# Development of converging-diverging multi-jet nozzles for molten smelt shattering in kraft recovery boilers

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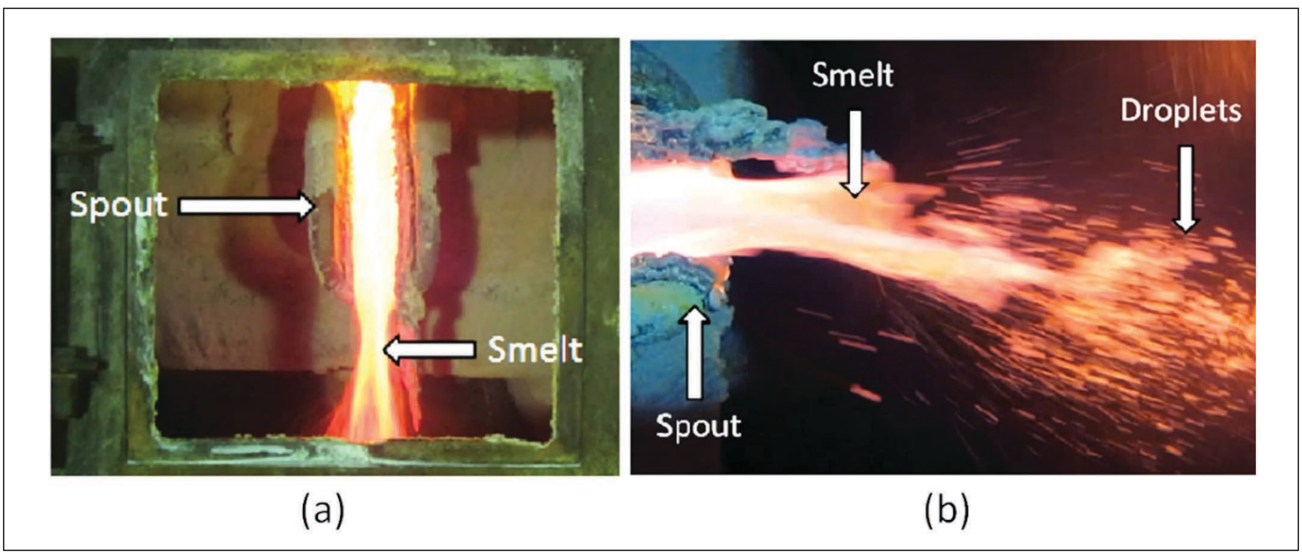
**ABSTRACT:** The effective shattering of molten smelt is highly desired in recovery boiler systems. Ideally, shatter jet nozzle designs should: i) generate high shattering energy; ii) create a wide coverage; and iii) minimize steam consumption.

This study proposes a novel converging-diverging multi-jet nozzle design to achieve these goals. A laboratory setup was established, and the nozzle performance was evaluated by generating jet pressure profiles from the measurement of a pitot tube array. The results show that the shatter jet strength is greater with a large throat diameter, high inlet pressure, and a short distance between the nozzle exit and impingement position. Increasing the number of orifices generates a wider jet coverage, and the distance between the orifices should be limited to avoid the formation of a low-pressure region between the orifices. The study also demonstrates that an optimized converging-diverging multi-jet nozzle significantly outperformed a conventional shatter jet nozzle by achieving higher energy and wider coverage while consuming less steam.

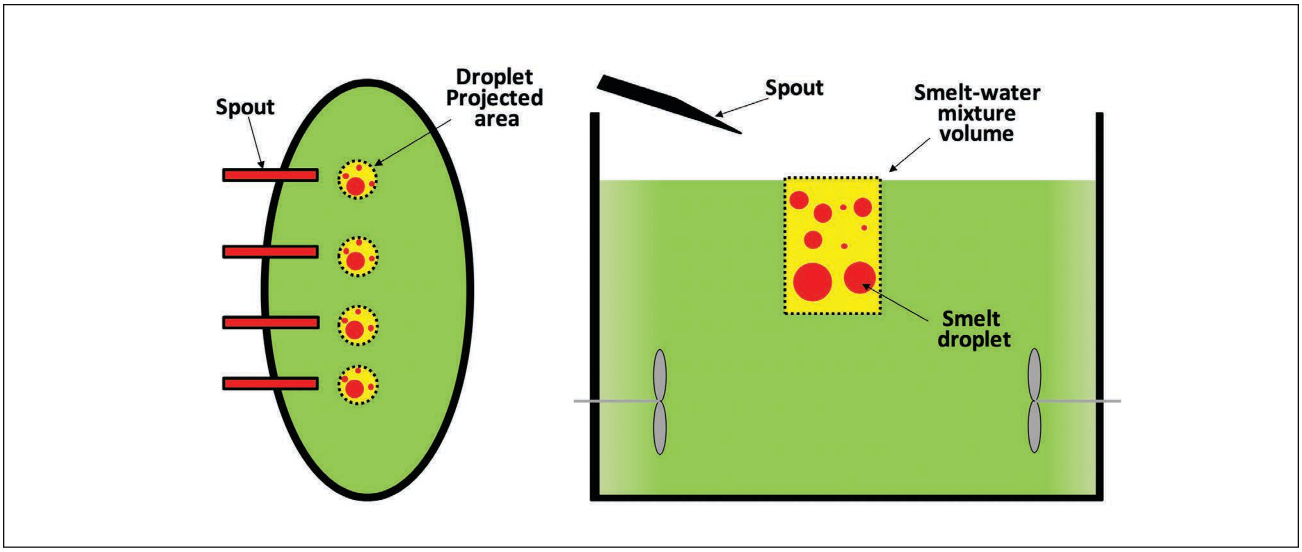
***Application:*** This paper showed the development of a shatter jet nozzle design that achieves better performance than traditional jets achieve. Readers can refer to this paper to understand the development process and theories behind the design. The data also allows future work to be conducted to further optimize the product.

In kraft pulp mills, black liquor is burned in a recovery boiler to recover the spent pulping chemicals and to produce steam for use in various processes and to generate power. The combustion results in the formation of a molten smelt pool at the bottom of the boiler that consists of mostly sodium carbonate ($Na_2CO_3$) and sodium sulfide ($Na_2S$). Molten smelt with a density of about 2000 kg/m$^3$ and surface tension of 0.21 N/m continuously flows out of the boiler at 780°C to 830°C (1440°F to 1530°F) through several spouts at a flow rate of about 1 L/s per spout. Each smelt stream is broken up by a steam shatter jet into small droplets of a few millimeters [1,2].

**Figure 1** shows a top view (a) and a side view (b) of a molten smelt stream being shattered by a steam jet as it pours out of a smelt spout. The shattered smelt droplets fall into the dissolving tank below where they dissolve in the weak wash (water recycled from the causticizing plant) to form green liquor. The interaction between molten smelt




***1. Smelt flowing down a spout into dissolving tank: (a) top view, and (b) side view.***




***2. Schematic of smelt droplet movement in green liquor: (a) tank top view, and (b) tank side view.***

and green liquor can be loud and often violent. In extreme cases, it causes dissolving tank explosions that result in equipment damages, personnel injuries, and costly boiler shutdowns [3]. As regulations on occupational health and safety have become increasingly stringent in recent years, effective and safe dissolving tank operation is a top priority in pulp mill operation.

Numerous projects have been conducted at the University of Toronto on dissolving tank safety over the past decade. These include a smelt shattering study in a laboratory setting using compressed air to simulate steam shatter jet and water-glycerin fluid mixtures to simulate molten smelt [1,3]. The distribution of the resulting droplets was examined as a function of nozzle geometries, fluid flowrate, air flowrate, the distance between nozzle and fluid, angle of impingement, and fluid viscosity. Another laboratory study investigated the explosion probability of a molten smelt droplet in water under various conditions using a high-speed video camera [4,5,6]. The results showed that molten smelt droplets often do not explode immediately when they meet water, but rather, remain stable in water for a few seconds before they explode. The explosion of one droplet may also trigger the explosions of other droplets nearby, leading to a chain of multi-droplet explosions. These findings imply that: 1) droplet-scale or "mini" smelt-water explosions are needed for effective smelt dissolution in the dissolving tank, and 2) large-scale explosions caused by either one large piece of molten smelt or many small droplets in a small confined area can be violent and must be avoided.

**Figure 2** schematically shows the interaction between smelt and water in the dissolving tank from top and side views. The distribution of smelt droplets and the projected area into which the droplets continuously fall are greatly affected by smelt shattering. As the droplets reach and continue to sink in the liquor, they form a cylindrical volume of smelt-green liquor mixture (rectangular box in Fig. 2). The worst-case scenario occurs when all the smelt droplets within the boundary of the control volume explode at the same time.

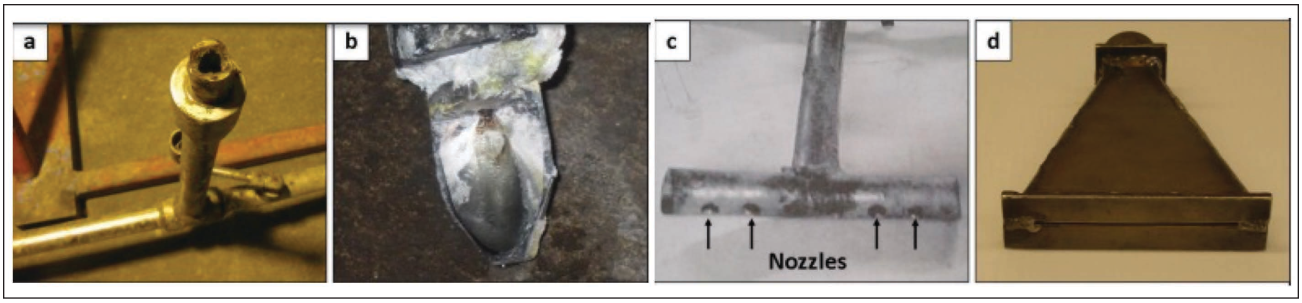
A thermodynamic model, based on Hicks-Menzies principles [7], was recently developed to calculate the energy released by a large smelt-water interaction in the dissolving tank [8]. The results showed that the conversion ratio *CR*, which is the ratio of the total explosion energy to the available thermal energy stored in the smelt, increases with increasing green liquor temperature and green liquor-to-smelt volume ratio. This implies that to reduce the probability of a dissolving tank explosion, the shatter jet design needs to be optimized so that molten smelt droplets can be uniformly distributed over a large area on the green liquor.

This paper discusses the design principles of shatter jet nozzles and the results of a bench-scale experimental study conducted to evaluate the performance of a novel converging-diverging multi-jet nozzle design.

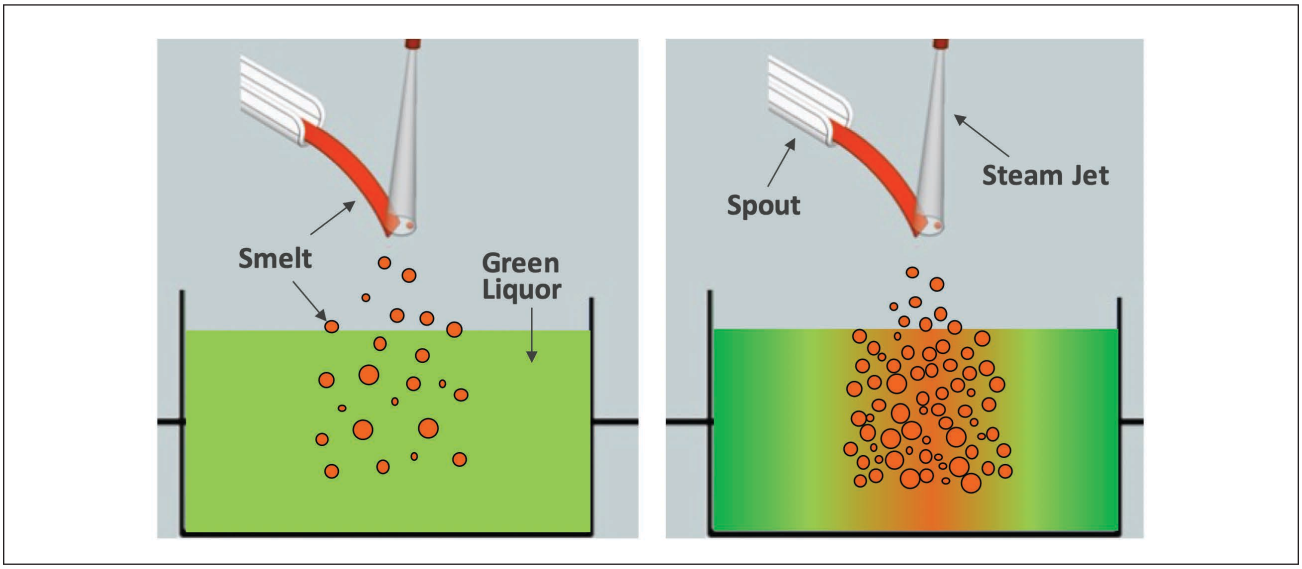
## SHATTER JET NOZZLE DESIGN PRINCIPLES

Smelt shatter jet designs and shattering practices vary widely from mill to mill with no clear guidelines in the industry for nozzle design, configuration, and operation [9]. Shatter jets, typically with saturated steam of 3.5 to 15.5 bar (50 to 225 psig) and 150°C to 250°C (300°F to 480°F), are directed vertically downward or slightly against the direction of smelt flow. There are various types of nozzles including round-profile nozzles, multi-hole nozzles, and slit profile nozzles (**Fig. 3**), and there is no consensus on which type of nozzle is best. Some mills even use an open pipe as a shatter jet.

Dissolving tank operation upsets often occur when the smelt flow exceeds the capacity of shatter jets. These include smelt runoffs (a sudden increase in smelt flow) [10]



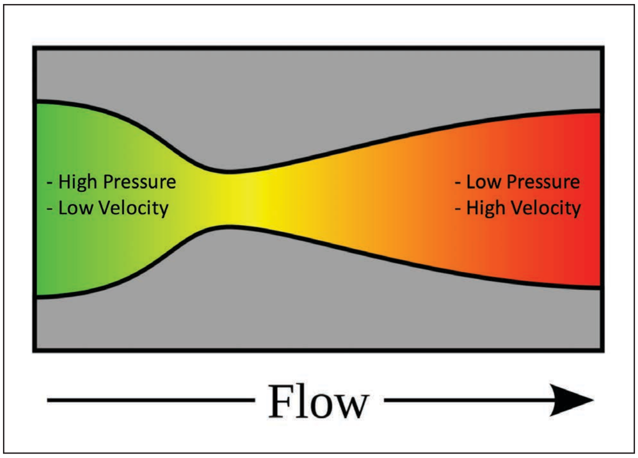

***3. Examples of shatter jet nozzles used by mills: (a) full cone, (b) flat with a guard, (c) multi-hole, and (d) slit.***




***4. Smelt-water interaction schematics during a smelt runoff.***

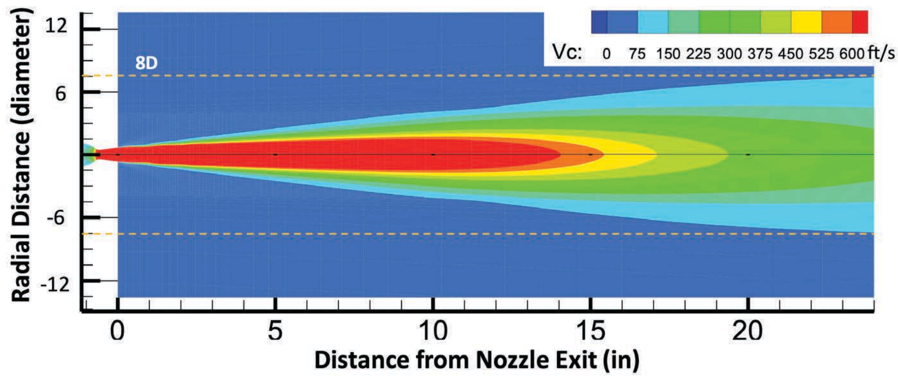
and “jellyroll” smelt. Jellyroll smelt can be caused by either sudden freezing of molten smelt, fallen deposits, or inclusion of a large amount of unburned char [11]. This slow-moving viscous smelt makes smelt more difficult to shatter, and when it is removed, the surge of molten smelt behind it can lead to a runoff situation. When this occurs, the smelt flow overwhelms the capacity of the smelt shatter jet, making it ineffective. As a result, the molten smelt becomes concentrated in an area directly below the spout, increasing the explosion energy, as shown in **Fig. 4**.

According to previous modeling of the smelt-water explosion energy [7], the energy conversion ratio *CR* is a function of the diameter of the projected area, and shatter jet design needs to be optimized so that molten smelt droplets can be uniformly distributed over a large area on the green liquor. This requires a shatter jet to have sufficient shattering energy to handle both normal smelt flow and upset conditions. Also, in some cases, the jet may miss a portion of or all the smelt flow due to a change in smelt flow characteristics. Avoiding this requires a shatter jet to have wide coverage. Finally, while smelt shattering should attain optimum droplet distribution, steam consumption should be minimized to reduce operating cost. Thus, ideal shatter jet nozzle designs should: i) generate high shattering energy, ii) create a wide coverage, and iii) minimize steam consumption.

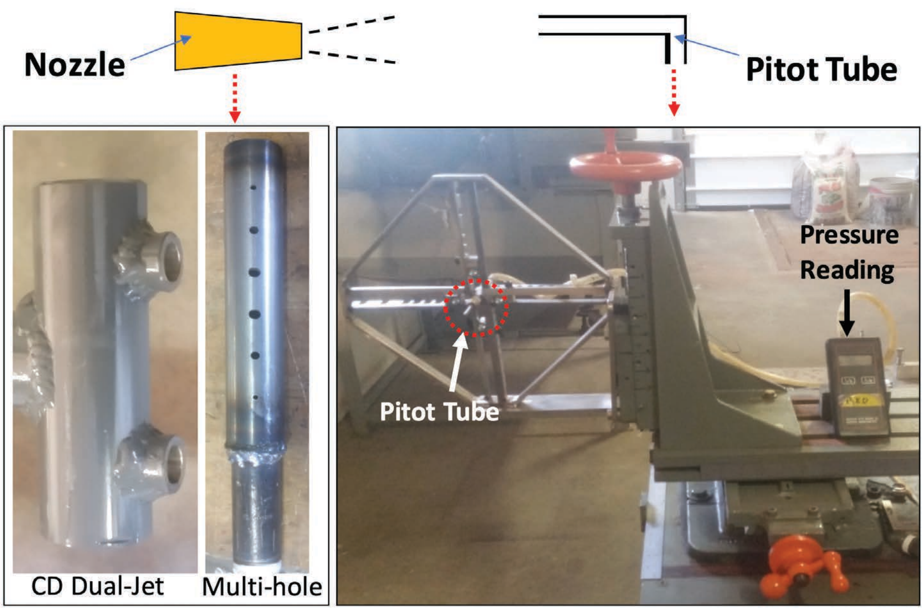



***5. Converging-diverging nozzle sketch.***

To improve shatter jet strength while minimizing steam consumption, a converging-diverging (CD) nozzle design can be used. The CD nozzle design is shown conceptually in **Fig. 5** and has been widely used in sootblower applications in recovery boilers. While the fluid dynamics in the nozzle are complex, the design allows the steam flow to




***6. Velocity contour of a converging-diverging shatter jet nozzle at 150 psig inlet pressure.***




***7. Shatter jet nozzle pressure profile measurement apparatus (left) and multi-hole jet nozzle (right).***

reach sonic velocity at the throat and higher at the exit. Design factors, including outlet diameter, throat diameter, expansion angle, and nozzle length, enable customization of the nozzle for use in various standard and non-standard recovery boiler designs. A CD nozzle with a proper throat-to-exit area ratio can attain higher impact pressure with the given steam flow than a cylindrical hole nozzle due to its more effective jet expansion, or it can achieve the same strength with less steam consumption. The flow rate of a nozzle can be calculated by:

$$m = C_d A \sqrt{\gamma \rho_o P_o (\frac{2}{\gamma + 1})^{\frac{\gamma+1}{\gamma-1}}}$$

where $m$ is the mass flow rate, $C_d$ is the discharge coefficient, $A$ is the cross-sectional area of the choke point, $\gamma$ is the heat capacity ratio of steam, and $\rho_o$ is the density at the inlet pressure $P_o$ and temperature.

To achieve wide coverage, multiple orifices can be placed adjacent to each other to attain a wider pressure profile. The spacing between the adjacent jet needs to be optimized: spacing that is too small would not achieve the desired coverage, while spacing that is too large may result in a low-pressure region between the orifices. **Figure 6** illustrates the velocity contours of a single jet developed from a CD nozzle with an inlet steam pressure of 10.3 bar (150 psig) based on two-dimensional asymmetric computational fluid dynamics modeling. The result shows that, for this jet, the optimum spacing between adjacent orifices should not exceed 8D (a distance that is equal to eight orifice diameters); otherwise, a low-pressure region will form in the middle.

Thus, a converging-diverging multi-jet nozzle design can generate a jet with both strength and coverage while minimizing steam consumption. While computational fluid dynamics modeling is a powerful tool, modeling of two adjacent jets requires a three-dimensional domain, and resolving the jet expansion in the supersonic regions requires special modeling techniques and specialized codes. Therefore, multi-jet nozzle performance was experimentally evaluated.

## LABORATORY PERFORMANCE TESTING

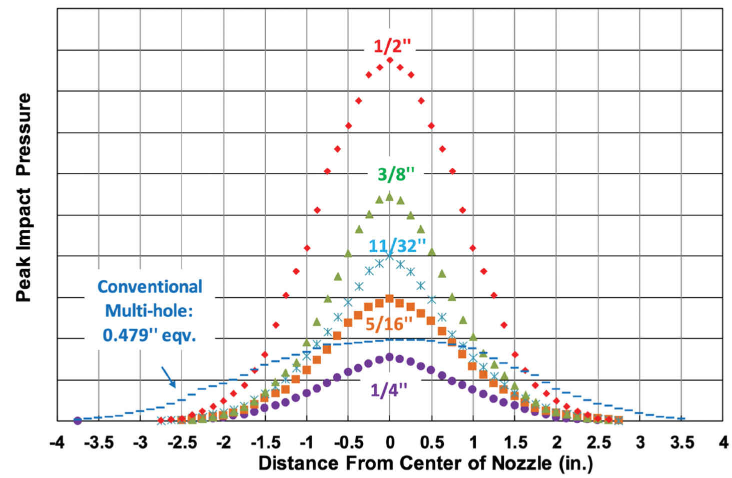
To evaluate the performance of the CD multi-jet nozzles, various design parameters were examined, while a conventional multi-hole (non-CD) nozzle was also tested for performance comparison. A summary of the experimental conditions is listed in **Table I**.

The experimental setup used in this study is shown in **Fig. 7**. Compressed air was used in the experiments to simulate steam. A pitot tube array was placed in front of the nozzle being tested to measure the jet peak impact pressure, which is an indication of shatter jet strength. The position of the pitot tube could be adjusted in the x-, y-, and z-directions. Variation of the x- and y- position generates a jet pressure profile, and the varying z-position changes the distance between the nozzle and the pitot tube.

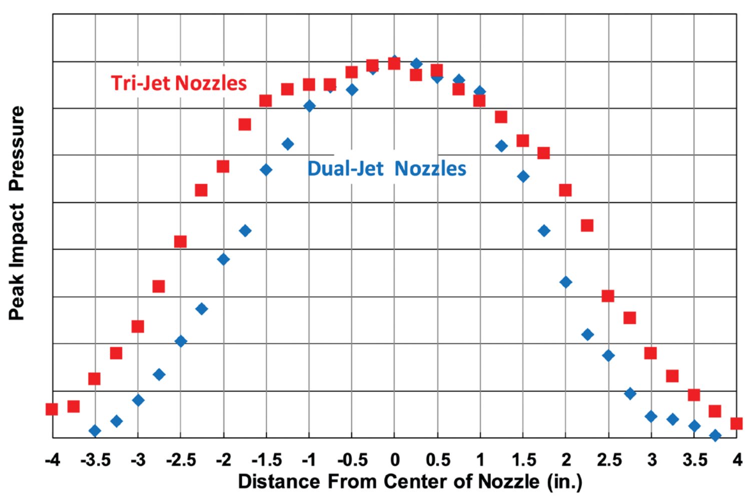
| Parameter | Condition |
|---|---|
| Nozzle throat diameter | 6.35 to 12.7 mm (1/4 to 1/2 in.) |
| Number of orifices | 1 to 3 |
| Spacing between orifices | 8D and 16D |
| Inlet pressure | 6.9 to 10.3 bar (100 to 150 psig) |
| Distance between nozzle and pitot tube | 508 to 610 mm (20 and 24 in.) |

*I. Experimental conditions for the evaluation of CD nozzle performance.*

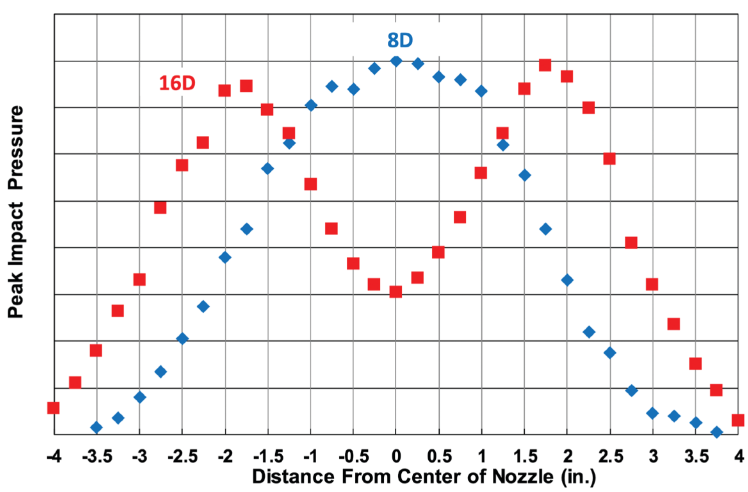
**Figure 8** shows the nozzle performance of five CD



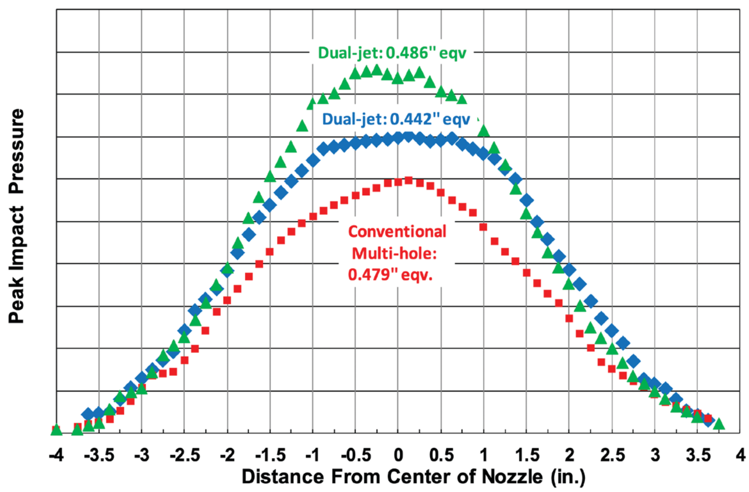

*8. Shatter jet pressure profile with different orifice sizes (distance: 20 in.; pressure: 150 psig).*




*9. Shatter jet pressure profile with a different number of orifices (distance: 20 in.; pressure: 150 psig).*




***10. Dual-jet nozzle pressure profile with different orifice spacings (distance: 20 in.; pressure: 150 psig).***



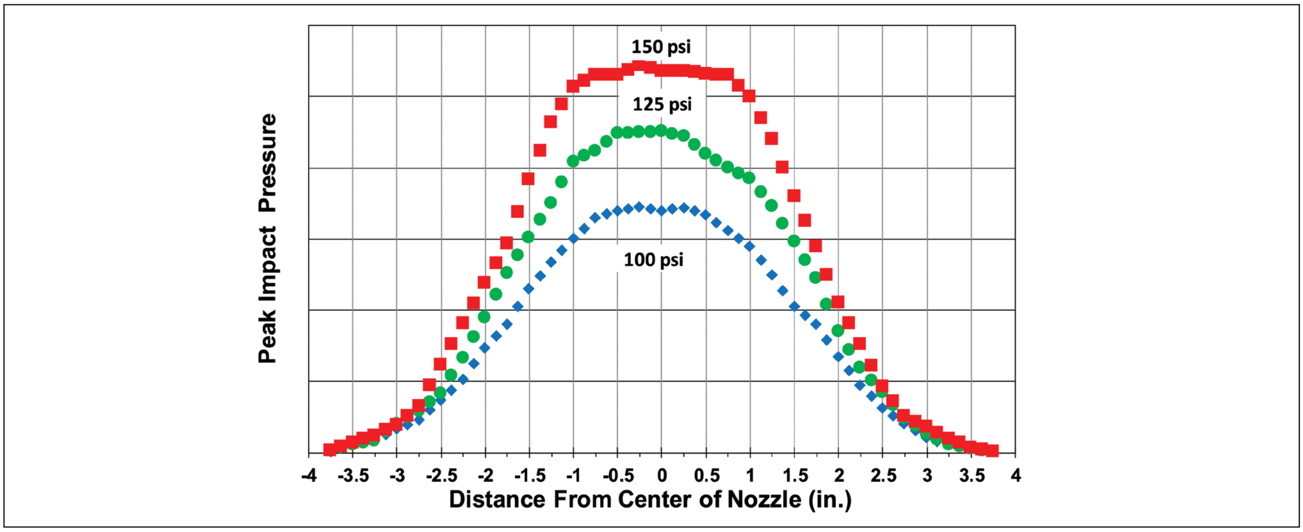

***11. Comparison of the jet pressure profiles from optimized nozzles and the conventional nozzle (distance: 24 in.; pressure: 150 psig).***

single-jet nozzles with different throat diameters: 1/4 in., 5/16 in., 11/32 in., 3/8 in., and 1/2 in. The results show that in general, a larger orifice size resulted in a higher jet strength. The conventional multi-hole nozzle used as a reference has an equivalent orifice diameter of 0.48 in. calculated based on the total open area, which is slightly smaller than the largest CD nozzle of 1/2 in. It generates a wider coverage than a CD single-jet nozzle due to the larger number of orifices, but the strength is significantly less than that of a CD nozzle with a similar orifice size.

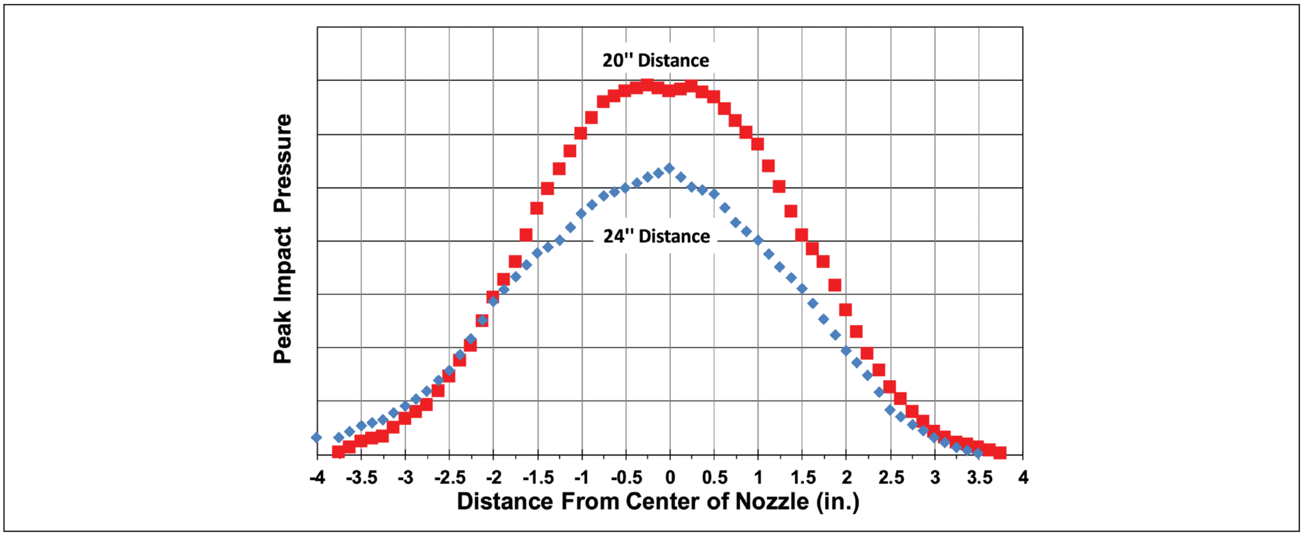
The effect of the number of nozzles and spacing between the CD orifices was also investigated. **Figure 9** shows the pressure profile for a dual-jet nozzle and a tri-jet nozzle, and **Figure 10** shows the pressure profile for a dual-jet nozzle with different spacings between the orifices: 8D (eight diameters) and 16D. The results show that increasing the number of nozzles generates a wider pressure profile with similar peak impact pressure at the centerline. When the orifices are placed too far apart, a low-pressure region in the middle is formed, which reduces the effectiveness of the shatter jet.

**Figure 11** presents the pressure profile of two CD dual-jet nozzles with the same orifice spacing but different throat sizes along with that of the conventional multi-hole shatter jet nozzle for comparison. The result demonstrates that the converging-diverging multi-jet nozzle can outperform a conventional shatter jet nozzle by achieving higher energy and wider coverage while consuming less steam.

The inlet pressure and distance between the smelt stream and shatter jet can also affect the performance of a shatter jet. **Figure 12** compares the performance of CD dual-jet nozzles with different inlet pressure, and **Figure 13** compares that with different distances from the pitot tube. The results show that the increase in pressure and decrease in distances leads to a higher jet strength and wider coverage.




*12. Shatter jet pressure profile at different steam pressures (distance: 24 in.).*



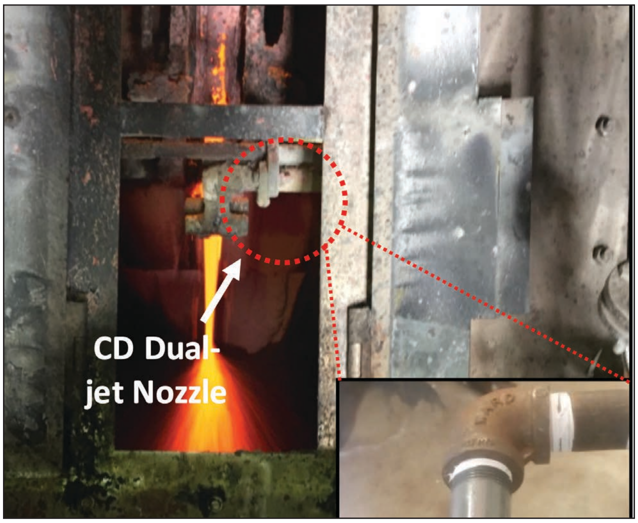

*13. Shatter jet pressure profile at different distances to the pitot tube (pressure: 100 psig).*

## FIELD INSTALLATION

Optimized shatter jet design can improve smelt shattering effectiveness and the safety of dissolving tank operation. At the time of this paper, CD dual-jet nozzles have been installed in two mills, one in December 2019, the other in February 2020. A third installation is scheduled for May 2021. **Figure 14** illustrates a typical installation of two CD dual-jet nozzles (one as a backup) in front of each spout.

## SUMMARY

Smelt-water explosions in dissolving tanks are of great safety concern in kraft pulp mills. Previous studies on dissolving tank safety suggested that to reduce the chance of a dissolving tank explosion, the shatter jet design should be optimized to uniformly distribute the smelt over a large area in the dissolving tank. Smelt shatter jet designs vary widely from mill to mill with no clear guidelines in the industry.




*14. Field installation of the CD dual-jet nozzle.*

Ideally, shatter jet nozzle designs should: i) generate high shattering energy; ii) create a wide coverage so that it would not miss a portion or all the smelt flow; and iii) minimize steam consumption and reduce cost. This study proposes a converging-diverging multi-jet nozzle design to achieve these goals.

The nozzle performance was evaluated by generating jet pressure profiles from the measurement of a pitot tube array in the laboratory. The nozzle throat diameter, number of orifices, spacing between orifices, inlet pressure, and distance between the nozzle and pitot tube were varied. The results showed that the shatter jet strength is greater with a large throat diameter, high inlet pressure, and a short distance between the nozzle exit and impingement position. Increasing the number of orifices generates a wider jet coverage, and the distance between the orifices should be limited to avoid the formation of a low-pressure region between the orifices. This study also demonstrated that an optimized converging-diverging multi-jet nozzle significantly outperforms a conventional shatter jet nozzle by achieving higher energy and wider coverage while consuming less steam. The converging-diverging multi-jet nozzle design has been implemented in two mills while a third installation is expected in 2021. **TJ**

### ABOUT THIS PAPER

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### ABOUT THE AUTHORS

Shatter jet nozzle design is of great importance in effective and safe dissolving tank operation. This study built upon the conclusions of the previous smelt-water explosion energy modeling work that the author (Jin) conducted at Babcock and Wilcox.

The most difficult aspect of the research was to combine knowledge from modeling theories with experimental results. It was interesting to see how incremental research eventually can create new technology that is of great value to the industry, and it is exciting to see a real product developed and commercialized based on such research.

The developed product is superior to the typical shatter jets currently used in the industry, and mills can achieve better dissolving tank performance and safety with these converging-diverging shatter jet nozzles. The next step is to inform the industry and encourage more mills to implement the converging-diverging multi-jet nozzle.

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