Physics of Direct-Contact Ultrasonic Cloth Drying Process^I

Chang Peng¹, Saitej Ravi¹, Viral K. Patel², Ayyoub M. Momen², and Saeed Moghaddam^{1*}

¹Department of Mechanical and Aerospace Engineering, University of Florida
Gainesville, FL, USA

²Building Equipment Research, Energy and Transportation Science Division, Oak Ridge National
Laboratory, TN, USA

*Corresponding author: Prof. Saeed Moghaddam, saeedmog@ufl.edu, phone: 352-392-0889

Abstract

Existing methods of drying fabrics involve energy-intensive thermal evaporation of moisture from clothes. Drying fabrics using high-frequency vibrations of piezoelectric transducers can substantially reduce drying time and energy consumption. In this method, vibrational energy generates instability on the liquid-air interface and mechanically ejects water from a wet fabric. Here, for the first time, the physics of the ultrasonic fabric drying process in direct-contact mode is studied. The kinematic and thermal responses of water droplets and fabrics on piezoelectric crystal transducers and metal mesh-based transducers are studied. The results suggest that on piezoelectric crystal transducers, the response of a droplet subjected to ultrasonic excitation is dictated by the relative magnitude of the surface tension and the ultrasonic excitation forces. The drying process for a fabric on the studied transducers consists of two regimes—vibrational and thermal. When the water content is high, the vibrational forces can eject bulk water rapidly. But the more strongly bound water within the smaller fabric pores evaporates by the thermal energy generated as a result of the viscous losses. This study finds that a metal mesh-based transducer is more suitable for dewatering fabrics, as it facilitates the ejection of water from the fabric-transducer interface to the opposite side of the mesh. A demonstration unit developed consumes 10–20% of the water latent heat energy at water contents greater than 20%.

Keywords: Ultrasonic fabric drying; Droplet atomization; Kinematics; Thermal effect

^I This manuscript has been authored by the University of Florida in collaboration with UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>).

1. Introduction

Drying, the removal of moisture from a substance, is an energy-intensive process that consumes about 10–15% of the energy generated in the United States [1]. In 2013, clothes dryers were responsible for approximately 6% of the annual residential electricity use in the United States, costing consumers about \$9 billion [2]. A commonly used tumbling drum clothes dryer using hot air requires about 1 MJ of energy per pound of water evaporated [3]. To improve efficiency, reduce energy consumption, and increase cost savings, a variety of technologies such as air-vented dryers, condensing dryers, and heat pump dryers have been commercialized [3–7]. Recently, high-frequency direct-contact vibrational drying of fabrics using ultrasonic transducers has been proposed by Oak Ridge National Laboratory scientists [8,9] as a promising technology to reduce both the drying time and the energy consumption of the drying process.

Non-contact ultrasonic-assisted drying for food preservation has been studied before [10–15]. In this method, ultrasonic pressure waves result in a higher heat transfer rate and lower operating temperature and a reduction in the drying time (by ~1.5 times) compared with the traditional convective drying process. To the best of our knowledge, the existing literature does not provide any insight on the physics of the high-frequency direct-contact vibrational fabric drying process. However, similarities may be drawn between this process and the ultrasonic atomization of droplets, which is based on the response of the droplet–air interface to incident oscillations. Many studies have been conducted to investigate the physics of the droplet atomization process. Although there is no general agreement in these literatures regarding the actual mechanism of the ultrasonic atomization process, there exist two major rival theories: capillary wave theory [17–19,22,23,25,26] and cavitation theory [16,19–21,24]. According to the capillary wave theory [17,19], upon the excitation of a liquid droplet, ultrasonic waves are transmitted through the liquid phase, generating capillary waves at the liquid–vapor interface. At sufficiently high oscillation intensities, these waves become unstable and undergo rupture to form a fine mist. The cavitation hypothesis [20,21], which is applied to high-frequency and high-energy systems, postulates that atomization occurs through the hydraulic shocks generated by the implosion of cavitation bubbles, especially near the liquid-gas interface.

Among different studies, the study of James et al. [22] is of particular interest because it evaluates the kinematics of the droplet atomization process and the bursting of droplets into a mist by measuring the effect of the acceleration amplitude on the atomization process. They conclude that a critical acceleration (152 g) is required to atomize a droplet. Goodridge et al. [18] conducted Faraday-wave experiments on fluid layers to determine the acceleration threshold for droplet ejection. This threshold acceleration corresponds to the minimum oscillation force (F_o) that would atomize a droplet by overcoming the surface tension force (F_s).

Assuming that the droplet forms a half-sphere on the transducer surface, the scale of F_o applied on the water droplet (droplet mass, m_{drop} , and density, ρ) can be presented as

$$F_o \sim m_{drop} A \omega^2 \sim \frac{1}{12} \pi d^3 \rho A \omega^2, \quad (1)$$

where A and ω are the vibration amplitude and angular frequency ($\omega = 2\pi f$), respectively. On the other hand, the scale of the surface tension force (F_s) experienced by the droplet surface can be presented as [27]

$$F_s \sim \sigma \pi d \cos \theta, \quad (2)$$

where σ is the liquid surface tension, d is the droplet diameter and θ represents the contact angle formed at the liquid-solid interface. The surface tension is temperature (T) dependent and the diameter of the atomizing droplet varies with time (t).

The relative magnitude of F_o and F_s can be expressed as

$$R \sim \frac{F_o}{F_s} \sim \frac{d^2 \rho A \omega^2}{12 \sigma \cos \theta}. \quad (3)$$

In this study, a comprehensive analysis of the direct-contact ultrasonic fabric drying process is presented. To facilitate understanding, first, the droplet atomization process on different transducers is investigated; infrared (IR) imaging is utilized for the first time to enhance understanding of the process. Then, the drying process of two types of fabrics on different transducers is studied and its similarities and differences with the droplet atomization process are discussed. Finally, a demonstration ultrasonic press dryer is introduced and preliminary data on its performance are presented.

2. Ultrasonic transducer

The detailed characteristics of the transducers tested in the studies are summarized in Table 1. Transducers A and B are traditional piezoelectric crystal transducers, the working surfaces of which consist of a piezoelectric crystal, as shown in Figure 1a–b. Transducer C, on the other hand, consists of a metal mesh sandwiched between two piezoelectric rings (Figure 1c) that vibrate the mesh. Unlike traditional ultrasonic piezoelectric crystal transducers A and B, with which the water droplets are in direct contact, the metal mesh-based transducers allow water to pass through the mesh.

3. Experimental setup

A schematic of the experimental setup for studying both the droplet atomization and the cloth drying process is shown in Figure 2. The setup consists of six major components: an ultrasonic transducer, a function generator (AFG2021, Tektronix Inc.), a power amplifier (HLA300, RM Italy Inc.), a high-speed camera (FastCam SA4, Photron USA Inc.), an infrared (IR) camera (IRC900, IR Cameras Inc.) and a microbalance (AL104, Mettler Toledo) with a resolution of 0.1 mg for measuring the fabric weights. The function generator supplied an electric signal to the amplifier. The amplifier output was connected to the transducers to allow the peak voltage and frequency of the signal to be adjusted to desired values. The droplet atomization and cloth drying process was captured using the high-speed camera. During the water droplet atomization process, the IR camera was also used to monitor the droplet and transducer temperature changes. An image of the experimental setup is provided in Figure 3.

In testing fabrics, two US Department of Energy (DOE) standard fabrics (hereinafter called F-1 and F-2) were tested. These fabrics have specified yarn compositions, contents, and densities. F-1 consists of 50% cotton and 50% polyester; F-2 consists of 100% cotton. The thickness of the F-1 and F-2 fabrics was 0.40 and 0.53 mm, respectively and the densities were 190.9 and 193.9 g/m², respectively. More details on these fabrics are provided elsewhere [28,29].

4. Experimental method

4.1. Droplet atomization

Using a micro-pipette, a water droplet of a specified volume was deployed at the center of the transducer. The atomization process was captured using the high-speed camera at 3600 frames per second rate. IR images of the droplet were also obtained during the atomization process. The recording was done over a period of 3 seconds. The camera line of view was normal to the vibrating surface, thus providing top-view images of the atomizing droplets (Figure 2). Trials were performed with three different droplet initial volumes 10, 50, and 100 μ L.

4.2. Fabric drying

At the beginning of the drying test, the weight of the dry fabric was measured on the microbalance. The fabric was then wetted with a known water volume to achieve a certain initial moisture content. After the fabric was wetted, the transducer was actuated to begin the drying process. After 5 seconds elapsed, the transducer was turned off and the fabric was weighed again. Immediately after this measurement, the fabric was dried completely by heating it to 80°C on a hot plate. The fabric was then wetted to its initial moisture

content again, and its weight was measured after the transducer was actuated for 10 seconds. The fabric was then completely dried again by heating. In this manner, the weight of the initially saturated fabric was measured after activation of the transducer in increments of 5–10 seconds, with the fabric dried after each measurement. For each time interval, tests were repeated at least three times. The maximum deviation across the three measurements was always below 5%. The measurements were recorded until the weight of the water remaining in the fabric was less than 3% of the initially saturated water mass. This method of determining the fabric drying rate was repeated for the two fabrics on the three transducers.

5. Results and discussion

5.1. Droplet atomization

5.1.1. Kinematics of droplet atomization

High-speed images recorded during the atomization of a 10 μL water droplet on transducer A are provided in Figure 4. A qualitative analysis of these images provided interesting clues to the kinetics of the atomization process. In the initial stage, after the transducer was turned on, capillary waves appeared on the droplet surface in less than a millisecond (Figure 4b). As time progressed, an azimuthal wave propagated and surface ligaments evolved (Figure 4c), followed by atomization of the droplet (Figure 4d–j), during which the droplet broke up via the ejection of a fine mist.

Toward the end of the atomization process, the droplet was broken up into smaller secondary droplets with various diameters (Figure 5a). When the smaller secondary droplets merged into a larger secondary droplet, a fine mist was ejected from the droplet surface (Figure 5b–f). At the end of this stage, as the volume of the droplet decreased, it reached a critical volume below which the energy of the vibrating surface was insufficient to cause atomization. Although some corrugations can be observed on the droplet surface in this regime (termed the “tail-off regime”; Figure 5g–h), no observable mist was generated. From this point onward, the sizes of the small secondary droplets gradually decreased. A similar process was observed on transducers B and C.

The observed kinematics of droplet atomization can be explained by analyzing the relative magnitudes of the oscillation force (F_o) and surface tension force (F_s) influencing the process. For a 10 μL water droplet on transducer A (Figure 4a), $F_o > F_s$ (i.e. $R > 1$). Consequently, the liquid–vapor interface transitioned through different forms of interface instability and finally ruptured (leading to atomization) within approximately 15 ms (Figure 4a–f). The interface rupture and atomization reduced the droplet diameter (d) and the ratio of the oscillation and surface tension forces (R). The atomization process continued until F_o dropped below F_s , at

which point the atomization process ceased (Figure 5g). This argument is supported by the images of the phenomena provided in Figure 5a–f, which show that the atomization process occurred for the smaller secondary droplets only when they merged and formed larger droplets. The small droplets that remained on the surface gradually decreased in size until they disappeared as a result of direct evaporation, as will be discussed in detail later.

5.1.2. Thermal responses of droplets

To understand the substantial differences in the characteristics of the atomization processes on different transducers and the dependence on droplet size, a set of studies was conducted in which changes in the liquid temperature were carefully monitored throughout the process, using the IR camera. Three different volumes of water—10, 50, and 100 μL —were tested on transducers A and B. Temporal variations in the maximum temperature of the droplets on transducer A and B are presented in Figure 6. The x-axis represents a non-dimensional time (t^*) defined as

$$t^* = \frac{t}{t_o}, \quad (4)$$

where t_o is the overall process time (Table 2). All three droplets on transducer A began to burst and atomize (i.e., kinematic response) as soon as the transducer surface was excited (Figure 7). It was observed that the bursting phenomenon was vigorous for larger droplets. This initial atomization phase lasted for $t^* = 0.082$, 0.148, and 0.221 for the 10, 50, and 100 μL droplets, respectively (marked on each curve in Figure 6a). This atomization process is clearly visible in IR images. Figure 7d shows the sequence of images before and after the process (for the 10 μL droplet) during which a cold mist emanates from the surface of the transducer A. During this primary atomization phase, the rate of temperature increase was dictated by the initial volume of the droplet. At the end of this phase, the maximum temperature of the remaining liquid from the 10 μL droplet was 37.8°C, while that of the 100 μL droplet was 25.4°C. In the case of the 50 and 100 μL droplets, the temperature of the remaining liquid gradually increased without any kinematic response (i.e., atomization) until the end of the process ($t^*=1$). However, for the 10 μL droplet, the temperature of the remaining liquid increased rapidly up to a peak value of 66.7°C at $t^*=0.69$, when a second, brief atomization event was observed. The ejection of mass due to this event caused an instantaneous drop in temperature, and the atomization ceased. Subsequently, the temperature of the remaining liquid rapidly increased to a steady value of 59.3°C.

The droplets on transducer B did not atomize when the surface of the transducer initially was excited (Figure 8). The primary response of the liquid on this transducer was thermal in nature—the temperatures of the droplets rapidly rose, with atomization induced when the droplets reached a certain threshold temperature (marked on each curve in Figure 6b). This threshold temperature was dependent on the initial volume of the droplet—the first bursting threshold temperature for atomization decreased as the droplet volume increased (Table 3). After atomization was initiated, the temperature of the remaining liquid on the transducer increased to a peak value before gradually decreasing. The peak temperature attained during this atomization phase was also dependent on the initial volume of the droplet—the peak temperature was higher for a droplet with a larger volume. The end of the atomization phase was marked by an almost instantaneous decrease in the temperature of the remaining liquid, following which the temperature of the remaining liquid stayed constant.

The distinct and contrasting thermal behaviors of water droplets excited on transducers A and B can also be understood by considering the relative magnitude of the two major forces involved in this process, F_o and F_s . When $F_o > F_s$ ($R > I$), the primary response of a droplet was kinematic (with an associated temperature rise), and the droplet burst. But, when $F_o < F_s$ ($R < I$), the primary response was thermal in nature and the temperature of the droplet increased as a result of viscous dissipation. For the droplets on transducer A, $F_o > F_s$ ($R > I$) at $t^*=0$, and the excitation of the transducer surface overcame the surface tension force and droplets began to burst. During this process, the diameter of the remaining droplet decreased, resulting in a decrease in R . This process continued until F_s exceeded F_o ($R < I$), at which point atomization ceased. The experimental observations on transducer A ($F_o > F_s$ at $t^*=0$) also suggest that the intensity of this atomization process was governed by the difference between F_o and F_s . As the droplet volume increased, the magnitude of this difference increased at $t^*=0$, resulting in an increase in the atomization intensity. Therefore, the 50 and 100 μL droplets burst more vigorously, causing the ejection of larger amounts of liquid outside the working area of the transducer than in the case of the 10 μL droplet. As a result, the volume of the remaining liquid at the end of this atomization phase decreased as the initial volume of the droplet increased. At the end of this phase, F_s exceeded F_o and the temperature of the droplets increased owing to viscous dissipation. The rate of temperature rise at this stage increased as the remaining liquid volume increased—the highest rate of temperature increase was observed for the 10 μL droplet. The rise in temperature of the 10 μL droplet ($0.082 < t^* < 0.689$) decreased the surface tension of the liquid until F_s dropped below F_o , which induced the second brief atomization event. The immediate loss of liquid due to this event resulted in a decrease in the droplet diameter, and atomization ended. Because of the low rate of temperature increase for the 50 and 100 μL droplets, F_s did not drop below F_o , and a second atomization event was not induced. The remaining liquid

after the second atomization event of the 10 μL droplet was then heated via viscous dissipation, and the temperature rapidly rose to a steady state value of 59.3°C.

In contrast to the observations on transducer A, for all three droplet volumes on transducer B, F_s was greater than F_o at $t^*=0$. Therefore, the primary response of the droplets upon excitation was thermal, and the liquid temperature rapidly increased (Figure 6b). The temperature increase caused the water surface tension to decrease until F_s dropped below F_o , resulting in atomization. After a period of atomization, the liquid volume decreased, resulting in an increase in the threshold temperature for atomization (Figure 6b). Subsequently, the temperatures of the remaining liquids increased to a peak value and decreased gradually owing to direct evaporation.

The thermal response of a 10 μL water droplet to external excitation was also investigated using transducer C. The working area of the mesh had pores with a conical shape. The droplets were placed in contact with the side of the mesh that had larger pore openings (Figure 9). The flexion of the mesh caused by the vibrating piezoelectric element pushed water into the pores and ejected liquid at the base of the transducer.

Figure 10 shows variations in the maximum temperature of the liquid when a 10 μL droplet was placed on the surface of transducer C. The droplet began to atomize as soon as the transducer was excited. The overall process time (t_o) for the droplet was 31.83 seconds. Although the thermal response of the 10 μL droplet on this transducer was similar to that on transducer A, the kinetic response was a single but slow atomization event. The end of this atomization event coincided with a drop in the temperature of the remaining liquid (Figure 10), after which the droplet diameter decreased and the atomization halted. The absence of a second atomization event on transducer C can be attributed to the differences in the operating mechanisms of the transducers. The flexion of the mesh plate excited by the piezo rings generates the acoustic pressure in the vicinity of the pores. The acoustic pressure generated in the pores, combined with the flexion of the mesh in transducer C, extracted liquid from the transducer surface and ejected it through the opposite side continuously. By contrast, on transducer A, the atomized droplets can only be ejected upward from the water droplet surface. The droplet ejection process halted until the water droplet was reduced to the volume for which F_s exceeded F_o . But after a while, a second atomization occurred as a result of the decrease in surface tension resulting from the temperature rise.

5.2. Fabric drying

5.2.1. Thermal drying behavior of fabric

The baseline dewatering time for fabrics was determined by thermal drying of two different saturated fabrics (F-1 and F-2) 4×4 mm² in size at 80°C. The fabric size was selected so that the sample area did not exceed the working area of the transducers. The amount of water required to saturate the 4×4 mm² fabric swatches was ~6.45 μL and ~8.55 μL, respectively. The results provided in Figure 11 show that the water content in a fabric varied linearly with time, since it was directly related to the amount of water stored in the fabric [30].

5.2.2. Ultrasonic drying behavior of fabric

Figure 12 presents the drying characteristics of saturated fabrics F-1 and F-2 on transducers A, B, and C. The results suggest that water shedding via ultrasonic excitation dewatered fabrics more quickly than the thermal drying process (Figure 11); drying time was reduced by up to 82% for fabric F-1 on transducer C. The data in Figure 12 show that the drying curve for each fabric on transducers A and C consisted of nonlinear and linear regions (indicated by the arrows in Figure 12a and c).

As can be seen in the scanning electron microscope (SEM) images of the two fabrics (Figure 13), there are two types of pores in the fabrics: large pores between fabric threads and small pores within the fabric threads. The surface tension forces (F_s) associated with these pores differ because of their different sizes. The large pores generate a large R . At $t^*=0$, the F_o generated by the transducer surface was sufficiently large to overcome the F_s in the larger fabric pores ($R>I$), resulting in rapid water shedding from the pores. The shedding of a large fraction of water via ultrasonic excitation resulted in a quick, nonlinear decrease in the fabric water content. The fraction of water shedding in this regime was dictated by the fraction of pores in which $F_o > F_s$.

Based on the data presented in Figure 12, it can be deduced that, compared with fabric F-2, fabric F-1 had a larger fraction of pores in which F_o was likely to exceed F_s , resulting in a greater decrease in water content during the initial nonlinear phase. This conclusion is also supported by Figure 13 that shows F-2 has a denser structure and smaller pores compared with the F-1 fabric. At the end of the nonlinear phase, liquid is mainly contained within very fine pores. The continued excitation of the transducer resulted in an increase in the temperature of the liquid trapped in such pores. This behavior was similar to the thermal response of droplets observed when $F_s > F_o$. The increase in the liquid (and the fabric) temperature induced thermal evaporation from the fabric, causing a linear decrease in the fabric water content (similar to the trend presented in Figure 11).

The data suggest that a larger volume of water was shed from the fabric during the nonlinear regime on transducer C than on transducer A (Figure 12), and, overall, fabrics dried more quickly on transducer C than

on transducer A. The high-speed images of the fabric recorded by the high-speed camera during the drying process revealed fundamental differences in the drying mechanisms of the fabrics on the two transducers. On transducer A, the fabric lost water to the gap between the fabric and the transducer surface. The water that exited the fabric was then atomized on the transducer surface. This was evident from the frequent lifting of the fabric from the transducer surface and the emergence of a mist from underneath the fabric. This process displaced the fabric. Figure 14d shows the wet area beneath the fabric after it had moved away from its initial position. After losing a substantial amount of water, the fabric was dried through the thermal evaporation mode, during which the fabric did not move. In contrast, on transducer C, the capillary pressure generated by the small pores in the mesh wicked the liquid away from the fabric. The vibration of the mesh then ejected this liquid through the base of the mesh. This mechanism produced a lower-resistance escape path for water to leave the fabric. In this case, the fabric remained on the surface (Figure 15) during the entire drying time.

The drying data on transducer B (Figure 12b) clearly show a linear decline in the fabric water content with time. The kinematics of fabric drying on transducer B were similar to those of droplet atomization, where $F_s > F_o$ at $t^*=0$; therefore, the primary response was thermal, and the fabric temperature rapidly increased because of viscous dissipation. Additionally, since the surface tension force (F_s) in the fabric is believed to be much greater than that of the 10 μL droplet, the increase in temperature did not cause F_s to fall below F_o . Therefore, ultrasonic drying was not induced on this transducer, resulting in the absence of a nonlinear drying region. As in the case of thermal drying, the drying time for the F-1 fabric was shorter than that of F-2 fabric.

5.3. Energy efficiency analysis

As part of the next applied stage of this research, a mid-scale press type ultrasonic cloth dryer was designed and fabricated. Ultrasonic transducer C from this work was used, in part because of its superior drying performance among the three transducers. The main objective was to scale up the process considerably and study the energy efficiency of ultrasonic drying of larger fabrics. Figure 16a shows the demonstration unit of this ultrasonic press dryer, in which fabrics larger than 100 in^2 can be dried. The energy consumption per unit mass of water content (kJ/g) removed from the fabric by this ultrasonic press dryer was measured. The results were compared with those for the latent heat of evaporation for water (at ambient temperature and pressure) and a typical electric resistance (ER)-based dryer (Figure 16b). The preliminary results show that the energy consumption of the direct contact ultrasonic drier is at least 10 times less than that of the typical ER-based dryer and 5 times less than the water latent heat of evaporation at water contents greater than 20%.

6. Conclusions

A study on ultrasonic droplets atomization and fabric drying processes was conducted. The experimental data on droplets atomization confirmed the validity of the capillary wave theory. Experimental observations of droplets atomization after merger illustrated the soundness of the force balance theory in predicting a threshold for atomization, dictated by the balance of forces. IR imaging showed that the droplet temperature substantially increased during the process resulting in subsequent atomization (due to drop in surface tension force) or thermally-driven direct evaporation.

The drying process for fabrics consisted of two regimes—water atomization and thermal evaporation, similar to the droplet atomization process. The drying time and energy use vastly differ between the two drying modes. The characteristics of these two modes strongly depends on the type and operational characteristics of the transducers as well as the fabric type. High speed images showed that water did not atomize from the surface of the fabric but migrated to the gap between the fabric and transducer surface and subsequently atomized in a process similar to droplets atomization. It was observed that the mist generated as a result of atomization must lift the fabric to escape to free space leading in separation of the fabric from the transducer surface. To avoid this source of deficiency, mesh transducers were implemented to facilitate ejection of water from the fabric–transducer interface to the opposite side of the mesh plate.

Two types of fabrics were tested. SEM images showed that the fabrics have two different pore sizes—large pores between fabric threads and small pores within the fabric threads. The variation in drying characteristics is mainly attributed to the difference in pores size. The large pores generated a large R . When the water content was high, the vibrational forces ejected bulk water trapped within large pores in the fabric rapidly at the beginning of the process. But, the more strongly bound water within the smaller pores and fabric threads evaporated by the thermal energy generated as a result of the viscous losses.

A demonstration unit was fabricated to show the efficacy of the process and its energy saving compared to thermal drying process. The preliminary results showed that the energy consumption of the direct contact ultrasonic press drier which was made of metal mesh-based transducer was an order of magnitude less than that of a typical ER-based dryer and 5 times less than the latent heat of evaporation at water contents greater than 20%.

Acknowledgments

This work was sponsored by the US Department of Energy’s Building Technologies Office under contract no. DE-AC05-00OR22725 with UT-Battelle, LLC. We would like to acknowledge Mr. Antonio Bouza, the

Technology Manager for HVAC and Appliances, for his support. The authors also would like to acknowledge support from Oak Ridge National Laboratory for its assistance.

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List of tables and figures

Table 1. Dimensions and resonant frequencies of the transducers in this study.

Transducer	Working diameter (mm)	Resonant frequency (kHz)	Type
A	20	1600	Piezo crystal
B	50	1060	Piezo crystal
C	4.2	135	Metal mesh

Table 2. Summary of the total process time for different droplet volumes on transducers A and B.

Initial volume (μL)	Process time, t_0 (sec)	
	Transducer A	Transducer B
10	3.29	157.33
50	3.23	248.67
100	2.43	265.00

Table 3. Threshold temperature and non-dimensional time at which atomization was induced on transducer B.

Droplet volume (μL)	Non-dimensional time (t^*)	Threshold temperature ($^{\circ}\text{C}$)
10	0.13	67.4
50	0.05	57.5
100	0.04	46.3

Figure 1. Images of the transducers used in this study: (a) transducer A, (b) transducer B, and (c) transducer C.

Figure 2. Schematic of the experimental setup for droplet atomization and cloth drying studies.

Figure 3. The experimental setup for studying fabric drying behavior (high-speed camera not shown).

Figure 4. Different regimes of droplet atomization process on transducer A: (a) unperturbed droplet, (b) capillary wave regime, (c) ligament regime, and (d)–(j) catastrophic drop breakup and atomization.

Figure 5. Time sequence of images showing the merging and atomization of two secondary droplets on transducer A.

Figure 6. The maximum temperature of liquid on the surface of (a) transducer A and (b) transducer B, extracted from the IR images recorded during liquid atomization.

Figure 7. Selected IR image sequences of droplet atomization recorded on transducer A. (a) 10 μL initial volume, (b) 50 μL initial volume, (c) 100 μL initial volume, and (d) the first atomization phase of 10 μL water volume.

Figure 8. Selected IR image sequences of droplet atomization recorded on transducer B. (a) 10 μL initial volume, (b) 50 μL initial volume, and (c) 100 μL initial volume.

Figure 9. Cross-section schematic of transducer C.

Figure 10. Temporal variation of the maximum temperature of a 10 μ L water droplet subjected to ultrasonic excitation on transducer C.

Figure 11. Thermal drying behavior of two different fabrics. The water volume in fabrics F-1 and F-2 was $\sim 6.45 \mu\text{L}$ and $\sim 8.55 \mu\text{L}$, respectively.

Figure 12. Drying behavior of different types of fabric on (a) transducer A, (b) transducer B, and (c) transducer C. The fabric size was fixed at $4 \times 4 \text{ mm}^2$, and the saturation water volumes for F-1 and F-2 were $\sim 6.45 \mu\text{L}$ and $\sim 8.55 \mu\text{L}$, respectively.

Figure 13. Scanning electron microscope images of the two DOE fabrics.

Figure 14. A time sequence of images (taken by the high-speed camera) showing the water shedding process of fabric F-1 on transducer A. The fabric size was $4 \times 4 \text{ mm}^2$ and the saturation water volume was $\sim 6.45 \text{ }\mu\text{L}$.

Figure 15. A time sequence of images (taken by the high-speed camera) showing the water shedding process of fabric F-1 on transducer C. The fabric size was $4 \times 4 \text{ mm}^2$ and the saturation water volume was $\sim 6.45 \text{ }\mu\text{L}$.

Figure 16. A demonstration unit of ultrasonic press dryer; inset figure shows the dryer during operation (a) and its energy consumption (b).