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ABSTRACT

Accurate system modeling of a clothes dryer requires a drum component model that displays correct trends with respect to changing conditions. In this work, a model of drum heat and mass transfer effectiveness is adopted. Within this framework, experimental measurements of drum effectiveness are investigated with respect to several variables: drum volume, load mass, cloth type, drum volumetric air flow rate, and drum entering air temperature. These data can inform the modeling and simulation of any clothes dryer with horizontal-axis, axial-flow tumble-type clothes dryer drum.

1 INTRODUCTION

Residential electric clothes dryers in the US have an annual primary energy consumption of approximately 620 TBtu (0.62 EJ) [1]. The vast majority of these clothes dryers are based on a tumble-type drum with electric resistance (ER) heating.

Given the importance of tumble type clothes dryers, models describing the process are needed. An important element to be modeled is the drying that occurs inside the tumbling drum. Sherwood [2] has described constant-rate and falling-rate periods of drying moist solids in air. Above a “critical liquid content” point, the drying rate is constant, and below this liquid content the drying rate transitions to a falling-rate drying. A third initial phase is often added to this description, as by Lambert et al [3]: initial transient, constant-rate drying and falling-rate drying.

In this work, we have adopted a definition for heat and mass transfer effectiveness and applied it to the drum process. Experimental measurements of this effectiveness were then conducted, using commercially available and prototype residential clothes drying drums, and using the clothing load size specified for that drum volume (as specified [4] for US energy factor evaluation). In future work, correlations will be derived from this experimental data, to provide effectiveness correlations useful for modeling the dryer drum component of a clothes dryer.

2 DRYER DRUM HEAT AND MASS TRANSFER EFFECTIVENESS

The drum effectiveness model was introduced by Shen et al. [5] and additional explanation is provided here. Braun et al. (1989) presented an effectiveness-based approach to model cooling towers and cooling coils, which assumes that Lewis number Le = 1. Since a dryer drum and a wet cooling tower both involve an air stream cooled via passing through a wet media, in this work we extend this modeling approach to the dryer drum. The driving potential for heat transfer between air and cloth is the difference between the entering air temperature and the cloth surface temperature; the driving potential for mass transfer is the difference in humidity ratio between air entering the drum and the saturated air at the wet surface. Thus, the effectiveness of heat and moisture transfer from the clothes to the air in a dryer drum can be described with equations (1) and (2).

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$$\varepsilon_{\mathrm{H}} = 1 - \frac{\mathrm{T}_{\mathrm{surf}} - \mathrm{T}_{\mathrm{out}}}{\mathrm{T}_{\mathrm{surf}} - \mathrm{T}_{\mathrm{in}}} \tag{1}$$

$$\varepsilon_{\mathrm{M}} = 1 - \frac{\omega_{\mathrm{surf}} - \omega_{\mathrm{out}}}{\omega_{\mathrm{surf}} - \omega_{\mathrm{in}}} \tag{2}$$

where ε_{H} is the heat transfer effectiveness and ε_{M} is the moisture transfer effectiveness. T_{in} and ω_{in} are the temperature and humidity ratio, respectively, of the air entering the drum. $\mathrm{T}_{\mathrm{out}}$ and ω_{out} are the temperature and humidity ratio, respectively, of the air exiting the drum. $\mathrm{T}_{\mathrm{surf}}$ and ω_{surf} are the temperature and humidity ratio of the cloth surface and are assumed to be uniform for all the cloth in the drum.

Using Eq. (1) and Eq. (2), heat and mass transfer effectiveness (ε) can be theoretically calculated by direct measurement of temperature (T) and humidity ratio (ω) at the drum inlet (T_{in}, ω_{in}), on the clothing surface inside the drum (T_{surf}, ω_{surf}), and at the drum exhaust (T_{out}, ω_{out}). However, due to the difficulties of accurately measuring clothing surface temperature and humidity ratio, T_{surf} and ω_{surf} have been calculated instead of measured.

Summarizing, Equations (1-2) contain 8 variables (ε_{H}, ε_{M}, T_{in}, $\mathrm{T}_{\mathrm{out}}$, ω_{in}, ω_{out}, $\mathrm{T}_{\mathrm{surf}}$ and ω_{surf}). We measured four of these (T_{in}, $\mathrm{T}_{\mathrm{out}}$, ω_{in}, ω_{out}), and Equation (1-2) provide two independent equations. Thus two additional equations are needed to solve the equation set. These are provided by making the two following key assumptions.

First key assumption: First, the clothing surface is assumed to be saturated (Equation 3), which allows the humidity ratio to be calculated as a function of surface temperature. Combining (2) and (3) yields Equation (4). Equation (5) describes $\omega_{\mathrm{surf.sat}}$ as a function of saturated vapor pressure (p_{ws}) at $\mathrm{T}_{\mathrm{surf}}$ and atmospheric pressure, p_a. A correlation or property call for p_{ws} as a function of T is required, such as provided in [6].

$$\omega_{\mathrm{surf}} = \omega_{\mathrm{surf,sat}} \tag{3}$$

$$\varepsilon_{\mathrm{M}} = 1 - \frac{\omega_{\mathrm{surf,sat}} - \omega_{\mathrm{out}}}{\omega_{\mathrm{surf,sat}} - \omega_{\mathrm{in}}} \tag{4}$$

$$\omega_{\mathrm{surf,sat}} = \frac{0.62198 p_{ws}|_{T_{surf}}}{\left(p_a - p_{ws}|_{T_{surf}}\right)} \tag{5}$$

Second key assumption: Second, heat and mass transfer effectiveness are assumed to be equal, as shown in Eq. (6). This is equivalent to assuming the Lewis number Le = 1.

$$\varepsilon_{\mathrm{H}} = \varepsilon_{\mathrm{M}} \tag{6}$$

Effectiveness can then be calculated by solving the set of simultaneous equations described in Equations (1, 4, 5, and 6), or, if preferred, Equations (1, 2, 3, 5, and 6). In this work, Engineering Equation Solver (EES) software was utilized to compute the heat and mass transfer effectiveness at each time step of the drying process.

3 EXPERIMENTAL SETUP

The process and instrumentation diagram is shown in Figure 1. Note that the drum inlet conditions were not measured directly; they were calculated based on an energy balance around the heater.

Note also that both the impact of leakage and the heat added to the process air by the blower were neglected in this study. In other words, the calculated inlet and measured outlet parameters were assumed to be the drum inlet and outlet parameters.

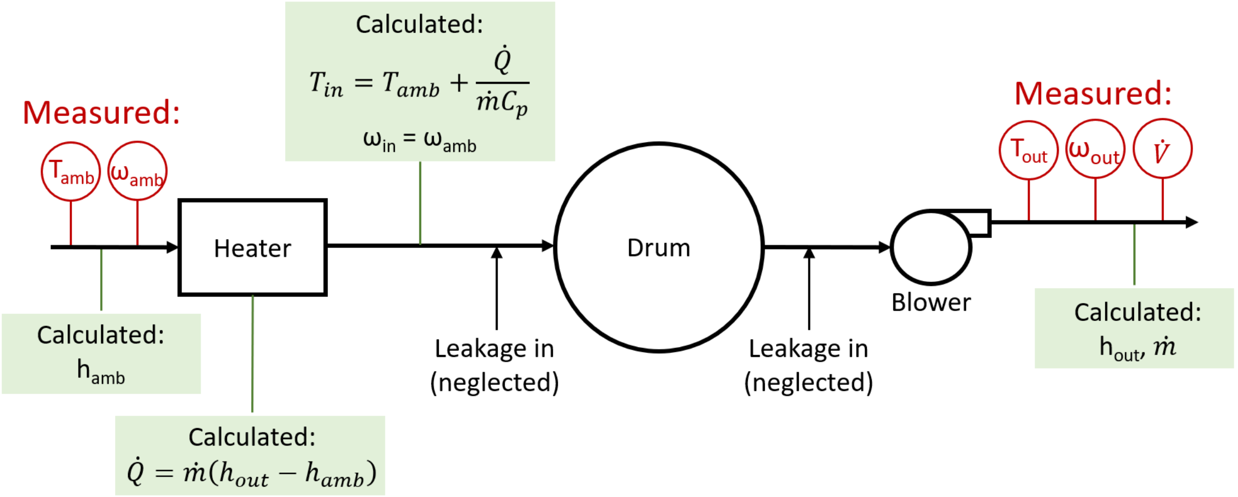

Figure 1: Process and instrumentation diagram of experimental evaluation

Experimental data were measured for a set of four commercially-available (three electric resistance and one gas model), and a single prototype dryer. Each commercially-available unit was used exclusively at its as-shipped air flow rate, and the prototype unit was evaluated at a variety of air flow rates by varying blower speed.

Table 1 provides key parameters of the dryer units evaluated in this work, and Table 2 provides properties of the fabric used.

Table 1: Key parameters of dryer units evaluated in this work

	ER 1	**ER 2**	**Gas**	**ER 4**	**TE**
Drum volume [ft^3] and size designation	8 (standard)	4 (compact)	7.2 (standard)	7.6 (standard)	6.6 (standard)
Drum depth [in]	29.5	23.75	22.5	30	21
Cloth load size [lb, bone dry]	8.45	3	8.45	8.45	8.45
Cloth type used	DOE	DOE	DOE	DOE	DOE
Volumetric air flow [CFM]	147	75	115	115	Various
Residence time [s]	3.27	3.20	3.76	3.97	3.4 – 4.8

Table 2: Properties of test load cloth utilized in this work

	DOE fabric
Cloth material	50% Cotton, 50% Polyester
Fabric type	Momie weave
Item types	Towels Wash cloths
Starting RMC	57.5%

4 RESULTS AND DISCUSSION

Figure 2 shows experimental data for four commercially available residential dryer models. A clear correlation is revealed between residence time and effectiveness, with longer residence times having higher effectiveness. Recall that all trials utilized the same type and mass of cloth. A longer residence corresponds to lower volumetric air flow per unit drum volume; or lower drum volume per unit volumetric air flow.

The experimental results for effectiveness are shown at five selected values of remaining moisture content (RMC). RMC was measured in real time by using a whole-dryer scale. A typical starting weight is the sum of the dryer appliance, the dry cloth, and the moisture in the cloth, while the ending weight is a few pounds lighter due to the removal of water from the process. The starting moisture content in all cases was 57.5% using an 8.45 lb load of DOE cloth. The RMC of 55% corresponds to very early in the drying process, while the RMC of 5% corresponds to a nearly dry load.

The residence time was calculated based on the measured exhaust air volumetric flow rate and the measured drum volume.

The definition of effectiveness does not allow for effectiveness greater than 1. Nevertheless, some of the experimental results show effectiveness greater than 1. This non-physical result may be attributable to three potential areas:

1. measurement uncertainty,
2. the impact of neglecting leakage in the calculations,
3. the impact of using fixed values of h_{fg}, C_p, and air density.

In future work, we plan to quantify measurement uncertainty, quantify the impact of the neglecting leakage, and use dynamically-calculated values of moist air properties. Nevertheless, clear relationships are shown, as follows:

- longer drum air residence time is associated with higher effectiveness
- higher RMC is associated with higher effectiveness
- effectiveness is in a narrow range (98 +/- 5%) for RMC 15% and higher; and much lower for RMC of 5%.

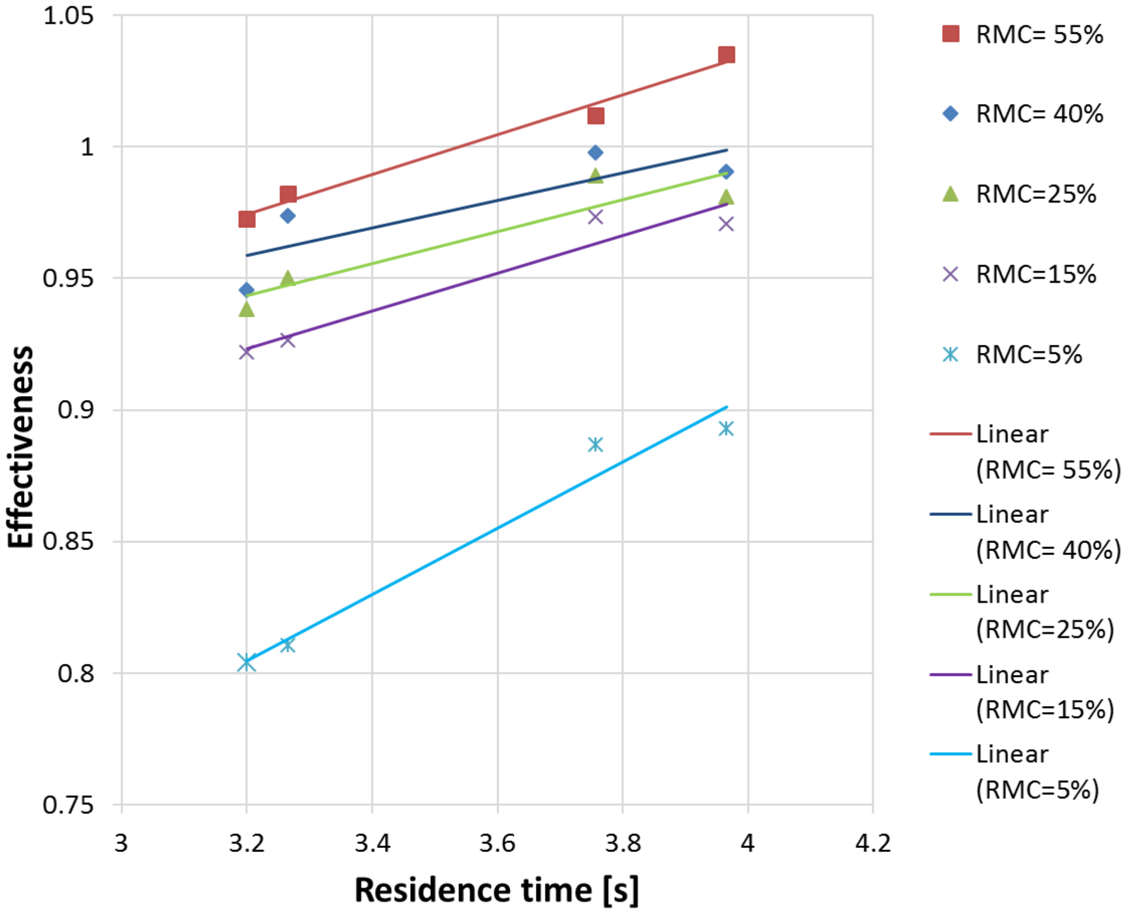

Figure 2: Effectiveness vs. residence time for four commercially-available residential dryer models (each model with its own residence time)

Figure 3 shows experimental data for a prototype thermoelectric heat pump dryer. The drum in this prototype unit was a conventional commercially-available standard size residential dryer drum. In general it had lower effectiveness than the unmodified units shown in Figure 2. The unit in Figure 3 also displayed a set of associations similar to those found for the commercially available units:

- longer drum air residence time is associated with higher effectiveness (approximately 2-4% higher effectiveness for each additional second of residence time)
- higher RMC is associated with higher effectiveness
- effectiveness is in a narrow range (84 +/- 8%) for RMC 15% and higher; and much lower for RMC of 5%.

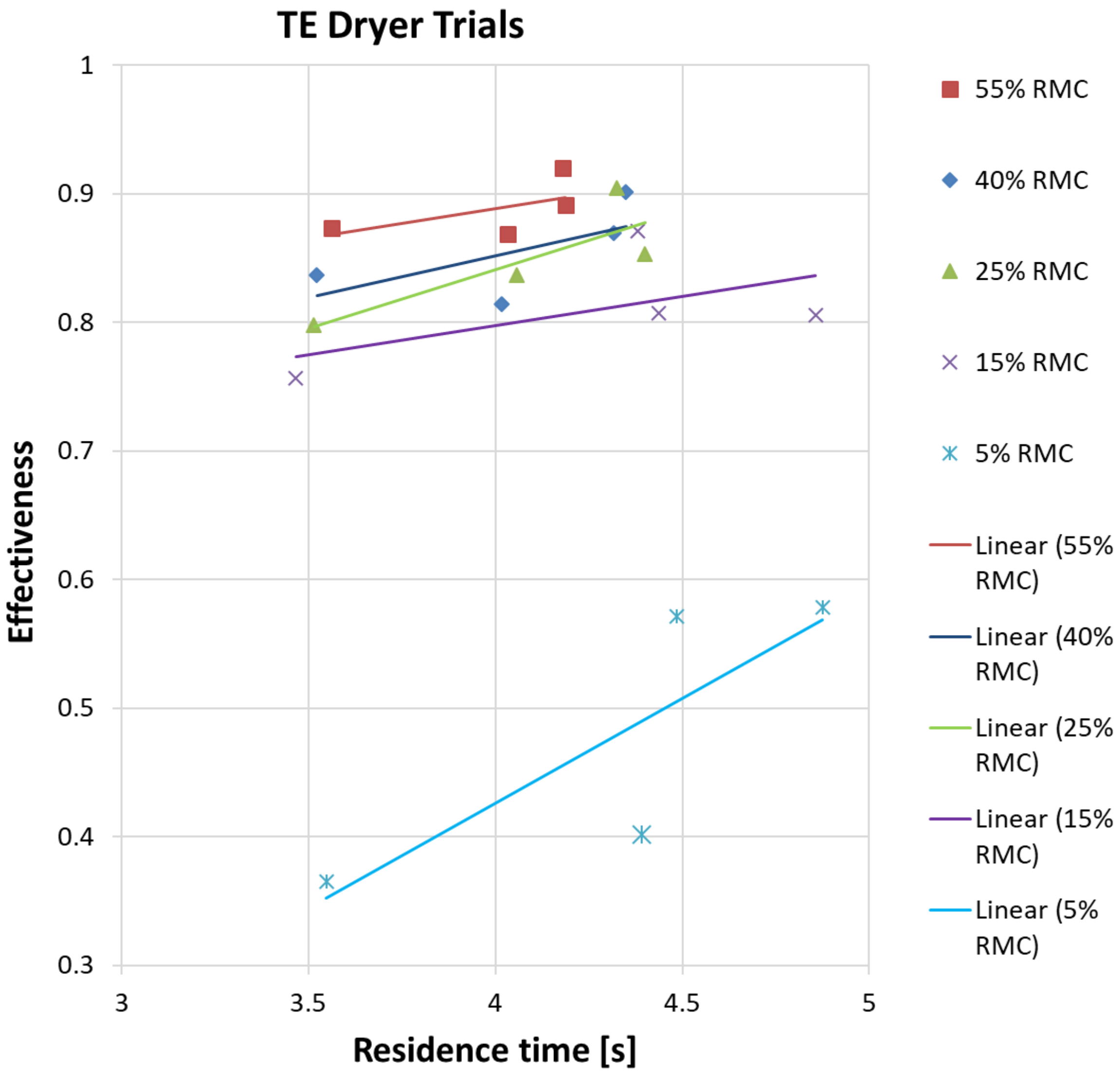

Figure 3: Effectiveness vs. residence time for a single prototype thermoelectric heat pump dryer model (blower speed was varied to obtain different residence times)

5 CONCLUSIONS

A definition of drum heat and mass transfer effectiveness was defined. Experimental measurements were obtained for four electric resistance dryer units and one prototype thermoelectric heat pump dryer unit. A clear trend was shown of increasing effectiveness with longer residence times, both across different models (each with different ratio of drum volume to volumetric air flow), and within a single model (by varying blower speed). Some inconsistencies were observed in the data, and future work will quantify uncertainties and address these inconsistencies.

NOMENCLATURE

C_p	specific heat [$kJ^1kg^{-1}K^{-1}$]
EJ	exajoule
ER	electric resistance
h	specific enthalpy [kJ^1kg^{-1}]
h_{fg}	latent heat of vaporization of water [kJ^1kg^{-1}]
$\dot{m}$	mass flow rate [kg/s]
p	vapor pressure
RMC	remaining moisture content [mass of moisture / mass of bone dry cloth]
T	temperature
TE	thermoelectric
$\dot{V}$	volumetric flow rate [CFM]
$\dot{Q}$	heat transfer rate [kW]
ε	effectiveness [-]
ω	humidity ratio [kg_{water}/kg_{dryair}]

Subscript

a	atmospheric
amb	ambient
H	heat
in	entering the drum
M	mass
out	exiting the drum
sat	saturation
surf	surface
surf,sat	saturation at the surface
ws	water saturation conditions

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