Breakup mechanisms of brittle deposits in kraft recovery boilers – a fundamental study

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ABSTRACT: The breakup mechanism of brittle deposits removed by sootblower jets in kraft recovery boilers was studied in the laboratory by blasting model deposits made of gypsum with an air jet, and documenting the process using high-speed cameras. The results show that thin brittle deposits fail quickly, as an axial crack forms and propagates through the sample. In thicker deposits, the jet first drills a small hole in the deposit. As the hole grows wider and deeper, an axial crack forms, allowing the air jet to penetrate the deposit. This causes the front side of the deposit to split, and subsequently the back side of the deposit to be blown apart. The mechanism implies that in order for a sootblower jet to remove a brittle deposit effectively, it must be able to drill a deep hole and form axial cracks in the deposit within the short blowing time.

Application: Understanding where brittle deposits are formed in recovery boilers, and how they are removed by a sootblower jet, can enable mills to devise strategies for improving and optimizing their own sootblowing operations.

The accumulation of fireside deposits on heat transfer surfaces in kraft recovery boilers greatly reduces boiler thermal efficiency, obstructs flue gas flow, and in severe cases, leads to unscheduled boiler shutdowns for water-washing of deposits [1]. During boiler operation, deposit accumulation is controlled by sootblowers, which periodically blast deposits off the tubes with high pressure steam jets. The efficiency of deposit removal depends greatly on the power of the sootblower jet, the strength of the deposits, and the sequence and frequency of sootblowing [2,3].

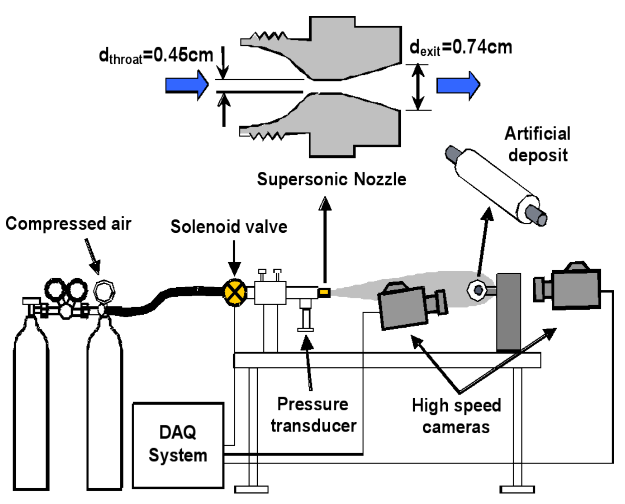
Deposits form differently at different locations in the boiler. They differ, depending on the type of particles entrained in the flue gas, the particle composition, and the local flue gas temperature. The most important factor that determines deposit strength is the amount of molten phase in the particles at the moment they strike the tube surface [4]. In the lower superheater region where the flue gas temperature is high, >780°C, deposits are highly fluid. They tend to spread when impinged by the sootblower jet, thereby absorbing most of the jet kinetic energy. As a result, deposit removal efficiency is poor in this region. In the upper superheater, where the flue gas temperature is much lower, and particularly in the generating bank and economizer regions, where the gas temperature is lower than the first melting temperature of deposits, 520°-620°C (968°-1148°F), deposits are brittle, and can be shattered and removed by the sootblower jet.

In recent years, advances in infrared imaging technologies have led to the development of inspection cameras that papermakers can use to inspect deposit buildup in recovery boilers as well as to evaluate sootblower performance during boiler operation. However, the hostile environment in the recovery boiler makes it very difficult to carry out *in-situ* studies to examine how deposits are removed. Our study focuses on the removal mechanism of brittle deposits, since they are the main type that contribute to fouling and plugging in the upper superheater, generating bank and economizer regions of recovery boilers.

EXPERIMENTS

Experimental setup

We examined the breakup process of model brittle deposits impinged by an air jet using an experimental setup shown schematically in **Fig. 1**. The air jet nozzle was a ¼-scale ver-



1. Experimental setup.

sion of an actual sootblower nozzle. It had a throat diameter of 0.45 cm and exit diameter of 0.74 cm, and was designed to be geometrically similar to an actual sootblower nozzle and produce a dynamically similar jet. Compressed air was forced through the nozzle via a solenoid valve. A pressure transducer recorded the nozzle inlet air pressure. For each experiment, we maintained pressure as constantly as possible at 1630 kPa gauge (236 psig). The combination of nozzle geometry and inlet pressure produced a fully expanded supersonic jet with a nozzle exit Mach number of 2.5, about the same as that of typical sootblower nozzles used in recovery boilers.

At a pre-determined distance from the nozzle exit, we placed model deposits in the centerline path of the jet. The nozzle was mounted on a slider so that the distance between the nozzle and the deposit could be varied. The deposit breakup process caused by the jet was captured and recorded using two high-speed cameras (4000 frames/sec). We placed one camera on the front side (the impingement side) of the deposit and the other on the back side. We synchronized the cameras so that they could capture the breakups of the front and back surfaces simultaneously. The pressure transducer, solenoid valve, and cameras were all controlled by a data acquisition system. Details of the experimental setup and procedures have been described in a previous paper [5].

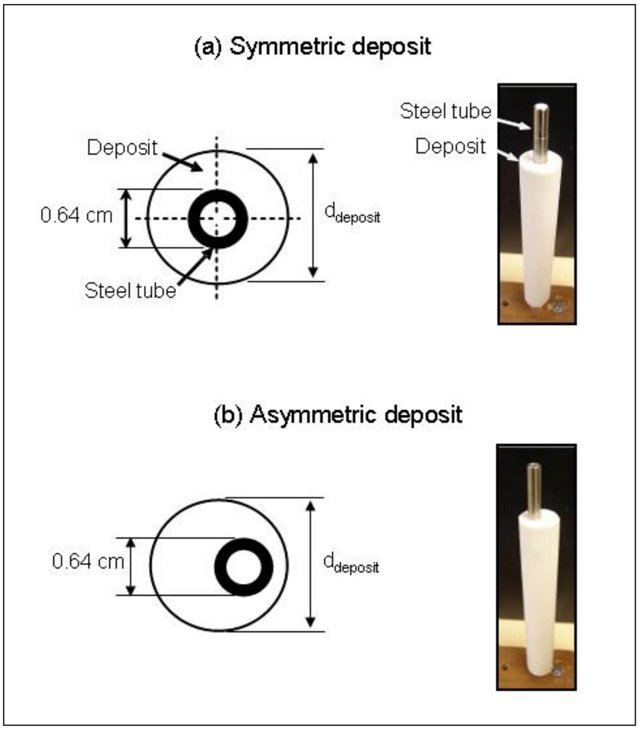
Model deposits

Model deposits were prepared by mixing plaster of Paris ($CaSO_4 \bullet \frac{1}{2}H_2O$) and water. Plaster slurry was used since it can be easily cast into desired sizes and shapes using appropriate molds. The resulting gypsum "deposit" is brittle and has physical properties (strength and porosity) that can be changed by varying the water-to-plaster mass ratio of the slurry, $\eta = m_{water}/m_{plaster}$. The tensile strength, σ_t (in MPa), of gypsum can be estimated using an empirical relationship obtained in our laboratory:

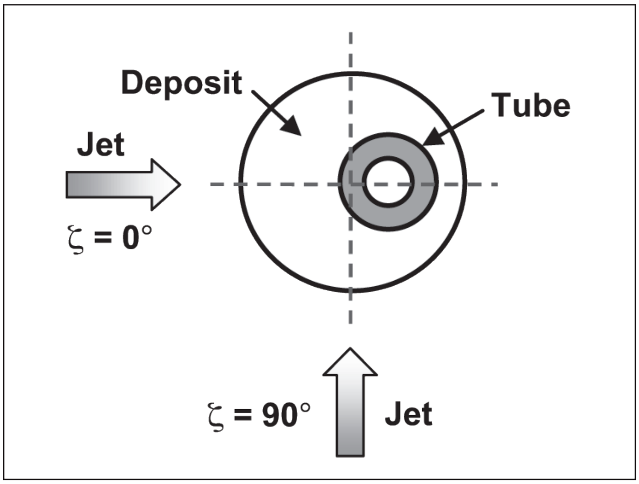
$$\sigma_t = 15\left(\frac{0.46}{\eta + 0.4} - 0.11\right)^{1.85}$$

where η varies between 0.5 and 2. Five plaster slurries with η values of 2, 1.8, 1.65, 1.5 and 1 were used to produce model deposits with corresponding tensile strengths of 0.15, 0.21, 0.27, 0.36, and 0.9 MPa. Deposits with η = 2 were the softest (0.15 MPa) as they broke under most test conditions, while deposits with η = 1 were the hardest (0.9 MPa), since they did not break at all.

Two different shapes of model deposits were examined. Symmetrical deposits with a circular cross-section and a length of 12.7 cm (5") were prepared by casting plaster slurry around a 0.64 cm (1/4") OD stainless steel tube placed at the center of a 12.7 cm (5") long Plexiglas mold. The diameter of the mold determined the thickness of the deposits. Thin deposits had a thickness of 0.32 cm (1/8"), while thick deposits were twice as thick at 0.64 cm (1/4"), as shown in **Fig. 2a**. Asymmetric deposits were prepared in the same way, except that the steel tube was placed off the center of the Plexiglas mold (**Fig. 2b**). It was necessary to examine the effects of asymmetry because, in recovery boilers, carryover deposits tend to form on the leading edge of the boiler tubes and are usually asymmetrical rather than symmetrical.



2. Cross-sections and photographs of thick deposits: (a) symmetrical and (b) asymmetrical.



3. Deposit orientation angle, ζ.

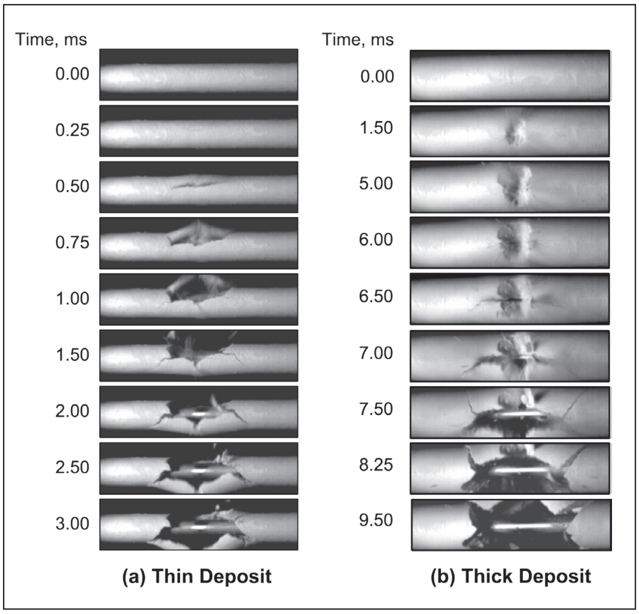
After the cast plaster slurry hardened, the deposit was removed from the mold and dried in an oven at 60°C for 1 hour. Breakup tests were performed by placing these deposits at distances of 5, 9, 12, and 15 cm from the nozzle. For each test condition, the experiments were repeated five times to obtain reasonable reproducibility. In the experiments using asymmetrical deposits, the deposit orientation angle, ζ, was also considered. As shown in **Fig. 3**, $\zeta = 0^\circ$ refers to tests in which the air jet was oriented directly at the thickest point of the deposit, while when $\zeta = 90^\circ$ the jet was oriented at the midpoint between the thinnest and the thickest points of the deposit.

RESULTS AND DISCUSSION

Symmetrical deposits

Effect of Deposit Thickness: **Fig. 4a** shows the breakup images of a thin deposit ($\eta = 2$) placed at 9 cm (3.5") from the nozzle at selected times. Time $t = 0$ represents the onset of breakup of the deposit (the first sign of deposit removal after the air jet reached the deposit surface). The jet penetrated the deposit through microcracks and pores on the surface, forcing the deposit to crack along the tube axis ($t = 0.25$ ms). As the axial crack grew deeper and larger ($t = 0.5$ ms), part of the deposit was blown off ($t = 0.75$ ms), exposing the tube underneath ($t > 1$ ms). The jet continued to "push", causing the remaining deposit to break. The entire removal process occurred in less than 3 milliseconds (ms). We observed a similar breakup mechanism for all thin deposits.

Figure 4b shows the breakup images of a thick deposit placed 9 cm (3.5") from the nozzle. In this case, breakup started with surface pitting as the jet drilled its way into the deposit ($t = 1.5$ ms). As the pit (hole) became larger and deeper, an axial crack formed at $t = 6$ ms, which then propagated rapidly ($t = 6.5$ ms), splitting the deposit apart ($t = 7.5$ ms). The entire removal process took about 10 ms to complete, compared to only 3 ms in the thin deposit case. The differ-



(a) Thin Deposit (b) Thick Deposit

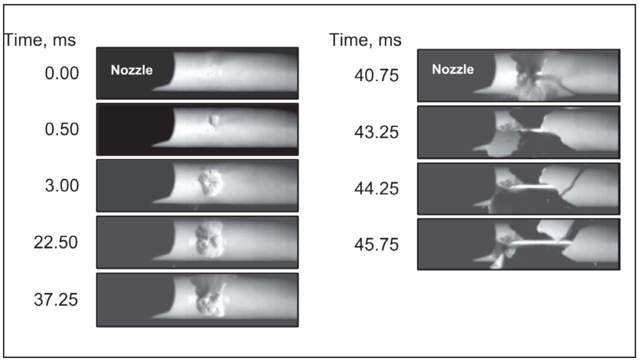
4. Breakup images of (a) thin and (b) thick deposits ($\eta = 2$) placed 9 cm from the nozzle.

Water-to-Plaster Mass Ratio, η	2	1.8	1.65	1.5	1
Tensile Strength σ_t, MPa	0.15	0.21	0.27	0.35	0.90
Distance from Nozzle Exit					
5 cm	0.45 (3)	9 (58)	0.25 (7.1)	0.25 (27)	NB
9 cm	0.60 (4.2)	12.6 (41.3)	0.28 (5.5)	NB	NB
12 cm	0.38 (3.1)	0.43 (5.0)	0.51 (9.5)	NB	NB

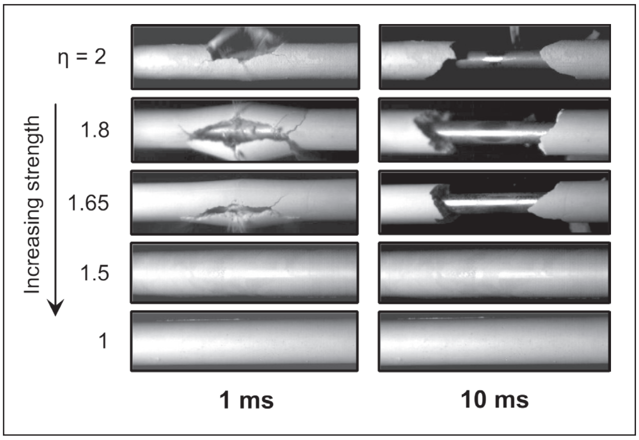
I. Time, in milliseconds, after onset of breakup required for axial cracks to form in thin deposits (in parentheses, time required for complete breakup). NB: Did not break.

Water-to-Plaster Mass Ratio, η	2	1.8	1.65	1.5	1
Tensile Strength σ_t, MPa	0.15	0.21	0.27	0.35	0.90
Distance from Nozzle Exit					
5 cm	No crack (46)	42.3 (44.4)	26.8 (31.5)	NB	NB
9 cm	11.7 (16.5)	79.9 (99.3)	27.3 (51)	NB	NB
12 cm	32.3 (38)	NB	NB	NB	NB

II. Time, in milliseconds, after onset of breakup required for axial cracks to form in thick deposits (in parentheses, time required for complete breakup). NB: Did not break.



5. Breakup images of a thick deposit ($\eta = 2$) placed 5 cm from the nozzle.

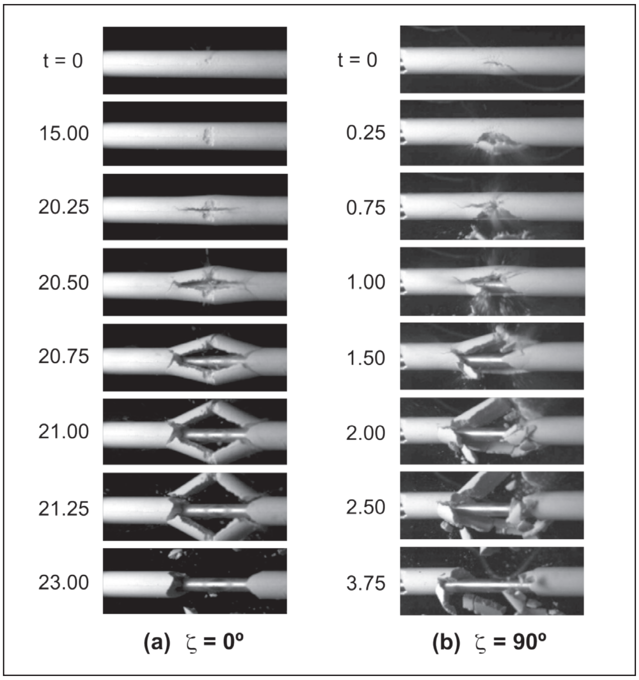


6. Breakup images of thin deposits prepared with different η values, at 1 and 10 milliseconds after the onset of the breakup process. Deposits were placed 9 cm from the nozzle.

ence was due mainly to the time required for an axial crack to form: 0.25 ms for the thin deposit versus 6 ms for the thick deposit. Thick deposits understandably took longer to crack than thin deposits; but once a crack formed, it propagated quickly and both the deposits were removed completely in about the same exposure time (2.5 to 3 ms) to the jet.

Effect of Distance between Nozzle and Deposit: **Fig. 5** shows the breakup images of a thick deposit placed 5 cm (1.27") from the nozzle. Due to the closer distance, the jet was stronger and had a smaller effective diameter compared to the case when the distance was 9 cm (3.5"), shown in Fig. 4b. The jet could drill only a small hole in the deposit and could not generate an axial crack. Once the hole became sufficiently deep and large, breakup occurred rapidly, without the formation of axial cracks.

Effect of Deposit Strength: We also performed breakup tests on deposits prepared with other η values: 1.8, 1.65, 1.5, and 1. **Tables 1** and **2** summarize, respectively, results obtained for thin and thick deposits placed at three different distances from the nozzle exit, along with those obtained with $\eta = 2$. For thin deposits, in most cases, it took less than 1 ms for an axial crack to form and a few milliseconds (<10 ms) for the deposit to break completely, but for thick deposits, it took a much longer time for an axial crack to form and to break completely. Lowering the η value from 2 to 1 resulted in a 6-fold increase in deposit tensile strength, from 0.15 to 0.90 MPa. Deposits with $\eta \geq 1.65$ ($\sigma_t < 0.27$ MPa) were weak, and were removed in most conditions. Deposits with $\eta = 1.5$ ($\sigma_t = 0.9$ MPa) were stronger; only thin deposits could be removed at 5 cm from the nozzle. Deposits with $\eta = 1$ were so hard that they could not be broken under any experimental condition.



7. Breakup images at selected times of a thin asymmetric deposit ($\eta = 2$) placed 9 cm from the nozzle exit; (a) $\zeta = 0°$; (b) $\zeta = 90°$.

Figure 6 shows breakup images of five thin deposits at two different time instants, 1 ms and 10 ms, after the onset of breakup. We prepared these deposits with different η values and placed them 9 cm away from the nozzle. Deposits prepared with $\eta = 2$, 1.8, and 1.65 broke completely in less than 10 ms, while deposits with $\eta = 1.5$ and 1 did not break at all. We obtained similar results for thick deposits placed at 9 cm from the nozzle. When placed 12 cm from the nozzle, thick deposits with $\eta = 2$ broke, but those with lower η values did not. These results confirm that the ability of a jet to remove a brittle deposit is greatly dependent on the peak impact pressure and the effective diameter of the jet and the strength of the deposit.

Asymmetrical deposits

We also performed breakup experiments on both thin and thick asymmetrical deposits. Since similar results were obtained for both cases, only the results for a thin deposit with $\eta = 2$ are presented here. **Figure 7** shows the breakup images at selected times for a thin asymmetrical deposit placed 9 cm from the nozzle for two jet orientation angles: $\zeta = 0°$ and 90° (Fig. 7).

At ζ = 0º, the jet faced the thickest part of the deposit. An axial crack formed in the deposit at about 20 ms, followed by rapid breakup that completed in less than 3 ms (Fig. 7a). The breakup behavior was similar to that of the symmetrical deposit (Fig. 4b), except that it took longer for the axial crack to form in the asymmetrical deposit. This is understandable since in this case, the deposit was thicker on the front side due to asymmetry and thus required more time to crack. At ζ = 90º, the deposit was struck by the jet from the side (Fig. 7b). The part of the deposit below the tube centerline was thinner (and presumably weaker) than the part above it. As a result, as the jet struck, a crack formed immediately in the lower part (t = 0), causing it to break and to be removed (t = 0.75 ms). The removal of the lower part reduced the total contact area between the deposit and the tube and weakened the bond between them, leading to the eventual removal of the upper (thicker) part (t ≥ 1 ms).

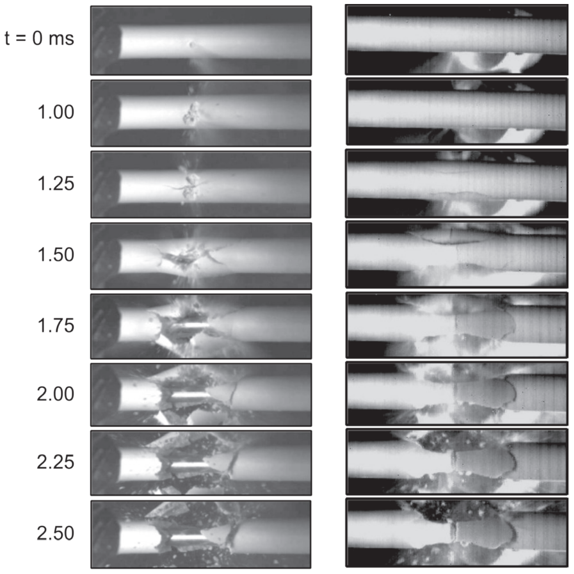
Breakup process

Figure 8 shows breakup images of a thin brittle deposit with η = 2 placed 5 cm from the nozzle. The breakup process was documented using two high-speed cameras operated simultaneously from the front and back sides of the deposit. At t = 0 ms, breakup started with slight pitting in the front side, and nothing happened on the back side. At t = 1.25 ms, an axial crack appeared on the front side, and two axial cracks appeared on the back side. At t = 1.5 ms, the front side of the deposit broke. The jet spread around the tube, causing circumferential cracks to form between the axial cracks and the subsequent breakup of the back side of the deposit. The entire breakup process occurred in less than 3 ms.

Based on the breakup images of thin, thick, symmetrical and asymmetrical deposits tested under various conditions in this study, the breakup mechanism can be summarized as follows. Thin deposits may fail due to the formation and propagation of an axial crack, opened by the jet pressure. For thicker deposits, the jet first drills a small hole in the deposit. As the hole grows wider and deeper, an axial crack forms in the front side, allowing the jet to penetrate and split the front side of the deposit apart, resulting in the formation of axial cracks in the back side. While the front side of the deposit is being removed, the jet spreads around the tube, causing circumferential cracks to form in the back side between the axial cracks, and subsequently pushes the back side of the deposit off the tube.

While the time required for complete deposit removal depends on jet strength (peak impact pressure) and deposit strength and thickness, it is mainly determined by whether or not the jet can cause axial cracks to form in the deposit. The breakup process occurs within a few milliseconds after cracks form.

When the jet nozzle is placed closer to the deposit, the jet is stronger but has a smaller effective diameter. Thus, depending on the distance between the deposit and the jet nozzle, the jet's deposit removal ability may vary. If the effective diameter of the jet is larger than the width of the deposit, the jet can remove the deposit rapidly, since it can drill a hole in the deposit and crack it. However, if the effective diameter of the jet is smaller than the width of the deposit, while the jet can still drill a deep hole in the deposit, it cannot crack it. Without causing cracks to form, the jet may still be able to remove the deposit, but this will take much longer. If the deposit is too hard for the jet to drill holes, make cracks and penetrate, it will not break.



(a) Front side (b) Back side

8. Breakup images at selected times of a thin symmetric deposit (η = 2) placed 5 cm from the nozzle exit: (a) Front side and (b) Back side.

PRACTICAL IMPLICATIONS

The breakup mechanisms of brittle model deposits shown in this study provide several implications for sootblowing operation. The effectiveness of a sootblower jet in removing a deposit depends greatly on the peak impact pressure of the jet, the strength and thickness of the deposit, and the exposure time of the deposit to the jet. Since the jet is constantly moving and rotating, the exposure time is short (typically around 100 ms, depending on the linear and angular speed of the sootblower). The jet must be powerful and have an effective diameter large enough to drill a hole in the deposit, cause axial cracks to form in it and thus break it within that short period of exposure time.

In the lower superheater region near the screen tubes, the flue gas temperature is usually high. The deposit surface is fluid and can readily absorb the force of the sootblower jet. This makes it difficult to cause cracks in the deposit. As a result, sootblowing efficiency in this region is low. In the upper superheater region and at the generating bank inlet of the recovery boiler, the flue gas temperature is typically lower than the deposit's first melting temperature. The deposit is brittle but hard and can be removed only when it is thin. However, if it is allowed to grow thicker, it may not be removed by a single blow and may need repeated blowing to crack and break up. It has been observed in several recovery boilers using inspection cameras that while the deposit in this region is brittle, it is sufficiently hard so that only a small portion is shattered each time the sootblower is activated. Fortunately, the interfacial bonding between the deposit and the tube in this region is sufficiently weak so that the entire deposit may be debonded from the tube by jet impingement. In the generating bank and economizer regions where the flue gas temperature is low, deposits are usually soft and can be cracked easily by sootblowers. The sootblowing efficiency in this region is high.

During thermal shedding (chill-and-blow) events, due to a sudden decrease in temperature, the deposit forms many cracks and often debonds from the surface; this greatly facilitates the deposit removal process.

SUMMARY

We performed a laboratory study to examine the breakup mechanisms of brittle gypsum deposit samples impinged by a supersonic air jet. Our results show that deposit thickness and strength play an important role in deposit breakup by a jet of given strength. Deposit breakup occurs rapidly when the jet is sufficiently large and strong enough to drill a hole in the deposit and to produce axial cracks. This implies that the efficiency of a sootblower jet in removing brittle deposits in recovery boilers increases with an increase in the jet peak impact pressure and a decrease in deposit strength. At the same strength, thick deposits require a longer time for the jet to break them than thin deposits. **TJ**

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INSIGHTS FROM THE AUTHORS

We chose this topic to research because of the importance of understanding how deposits are removed by a sootblower in order to optimize recovery boiler operation, as a part of the objectives of the research program on "Increasing Energy and Chemical Recovery Efficiency in the Kraft Process," as cited in the acknowledgements.

This study complements our previous research on recovery boiler deposit formation and removal, but differs from it in focusing more on the fundamental aspects of removal mechanics.

The most difficult aspect of this study was capturing the deposit breakup process. We solved this problem by using a high-speed camera (4000 frames/sec) and by performing numerous experiments to ensure reliable results.

Our research confirmed that deposit removal is an extremely complicated process involving several removal mechanisms. We were able to sort out one of the mechanisms: the breakup of brittle deposits. We found that for a sootblower jet to remove a brittle deposit effectively, it must drill a deep hole in the deposit so that axial cracks can form. Mills may be able to use this information to improve their own sootblowing operations.

Our next step is to conduct a systematic study on the mechanics of deposit removal by debonding.

All authors except Bussmann are associated with the University of Toronto's Department of Chemical Engineering and Applied Chemistry and its Pulp & Paper Centre. Bussmann is associated with the University of Toronto's Department of Mechanical and Industrial Engineering and the Pulp & Paper Centre. For more information on this research, email Tran at honghi.tran@utoronto.ca.