

Modeling of the energy of a smelt-water explosion in the recovery boiler dissolving tank

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ABSTRACT: The explosion energy generated as molten smelt droplets interact with water was evaluated as a function of smelt distribution, water temperature, and smelt temperature using a thermodynamic model. The results show that increasing smelt-to-water volume ratio and water temperature significantly increases the explosion energy, converting a larger proportion of the thermal energy of smelt into mechanical work. To reduce the chance of violent smelt-water explosions, it is important to: i) optimize the shatter jet design and operation to uniformly distribute the smelt over a large area in the dissolving tank; ii) avoid high green liquor temperature and ensure adequate liquor mixing; and iii) avoid upsets that may cause heavy smelt runoff or jellyroll smelt.

Application: This paper on the modeling of smelt-water explosion energy helps mills improve their understanding and practices of dissolving tank operation to ensure tank safety.

In kraft pulp mills, black liquor is burned in a recovery boiler to recover the spent pulping chemicals and to produce steam and power for use in various processes. The combustion leads to the formation of a pool of molten smelt at the bottom of the boiler, which consists of mostly sodium carbonate (Na_2CO_3) and sodium sulfide (Na_2S). Molten smelt flows out of the boiler at about 800°C through smelt spouts. The smelt streams are shattered by steam jets into droplets, which fall into the dissolving tank and dissolve in weak wash, process water with a low concentration of sodium hydroxide (NaOH), to form green liquor. The green liquor is subsequently sent to a causticizing plant to convert Na_2CO_3 into NaOH for reuse in the pulping process.

The interaction between smelt droplets and green liquor often causes the dissolving tank to rumble and vibrate, and at times, cause excessive noise and shaking of the ground and buildings nearby. In extreme cases, a catastrophic dissolving tank explosion may occur, resulting in property damage, personnel injury, and costly boiler shutdowns [1]. Since the interaction of smelt and green liquor cannot be seen from outside of the tank, boiler operators often rely on the noise level and tank vibration to determine actions. They may, for example, clean the clogged smelt spouts and/or adjust the shatter jets when the tank becomes too violent. This can be challenging, because dissolving tank design and operation are often less standardized compared to other recovery boiler systems.

Smelt-water explosion is a physical phenomenon known as vapor explosion that occurs when a “hot” liquid interacts with a “cold and more volatile” liquid [2-4]. The interaction

between molten smelt and water in the dissolving tank can result in a high heat transfer rate and rapid water vaporization. The instant volume expansion of the water vapor can then cause mechanical damage to the surroundings. Similar phenomena are known to occur in nuclear and metal industries, transportation of liquefied natural gas, domestic cooking, and underwater volcanic eruptions [4-7]. Research on vapor explosion, however, has mostly been conducted in the nuclear industry due to the catastrophic consequences of a nuclear reactor vessel failure.

In the pulp and paper industry, smelt-water explosion research was performed mostly between the 1960s and 1980s due to large recovery boiler explosion accidents caused by tube leaks in the furnace that sprayed water into the molten smelt pool. The fundamental principle of smelt-green liquor interaction in the dissolving tank is the same as smelt-water interaction in the recovery boiler, but only two studies were conducted in the mid-1950s in the context of dissolving tank explosion [8,9]. These smelt-water explosion studies were reviewed by Krause et al in 1973 [10], and by Shick and Grace in 1982 [2]. Improved understanding of smelt-water explosion and safe operation practices in the recovery boiler spearheaded by the Black Liquor Recovery Boiler Advisory Committee (BLRBAC) and the American Forest & Paper Association (AF&PA) Recovery Boiler Committee have, over the years, significantly reduced the frequency of recovery boiler explosions. Dissolving tank explosions, however, continue to occur [11].

As part of a research program at the University of Toronto on dissolving tank safety, a laboratory study investigated the interaction between a single smelt droplet and

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water under various conditions [12-14]. The behavior of molten smelt droplets when they contact water was documented using a high-speed video camera coupled with a high-quality microphone and a vibrometer. The time starting from the moment a molten droplet contacts the water surface to the moment it explodes was defined as explosion *delay time*. The results showed that both the explosion probability and delay time were a strong function of water temperature. Smelt droplets exploded immediately upon contact with water below 60°C, exploded after a short delay of a few seconds in water between 60°C and 80°C, and did not explode when water was close to boiling. Exploded droplets dissolved in water instantly, whereas unexploded droplets froze and took much longer to dissolve. There was also clear evidence that as one droplet exploded, it quickly triggered the explosion of other droplets nearby, leading to a multi-droplet explosion. These results imply that droplet-scale, or “mini”, smelt-water explosions are required for effective smelt dissolution in the dissolving tank, but an explosion of a large amount of molten smelt that involves hundreds of thousands of small droplets can be violent and dangerous, and so should be avoided.

The present study extends the existing knowledge of droplet-scale smelt-water explosions to that of multi-droplet explosions. The explosion energy of molten smelt-water interaction in the dissolving tank is estimated using a thermodynamic model. The modeling results are then used to determine the key operating parameters that may cause a dissolving tank explosion.

THERMODYNAMIC MODELING

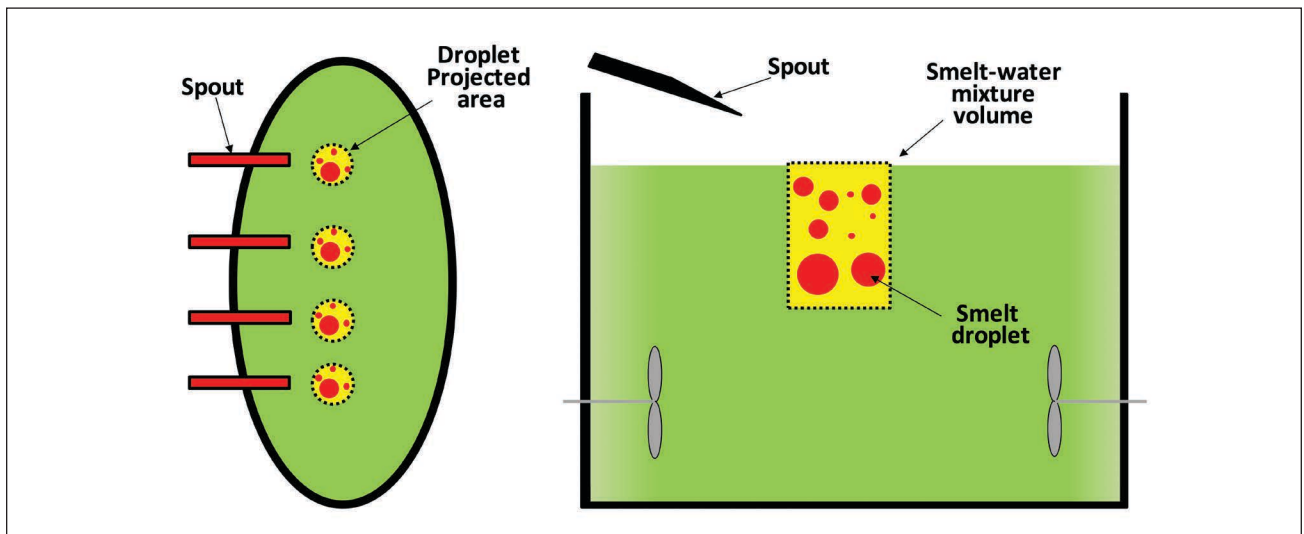
In this study, the explosion energy of multi-droplet smelt-water explosions in the dissolving tank was evaluated using a thermodynamic model. The modeling procedure was adopted from the Hicks-Menzies method [15], which

was originally developed for calculating the maximum conversion of thermal energy to mechanical work in a nuclear reactor meltdown accident, and subsequently widely used in the nuclear industry and volcanism [5,16].

Figure 1 schematically shows the top and side views of smelt-water interaction in the dissolving tank. After being shattered by the steam jets, thousands of smelt droplets continuously fall into the green liquor within a projected area under each spout. As the droplets travel in the liquor, they form a cylindrical volume of smelt-green liquor mixture (rectangular box). Within the volume, smelt droplets explode stochastically, i.e., some droplets explode independently by themselves, while others are triggered to explode by the shock they receive from nearby droplet explosions [14].

The amount of smelt and green liquor involved in each explosion is often not known. In this study, the shock of the explosion of one droplet is assumed to propagate through a uniformly distributed smelt-liquor mixture, triggering all the smelt to explode within the boundary of the control volume, and so the amount of smelt and liquor in the control volume can be obtained. This study also treats green liquor the same as water and assumes that the density and specific heat of smelt and water/liquor remain constant with changing temperature and pressure.

In this model, the smelt-water explosion is described in two stages. The first stage is the instantaneous mixing of the smelt at temperature T_s and water at temperature T_w in the control volume to reach an equilibrium temperature of T_e . The second stage is the vaporization and isentropic expansion of the water vapor from the equilibrium state to the final state. Since vapor separates smelt from water, no further heat transfer between smelt and water occurs during the expansion. The final state has an ambient pressure



1. Schematic of a top view (left) and side view (right) of the interaction between molten smelt droplets and green liquor in the dissolving tank.

P_s with the corresponding saturation temperature T_s , and the weight percentage of water vaporized x_2 can be calculated. The explosion energy conversion ratio CR , defined as the ratio of total explosion energy to the available thermal energy stored in the smelt, can be calculated as:

$$CR = \frac{E_{\text{explosion}}}{m_s u_{\text{smelt}}} = \frac{m_w (c_{v,w}(T_e - T_2) - x_2(h_v - P_2 v_v))}{m_s [c_{v,s}(T_s - T_w)]} \quad (1)$$

where $E_{\text{explosion}}$ is the explosion energy; u_{smelt} is the thermal energy density of smelt, or energy per unit mass; m_s is the mass of smelt; m_w is the mass of water; $c_{v,w}$ is the heat capacity of water; $c_{v,s}$ is the heat capacity of smelt; v_v is the specific volume of vapor; and h_v is the latent heat of water vaporization. More detailed steps for calculating CR can be found in the next section.

The total amount of smelt involved in an explosion depends on the smelt thermal energy density, smelt flow rate Q , and time of smelt accumulation before an explosion, which is the explosion delay time t_{delay} . Thus, the maximum explosion energy can be expressed as:

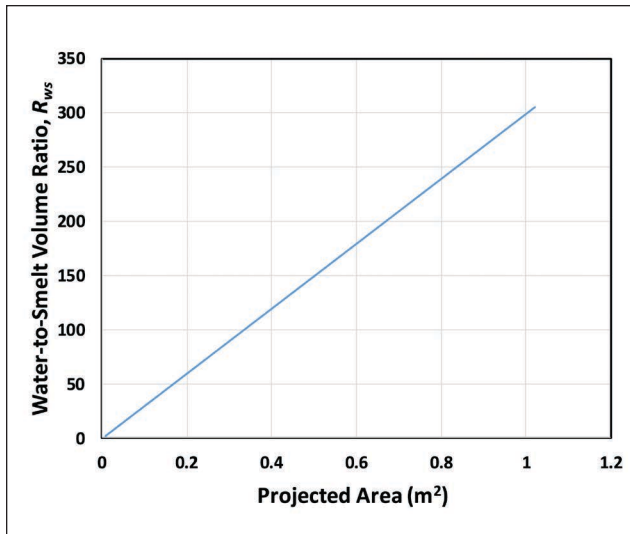
$$E_{\text{explosion}} = u_{\text{smelt}} * Q * t_{\text{delay}} * CR \quad (2)$$

MODELING RESULT AND DISCUSSION

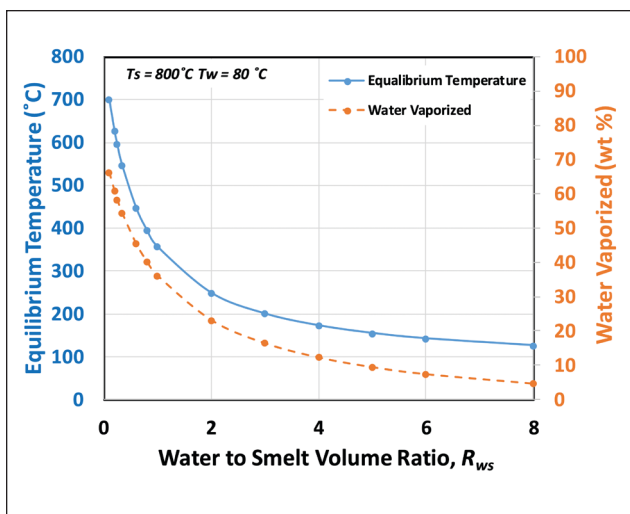
Equation 1 shows that CR is a function of the thermal properties of smelt and water, water temperature T_w , smelt temperature T_s , and the relative mass of water and smelt, $\frac{m_w}{m_s}$. This mass ratio can also be quantified by the water-to-smelt volume ratio R_{ws} , assuming constant densities. The R_{ws} strongly depends on smelt shattering. A large value of R_{ws} means that the smelt droplets are dispersed into a large projected area in the dissolving tank and interact with a large amount of water.

Since water is abundant in the dissolving tank, R_{ws} is usually greater than 1 in the control volume. Assuming a smelt flow of 1 L/s per spout lands uniformly into a projected area underneath the spout, R_{ws} of the control volume can be estimated to be on the order of tens to hundreds as a function of the size of the area, shown in **Fig. 2**. It should be noted that in an actual dissolving tank, smelt distribution is seldom uniform and smelt is typically less concentrated near the perimeter of the projected area and more concentrated in the middle. Thus, the explosion of the smelt concentrated in the middle of the projected area may be characterized by a local R_{ws} much smaller than the average R_{ws} of the entire control volume.

To model the energy of a smelt-water explosion, the equilibrium temperature T_e and percent of water vaporized to steam at the end of the isentropic expansion x_2 was first calculated at different R_{ws} , $T_s = 800^\circ\text{C}$, and $T_w = 80^\circ\text{C}$. **Figure 3** shows that an increase in the amount of water relative to smelt leads to a lower T_e after the instantaneous mixing of smelt and water. This results in less thermal en-



2. Water-to-smelt volume ratio, R_{ws} , as a function of the projected area into which the smelt lands.

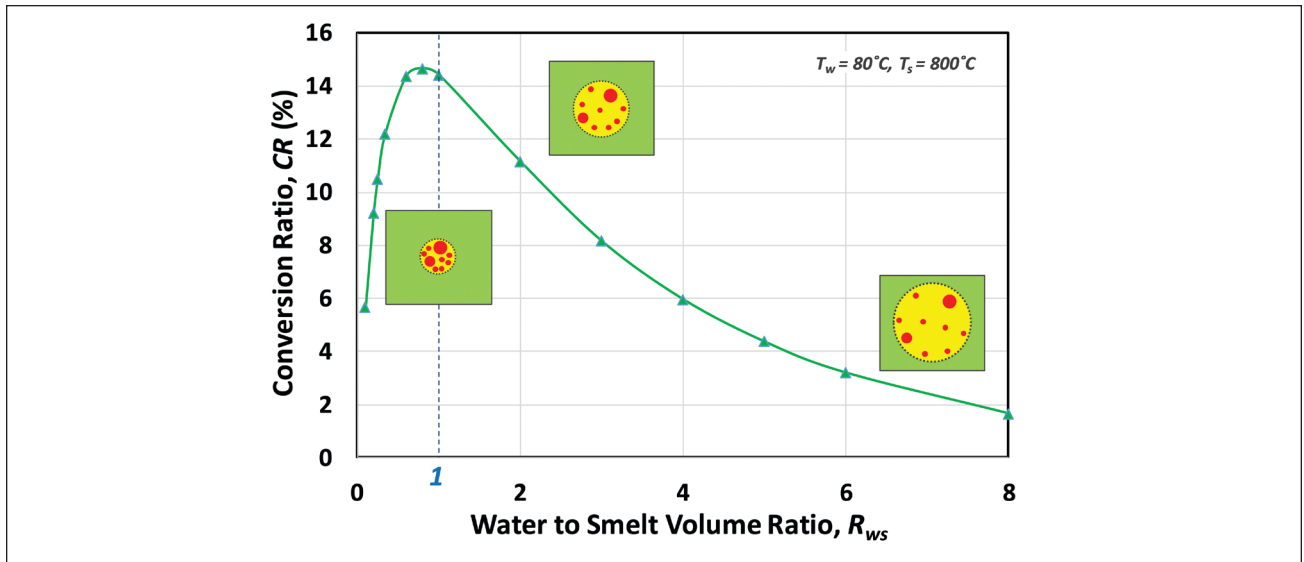


3. Predicted equilibrium temperature T_e and water vaporized x_2 at different R_{ws} (T_w = water temperature; T_s = smelt temperature).

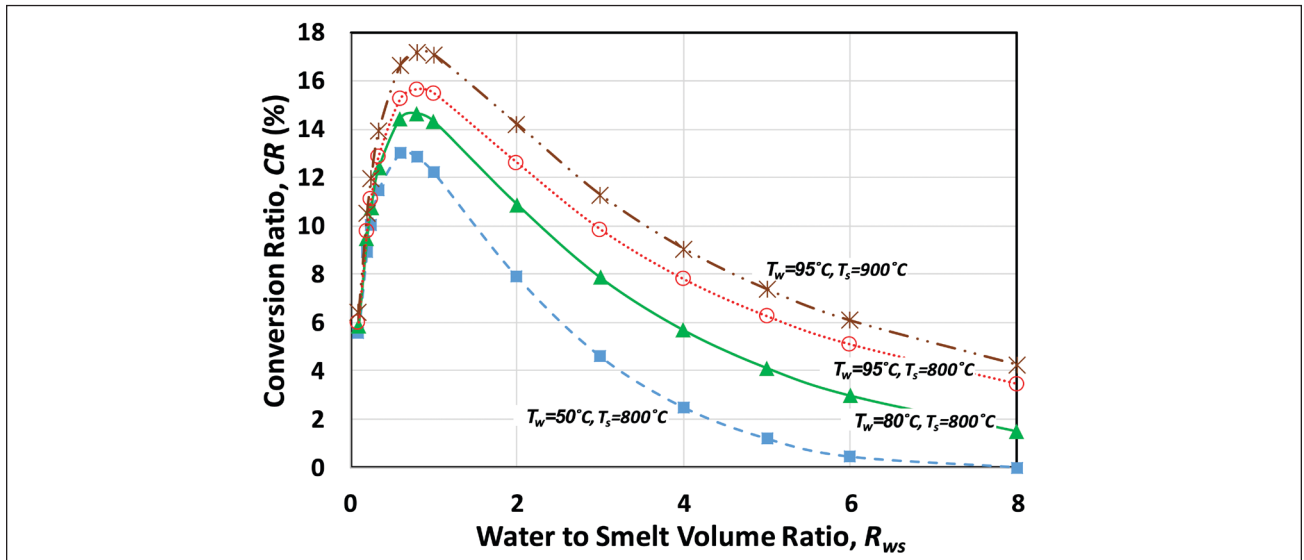
ergy available at the volume expansion stage, and so less water is vaporized.

The explosion energy conversion ratio CR was then computed for different R_{ws} . **Figure 4** shows the peak CR of about 15% can be obtained at roughly $R_{ws} = 1$, and CR becomes smaller as the relative amount of smelt and water becomes more disproportional. This is because, for a given amount of smelt, too much water leads to a small T_e in Eq. 1, resulting in the conversion of a large amount of thermal energy from smelt into the sensible heat of water instead of mechanical work. On the other hand, too little water interacting with it, reflected by a small m_w in Eq. 1, limits the amount of water vaporization and volume expansion, and so little mechanical work is generated.

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4. Effect of R_{ws} on energy conversion ratio CR (T_w = water temperature; T_s = smelt temperature).

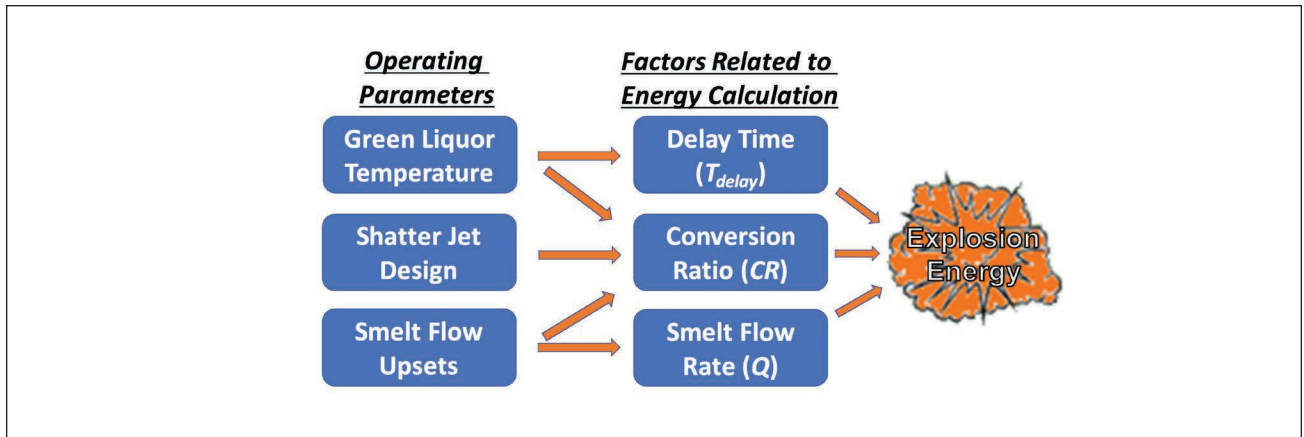


5. Effect of smelt and water temperatures on CR.

Figure 5 shows the effect of T_w and T_s on CR, at different R_{ws} . In general, increasing T_w from 50°C to 95°C decreases the amount of sensible heat absorbed by the surrounding water, converting more thermal energy to mechanical work, resulting in a larger CR. The result also suggests that the effect of T_w and T_s is less significant than that of R_{ws} as, regardless of T_w and T_s , CR decreases substantially from the peak value as R_{ws} increases further above 1. The effect of T_w on CR is only significant when the amount of water is much more than the amount of smelt. For example, at $R_{ws} = 6$, increasing T_w from 50°C to 95°C leads to an increase of CR by six-folds, from 1% to 6%, whereas, at $R_{ws} = 1$, CR only increases slightly from 13% to 16%. An increase in T_s also leads to a slight increase in CR, because the explosion becomes more efficient with a larger amount of thermal energy available. However, the effect

of T_s on CR is minor compared to that of T_w and R_{ws} .

Once CR is known, the total explosion energy can be calculated with Eq. 2. Using a smelt temperature of 800°C, a water temperature of 80°C, a typical smelt density of 1923 kg/m³, the heat capacity of 1.34 kJ/kg°C [17], and CR of 15%, the energy from the explosion of 1 kg of smelt was calculated to be 0.14 MJ. The trinitrotoluol (TNT) equivalent is typically used to describe the energy released in an explosion, and 1 kg TNT is defined as 4.184 MJ. Thus, each kilogram of smelt involved in a smelt-water explosion in the dissolving tank is roughly equivalent to 0.033 kg TNT. Assuming a smelt flow rate of 1 L/s and a delay time of 5 s, a total of 5 L, or 9.6 kg, of smelt may explode at the same time, generating an explosion with 1.4 MJ of energy, equivalent to 0.33 kg TNT. When the TNT equivalent, W in lb, is given, Cole's correlation [18] can be used to cal-



6. Relationship between dissolving tank operating parameters and explosion energy.

culate the overpressure, P_m in psi, an important parameter for assessing the impact of an underwater explosion on an object at a distance, D , in feet:

$$P_m = 2.16 * 10^4 (W^{1/3} D)^{1.13} \quad (3)$$

PRACTICAL IMPLICATIONS

The intensity of the smelt-water explosion in the dissolving tank that causes a loud and violent tank can be affected by tank design and operating parameters. At some conditions, explosion energy may increase by orders of magnitude, leading to a catastrophic dissolving tank explosion accident. Based on Eq. 2, the potential mechanical energy generated by a smelt-water explosion depends on four factors:

1. Energy density in smelt (u_{smelt}):

The energy density in smelt depends on smelt temperature and thermal properties of smelt. Since neither smelt temperature nor smelt thermal properties change significantly in recovery boiler operation, mills should focus on the other three factors.

2. Smelt flow rate (Q):

Smelt flow rate is dictated by the number of smelt spouts on the boiler wall and the firing rate of the boiler, which is typically about 1 L/s and does not change much under normal operating conditions. It may, however, change dramatically during operational upsets [19].

3. Explosion delay time (t_{delay}):

The delay time, which is the time starting from the moment the smelt contacts the green liquor surface to the moment of explosion, dictates how much smelt can accumulate in the tank before an explosion. Longer delay time results in a larger amount of smelt involved in an explosion, generating higher explosion energy. Laboratory tests showed that explosion delay time can vary significantly between tens of milliseconds and a few seconds depending on the water/green liquor temperature [14].

4. Explosion energy conversion ratio (CR):

The results of this work show that CR increases with an increase in green liquor-to-smelt volume ratio, which is strongly dependent on the shatter jet design and the characteristics of smelt flowing out of the spouts. Increasing green liquor temperature also increases CR , especially at a high liquor-to-smelt ratio.

This analysis suggests that green liquor temperature, shatter jet design, and smelt flow upsets play important roles in determining the intensity of a smelt-water explosion.

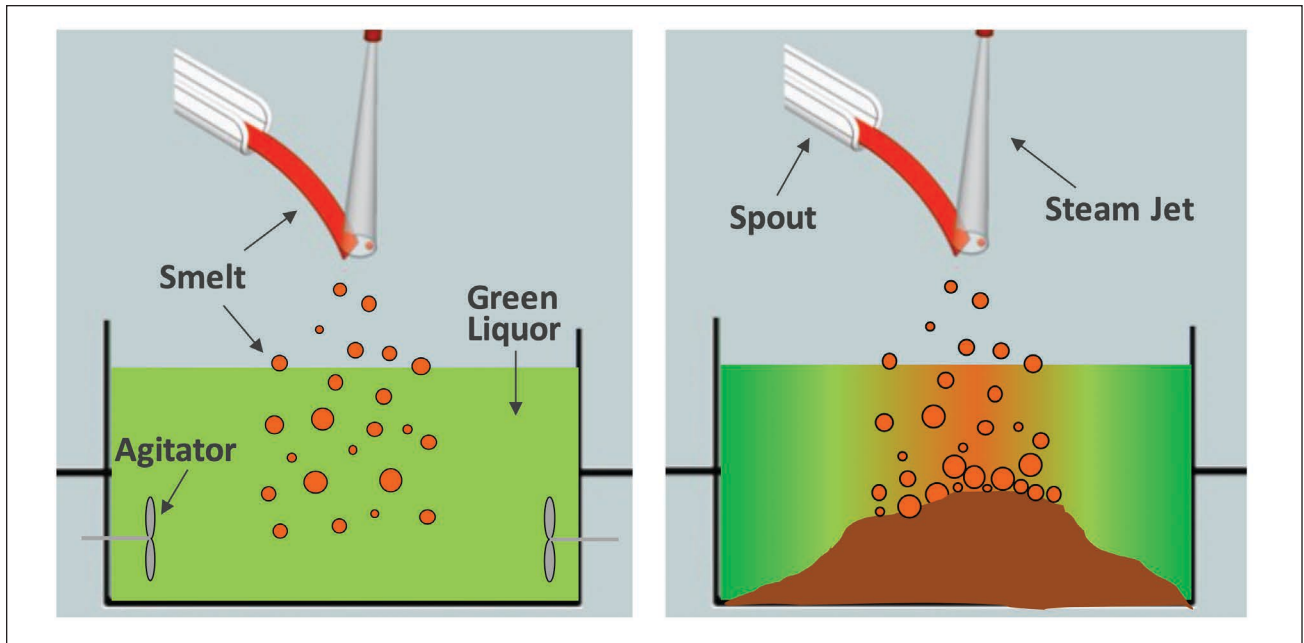
Figure 6 summarizes the relationship between the energy of smelt-water explosions and key dissolving tank design and operating parameters. Each of these parameters is discussed in the following sections.

Shatter jet design

Shatter jet design plays an important role in optimizing smelt shattering. When not well shattered, smelt concentrates in a smaller area. This modeling work clearly shows that poorly shattered smelt with a small green liquor-to-smelt volume ratio leads to high explosion energy. To reduce the chance of a dissolving tank explosion accident, it is desired to uniformly disperse smelt over a large projected area in the tank.

A good shatter jet design should accomplish three important goals: i) the shatter jet should be able to atomize the smelt stream into desired droplet distribution; ii) the shatter jet should be wide enough that it would not miss the smelt when there is a change in the smelt flow pattern; and iii) steam consumption should be minimized to reduce cost. Current smelt shattering practices and shatter jet design vary significantly between pulp mills and there is no standard guideline on smelt nozzle design, configuration, and operation [20]. Typical shatter jet nozzle design includes round profile nozzles, multi-hole nozzles, and slit profile nozzles. The jet orientation typically directs vertically downward or slightly against the direction of smelt flow. The steam for shatter jet operation typically has a

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7. Well-agitated tank (left) vs. poorly agitated tank (right).

pressure ranging from 3.5 to 15.5 bar, a temperature from 150°C to 250°C, and a flow rate from 180 to 2250 kg/hr.

Green liquor temperature

This study shows that high green liquor temperature leads to high explosion energy by increasing both the delay time and explosion conversion ratio. In the mills, the green liquor temperature is typically set between 70°C and 90°C. The ability to adjust this temperature is limited by the downstream causticizing process, as cold green liquor inhibits the reaction kinetics in the causticizing plants. Furthermore, low green liquor temperature can also cause pirssonite formation and scaling problems [21]. Since smelt-water interaction behavior depends on the local green liquor temperature surrounding the smelt, mills should focus not only on the green liquor temperature but also on the uniformity of the temperature in the dissolving tank. Thus, agitation should be optimized to ensure temperature uniformity and avoid a “hot spot” in the dissolving tank.

Figure 7 schematically shows a dissolving tank under well-agitated and poorly agitated conditions. Since smelt droplets with high thermal energy fall in the middle of the area beneath the smelt spout, without adequate agitation, the locally high green liquor temperature can lead to long delay time, allowing smelt to accumulate on the bottom of the tank. Furthermore, due to the high green liquor temperature, some smelt droplets freeze without explosion, making it more difficult for them to dissolve. Molten smelt may then land on top of the frozen smelt pile, resulting in a low liquor-to-smelt volume ratio locally and high explosion energy. Therefore, high green liquor temperature should be avoided so long as process constraints allow,

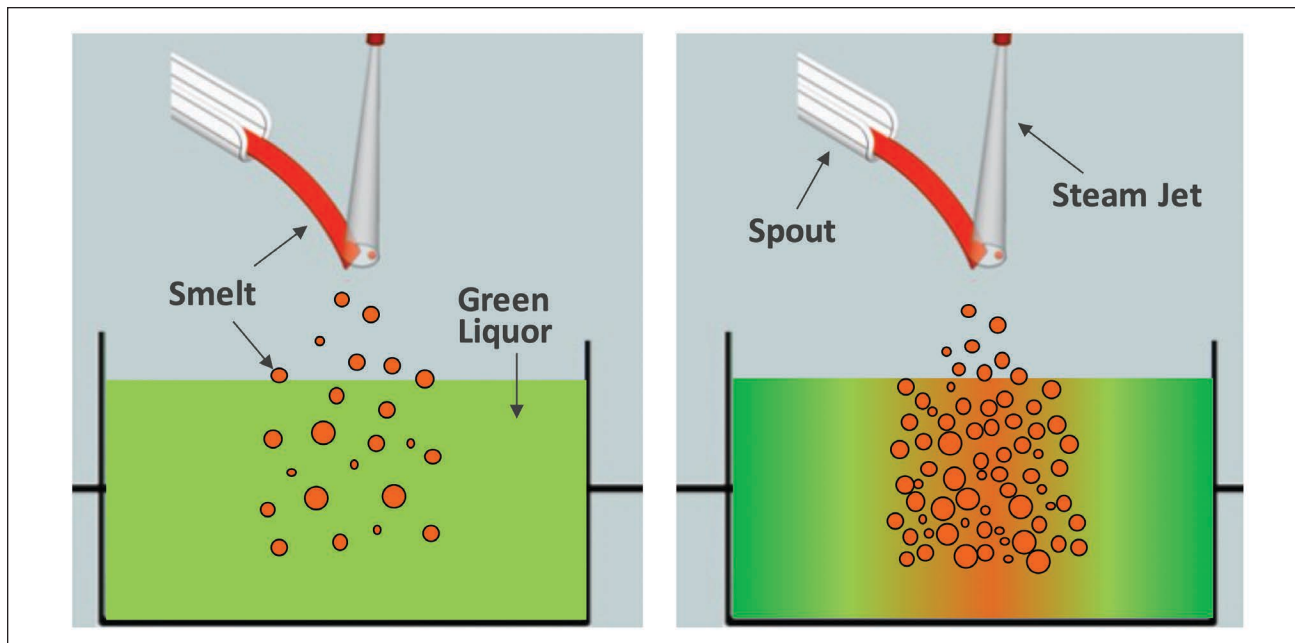
and agitation should be optimized to ensure a uniform temperature.

Mill experience is that the dissolving tank generates loud noise when the tank temperature is low, which appears to contradict the explosion energy analysis in this study. One possible explanation is that, when the liquor temperature is low, smelt droplets explode quickly after landing into the green liquor [14], generating constant “mini” droplet explosions and louder noise. However, once a smelt droplet has exploded, it is no longer available to participate in a multi-droplet explosion. On the other hand, when liquor temperature is high, smelt droplets may accumulate in the tank without exploding, generating less noise, but potential high explosion energy. This agrees with the anecdotal report of an intense explosion shortly after the tank had gone quiet.

There are also other complex principles of acoustic and wave physics behind the argument of loud versus dangerous tank, which is not the focus of this paper. For example, at low green liquor temperatures, explosions tend to occur on the green liquor surface, generating sound with a frequency that human ears are more sensitive to than sound generated by explosions deep in the liquor that occurs at high liquor temperatures. On the other hand, since green liquor is incompressible, the same amount of energy usually results in greater physical damage underwater than it would have in the air.

Smelt flow upsets

This study shows that the increase in the smelt flow rate directly increases the amount of thermal energy of smelt in the dissolving tank, making an intense smelt-water explosion more likely. During normal operation, the smelt flow characteristics do not change significantly. However, most



8. Normal smelt flow (left) vs. runoff (right).

mills have experienced smelt runoff problems, which can be caused by opening plugged spouts, burning down a large bed, low sulfidity black liquor, boiler startup with a bed or smelt in the unit, improper firing practices, misuse of auxiliary fuel, and bed collapse [19]. “Jellyroll” smelt is another common upset that many mills have encountered. The formation of jellyroll smelt may be due to the cooling and freezing of the molten smelt, smelt composition change due to fallen deposits, or inclusion of a large amount of unburned char [22]. This slow-moving viscous smelt makes smelt more difficult to shatter, and when the jellyroll smelt is finally removed, the surge of molten smelt behind leads to a runoff situation. When smelt flow surges, smelt becomes larger in quantity and more concentrated in a certain space of the green liquor, reducing liquor-to-smelt volume ratio and leading to higher explosion energy, as illustrated in **Fig. 8**. The situation could be aggravated by a higher liquor temperature in the middle of the tank if agitation is inadequate.

IMPLICATION ON RECOVERY BOILER SAFETY

Compared to dissolving tank safety, smelt-water explosion in the recovery boiler has the potential to inflict much more damage. The theory behind this thermodynamic modeling of smelt-water explosion can also be applied to a recovery boiler explosion scenario in which water from leaked tubes contacts the smelt pool at the bottom of the recovery boiler. In this case, water temperature is close to saturation, and smelt temperature may range from 800°C to 1000°C. Since smelt is abundant in the boiler, especially with a decanting bottom furnace, the volume ratio of water to smelt is much smaller than 1 in a control volume of the space surrounding the smelt-water interaction. As the amount of water and smelt in the control volume approaches equal

proportion, or as the water-to-smelt volume ratio approaches 1, the maximum explosion energy conversion ratio is reached, leading to high explosion energy. This suggests that the instant vaporization of the water in a small and confined molten smelt area could result in a more intense smelt-water explosion than if the water is dispersed into a large area of smelt. For example, a floor tube leak with water concentrated locally would be more dangerous than a tube leak from the upper furnace that disperses water onto a large area of the smelt pool.

SUMMARY

Smelt-water explosion in the dissolving tank is of a great safety concern in kraft pulp mills. This study extended our previous knowledge of droplet-scale smelt-water explosion to a large-scale multi-droplet smelt-water explosion. The energy of a smelt-water explosion in the dissolving tank was assessed using thermodynamic modeling, and the explosion energy created by a given amount of molten smelt was estimated as a function of green liquor-to-smelt ratio, green liquor temperature, and smelt temperature. The results showed that increasing green liquor-to-smelt ratio and green liquor temperature greatly increases the explosion energy conversion ratio, converting a large portion of the thermal energy in molten smelt into mechanical work that can potentially cause damage to the dissolving tank.

The results also showed that the total energy from a smelt-water explosion heavily depends on the explosion conversion ratio, explosion delay time, and smelt flow rate. To reduce the chance of a dissolving tank explosion accident, it is important to: i) optimize the shatter jet design and operation to uniformly distribute the smelt over a large area in the dissolving tank; ii) avoid high green liquor tem-

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perature and ensure adequate liquor mixing; and iii) avoid upsets that may cause heavy smelt runoff or jellyroll smelt.

The thermodynamic model developed for this study can also be used to assess the energy of a smelt-water explosion that occurs in the recovery boiler. **TJ**

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APPENDIX A: CALCULATION OF EXPLOSION ENERGY CONVERSION EFFICIENCY

In this work, smelt-water explosion is modeled in two stages. The first stage is the instantaneous mixing of the smelt at temperature T_s and water at temperature T_w in the control volume to reach an equilibrium temperature of T_e in degrees kelvin. The equilibrium temperature can be calculated as:

$$T_e = \frac{m_s c_{v,s} T_s + m_w c_{v,w} T_w}{m_s c_{v,s} + m_w c_{v,w}} \quad (A1)$$

where m is mass; $c_{v,s}$ is constant volume specific heat; and subscripts s and w represent smelt and water, respectively. Since the equilibrium state is established instantaneously, water and smelt remain in the liquid phase and do not undergo a phase change. The corresponding equilibrium pressure of P_e can be estimated using the ideal gas equation of state or from the steam table.

In the second stage, the water vaporizes and expands isentropically from the equilibrium state to the final state. Since the vapor generated can insulate smelt from water, it is assumed that no heat transfer occurs between smelt and water during the expansion. The total amount of mechanical work created is based on the conditions calculated at the end of the expansion.

Since the change in entropy is zero during an isentropic expansion:

$$T_w ds_w = dh_w - v_w dp_w = 0 \quad (A2)$$

where T_w , s_w , h_w , and p_w are the temperature, entropy, enthalpy, and pressure of water, respectively, and v_w is the specific volume of water vapor. Assuming the specific volume of smelt and water are negligible in comparison to that of the water vapor, and the expansion occurs mostly in the two-phase region, ideal gas law and Clausius-Clapeyron equation can be applied to arrive at the following:

$$dh_w = c_{p,w} dT + h_v dx \quad (A3)$$

$$v_v = \frac{x R_w T}{p} \quad (A4)$$

$$dp = \frac{p h_v}{R_w T^2} dT \quad (A5)$$

where $c_{p,w}$ is the constant pressure specific heat of water; x is the percentage of water vaporized to steam; h_w is the latent heat of vaporization of water; and R_w is the gas constant for water.

At the final state ambient pressure P_2 and its saturation temperature T_2 , substituting Eq. 6, Eq. 7, and Eq. 8 into Eq. 5 and integrating from the equilibrium state to the final state gives the percentage of water vaporized at the final state:

$$x_2 = T_2 \left[\frac{(m_w c_{p,w} + m_s c_{p,s})}{m_w h_v} \ln \frac{T_e}{T_2} \right] \quad (A6)$$

If x_2 is less than 1, water is in the two-phase region at the final state. If x_2 is greater than 1, the final water state is superheated. Under this condition, integrating pressure and temperature between the equilibrium and final state with $x_2 = 1$ gives the final temperature of the superheated vapor:

$$T_2 = T_e \left(\frac{P_2}{P_e} \right)^{\frac{R_w}{c_{p,w}}} \quad (A7)$$

Once x_2 and T_2 are known, and the total energy is conserved during the expansion, the theoretical maximum energy release of a smelt-water explosion can be calculated from the change in internal energy of water:

$$E_{\text{explosion}} = -m_w \Delta u_w = m_w (c_v (T_e - T_2) - x_2 (h_v - P_2 v_v)) \quad (A8)$$

ABOUT THIS PAPER

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The explosion energy conversion ratio, CR , defined as the ratio of explosion energy to the available thermal energy stored in smelt, can be calculated as:

$$CR = \frac{E_{\text{explosion}}}{E_{\text{smelt}}} = \frac{E_{\text{explosion}}}{m_s u_{\text{smelt}}} = \frac{m_w (c_{v,w} (T_e - T_2) - x_2 (h_v - P_2 v_v))}{m_s [c_{v,s} (T_s - T_w)]} \quad (A9)$$

where $E_{\text{explosion}}$ is the explosion energy, and u_{smelt} is the thermal energy density of smelt, or energy per unit mass.

ABOUT THE AUTHORS

Understanding smelt-water explosion energetics is of great importance in the safe and effective operation of recovery boiler dissolving tanks. This study built upon the conclusions of the previous studies conducted as part of the dissolving tank research program at the University of Toronto. It examines the smelt-water explosion topic with a thermodynamic modeling approach instead of conducting experiments as in the previous studies.

The most difficult aspect of this research was adapting a modeling method from a different industry: the nuclear industry. A comprehensive literature review was completed to ensure the applicability of the method for the recovery boiler dissolving tank. We discovered that, in research, there is great value to learn from the other industries instead of starting from scratch.

Many methods and theories from this study on smelt-water explosion in the dissolving tank can be potentially expanded to the smelt-water explosion in the recovery boiler. It would be interesting to explore



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Tran

smelt-water explosion theories in the recovery boiler with our recent understanding.

The authors are taking this effort a step further and working on another paper on smelt shatter jet design. That study will give the industry practical information on smelt shattering to improve dissolving tank safety.

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