AN ULTRAFAST, COMFORTABLE HAND DRYER

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1. Introduction

In the more than half century since warm air hand dryers were introduced, they have established a significant market niche as a rapid payback means to eliminate the cost and inconvenience of towels in commercial bathrooms. Paper towels are expensive, as are the devices that dispense them, and they also add substantial cost for janitorial service and for waste disposal. Substituting an effective electrically powered dryer for paper towels can save hundreds of dollars each year and can quickly pay for the cost of the dryer. Additionally, if the dryer uses the same power as conventional dryers, but runs for much shorter time per cycle, less total energy is used and the cost of energy is proportionally less.

However, the degree of market penetration of these dryers has always been disappointing. People still prefer to use towels. This is primarily because dryers of the present state of the art are slow, involving drying times of 30 to 45 seconds. Added to this, because the hands often do not feel really dry, the dryer is frequently used for an additional time. The second reason for dissatisfaction with these dryers is that they usually leave some residual moisture on the hands with a consequent feeling of discomfort and coldness as this moisture evaporates. Cool air dryers that depend on intense air impact, without heating that air, do speed up drying, but always leave the user with uncomfortably cold hands.

We are led to the conclusion that were airstream dryers faster and at the same time more comfortable after the conclusion of the drying cycle, they would find far more acceptability in the marketplace. Our definition of specific objectives for the desired optimum dryer follows: time to attain dryness (defined as 0.2 residual grams of water remaining on hands) of 10 to 15 seconds. This is a time psychologically acceptable to most people as “not too long.” (Implied in this objective is that there be an established “Measurement Standard for Rate of Water Removal”); comfort to be maintained during the drying process; hands to feel comfortable and warm after the drying process; maintenance free; reduced energy consumption; and power line requirements not to differ from present ones of a 115 V, 15 Amp or 220, 20 Amp line.

2. Block diagram of basic components

Figure 1 shows the basic components of the hand dryer as a block diagram. The blower is a centripetal blower powered by a high-speed motor. This generates an airstream far more forceful than conventional blowers do. Following the blower/motor is an air heater. (In some air dryers, the heater is located before the blower/motor and this causes a delay because of the heat lost in heating the blower. This arrangement of heater before the blower is not recommended.) An important part of our design is the control of the air exit port—the “air outlet”--that determines the force of the exiting air. We control the air outlet design to enhance the mechanical blowoff of the loose water on the hands. At the same time, the forceful airflow enhances the evaporation of the remaining, still adhering, water layer.

Associated with the major modules is the electronics module that controls drying time and includes a sensor determining proper location of the hands for drying. Figure 2 is a layout sketch showing deployment of most of these major components of the XLerator with the cover removed.

3. Theory of Water Removal Processes

The key to inventing the improved dryer was the identification of the physical forms in which water appears on wet hands together with developing the optimum physical processes for removal of each of them. Observation showed that the water on the hands after washing was in two physical forms. These are loose or unbound water, most in the form of droplets, on the hands plus a layer of water that adheres to the hands after the loose water is removed. Some of the loose water could be easily disposed of by shaking the hands several times, as people usually do. Measurements showed that the amount of water remaining on the hands depended upon the number of shakes. We standardized on the use of two shakes before the warm air drier measurements were made. The amount of water on average hands after two shakes was about 5 grams, and it was found that if the hands were washed with soap, the residual water increased to about 6 grams. This is probably due the bonding action of the surfactants in the soap.

About three quarters of the water was found to be the loose water portion and the remaining quarter was the adherent water layer portion. We next addressed the challenge of removing each of these separately and with a method especially tailored for each.

We decided to remove the loose water by blowing it off with a strong blast of air--a process that is inherently swift and modest in energy demand. This differs from present warm air dryer practice in that present dryers generate an airstream that has far less velocity and force than what is required to achieve significant blowoff of loose water. This means that they must therefore rely almost exclusively on evaporation to remove all the water.

In our approach, the loose water is mechanically blown off the hands in the first few seconds by a forceful flow of air from the dryer generated by a more forceful blower system than is normally used. Evaporation is not dominant in this first phase so that the few seconds required for the electrical heater to warm up does not delay the overall drying process. Also, for a sufficiently forceful air stream, final drying time turns out not to be a sensitive function of the number of hand shakes. This is because loose water is so easily blown off in just a few seconds that its amount is relatively unimportant.

The remaining time required for drying is utilized for the evaporation of the surface layer of water remaining on the hands that cannot be mechanically blown off. Calculation shows that using evaporation alone to remove all the 6 grams of water on an average pair of hands, about 4 watts are required to be delivered in 30 seconds. This translates into heater power rated to deliver at about a 500-watt rating. Present dryers deliver 3 to 4 times this amount of power to the heater, which indicates inherent inefficiencies where the device itself and ambient air distant from the hands absorb much of the energy.

In the XLerator, due to most of the water already having been blown off, only the remaining 1.5 grams of water needs to be evaporated away, which would seem to be much easier task to accomplish. Yet, even this poses a substantial challenge because of the necessity to reduce the stagnation boundary layer of air and water vapor that normally resides above the adherent surface layer of water.

The stagnation boundary layer (Figure 3), a region adjacent to the surface of the water, constitutes a major inhibition to evaporation. It is a transition zone extending from the water surface to the region where moving air removes evaporated water molecules. This stagnation boundary layer region consists of slower moving air adjacent to the water layer surface (or any other surface), and which contains evaporated water molecules. In this stagnation boundary layer, the water molecules evaporating will accumulate, and many water molecules will flow back to the water surface, while some will flow into the flowing stream of air to be removed. This reduces the net evaporation of surface water.

By physically breaking up the stagnation boundary layer with a strong and turbulent blast of airflow having its major component perpendicular to the surface, the evaporation ceases to be inhibited and its rate increases. Rather than accumulating in the stagnation boundary layer and slowing the net evaporation of water, the water molecules in the stagnation boundary layer are swept away as fast as they accumulate by the force of the air breaking up the stagnation boundary layer. This is the second function of the same intense air blast that accomplishes blowoff. As long as it persists in impacting the hands after blowoff has been completed, the stagnation layer will be reduced.

Evaporation by warm air is a function of temperature and the evaporation rate is an exponential function of the air temperature in absolute degrees Kelvin. The air temperature is limited by the amount of power available for the air heater, and even more limited by the safety requirement of not burning the users'

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hands. Within these limitations, to speed up the drying process, we must maximize the temperature of the air stream while still not causing discomfort to the user. For no more than the 10 to 15 seconds of drying programmed here, a temperature of 135 ^{o}F (57 ^{o}C) at about 6 inches (15 cm) from the air outlet is quite acceptable. This temperature was at first not attained with a forceful air stream because of entrainment of room temperature air, which diluted the airstream out of the dryer and lowered its temperature. Our air outlet design reduced the air entrainment and preserved the warm air temperature.

Entrainment was found to be high with a slot-shaped opening at the air outlet. This was corrected when the airstream was delivered out of a circular air outlet, which resulted in a cylindrical shape of that airstream. The more surface to cross- sectional area ratio an airstream has--as when it is delivered out of a narrow slot--the more it will entrain the surrounding air. The lowest ratio occurs when the air stream is circular in aspect. Thus the air outlet of the XLerator is a circular pipe, designed to reduce airflow spreading.

Temperature measurements across the diameter of the air stream show a cool sheath of entrained air, but the core air of the air stream, which is the major portion of the cross section, is undiluted by room air. It maintains its temperature for the required 6-inch distance and at the same time loses little of its impact force. There is an optimum diameter of air stream for both maximum impact force and maximum core temperature and this has been determined to be at about 0.8 inch (2 cm) for this system.

In the evaporation process described above, the stagnation layer is reduced by the air blast and the evaporation is carried out at maximum allowable temperature, This leaves the hands so free of water that there is no uncomfortable cooling of the hands after drying as is the case in most conventional dryers.

Figure 4 is a graph of an actual test run with an early model of the XLerator where the weight of water remaining on hands is plotted as a function of drying time in seconds when the drying process uses the theory and approach described above. It is an experiment for a single individual with average size hands, and with an initial hand wetness of 5 grams after two shakes. We have defined Phase 1, the blowoff phase, for this case, as consuming 2.5 seconds at which point residual water amounts to 1.25 grams. In Phase 2, the evaporation phase, the comfort level of 0.2 grams is attained in 13.5 seconds. (See the following section for a definition of comfort level.) The transition between Phases 1 and 2 is not sharp. In the region of the curve between 2.5 and 4 seconds the ending of blowoff and the beginning of evaporation occur simultaneously.

4. Systematic Measurement of Rate of Water Removal

A key step was the development of a scientific method of measuring and quantifying the amount of water on the hands during and after the drying process as various changes in the dryer were made and tested. This measurement technique was also used on competitive dryers in order to provide comparisons.

After considering possible substitutes for hands (various plastics, leather, etc.) in the wetting and drying tests, hands themselves were found to give the most reproducible results and were used in the tests. Additionally, because much of the water remained in the spaces between the fingers, the drying technique adopted by many users involved rubbing the hands during drying with attention to wiping the regions between the fingers to spread the water out to the airflow region where evaporation takes place. Thus testing with actual fingers and wiping was needed to provide valid test conditions.

To measure the weight of water on the hands at various stages of the drying process, and after modifications of the device, we used a technique involving weighing paper towels before and after wiping the hands. The weights of the paper towels before and after were determined using a digital scale with a resolution of 0.01 grams. The incremental added weight on a towel was taken as the weight of residual water remaining on the hands since it was assumed that all of that water had been transferred from the hands to the towel.

A sequence of interrupted drying procedures with drying times such as 2, 4, 6, 8, 10, 15, 20, 25, 30, 35, 45 seconds was used to measure the progress of drying as a function of time. Measurements were made of the weight of water remaining on the hands for each drying time. The data were entered in spreadsheets. To help insure accuracy, multiple measurements were made and recorded for each set of conditions. Also, when plotted as in Fig. 4, they provided useful drying curves.

After initial tests produced reproducible data for a single individual in evaluating a wide range of experimental dryer constructions and drying procedures, the results were verified using a larger population of subjects covering a range of hand sizes, and from women, men and children. Average values were used.

This test and comparison procedure is described in detail in the Appendix, and this method is offered as a Standard Measurement Test for Hand Air dryers.

Identifying the residual water on the hands corresponding to comfort involved subjective judgment by the users. The consensus of the test subjects was that comfort (defined as warm and dry) corresponded to residual water on the average hands of no more than 0.2 grams. This means that a feeling of comfort requires that no more than 4 to 5 percent of water should remain on the hands. Interestingly, the “wetness” of dry hands, not washed, when evaluated by our water weighing protocol was about 0.01 grams, which probably is a measure of the intrinsic wetness of skin combined with the weight of natural oils on the skin.

5. Method of Approach

Increasing the effectiveness of the airflow was one of the major challenges to be addressed. Very forceful airflow is a key factor in both the blowoff of loose surface water, and in the evaporation of the surface layer of water by producing turbulence to reduce the stagnation boundary layer. In using a rapid flow of air, heated or not heated, to rapidly remove water from the hands, the parameters for the blower should be selected or optimized according to the physics involved.

Effectiveness was improved by significantly increasing the velocity of the airflow. This is because the energy used in blowing off the surface water is provided by the kinetic energy of the airflow that is proportional to mass, M, times the square of the velocity, V, and is proportional to ($M \times V^2$). There is a greater benefit from increasing the velocity than in increasing the mass flow. A 10 percent increase in the air velocity is twice as beneficial as a 10 percent increase in the air mass because the kinetic energy increases as the square of the velocity.

The velocity of the exiting air can be increased by increasing the blower rotation speed. Thus using a blower with a highest rotation speed and/or a blower with larger rotator radius can increase the dryer performance. The required speed was attained with a two-stage blower such as is employed in advanced vacuum cleaners. It was used in combination with a very high speed DC motor driven by a powerful high frequency oscillator so that rotation at around 30,000 rpm was attained. The combination gave large quantities of high velocity air. The selected motor does not use brushes and will have longer life because there are no brushes to wear out or to be replaced.

The area of the air outlet was selected to provide high air impact force on the hands while at the same time providing sufficient air for drying. The product of the airflow force and the airflow volume is the important measure of the impact on the loose water on the hands.

It can be shown that there is an optimum value for the cross sectional area of the air outlet. If the air outlet area is reduced to zero, the air pressure increases towards the high blankoff pressure of the blower/motor combination but the amount of airflow reduces to zero. If the air outlet area is increased, the airflow rate increases to the maximum air output of the blower/motor combination, but the force on the hands decreases to the point of becoming “gentle” for very large orifices. There is an optimum value for the air outlet area and it corresponds to the case where the back pressure on the blower is about one half of the blankoff pressure.

This optimization is similar to the well-known case of load matching in electrical circuits. For example, the power delivered to a resistive load on a battery is maximized when the load resistance is made equal to the output impedance of the battery. In this case, the voltage across the load resistor is half of the open circuit voltage of the battery, and the current is one half of the short circuit current. The product of the load voltage and load current represents the power delivered.

Entrainment of air to increase the mass of flowing air is also a factor to consider and this is influenced by the ratio of the periphery of the airflow and the airflow cross section. The entrained air enters through the periphery.

The temperature of the exiting air is also a factor that affects the drying time. A heater is located after the blower/motor and the exiting temperature depends upon the volume of the airflow and decreases as the air flow increases. About half of the available electrical power was used to operate the blower/motor and half was used for the heater. Code constraints determine the maximum air temperature at the air outlet to no more than 170 degrees Fahrenheit (77 degrees C). The XLerator operates at an air outlet temperature well below this, while still maintaining at a temperature around 135 Fahrenheit (57 degrees C) 6 inches downstream, where hands are held.

6. Experimental Results

For optimizing Phase 1, the blowoff phase, the effect of air impact force as a function of air outlet diameter was measured as illustrated in Fig. 5. This was done for a drying time of 10 seconds for each measurement. For small air outlet diameters, the impact force is large enough to be uncomfortable at the point of impact. In addition the coverage of the hands is small, requiring the hands to be moved rapidly in the air stream in the evaporation phase order to cover all of the hand area, which increases the drying time. For large diameter air outlets, the force of the exiting air is smaller, thus reducing the blowoff contribution.

It can be seen from Fig. 5 that the drying is nicely effective at a “medium” air outlet diameter of 0.815 inches (2.07 cm), which provides acceptable force on the hands together with good blowoff and evaporation. Note that better drying resulted with an air outlet diameter of 0.76 inches (1.93 cm), but some test subjects found the airstream impact force to be uncomfortable, which is what led us to settle on the slightly larger diameter outlet as a practical tradeoff. .

The preservation of blowoff force as a function of hand position with respect to the location of the air outlet was another factor to consider. The hands are usually dried about 4 to 6 inches (10 to 15 cm) away from the air exit. The air outlet diameter influences the uniformity of the air exit force with distance. If the force drops off too rapidly, then the placement of the hands become more critical, and this is not desirable.

Fig. 6 shows the measured air impact force (measured as pressure on a selected test coupon) as a function of axial distance from the air outlet and for different air outlet diameters. Curve number 1 in Fig. 6 gives a larger force but the force drops more with distance. Also the force on the hands is not comfortable. Curve number 7 in Fig. 6, at the other extreme, shows force to be very uniform with axial distance but is too small for effective blowoff.

As usual, a compromise is more useful, and curve number 3 in Fig. 6, corresponding to an exit diameter of 0.815 inches gives effective force out to 6 inches axial separation and, as shown in Fig. 4, will give good drying effectiveness when combined with good evaporation.

Good evaporation results from maintaining the airstream temperature between values that are safe for hands and values that provide effective evaporation of the remaining surface layer of water. Fig. 7 shows measured airflow temperature as a function of distance from the air outlet. With an air outlet diameter of 0.815 inches, the temperature remains in a comfortable range of about 135 ^{o}F to about 145 ^{o}F (57 ^{o}C to 62^{o}C) at six inches from the air outlet. The actual values will be slightly influenced by the room temperature, but in most locations this is not critical.

A comparison of the XLerator dryer with other commercially available dryers is provided in Fig. 8 that shows the measured drying performance of various air dryers.

Curves number 1, 2, and 3 in Fig. 8 are for warm air dryers from three different manufacturers. It can be seen that the removal of water in the first 3 seconds leaves a large fraction of water on the hands (around 70%) compared to 30% for the XLerator of curve 5 of Fig. 8. Also, even after 30 seconds, the residual water is above the value we determined to correspond to a feeling of dryness for two of these dryers with comfort for them not attained for at least 45 seconds (45 second data not shown in Fig. 8). The residual water in those cases will continue to evaporate after 30 seconds, leaving the hands feeling clammy and cool.

The cold (unwarmed) air from the dryer from vendor number 4 in Fig. 8 will blow off more water in 3 seconds than the other three, leaving about 50% as residual water, because although the airflow is faster it will still leave much water to be evaporated by the cool air. The result is longer drying compared to the Xlerator and clammy and cool hands both during and et the end of the drying cycle.

The performance of the XLerator is shown in curve number 5 in Fig. 8. The blowoff is effective and swift, and the residual water in the evaporation phase is lowest--already at comfort level in 14 seconds--compared to the others. While this performance is superior to the present state of the art, preliminary experimental data obtained as this paper goes to press indicate that we can realistically expect this number to come in in the 10 to 12 second range in the near future.

7. Benefits

There are a number of benefits resulting from our new warm air dryer. Benefits for the user include three times faster dryer and hands continue to feel warm and comfortable after the drying process. Benefits for the owner of the dryer include over 90% cost saving compared to paper towels, reduced energy and cost the power line requirements do not differ from present ones.

8. Conclusions

After many years of air dryers without significant improvement of comfort and reduction of drying time it was possible by a systematic and scientific analysis of the physical process involved in warm air-drying of hands to significantly improve the design and performance of such hand dryers.

Acknowledgements

We acknowledge the highly competent participation of Messrs. Thomas Koetsch and David Ryzcek of Excel Dryer Inc. who contributed greatly to the experimental portions of this program.

FIGURE 1: Block Diagram for XLerator Hand Dryer

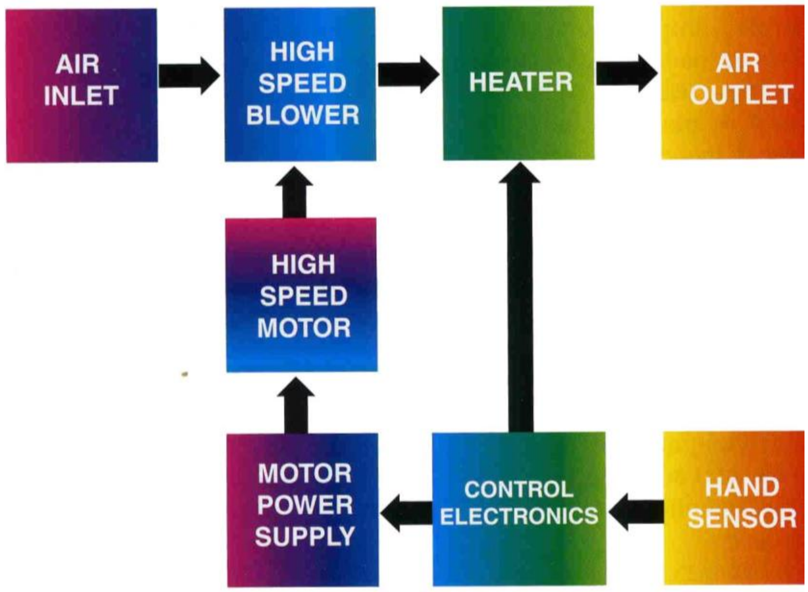


FIGURE 2: XLerator Hand Dryer with Cover Removed

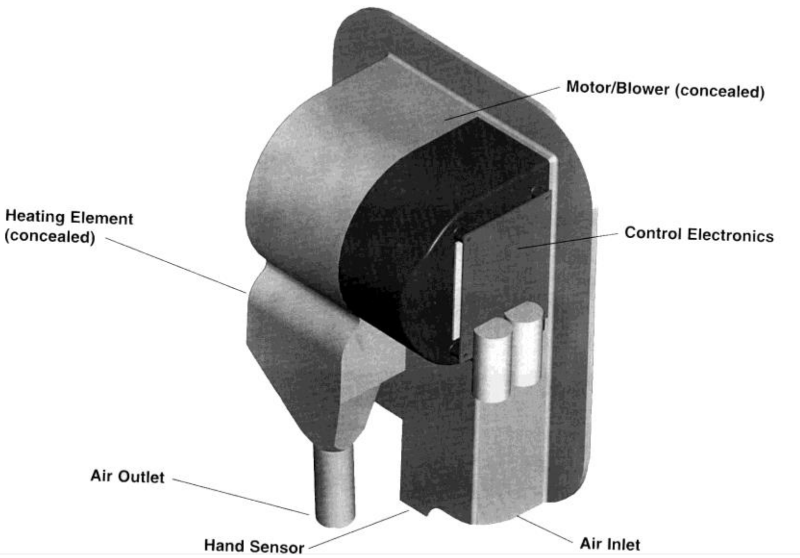


FIGURE 3: Stagnation Boundary Layer

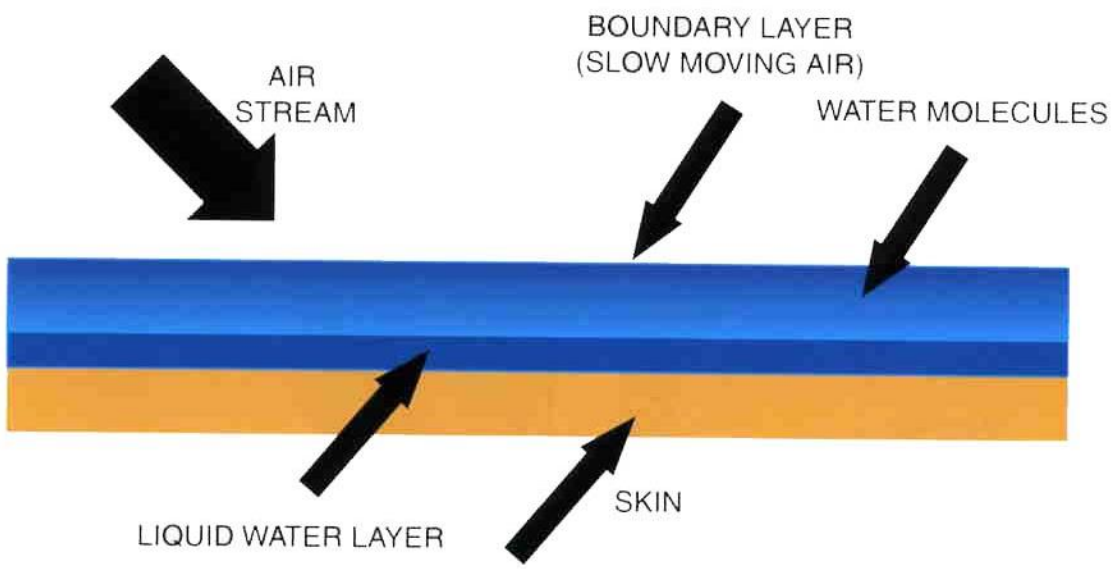


FIGURE 4: Phases of Hand Drying

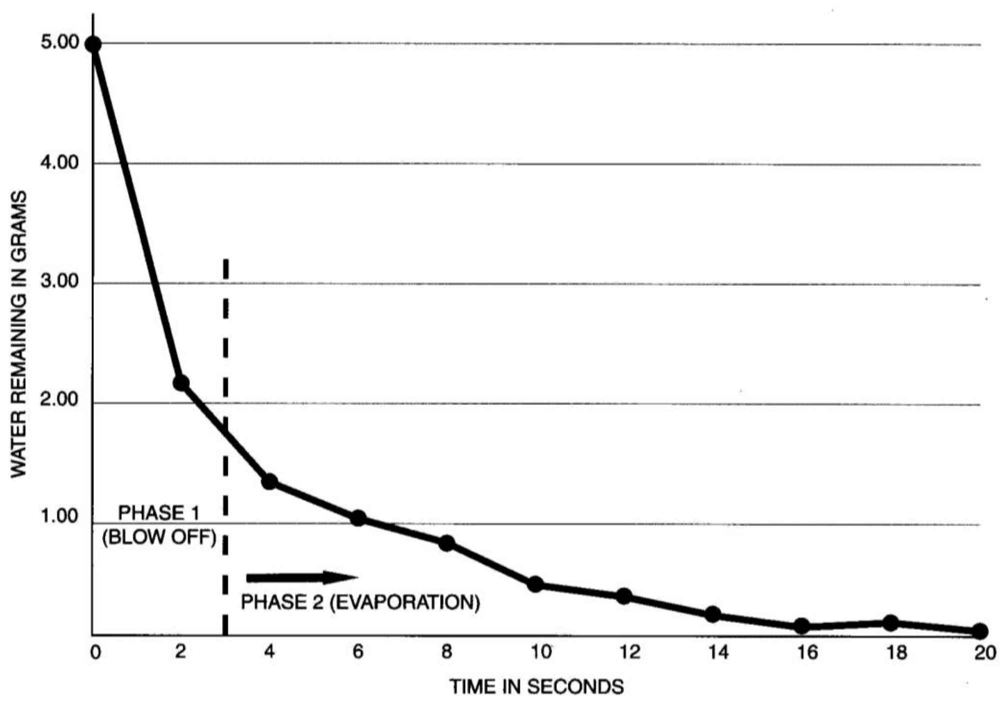


FIGURE 5: Water Remaining on Hands After 10 Seconds

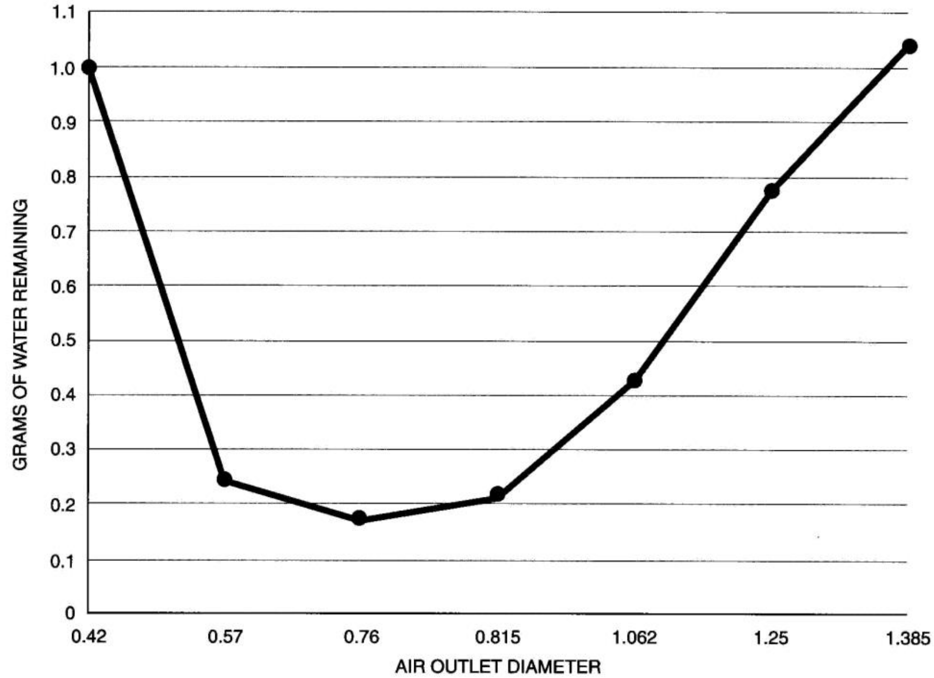


FIGURE 6: Air Impact Force as a Function of Distance

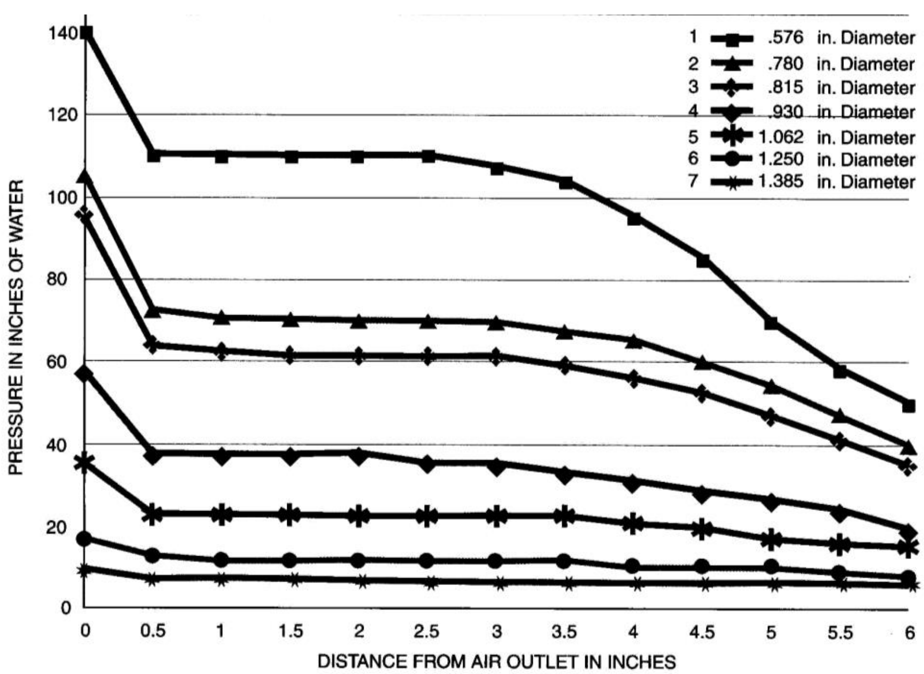


FIGURE 7: Airflow Temperature as a Function of Distance

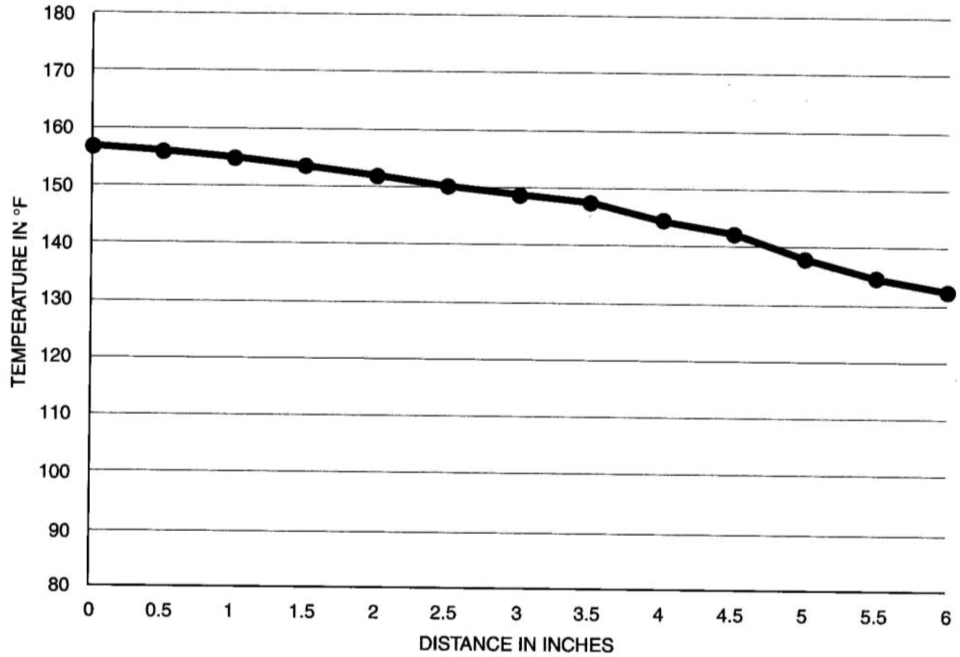
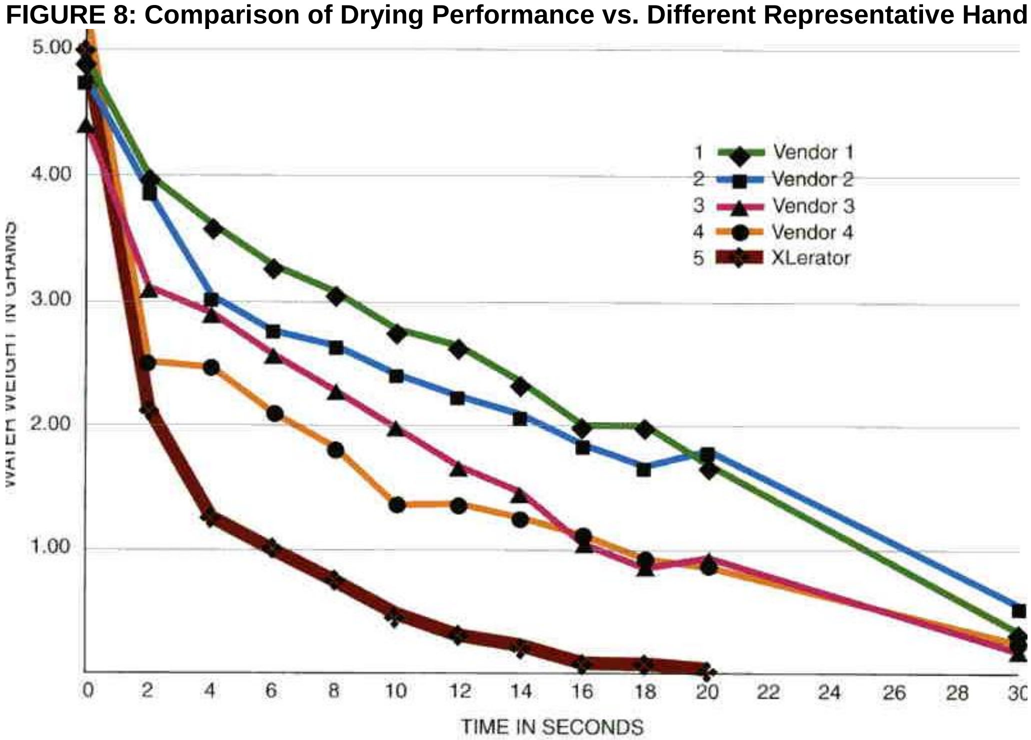


FIGURE 8: Comparison of Drying Performance vs. Different Representative Hand Dryers



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