Applied Energy 102 (2013) 484–491

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Potential energy savings made by using a specific control strategy when tumble drying small loads

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HIGHLIGHTS

► A theoretical model over the venting dryer correlated well to test results.
► By using a control strategy, the SMER can be improved by 6% for small loads.
► It was not possible to reach the same SMER for small loads as for the maximum load.

ARTICLE INFO

Article history:
Received 4 August 2011
Received in revised form 30 June 2012
Accepted 26 July 2012
Available online 8 November 2012

Keywords:
Drying load
Energy efficiency
Theoretical model
Venting tumble dryer

ABSTRACT

Tumble dryers manufactured today are optimised for their maximum capacity, i.e., 6–8 kg of dry load. An average washing load in ordinary households lands at between 2 and 3.5 kg dry load, which implies that the drying load is even smaller. The energy efficiency decreases with reduced drying load. The aim of this study is to establish a mathematical model for studying alternative control strategies for the venting tumble dryer in order to increase the energy efficiency of drying small loads. Two series of test runs were performed: the first series with three different drying loads was used as reference tests for validation of the mathematical model, and the second series was performed with airflow reduction. The model shows good agreement with the test runs. Two control strategies were tested using the model on the smallest drying load. By lowering the heat supply to the heater and by reducing the airflow, the energy efficiency increases by 6% in a small load drying cycle. It was not possible, however, for the investigated dryer, to reach the same energy efficiency for small loads as for the maximum drying load by using a control strategy.

1. Introduction

Today, tumble dryers are frequently used in ordinary households to dry clothes. They require little space and they dry clothes rapidly independent of weather conditions. They do require, however, high levels of electricity, which is the one disadvantage of using tumble dryers. According to the International Energy Agency [1], approximately 77 TW h (or 3.3% of the residential electricity consumption) were used in 2000 for the drying of textiles in 22 IEA member countries (Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom and the United States).

Tumble dryers manufactured today are optimised for a drying load of 6–8 kg (dry load), which is also the dryer's maximum drying load. This load is used when setting the energy label for the dryer, displaying its energy efficiency. In ordinary households, people rarely make use of the maximum load. According to a survey made by Berkholz et al. [2] involving 100 households in Germany, an average washing load weighs 2.9 kg (dry load). Shove [3] presents a study where the average washing load in American households weighed 3.4 kg, and in the UK they weighed 2 kg. The drying load inserted in the tumble dryer is most likely smaller than this as not all fabrics are suitable for tumble-drying.

In the tumble dryer, heated air is led into a rotating drum where the textiles are found. The contact between the textiles and the air is of great importance in order to attain an efficient drying process. The textiles meet the airflow in the drum as they move or "fall" due to the rotation of the drum. Depending on the size of the drying load, the contact time and area between the textiles and the air will differ. A large load will fill the drum well and the contact area between the textiles and the air is large. The air leaving the drum is likely to be saturated with water. If the drying load is small, however, there is a high probability that the air is not saturated when leaving the drum due to poor contact between the textiles and the drying air.

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http://dx.doi.org/10.1016/j.apenergy.2012.07.045

Nomenclature

a	water activity [–]
A_{hc}	area of heater coils [m^2]
c_a	specific heat capacity of air [kJ/kg °C]
c_d	specific heat capacity of the drum [kJ/kg °C]
c_h	specific heat capacity of the heater (coils and wall) [kJ/kg °C]
c_t	specific heat capacity of textiles [kJ/kg °C]
c_v	specific heat capacity of water vapour [kJ/kg °C]
c_w	specific heat capacity of water [kJ/kg °C]
h_{out}	enthalpy of the outlet air from the dryer [kJ/kg]
h_{in}	enthalpy of the inlet air into the dryer [kJ/kg]
h_h	enthalpy of the air between the heater and the drum [kJ/kg]
h_0	enthalpy of evaporation [kJ/kg]
h_mA_t	coefficient describing mass transfer from textiles to air [kg/sPa]
kA_{hc}	coefficient describing heat losses from heater coils [kW/°C]
kA_{hwi}	coefficient describing heat losses from heater wall, inside [kW/°C]
kA_{hwo}	coefficient describing heat losses from heater wall, outside [kW/°C]
k_dA_d	coefficient describing heat losses over the drum [kW/°C]
k_hA_h	coefficient describing heat losses over the heater [kW/°C]
$\dot{m}_a$	mass flow of air [kg/s]
$\dot{m}_{eV}$	evaporation rate of water [kg/s]
m_{ev}	mass of evaporated water [kg]
m_h	total mass of the heater [kg]
m_{hc}	mass of the heater coils [kg]
m_{hw}	mass of the heater wall [kg]
m_t	mass of the dry textiles [kg]
m_w	mass of the water in the textiles [kg]
m_d	mass of the drum [kg]
P_h	energy supply to the heater [kW]
P_{motor}	energy supply to fan and rotation of the drum [kW]
p_t	vapour pressure at the textile surface [Pa]
p_h	vapour pressure of air entering the drum [Pa]
p_{sat}	saturation water vapour pressure [Pa]
$\dot{Q}_{in}$	energy of the inlet airflow [kW]
$\dot{Q}_{out}$	energy of the outlet airflow [kW]
$\dot{Q}_{loss,h}$	heat loss over the heater [kW]
$\dot{Q}_{loss,d}$	heat loss over the drum [kW]
$Q_{load,in}$	energy in wet drying load [kJ]
$Q_{load,out}$	energy in dried drying load [kJ]
$Q_{v,in}$	energy of the water vapour in the inlet air [kJ]
$Q_{v,out}$	energy of the water vapour in the outlet air [kJ]
$Q_{a,in}$	energy of the dry inlet air [kJ]
$Q_{a,out}$	energy of the dry outlet air [kJ]
RH_{in}	relative humidity of the inlet air [%]
RH_{out}	relative humidity of the inlet air [%]
SMER	specific moisture extraction rate [kg/kW h]
T_h	temperature of air between heater and drum [°C]
T_{hc}	temperature of heater coils [°C]
T_{hw}	temperature of heater wall [°C]
T_{in}	temperature of the inlet air [°C]
T_{out}	temperature of the outlet air [°C]
T_{room}	room air temperature [°C]
T_t	temperature of the textiles [°C]
t	time [s]
X_t	water content per kg of dry textile [kg/kg]
Y_{in}	inlet humidity of the air [kg/kg]
Y_{out}	outlet humidity of the air [kg/kg]
ε_{hc}	emissivity of heater coil [–]
σ	Stefan–Bolzmann constant [W/m^2 K^4]

It has been documented in several studies that the energy efficiency is lower when tumble drying loads that are smaller than the maximum drying load [4,5]. Bassily and Colver [6] use an area mass transfer coefficient in order to describe the drying process of a venting tumble dryer. They found that three factors will affect the area mass transfer coefficient and thereby the drying rate of a fixed drum geometry: drum speed, airflow rate and the total weight of the textiles. Another study performed by Bassily and Colver [7] conclude that the minimum cost of the venting tumble dryer corresponds with the highest drying load. Yadav and Moon [8] investigated the energy efficiency of a venting tumble dryer as regards different drying loads. Drying large loads resulted in significantly higher energy efficiency. According to Stawreberg and Wikström [9], the smaller the load, the larger the reduction in energy efficiency, as compared to the maximum load in both the condensing tumble dryer and the heat pump dryer. Drying loads smaller than 3 kg displayed significantly lowered energy efficiency. In a study by Deans [10], no difference in energy efficiency was found for the venting tumble dryer when comparing two different loads. The smallest load tested in this report, however, was 2.86 kg (bone dry) and the relative humidity of the outgoing air remained at 100% for both tested drying loads. The commercial tumble dryer is optimised for drying a large load and the energy efficiency is the most affected when drying small loads [9].

A number of studies have been published on models of tumble dryers that are used to find ways of improving the energy efficiency or reducing the drying time. Lambert et al. [11] made a model of the tumble dryer that was in good agreement with the experimental data. The drying air leaving the drum was assumed to be saturated during the constant drying rate period of the drying process. Transfer coefficients for the constant drying rate period and sorption-isotherms for the falling-rate period were manipulated in the model to match the experimental data. Using this model, Lambert et al. [11] showed improvements in the energy efficiency by recirculation of the air. Conde [5] developed the model further and suggested using heat exchangers for energy recovery instead of recirculation of the air. Deans [10] constructed a similar model in order to describe the performance of the tumble dryer. He saw that the results of the model and the experiments agreed well. Deans [10] also concluded that the energy efficiency decreased with material porosity. Yadav and Moon [12] made a model over the tumble dryer in order to evaluate the dryer for three different energy performance standards.

Control strategies for drying processes can be used to improve the energy efficiency, especially of heat sensitive products [13]. When it comes to tumble dryers and the drying of textiles, most of the attention has been focused on interrupting the drying process in order not to overly dry the textiles [14,15]. In a study made by Piccagli et al. [16], a control strategy was used to improve the energy efficiency during the drying process. This was an experimental study and it was only performed on loads of 6 kg (dry load), and it showed a possible increase in energy efficiency of up to 3%.

Studies that aim at improving the energy efficiency when drying small loads have not been found in the literature. As small loads seem to be the most frequently used in ordinary households, and as the energy efficiency is considerably reduced when drying