Chapter 20
Novel Applications of Power Ultrasonic Spray

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1 Introduction

Atomization is a process where a liquid is dispersed into droplets in a gas. Ultrasonic atomization was discovered in the 1920s (Loomis and Woods, 1927). Since then, atomization has seen diversified applications in devices such as drug nebulizers, room humidifiers, and air refreshers, as well as in industrial processes such as combustion, prilling, and web coating. In contrast to conventional liquid atomizers, ultrasound atomizers generally handle lower flow rates, and atomization of the liquid is achieved not by pressure, but by the vibration of ultrasonic waves (Morgan, 1993). This latter feature decouples the requirement of orifice geometry and pressure from the flow rate, allowing the flow to be controlled independently. Typically, ultrasonic atomizers excel in accurately processing low flow rates and slurry without clogging issues.

2 Snack Food Seasoning Coating

In food processing, it is common to deposit a coating on a food substrate. The coating material may be solid, liquid, or slurry. If the coating material is a fluid or slurry, it is often applied to the food substrate with conventional spray nozzles. These nozzles dispense the fluid in a spray pattern, using only hydrostatic pressure. Solid coating may be accomplished by dropping the slurry directly onto the substrate or through tumbling in a rotating drum. The coating materials may consist of seasoning, flavor additives, nutrients, and other elements, and generally make up a small portion of the whole compared to the weight of the food substrate.

In practice, there are a number of limitations in applying the conventional spray nozzle. One of the difficulties involves the ability of applying low flow rates, especially below 500 ml/min, while maintaining a steady spray pattern. Another problem

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resides in the momentum of spray, which, if closely coupled with the food product, can be destructive to the shape and texture of the product. The momentum may also disorient the packing arrangement of the product on the process line. Yet another disadvantage involves the difficulty of spraying a slurry of large particles. This problem is due to the fact that the orifice of a conventional nozzle can be smaller than 500 μm in diameter. Nozzle clogging is known to be a major drawback, especially for slurry applications. Since most processing lines are generally continuous, the cost of downtime due to build-up and clogging can be significant. The drawbacks of the conventional nozzle technologies limit the usage of the nozzle spray in the food industry.

Among the different sectors in the food industry, snack foods have annual sales of more than $25 billion (Enggalhardjo and Narsimhan, 2005), of which potato chip sales in the United States exceed $6 billions (Berry, 2003). Seasoning is an important part of the snack food experience, influencing the acceptability of the snacks (Kunt, 1996). In order to gain consumer loyalty in this competitive market, companies need to be able to consistently produce well-coated products. In particular, even distribution of seasoning topping is highly desired as it is essential to providing uniform appearance and taste of the product. From the processing point of view, this represents a challenge in at least two areas: (1) consistent rate of dispensing of the coating materials onto each food substrate and (2) consistent rate of adhesion of the coating materials onto each food substrate.

Many snack foods are fried and powder coated. The two most common ways to apply seasoning are by tumble drum and conveyor belt. In the case of conveyor belt, the powder is usually dispensed directly onto the moving chips. Over-dispensing in order to compensate for poor adhesion increases material and line cleaning cost. Potato chips contain about 35% oil (Pedreschi, and Moyano, 2005). Oil on the surface of the chip contributes to the adhesion of the seasoning, so most manufacturers coat the chips immediately after frying or applying the oil and seasoning simultaneously (Berry, 2003). In addition, Buck and Barringer (2007) report that solid size, shape, and chip temperature also have an impact on the rate of adhesion. Other deposition processes, such as electrostatic coating (Abu-ali and Barringer, 2005), have been tested to improve both adhesion and uniformity.

3 Ultrasonic Atomization Fundamentals

The most widely used ultrasonic atomizers are capillary wave-type atomizers. In this case, atomization occurs predominately from the effects of the surface capillary waves produced in a thin film of liquid as it wets an oscillating surface. The leading commercial suppliers for this type of atomizers are Sono-Tek Corporation (http://www.sono-tek.com/) and Sonics and Materials Inc. (http://www.sonics.biz/), both of which provide a range of nozzles that have the liquid atomized at the nozzle tip. Figure 20.1 shows a typical design of an atomizer by Sono-Tek Corporation, where the ultrasonic transducer and the nozzle are integrated as one piece. The

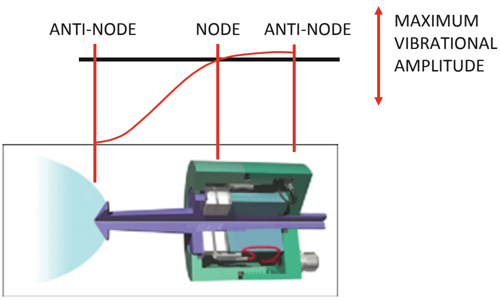

Fig. 20.1 Ultrasonic atomizer by Sono-Tek Corp.

source of vibration is provided by a stack of piezoelectric transducers located at the pressure node plane where the vibration amplitude is at the minimum. The tip of the nozzle is located at the pressure anti-node where the amplitude is at the maximum. The fluid is supplied through the center tube to the nozzle tip, where it forms a thin film as it wets the tip. Typically, the nozzles provided by Sonics and Materials, Inc. are designed as a separate part, which can be screwed onto an ultrasound transducer (Fig. 20.2). A side port is made at the node plane as the liquid inlet.

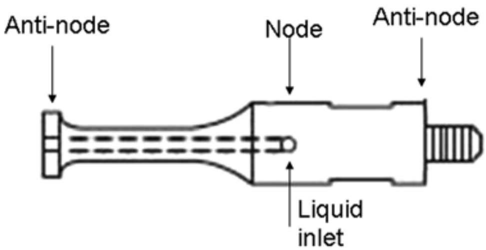

Fig. 20.2 Ultrasonic atomizer by Sonics and Materials, Inc.

These atomizers operate at low ultrasonic frequency up to 120 kHz and generally operate with power less than 20 W. The mean droplet size at a given frequency is predicted by the Lang equation (Lang, 1962):

$$D = 3.4 \times 10^{-3} \left(\frac{8\pi\sigma}{\rho f^2} \right)^{1/3} \tag{20.1}$$

where σ is the surface tension (liquid/gas) (N/m), ρ is the liquid density (kg/m^3), f is the ultrasound frequency (Hz), and D is the droplet diameter (m). The distribution of water droplet size at different frequencies has been reported by Berger (1998). If, however, the amplitude is operated beyond the cavitation threshold, the disturbances caused by cavitation will broaden the droplet size distribution (Topp and Eisenklam, 1972).

At high liquid flow rates the empirically derived equation of Mochida (1979) applies:

$$D = 2.21 \times 10^{-2}\,(\sigma/\rho)^{0.354}\,\eta^{0.303} q^{0.139} \tag{20.2}$$

where η is the liquid viscosity (Pa s) and q is the volumetric flow rate (l/s).

The flow of the liquid can be supplied by a positive displacement pump. Since atomization does not depend on hydrostatic pressure, the nozzle diameter can be enlarged (typically on the order of several millimeters), making the ultrasonic nozzle attractive to spraying slurry without clogging issues.

4 Ultrasonic Atomizers for Seasoning Applications

To be useful for seasoning applications, the atomizer must be versatile over a wide range of operating conditions. The table below lists the range of conditions likely to be encountered by a single nozzle.

Some combinations of high-end requirements demand an ultrasonic nozzle capable of ultra-high amplitude. At 20 kHz, it was found that the amplitude requirement for these conditions ranges from 20 to 200 µm. None of the commercial units were capable of the full range of the conditions listed in Table 20.1. Specialty nozzles were therefore developed in collaboration with Sonics and Materials, Inc. (Fig. 20.3).

Table 20.1 Operating conditions for an ultrasonic nozzle

Operating parameters	Low	High
Flow rate (ml/min)	0.1	1,000
Viscosity (cp)	1	500
Solid content (%w/w)	0	50
Solid particle size (µm)	0	500

Fig. 20.3 One of the specialty nozzles used for seasoning application

4.1 Continuous Atomization

A design of continuous atomization process is schematically illustrated in Fig. 20.4. A fluid or slurry was prepared in a mixing tank. The flow rate to the nozzle was controlled by a positive displacement pump, with optional feedback control through a flow meter. The feed temperature can be controlled with a heating element, preferably just before the nozzle. This feature is particularly useful for slurry applications, where slurry viscosity is kept high for solid suspension, and only lowered for a very short time period before atomization.

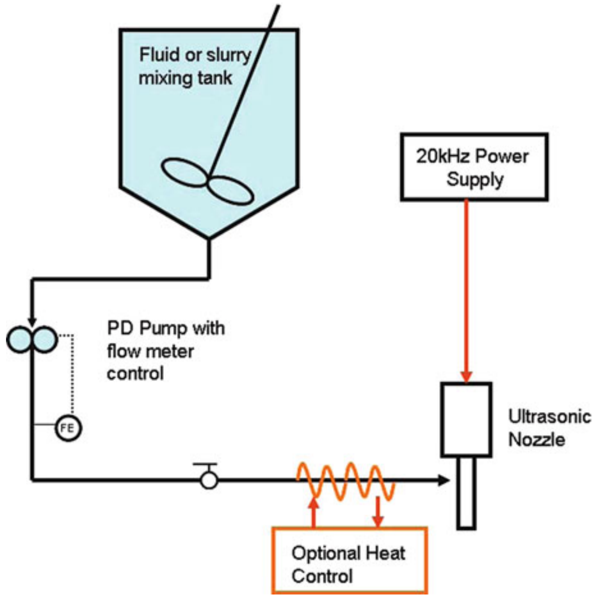

Fig. 20.4 One of the specialty nozzles used for seasoning application

In one application, the system was tested to spray salt/vegetable oil slurry on potato chips on a moving conveyer. The operating condition is presented in Table 20.2. The result of salt adhesion measurement is compared to a process where the salt was applied directly onto the chips as dry particles (Table 20.3). Note that two adhesion rates are shown. One is calculated by mass balance, i.e., the total salt

Table 20.2 Conditions for salt/vegetable oil slurry spray

Flow rate	50–500 ml/min
Salt load	15–25%w/w
Mean solid particle size	130 μm
Ultrasonic vibration amplitude	60 μm
Ultrasonic frequency	20 kHz

Table 20.3 Salt distribution

	% salt	SD	% adhesion (mass balance)	% adhesion (actual)
Baseline	1.29	0.24	50	66.7
Ultrasonic	1.31	0.08	74	98.6

deposited on the chips vs. the total salt applied. The actual percentage of adhesion was calculated by taking into account the spacing between chips. The ultrasonic slurry application significantly improved salt adhesion and reduced the variation of seasoning coating.

4.2 Registered Pulsed Spray

Registered pulsed spray refers to targeting of the atomization at the individual chips on a moving conveyor. This capability is desired, as it eliminates overspray in the gap between chips. If multiple nozzles are used, each with a different additive/flavor, they can be programmed to produce a variety of products with unmatched process flexibility. However, to be useful on the production scale, the nozzle must be able to pulse the spray accurately at a rate, in pulses per minute, that matches the number of chips per minute to be coated, which could be higher than 500. The target pulse must be focused on each chip so that flavor contamination across chips is kept at the minimum.

A block diagram (Fig. 20.5) shows the control of the registered pulsed ultrasonic spray. A seasoning/flavor liquid or slurry is supplied by a positive displacement pump at a constant flow rate. An optional heating element may be applied just before the ultrasonic nozzle. The nozzle is powered on at all times. However, the amplitude of the nozzle is switched between a “resting” mode, which is below the threshold of atomization, and an “active” mode, which is above the threshold of atomization. In the resting mode, the seasoning liquid wets the atomizer surface. In the active mode, the accumulated liquid is sprayed onto the substrate. The position of the chip on a moving conveyor can be detected by an optical sensor. Given the moving speed of the conveyor, the control sets a delay time for the amplitude to switch from resting to active, so that a pulsed spray targets the desired position on a chip. The ratio of the chip length over the conveyor speed is used to set the active duration so that the length of the pulsed spray can either fully or partially cover the entire chip. This amplitude modulation approach is the key to ensure that the pulse can respond at the production rate. Since the flow rate is unchanged, the setup is ideal for a conveyor where the chips are spaced equally.

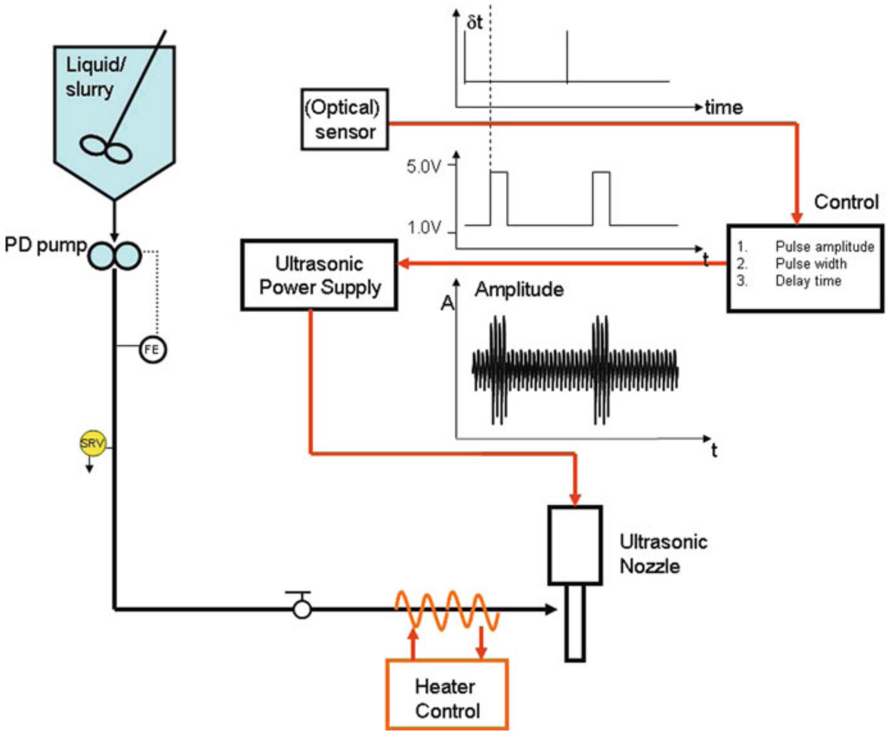

Fig. 20.5 Block diagram of registered pulsed ultrasonic spray

Operation of a single nozzle is illustrated by images captured with a high-speed video camera (Fig. 20.6). In this case, a row of equally spaced chips was moved at a constant speed under a nozzle. The sequence of seasoning spray over a single chip is illustrated.

An ultrasonic seasoning unit consisting of multiple nozzles to cover the width of a conveyor is shown in Fig. 20.7. This arrangement allows the seasoning of multiple rows of chips on the conveyor, with each nozzle targeted at a single row of chips. Because of the accuracy of the spray, an individual nozzle can have different flavors without concern of cross-contamination between the rows. Since the seasoning is fed to each of the nozzles individually, each row can have a different seasoning if desired, so that different flavored products can be made on the same conveyor at the same time. Further, if using two nozzles along the same row of chips and each having a different flavor, a variety of flavored chips may be created. For example, the first nozzle can be timed to spray every other chip and the second nozzle to spray on the chip in between. It is also feasible to time the two nozzles so that each can spray on multiple chips before activating the other nozzle.

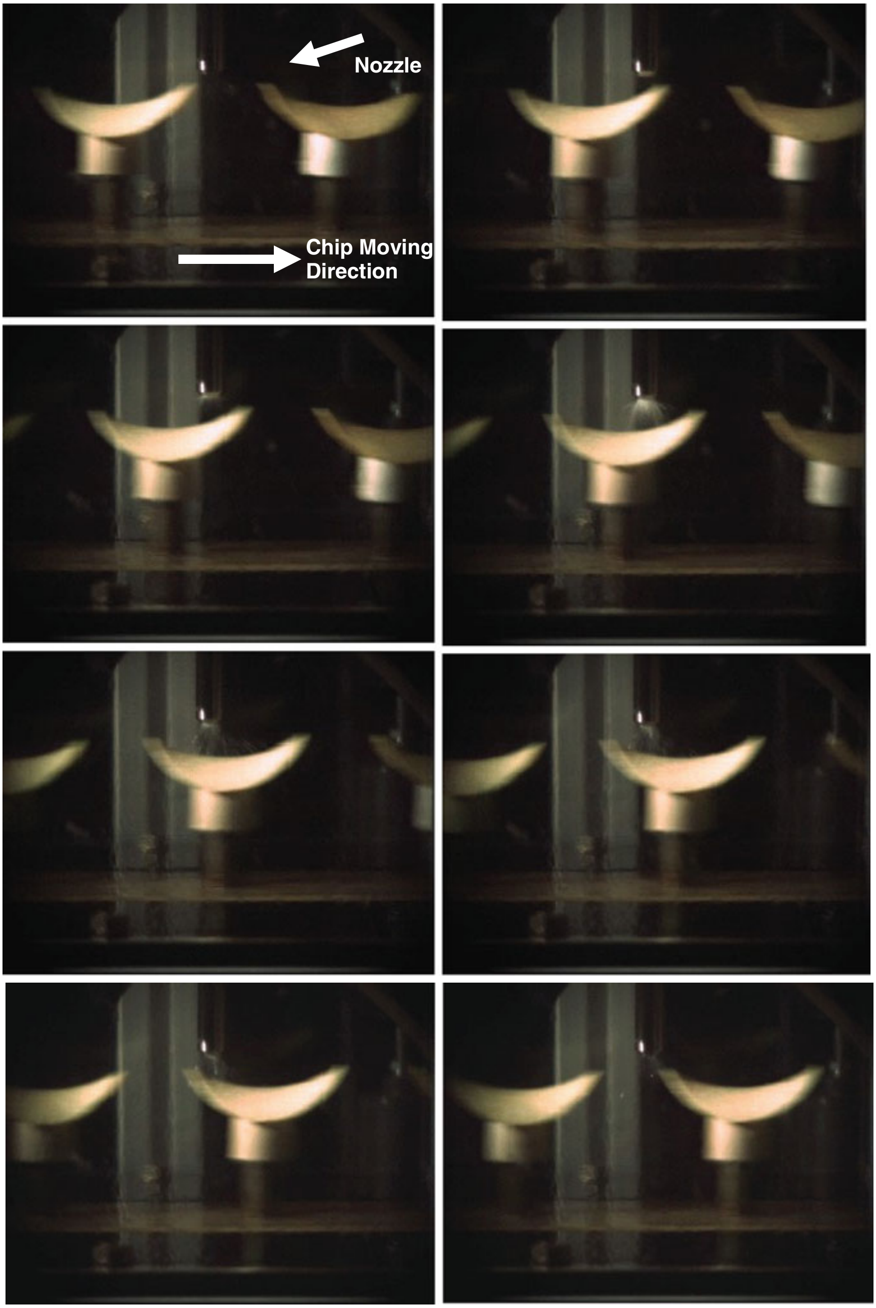

Fig. 20.6 High-speed video images showing registered pulsed spray over a row of chips

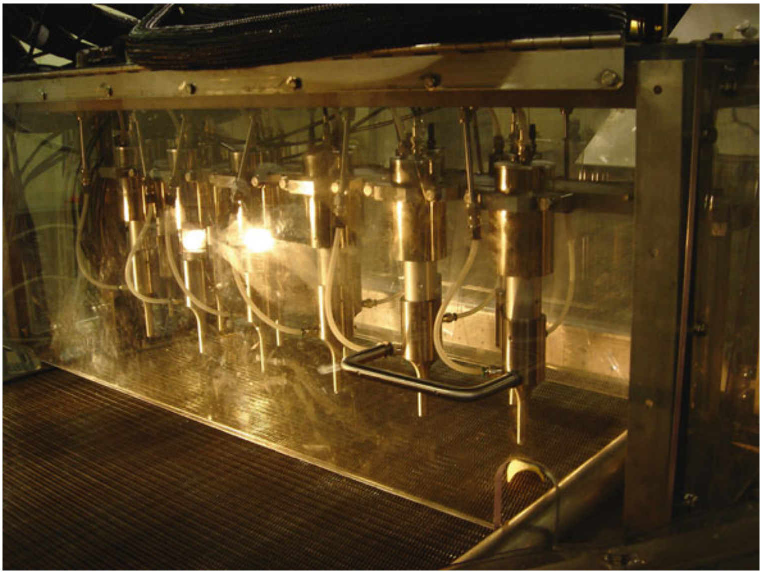

Fig. 20.7 An ultrasonic seasoning unit on a conveyor, consisting of an array of nozzles

5 Conclusions

High-power ultrasonic spray has been explored within Procter and Gamble Company for food seasoning applications. This method provides an alternative to the conventional spray nozzle in a rotating drum. The main advantages of ultrasonic sprays are as follows:

- Accurate metering of flow rate
- Clogging resistance enabling slurry applications
- Gentler spray minimally impacting the substrate

The ability to spray large particles without clogging opens the possibility of spraying solid seasoning in slurry, which improves solid adhesion and reduces variability in seasoning coating. With appropriate control, ultrasonic spray can be pulsed to target individual chips. This new process capability offers not only superior seasoning accuracy, but also unmatched flexibility in product innovation.

Handling the range of flow rates and the variety of liquid properties appropriate to seasoning applications stretches the limit of ultrasonic nozzle design, in particular vibration amplitude. Design changes create challenges in control, power supply, and connector interface to the nozzle. More research is needed in high-power ultrasonic nozzle development in order to ensure the robustness of this technology in industrial applications.

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