VISUALIZING THE INTERACTIONS BETWEEN A SOOTBLOWER JET AND A SUPERHEATER PLATEN

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ABSTRACT

Laboratory experiments were performed using a schlieren optical technique combined with high-speed imaging to visualize the interactions between a supersonic air jet and single and multiple tubes, meant to represent deposits and superheater platens. The results show that upon impingement on a tube, the primary jet terminates in a shock wave, and gives rise to a weaker secondary jet. This jet increasingly deviates from the original flow direction and becomes weaker as the interaction of the primary jet with the tube becomes stronger. As a result, there is little sootblower jet flow beyond the first few tubes of a platen whenever there is any interaction between the jet and the first tube. The results also show that it may be possible to clean superheater platens more effectively with slightly inclined nozzles in order to exert a greater debonding force on deposits. An inclined jet yields more direct but also more complicated jet-platen interactions than a straight jet, due to the formation of complex shock and expansion waves.

INTRODUCTION

In kraft pulp mills, black liquor is burned in recovery boilers to recover chemicals and to produce steam and power for use in mill processes. Unfortunately, due to the high ash content in the black liquor, fouling of heat transfer tube surfaces is a persistent problem. Deposits lower the boiler thermal efficiency, cause tube corrosion, and in severe cases, lead to unscheduled boiler shutdowns for water wash [1]. As a result, control of deposit build-up is of vital importance to recovery boiler operation. The means of control is by sootblowers, which use supersonic steam jets to blast deposits off of the tubes (Figure 1). However, sootblowers consume a large amount of valuable high pressure steam generated by the boiler, and thus must be used efficiently.

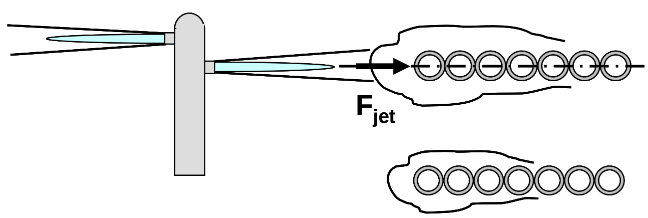
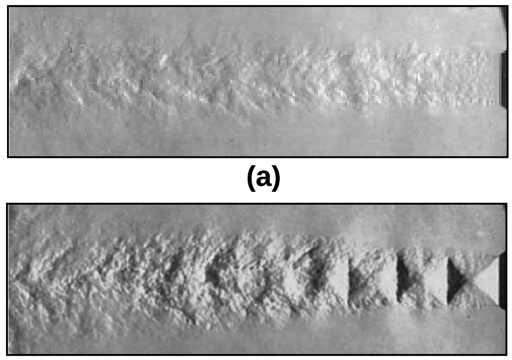


Figure 1. Sootblower in action.

Jet peak impact pressure (PIP) and jet force are the two main attributes of a sootblower jet, by which the jet erodes a deposit, and either shatters it into pieces, or debonds it from the tube as a chunk. Maximum impact of the sootblower jet onto a deposit is desired, which only occurs if the jet impinges directly on the deposit as a free jet. However, in a boiler, the sootblower jet must also propagate between superheater platens, generating bank tubes and economizer tubes. The tube arrangement and spacing in each of these sections is quite different, with large spacing in the superheater and small spacing in the generating bank and economizer. These tubes act as obstacles to the jet flow, and in some cases, may completely block the jet, preventing it from reaching a deposit. Furthermore, the size and shape of a deposit will also affect sootblower jet flow around it.

Fluid jets encountered in many day-to-day industrial applications are either incompressible or low subsonic (Mach number much smaller than 1). Strong compressibility effects, such as shock waves, are absent in such jets. Figure 2a shows an instantaneous image of a subsonic jet exiting from a converging nozzle [2]. The image shows only the presence of turbulence in the jet identified by variations in light intensity. By contrast, compressibility effects are dominant in a supersonic jet (Mach number greater than 1). As a result, its structure is very sensitive to small disturbances in nozzle geometry and supply pressure, and such a jet is strongly affected by the presence of any obstacle in its path. Figure 2b shows an instantaneous image of a free supersonic jet. In addition to turbulence, expansion and compression waves can also be seen in the core of the jet, which form because the supply pressure is slightly off of the design pressure of the nozzle. These waves cause the PIP and static pressure in the jet core to oscillate significantly, and lead to a loss of jet energy. As well, any obstacle in the path of a supersonic jet will create a series of complicated shock and expansion waves, which directly affect the jet structure, and hence jet strength and penetration.



(a)

(b)

Figure 2. (a) Subsonic jet; (b) supersonic jet (taken from [2]).

Therefore, studying the interaction between the jet and tubes is necessary for understanding the operation of sootblowers inside a boiler. At times during operation, the sootblower jet flows exactly between two platens of tubes, and at times, it impinges on the tubes, either head-on or at some offset. Such interactions with tubes will affect the sootblower jet structure and penetration between platens. As a result, the jet PIP and force exerted on the deposits will be reduced, and this in turn will lower the sootblowing efficacy. An understanding of these interactions can help identify strategies to operate and improve sootblowers, to maximize deposit removal efficiency.

Earlier sootblowing studies have concentrated on understanding sootblower jet dynamics [3,4] and deposit properties such as tensile strength [5], and some laboratory scale experimental work has been done to visualize brittle deposit breakup by a supersonic jet [6,7,8]. In the aerospace field, studies have been conducted to understand the interaction between a supersonic jet and a flat solid surface (horizontal and inclined) (see for instance, [9] and [10]). However, the interaction between a supersonic jet and a tube or a tube bundle has not been studied previously. This work, for the first time, visualizes this interaction to yield valuable information about the flow field, such as the disturbances caused by jet/tube interaction, and the penetration of a jet between tubes. This work allows us to corroborate and explain previous findings, and to evaluate current sootblowing practices. Specifically, the present work focuses on the interaction between a supersonic jet and model superheater platens, as well as single tubes of various sizes to simulate hard deposits, characteristic of the superheater section.

Supersonic jets cannot be seen by the naked eye, or visualized with regular photographic equipment. The only way to visualize such jets is by taking advantage of the unique flow characteristics of supersonic flow, such as shock and expansion waves. These waves create strong density gradients, and consequently, refractive index gradients in the jet fluid. Such refractive index gradients can be captured by the schlieren optical technique, which uses parallel light to intensify the gradients relative to their surroundings, and thus makes the jet and its interaction with tubes visible.

The objective of the present work was to visualize and document the flow of a supersonic jet impinging onto geometries characteristic of sootblower use in the superheater section of a recovery boiler. For this purpose, we performed scaled-down experiments in the laboratory to visualize the impingement of an air jet onto: (i) a single scaled-down superheater tube, (ii) larger single tubes to represent tubes with deposits, and (iii) a model superheater platen. We adopted the schlieren technique combined with high-speed photography to visualize the interaction. Results of these experiments are presented in this paper. We also conducted a preliminary study of the possibility of using inclined sootblower nozzles as an alternative to conventional straight ones. Sootblower jets from inclined nozzles may exert a greater debonding force on deposits that form between platens, and on the large, hard deposits that can only be removed by debonding from the tubes. However, compared to jets from straight nozzles, jets from inclined nozzles will not penetrate as far between platens. We obtained schlieren images of such interaction, and studied the effect of nozzle inclination angle on jet penetration by formulating a simple mathematical model. These results are also presented here.

EXPERIMENTS

Nozzle and Tube Apparatus

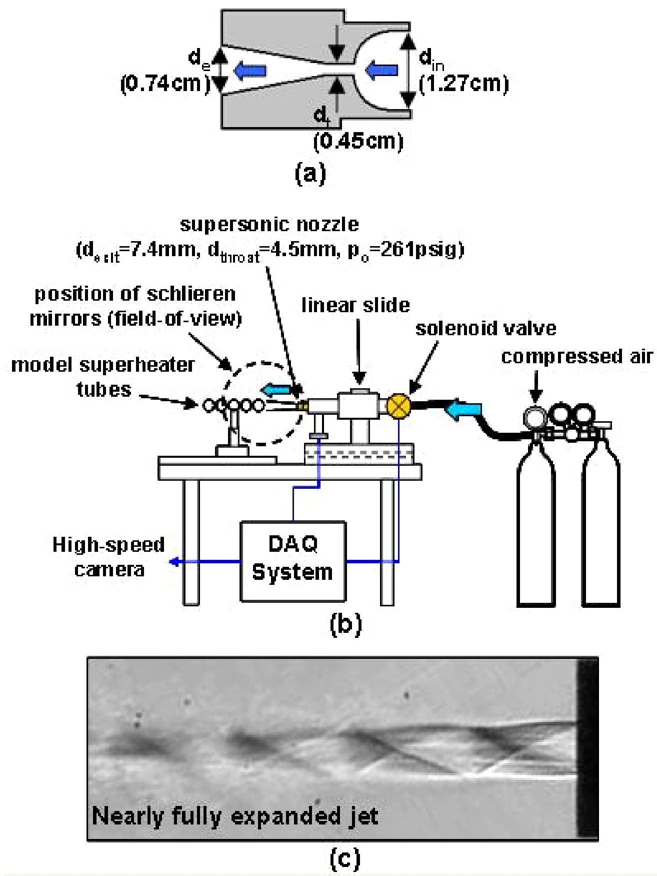


Figure 3. (a) Schematic of supersonic nozzle used in the experiments; (b) experimental setup; (c) schlieren image of supersonic jet used in the experiments.

The main components of the experimental setup were ¼ scaled-down models of a typical sootblower nozzle, a superheater tube, and a superheater platen. We represented deposits with steel tubes of different diameters, as using actual deposits (that could shatter) posed a danger to the delicate schlieren mirrors. The conical nozzle, shown schematically in Figure 3a, has a throat diameter 0.45 cm (0.18") and exit diameter 0.74 cm (0.29"). This nozzle yields a jet exit Mach number of 2.53, similar to that of an actual sootblower jet.

Figure 3b shows the experimental setup. Compressed air from cylinders was supplied to the nozzle through a solenoid valve. The supply pressure was set such that, accounting for friction losses through the tubing, the pressure at the nozzle inlet yielded an almost fully expanded jet. The static pressure close to the nozzle inlet was measured by a pressure transducer. Figure 3c shows a typical schlieren image of a jet. Weak compression and expansion waves can be seen inside the jet because of the slight difference between the jet static pressure at the nozzle exit and the ambient static pressure. Due to the high velocity of a supersonic jet, we employed a high speed camera to capture and record the steady-state and transient flow fields at a high temporal resolution of 6010 frames/s, with 166 µs exposure time. A special aluminium assembly was constructed to position the supersonic nozzle and tubes. The camera, solenoid valve, and pressure transducer were controlled using Labview data acquisition system.

Schlieren Optical System

The operating principle of the schlieren technique is that parallel light rays refract as they pass through optical inhomogeneities, such as density gradients, in a transparent medium. Supersonic gas jets exhibit such density gradients. For a gas, the local value of the refractive index is directly proportional to the local value of the density, as per the Gladstone-Dale relationship [11]. These density gradients give rise to refractive index gradients in the surrounding medium. When light passes through an optically inhomogeneous medium, the refractive index gradients cause the light rays to bend in different directions and this refraction can be captured as a schlieren image.

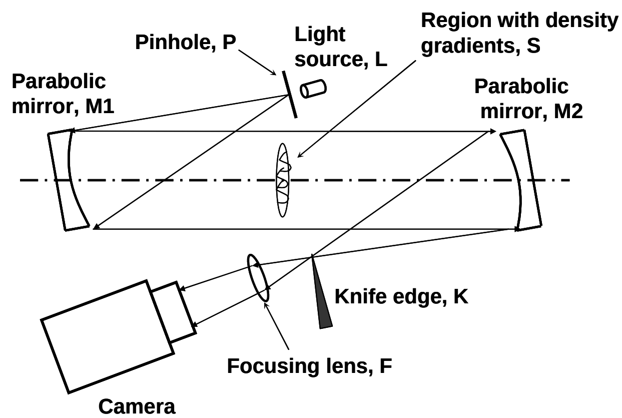


Figure 4. Schematic of a conventional 2-mirror schlieren system (adapted from [11]).

Figure 4 shows the conventional 2-mirror schlieren system used in the present work. A light source, L, is placed at the focus of a concave mirror, M1. Light from L passes through a pin-hole, P, and a conical, diverging set of light rays proceeds to M1. The light rays are collimated by M1 and sent through the test section, where they encounter the density gradients, S, within the supersonic jet, which cause the light rays to refract in different directions. These rays, along with other parallel rays reflect off a second concave mirror, M2, which refocuses them. A knife edge is placed at this focal plane to reduce the deflected light rays. The remaining light rays then proceed to the focusing lens F, which creates a schlieren image of S on a camera sensor.

All optical components were aligned as shown in Figure 4. A continuous halogen light source with homogeneous brightness was used. The two concave mirrors have a diameter and hence a field-of-view of 14 cm (5.5 in). The mirrors have a focal length of 152.4 cm (60 in or 5 ft). The knife edge was oriented vertically and placed near the camera lens.

Experimental Program

Experiments involved impingement of a supersonic jet on four types of obstacles – 3 single steel tubes of 1.27 cm (0.5 in), 1.91 cm (0.75 in) and 2.54 cm (1 in) outer diameters (OD), and a small platen consisting of five 1.27 cm (0.5 in) OD steel tubes welded together. We also studied jet flow between two such platens. The smallest diameter tube (1.27 cm) can be considered 'clean', whereas the larger tubes can be thought to represent increasingly thick deposits. The variables considered in the experiments were: (i) tube size (d_T), (ii) offset (x), defined as the distance between the tube/platen centerline and jet centerline, (iii) distance between the tube surface and nozzle exit plane (z), and (iv) jet inclination angle (α) relative to the platen centerline. These are illustrated in Figure 5. In the experiments, distance z was set to 5, 9 and 12 cm. The offset x was varied by 0.2 cm increments. The platen inclination angle was set to 0°, 9° and 13°.

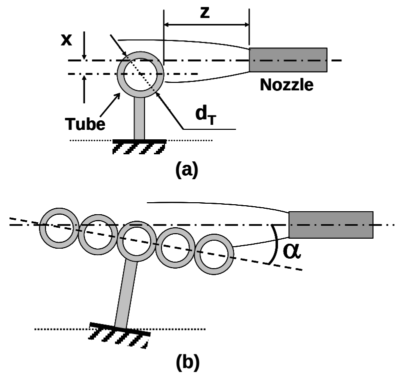


Figure 5. Definition of operating parameters; (a) offset x, tube size d_T, and jet-tube distance z; (b) platen inclination angle, α.

RESULTS AND DISCUSSION

Jet Impingement onto Single Tubes

Figure 6 shows schlieren images of a jet impinging onto three tubes of increasing size. The tubes were located within the potential core of the jet (i.e. within about 10-15 nozzle diameters of the nozzle exit). Hence, the jet core is visible in these images, and expansion and compression waves can be seen in the core, forming diamond-shaped cells. As mentioned earlier, these waves form because the jet static pressure at the nozzle exit is slightly higher or lower than the ambient pressure outside the nozzle. In reality, it is very difficult to achieve a nozzle exit static pressure exactly equal to the ambient pressure, that will yield a fully expanded jet that makes most efficient use of the flow energy. The core has maximum PIP, as can be seen in Figure 7, which presents the jet centerline PIP distribution [12], and is considered to be the most important region of the sootblower jet for removing deposits. Oscillations in the PIP distribution of Figure 7 are caused by the expansion-compression waves. The jet entrains air from its surroundings, which cannot be seen in the images. Due to this entrainment and mixing, the jet core dissipates within 10-15 nozzle diameters downstream of the nozzle exit, and the jet then spreads radially.

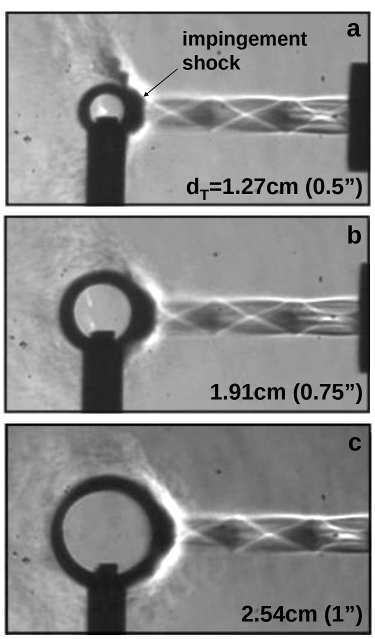


Figure 6. Effect of tube size (d_T) on jet-tube interaction.

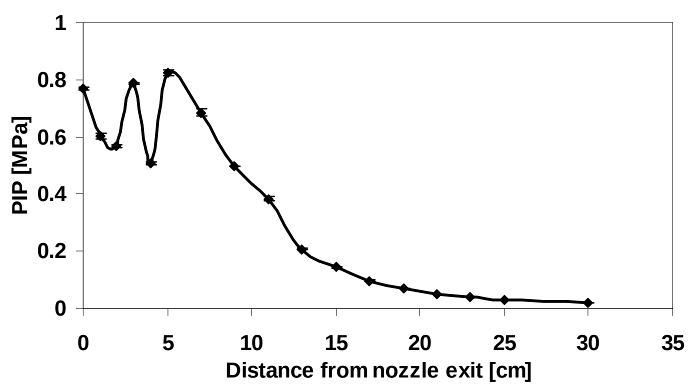


Figure 7. Peak impact pressure (PIP) along centerline of jet (taken from [12]).

Returning to Figure 6, when the primary jet impinges on a tube, a strong impingement shock forms just upstream of the tube as can be seen in all three images. As shown in image *a*, one can observe two small secondary supersonic jets that form (although the lower secondary jet cannot be seen because of the tube stand). As the primary jet is supersonic and the tube size is small, the secondary jets are also supersonic, and propagate at some angle to the original flow direction. These images of jet separation are consistent with previous results for incompressible jets impinging onto a cylinder [13,14]. Separation occurs when the tube is located in the potential core of the jet, and when the jet is smaller than the tube. As the tube size increases, the secondary jets cease to separate from the tube surface, and a weaker flow (attached to the surface) is observed around the tubes.

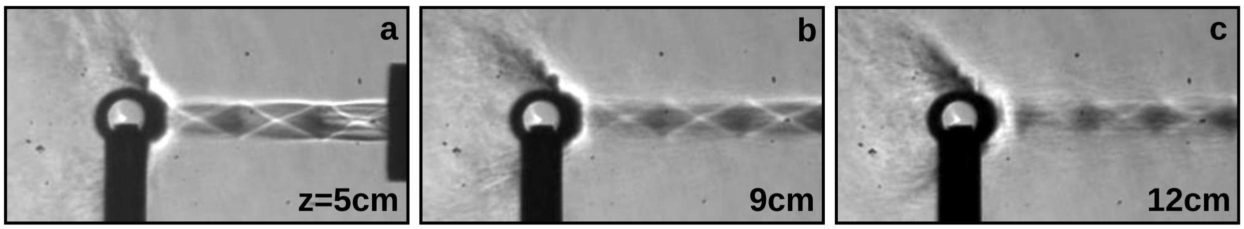


Figure 8. Effect of distance between nozzle and tube on secondary jets.

Figure 8 shows images of the jet impinging on the smallest tube when placed at different distances from the nozzle. Notice that as the jet length increases, the secondary jet deviates less from the original flow direction. This is understandable, because the jet strength decreases with distance from the nozzle exit. As secondary jets do not form when impacting the two larger tubes, images of jet-tube interaction when the tubes were placed further yet from the nozzle are not presented.

Jet Impingement onto a Single Platen and Flow between Two Platens

To simulate the flow of a sootblower jet over superheater platens, images of a jet impinging onto a single platen at different offset values were recorded, and are presented in Figure 9. At zero offset, or head-on impingement (image *a*), the primary jet splits into the two symmetric secondary jets described earlier. As the offset increases (images *b-d*), one of the secondary jets becomes weaker (the lower jet in this case) while the other becomes stronger, and its deviation from the original flow direction decreases. As the offset increases further, the interaction between the jet and tube quickly becomes weak (images *e-g*), and at some offset, the jet no longer interacts with the platen (images *h* and *i*). Since the strength of the secondary jet decreases and its deviation from the original flow direction increases when the interaction between the primary jet and tube becomes strong, there is little or no jet flow at all beyond the third or fourth tube in the platen whenever a secondary jet forms, as can be observed in the images. This means that when sootblowing in the superheater section of a boiler, there is little or no jet flow beyond the first few tubes of a platen whenever there is some interaction between the jet and the first tube of the platen. The core length of the secondary jet appears to be much smaller than the spacing between two platens. Hence, it is unlikely that a secondary jet will be of any use in removing deposit from an adjacent platen.

The flow of a jet exactly between two model superheater platens is shown in Fig. 10a and clearly illustrates that there is no interaction between the platens and the jet. The jet propagates undisturbed between the two platens. Noticeable interaction between the jet and platen takes place only when the jet actually ‘touches’ the platen, as shown in Figure 10b, which is similar to image *g* in Figure 9. Thus, if the jet is too far from the platen, then there is no interaction between the jet and platen. Consequently, deposits that have accumulated on the platen will not ‘feel’ the sootblower jet, and sootblowing effectiveness will drop, unless the deposit extends into the middle of the passage between the platens. Figure 10 suggests that the use of inclined sootblower nozzles, to direct a jet onto a superheater platen at an angle, could be an effective alternative to the currently used straight nozzles. This is the topic of the next section.

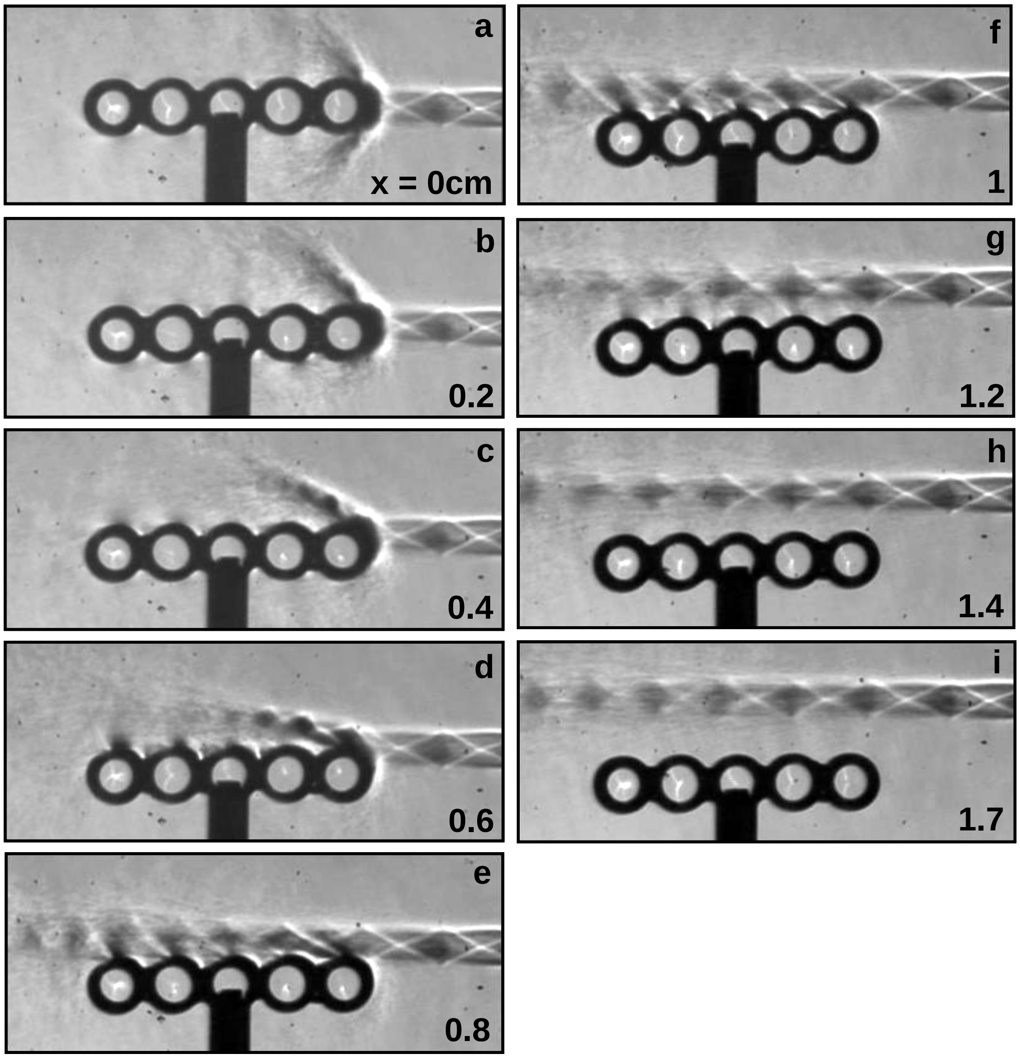


Figure 9. Jet impingement onto a platen at different offset values (x cm).

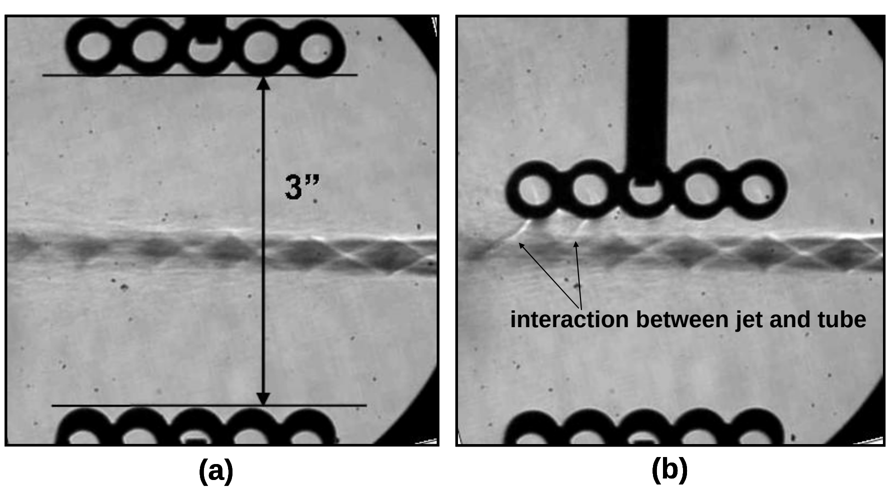


Figure 10. (a) Jet between two platens – no interaction; (b) jet touching one platen – interaction can be seen.

Impingement of an Inclined Jet onto a Platen - Effect of Inclination Angle α

Currently used sootblower nozzles are oriented normal to the sootblower lance, as shown in Figure 1. Thus, during operation, the sootblower jet impinges 'head-on' to the deposits formed on the first tube of a platen, and pushes the deposit against the tube. If the deposit is strong, the stresses induced by the jet impingement will not be sufficient to break it. Such a deposit will act as a site for further deposit accumulation that will eventually lead to plugging of the flue gas passage.

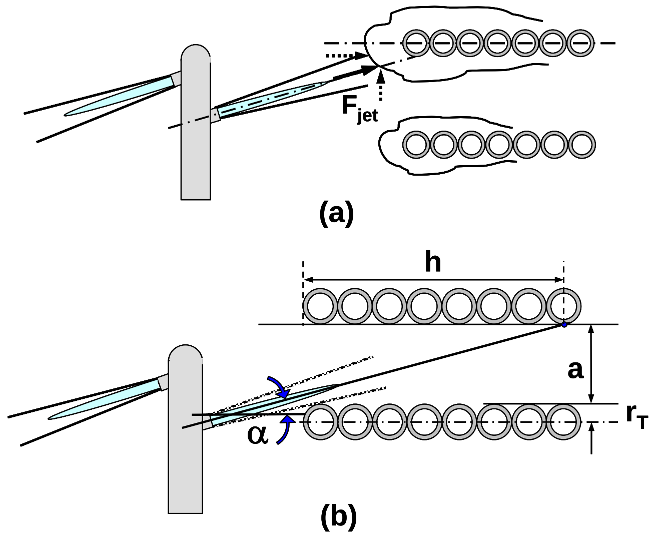


Figure 11. (a) Sootblower jet from inclined nozzles; (b) loss in jet penetration between platens due to inclination angle, α.

If a sootblower nozzle were inclined at some angle relative to the lance, as shown in Figure 11a, then a component of the jet force would act normal to the platen centerline, and exert a debonding force. Impingement of the jet on deposits accumulated on the sides of the platen would also be more direct than for jets from straight nozzles. On the other hand, inclined jets would penetrate less far into the platens. Nevertheless, there may be an optimum inclination angle at which a large debonding force may be obtained, with little loss in penetration. Hence, the objective of the following analysis was to assess the possible use of inclined nozzles to clean superheater platens, and to determine the relationship between the nozzle inclination angle and the reduction in jet penetration.

A simple measure of the loss in jet penetration as a function of the inclination angle, α, is the reduction in the maximum length of the platen, h, which would feel the jet. A simple geometrical analysis involving the surface-to-surface distance between two platens, a, the tube radius, r_T, the nozzle inclination angle, α, and the nozzle exit diameter, d_e, yields the following expression for h:

$$h = (a \cot\alpha) - \left[\left(\frac{d_e}{2}\right) \operatorname{cosec}\alpha \right] + \left[r_T (\cos\alpha) \left[\tan\left(\frac{\alpha}{2}\right) + \cot\left(45 + \frac{\alpha}{2}\right) \right] \right] \quad \cdots (1)$$

for 0° < α < 90°.

The typical distance between two superheater platens in a recovery boiler is 25.4-30.5 cm (10-12 in); for the present calculation, we assumed a = 25.4 cm (10 in). From schlieren images of scaled-down supersonic jets obtained in the laboratory, as well as theoretical considerations [3], it can be shown that the effective diameter of the jet close to the nozzle (~7 nozzle diameters) is almost the same as the nozzle exit diameter, d_e. The typical value of d_e for commercial sootblower nozzles is 3.18 cm (1.25 in). The typical superheater tube radius is 2.54 cm (1 in). Applying these values to equation (1), Figure 12 illustrates h as a function of α. Obviously, h → ∞ as α → 0, which corresponds to straight jets; in practice, the jet would diffuse completely within a finite distance. At high values of α, very low values of h are obtained, as expected.

However, there is a range of α that yields penetration depths h that would be long enough to fully cover a superheater platen. The typical length of superheater platens in a recovery boiler is about 1.5 m. Since sootblowers are operated from both sides of the platen, the required cleaning radius for each sootblower can be considered as half of the platen length, or 75 cm. From equation (1), h = 75 cm corresponds to α ≈ 17°. Thus, it would seem feasible to use a 17° inclination to exert greater debonding force on deposits, yet still clean half of a platen, without affecting the jet cleaning power or PIP.

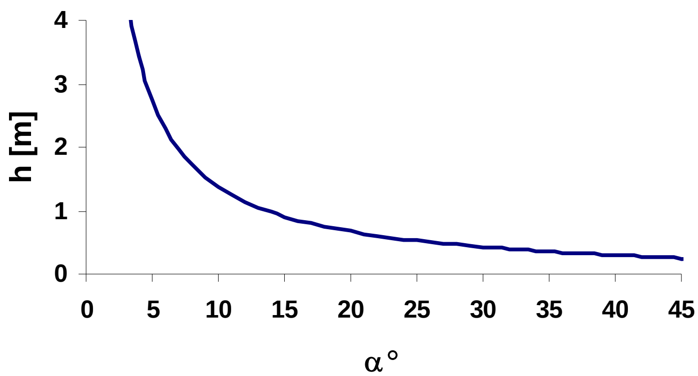


Figure 12. Behaviour of h as a function of α.

The schlieren technique was also used for a preliminary investigation of the flow field of inclined jets impinging on a platen. In the experiments, the platen position was adjusted, rather than the nozzle orientation, to achieve different inclination angles. Schlieren images are presented in Figure 13. Compared to the interaction at α = 0° (offset = 1 cm, Figure 13a), the jet-platen interaction at 9° and 13° is more direct, but also more complicated. Due to inclination, the jet impinges more directly on the side of the platen, and so a greater PIP will be exerted on deposits accumulated in this region. Such interaction is not possible with a straight jet. Following impingement, the jet reorients to the direction of the platen via a complicated shock-expansion system. With increasing α, the shock-expansion system becomes stronger.

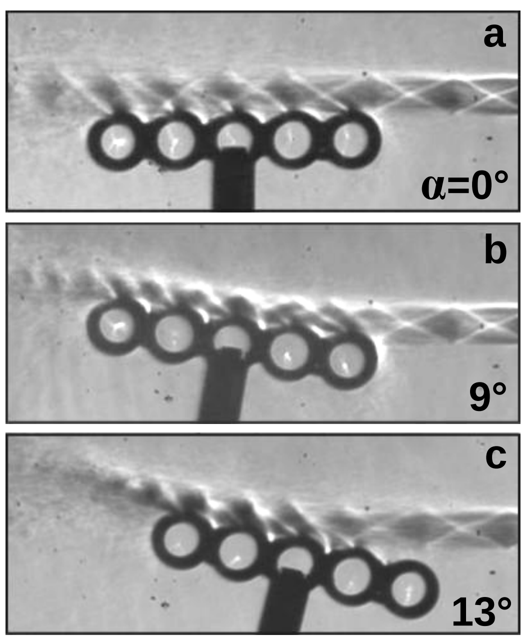


Figure 13. Effect of inclination angle α on the jet flow field.

CONCLUSIONS

A schlieren apparatus combined with high-speed imaging was used to examine the interaction between a scaled-down sootblower jet and single tubes of different sizes, as well as model superheater platens. This was done to simulate the jet-tube/platen interaction that occurs inside the superheater section of a recovery boiler, to determine the effects of tube and platen geometry on the jet structure and flow field. The results show that upon impingement on a tube, the primary jet terminates in a shock wave, and gives rise to a weaker secondary jet (two jets in the case of head-on impingement). The strength of this jet decreases and the deviation from the original flow direction increases as the interaction between the primary jet and the tube becomes strong (the jet impinges on a greater portion of the tube). This implies that whenever there is some interaction between the jet and the first tube of a platen, there is little or no sootblower jet flow beyond the first few tubes of the platen. Jets that impinge onto large deposits will not form secondary jets. A mathematical model was developed to study the effect of jet inclination angle on jet penetration between platens. The model suggests that it may be possible to clean superheater platens with slightly inclined nozzles, to exert greater debonding force on deposits. Visualization of impinging jets on platens revealed that an inclined jet yields more direct, but also more complicated jet-platen interactions than a straight jet, due to the formation of complex shock and expansion waves.

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