BREAKUP MECHANISMS OF BRITTLE DEPOSITS IN KRAFT RECOVERY BOILERS – A FUNDAMENTAL STUDY

Ameya Pophali, Morteza Eslamian, Andrei Kaliazine, Markus Bussmann* and Honghi Tran
The Pulp & Paper Centre and
*Department of Mechanical and & Industrial Engineering
University of Toronto
Toronto, ON, CANADA

ABSTRACT

The breakup mechanism of brittle deposits removed by sootblower jets in kraft recovery boilers is 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 becomes wider and deeper, an axial crack forms, allowing the air jet to penetrate into 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 effectively remove a brittle deposit, it must be able to drill a deep hole and form axial cracks in the deposit within the short blowing time.

INTRODUCTION

The accumulation of fireside deposits on heat transfer surfaces in kraft recovery boilers greatly reduces the boiler thermal efficiency, obstructs the flue gas flow, and in severe cases, leads to unscheduled boiler shutdowns to water-wash 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 a sootblower in removing deposits depends greatly on the power of the sootblower jet, the strength of the deposits, and the sequence and frequency of sootblowing [2,3].

At different locations in the boiler, deposits form differently. They may have different strengths 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 the 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^{o}C, the deposit is highly fluid. It tends to spread out when impinged by the sootblower jet, thereby absorbing most of the jet kinetic energy. As a result, the 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 the deposit, 520-620^{o}C (968-1148^{o}F), the deposit is brittle, and thus, 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 can be used to inspect deposit buildup in recovery boilers as well as to evaluate the 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. The present study focuses on the removal mechanism of brittle deposits, since they are the main type of deposits that contribute to fouling and plugging in the upper superheater, generating bank and economizer regions of recovery boilers. Understanding how brittle deposits are removed by a sootblower jet is of vital importance for devising strategies to improve and optimize sootblowing operation.

EXPERIMENTAL PROCEDURE

Experimental Setup

In this study the breakup process of model brittle deposits impinged by an air jet was examined using an experimental setup shown schematically in Figure 1. The air jet nozzle was a ¼ scaled-down version 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 passed through the nozzle via a solenoid valve. A pressure transducer at the nozzle inlet recorded the nozzle inlet air pressure. For each experiment, this pressure was maintained as constant 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, a model deposit was placed normal to the centerline 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/s): one was placed on the front side (the impingement side) of the deposit and the other on the back side. The cameras were synchronized so that the breakup of the front and back surfaces of the deposit was captured 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].

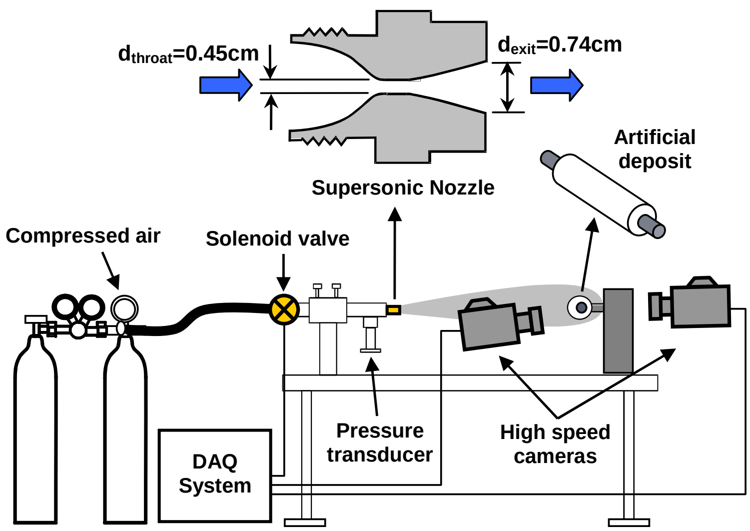

Figure 1. Experimental Setup.

Model Deposits

Model deposits were prepared by mixing plaster of Paris ($CaSO_4 \bullet ½H_2O$) and water. Plaster slurry was used since it can be easily cast into desired sizes and shapes using appropriate moulds. 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 gypsum 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, whereas 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. Symmetric 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 mould. The diameter of the mould determined the thickness of the deposits. Thin deposits had a thickness of 0.32 cm (1/8"), while thick deposits were twice as thick, 0.64 cm (1/4"), as shown in Figure 2a. Asymmetric deposits were prepared in the same way as symmetric deposits, except that the steel tube was placed away from the centre of the Plexiglas mold (Figure 2b). It was necessary to examine the effect of asymmetry because in recovery boilers, carryover deposits tend to form on the leading edge of the boiler tubes; they are usually asymmetrical rather than symmetrical.

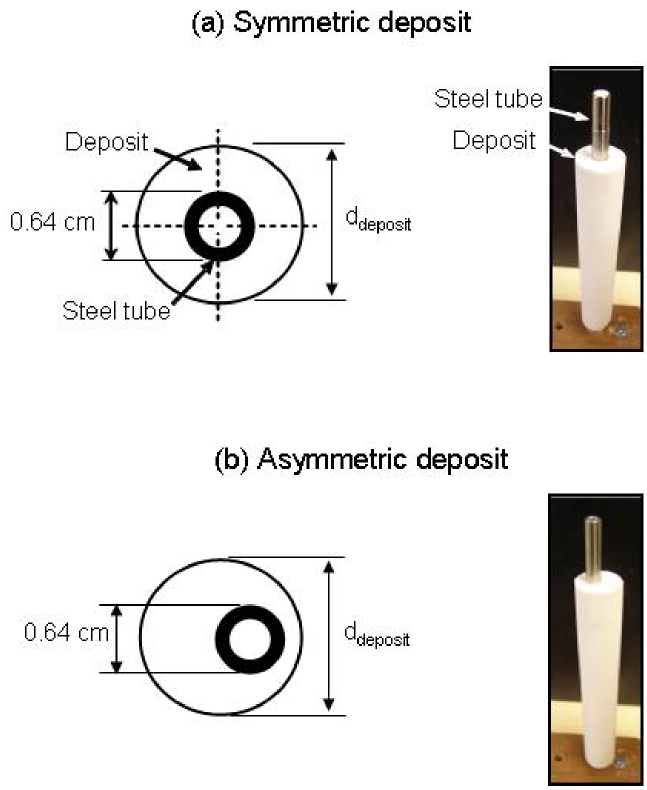

Figure 2. Cross-sections and photographs of thick deposits; (a) symmetric and (b) asymmetric.

After the cast plaster slurry hardened, the deposit was removed from the mould and dried in an oven at 60°C for 1 hour. The resulting gypsum deposit was used in the breakup experiment. Breakup tests were performed by placing the deposit at a distance 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 asymmetric deposits, the deposit orientation angle, ζ, was also considered. As shown in Figure 3, ζ = 0° refers to tests in which the air jet was oriented directly at the thickest point of the deposit, while ζ = 90° was when the jet was oriented at the midpoint between the thinnest and the thickest points of the deposit.

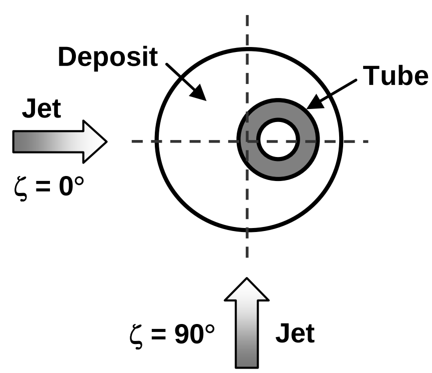

Figure 3. Deposit orientation angle, ζ.

RESULTS AND DISCUSSION

Symmetric Deposits

Effect of Deposit Thickness

Figure 4a shows the breakup images at selected times of a thin deposit (η = 2) placed at 9 cm (3.5”) from the nozzle. 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 became deeper and larger (t = 0.5 ms), a 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 ms. A similar breakup mechanism was observed for all thin deposits.

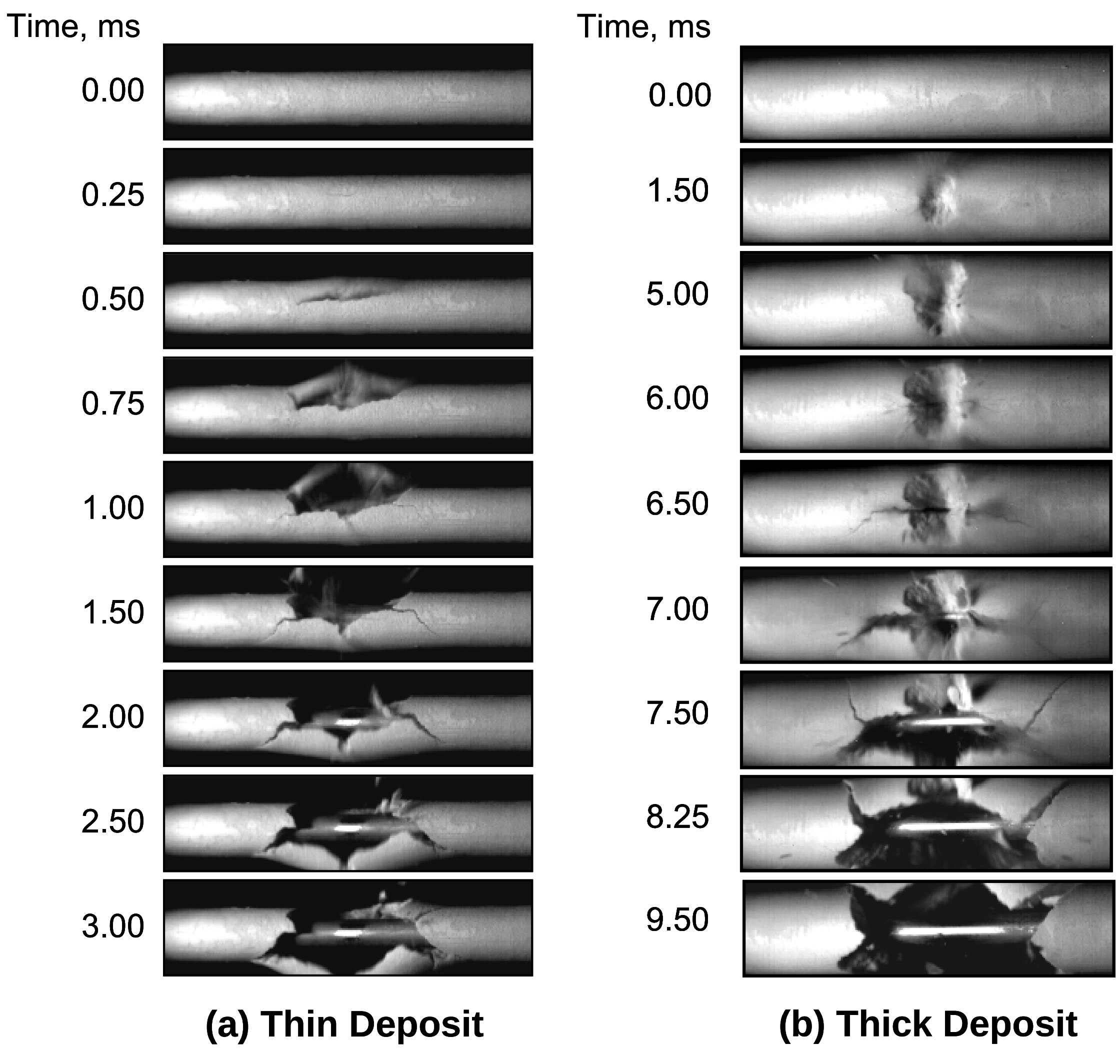

Figure 4. Breakup images of (a) thin and (b) thick deposits (η = 2) placed 9 cm from the nozzle.

Figure 4b shows the breakup images of a thick deposit placed 9 cm (3.5”) from the nozzle. In this case, the breakup started with surface pitting as the jet drilled its way into the deposit, from the surface inwards (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 difference was due mainly to the time that was 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

Figure 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 Figure 4b. The jet could only drill a small hole in the deposit, but could not generate an axial crack. Once the hole became sufficiently deep and large, breakup occurred rapidly, without the formation of axial cracks.

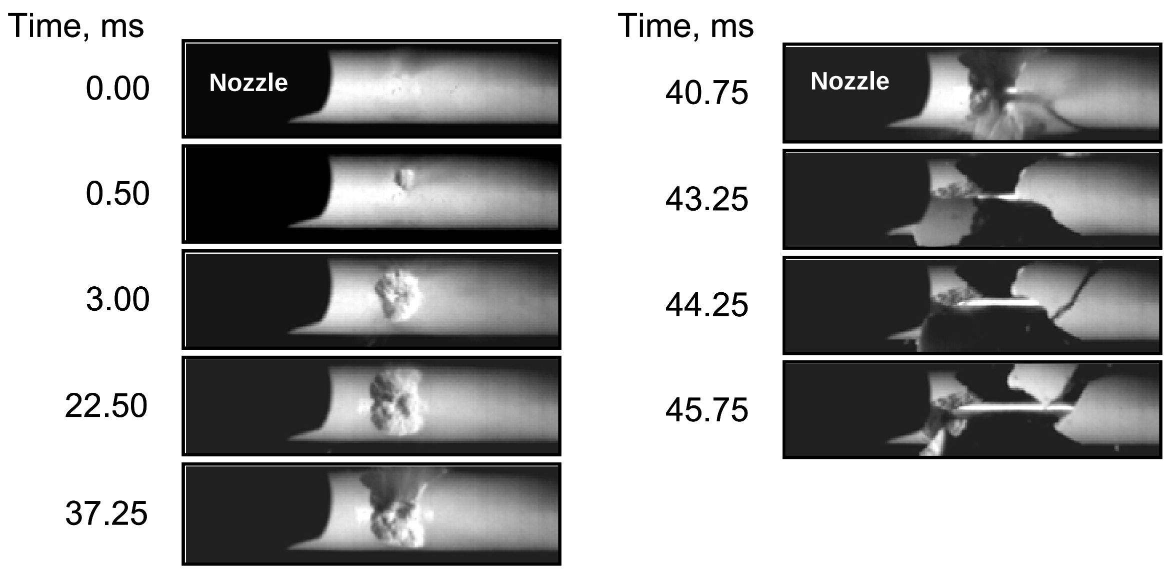

Figure 5. Breakup images of a thick deposit ($\eta = 2$) placed 5 cm from the nozzle.

Effect of Deposit Strength

Breakup tests were also performed 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 η=1.5 (σ_t=0.9 MPa) were stronger; only thin deposits could be removed at 5 cm from the nozzle. Deposits with η=1 were so hard that they could not be broken under any experimental condition.

Figure 6 shows breakup images of five thin deposits at two different time instants, 1 ms and 10 ms, after the onset of breakup. These deposits were prepared with different η values and were placed 9 cm away from the nozzle. Deposits prepared with η = 2, 1.8 and 1.65 broke completely in less than 10 ms, whereas deposits with η = 1.5 and 1 did not break at all. Similar results were obtained for thick deposits placed at 9 cm from the nozzle. When placed 12 cm from the nozzle, thick deposits with η = 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 effective diameter of the jet and the strength of the deposit.

Table 1. Time, in milliseconds, after onset of breakup required for axial cracks to form in thin deposits (in parentheses, time required for complete breakup).

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

NB: Did Not Break

Table 2. Time (in milliseconds) after onset of breakup required for axial cracks to form in thick deposits (in parentheses, time required for complete breakup).

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

NB: Did Not Break

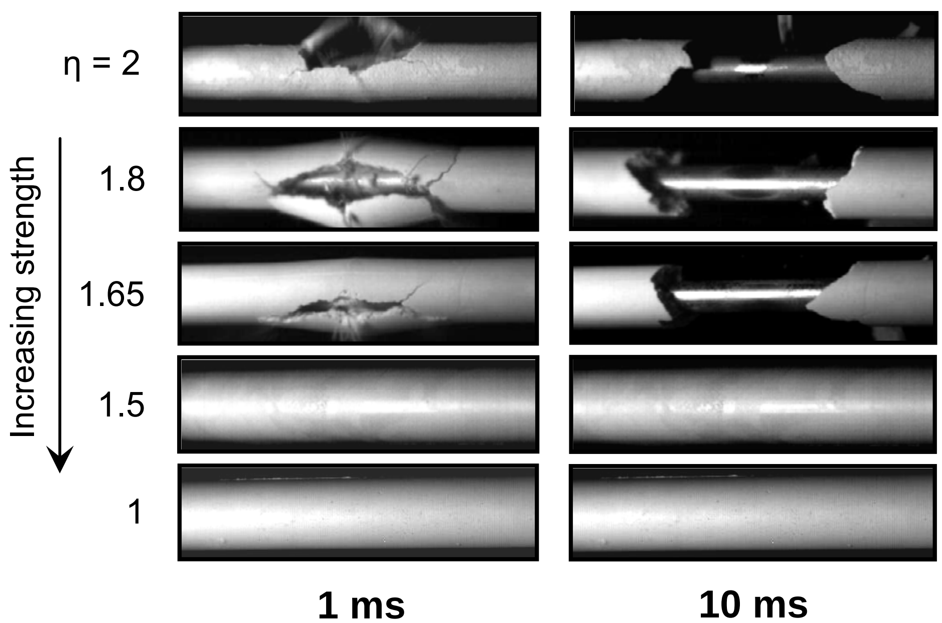

Figure 6. Breakup images of thin deposits prepared with different η values, at 1 and 10 milliseconds after the onset of the breakup process. Deposits were placed 9 cm from the nozzle.

Asymmetric Deposits

Breakup experiments were also performed on both thin and thick asymmetric deposits. Since similar results were obtained for both cases, only results for a thin deposit with η = 2 are presented here. Figure 7 shows the breakup images at selected times of a thin asymmetric deposit placed 9 cm from the nozzle for two jet orientation angles: ζ = 0º and 90º (Figure 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 (Figure 7a). The breakup behavior was similar to that of the symmetric deposit (Figure 4b), except that it took longer for the axial crack to form in the asymmetric deposit. This is understandable since in this case, the deposit was thicker on the front side due to asymmetry and hence required more time to crack. At ζ = 90º, the deposit was struck by the jet from the side (Figure 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).

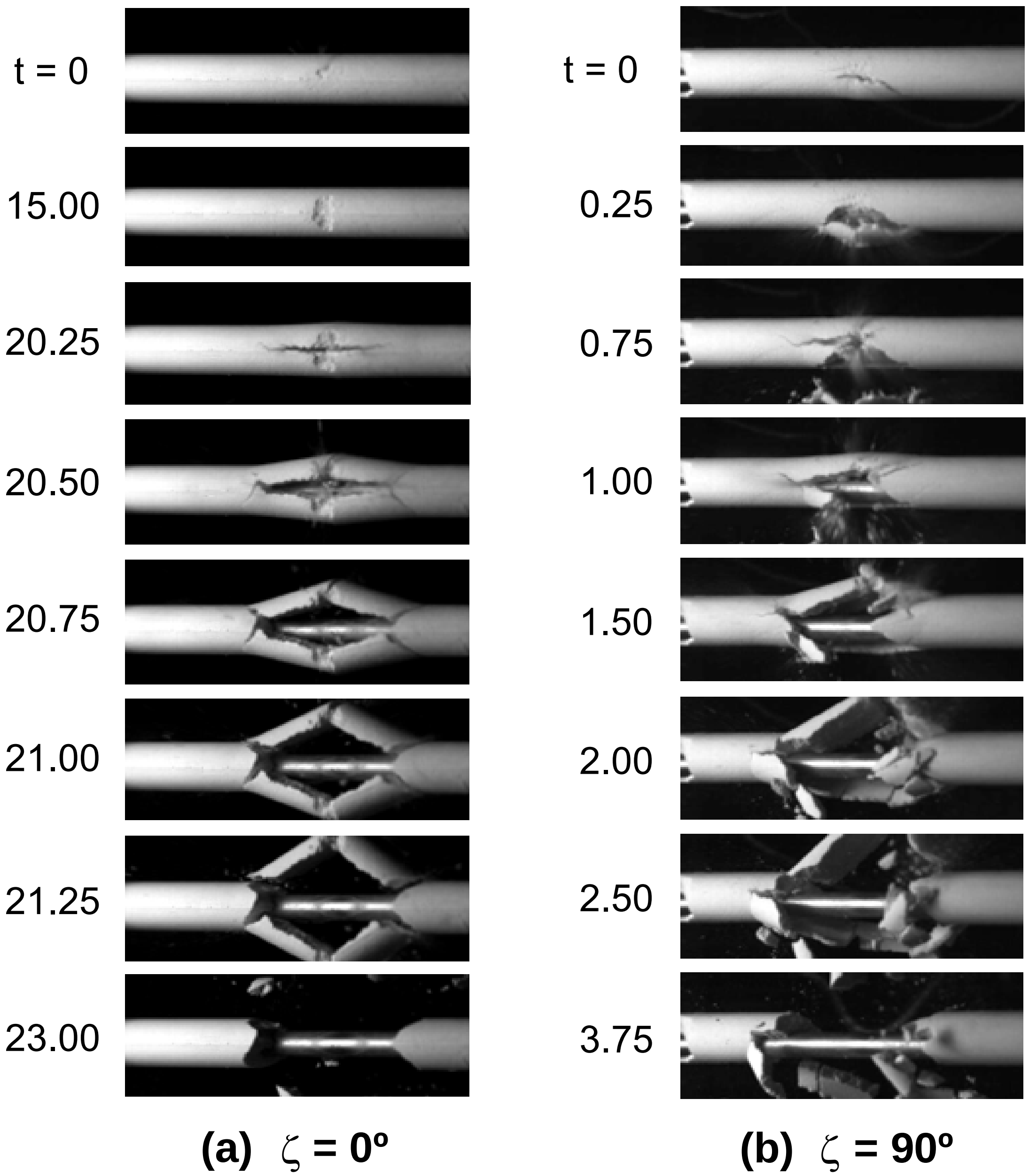

Figure 7. Breakup images at selected times of a thin asymmetric deposit (η = 2) placed 9 cm from the nozzle exit; (a) ζ = 0º; (b) ζ = 90º.

Breakup Process

Figure 8 shows breakup images of a thin brittle deposit with $\eta = 2$ and placed 5 cm from the nozzle. The breakup process was documented using two high speed cameras operated simultaneously from the front side and the back side 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.

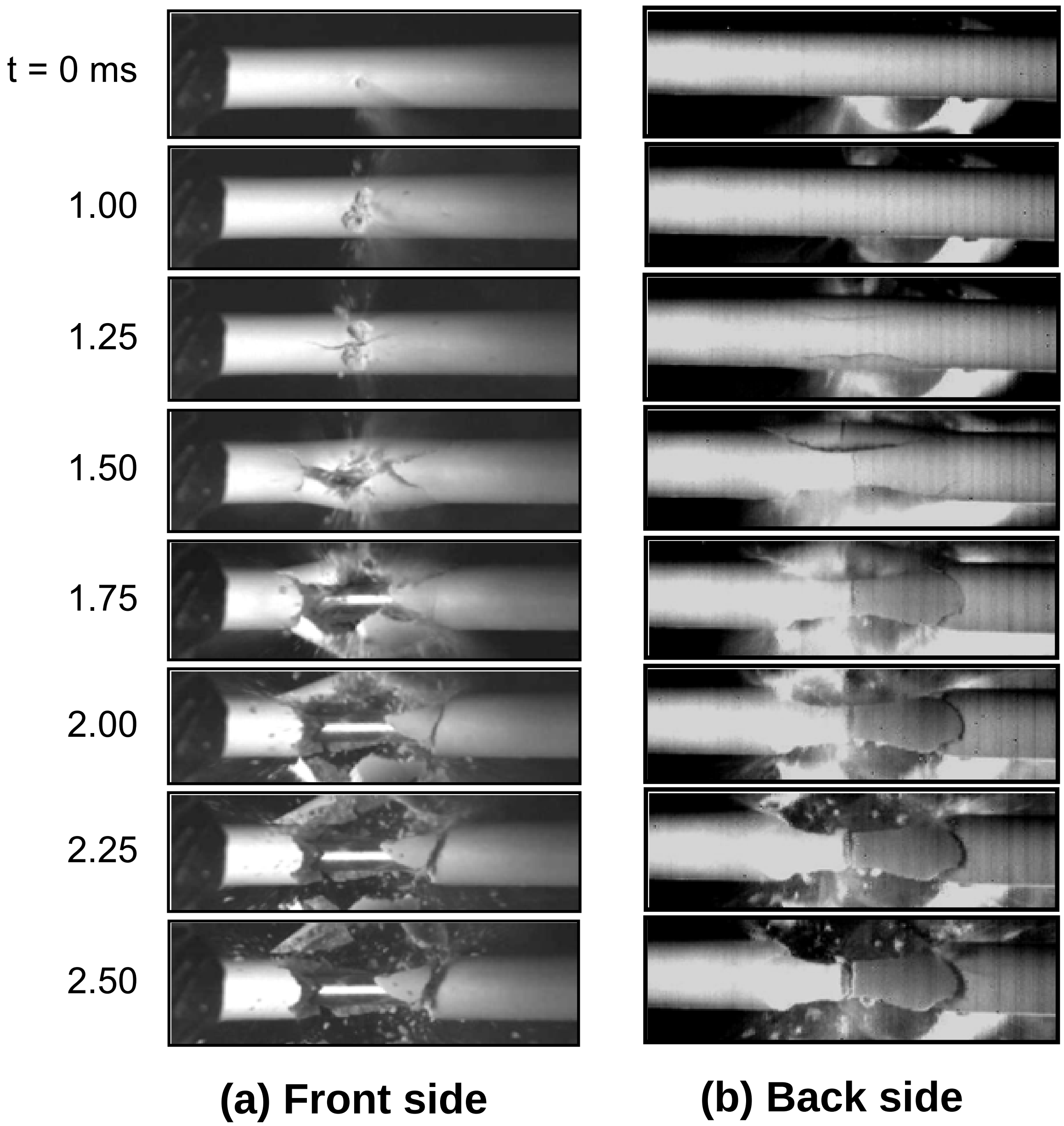

Figure 8. Breakup images at selected times of a thin symmetric deposit ($\eta = 2$) placed 5 cm from the nozzle exit: (a) Front side and (b) Back side.

Based on the breakup images of thin, thick, symmetric and asymmetric 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 becomes 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, it is stronger but has a smaller effective diameter. Thus, depending on the distance between the deposit and the jet nozzle, the ability of the jet to remove the deposit may vary. If the effective diameter of the jet is larger than the width of the deposit, the jet can rapidly remove the deposit 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, the jet can still drill a deep hole in the deposit, but cannot crack it. Without causing cracks to form, the jet may still be able to remove the deposit, but this will take a much longer time. If the deposit is too hard for the jet to drill holes, make cracks and penetrate, it will not break.

PRACTICAL IMPLICATIONS

If the breakup mechanism of brittle model deposits obtained in this study is applicable to actual conditions in kraft recovery boilers, it provides 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 impact force of the sootblower jet. This makes it difficult for cracks to form in the deposit. As a result, the 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 first melting temperature. The deposit is brittle but hard; it may 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 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 that the entire deposit may be debonded from the tube as a result of 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

A laboratory study was performed to examine the breakup mechanisms of brittle gypsum deposit samples impinged by a supersonic air jet. The 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 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.

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