EFFECT OF LANCE PRESSURE ON SOOTBLOWER JET CHARACTERISTICS

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ABSTRACT

Fireside deposit accumulation in kraft recovery boilers is controlled by sootblowers, that remove deposits via high pressure supersonic steam jets. In this paper, we report the most recent results of the application of a CFD model to the interaction of jets with deposits, the application of the model to steam flow within a sootblower nozzle, and the incorporation of the model into the commercial CFD software Fluent, that makes this model much more accessible to the wider engineering community.

The model can now very accurately predict sootblower jet pressure and velocity for realistic off-design sootblower jets, as are encountered in practice when the supply pressure to the sootblower does not match the nozzle design pressure. These off-design jets are less efficient, and the way that they interact with deposits is more complicated than so-called fully expanded (or ideal) jets. Results to be presented include the effect of lance pressure and rotation rate on jet strength, and the characteristics of jet interaction with model tube bank geometries. We have also applied the model to examine flow through typical geometries of a sootblower nozzle. The results demonstrate the important link between nozzle geometry and the supply pressure required to generate a fully-expanded jet, and show that the supply pressure predicted by a simple isentropic gas dynamics relation significantly underestimates the required pressure.

BACKGROUND

Sootblowers are used to remove fireside deposits from heat transfer surfaces in kraft recovery boilers, and are of vital importance for maintaining the thermal performance and production capacity of the boilers. Sootblowers utilize boiler steam to generate an opposed pair of supersonic jets that are directed onto deposits; the efficacy of sootblowing is directly related to the jet strength (or force) exerted on a deposit during blowing.

In order to generate a supersonic jet, sootblowers are equipped with so-called "converging-diverging" nozzles that accelerate the flow past Mach 1; such flows are usually only seen in aerospace applications. Unlike a subsonic flow through any nozzle, a supersonic flow will not necessarily exit the nozzle at the ambient pressure. Instead, there is only one lance pressure that will yield a nozzle exit pressure equal to the ambient pressure; that pressure is referred to as the "design pressure" of the nozzle, and the corresponding jet is referred to as "fully-expanded". (Isentropic gas dynamics relations can be used to esimate the flow parameters associated with a fully-expanded jet.) A fully-expanded jet is characterized by a supersonic core within which the flow properties remain almost unchanged.

At any supply pressure other than the design pressure for a given nozzle, the resulting supersonic jet will be "off-design" because the jet pressure at the nozzle exit will be lower (over-expanded) or higher (under-expanded) than the ambient boiler pressure. Unlike a fully-expanded jet, off-design jets are characterized by a multi-cell shock structure downstream of the nozzle exit that consists of shock and expansion waves, that form as the jet adapts to the ambient pressure; as a result, the centerline pressure along an off-design jet fluctuates.

Over many years, experimental research at the University of Toronto has examined many aspects of sootblower operation. More recently, that research has also led to the development of computational fluid dynamics (CFD) models of a supersonic steam jet, that have been used both to corrobate experimental measurements of such jets, and to provide detailed information (on variations in pressure, velocity, density and Mach number) that cannot be readily measured. Until recently, all of our sootblower simulations were conducted using CFDLib, a CFD code developed at the Los Alamos National Laboratory, to which we added several turbulence model corrections [1-6] to accurately simulate sootblower jets operating over a wide range of conditions. We refer to the corrected turbulence model as the Sootblower Jet Turbulence (SJT) model, and to the improved code as CFDLib-SJT. The CFDLib-SJT code was validated by comparing numerical results to a wide range of available experimental data [1-3]; it successfully predicted all of the cases examined. The CFDLib-SJT code was also used to corroborate actual sootblower experimental data obtained from several sets of tests carried out by Andritz in recovery boilers in Sweden and Finland [7-8]. The simulation results yielded surprisingly good agreement with the measurements, given that the experiments were difficult to perform.

Over the past couple of years, we have incorporated most of the SJT model into Fluent, a commercial CFD code, via their User Defined Function (UDF) tool and the C++ programming language. Fluent offers the advantage of a friendly user interface and meshing capabilities that allow a user to define complex geometries much more easily than CFDLib. We refer to this improved version as Fluent-SJT. Fluent-SJT has been used to simulate many of the cases that were previously modeled using CFDLib-SJT. CFDLib-SJT and Fluent-SJT yield very similar results, indicating that the SJT model has been properly implemented into Fluent.

In this paper, we present a number of simulation results, most of them from Fluent-SJT, that examine the effect of lance pressure on sootblower jet characteristics, and in particular on the distinction between fully-expanded and off-design jets. Results of the effect of lance rotation rate and lance pressure on fully-expanded jets are presented first; then the effect of an off-design lance pressure is considered, followed by a study of the impact of off-design jets onto model geometries of superheater deposits; finally, the paper presents a preliminary study of flow through a sootblower nozzle, to consider the effect of the internal geometry of a nozzle on the steam flow, and the extent to which the actual flow deviates from that predicted by a simple isentropic gas dynamics relation.

THE EFFECT OF ROTATION RATE

During operation, a sootblower lance rotates slowly (at a few rpm) as it traverses into and out of a boiler, in order to maximize the interaction between the jet and the deposits that cover heat transfer surfaces. To assess the effect of the rotation rate on the overall jet dynamics, the CFDLib code was modified to take the rotation into account, by adding the Coriolis and centrifugal accelerations that result from rotation. A series of simulations were then run, of a fully expanded jet corresponding to a supply pressure of 236 psig, to assess the effect of different rotation rates. The results clearly showed that the effect of a typical sootblower rotation rate has a negligible effect on the jet structure. Figure 1 compares the centerline jet PIP versus distance from the nozzle for the case of a non-rotating jet with one that is rotating at 100 rpm, a rate that far exceeds actual practice. The difference is negligible, which should come as no surprise, as even at 100 rpm, the characteristic velocity associated with the lance rotation is orders of magnitude less than the characteristic jet velocity.

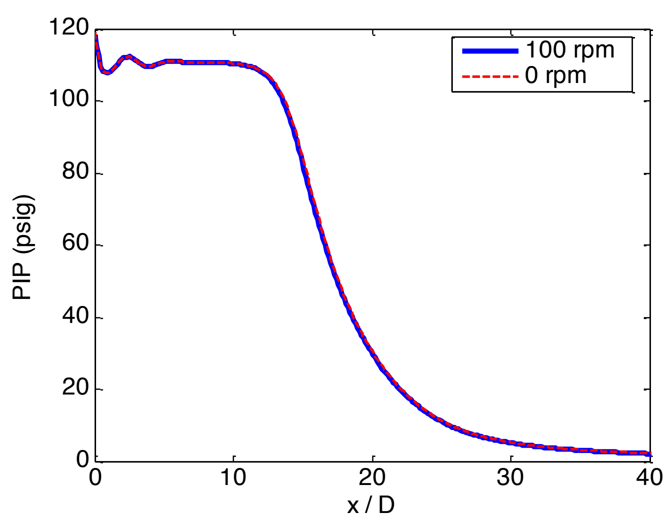

Figure 1. *The effect of lance rotation rate on jet centerline PIP. Even at a very fast 100 rpm, the effect of lance rotation is negligible.*

THE EFFECT OF LANCE PRESSURE

The effect of lance pressure on the performance of a fully-expanded supersonic sootblower jet was studied in two ways. First, different lance pressures (100 to 500 psig) were considered, while keeping the nozzle exit diameter constant (7.3 mm). As discussed earlier, any supersonic nozzle is associated with a single supply pressure that will yield a fully-expanded jet; as a result, these five jets are each associated with a different throat diameter within the nozzle (that can be estimated via the isentropic gas dynamics relations). Figure 2 (left) illustrates the results of that first study, the jet centerline peak impact pressure (PIP) versus lance pressure. (PIP is the pressure measured by a pitot tube inserted axially along a jet centerline, that represents the pressure that a sootblower jet will exert on a deposit.) Since the nozzle exit diameter was held constant, steam mass flow rate is the same for each jet, and the jet core lengths are similar, roughly 10-15 nozzle diameters in length. Beyond the core, the higher pressure jets decay more quickly, and thus the PIP curves converge further downstream. Finally, note that the PIP within the core (at the exit of the nozzle) does not scale linearly with lance pressure. This is because a supersonic flow forms a normal shock just upstream of any obstacle (like a pitot tube or a deposit); the stronger the supersonic flow, the stronger the shock that forms, and the greater the pressure loss.

A second set of results was computed, this time maintaining a constant steam mass flow rate by decreasing the nozzle exit diameter as lance pressure increased. Three fully-expanded jets, at lance pressures of 100, 300 and 500 psig, were calculated; the PIP along the centerlines of these jets is shown in Figure 2 (right). Again, the higher the lance pressure, the higher the corresponding PIP. But this time, because the nozzle exit diameter varies inversely with lance pressure (i.e. nozzle exit diameter decreases as lance pressure increases), the jet core length decreases as the lance pressure increases. Given a certain steam mass flow rate, the choice of an optimum lance pressure (and corresponding nozzle) depends on the typical distance between the nozzle exit and a deposit.

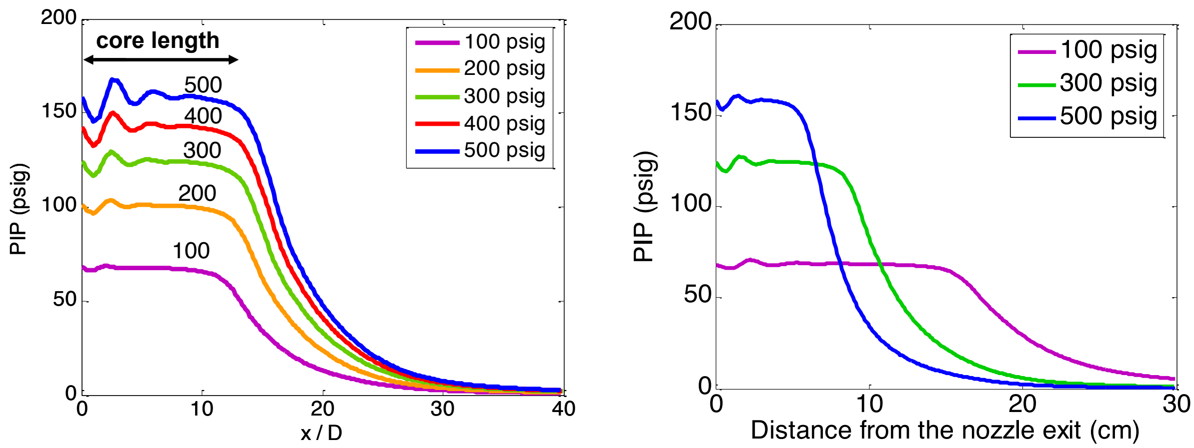

Figure 2. *The effect of lance pressure on jet centerline PIP, for fully expanded jets. Left: constant nozzle exit diameter; right: constant steam mass flow rate.*

THE EFFECT OF OFF-DESIGN LANCE PRESSURE

Simulations were run to study the sensitivity of a sootblower jet to off-design conditions that are typical of sootblower use in practice, as it is difficult to maintain the steam supply pressure at exactly the nozzle design pressure. For a nozzle with an exit diameter of 3.7 cm and a throat diameter of 2.54 cm (which corresponds to a design supply pressure of about 160 psi, characteristic of low pressure sootblowing), three simulations were run, of a sootblower jet operating at the design pressure, and $\pm$ 50 psi of the design pressure.

Figure 3 shows the axial velocity contours corresponding to these three sootblower jets, operated at lance pressures of 110, 160 and 210 psi. Notice first that the fully-expanded jet core length is longer than those of the off-design jets. This is because in the off-design jets, a portion of the flow energy is converted to heat through the shock-cell structure, that can also be seen in Figure 3 as fluctuations in the red core profiles. Figure 4 (left) presents the centerline PIP of each of the three jets. Notice that the PIP for the two off-design jets fluctuates dramatically throughout the core region, due to the expansions and compressions in the flow as these jets adapt to the ambient pressure. The off-design jets also have a shorter core than the fully-expanded jets; this is more clearly illustrated in Figure 4 (right), which plots jet core length (normalized by the nozzle exit diameter) as a function of the deviation of lance pressure from the design value (this figure also contains data from simulations of jets for lance pressures ± 25 psi of the design value). Clearly, the greater the deviation from the design pressure, the stronger the shock-cell structure, and the shorter the jet core length. This is important, because the jet core length characterizes the distance from the nozzle exit within which a sootblower jet has maximum deposit removal power. These results confirm that sootblower jets are most efficient when operated at their design lance pressure; any deviation from the design pressure leads to a significant reduction of the sootblower efficiency.

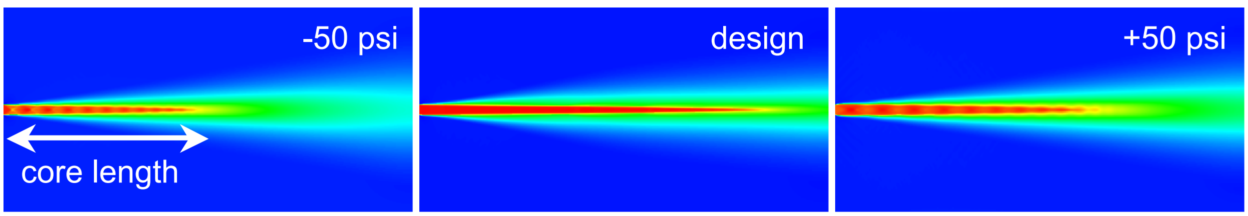

Figure 3. *Axial velocity contours corresponding to sootblower jets operating at lance pressures that correspond to the design pressure of the nozzle (center), 50 psig less than the design pressure (left), and 50 psig more (right).*

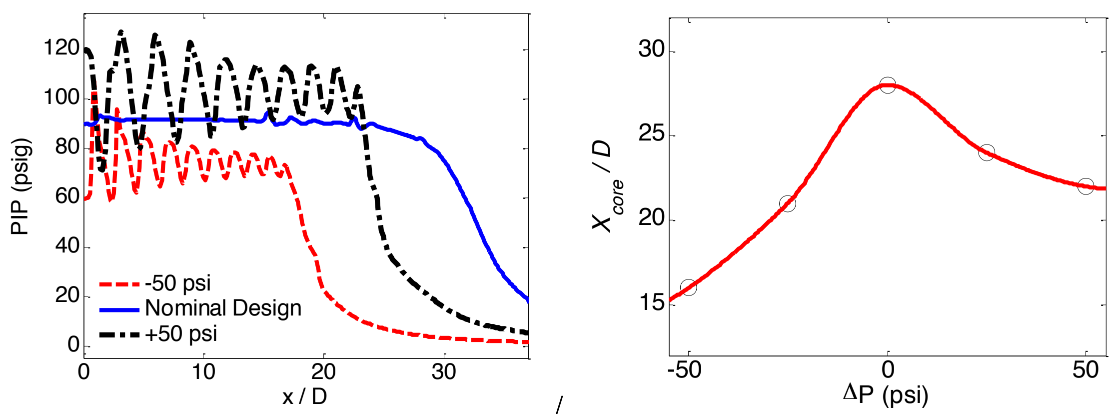

Figure 4. *(left) Peak impact pressure (PIP) along the centerline of sootblower jets operating at ± 50 psi of the design pressure. (right) Sootblower jet core length (normalized by the nozzle exit diameter D) versus the deviation of lance pressure from the design value.*

SOOTBLOWER JET / TUBE BANK INTERACTION

We now consider the interaction of a sootblower jet with an idealized model of a deposit in the superheater section of a recovery boiler. Figure 5 (top) shows an actual chunk of deposit, detached from the tube surface of a kraft recovery boiler. Figure 5 (bottom) shows a schematic of an idealized tube bank/deposit model. As illustrated, the tube bank is modeled as a series of joined tubes, and the deposit is represented by a solid cylinder attached to the front tube of the tube bank. The jet was specified to be slightly off-design, to reflect a typical operating condition. Simulations were run to study the effect of the position of the jet relative to the tube bank (referred to as the "offset"), and the size of the deposit.

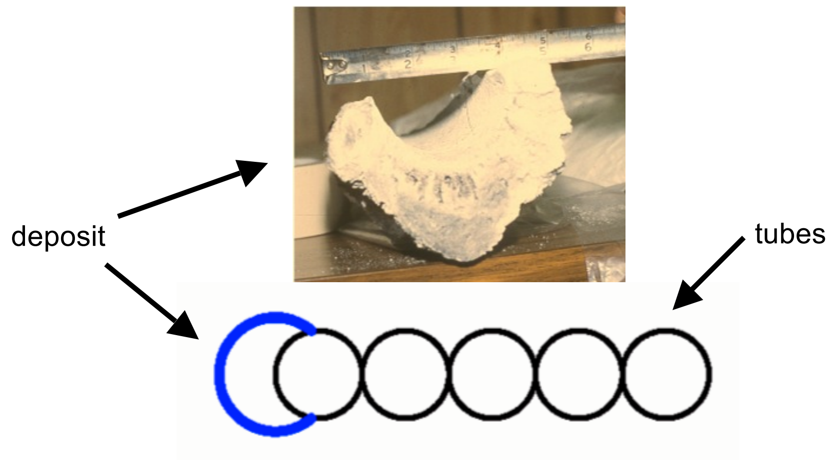

Figure 5. *Photo of an actual chunk of deposit (top), and a schematic of the idealized geometry of a tube bank and deposit (bottom).*

Effect of the Jet / Tube Bank Offset

To examine the effect of the offset (defined in Figure 6 as the distance from the centerline of a tube bank to the centreline of a jet), we ran a set of 3D simulations at various offsets to assess the extent of the interaction between a jet and a tube bank when the jet does not impinge directly onto a deposit. Figure 6 is a typical result: the sootblower nozzle was positioned slightly below the bottom of the deposit, yet the interaction between the jet and the deposit and tube bank is negligible, because these supersonic jets, at least for the length of the core, do not expand nearly as much as a subsonic (or incompressible) jet does. The results clearly indicate that, unless the sootblower jet impinges on the deposit even slightly, the jet will behave essentially as a free jet; conversely, unless a jet impinges on a deposit, the deposit and tube bank will not feel the jet.

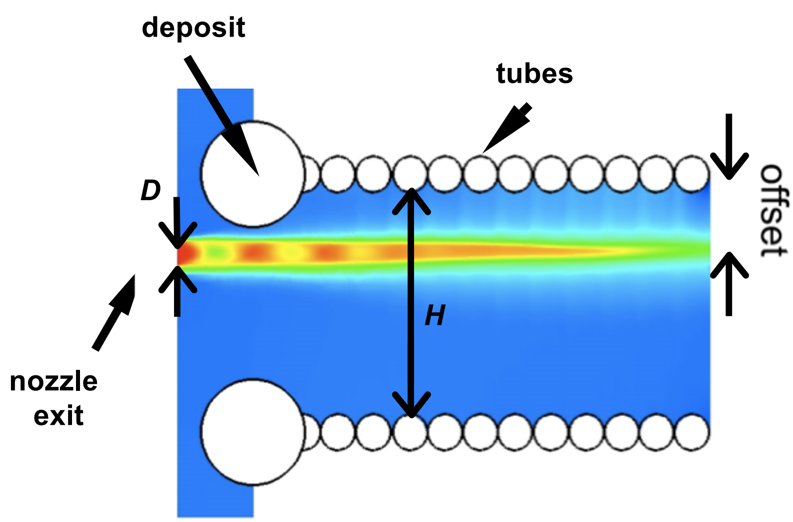

Figure 6. *A schematic of a sootblower jet between superheater tube banks.*

Effect of the Deposit Size

The effect of deposit size on jet/deposit interaction was studied via 3D simulations of a sootblower jet impinging normally onto deposits of three different diameters ($4\times D$, $3\times D$, and $2\times D$, where D is the nozzle diameter), as shown in Figure 7. We refer to these deposits as "large", "medium", and "small", respectively. The size of a deposit affects the distance between the sootblower nozzle exit and the leading edge of the deposit; the distance decreases as the size of the deposit grows. As a result, deposit size is expected to affect its interaction with the shock cell structure of an off-design jet.

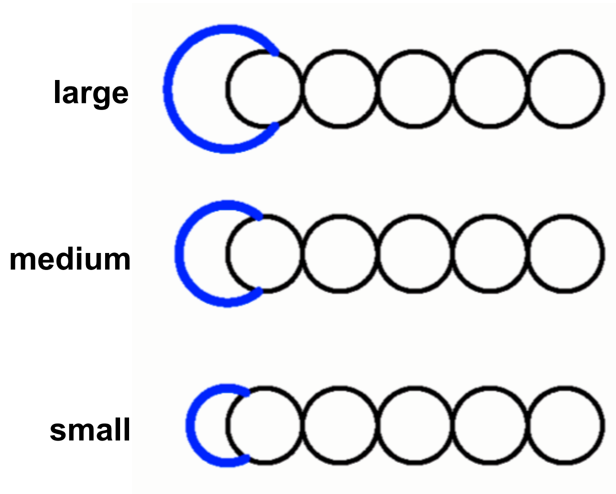

Figure 7. *Schematic of the three tube bank/deposit configurations.*

Figure 8 shows the density contours for the jets impacting the three deposits, where the distance from the nozzle exit to the tube bank is kept constant. In each of the three plots, notice that the fluid density varies along the jet, in response to the pressure fluctuations that are characteristic of off-design jets (as previously shown in Figure 4 (left)). As well, each of the plots shows a normal shock just upstream of the deposit, represented by a high fluid density. For the large deposit, impingement occurs approximately one nozzle exit diameter downstream of the nozzle exit, and so the jet impinges on the deposit surface before the formation of the first expansion/compression region. The nozzle exit is further from the medium deposit, and so in this case the jet impinges on the deposit surface in the middle of an expansion region, and the corresponding pressure exerted on the medium deposit is thus lower. For the small deposit, even further away, the sootblower jet/deposit interaction occurs in a compression region, and as a result, the pressure exerted on the small deposit is actually greater than that on the medium deposit, even though the small deposit is much further from the nozzle exit.

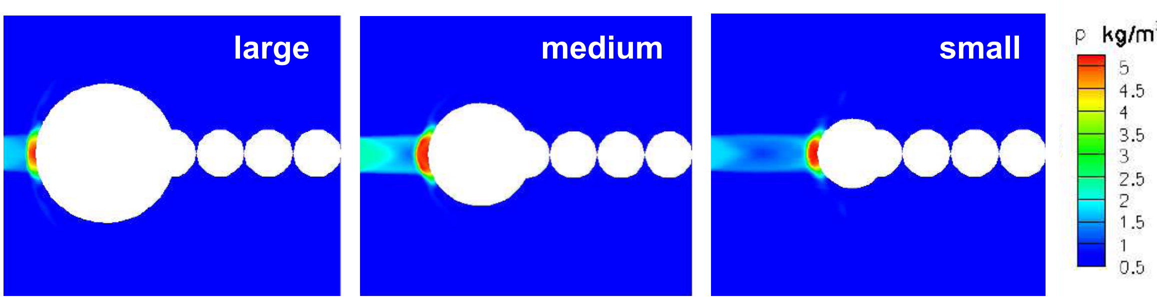

Figure 8. *Density contours for the jets impacting the three sizes of deposit.*

This can be better illustrated by comparing the pressure (normalized by the ambient pressure) along the centerlines of the jets impinging on the three deposits, as shown in Figure 9. Notice that the pressure suddenly increases close to each deposit surface, indicating the normal shock wave that forms in front of each deposit. The pressure exerted on each of the three deposits is the maximum value of pressure at the end of each curve. Although the distance between the nozzle exit and deposit increases as the deposit size decreases from large to small, the impingement pressure on the surface of the medium deposit is actually lower than the pressure on either the small or large deposit, because the jet interaction with the medium deposit occurs in an expansion region.

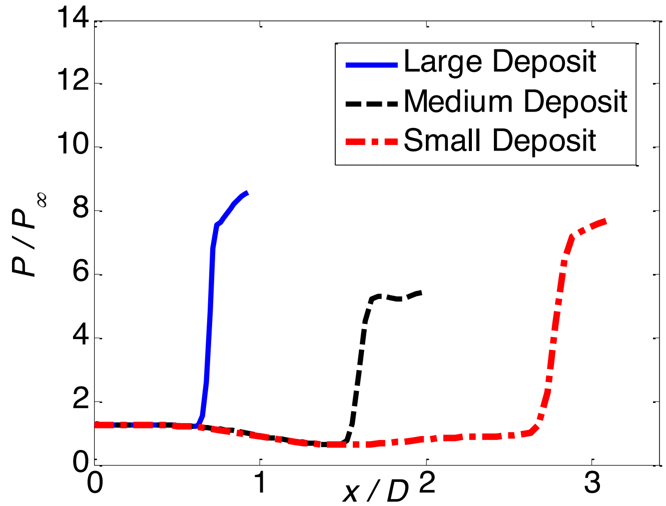

Figure 9. *Comparison of the centerline pressures, for the jets impinging on the three deposits.*

Figure 10 shows the circumferential distribution of pressure over the surfaces of each of the three deposits. In each case the maximum pressure occurs at the leading edge, at θ=0, but again, this figure illustrates that the medium deposit experiences the lowest impact pressure. As well, for each case, the pressure decreases from the value at θ=0 to slightly less than the ambient pressure before asymptoting to the ambient value.

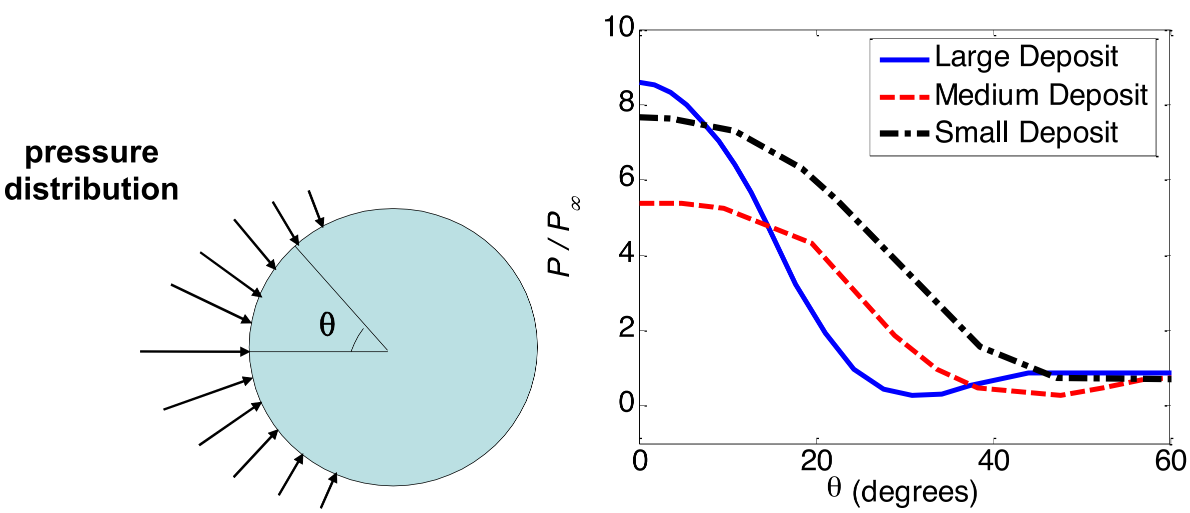

Figure 10. *The circumferential distributions of pressure over the surfaces of the three deposits.*

Finally, Figure 11 shows the axial distribution of pressure over the surfaces of the cylindrical deposits. Again, for any of the cases the maximum pressure occurs at the point of impingement, at x=0 in Figure 11, but the medium deposit experiences a lower pressure than either of the large and small deposits. Notice too that for the large and small deposits, the pressure decreases monotonically from the stagnation value until some small fluctuations due to expansions and compressions of the flow, far from the point of impact. In the case of the medium deposit, however, the pressure increases slightly between x/D=0.5 and 0.75, because of the formation of a compression region close to the jet centerline.

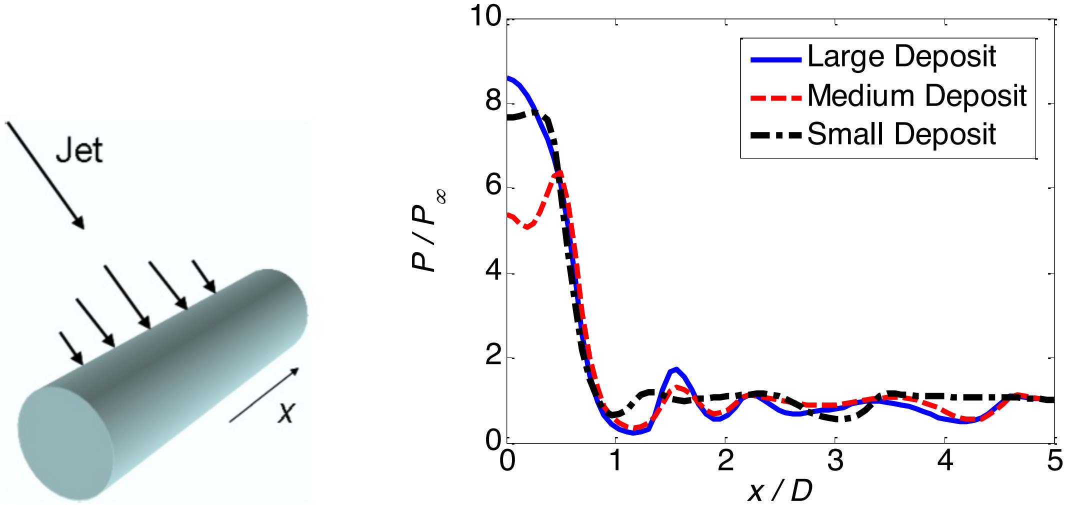

Figure 11. *The axial distributions of pressure over the surfaces of the three deposits.*

To summarize, the results indicate that the size of a deposit, as it affects the distance to the nozzle exit, can affect the peak pressure exerted by an impinging jet. However, the relationship between peak pressure and distance depends on the complex shock structure within an off-design jet, and as a result, the variation of peak pressure with distance may not be monotonic.

FLOW THROUGH A SOOTBLOWER NOZZLE

Our simulations of steam jets presented here (and in previous work (e.g. [1-3])) have always considered only the flow from the exit of the sootblower nozzle, by specifying boundary conditions at the nozzle exit (mass flow rate, pressure). These boundary conditions are related to nozzle geometry and the upstream lance pressure, but to date we have relied on well-known isentropic gas dynamics relations to make that connection. In this final section, we present a preliminary study of the actual flow through a nozzle, to assess the validity of those simplified relations.

Figure 12 illustrates the geometries of a pair of nozzles: a "base" nozzle that we have used extensively for experimental work in our lab, that is characterized by a sharp entrance into the throat; and a "smooth" nozzle that has the same throat and exit diameters. Of interest is the design pressure of these nozzles: in other words, the supply (or lance) pressure at the entrance to the nozzle that will yield an exit pressure equal to the ambient pressure. For the geometries of the nozzles illustrated in Figure 12, the isentropic relations indicate a design pressure of 312 psig. Taking losses into account, the actual design pressure will be higher.

To determine the actual design pressure, we ran a series of simulations at different lance pressures, in each case to determine the exit pressure. Figure 13 summarizes these simulations, for both nozzles. Each data point represents a simulation: the horizontal axis indicates the specified upstream pressure, the vertical axis the predicted exit pressure. For both nozzles we ran a simulation for the case of 312 psig; the base nozzle exit pressure (normalized by the ambient pressure) was 0.79; for the smooth nozzle the value was 0.85, as one would expect, because flow through a smoother nozzle will incur fewer losses. We then ran simulations at other lance pressures, until we identified the design pressure of the nozzle.

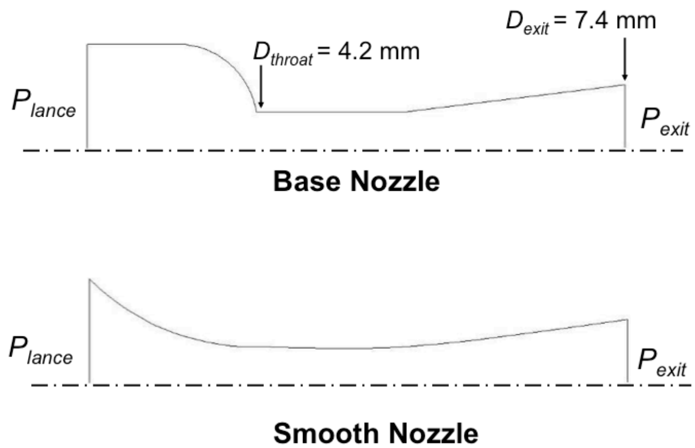

Figure 12. *The geometries of the two converging-diverging nozzles.*

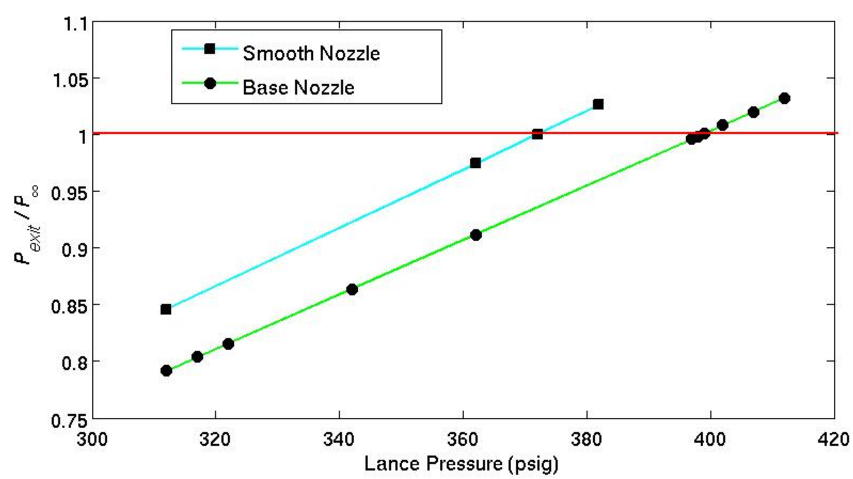

Figure 13. *Calculated pressure at the nozzle exit versus lance pressure, for each of the two nozzle geometries.*

For the base nozzle that value was 399 psig, and for the smooth nozzle 372 psig; both values are substantially higher than the 312 psig predicted by the isentropic relations. Figure 14 illustrates how the pressure varies through the base nozzle for three supply pressures: 312, 362 and 399 psig. Although it appears that all three curves converge to the same value at the nozzle exit, it is important to recognize that the exit pressures vary by a few psig, which has a dramatic effect on the jet that exits the nozzle. The fully-expanded jet that results from a supply pressure equal to the design pressure will be relatively free of the expansion and compression waves that will characterize the other jets. If the supply pressure is less than the actual design pressure, the jets will be over-expanded; conversely, too high a supply pressure will yield an under-expanded jet.

Finally, Figure 13 illustrates that the variation between the lance pressure and exit pressure is relatively linear, and so points to the use of simulation as a very attractive tool for nozzle design. Although we ran many simulations, in retrospect it seems clear that simply running a pair of simulations to estimate the slope of either of the two lines in Figure 13 would then point to a reasonably accurate prediction of the design pressure.

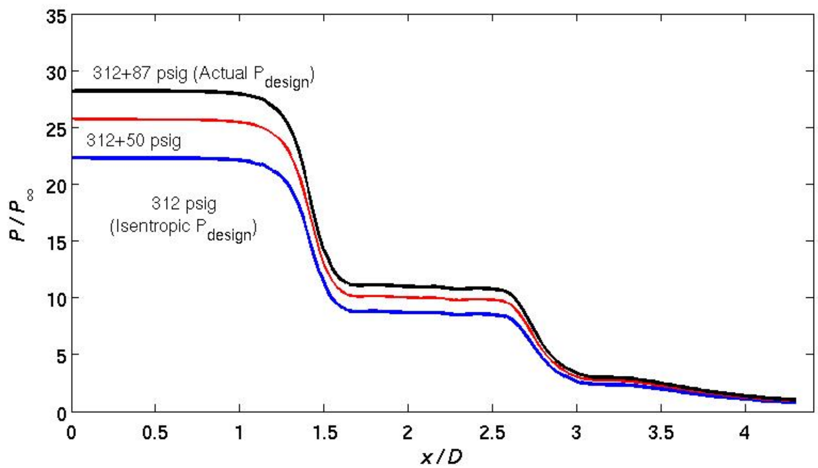

Figure 14. *Pressure distributions through the base nozzle, for different lance pressures.*

CONCLUSIONS

A CFD model of sootblower jets, originally developed within the framework of a research code, has been successfully transferred to the commercial CFD software Fluent, making it more readily accessible to the wider engineering community. Here we presented a series of simulation results that examined the effect of lance pressure on sootblower jet characteristics.

Any sootblower nozzle is characterized by a design supply pressure, that will yield a fully-expanded sootblower jet. Sootblower operation at any other pressure will yield an off-design jet, one characterized by expansion and compression waves and a fluctuating pressure. Such jets are inherently less efficient than a fully-expanded jet, because the expansion and compression waves remove energy. Nevertheless, in actual practice sootblower jets will always operate at least somewhat off-design.

The pressure fluctations in a jet can be dramatic, which can affect the force exerted on a deposit. Simulation results of an off-design jet impacting deposits of various size clearly show that the exerted force may not scale with the distance between the nozzle and the deposit, because of the fluctuating pressure. These results point to the importance of operating sootblowers at or near the design condition.

Finally, we presented a preliminary study of flow through a sootblower nozzle, to assess the validity of the isentropic relations usually used to estimate the nozzle design pressure. The results indicate that the isentropic relations seriously underestimate the design pressure, as the flow losses through a nozzle are not negligible. The results also demonstrate the utility of CFD simulations for obtaining a good estimate of the design pressure, by taking advantage of a near-linear variation of supply to nozzle exit pressure.

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