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Experimental Drying Characteristics Of Fabrics Under Vacuum

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ABSTRACT

A significant amount of the energy consumed in both residential and commercial sectors is used for clothes drying. In conventional convective clothes drying, hot dry air at atmospheric pressure is passed over and through the clothes in order to remove moisture. Both the heat and water carried out are wasted to ambient resulting in an inefficient process. Additionally, the elevated drying temperatures can damage the fibers of the clothes, reducing their useful lifespan. By drying clothes at pressures below atmospheric, the temperature required to drive out moisture can be reduced. The objective of this study is to investigate the drying behavior of different fabrics under sub-atmospheric conditions. A special apparatus is designed and used for this study with appropriate control on the pressure and contact surface temperature. A wet cloth is placed on a heated plate within a vacuum chamber. The mass of the cloth is measured by a balance while the plate's temperature and the vacuum chamber's pressure are maintained. Moisture is driven out of the cloth by conduction from the plate. Clothes are dried from approximately 60% to 0% of moisture by mass and curves of moisture percentage versus time are developed for each fabric at set temperatures and pressures. The overall goal of the analysis to establish the drying behavior of clothes under reduced pressure conditions. The resulting data is summarized in form of appropriate performance correlations which can be used for the design of full-scale devices capable of drying under the considered conditions.

1. INTRODUCTION

It is well known that the clothes drying is on the most energy intensive process in both residential and industry sectors. Approximately $1.925\text{x}10^{11}$ kWh of energy is used drying clothes in the USA annually (EIA, Baseline Energy Calculator, 2020). Conventional clothes dryers use convection as the main mechanism for drying wherein hot gasses pass through the clothes while evaporating the water. The exhaust from the drum contains hot air and water vapor. The hot air is generally produced by high power electric heaters. The whole process is performed under atmospheric conditions which means that the operating temperature is always higher than 120 C. Drying at such high temperatures has two major implications, I- extensive power is required to heat the air before it enters the drum; and II- the fabric quality degrades due to exposure to extreme temperatures and thermal cycling. Furthermore, the process rate is limited by multiple factors including contact area, fabric type, air flow rate, and the remaining moisture content. Overall, it has been reported that a standard residential clothes dryer can take around 45 minutes to dry around 3.9 kg of laundry.

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In the present study, the focus is on the drying kinetics of fabric under vacuum pressure conditions. The experiments were conducted in a benchtop chamber, where the pressure is reduced by use of a vacuum pump. An assembly of weight scale, hot plate, and single layer fabric were placed in the chamber to simulate the drying process. Parametric studies including chamber pressure, hot plate temperature, and fabric type were carried out for further understanding the vacuum drying process. An empirical model for predicting the drying time by temperature and pressure is also developed.

2. EXPERIMENTAL SETUP AND PROCEDURE

This section describes the equipment and materials used in these experiments. It also details the procedure of the tests.

2.1 Equipment

Most of the equipment for these experiments is contained within the vacuum chamber shown in Figure 1. A simple diagram of the setup is shown in Figure 2. The vacuum chamber consists of an openable acrylic enclosure with internal dimensions of 50 cm x 50 cm x 50 cm and is capable of a vacuum of 75 microns. Passthrough ports allow for USB communications and DC power within the chamber.

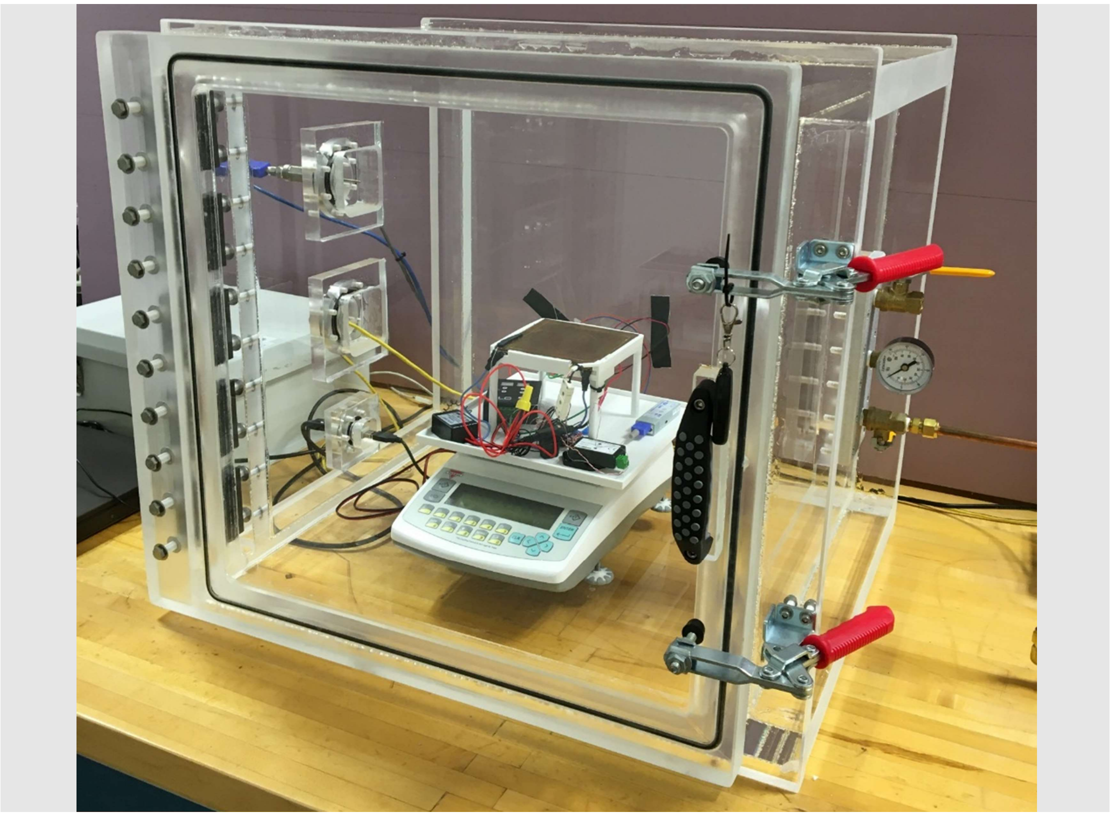


Figure 1: Vacuum chamber and equipment

Measurement of mass is accomplished using a digital balance with an accuracy of 0.01 g. The balance is connected remotely to the logging computer via USB. A 3-d printed shelf is placed atop the balance to hold the instrumentation and controls necessary for the experiment as well as the test surface at the top of the shelf.

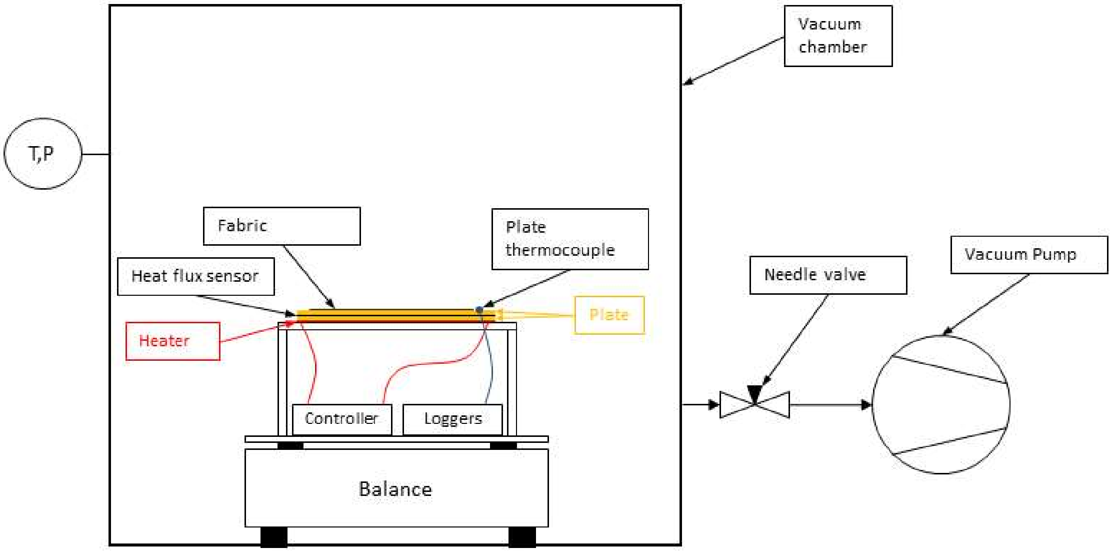


Figure 2: System diagram

The test surface consists of a copper plate 125 mm wide by 125 mm long and a thickness of 3.175 mm. Beneath this plate is another copper plate of the same dimensions, with a heat flux sensor and thermal paste sandwiched between. Attached to the bottom of the lower plate by adhesive is a 3.34 ohm W thin-film heater of the same width and length of the plate capable of 235 W. Power for the heater is supplied by a DC variable power supply located outside the chamber. The heater controller operates in an on-off manner based off feedback from a thermistor potted into the upper surface of the top plate, controlling to the set temperature. A closeup of the heater plate and equipment on the tray is shown in Figure 3

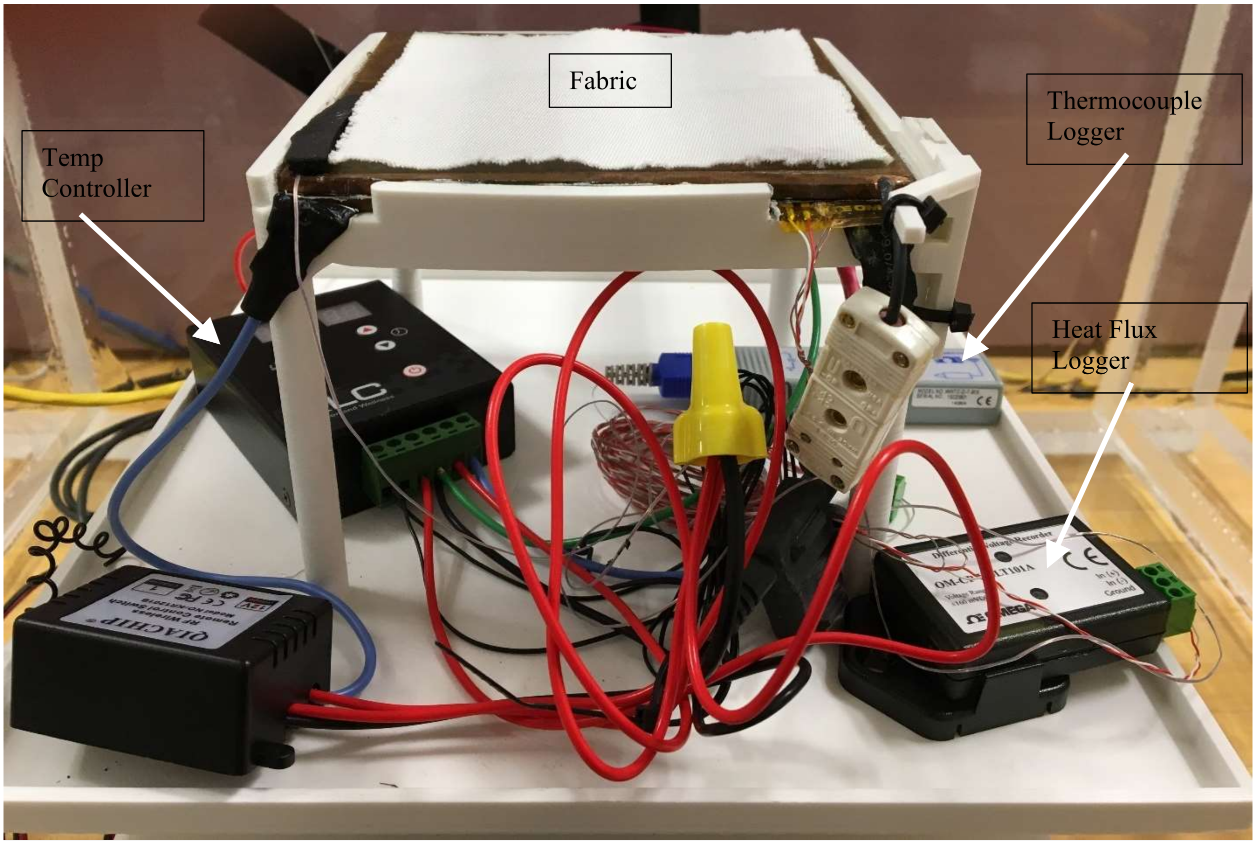


Figure 2: Heater place closeup

Other instrumentation includes a T-type thermocouple also placed into the top surface of the plate, a T-type probe measuring the chamber air temperature, and a 0-30 psia pressure transducer with an uncertainty of ± 0.08%. Data from the embedded thermocouple was collected using a miniature remote logger with a resolution of 1 °C and was placed on the 3d printed tray. Data from the pressure transducer and air temperature thermocouple were collected using a logger outside the chamber collecting at a rate of 1 sample/second.

Vacuum for the chamber is provided by a rotary vane vacuum pump capable of 27 L/min. Flow from the chamber is regulated by adjustment of a needle valve placed between the chamber and the pump. Regulation of flow is how pressure is controlled within the chamber.

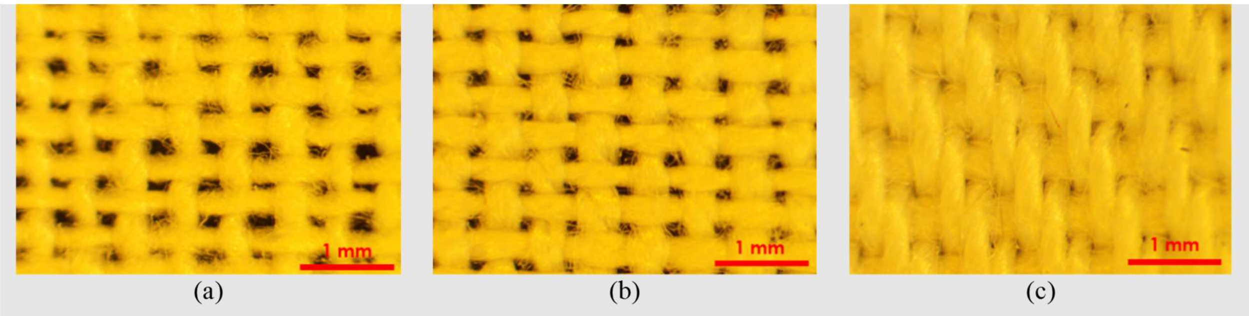
2.2 Materials Tested

Table 1 summarizes the three different fabric samples have been tested. Differences include both weave and percentages of cotton and polyester fibers.

Table 1: Fabric characteristics

Fabric	Weave	Density (g/m^2)
100% Cotton	Plain	162
50% Cotton / 50% Polyester	Plain	144
35% Cotton / 65% Polyester	Cross-linked	239

Microscopic images of the three fabrics are shown in Figure 3. If viewing in color, note that the yellow color is due to lighting; the fabric is white.



(a) (b) (c)

Figure 3: Microscopic images of fabrics - (a) 100% Cotton, 50/50% Cotton/Poly, 35/65% Cotton/Poly

2.2 Procedure

A test begins by first heating the plate to the desired testing temperature by adjusting the temperature controller. The balance is then tared such that the mass reading is zero. The fabric sample to be tested (cut to be smaller than the plate) is placed on the test surface.

Distilled water is added to the fabric by dropper to reach a high moisture content more than 60%. Depending on the desired plate temperature and vacuum, significant saturation of the cloth (in excess of 400% moisture content) may be necessary in order for enough water to still remain within the fabric by the time the desired pressure is reached and controlled. Moisture content is defined in equation (1) by

$$X=\frac{M_w}{M_{dry}}=\frac{M_{reading}-M_{dry}}{M_{dry}} \tag{1}$$

where X is the moisture content, M_w is the mass of water in the fabric sample, M_{dry} is the mass of the dry fabric, and $M_{reading}$ is the mass indicated by the balance.

Once the cloth is saturated, the vacuum chamber door is closed and the full vacuum possible by the pump is applied. When the desired vacuum level is reached, the needle valve is partially closed and continually adjusted to maintain the desired vacuum. The reading of the balance is monitored and the vacuum maintained until the mass shown has reached the mass of the dry fabric sample. Data from each logger is then compiled and analyzed.

3. RESULTS AND DISCUSSION

In this section, example drying curves from testing will be shown. Correlations for drying times of each fabric as a function of pressure and temperature will also be presented. Finally, the implications of the results will be discussed.

3.1 Example Drying Curves

Across all three fabrics, a total of 34 tests were conducted, with pressures ranging from 8 kPa to atmospheric, and with plate temperatures from 12 to 90 °C. Representative curves of moisture content vs. time are given. Figure 4 shows the effect of pressure on the drying curve of 100% cotton with a plate temperature of 65 °C. As pressure within the chamber decreases, the drying time of the fabric sample decreases, with a difference of approximately 100 seconds between the drying times at atmospheric and a chamber pressure of 35 kPa.

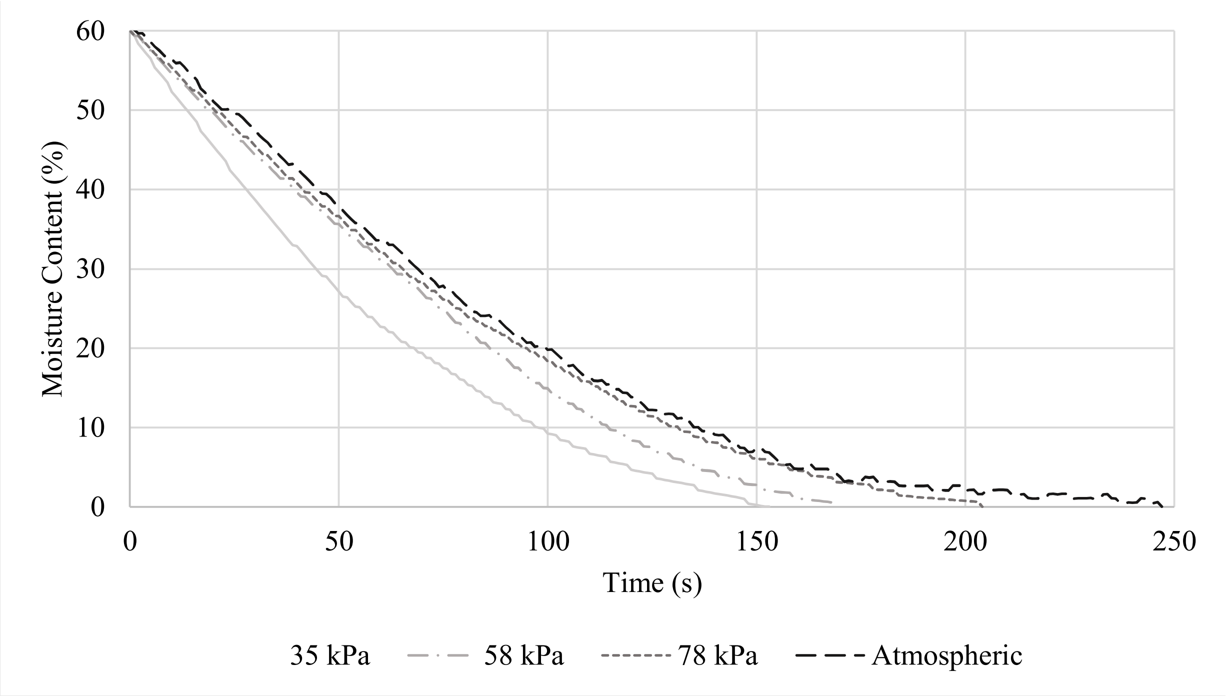


Figure 4: Drying curves for 100% cotton with a plate temperature of 65 °C and varying chamber pressure

Similarly, Figure 5 shows a comparison of the curves for 100% cotton with a chamber pressure of 58 kPa.

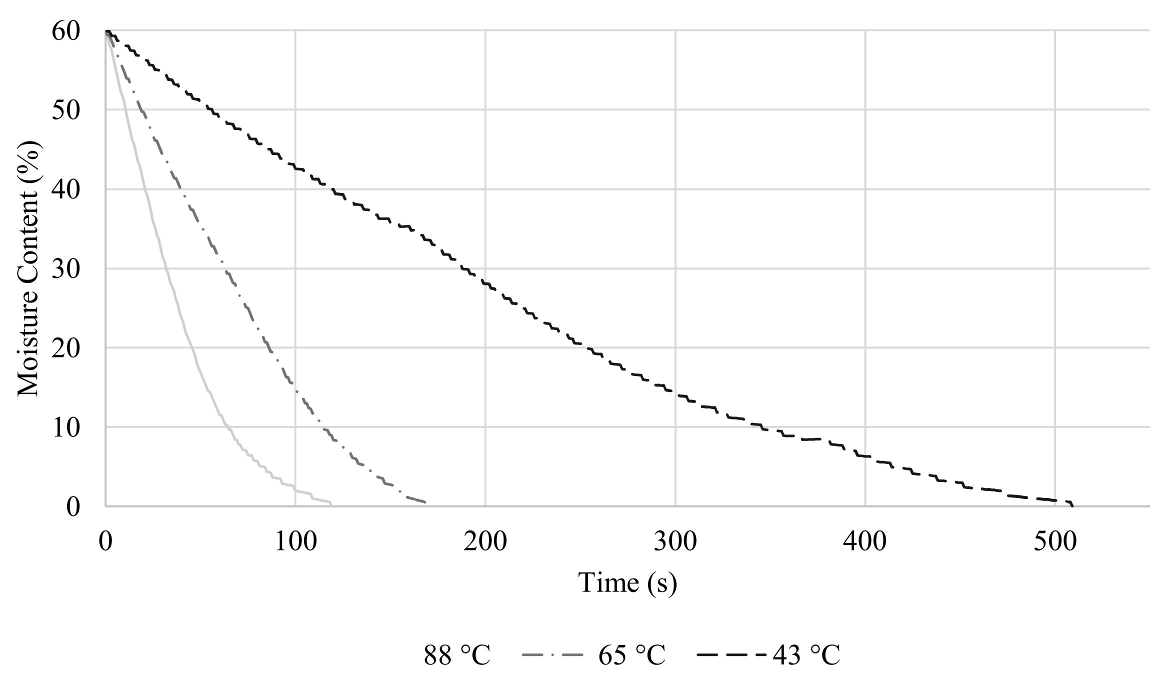


Figure 5: Drying curves for 100% cotton with a chamber pressure of 58 kPa and varying plate temperature

As plate temperature increases, drying time dramatically decreases. Approximately 23 °C differentiates each of the curves of Figure 5, but a dramatic difference in drying times is seen between 88 °C to 65 °C and 65 °C to 43 °C, indicating a non-linear response of drying time to plate temperature.

3.2 Drying Time as a Function of Temperature and Pressure

Linear regressions of the full dataset for each fabric finds equation (2) predicts the total drying time of each sample from 60% moisture content to 0%.

$$t_{dry}=A+B\cdot T+C\cdot T^2+D\cdot P+E\cdot P^2+F\cdot T\cdot P \tag{2}$$

Here, t_{dry} is the drying time from 60% to 0% moisture, T is the plate temperature in °C, P is the chamber pressure in kPa, and A through F are coefficients given in Table 2 for each fabric.

Table 2: Coefficients for Equation (2), drying time as function of pressure and temperature

Coefficient	100% Cotton	50/50% Cotton/Poly	35/65% Cotton/Poly
A	2.6073E+03	2.1706E+03	2.4481E+03
B	-7.3129E+01	-6.7466E+01	-7.2000E+01
C	5.1957E-01	5.4236E-01	5.5120E-01
D	5.5665E+00	1.1906E+01	1.4748E+01
E	1.4485E-02	1.5787E-02	3.1769E-02
F	-8.2335E-02	-1.8838E-01	-2.2675E-01
R^2	97.46	99.09	98.15
RMSE	7.8863E+01	3.7052E+01	6.2560E+01

3.3 Discussion

Practically speaking, the range of temperatures for drying any fabric will be in the range from above freezing at 0 °C to boiling at 100 °C due to the properties of water. Typically, fabrics are dried at an atmospheric pressure of approximately 100 kPa. If a vacuum is applied to hasten the drying process, the lowest possible vacuum would be at 0 kPa. Examining Figures 4 and 5, we can see that at relatively higher temperatures and pressures, temperature is a stronger driver of drying time than pressure. A decrease in plate temperature of 45 °C at a constant pressure of 58 kPa increases drying time by nearly 400 s, while a drop of 43 kPa at a constant plate temperature of 65 °C only decreases drying time by 100 s. Plotting a contour plot of drying time using Equation 2 and the coefficients of Table 2 for 100% cotton, Figure 6 further shows that temperature is a stronger driver than pressure.

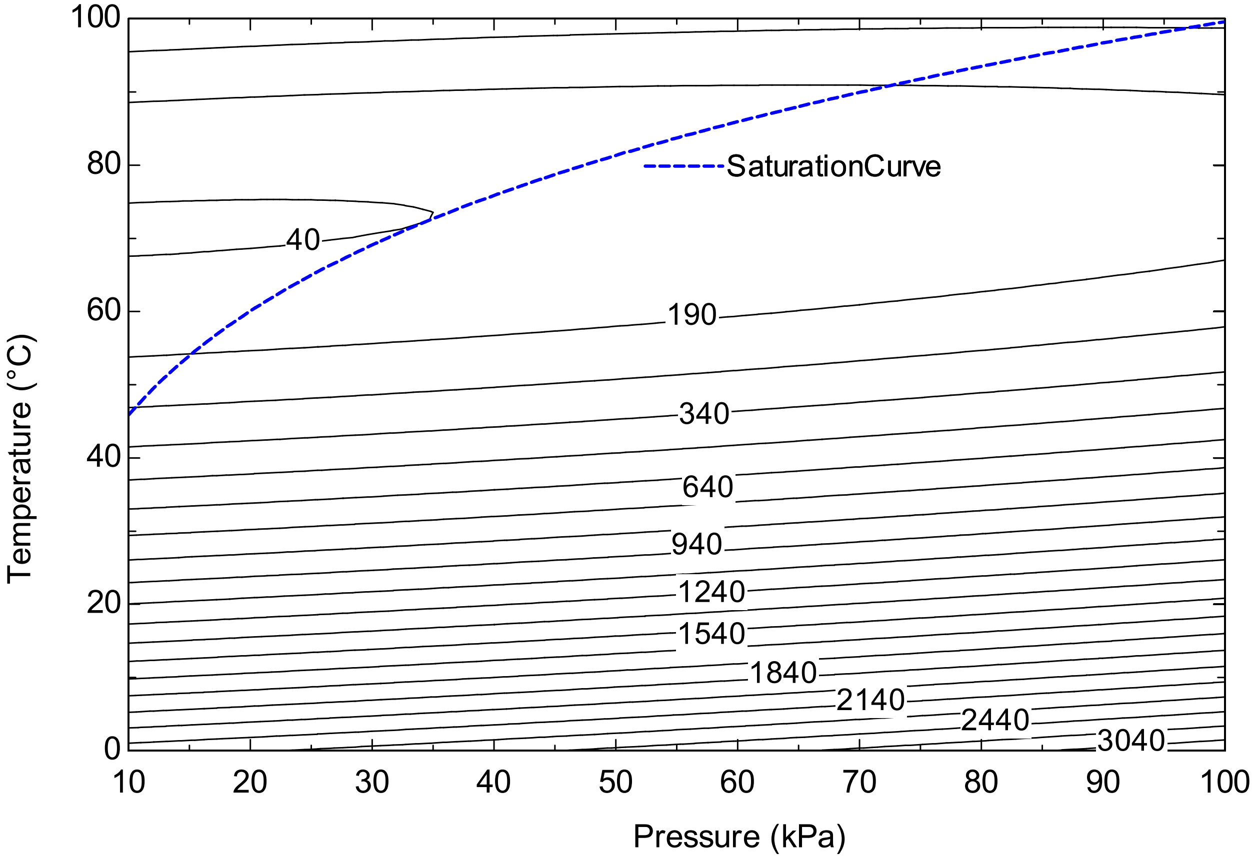


Figure 6: Contour plot of drying time in seconds for 100% cotton as a function of pressure and temperature using Equation 2 and coefficients from Table 2. Plot overlaid with water saturation curve.

Care must be taken when applying Equation 2 at the extreme opposites of pressure and temperature, meaning conditions approaching 0° C at higher pressures or 0 kPa at higher temperatures, as few data points were taken in those regions. It is difficult to test at these conditions due to either the extremely short or extremely long drying times that occur.

The inclusion of vacuum conditions to the drying process can increase the speed of drying. Interesting results in drying times may occur in the areas beyond the saturation curve shown in Figure 6 (high temperature, low pressure). Pressure may become more of a driving force than temperature in this region, with the plate temperature higher than the saturation temperature. Further study in this region, though difficult, may prove useful.

4. CONCLUSIONS

- Clothes drying is an energy intensive process and conventional convective dryer require significant amount of power to operate. It is possible to dry clothes at sub-atmospheric pressures in less time and with less heat which can make the overall process highly efficient and fast.

- Three fabrics were dried in a controlled environment at various sub-atmospheric pressures with the objective of analyzing the drying behavior under sub-atmospheric condition. It was observed that the drying process can be accomplished at lower temperatures which is favored for durability of fabrics.
- Based on the experimental data empirical correlations have been developed to predict the drying time of each fabric for a given temperature and pressure. These correlations can be used for the design of drying facilities capable of achieving accelerated drying at sub-atmospheric operating conditions.

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EIA (U.S. Energy Information Administration). (2020). Baseline Energy Calculator. Scout. https://scout.energy.gov/baseline-energy-calculator.html.

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