My world is spinning, stop the drum, I want out! A field study of residential dryers in situ.

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ABSTRACT

The residential clothes dryer is a common household appliance that has moved from simply a convenience to an item often viewed as a necessity for modern life. The function of the clothes dryer is to dry the textile, but how does that process work? What really happens in the dryer and its environment?

Heavy loads (towels) were run in residential dryers, not for assessing energy efficiency (EE) comparisons, but for study of the drying process in situ. More than twenty dryers of varying ages were tested across the Midwest, northern and west coasts of the US and southern Canada. Electric and gas dryers were tested, with continuous humidity and temperature measurements taken in the drum during the drying process. Ambient conditions and air flow were recorded; some dryer tests included measurement of total electricity consumption for the load. Installation problems and appliance failures were also recorded.

Observations made during the research have implications for the efficacy and EE of the dryer. Dryers interact with their environment, not just in emitting heat or possibly pulling in conditioned air, but also because the length and efficacy of the drying process is affected by the temperature and humidity of the dryer's environment.

Introduction

This research developed a description of the clothes-drying process and table-driven psychrometric process model of the drying process in residential clothes dryers as they are used in the field. The focus of much of the prior dryer research has been either to develop improved dryers or for energy efficiency (EE) comparisons. Prior process research often treated a dryer as a "black box": the testing was done from outside the dryer, then a model built to reflect what the researchers believed was happening in the dryer (Denkenberger 2011). Recent developments in sensing and data logging have made more direct observations possible.

During the research to develop the model, observations and data provided insights which could affect energy consumption and have implications for future research and development of residential dryers.

Procedure

The testing characterized dryers as installed and in use, not in a controlled lab environment. This approach differs from the test method used for Energy Star (DOE 2015) in several important aspects. The test load is composed of towels, rather than either the DOE D1 or D2 fabrics, because hygroscopic fabrics present one of the more difficult fabrics to dry (Hannas and Gilman 2014). To further the "hard to dry" case, the towels were washed in cold water. The dry weight for a six towel load is approximately 10lb (4.6kg). Because this is a field study, the initial moisture content (IMC) entering the dryer was determined solely by the washer; no additional moisture was added or removed between the wash cycle and the start of the dryer cycle.

Collecting relative humidity (RH) and temperature within the drum requires a combination of NIST-traceable sensors and data logger[1]. A simple open ball made of rubber acts as the scaffold (Figure 1) protecting the sensor assembly and preventing its metal housing from damaging the dryer drum during tumbling. The assembly is placed loose in the drum to tumble with the test load. A series of tests verified that the ball did indeed remain untangled from the test load and provided accurate measurements inside the drum. Other equipment for the testing was selected for small size, repeatable results, and rugged construction because much of the testing required extended travel.

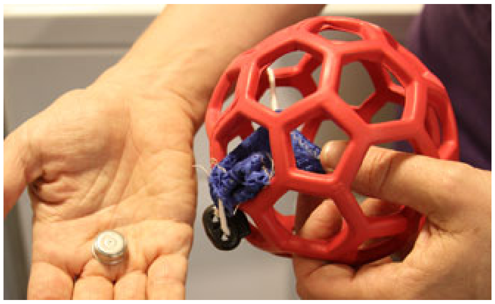

Figure 1. iButton sensor/data logger and the modified dog-toy ball inside which it is suspended before being set in the dryer drum.

The test procedure for this research will be referred to as the “T6” model, short for “towels six”. While portions of the procedure are similar to the DOE test method, the process was designed for use in situ. Observations about the dryer were recorded: make, model, serial number, location, and duct lengths, etc. The sensor/data logger package was in the dryer with the loads. No modifications were made to the dryers.

The towels were weighed as needed to determine moisture content. The ambient conditions were noted, and the sensor package was tumbled on air fluff to record initial conditions before adding the wet towels. As the research progressed additional data were collected: air flow, lint generated, limited energy measurements, observations about the room and building, thermal imaging pictures and ambient temperatures nearby to capture thermal effects outside of the dryer.

Testing was done on the dryer’s medium heat setting, if available; otherwise the high heat setting was used, as initial tests showed that typical temperatures for medium and high heat settings were relatively close. The automatic termination capability of the dryer was used. The towels were checked for moisture at the end of a cycle with a simple pin tester or a thermal camera; damp loads were restarted for 15 minutes.

Dryers were tested in 10 states and provinces in the northern US, southern Canada and west coast, representing 7 ASHRAE climate zones (ASHRAE 2013). The locations were determined by the ability to locate willing residents and the ability to travel to the site. Testing has been ongoing since the spring of 2014, with additional sites and data merging into the model

[1] The sensors selected were Maxim DS1922T (125C max) and the DS1923-F5 (85C max) iButton Hygrochron.

as they are completed. Tests were performed in every season, and at a wide range of times, including the middle of the night, to include diverse ambient conditions.

Results and Analysis

As of February 2016, data had been collected from 120 dryer runs. The breakdown of these is shown in Table 2. There are 62 runs done following the T6 procedure; another 4 done following the T2 procedure (the same procedure, using only two towels); 28 other towel loads which did not terminate correctly, or were otherwise unsuitable for inclusion in the T6 model; and 26 other investigative runs.

Table 2. Dryer test run breakdown.

Dryer fuel	**T6**	**T2**	**Other towel**[2]	**Investigations**	**Total**
Gas	38	3	14	14	69[a]
Electric	24	1	14	1	40
Air (hang dry)	0	0	0	11	11
Total	62	4	28	26	120

[a] US installed base of dryers is 20% gas; 65% of the tested dryers were gas. Northern tier states have a larger percentage of gas dryers than other regions.

Plotting the temperature data from the dryers, Figure 2, illustrates the wide variation in control systems and termination algorithms. For visual clarity, only a sampling of the runs are shown in the chart, along with a composite (average) and plus- and minus-one standard deviation. Another way of visualizing the variety is a histogram of cycle duration, shown in Figure 3.

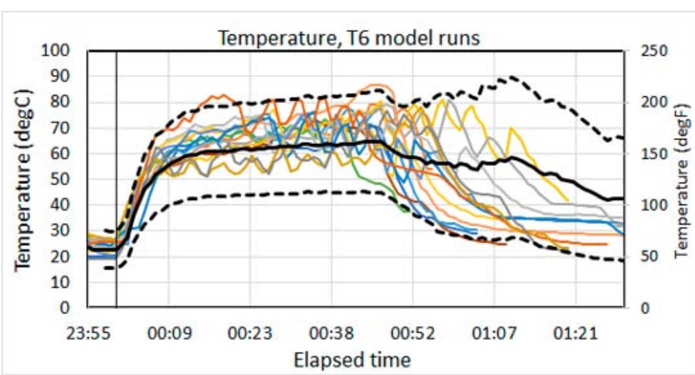

Figure 2. Temperature variation for a sampling of T6 dryer loads.

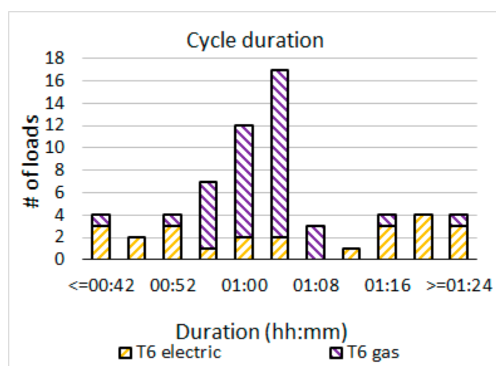

Figure 3. Cycle duration for all T6 runs. Cycle length is determined by auto-termination.

Examining the chart for relative humidity, Figure 4, shows the initial spike due to the addition of the wet towels followed by the steady decrease during the drying process. Only a sampling of the

[2] "Other towel" runs were not suitable for inclusion in the T6 model, often due to incorrect auto-termination, but yielded important observations about field conditions.

runs are shown, along with the composite and plus- and minus-one standard deviation. Unlike the variation seen in temperature, there is less difference in the humidity profiles of the various dryers.

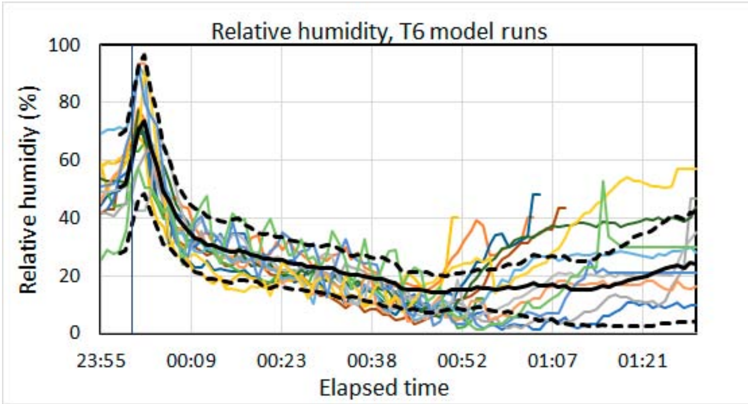

Figure 4. Relative humidity variation for a sampling of T6 dryer loads.

The T6 field data were combined to create a composite model[3] of the drying process, shown in Figure 5. Relative humidity is important for determining when the load is dry; various researchers have used 5% to 15% relative humidity, typically measured at the dryer exhaust (Bassily and Colver 2003; Bendt 2010; Guadalupe et al 2013). For this research, the criteria is three minutes at 10% or less relative humidity in the air inside the drum.

Figure 5 also contains the humidity ratio[4], *w*, calculated from the temperature and relative humidity data. The humidity ratio of the air in the drum is essential to understanding the various periods which make up the dryer cycle (Bassily and Colver 2003). Each period will be discussed below.

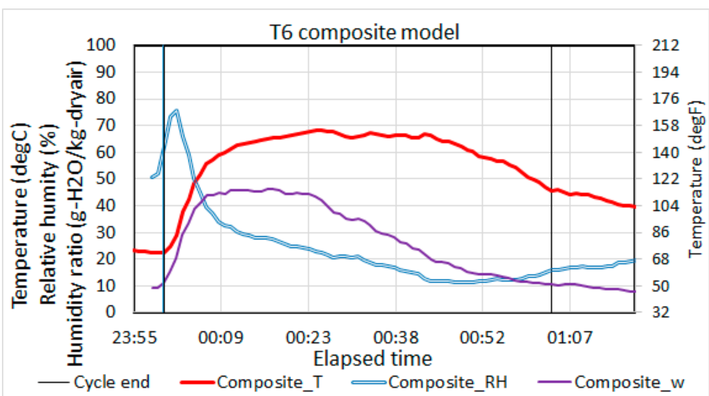

Figure 5. T6 composite model.

[3] Unless explicitly stated otherwise, references to the drying cycle refer to the T6 composite model results rather than results for individual runs.

[4] Humidity ratio, given in lb of moisture per lb of dry air (kg of moisture per kg of dry air), may be thought of as "absolute humidity", in contrast to relative humidity, which is given in % of the maximum possible moisture carried in the air.

Because the type and size of the load was held constant, initial moisture content[5] (IMC), shown in Figure 6, is a function of the washing machine. There is some variation in the residual moisture content (RMC) after drying, but as can be seen in Figure 7, most loads are bone-dry[6] when done. These loads feel warm, and dry to the touch. However, they regain moisture from the ambient air once they are out of the dryer. Experimental data confirmed the conventional wisdom that the RMC stabilizes at approximately 5% after regain.

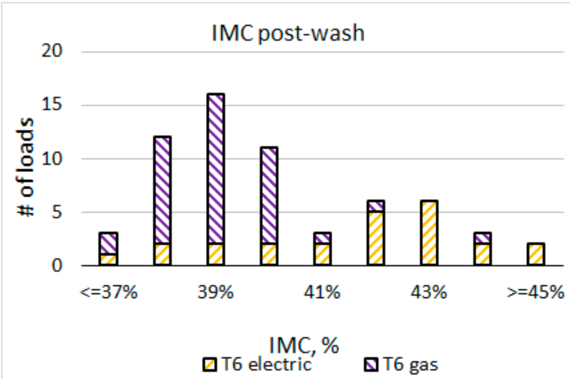

Figure 6. Initial moisture content of T6 loads.

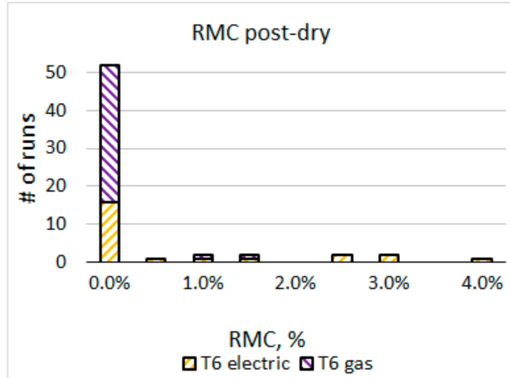

Figure 7. Residual moisture content of completely-dry T6 loads.

Stopping the load after 3 minutes at 10% relative humidity may lead to the fabric "feeling" vaguely damp; however, use of a pin-tester as a simple go/no-go indicator for moisture repeatedly confirms the same reading as dry towels[7] which have been sitting on a shelf in the same room. Results from this research and prior work confirm that drying to a relative humidity below 10% generally results in towels which weigh less after drying than they did when dry before washing.

Human skin has no true capacity for feeling moisture; dryness is perceived instead in terms of other physiological sensations such as relative temperature and the relative friction between the skin and the fabric (Okamoto, Nagano and Yamada 2012; Filingeri and Havenith 2015). This dichotomy contributes to over-drying laundry; fabric which is bone dry is uniformly perceived as dry.

Periods of the drying process

The authors have generally defined the periods of the drying process consistently with (Bassily and Colver 2003); however, the data in this study reveals the need for one period not previously identified: the period during which the load is over-dried. In other words, the in situ drying process often contains a "fry period". The drying periods are shown in Figure 8. They are discussed individually in the following sections.

The warmup period

The warmup period, as might be expected, is the time during which the mass of the dryer and the load come up to a set temperature, typically 120-130F (50-55C). Figure 8 indicates the

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[5] MC (both IMC and RMC) = (m_{wet} – $m_{bonedry}$) / m_{wet}.
[6] Bone dry is the state in which no more moisture can be extracted, and RMC is zero.
[7] Pin testers are not calibrated for fabric moisture content; their use in this research was verified by matching their 0% readings with RMC calculated by weigh, thermal camera images and RH readings from the cycle.

“position” of the warmup period on the temperature and relative humidity chart, while Figure 9 shows the relatively tight spread of warmup period durations. The warmup time is determined by the combined thermal mass of the load and dryer; unless the load is very small, the moisture in the load is the major factor.

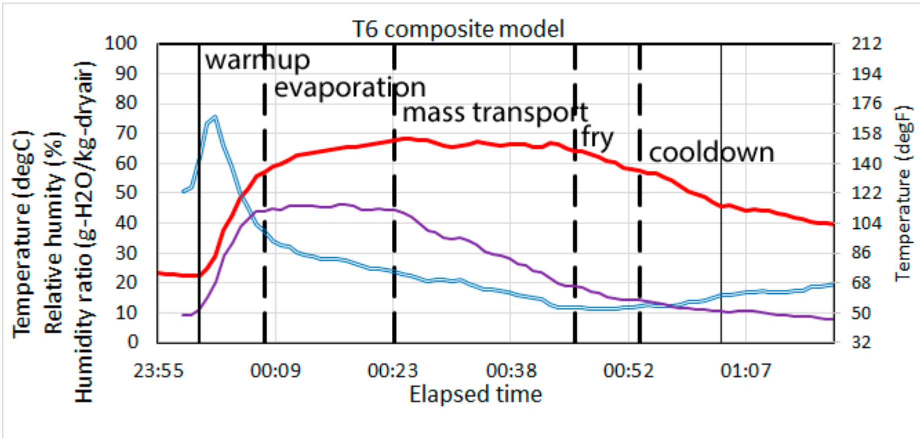

Figure 8. The drying periods.

Because the laundry is at its wettest during the warmup period, this is the period with the greatest risk of abrasion damage to the fabrics. Happey (1978) discusses the causes of fabric-on-fabric and fabric-on-surface friction increasing with increasing fabric moisture content.

The evaporation period

Once the dryer and laundry masses are sufficiently warm, the evaporation period begins (see Figure 8). This is sometimes called the “constant rate” period. The rate of drying is determined by the difference in partial vapor pressures of moisture at the surface of the towels, as long as the airflow is sufficient to remove the moisture at the same rate. The partial pressure of the incoming heated air is determined by the relative humidity of the ambient air. The variation in duration for the evaporation period is shown in Figure 10.

During this period, the flexing of the wet fabric leads to softer dried fabric and begins wrinkle removal, but there is also risk of fabric damage from abrasion if this period is overly long (Higgins 2003).

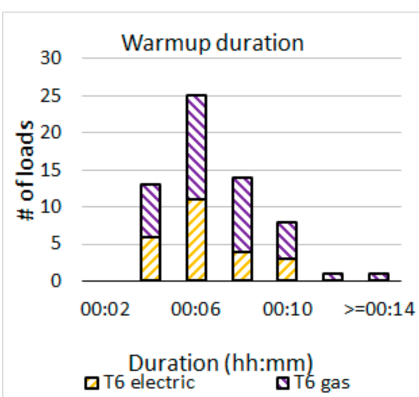

Figure 9. Warmup period duration.

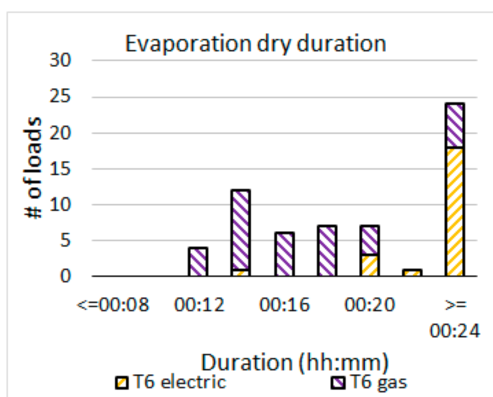

Figure 10. Evaporation period duration.

Water has a strong attraction between its polar molecules; this contributes to matting of fibers during the washing process. The data from this research shows that the first 10 to 15 minutes of the evaporation period are critical to un-matting the fibers and achieving fabric softness. Laundry hung outside illustrates the lack of this process – line-dried laundry will dry but not be as soft as it would be if dried in the dryer. Line drying lacks the critical repeated fabric flexing while heat is applied during the evaporation period.

For the drying process to be successful, the nearly saturated air must be replaced with fresh, lower-humidity air[8]. Vented dryers direct this moisture to the outside environment while pulling in air from the climate-conditioned living space. Dryers for which the manufacturer will specify airflow indicate a range of 100-150 ft^3/min (47-71 l/sec). Airflows were measured at the dryer vent outlets; the results are summarized in Figure 11; airflow may be reduced by overloading the dryer, long or blocked ducts, excessive lint or dryer malfunction.

Vented dryers direct VOCs from the drying fabric and the combustion products of gas dryers outside of the building envelope. Venting also contributes to a controlled cooldown period; ventless dryers must transfer the heat into the space they occupy.

The mass transport period

Once much of the surface moisture has evaporated, the drying transitions to mass transport of water molecules from within the individual fibers; this period is illustrated in Figure 12. The duration of this period is determined by fiber type. Plant fibers such as cotton absorb moisture into the fiber core; this moisture must by transported to the fiber surface before it will evaporate. Synthetic fibers which do not readily absorb moisture, or do not have a tubular structure will have very short mass transport periods. The mass transport period is defined to end when the load is dry, although mass transport activity may continue into the next period.

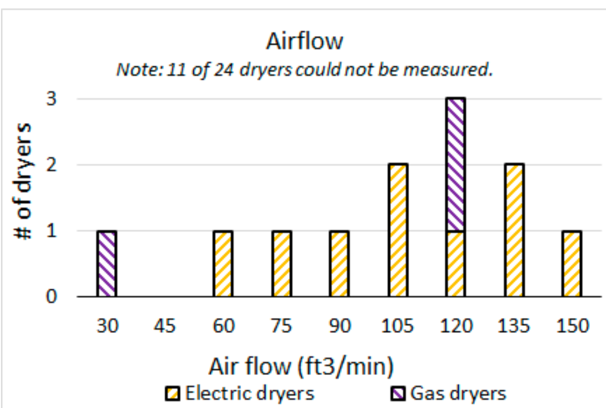

Figure 11. Distribution of exhaust air flow over all dryers tested.

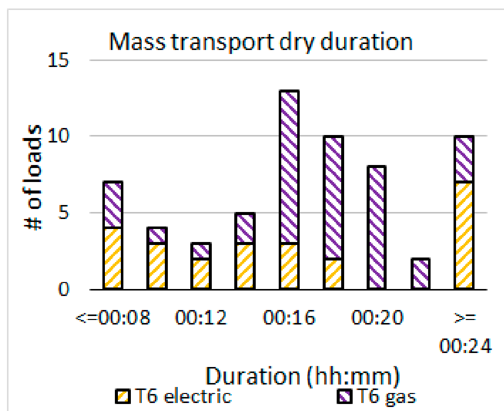

Figure 12. Mass transport period duration.

The fry period

The shorter the fry period the better for energy use, drying time, consumer convenience, and fabric wear. The load is dry, having reached its target 10% relative humidity for the specified time but the dryer continues heating. Figure 13 shows one such run with a 19-minute fry period.

[8] Airflow through the drum serves 3 purposes, carrying away moisture, heat and lint.

Depending upon the dryer control system, there may be a significant temperature rise in the fry period. While moisture is evaporating, evaporation of the moisture absorbs heat energy, moderating the air temperature inside the drum. However, in the fry period the lack of moisture means that all heat input raises the air temperature.

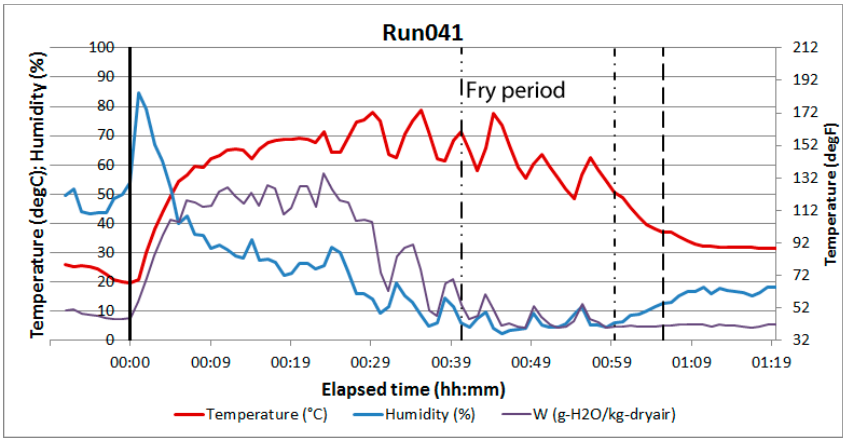

Figure 13. The fry period for one run.

The fry period is entirely determined by the dryer control system. See Figure 14 for the wide length variation caused by these control systems and termination algorithms.

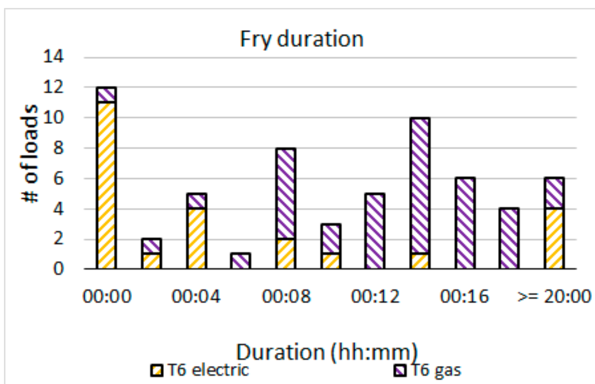

Figure 14. The wide variation in the duration of the fry period.

During winter tests in Montana, it became apparent that the fry period is also when static charge can develop in the load, especially when the ambient relative humidity hovered around 30%. Eliminating the fry period reduces the static electricity – the RMC, although small, provides enough conductivity to dissipate static charge.

Low ambient humidity can affect dryer termination, especially for controllers using temperature to determine the start of the cooldown period. In extremely dry air, the partial pressures force the water to evaporate off the fabric quickly; as can be seen in Figure 15, the result is a long fry period which reaches “negative” relative humidity. For visual clarity, the x-axis (zero moisture content) is highlighted with a dashed gold line. The build-up of static electricity fools the capacitive moisture sensor into indicating a negative number; when this load was removed from the dryer, the hairs on the tester’s arms stood up.

For dryers using temperature as the termination method, this period is the "high heat" stage; temperature inside the drum can rise rapidly because there is no moisture to absorb the thermal energy in the form of latent heat. Well-designed controllers will sense this after only a few minutes, and move into the cooldown period.

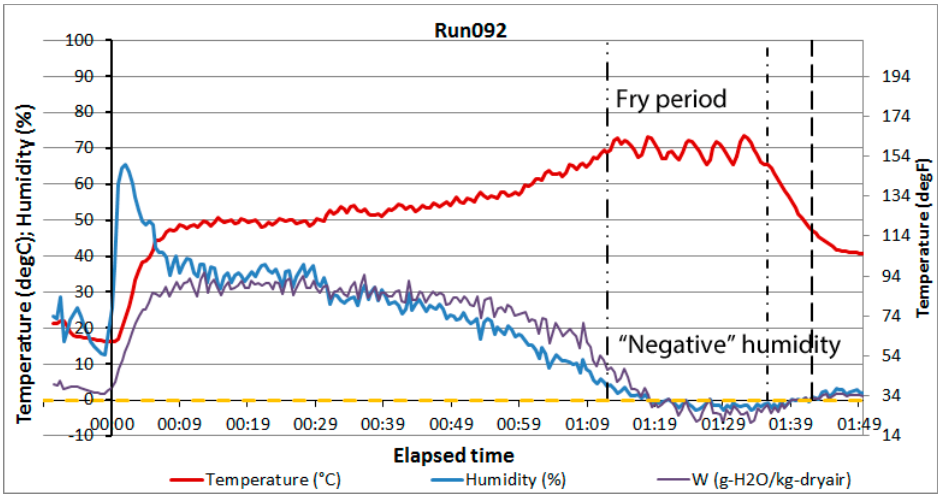

Figure 15. Static charge developed in the fry period in a run with 20% ambient relative humidity.

Approximately half of the occupants told the authors that the auto-termination on the dryer was untrustworthy, and that they preferred to set the cycle time manually for at least certain types of loads. Because of the human tendency to expect dried laundry to feel bone dry, manual time settings often create a longer fry period.

The cooldown period

The cooldown period allows the load to cool while tumbling just long enough to prevent undue wrinkling. Determination of the end of cycle (the end of cooldown) from data is somewhat arbitrary, as many dryers on automatic termination have a "wrinkle free" periodic tumbling mode which may go on for an hour or so after the end of the dry or fry period. For consistency during this research the end of the cooldown period was set at an inflection point in the curve of decreasing temperature in the drum. The length of the cooldown period (Figure 16) should be dominated by the thermal masses of the dryer, which is typically large compared to the thermal mass of the dry laundry. This was confirmed by the similar cooldown times for both the T2 loads and T6 loads.

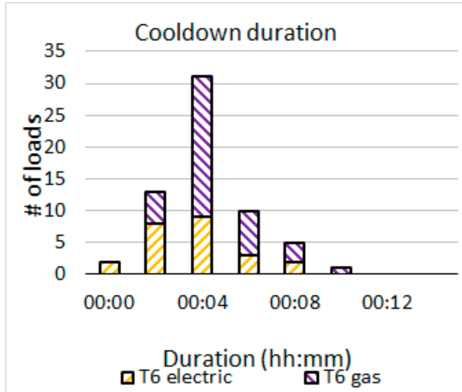

Figure 16.The variation in the duration of the cooldown period is relatively small.

As laundry dries, it fluffs, expands and impedes the airflow through the drum (Yi et al 2015). Overloading the dryer increases the drying time, and in the extreme case, prevents the load from drying completely. Figures 17a through 17d illustrate common air flows through dryer drums; Figure 18 illustrates why that matters. The load in that photo was originally a standard T6 load, washed in a space-saving washer located under the dryer. However, it became apparent that the dryer would be overloaded with 6 towels, so only 4 were dried together. Even four towels required restarting the dryer to finish the drying process; they completely filled this dryer when they were dry.

Near the end of the research, a modified "T6" test, called the "T2", was added; T2 loads have one-third the surface area and one-third the weight of the T6 load. Adding T2 tests was prompted by test runs which revealed that some of the dryers exhibited very different termination results on small loads. These dryers' auto-termination controls worked well on the large T6 load, but the small T2 loads terminated too soon, before the towels were dry.

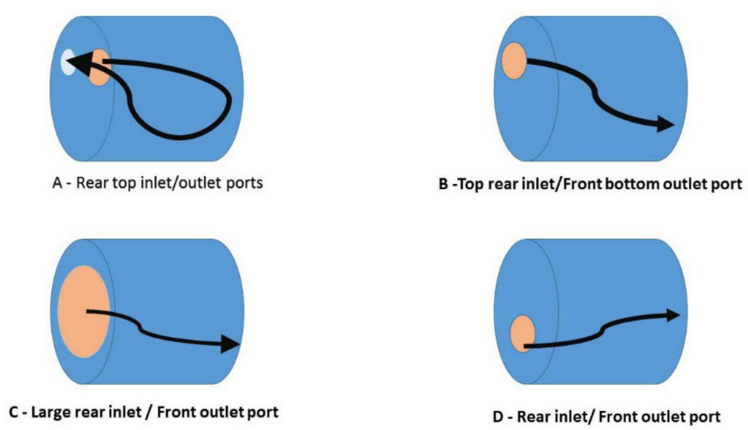

Figure 17. a), b), c) and d) Typical air paths through residential dryers.

Figure 18. Partially-dried towels fill a dryer, reducing the air path so that they do not dry without a large added time.

Summarizing the Drying Process

Psychrometric charts are a useful way to visualize the drying process. Figure 13 shows the charts for two representative T6 runs. The drying process starts at the triangle mark toward the lower left, at ambient room temperature and humidity, then moves right and curves down and back in a horseshoe shape. During warmup, the dryer and load gain temperature and the air inside the drum gains humidity from the load. Electric dryers (Figure 19) follow the curving lines of constant relative humidity more closely; gas dryers (Figure 20) add humidity to the air in the drum from the combustion process.

During evaporation drying, the load moves to the right on a more-or-less straight line. Mass transport drying occurs in the curve at the right end of the horseshoe. A dry load reaches 10% relative humidity (the curved solid line closest to the lower right corner) and follows that curve back toward the left as it cools, shown in Figure 19. A load with a significant fry period, as shown in Figure 20, drops below 10% relative humidity toward 5% (the curved dashed line), and does not get back up towards 10% until well into the cooldown period.

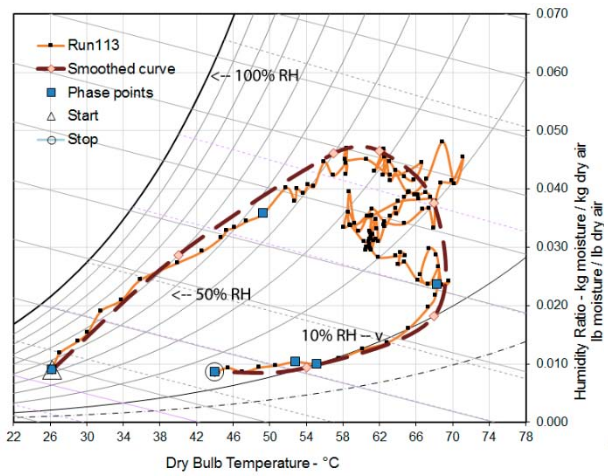

Figure 19. a) Psychrometric chart from one T6 electric dryer run.

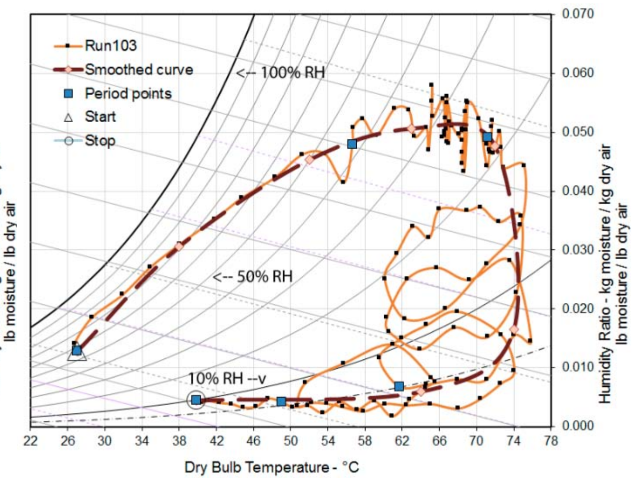

Figure 20. Psychrometric chart from one T6 gas dryer run with a significant fry period.

The heavy dashed lines on the psychrometric charts show idealized processes. Moving from left to right (increasing temperature) requires the addition of heat energy. Moving from upper left toward the lower right requires energy to evaporate the moisture. Tumbling requires energy throughout the process. Therefore the smoothest, shortest-length horseshoe is the most energy-efficient and time-efficient cycle. It is also the cycle which radiates the least heat into the laundry area. Some path looping is expected, due to necessary hysteresis in process controllers, but the smaller the loops, the more efficient the process.

Energy Efficiency

The obvious target for EE is shortening the fry period; this reduces both power and energy consumption, as well as decreasing stress on the fabric and increasing consumer convenience via shorter cycle times. Other EE measures such as longer drying cycles with lower temperatures must be examined not only from the energy perspective but also consumer perspectives. Longer cycles increase fabric abrasion; while one longer cycle makes essentially no difference to fabric life, the effects of repeated long cycles should be examined. Lower drying temperatures also have potential drawbacks; the techniques for adding wrinkle-resistance and permanent sharp creases often require a specified temperature range for a minimum specified time to perform effectively.

Delaying the start of the cycle for more than a very short amount of time will not be acceptable to consumers. Wet laundry left in a dryer for any length of time will begin to dry; evaporation without the heat and motion allows wrinkles to set into the fabric which later drying will not release. Taken to greater length, a delayed start may allow undesirable effects such as the growth of mold spores.

During the warmup period, slowing or stopping the dryer will have a negative impact on EE as additional heat will be required to re-start the warmup, and possibly more wrinkling due to partially warmed wet laundry cooling off and sitting in a rumpled state.

Interrupting the evaporation period is also not productive for the drying process. Lowering the temperature below the threshold for maximum evaporation rate increases drying time, which may be unacceptable to consumers. Continuous tumbling plus temperatures within the range required for wrinkle-release and crease recovery is required for satisfactory results in the consumer's experience. Rough- or scratchy-feeling towels may result if the cycle is interrupted during the warmup and evaporation periods. The warmup and evaporation periods are also when there is the most wet-abrasion on the fabrics (Happey 1979); added time in these periods will impact fabric life, especially for plant-based- or animal-hair fabrics.

The best opportunities for implementing demand response in a manner acceptable to consumers are in the mass transport and cooldown periods. Slowing the mass transport by lowering heat or slowing tumbling does not seem to have deleterious effects on the drying process or fabric condition. The cooldown period, having no heat input, could be changed by slower tumbling, lower airflow, and possibly, intermittent tumbling.

Summary

Heavy loads (towels) were run in residential clothes dryers to study the drying process in situ. In addition to developing the drying process model which was the goal of this research, many of the observations have important implications for the dryer control systems and therefore also the dryer EE.

Dryers interact with their environment, not just in emitting heat and VOCs or possibly pulling in conditioned air, but also because the length and efficacy of the drying process is affected by the temperature and humidity of the dryer's environment. It's worth remembering that the clothes dryer is primarily a convenience item. Energy and thermal efficiencies may be improved, but adoption of these changes will fail if convenience is significantly compromised in the eyes of the consumer.

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