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AN EMPIRICAL STUDY OF ENERGY EFFICIENCY OF CLOTHES DRYERS

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ABSTRACT

The domestic clothes dryer is one of the most energy-consumptive appliances in the residential sector, but there has been relatively little work to study its environmental aspects and improve upon its design and efficiency. Our research group is beginning such a project, the ultimate goal of which is to provide decision-making tools for the public (e.g. when buying a dryer) and for policy makers (e.g. when mandating appliance performance criteria). Our first step is to study the behaviour of a clothes dryer to (a) gain experience with the devices and (b) create baseline empirical models of their general behaviour. In this article, we will report our results to date, including what how we modelled and analyzed a specific test dryer, and the results we gathered from experiments. We identify behavioural characteristics of the dryer that may suggest either re-design opportunities or guidelines for dryer use. While studying a single dryer is clearly a limiting factor, we do expect to find general trends to be consistent with other dryers of similar design.

Keywords: clothes dryer, sustainability, energy efficiency

INTRODUCTION

Among North American household appliances, the refrigerator has received the greatest attention from the standpoint of environmental impact. The clothes dryer is also often cited as being a very high energy consumer – sometimes ranked as consuming more energy than a refrigerator [1, 2, 3]. However, the dryer has been relatively neglected in terms of its visibility in applied research and in the public as an environmental problem, even though there are several European efforts in this regard, such as EU Directive 2003/66/CE. This has come to the attention of our research group, so we have undertaken to address this matter. Our long-term goal is to develop a capacity to effectively assess the environmental impact of sundry products. Working on clothes dryers is our first major project in this regard.

While research on the scientific and engineering foundations of clothes dryers does exist, the authors have found little in the way of tools that can be of direct use to non-academics. Specifically, we hope to address three stakeholder groups.

Appliance designers and manufacturers. Those who design and manufacture clothes dryers do not need the detailed thermodynamic analyses typical in academic settings, largely because in product development, there are many other factors besides energy efficiency that must be balanced against one another. A general, empirical model that is widely usable is sufficient. Such a model would suggest to designers and manufacturers general directions in which products can be improved. These models can be incorporated more easily into extant product development processes.

Users. The owners of clothes dryers would benefit from a simple to use tool to understand which (a) dryer model could be best suited for their lifestyle, and (b) what alternatives exist (from a sustainability point of view) when considering the purchase of a dryer. Increased efficiency over the lifecycle of the dryer need to be weighed against potentially higher purchase costs. Based on an average residential electricity rate of 8.3 cents/kWh [2] and an annual dryer power consumption of 1079 kWh, each 10% efficiency improvement would reduce consumer operating cost by about $9 annually. A potentially larger impact could be safety if greater efficiency is achieved through lower operating temperature. The Consumer Product Safety Commission estimated that dryers caused 15,600 fires, 20 deaths, 370 injuries and $75.5M direct property damages in 1998 [4]. For this type of appliance modelling, a high degree of precision is not as important as accuracy and usability.

Policy makers. Governments at all levels may need to mandate standards and otherwise regulate the kinds of appliances that can be marketed or used in a region. As such, they need a general tool that can indicate performance trends - again, accurately but not necessarily precisely - so that they can make informed decisions. It is estimated that clothes dryers in the U.S. consume 66 billion kWh annually, equivalent to seven 1 GW power plants at 100% utilization. A worst-case analysis based on coal-fired power plants suggests a 10% efficiency improvement in electric dryers alone would reduce U.S. carbon dioxide emissions by 7 million metric tons annually [6]. This is roughly the equivalent of the carbon dioxide emitted by a million passenger cars driven an average of 12,000 miles per year [7].
In other words, our perspective is very strictly *not* that of the scientist, but that of the user, and our models are all developed from that perspective. As such, they tend to be empirical in nature and systemic in scope.
To begin such a project, we have undertaken to gain basic insights into dryer design, operation, and performance by trying to build empirical relationships (rather than scientifically precise thermodynamic models) of a particular dryer. The point of this work is to gain experience in developing such models and to look for easily identified characteristics of clothes drying operations. In this paper, we will focus on the development of the preliminary model of overall dryer performance and the experiments we have conducted in that regard. What follows in this section is a brief summary of the basic theory upon which our model is based.
As a result of the experiments we have conducted so far, we have identified four key factors affecting water evaporation in clothes dryers: air velocity, relative humidity, temperature, and vapour pressure. Other factors, such as surface area and hydro-conductivity of the medium have not been taken into consideration because their effects have been secondary in nature. We will include such effects in the future; for now, we are focusing only on "first-order" effects.
A psychrometric chart neatly captures the relationship between the relative and absolute humidity, and wet- and dry-bulb temperatures. As illustrated in the Figure 1 (developed using Hands Down Software, http://www.handsdownsoftware.com), with the knowledge of any two variables of the air property, other properties of gas-vapour properties can be determined.

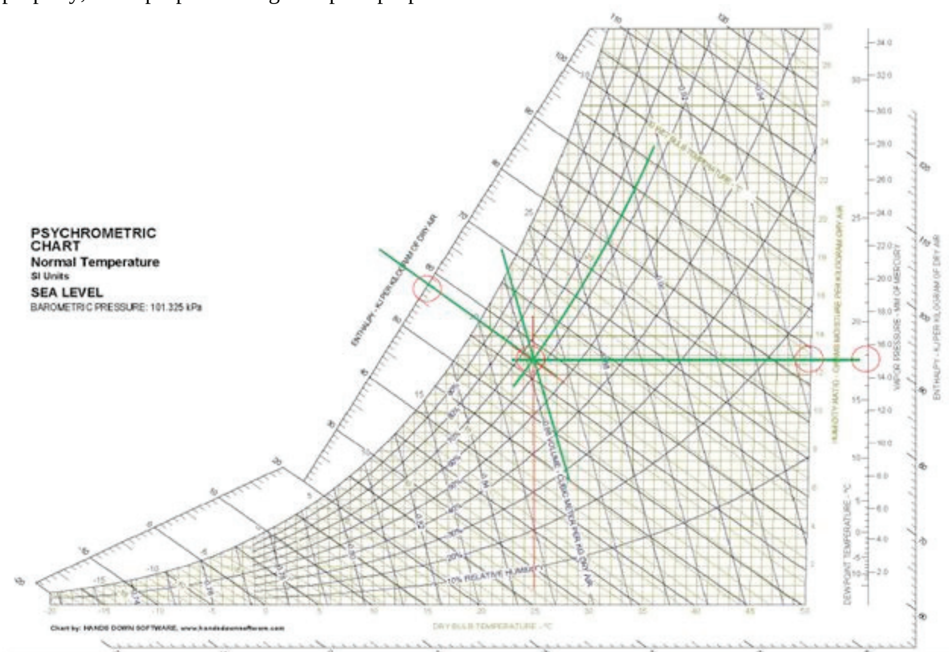

Figure 1: Psychrometric Chart in SI units.

A simple algebraic representation of psychrometric chart information was also developed and is briefly described here. First, assuming standard temperature and pressure, saturation pressure is a function of the temperature.

$$P_{sat} = 6.1078 \times 10^{\frac{7.5T - 2048.625}{T - 85.82}} \tag{1}$$

The vapour pressure is the product of the percent relative humidity and the saturation pressure.

$$P_V = \%RH \times P_{sat} \tag{2}$$

The total atmospheric pressure is the sum of the partial pressure of air and partial pressure of water vapour.

$$P_{atm} = P_{dry} + P_V \tag{3}$$

Using ideal gas law, the density of the humid air is also quantified by the following expression.

$$\rho_{humidAir} = \frac{P_{dry}}{287.05\,J/kgK} + \frac{P_V}{461.495\,J/kgK} \tag{4}$$

This equation can be simplified to following expression.

$$\rho_{humidAir} = \frac{0.0035P_{dry}}{T} + \frac{0.0022P_V}{T} \tag{5}$$

Dryer efficiency is the ratio of heat of vapourization of water in the dryer load versus the total electrical energy used during the drying cycle. The heat of vapourization is the product of latent heat of water of 2402.8 kJ/kg and the mass of water in kg. The electrical energy is the product of electrical power consumption in watts (W) and the duration of the drying cycle in seconds.

$$\eta_{dryer} = \frac{Heat\ of\ vapourization}{Electrical\ energy} = \frac{2402.8\,kJ/kg \times M_{water}}{P\Delta t} \tag{6}$$

EXPERIMENTAL WORK

In this section, we will describe the experimental work performed so far during this project.

Experiment setup

The clothes dryer that we used is a General Electric Spacemaker® model #DSKS443EBWW (240V, 3.6 cubic feet). Figure 2, below, is a schematic representation of the dryer's major systems, inputs, and outputs. Electric power (black lines) generally moves left to right, while material flows generally move from top to bottom. This architecture was determined by partially disassembling the dryer and observing it in operation. The exhaust was ducted as recommended by the manufacturer to a grate in the laboratory leading outside the building. The grate was partially obstructed by a fan, but the opening was far wider than the duct itself - we expect any impedance to airflow from the stationary fan to be negligible, at least to the accuracy of these preliminary tests.

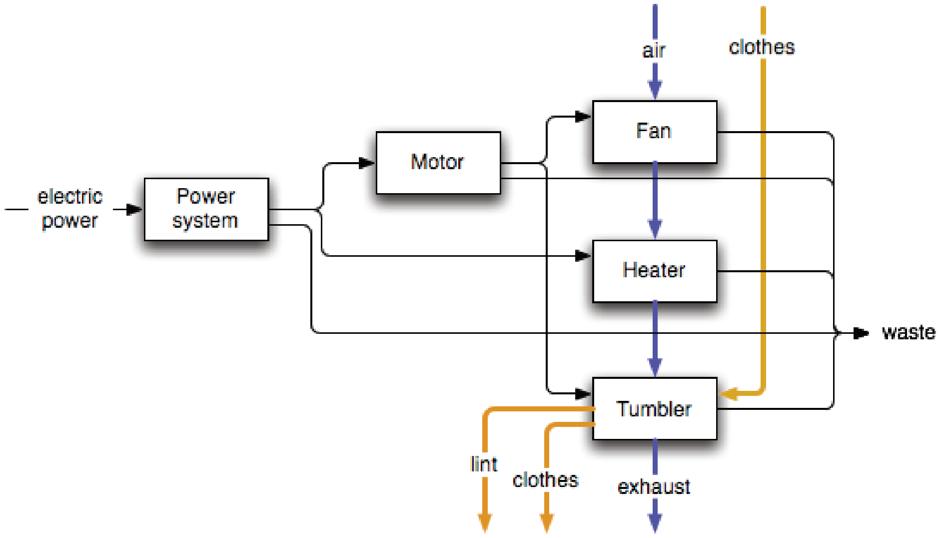

Figure 2: Systems block diagram of the GE Spacemaker® dryer.

Our experimental goal was to understand the performance of the dryer for the sake of constructing an empirical model of its behaviour. To do this, we instrumented the dryer using sensors to measure:

- ambient temperature and humidity,
- amount of water in wet clothes going into the dryer,
- electricity usage by the dryer during its complete cycle,
- dryer exhaust temperature and humidity, and
- amount of water remaining in clothes after drying cycle.

Figure 3, below, shows the arrangement of the sensors schematically. A Windows-based PC laptop running software provided with the sensors was used as a data acquisition system.

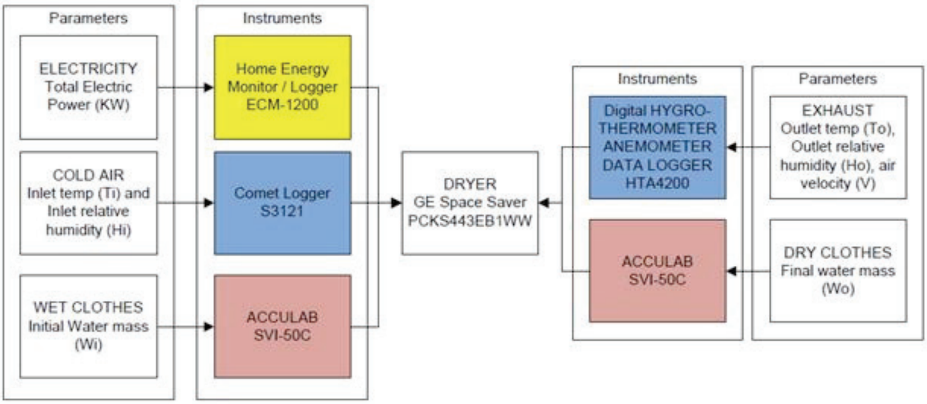

Figure 3: Illustration of data logging equipment setup and parameters measured.

Experimental Procedure

Two different kinds of materials were used in the experiments: typical blue jeans (pants) and wool sweaters. Each run consisted of the following general steps:

1. The dry weight of clothes was measured.

2. The clothes were soaked in water then wrung out to simulate the spin cycle of a conventional clothes washer.
3. The damp clothes were weighed, and the amount of water in the clothes was calculated as the difference from the initial dry weight.
4. The damp clothes were placed in the dryer.
5. The data logging equipment was initialized and the dryer was started.
6. The dryer was stopped when the absolute humidity of the exhaust air reached ambient absolute humidity.
7. The clothes were weighed again to determine if any noticeable moisture was left.

Tests were run using two different fan speeds and two different load types. These are summarized as follows:
1. Three jeans and exhaust air speed of 5 m/s.
2. Three jeans and exhaust air speed of 5.65 m/s.
3. Three sweaters and exhaust air speed of 5.65 m/s.

Test Results
The following graphs (Figures 4, 5, and 6) plot mass flow rate of water vapour (calculated from absolute humidity measurements) and exhaust temperature versus time. In each graph, the top purple line represents the total mass flow rate of water vapour measured at the exhaust. The green line (third from the top) represents the total mass flow rate of water entering the dryer (i.e. ambient humidity). The light blue line (second from the top) represents the difference in the exhaust and inlet water mass flow rate; this is the water evaporated from the clothes. The red line (fourth from the top) represents the exhaust air temperature. The navy blue line (fifth from the top) represents the inlet air temperature. A drying cycle starts at time 0.0 and ends when the exhaust humidity reaches ambient; this is denoted in the plots as the (near) intersection of the purple and green data lines.
The black lines partitioning the data in the plots will be explained in the next section.

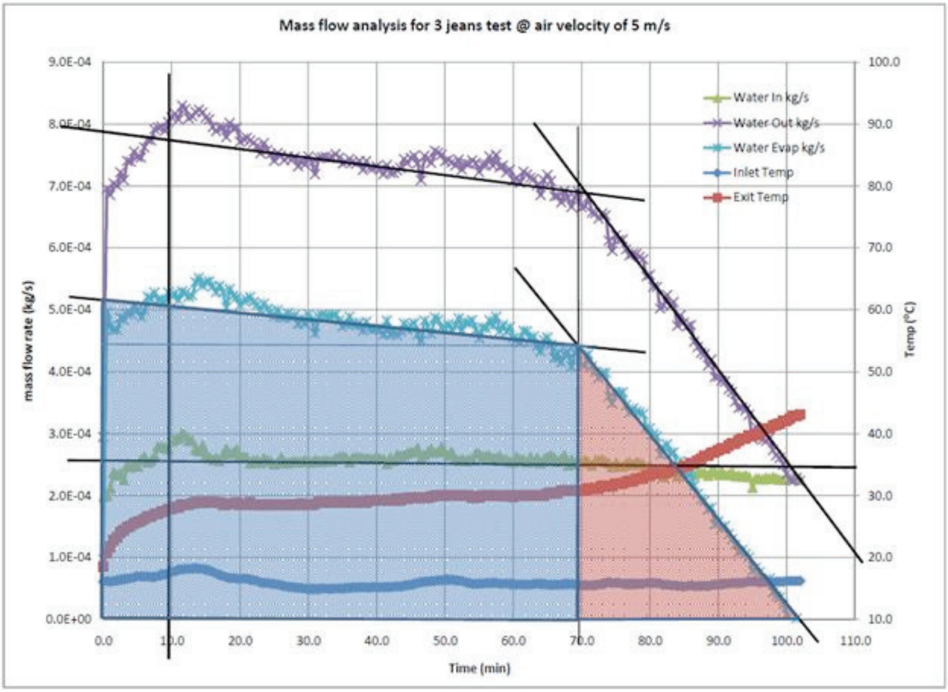

Figure 4: Mass flow rate of 3 jeans test at air velocity of 5 m/s.

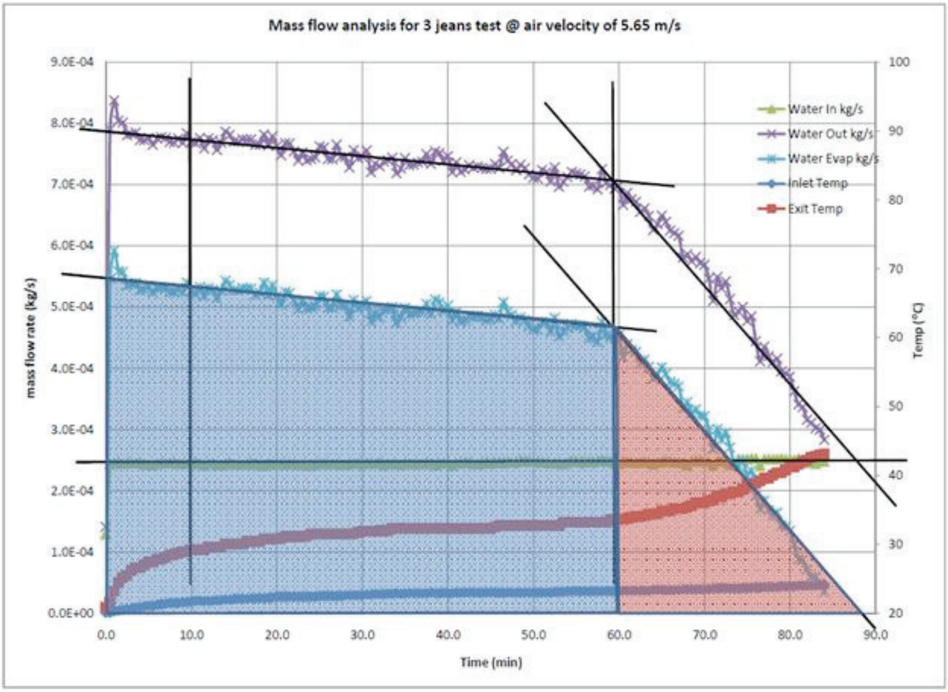

Figure 5: Mass flow rate of 3 jeans test at air velocity of 5.65 m/s.

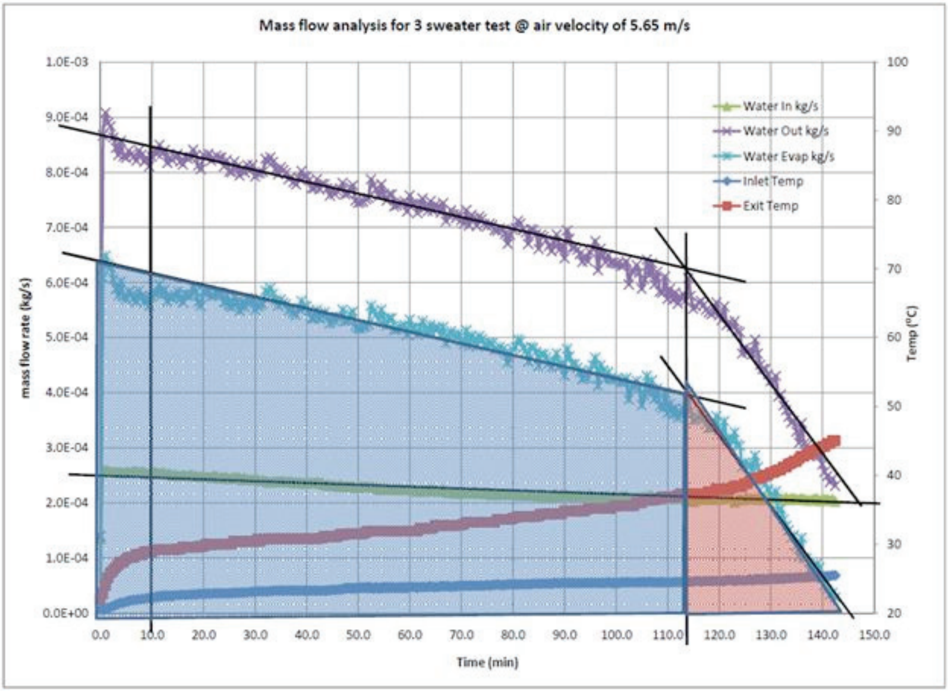

Figure 6: Mass flow rate of 3 sweaters test at air velocity of 5.65 m/s.

DATA ANALYSIS

The first two tests, using three blue jean pants, were identical except for two specific differences. The inlet water mass flow rate (representing ambient humidity) decreased 7.7% in the second test. This was due to an uncontrollable change in ambient humidity in the laboratory where the tests were conducted. The other difference was an intentional increase of 11.5% in the air velocity through the dryer. The flow rate was changed to get a sense of its impact on rate of drying. We found that the drying time with increased flow rate (and lower ambient humidity) shortened the drying time from 102 minutes to 88 minutes – a change of 13.7%. We lacked the time to run sufficient tests to separate the effect of ambient humidity from that of airflow rate, but we intend to investigate this in the future.

It would be valuable to have compared energy usage to achieve the increased airflow with the increase in overall drying efficiency. Unfortunately, this was not possible. The change in airflow rate was achieved by turning on the fan at the end of the exhaust duct, described in the "Experiment Setup" section. Because of this fan's location, we were unable to measure its power usage. However, we have plans for future tests that will account for the power usage of the extra fan.

We found that the exhaust temperature varied only slightly, regardless of the materials being dried or the airflow rate, throughout most of the drying cycle. Ambient temperature was (approximately) 20°C, and the exhaust temperature was generally between 30°C and 35°C. At the end of the drying cycle, exhaust temperature rose to between 43°C and 45°C coincidentally with a pronounced decrease in evaporation rate (see Figures 4, 5, and 6). Presumably, these rather sudden changes near the end of the drying cycle are indicative of heat energy no longer contributing to changing the state of water in the clothes to vapour.

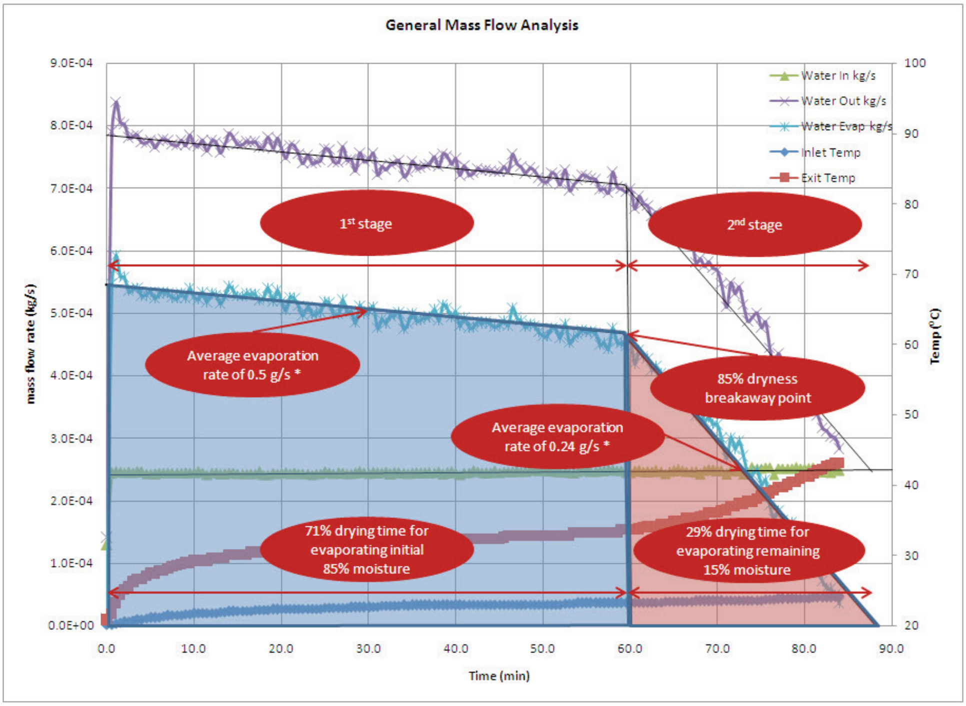

Figure 7: General mass flow rate analysis for the dryer.

This point where temperature rises demarcates two distinct regions of drying. The first stage (and what might be called the equilibrium operating state), accounting for most of the drying cycle, is marked by relatively gentle changes in evaporation rates and other key variables. The second stage, at the end of the drying cycle, is when there is very little water left to be evaporated. While this is entirely consistent with basic physics and not very surprising, it is important to us that we can observe these behaviours so clearly in the data. It demonstrates a certain reliability in data collection and analysis that will matter in the future, as we explore alternatives to conventional drying methods.

Of particular interest to us is the observation that roughly 85% of water was evaporated during the first stage of the drying cycle, and that this first stage covers about 70% of the drying time, regardless of material type or other variations of parameters. Furthermore, the efficiency (per Equation 6, above) of the dryer was approximately 33% during the first stage, but dropped to only about 15% in the second stage. While other kinds of clothes dryers might behave differently at the end of the drying cycle, this particular model – and any other model that uses the same basic control system - will clearly pay an energy penalty by not adjusting its behaviour at the end of the drying cycle.

These results are summarized graphically in Figure 7, above.

EMPIRICAL RELATIONS

The authors have constructed empirical relationships for key behaviours of the dryer that we tested. We understand that these relationships are accurate only for the specifics of the tests we have conducted so far, but we intend to refine the relationships in the future as we can test other kinds of dryers. More importantly, we are developing the methodological capacity to understand and create new empirical relationships from data.

One empirical relationship we have considered regards the amount of water trapped in the fabric. With the average mass of jeans and sweaters measured at 0.717Kg, and 0.815Kg respectively and average fabric to water ratio of jeans being 1:1 and sweaters being 1:1.5, the following empirical relationship can be obtained.

$$m_{water} = 0.717 N_{jean} + 0.815(1.5) N_{sweater} \tag{7}$$

where N_{jean} is the number of jeans and $N_{sweater}$ is the number of sweaters.

A second empirical relationship is that of drying time to mass of water in the load. The trend in this relationship is very clear from the experimental data above (Figures 4, 5, and 6). With our experimental data indicating 85% dryness taking 71% of drying time at an evaporation rate of 0.5g/s, the total drying time can be estimated by the following very simple empirical relationship.

$$t_{dry} = 40 \frac{\min}{kg} \times m_{water} \tag{8}$$

However, the evaporation rate of 0.5g/s will vary between dryers. The evaporation rate of a dryer can be estimated from the data result of 0.5g/s during the 33% efficiency and 0.24g/s during the 15% efficiency. Based on these two data, a linear empirical relationship can be established to relate the evaporation rate to the dryer efficiency. The following empirical relationship estimates the evaporation rate of any dryer, in grams of water per second, based on the dryer efficiency.

$$\dot{m}_{evap} = 0.0144 \frac{g}{s} \times \eta_{dryer} + 0.0248 \frac{g}{s} \tag{9}$$

Alternatively, it is also possible to construct an equation for the theoretical mass evaporation rate based on the known values for the volumetric flow rate, temperature, and humidity at both the inlet and outlet conditions and the atmospheric pressure of the space where the dryer is operating. Simplifying, we achieve:

$$\int_i^o \left[\frac{(VA)_x}{T_x} \left(k_1 P_{atm} - k_2 H_x 10^{\frac{7.5 T_x - 2048.625}{T_x - 35.85}} \right) \right] \tag{10}$$

where, k_1=0.003483713639, k_2=0.008043276587012 and limits for the integral, i and o, reflect the inlet and outlet conditions respectively. This is useful since the empirical values for drying different types of materials can then be substituted into this equation to determine a fully empirical formula for the mass evaporation rate.

The point of these equations is to develop a simple, yet relatively accurate, model of dryer performance. So far – and limited to the nature of materials we have tested – we can predict the drying time trivially with these relationships, knowing only the amount of water, the efficiency and the proportional amounts of clothes. We will use these relations to build models for our identified stakeholder groups, as described in the Introduction.

POSSIBLE DESIGN IMPLICATIONS

The authors understand that our analysis of this clothes dryer represents essentially only one data point. It is not reasonable to extrapolate from only this to any generalizations about clothes dryers. However, based on our work to date, there are some broad trends that we will pursue with the intent of devising design guidelines for our user groups.

It is possible to rate how "hard" it is to dry clothes based on amount, size, and material. These ratings will be quite coarse, but they could be useful to both users and manufacturers. We hope to develop a rating system that will quickly allow users to estimate how to mix different kinds of clothing to minimize the amount of time needed to dry them. Small loads of materials that hold relatively little water (loose woven cottons, for example) will dry faster than large loads of dense, absorbent weaves (e.g. thick wools). This is obvious. However, small loads will require more runs of the dryer. Furthermore, adding easily dried clothes to loads containing absorbent materials may help "wick" moisture from the absorbent materials, distributing the moisture throughout the load and increasing the contact area with the hot air.

Thus, we may be able to design simple processes for dryer owners to user the machines more effectively.

The contribution of airflow rate to drying. It makes sense that increased airflow (at constant temperature) would improve drying rate, because one is increasing the dry air reservoir that can carry away moisture. This begs questions. What is the energy cost of increased airflow? In what performance regimes will increased airflow improve energy consumption? Can a dryer with, say, variable airflow rates be more energy efficient? The answers to these questions could lead to new dryer designs.

Dehumidification by other means. It is apparent from our analyses that the use of heat is not necessary; rather it is the means to achieve the end of transferring humidity from one medium (clothes) to another (air). What other technologies exist to achieve this end? There is some anecdotal evidence (e.g. http://wiki.diyfaq.org.uk/index.php?title=Clothes_Dryer) hanging wet clothes in an enclosed space with an appropriate dehumidifier is far more energy efficient than the most efficient conventional dryers. The disadvantages to such designs are obvious: increased drying time and increased space needed for the device. In addition, the unconventional nature of such devices makes prospective users apprehensive. Still, as people become more sensitive to energy consumption, such "radical" approaches may find their place and should be supported with more design work.

Air circulation is vital. The purpose of the tumbler in conventional dryers is to improve air circulation. When large articles of clothing become twisted and tangled in the tumbler, air cannot reach them. Anything that can be done to increase air circulation or, alternatively, keep clothes from becoming twisted and tangled, will help. Future tests will measure the impact of this effect by measuring the time needed to dry clothes of varying sizes. We expect tumbler size and clothing size will both affect the point at which clothes start to become twisted and tangled. Knowing this point will inform dryer designers regarding sizes of tumblers and hopefully suggest other solutions.

CONCLUSIONS

We have studied the behaviour and performance of a clothes dryer, and reported the results of our tests. Our study indicates that the major factors impacting the drying efficiency in the clothes dryer are the air velocity and the ambient humidity. We determined the particular performance characteristics of one type of dryer and studied variation of performance under a few different loading conditions. Further testing is required with more attention paid to details of each test (e.g. the particular nature of each material, the relative amounts of different materials in a given run, etc.). Still, even with the relatively small amount of data, certain performance trends appear quite clear. This allowed the authors to develop some empirical relationships for the dryer.

For this kind of dryer, we found that drying efficiency dropped significantly at the end of the drying cycle. An obvious way to improve energy performance would be to add a control that can modulate the heating of the air and the speed of the tumbler in the second transient stage of operation, when temperature increases. This could be done by sensing either the temperature or the humidity at the exhaust port of the dryer, features that have been included in many dryers. A second improvement would increase the flow of air through the dryer; we noted in our tests that faster airflow was at least partially responsible for shortening drying time. By using a more efficient fan, the power drawn by the fan need not increase. Finally, anything that can be done to de-humidify incoming air will increase the vapour pressure difference and improve dryer efficiency.

We have funding to continue our tests and further refine our testing procedures through 2009. We expect to have updated information at ICED 2011.

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