ULTRASONIC ATOMIZATION OF pMDI WOOD RESIN

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(Received May 2008)

Abstract. A novel, patent-pending approach to the application of wood resins based on an ultrasonic principle was developed in this study. Liquid polymeric methane diphenyl–diisocyanate (pMDI) resin was successfully atomized using a bench-scale 25 kHz ultrasonic atomizer. The optimal average sizes of the resin droplets generated at a flow rate of 0.7 mL/min and power input of 5.0 J/s were about 90 μm. In addition to fewer fine droplets than that produced by conventional spinning-disk atomizers, the droplets of pMDI resin produced by the ultrasonic atomizer had a more uniform droplet size distribution. These results indicate the potential advantages of implementing ultrasonic atomization in oriented strandboard production, including elimination of the hazardous fraction of fine resin droplets and potential production cost savings from improved resin efficiency. The ultrasonic atomization of wood resins appears to be a promising alternative to the spinning-disk atomizer.

Keywords: Ultrasonic atomization; droplet size and size distribution; pMDI resin.

INTRODUCTION

The importance of resin efficiency in the production of oriented strandboard (OSB) as well as other engineered wood composites has been a topic of continued study over the past 50 yr (Marian 1958; Burrows 1961; Carroll and McVey 1962; Lehmann 1965, 1968; Schwarz et al 1968; Christensen and Robertschek 1974; Wilson and Krahmer 1976; Hill and Wilson 1978; Youngquist et al 1987; Ellis 1993; Smith 2003). The primary reason for interest in resin efficiency is that the resin cost is up to 60% of the total manufacturing costs for wood-based composites (Burrows 1961) and still averages about 25% of the total variable costs in OSB production (Spelter 1994; Knudson 2005). Two possible ways to improve resin efficiency have been examined: modifying the resin composition and modifying composite manufacturing techniques (Carroll and McVey 1962).

Different resin systems have been developed, including phenol–formaldehyde, urea–formaldehyde (UF), melamine–formaldehyde, polymeric methanyldiphenyl–diisocyanate (pMDI), and mixed or cocondensed resins such as melamine–urea–formaldehyde, phenol–urea–formaldehyde, and UF/pMDI mixtures. However, most resins are formaldehyde- and urethane-based, and their raw materials are typically derived from natural gas or oil. These types of resins can be considered environmentally challenging materials, and resin

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Wood and Fiber Science, 41(1), 2009, pp. 84–89

costs in the manufacturing of wood composites continue to increase in response to increases in petroleum costs (Winterowd 2005). Therefore, it can be concluded that improving resin efficiency through modifications of resin composition has not been entirely successful.

Modifying the composite manufacturing process is another possibility for improving resin efficiency, but there is a need to know the optimum way to apply resin. Resins are typically spray-applied on wood strands using spinning-disk atomizers that were introduced into the OSB industry in the early 1980s. Compared with the conventional atomization methods of air spray and airless spray, the introduction of the spinning-disk atomizer has contributed significantly to the effectiveness of resin application over the past two decades (Beattie 1984; Coil 1991). However, a recent study has concluded that the spinning-disk atomizer produces a pMDI resin spray with several deficiencies, including the production of a large volume of fine resin droplets smaller than 20 μm (Zhang et al 2008). These fine resin droplets have a high probability of becoming airborne and could contribute to environmental and industrial hygiene problems. Another well-known phenomenon that occurs during spinning-disk atomization is that excessive resin buildup can occur on the blender walls, necessitating costly and hazardous manual cleaning procedures. Resin efficiency using the spinning-disk atomizer is far from optimal; therefore, there is clearly a need for developing alternative approaches to applying resins that are efficient, cost-effective, and environmentally friendly.

A promising alternative solution for improving resin efficiency is spray atomization based on an ultrasonic principle, in which a liquid is atomized at a vibrational frequency over 20 kHz. When a thin liquid film spreads on an atomizer surface vibrating at ultrasonic frequencies, the longitudinal vibration first introduces surface waves on the liquid-free surface. As resonance is reached, the wave amplitude increases until droplets are ejected through a crest breakup mechanism. Finally, a fine uniform spray forms with a particular narrow droplet size distribution and very low spray velocity, typically 1 m/s (Berger 1998; Dobre and Bolle 1999). Using ultrasonic spray technology, the droplet distribution can be engineered very precisely to match specific desired droplet sizes for optimal product properties such as internal bond strength and durability. Unlike conventional atomizing nozzles or spinning-disk atomizers, ultrasonic atomizers do not have mechanical connectors or moving parts that are subject to wear and/or cause noise pollution. The droplets are released without significant kinetic energy, eliminating the process of the primary output droplets breaking into the extraneous finer droplets. In short, ultrasonic atomization compares quite favorably with other conventional atomization methods from the precisely controlled droplet size, low droplet momentum, and low energy requirements (Rajan and Pandit 2001).

Ultrasonic atomization has been successfully used in various fields such as the medical, cosmetic, and electronic industries. It has also been used to apply adhesives in cigarette packaging (Heide 2004). Because no work has been reported on the application of ultrasonic atomization in the area of wood resins, the following topics were studied:

1. The applicability of a bench-scale ultrasonic atomizer to effectively spray wood resins.
2. The maximum flow rate of the ultrasonically atomized wood resins.
3. The spray characteristics of ultrasonically atomized wood resin.

EQUIPMENT

The experimental atomization unit included an atomization chamber made of transparent acrylic sheets, a Sono-Tek ultrasonic atomizer (Sono-Tek Corporation, Milton, NY), a Cole Parmer peristaltic pump (Model 77200-60, Cole-Parmer Instrument Company, Vernon Hills, IL) with Teflon tubing for flow rate control, and a Malvern laser diffraction analyzer (Spraytec; Malvern Instruments Inc, Westborough, MA) for spray characteristics analysis (Fig 1). The ultrasonic atomizer consisted of a bench-scale atomizing nozzle (Model S/N 25048) (Fig 2) and a power generator (D/N 06-04069). The atomizing nozzle was located at the top center of the atomization chamber. The analyzer consisted of a laser transmitter and receiver and control and data acquisition unit. The distance between the nozzle tip (atomizing surface) and the laser beam for droplet size analysis was 64 mm. The ultrasonic frequency of the atomizer was 25 kHz and the maximum input power of the power generator was 15 J/s.

The resin tested in this study was Huntsman pMDI resin Rubinate 1840 with an apparent viscosity of 0.233 Pa/s measured at 25°C using a Brookfield DV-I+ Digital Viscometer (Brookfield Engineering Laboratories, Inc, Middleboro, MA).

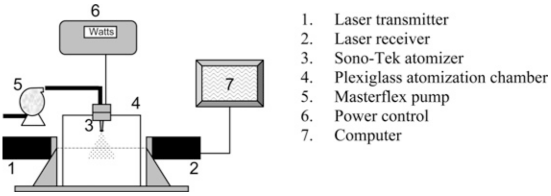

Figure 1. The schematic diagram of the bench-scale ultrasonic atomization experimental setup.

TESTING PROCEDURE

The testing consisted of the following steps:

1. Distilled water followed by acetone was used to clean all the necessary channels through which the resin would pass, including the glass beaker, Teflon tubing, feed tube inside the atomizer, and the nozzle surface (Fig 2).
2. The resin was fed at a prescribed flow rate by the pump from the beaker through Teflon tubing into the inner annulus path inside the nozzle until it spread over the conical surface of the nozzle tip, after which the pump was stopped.
3. The resin on the nozzle surface was cleaned using a paper towel and acetone, and then the nozzle was powered on. Input power between 0 and 15 J/s was controlled manually.
4. Immediately after the atomizer was powered, the pump was restarted, and the resin was atomized on the nozzle tip surface (Fig 3) where the maximum vibration amplitude occurred if power input was sufficiently high.

There is a narrow band of input power at which the amplitude of the nozzle is optimal for stable atomization of given liquid into fine low-velocity sprays at a given flow rate (Berger 1998). Lower power levels may not generate amplitudes necessary to break the liquid sheet on the

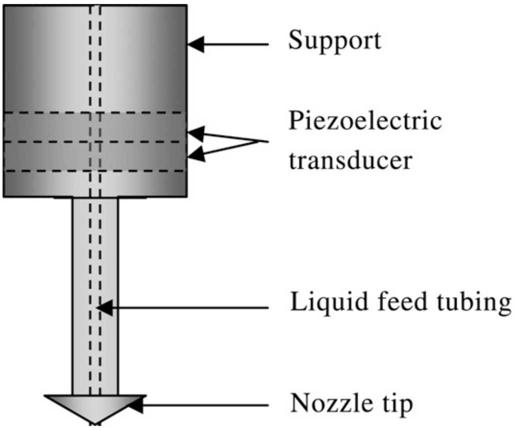

Figure 2. The schematic configuration of the Sono-Tek ultrasonic atomizer.

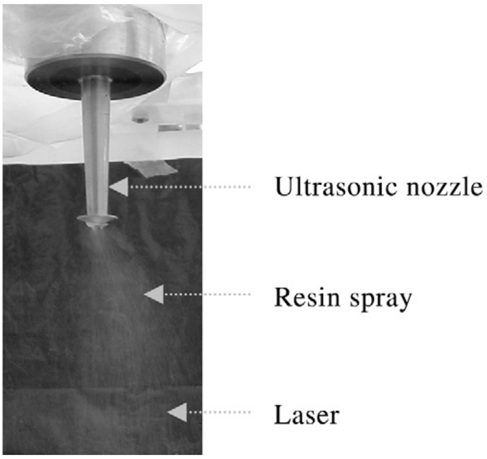

Figure 3. The pDMI resin spray atomized using a Sono-Tek ultrasonic nozzle.

nozzle tip, whereas excessive power will rip apart the sheet of liquid and eject large parts of it without proper atomization. To determine the maximum flow rates, the lowest power levels necessary to generate stable spray at a given flow rate, and the highest flow rates at which the atomization is possible for a given input power level, the following trial and error procedure was used. The resin at a prescribed flow rate was atomized at several power levels within a range of 1 – 15 J/s. If the atomization did not succeed within this range, the flow rate was reduced until atomization succeeded. If stable atomization succeeded for at least 1 min at a particular power input, the power was slowly reduced until atomization failed, determining the minimum power input for that flow rate. Once the minimum power input for that specific flow rate was set, the next trials were performed to find the minimum power input at a slightly higher flow rate. Finally, the maximum flow rate and corresponding minimum power for stable atomization was found.

Once the resin atomization stabilized, a laser beam was passed through the center of the cone-shaped spray cloud (Fig 3) and was diffracted by the atomized droplets. The detector received the diffracted laser light to form a diffraction pattern that was transformed into the droplet size and size distribution. After recording the measurement data, the spray characteristics were interpreted and analyzed using the Malvern Spraytec RTSizer v5.40 software.

During the atomization process, the high energy intensity of the ultrasonic vibration increased the temperature of the nozzle body, which was expected to affect the resin viscosity (Sindayihebura et al 1997). In this study, nozzle heating was originally observed by manual inspection and then confirmed by targeting an infrared thermometer on the atomizer tip during atomization. The relationship between the temperature and apparent viscosity of pMDI resin was investigated over a temperature range of 21 – 80°C using a Brookfield DV-I+ Digital Viscometer.

RESULTS AND DISCUSSION

The pMDI resin was successfully atomized using a Sono-Tek ultrasonic atomizer at 25 kHz based on trial and error. The maximum flow rate of pMDI resin atomized was 0.7 mL/min. At this flow rate, the atomized resin needed a minimum power input of 4.3 J/s (Table 1). It has been reported in the literature (Berger 1998) that applications of ultrasonic spraying are limited to liquids with a viscosity of less than 0.05 Pa/s, whereas we were able to spray pMDI resin with a viscosity of 0.25 Pa/s. The decrease of pMDI resin viscosity from heating of the ultrasonic nozzle was clearly one of the most likely reasons for the successful ultrasonic atomization, according to the study of Sindayihebura et al (1997). The maximum temperature measured at the tip of the ultrasonic nozzle was about 32 – 38°C at different flow rates and power inputs. Within this temperature range, the apparent viscosity of pMDI resin is about 0.15 – 0.08 Pa/s as shown in Fig 4, which is a dramatic decrease of viscosity from 0.25 Pa/s at 21°C.

Table 1. *The statistical characteristics of sprayed pDMI resin droplets at 0.7 mL/min.*

	Power input (J/s)					
	4.3		5.0		8.0	
	Avg	SD	Avg	SD	Avg	SD
Dv10 (μm)	33.55	2.53	61.52	2.44	51.22	2.51
Dv50 (μm)	61.46	4.51	91.13	4.14	78.65	4.51
Dv90 (μm)	110.18	6.15	152.55	7.89	140.86	8.91

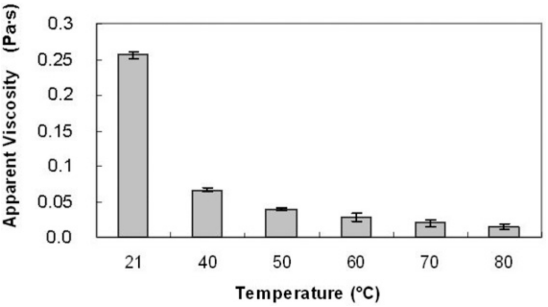

Figure 4. The relationship between the temperature and apparent viscosity of pDMI resin measured using a Brookfield DV-I+ Digital Viscometer.

The droplet size distributions of the pMDI resin spray at 0.7 mL/min were collected at three power inputs, 4.3, 5.0, and 8.0 J/s (Table 1). The statistical variables Dv10, Dv50, and Dv90 represent average diameters at the 10th, 50th, and 90th percentiles, respectively, of the total spray volume; Dv50 is also called the volume median diameter (VMD). The results showed that droplet sizes and distribution of the sprayed resin varied when power input was increased. Berger (1998) concluded that optimal conditions for spray generation occur when the input power is about 1 J/s above the minimum to atomize the liquid. In this study, the minimal input power necessary to generate a stable resin spray was 4.3 J/s. The spray atomized at 5.0 J/s (0.7 J/s more than the minimum) was characterized with a relatively narrow droplet size distribution with the VMD at about 90 μm. Sprays with a resin droplet size of 94 μm are considered optimal for maximizing mechanical properties of strand-based wood composites (Smith 2003). Therefore, the droplet size generated at 5.0 J/s was concluded to be optimal.

Comparing the spray characteristics under spinning-disk atomization at 10,441 rpm and 100 mL/min (Zhang et al 2008) (Table 2), the optimally ultrasonically sprayed droplets at 0.7 mL/min and 5.0 J/s were on average much larger. Using the terms characterizing the uniformity of the droplet size and distribution (Panneton et al 1991): range = Dv90 – Dv10; relative span = range/Dv50, it can be calculated that the relative span of pMDI resin spray generated under ultrasonic atomization and spinning-disk atomization would be 1.00 and 5.38, respectively, indicating that the ultrasonic atomization in this study produced a resin spray with a greater uniformity in droplet size distribution.

It should be stressed that the values of Dv10 between 51 and 61 μm meant that no more than 10% of ultrasonically atomized pMDI resin spray volume consisted of droplets smaller than 51 – 61 μm (at input powers between 5 and 8 J/s), whereas in spinning-disk atomization, about 50% of the spray volume is generated with droplets smaller than 20 μm. This comparison indicates that with ultrasonic atomization, the volume of aerosolized resin droplets could be significantly reduced.

Ultrasonic atomization technology brings a potential of mitigating possible environmental risks and industrial hygiene contamination during resin blending operations and increasing resin efficiency in the manufacture of engineered wood composites. Because of this potential, a US patent application has been filed based on the result of this study of ultrasonic atomization of woods (Gardner et al 2005).

Table 2. *Comparison of pMDI resin spray characteristics under spinning disk atomization and ultrasonic atomization.*

Spray generation conditions	pMDI resin spray characteristics		
	Dv10 avg (μm)	Dv50 avg (μm)	Dv90 avg (μm)
Spinning-disk atomization (10,441 rpm, 100 mL/min)	6.93	16.88	97.08
Ultrasonic atomization (0.7 mL/min, 5.0 J/s)	61.52	91.13	152.55

CONCLUSIONS

pMDI resin was successfully atomized using a bench-scale Sono-Tek ultrasonic atomizer at 25 kHz. At a power input of 5 J/s, the volume average droplet size of optimally ultrasonically atomized pMDI resin measured using a laser diffraction analyzer was about 90 μm. Fewer fine droplets were produced using ultrasonic atomization compared with spinning-disk atomization suggesting great potential for resin efficiency improvement using ultrasonic atomization in industrial applications.

The self-heating of the ultrasonic nozzle was a primary factor causing the decrease of the apparent viscosity of pMDI resin, thus contributing to the successful atomization of pMDI resin at the nozzle tip.

The maximum flow rate using ultrasonic atomization was relatively low, 0.7 mL/min for the sprayed pMDI resin, which provides a challenge for scale-up that needs to be further studied.

ACKNOWLEDGMENTS

The authors acknowledge the support of W.W. Henry Company and the Maine Agricultural and Forest Experiment Station McIntire-Stennis Project ME09615-03, and also thank Huntsman International LLC for providing pMDI resin used in this study. This is paper 2987 of the Maine Agricultural and Forest Experiment Station.

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