

MICROSPRAY

Ultrasonic Atomization for Bio-Oil-to-Syngas Conversion

25 kHz liquid-feed atomization, non-catalytic partial oxidation, and entrained-flow gasification

Colorado School of Mines and NREL demonstrated that a 25 kHz ultrasonic nozzle could deliver bio-oil/methanol feed as a fine mist into a heated reactor, enabling rapid mixing and high carbon-to-gas conversion.

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Abstract

Bio-oil and bio-crude are attractive renewable intermediates because they convert dispersed biomass into pumpable, energy-dense liquids that can be transported to centralized or distributed conversion systems. Their use in gasification, however, presents a difficult liquid-feed problem: these oxygenated, multicomponent liquids can be viscous, thermally unstable, and prone to polymerization, char formation, wall deposition, and incomplete vaporization. Atomization therefore becomes part of the reaction engineering—not merely a feed-delivery step.

A landmark Colorado School of Mines/NREL study addressed this problem by feeding poplar-derived bio-oil through a 25 kHz ultrasonic nozzle into a vertical quartz reactor for non-catalytic partial oxidation (NPOX). The published work used a 50:50 wt% bio-oil:methanol mixture for the principal experimental matrix and reported 85–95% carbon-to-gas conversion under favorable oxygen-to-carbon conditions, with substantial CO production and limited residual carbon. The associated Colorado School of Mines dissertation further documents why the 25 kHz nozzle was selected: a 120 kHz nozzle could not reliably feed neat bio-oil, whereas the 25 kHz device atomized progressively higher bio-oil fractions and could feed bio-oil without methanol addition at the highest tested power.

This white paper reviews that research, places it in the broader literature on bio-oil evaporation and entrained-flow gasification, and identifies the engineering variables that govern successful ultrasonic delivery of bio-oils and bio-crudes to high-temperature reactors.

Key Findings

- The 2009 peer-reviewed Colorado School of Mines/NREL study explicitly used a 25 kHz ultrasonic nozzle to disperse bio-oil/methanol feed as a fine mist at the reactor inlet.
- The dissertation reports that the 25 kHz nozzle could feed bio-oil with less methanol than a 120 kHz nozzle and could atomize neat bio-oil, although higher electrical power was required.
- At an effective O:C ratio of approximately 1.5–1.6, the study reported roughly 85–95% carbon-to-gas conversion and conservative bio-oil CO yields of about 50–65%.
- The same research found little clear benefit to operation above roughly 700 °C under its NPOX conditions; oxygen addition had a stronger effect on conversion than temperature.
- Independent peer-reviewed work shows that high heating rate and fine atomization can sharply reduce char formation during pyrolysis-oil evaporation.
- Current Colorado School of Mines MODES Lab research again identifies bio-crude gasification, atomization, and characterization as an active entrained-flow research area.

1. Why Bio-Oil Atomization Matters

Fast pyrolysis converts lignocellulosic biomass into a liquid commonly called bio-oil or pyrolysis oil. This liquid can be produced near the biomass source and transported more readily than untreated biomass, creating a pathway in which local pyrolysis is followed by gasification or reforming at a larger conversion facility. Bio-oil can then be converted to synthesis gas (syngas), principally H₂ and CO, for hydrogen, methanol, Fischer–Tropsch fuels, or other chemical synthesis routes.

The feed properties that make bio-oil difficult to handle are also the properties that make atomization important. Published reviews describe pyrolysis bio-oils as highly oxygenated, multicomponent liquids whose viscosity, water content, surface tension, chemical stability, and solids content can vary significantly with feedstock, pyrolysis conditions, storage, and aging. These factors influence pumping, ligament breakup, droplet formation, evaporation, and the tendency to form coke or char during heating [6,8].

Engineering consequence: in a gasifier or reformer, the atomizer controls initial interfacial area, droplet heating time, penetration, wall impingement, oxygen/steam contact, and the fraction of material that reaches the hot reaction zone as vapor, droplets, or nonvolatile aerosol.

2. Why Ultrasonic Atomization Is Different

Ultrasonic atomization creates droplets by imposing high-frequency mechanical vibration on a liquid film at an atomizing surface. Lang's classical work related the characteristic droplet diameter to the capillary wavelength generated by the excitation frequency [1]. Later work by Rajan and Pandit showed that frequency alone is not sufficient to predict real spray behavior; viscosity, surface tension, density, liquid flow rate, vibration amplitude, and active atomizing area also influence droplet formation [2].

For reactive liquid feeds, the practical advantage is that atomization energy is supplied at the vibrating surface rather than by forcing the liquid through a small high-pressure hydraulic orifice. Ultrasonic droplets also emerge at comparatively low momentum. For bio-oil service, this architecture can be useful where high viscosity, solids, or thermal sensitivity make conventional fine-orifice atomization difficult, provided the liquid can continuously wet and replenish the vibrating surface.

3. Process Architecture: From Bio-Oil to Syngas

Meter	Atomize	Entrained Heating	Partial Oxidation / Gasification	Syngas Conditioning
Controlled liquid feed	25 kHz acoustic breakup	Rapid heat and mass transfer	$\text{CO} + \text{H}_2 + \text{CO}_2 + \text{CH}_4$	Shift / reforming / cleanup

The key coupling is between atomization and thermal chemistry. A smaller, well-directed droplet field increases surface area and can shorten heating and evaporation times, but droplets that strike a relatively cool wall or remain in the polymerization temperature window may form carbonaceous deposits. Reactor geometry, shroud gas, nozzle location, feed composition, and residence time therefore have to be developed together.

4. Colorado School of Mines / NREL Case Study

Marda and co-workers at the Colorado School of Mines and the National Renewable Energy Laboratory developed a laboratory system for converting biomass-derived bio-oil to synthesis gas by non-catalytic partial oxidation [3]. The feedstock was a poplar-derived fast-pyrolysis oil containing approximately 48.2 wt% carbon, 7.2 wt% hydrogen, and 44.6 wt% oxygen, including about 17 wt% water. For the principal published experimental matrix, the bio-oil was blended 50:50 by weight with methanol to reduce viscosity and homogenize the feed.

The liquid was metered with a syringe pump and dispersed by a 25 kHz ultrasonic nozzle located at the top of a vertical quartz reactor. The authors specifically state that the fine mist was intended to improve mixing, heat transfer, and contact between the bio-oil/methanol feed and oxygen, including contact with nonvolatile components of the bio-oil [3].

Published Reactor and Feed-System Parameters

Parameter	Reported value	Engineering significance
Ultrasonic nozzle	25 kHz	Low-frequency atomization selected for viscous bio-oil feed
Pump capability	0.1–10 mL/min	Metered low-rate liquid delivery
Main feed composition	50:50 wt% bio-oil:methanol	Reduced viscosity and improved homogeneity
Reaction temperature	625–850 °C	NPOX temperature window
Effective O:C	0.7–1.6	Controls oxidation severity and conversion
Hot-zone length	~10 cm	Defines high-temperature reaction region

Parameter	Reported value	Engineering significance
Estimated hot-zone residence time	~0.3 s	Rapid conversion regime
Helium flow	400–550 sccm typical	Carrier/diluent and residence-time control
O ₂ flow	27.3–65.4 sccm	Adjusted to maximize CO and H ₂
Reactor	32 cm long; 1.1 cm nominal ID	Vertical quartz microreactor
Entrance region	2.0 cm ID for first ~10 cm	Reduced wall impingement and carbon plugging
Nozzle shroud gap	0.23 mm	Directed He/O ₂ around nozzle to keep spray centered

The enlarged entrance region is particularly revealing. The authors reported that nonvolatile material deposited on the wall could form a carbon plug, so the first 10 cm of the reactor was enlarged to reduce spray-wall interaction [3]. This is a direct example of how injector design and spray trajectory affect reactor operability.

5. Why the 25 kHz Nozzle Was Selected

The associated Colorado School of Mines doctoral dissertation provides a deeper view of the atomizer-development sequence [4]. A 120 kHz ultrasonic nozzle was evaluated first. The thesis reports that it was not suitable for feeding bio-oil without at least 50% methanol. Samples were then evaluated with a 25 kHz nozzle, which successfully atomized bio-oil without methanol.

Bio-oil : methanol	25 kHz reported power	Observation
50:50	2.9–3.4 W	Efficient atomization
70:30	5.0–5.5 W	Higher power required
90:10	8.2–8.3 W	High bio-oil fraction remained atomizable
100:0	12.9–15.0 W	Neat bio-oil atomized at the upper end of the rated power range

The dissertation further states that the 25 kHz nozzle produced more efficient atomization than the 120 kHz unit even for the 50:50 mixture [4]. This does not mean that lower frequency universally produces a 'better' spray. Higher-frequency ultrasonic atomization generally shifts the capillary-wave scale toward smaller characteristic droplets, while viscous-feed capability also depends on amplitude, available acoustic power, liquid-film behavior, surface area, and rheology [1,2]. In this case, the 25 kHz configuration provided the acoustic authority needed to handle a much more viscous feed.

Historical attribution note. The 2009 publication identifies the atomizer as a Sono-Tek 25 kHz ultrasonic nozzle. MicroSpray identifies this 25 kHz nozzle as part of the technology lineage associated with its present ultrasonic atomization work. For technical accuracy, the original publication should continue to be cited using the manufacturer attribution reported by the authors.

6. Syngas and Conversion Results

The most important reaction result was that oxygen addition had a stronger influence on conversion than temperature across much of the studied NPOX window. At lower oxygen-to-carbon ratios, temperature strongly affected conversion; at higher effective O:C, partial-oxidation chemistry dominated and temperature dependence became weaker [3].

Performance metric	Reported result	Interpretation
Carbon-to-gas conversion	85–95% at effective O:C ~1.5–1.6	Strong gasification of bio-oil carbon

Performance metric	Reported result	Interpretation
Bio-oil CO yield	At least ~50–65%; alternate estimate ~70–80%	High non-catalytic CO production
H ₂ yield	Maximum ~25%	Additional H ₂ available through downstream shift/reforming
Estimated bio-oil CO ₂ yield	~8–13% under favorable conditions	Partial oxidation did not simply drive all carbon to CO ₂
CH ₄ yield	~8% under favorable conditions	Minor permanent-carbon product
Residual carbon	Typically ~5–7% maximum bio-oil yield	Deposit formation remained important but limited
Benzene	Typically ~2–2.5% maximum bio-oil yield	Aromatic byproduct remained measurable

The authors concluded that there was no clear advantage to temperatures above roughly 700 °C in their reactor, except a possible increase in hydrogen yield at 850 °C, and they observed indications that higher temperature could increase undesirable residual carbon and perhaps benzene. This is an important design point: the objective is not simply maximum temperature, but a coupled window of atomization, oxygen addition, heating rate, residence time, and downstream chemistry [3].

7. Atomization, Heating Rate, and Char Formation

Independent work by van Rossum and co-workers helps explain why fine liquid dispersion matters. In peer-reviewed AIChE Journal experiments, pyrolysis oil was subjected to heating rates ranging from slow thermal analysis to very rapid atomized heating. At approximately 10⁶ °C/min, char formation was reduced to about 8% on a carbon basis, compared with approximately 30% under slow TGA heating. The authors attributed much of the char formation to polymerization reactions occurring while the liquid passed through approximately 100–350 °C [5].

The practical implication for an entrained-flow reactor is that atomization can change the thermal history of the liquid. Increasing interfacial area and rapidly transferring heat into small droplets can shorten the time spent in the temperature range where polymerization competes with vaporization. Conversely, large droplets, poor spray distribution, or wall wetting can create slower-heating liquid films and favor carbonaceous residue.

8. Entrained-Flow Gasification and the Colorado School of Mines Research Platform

Colorado School of Mines subsequently developed a high-temperature, high-pressure entrained-flow laboratory gasifier. Kelley, Jakulewicz, Dreyer, Parker, and Porter reported a system capable of operation up to 1650 °C and 40 bar, with a 50 mm internal diameter and a 1 m heated section [7]. Although the 2015 characterization work focused on solid feedstocks, the platform established the institution's broader capability in entrained-flow reaction engineering.

The current Mines MODES Lab now lists 'Entrained-flow gasification of bio crude: atomization and characterization' as an active research project and identifies Stewart Grimshaw and Eric Hay with the bio-crude gasification program [9,10]. That continuity is significant: atomization remains an explicit research problem in modern bio-crude gasification, not a solved ancillary detail.

9. Why Atomization Remains a Central Research Problem

A 2019 peer-reviewed review of bio-oil gasification emphasized atomization and entrained-flow gasifiers as central technical topics for scale-up [6]. A 2026 Energy & Fuels review likewise describes bio-oil atomization as unusually challenging because high viscosity, surface tension, thermal instability, water content, and multicomponent evaporation all interact during spray formation and heating [8].

- Viscosity controls liquid-film replenishment, ligament breakup, and the acoustic power required to maintain atomization.

- Surface tension and density influence capillary-wave breakup and characteristic droplet size.
- Water and light oxygenates may evaporate preferentially, changing droplet composition during flight.
- High-boiling and lignin-derived fractions can remain as nonvolatile aerosol or char-forming residue.
- Wall impingement creates a fundamentally different thermal history from free-flight droplets.
- Carrier-gas velocity and injector geometry influence spray penetration, residence time, mixing, and reactor-wall loading.
- Feed aging can increase viscosity and alter phase stability, meaning the atomizer must tolerate batch-to-batch and time-dependent variability.

10. Engineering Implications for MicroSpray Systems

The literature supports a process-development strategy in which the ultrasonic nozzle is treated as the first stage of the reactor rather than as a stand-alone spray component. For modern bio-oil and hydrothermal-liquefaction bio-crude work, a useful development program should quantify both spray behavior and chemical conversion.

Recommended Development Variables

Variable	Why it matters	Recommended measurement
Ultrasonic frequency and power	Sets atomization regime and viscous-feed capability	Stable atomization threshold; electrical power
Liquid flow rate	Controls film loading at the atomizing surface and reactor fuel rate	Gravimetric or calibrated volumetric flow
Feed temperature	Reduces viscosity but can accelerate aging/polymerization	Viscosity vs. temperature; stability time
Diluent / co-solvent fraction	Changes viscosity, surface tension, volatility, and chemistry	Rheology, phase stability, carbon balance
Droplet distribution	Controls heating rate, vaporization, and penetration	Laser diffraction / phase Doppler where practical
Carrier/shroud gas	Controls plume direction and mixing	Gas flow, momentum ratio, spray angle
Wall clearance	Determines impingement and deposit risk	Deposit mapping / run-time pressure drop
Reactor temperature	Controls cracking, oxidation, gasification, and aromatic formation	Axial temperature profile
O:C and steam:C	Controls syngas yield, conversion, and carbon deposition	Mass-flow-controlled gas ratios
Residence time	Controls completion of gas-phase chemistry	Tracer/flow model and reactor pressure
Product gas	Defines process value	GC/MBMS: H ₂ , CO, CO ₂ , CH ₄ , light hydrocarbons
Solid carbon / tar	Primary operability and efficiency penalty	Gravimetric deposits, tar collection, carbon balance

11. Practical Design Rules

- Select frequency and available acoustic power for the actual feed rheology, not for water. The Mines dissertation is a clear example: the 25 kHz system handled substantially higher bio-oil fractions than the 120 kHz system.
- Keep the spray centered and away from relatively cool walls. The Mines reactor enlarged the inlet specifically to reduce wall deposition and carbon plugging.
- Minimize the time that droplets or wall films spend in intermediate-temperature polymerization regimes. Rapid heating is associated with lower char formation in pyrolysis-oil evaporation studies.
- Do not assume that the smallest possible droplet is automatically optimal. Reactor penetration, evaporation before the reaction zone, carrier-gas entrainment, and wall contact must all be considered.

- Treat feed conditioning as part of the atomization problem. Methanol, water, temperature, or other conditioning steps can alter viscosity and atomization, but they also change reaction stoichiometry and downstream product distribution.
- Close the mass and carbon balance. Spray appearance alone cannot establish successful gasification; gas composition, carbon-to-gas conversion, deposited carbon, and unconverted organics must be measured.

12. Applications Beyond the Original Study

The same atomization principles can be relevant to a broader range of thermochemical feeds, including fast-pyrolysis oils, hydrothermal-liquefaction bio-crudes, bio-oil/char slurries, waste-derived oxygenated liquids, renewable refinery intermediates, and model-compound studies used to isolate reaction chemistry. The optimum ultrasonic frequency, tip geometry, liquid preconditioning, and gas-assist architecture will depend on the feed and reactor.

Potential syngas end uses include hydrogen production, methanol synthesis, Fischer–Tropsch fuels, sustainable aviation fuel intermediates, ammonia production, and other CO/H₂-based chemical synthesis routes.

13. Conclusions

The Colorado School of Mines/NREL work provides unusually direct evidence that ultrasonic atomization can solve a real feed problem in bio-oil conversion. A 25 kHz ultrasonic nozzle was not used merely to make a visually fine mist; it was integrated into the reactor to improve mixing, heat transfer, oxygen contact, and delivery of nonvolatile bio-oil components. The resulting NPOX experiments achieved high carbon-to-gas conversion and substantial CO yield at sub-second residence time.

The deeper lesson is that bio-oil gasification begins at the injector. Droplet formation determines thermal history. Thermal history influences evaporation, polymerization, char formation, mixing, and reaction. Reactor geometry determines whether the spray remains an entrained droplet field or becomes a wall film. For that reason, ultrasonic frequency, acoustic power, feed rheology, carrier gas, wall clearance, oxygen/steam ratio, and residence time should be developed as one coupled system.

MicroSpray Process Development

MicroSpray develops ultrasonic liquid-delivery and atomization approaches for low-flow, difficult-to-atomize, and high-temperature process applications. Development can include feed characterization, nozzle-frequency screening, air shaping, controlled metering, heated-reactor integration, and scale-up from feasibility testing to automated systems.

No flow too low. No film too thin. No feed problem treated in isolation.

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