the use of conventional dryers [2]. Heat pump has been recognized as a very attractive technology from a perspective of energy saving. Heat pump dryers use nearly 50 % less energy compared to conventional dryers [1]. Since heat pump dryers appeared on the market in 2006 the number of sold units has been increasing rapidly over the years and they already represent 50 % of the market share [1].

Many studies have been carried out to improve the energy efficiency and reduce the drying time of tumble dryers. Bassily and Colver [3] evaluated a commercial venting dryer for energy performance by changing operating parameters including heater power, fan speed, drum speed, weight and initial moisture of the clothes. Based on the experimental results of 32 runs Bassily and Colver [4] investigated the mass transfer process inside the drum and its impact on the performance by developing a correlation for the area-mass transfer coefficient. They concluded that the area of mass transfer depends on the clothes weight and drum speed while the mass transfer coefficient depends on the airflow rate, dry bulb temperature, outlet air relative humidity and clothes material. Yadav and Moon [5] performed a theoretical analysis of a venting dryer to determine the effects of various parameters on the energy efficiency. They developed an empirical correlation for the specific moisture extraction rate, which was found to be significantly affected by the mass per unit area of the clothes. Bansal et al. [6] achieved an energy efficiency improvement and drying time reduction of a venting dryer by replacing a traditional electric heater with a water heat exchanger. Huelsz et al. [7] established a total energy balance method to describe energy inputs and outputs in a venting tumble dryer. In a more recent work Wei et al. [8] developed a computer-controlled prototype platform of a venting dryer with an individual control of key drying parameters such as heater power, airflow velocity and drum rotating speed. A new drying model was divided into four stages based on the

humidity of the exhaust air. The experimental results indicated that the staged controlling of heating power improves the energy efficiency and fabric smoothness after the drying. Stawreberg and Nilsson [9] established a statistical model from 19 experiments in a condensing dryer to find the best settings for the heater power, internal airflow and external airflow. The results showed that a high heater power, a high internal airflow and a low external airflow give the highest energy efficiency. Stawreberg et al. [10] estimated air leakage out from the condensing dryer through measurements and modeling using energy and mass balances. They concluded that the main amount of leakage, located between the heater and the drum, has a huge impact on the energy efficiency and it must be reduced in order to decrease the energy use. The leakage in heat pump dryers was researched by Bansal et al. [11] who developed a method for quantifying leakage and its locations through the air circulation system based on the leakage volumetric flow and pressure measurements. Stawreberg and Wikström [12] measured the energy efficiency of three tumble dryers, two condensing and one heat pump, with different mass loads. The results indicated that all tested dryers have significantly lower energy efficiency when drying small loads. Stawreberg and Nilsson [13] presented a way of saving energy when drying small loads in a venting dryer. By using a control strategy, which reduces the heat supply and the airflow through the dryer, the efficiency increases by 6 % in a small load drying cycle. Pal and Khan [14] built mathematical models to design different components of a heat pump-assisted dryer using heat and mass balance of refrigerant and air circuit. Rezk and Forsberg [15] presented a numerical based approach for developing the air duct geometry of a heat pump dryer and evaluated two modifications for the pressure drop of the circulating air. Mancini et al. [16] investigated a possibility of using CO₂ as a working fluid in a heat pump dryer. Tests performed on a prototype showed negligible decrease in the electric power consumption and a 9 % increase in the cycle time, compared with the reference R134a heat pump dryer. Similar investigation of the CO₂ refrigerant was performed by Erdem and Heperkan [17] who developed a computer model to determine properties of the system such as temperature, pressure and relative humidity. Junior et al. [18] introduced a new concept of a recuperative thermoelectric cycle for tumble dryer as an alternative to substitute the compression heat pump, which utilizes environmental unfriendly refrigerants. Ganjehsarabi et al. [19] carried out an exergoeconomic analysis of a heat pump dryer to investigate the system performance and components costs, depending on the operating temperature and mass flow rate of the air. Bengtsson et al. [20] examined the influence of compressor size and the total heat transfer of condenser on the electricity use and drying time in a heat pump dryer. The results showed that increasing the cylinder volume of the compressor by 50 % decreases the drying time by 14 % without using more electricity. Novak et al. [21] performed an experimental analysis of the textile drying in a domestic open cycle tumble dryer to examine the influence of the drum inlet air conditions on the drying process. They developed a correlation for the total drying time in relation to the airflow rate, temperature and relative humidity of the drum inlet air using a regression analysis.

Although tumble dryers have been studied widely in the open literature, no study has been found in which the influence of crucial process variables on the heat pump dryer performance is investigated. The aim of this paper is to present two linear regression models for energy consumption and drying time with three independent process variables including mass load, drum speed and fan speed in a commercial heat pump dryer. An optimum drum speed, depending on the mass load, improves the energy efficiency due to enhanced heat and mass transfer rate inside the drum. The effects of different mass loads and drum speeds on the moisture transport rate are examined through measurements of the air relative humidity at the drum outlet. Higher fan speeds increase the airflow rate through the closed air circuit, which has a negative effect on the energy efficiency due to lower drying potential and higher electrical power. Increased airflow rate reduces the drying time due to increased leakage of humid air.

The total leakage amount is determined by evaluating the condensation efficiency, which is a ratio of condensed and evaporated water mass. The experimental results can be used for further optimization of a drying process for the heat pump dryer used in this study.

2. Description of a heat pump tumble dryer

The essential components of a typical heat pump tumble dryer are shown in Figure 1. The centrifugal fan, used to propel drying air inside a closed-loop circuit and the drum (a), which is an integrated part of the air circuit and is provided for mixing the textiles are driven by the electric motor (b). The vapor compression heat pump system consists of four main components: a compressor (c), an evaporator (d), a condenser (e) and an expansion device [22]. The most commonly used expansion device is capillary tube of a relatively small inner diameter. The purpose of heat pump system in tumble dryers is to provide cooling and heating of the drying air in evaporator and condenser, respectively.

Figure 1. The components of a typical heat pump tumble dryer and scheme of the drying process

The drying process, illustrated schematically in Figure 1, can be described in three stages regarding the drying air: humidification (1-2), dehumidification (2-3) and heating (3-1) [16]. The change in state of the air around the circuit is shown in h-x diagram in Figure 2. The humidification takes place in rotating drum where hot and dry air (1) flows over wet textiles. At the textile surface, two transport processes occur simultaneously: a heat transfer from the drying air to the textile surface due to temperature difference and a moisture transfer from the textile surface to the drying air due to mass concentration difference [23, 24]. The air leaves the drum saturated with relative humidity close to 100% (2) and is dehumidified in the evaporator where it is cooled below the dew-point temperature (3). Thereafter the air flows across the condenser where it is heated before entering the drum and the air circuit is closed.

Figure 2. The change in state of the circulating air in h-x diagram

3. Experimental setup

The experimental setup using a modified commercially available heat pump tumble dryer with 8 kg of maximum dry load capacity is shown in Figure 3. In the existing appliance, single BLDC motor drives both the centrifugal fan and the drum. For the purpose of this study, the additional electric motor of the same type was installed outside the tumble dryer to drive the centrifugal fan independently. This enabled a separate study of the fan and drum speed influence on the drying performance. The tumble dryer was placed on the stand at a height of approximately 40 cm. Below the stand there was a container, placed on the weighing scale, providing measurement of the condensed water mass. The condensed water leaving the evaporator was led directly to container through the hose, attached to the housing of drain pump, which was removed. The axial fan, which is used for compressor cooling, was turned off to eliminate its impact on the heat pump performance.

Figure 3. A commercial heat pump tumble dryer with the additional electric motor

The tumble dryer was equipped with pressure, temperature, humidity and electric power sensors, located as shown in Figure 4. Two piezo-resistive pressure transmitters HD20V4T (Delta Ohm), with a measuring range from 0 bar to 40 bar and accuracy of $\pm 0,25$ % full scale,

were used to measure the suction ($p1$) and discharge pressure ($p2$). Two type T thermocouples, with an accuracy of $\pm 0,5$ °C, were used to measure the drum inlet ($T1$) and outlet air temperature ($T2$). The air relative humidity at the drum inlet ($RH1$) and outlet ($RH2$) were measured with the capacitive humidity transmitters HD9817T1R (Delta Ohm), with an accuracy of $\pm 2,5$ % within the measuring range from 0 % to 100 %. The electrical currents of compressor ($I1$), internal ($I2$) and external electric motor ($I3$) were measured using current clamps PNA-CLAMP-5 (Dewetron), with an input range from 0,04 A to 6 A and accuracy of $\pm 0,5$ %. The electrical power was calculated by a software power module, which provides power measurement and analysis. Integration of electrical power was used to determine the energy consumption. All measured variables were recorded with a 16-slot chassis DEWE-2600 (Dewetron) data acquisition system. Two scales Viper SW 15 (Mettler Toledo), with a resolution of 1 g and accuracy of ± 1 g were used for weighing clothes before and after each test and measuring the condensed water mass. The settings of fan and drum speeds were checked with a contact tachometer DT-2268 (Lutron), with a resolution of 1 rpm and accuracy of $\pm 0,05$ %.

Figure 4. Locations of sensors connected to the tumble dryer

4. Experimental procedure

The drying tests were carried out in a test room, equipped with climate control system, where temperature and relative humidity were maintained at 23 °C ± 2 °C and 55 % ± 5 %, respectively [25]. The voltage regulator ensured constant supply voltage of 230 V ± 2 % and frequency of 50 Hz ± 1 %. Three cotton mass loads, composed of certain number of sheets, pillowcases and towels as in the standard test loads used for energy labelling, were used: 4 kg, 6 kg and 8 kg. Each load was conditioned in a room with the temperature of 20 °C ± 2 °C and relative humidity of 65 % ± 5 % before they were weighed. All tests were run using the drying program for measuring the performance of tumble dryers [25]. The textiles were wetted homogenously to the moisture content of 60 % ± 1 % using washing machine and inserted into the drum piece by piece according to the internal procedure to reduce the variation in results. The drying cycle ends automatically when the textiles reach the desired moisture content, detected by humidity sensor in the drum. The remaining moisture content in the textiles after the drying must be within 0 % ± 3 % relative to the conditioned mass load otherwise the test was considered not valid [25]. The energy consumption E and drying time t were corrected for the initial and final moisture content in the textiles using:

$$E = \frac{E_m * (\mu_{i0} - \mu_{f0}) * c}{W_i - W_f} \quad (1)$$

$$t = \frac{t_m * (\mu_{i0} - \mu_{f0}) * c}{W_i - W_f} \quad (2)$$

where E_m and t_m are measured energy consumption and drying time, μ_{i0} is the nominal initial moisture content, μ_{f0} is the target final moisture content, W_i is the weight of the textiles after wetting, W_f is the weight of the textiles after drying and c is the rated capacity of the tumble dryer [25]. The mass of condensed water collected in the container W_w was registered after each drying test for evaluating the condensation efficiency, which represents a ratio between the mass of condensed water and the mass of water removed from the textiles, using [25]:

$$C = \frac{W_w}{W_i - W_f} \quad (3)$$

5. Regression analysis

The regression analysis was used for modeling the relationship between two response variables such as the corrected measured energy consumption E (Wh) and drying time t (min) and three independent process variables including fan speed n_f (rpm), drum speed n_d (rpm) and mass load m (kg). The relationship between these variables is characterized by linear regression model:

$$y = \beta_0 + \beta_1 n_f + \beta_2 n_d + \beta_3 m + \varepsilon \quad (4)$$

where y is a response variable, β 's are unknown regression coefficients and ε is a statistical error, which represents the difference between the measured and the exact value of y [26]. The regression coefficients were estimated using a method of least squares, which minimizes the sum of the errors squares. Each process variable was considered at three values, low, intermediate and high, as shown in Table 1. The mass load of 8 kg represents the maximum dry load capacity, which is limited to the drum volume. A low value of 4 kg was chosen according to the requirements for energy labelling, which is determined using the drying cycles with full and half loads. The fan speed of 2900 rpm corresponds to the actual motor speed in the existing appliance. A high value of 3400 rpm was chosen considering the motor speed limit. The drum speed values were selected in the same way as fan speed values. The combination of these values gives a total number of 27 operating points.

Table 1. Values of the process variables

Process variable	Value	Low	Intermediate	High
Fan speed (rpm)		2400	2900	3400
Drum speed (rpm)		36	47	58
Mass load (kg)		4	6	8

The validation of the model was performed by evaluating the coefficient of determination R^2 . A large value of R^2 does not necessarily imply that the model is a good fit to measured data because adding a variable to the model always increase R^2 , regardless of whether the additional variable is statistically significant or not [26]. Accordingly, the adjusted R^2 statistic was used for the model validation, which decreases if the unnecessary terms are added to the model. The adjusted R^2 is defined as:

$$R_{adj}^2 = 1 - \left(\frac{n-1}{n-k-1}\right)(1 - R^2) \quad (5)$$

where n is a number of observations and k is a number of process variables [26]. The significance of the individual process variable was checked by testing hypothesis $H_0: \beta_j = 0$, assuming that there is no linear relationship between the response and the process variable [26]. The test statistic for this hypothesis is computed as:

$$t_0 = \frac{\hat{\beta}_j}{se(\hat{\beta}_j)} \quad (6)$$

where $\hat{\beta}_j$ is a least square estimator of the regression coefficient and $se(\hat{\beta}_j)$ is a standard error [26]. The hypothesis is rejected when the absolute value of t_0 is more than the critical value $t_{\alpha/2, n-k-1}$, where α is a level of significance. If the hypothesis is not rejected, it means that the process variable x_j can be deleted from the model [26]. The model adequacy was checked by examination of the standardized residuals, which are useful in looking for outliers. Any observation with a standardized residual outside of the interval $-3 \leq d_i \leq 3$ must be carefully investigated, because it may represent a simple data-recording error or something of more serious concern, such as a region of poor approximation of the fitted model [26]. The standardized residuals were determined as:

$$d_i = \frac{e_i}{\hat{\sigma}} \quad (7)$$

where e_i is a residual, which represents the difference between the measured and the fitted value of y_i , and $\hat{\sigma}$ is a least square estimator of the standard error [26].

6. Results and discussion

6.1. The effect of changing mass load

The interaction of textiles with the drying air in a rotating drum is of great importance for improving the energy efficiency. Increasing the mass load in a constant drum volume increases the contact area between the textiles and the drying air, which improves the energy efficiency [4]. This can be explained by the relationship between the contact area and the heat and mass transfer rate. A large contact area increases the heat transport from the drying air to the textile surface and gives larger moisture transport from the textile surface to the drying air. If the mass load is too small, it is possible that the air is not saturated when leaving the drum due to poor contact with the textiles [12]. The effect of changing mass load on the drying process is presented in Figures 5 and 6. Figure 5 shows the variation of air relative humidity measured at the drum inlet and outlet at a constant fan speed of 2400 rpm and drum speed of 36 rpm. The results show that larger loads increase the drum outlet air relative humidity, which indicates a higher moisture transport rate within the drum. However, the total energy consumption is increased as the mass load increases, therefore it is more illustrative to present the energy consumption per kg of drying load, such as in Figure 6. Figure 6 shows the effect of mass load and fan speed on the energy consumption per kg of load or energy efficiency at a constant drum speed of 47 rpm. Increasing the mass load clearly results in higher energy efficiency at all fan speed values.

Figure 5. The variation of drum inlet and outlet air relative humidity for different mass loads at a constant fan speed of 2400 rpm and drum speed of 36 rpm

Figure 6. The effect of mass load and fan speed on the energy efficiency at a constant drum speed of 47 rpm

6.2. The effect of changing drum speed

The mass load and drum speed are only two factors that influence the size of contact area between the textiles and the drying air when studying the same drum geometry and the location of the air inlet to the drum [4]. The drum speed affects the energy efficiency and drying time depending on the textiles movement in a rotating drum. If the drum speed is too high, the resultant force that acts on the textiles upward is more than the resultant force that acts downward, so the textiles do not fall toward the center of rotation. This causes a poor contact of textiles with the airflow, which reduces a moisture transport rate and thereby the drum outlet air relative humidity. Improving the energy efficiency and reducing the drying time require an optimum setting of drum speed, depending on the mass load, in order to reach the highest relative humidity of the drum outlet air [4]. For analyzing the effect of drum speed on the drum inlet and outlet air relative humidity the fan speed and mass load were held constant at 2900 rpm and 4 kg, respectively. Figure 7 shows that higher drum speeds increase the drum outlet air relative humidity and reduce the total drying time. The differences in measured outlet air relative humidity at different drum speeds was found to be larger when drying smaller loads. This indicates that smaller loads are more sensitive to the drum speed than large ones because they do not fill the entire drum [12]. However, the negative effect on the energy efficiency by increasing the drum speed to the highest value of 58 rpm was not observed, which means that optimum drum speed cannot be determined from the experimental data. The relationship

between drying time and two factors including mass load and drum speed is presented in Figure 8 at a constant fan speed of 2900 rpm. The results show that larger mass loads increase the drying time at all drum speeds due to additional amount of moisture in the textiles, which must be removed. On the other hand, higher drum speeds reduce the drying time due to enhanced moisture transport rate inside the drum, which results in higher air relative humidity at the drum outlet as shown in Figure 7.

Figure 7. The variation of drum inlet and outlet air relative humidity for different drum speeds at a constant fan speed of 2900 rpm and mass load of 4 kg

Figure 8. The effect of mass load and drum speed on the total drying time at a constant fan speed of 2900 rpm

6.3. The effect of changing fan speed

The airflow rate around the closed air circuit is correlated to the fan speed and has a huge impact on the heat and mass transfer rate through the drum and the heat pump system. The moisture transfer process within the drum intensifies as the airflow rate is increased, which results in higher drying rate and shorter drying time [21]. The effect of changing fan speed is significant to the drum inlet air conditions as shown in Figure 9. Figure 9 shows the variation of air temperature and relative humidity at a constant drum speed of 47 rpm and mass load of 6 kg. Increased airflow rate reduces the refrigerant pressure in the condenser due to more extensive heat exchange from the refrigerant to the drying air. Consequently, the air temperature decreases and its relative humidity increases before entering into the drum, which reduces the drying potential of air for moisture transport [27]. Despite the lower drying potential, the total drying time is shorter at higher fan speeds, which means that increasing the airflow rate

contributes more to the drying time reduction. In addition, reducing the drying time by increasing the fan speed is also related to the increased air leakage due to higher pressure differences between inside the air circuit and the surroundings [12]. The air leakage is difficult to determine without understanding the relationship between the leakage volumetric flow and the pressure distribution in the air circuit [11]. However, a convenient way of estimating the total leakage amount is by evaluating the condensation efficiency, which is a ratio of condensed and evaporated water mass (Eq. 3). A higher condensation efficiency means that more of the humidity removed from the textiles is condensed in the evaporator instead of expelled to the room air. Figure 10 shows the effect of fan speed and mass load on the condensation efficiency at a constant drum speed of 58 rpm. It is clear that higher fan speeds cause a condensation efficiency reduction, which is explained by increased leakage of humid air. Figure 10 also indicates that increasing the mass load has a positive effect on the air leakage rate. Larger mass loads increase the pressure drop through the drum and reduce the airflow rate slightly, which results in decreased air leakage and higher condensation efficiency.

Figure 9. The variation of drum inlet air temperature and relative humidity for different fan speeds at a constant drum speed of 47 rpm and mass load of 6 kg

Figure 10. The effect of mass load and drum speed on the condensation efficiency at a constant drum speed of 58 rpm

6.4. Regression models

Table 2 shows results of regression analysis for the energy consumption and drying time, including adjusted R^2 and t test information. The results indicate that higher fan speeds and larger mass loads increase the total energy consumption while the total drying time is increased

only as the mass load increases. The models have a good fit to measured data, since the adjusted R^2 are close to 1. The critical value of t statistic for this test using $\alpha = 0,05$ is 2.069, which means that all process variables are statistically significant in relation to the energy consumption and drying time [26]. The magnitude of t value gives information about the strength of the linear relationship between the process variable and the response. Basically, the larger the t , the stronger the linear relationship [26].

Table 2. Regression analysis for the energy consumption and drying time

Regression equations	R^2_{adj}	t value		
		β_1	β_2	β_3
$E = 175,5 + 0,157n_f - 5,56n_d + 151,4m$ (7)	0,975	7,9	-6,2	30,5
$t = 114,2 - 0,01n_f - 0,84n_d + 16,56m$ (8)	0,984	-5,9	-10,7	38,2

Plots of predicted versus corrected measured energy consumption and drying time are shown in Figures 11 and 12, respectively. Both plots indicate a strong linear relationship between the process variables and the response because the points lie close to the equality line.

Figure 11. Predicted versus corrected measured energy consumption

Figure 12. Predicted versus corrected measured drying time

7. Conclusions

The total number of 27 drying tests were run at different mass loads, drum speeds and fan speeds using a modified commercial heat pump tumble dryer. The measured energy consumption and drying time were corrected to the initial and final moisture content in the textiles and modeled using a regression analysis. The linear regression models for energy consumption and drying time were developed with a good fit to measured data. A high value of adjusted R^2 makes sure that a linear model is suitable for modeling the relationship between the variables. The results showed that larger mass loads and higher drum speeds improve the energy efficiency of a drying process due to enhanced heat and mass transfer rate inside the drum. Increasing fan speed has a negative effect on the energy efficiency due to lower drying potential and higher electrical power. Higher drum and fan speeds cause a drying time reduction while larger loads extend the length of the drying cycle. The air leakage was also found to be an important factor affecting the energy efficiency and drying time. Higher fan speeds increase the airflow rate through the air circuit and thereby increase leakage of humid air, which results in shorter drying time. The results provide relations, which can be used for optimization of the drying process in the heat pump tumble dryer used in this study. This is the first such parametric analysis performed on a heat pump dryer, where drying air circulates in a closed circuit, as other authors have studied mainly conventional dryers with a modified open-air circuit.

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