# ADVANCED CFD SIMULATIONS OF SOOTBLOWER JETS

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## ABSTRACT

A CFD model of a turbulent supersonic sootblower jet has been developed, that yields accurate predictions not only of the flow associated with "fully-expanded" jets (that result when the lance pressure upstream of the sootblower nozzle matches the design pressure of the nozzle), but also the much more complicated flow physics of "off-design" jets that are characterized by multi-cell shock structures that decay with distance from the nozzle exit due to turbulent mixing. This paper includes a brief overview of the development of the turbulence model that is key to the improved predictions of off-design jets, and then presents predictions of flow phenomena corresponding to experimental data obtained both in the lab and via experiments conducted in an actual recovery boiler, as evidence that the model is well suited for use in the further analysis and development of sootblower technology.

## INTRODUCTION

Fireside deposit accumulation on heat transfer tubes in recovery boilers is controlled by ssootblowers that blast deposits with high pressure steam jets. The steam flows down the sootblower lance and expands through twin convergent-divergent nozzles. The two opposed jets that form downstream of the nozzle exits are supersonic, with a typical Mach number of 2.5.

Over many years, research at the University of Toronto, including experiments and modeling, has examined various aspects of sootblower operation in order to articulate the underlying principles and to quantify the effectiveness of sootblower use. Sootblower effectiveness, as measured by deposit removal efficiency, is related both to the peak impact pressure (PIP) of the jet and to the overall jet force. At a fixed distance from the nozzle exit along the jet centerline, the PIP increases with increasing nozzle size, steam flow rate and pressure, but decreases rapidly with distance off of the jet centerline due to the turbulent entrainment of surrounding gases. The fact that the jet is supersonic also means that flow characteristics are dramatically affected by obstacles (tubes, platens, deposits) in the jet path.

Our modeling of the flow physics of supersonic steam jets serves two purposes. It provides a means of corroborating experimental results obtained both in the lab and via *in-situ* experiments, and is especially important because these experiments are often difficult to carry out and can be associated with significant uncertainty. The modeling also yields data, such as contours of flow variables including velocity, pressure, density, and turbulence intensity, that cannot be obtained experimentally, and so enhance our understanding of the complex phenomena associated with sootblower jets. This complexity, however, also means that models of these steam jets will be mathematically complex.

This paper presents development details of our sootblower jet model, and simulation results both of laboratory experiments and of experiments conducted in an actual recovery boiler. The model is a computational fluid dynamics (CFD) code originally developed to simulate the flow of a turbulent supersonic sootblower jet and its interaction with simple geometries representative of superheater platens. We refer to this as the original CFDLib-SJT model as it couples the open source code CFDLib (developed at the Los Alamos National Laboratory) with the "Sootblower Jet Turbulence" model developed by us [2]. Over the past four years, a much improved CFDLib-SJT model has been developed, by further correcting the SJT model to account for turbulence realizability and shock unsteadiness. The improved model predicts jet characteristics more accurately, for longer distances from the nozzle, and has been used to simulate numerous cases of supersonic jet impingement onto solid surfaces, corresponding to experimental results obtained both by our research group and by others in the literature.

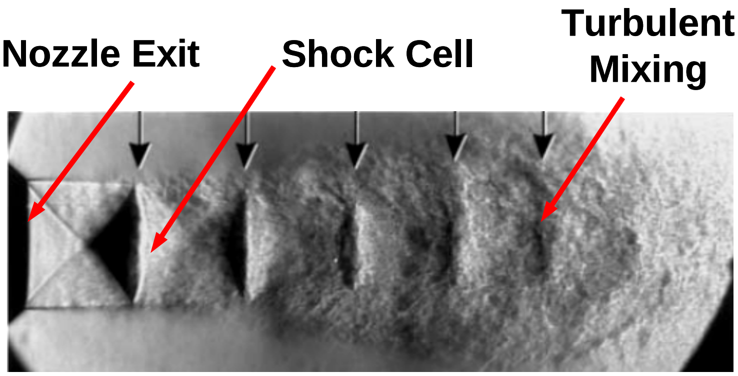

**Figure 1.** Flow visualization of an off-design supersonic jet (by Panda [2]); Note the shock-cell structure in the flow.

## ORIGINAL MODEL FOR FULLY-EXPANDED JETS

Sootblower nozzles are designed so that when the pressure at the nozzle exit is equal to the ambient boiler pressure, a "fully-expanded" supersonic jet forms downstream of the nozzle exit. For any given nozzle, there exists only one lance pressure that yields a fully-expanded jet. For any other lance pressure, the nozzle yields an "off-design" supersonic jet that has not expanded to exactly the ambient boiler pressure. In off-design jets, a multi-cell shock structure forms downstream of the nozzle exit, consisting of shock and expansion waves. This shock/expansion wave structure allows the jet pressure to fluctuate and adjust to the ambient value. Off-design jets involve very complicated phenomena, because of these shock waves and because the shock cells decay with distance from the nozzle exit due to turbulent mixing. Figure 1 shows a flow visualization of an off-design jet by Panda [1]; note the shock-cell structure and its decay because of turbulent mixing. The flow structure of an off-design jet can be considered to consist of near and far field areas. The near field includes the first few shock cells from the nozzle exit, where turbulence is not significant. In the far field, further downstream, turbulent mixing reaches the jet centerline and so engulfs the whole flow field.

The CFDLib code obtained from Los Alamos, which included an implementation of the standard $k-\varepsilon$ turbulence model, did not yield accurate predictions even of the relatively simple fully-expanded high speed jets characteristic of sootblowers. We then modified the turbulence model by adding compressibility corrections [2]; the resulting original model yielded much better agreement with select measurements of fully-expanded free jets and jet flows between platens. This model has been further validated against a wide range of available experimental data related to fully-expanded free jets and jets impinging on solid surfaces (that lead to the formation of normal shock waves ahead of the surface, characteristic of supersonic flow), and successfully predicted all cases. Figure 2, for example, illustrates the axial velocity, $u$, versus the axial distance from the nozzle exit, $x$, along the centerline of a fully-expanded jet, compared to the experimental data of Panda and Seasholtz [3]. The simulation predicts the measurements reasonably well, and illustrates the typical characteristics of a fully-expanded jet: a relatively constant flow for a distance of about 10 nozzle diameters downstream of the nozzle exit (this is the inviscid core of the jet, in which the PIP also remains relatively constant), followed by a region in which velocity and pressure decay as the surrounding fluid that is entrained by the jet finally reaches the jet centerline.

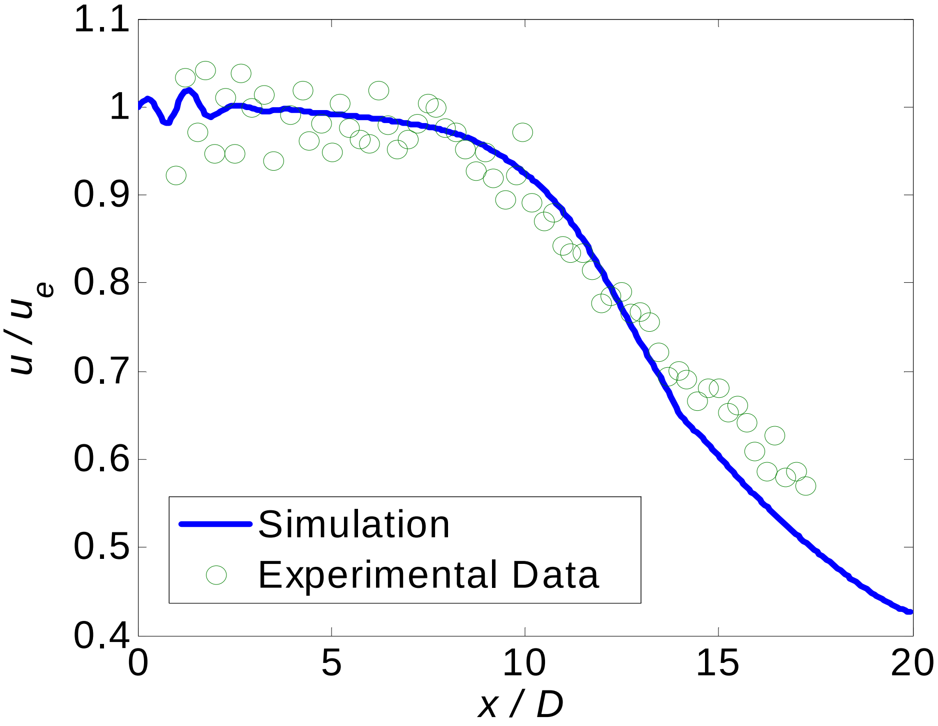

**Figure 2:** Distribution of the axial velocity along the centerline of a free supersonic jet: comparison of simulation results with the experimental data of Panda and Seasholtz [3]. $u_e$ and *D* represent the nozzle exit velocity and diameter, respectively.

## IMPROVED MODEL FOR OFF-DESIGN JETS

Numerical simulation of off-design jets is much more challenging, because of the complex nature of the flow structure. While the original model yielded accurate predictions of fully-expanded jets, predictions of off-design supersonic jets did not agree as well with experimental data, seemingly because of an inability to capture the complex interaction of turbulence and the shock-cell structure that is characteristic of such jets. The source of the problem was determined to be the already modified turbulence model. By imposing further corrections: a realizability condition [4], and taking into account shock unsteadiness effects [5], an improved turbulence model was developed [6]. When coupled to CFDLib, this improved model yielded much better agreement with experimental data of off-design jets.

Figure 3 presents predictions of centerline pressure versus axial distance from the nozzle exit for an off-design jet, obtained using the original and improved models, and compares the results with the experimental data of Norum and Seiner [7]. The results are very different from those presented in Figure 2, in that the pressure even within the core of the jet is oscillating strongly as the flow compresses and expands as it adjusts to the ambient pressure via the shock-cell structure that is similar to that illustrated in Figure 1. This can be better seen in Figure 4, which presents the pressure contours calculated by the improved model. The pressure fluctuates within the core of the jet, and the fluctuations die out only after many nozzle diameters downstream of the nozzle exit.

Close examination of Figure 3 shows that the original model predicts the positions of the first few waves correctly, but dramatically under-predicts the amplitudes of the waves, which decay much more rapidly than they should. The improved model, on the other hand, yields a much better agreement with the experimental data, by limiting the rate of dissipation of the jet. Figure 5 presents further experimental data of Norum and Seiner [7], this time the axial distribution of pressure 0.25*D* (*D* is the nozzle exit diameter) off of the centerline of the same off-design jet as in

Figure 3. Again, the original model does not satisfactorily predict the shock waves in the far field region, while the improved model yields far more accurate results.

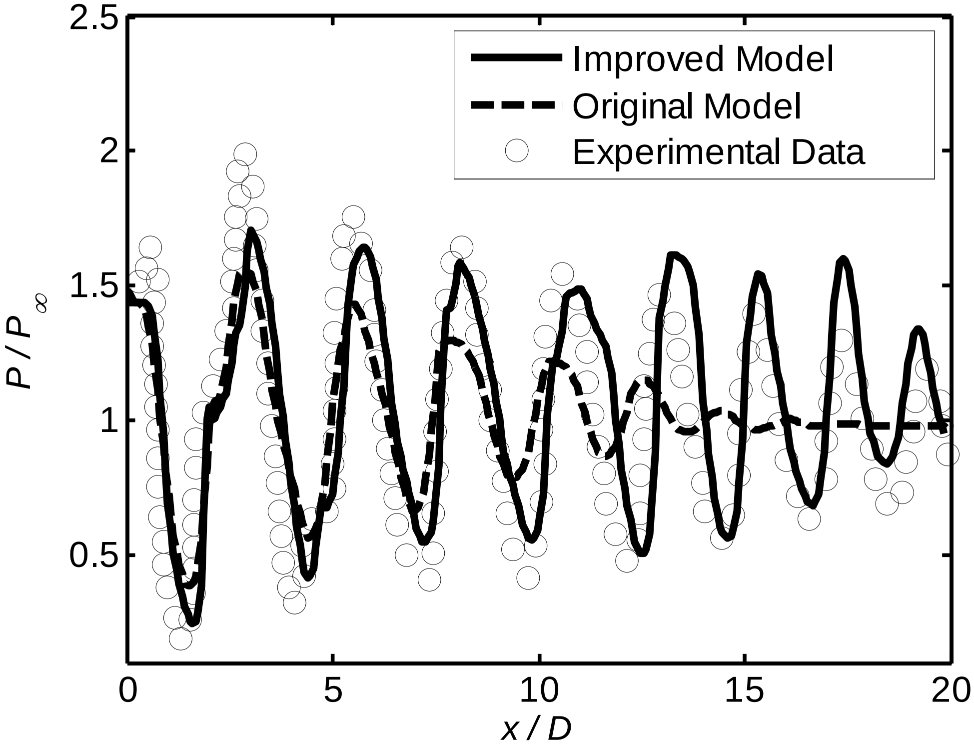

**Figure 3.** Normalized pressure along the centerline of an off-design jet. $P_\infty$ and $D$ represent the ambient pressure and nozzle exit diameter, respectively. The nozzle exit to ambient pressure ratio is 1.45 and the flow speed at the nozzle exit is twice the speed of sound (i.e. the Mach number is 2). Experimental data is that of Norum and Seiner [7].

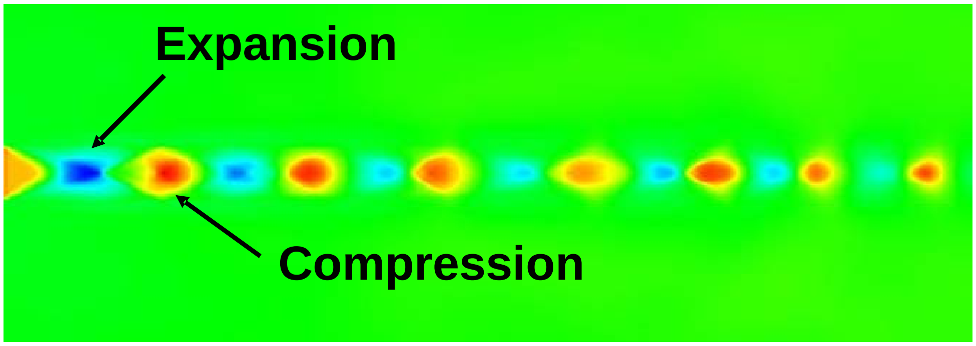

**Figure 4.** Pressure contours calculated by the new model: the compression and expansion regions are related to the shock wave structure in the flow.

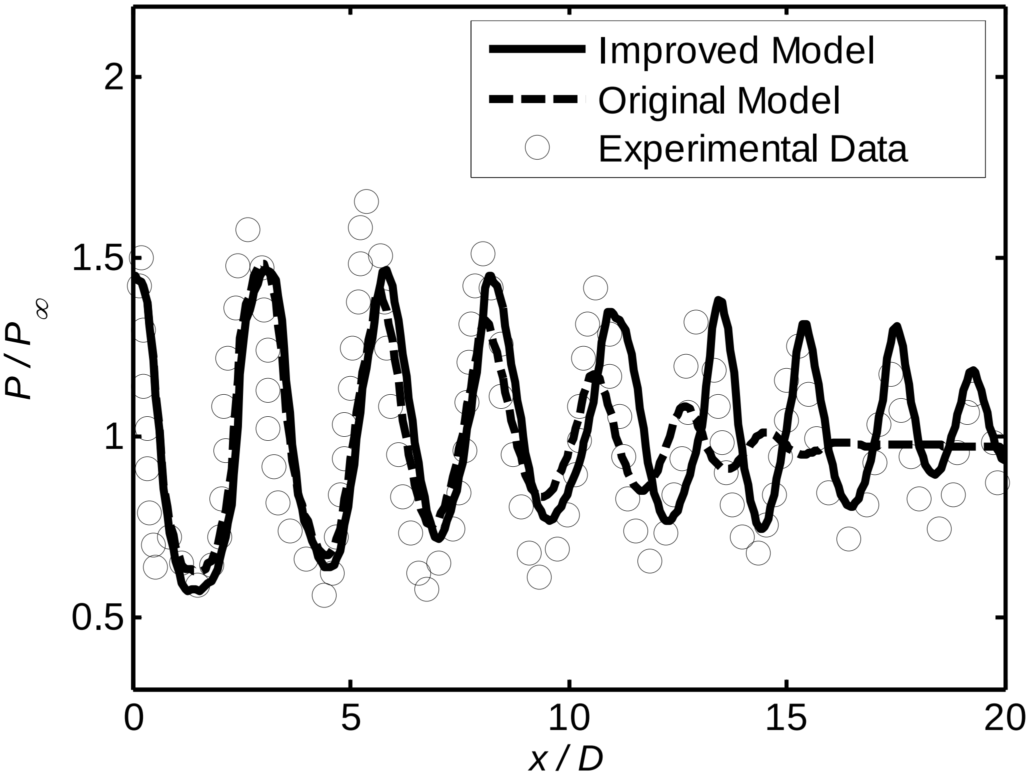

**Figure 5.** Axial distribution of the normalized pressure 0.25 D off the centerline of an off-design jet. Experimental data is that of Norum and Seiner [7].

## PREDICTIONS OF ACTUAL SOOTBLOWER DATA

Finally, the improved model was used to predict data measured during a series of tests carried out at a kraft pulp mill in Sweden [8]. The experiments measured the force exerted by an actual sootblower jet on a circular probe of 4.8 cm in diameter, positioned between two tube banks in a recovery boiler, as illustrated in Figure 6.  Figure 7 shows the experimental apparatus outside the boiler: the measuring probe was mounted on the boiler wall and extended into the boiler interior. A detailed description of the experimental setup and of the data that was collected is in [8].

Two tests were carried out, in September and November of 2007. During the first test, the boiler was not operating and steam for the sootblowers was delivered from another boiler; for the second test, the boiler was operational. The first set of measurements was obtained for lance pressures of 4, 6, 8, 10 and 12 bar (gauge). During the second test, the lance pressures fluctuated slightly and so the lance pressures were characterized as 10-11, 13-15 and 17-18 bar (gauge). The design lance pressure for the sootblower nozzles installed in the boiler was about 11 bar (gauge), and so all of the jets were at least somewhat off-design.

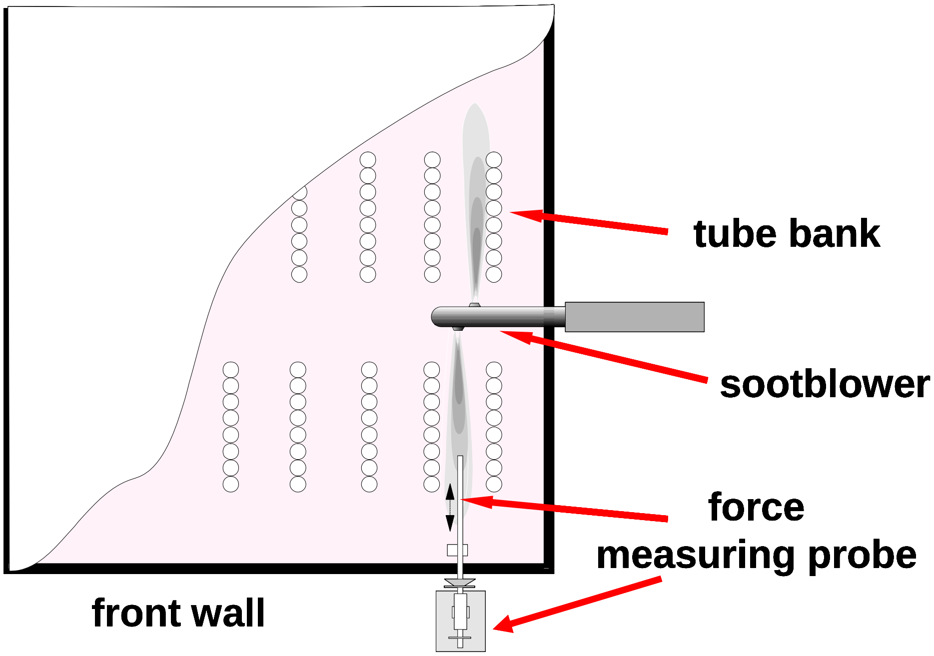

**Figure 6.** A schematic of the experimental setup at the SCA Obbola mill, Sweden.

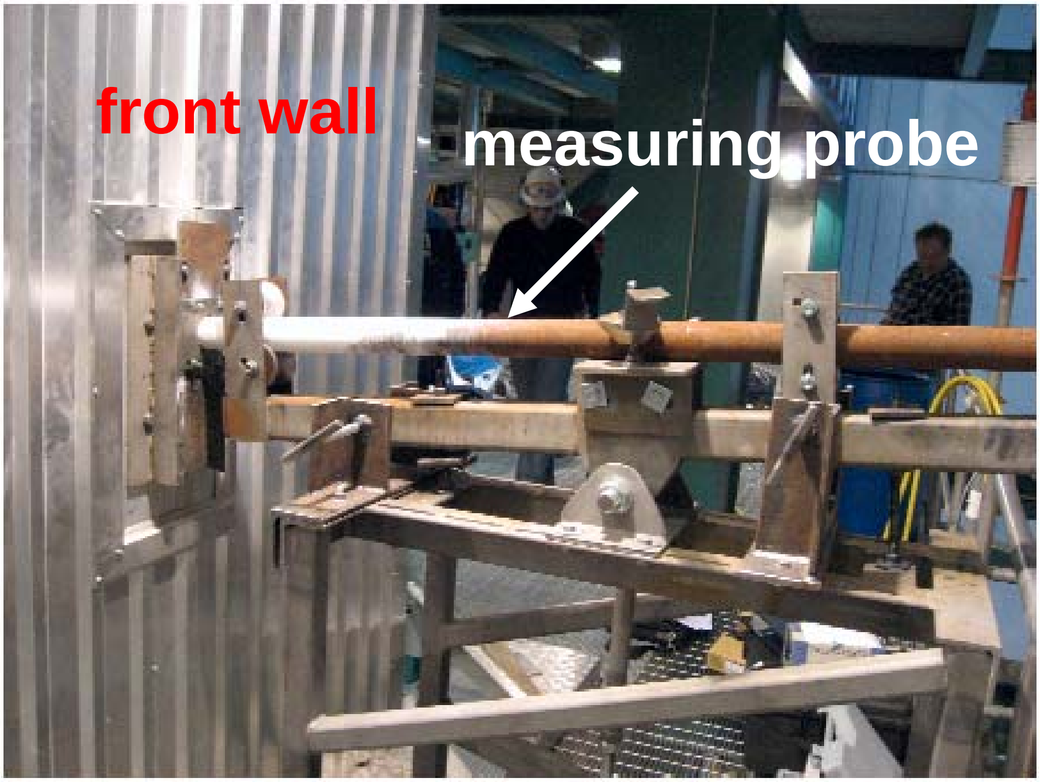

**Figure 7.** Experimental setup as seen from outside the boiler: the measuring probe extends through the boiler wall.

Simulations were run using the improved model to predict these measurements, although the properties of air were used instead of steam, and the tube banks were approximated as platens, as can be seen in Figure 8. These simplifications are unlikely to have had a significant effect on the computed results. The predicted force exerted by the jet on the probe was then calculated by integration of the Peak Impact Pressure (PIP) over a circular region corresponding to the front plate of the measuring probe (i.e. a circle of diameter 48 mm).

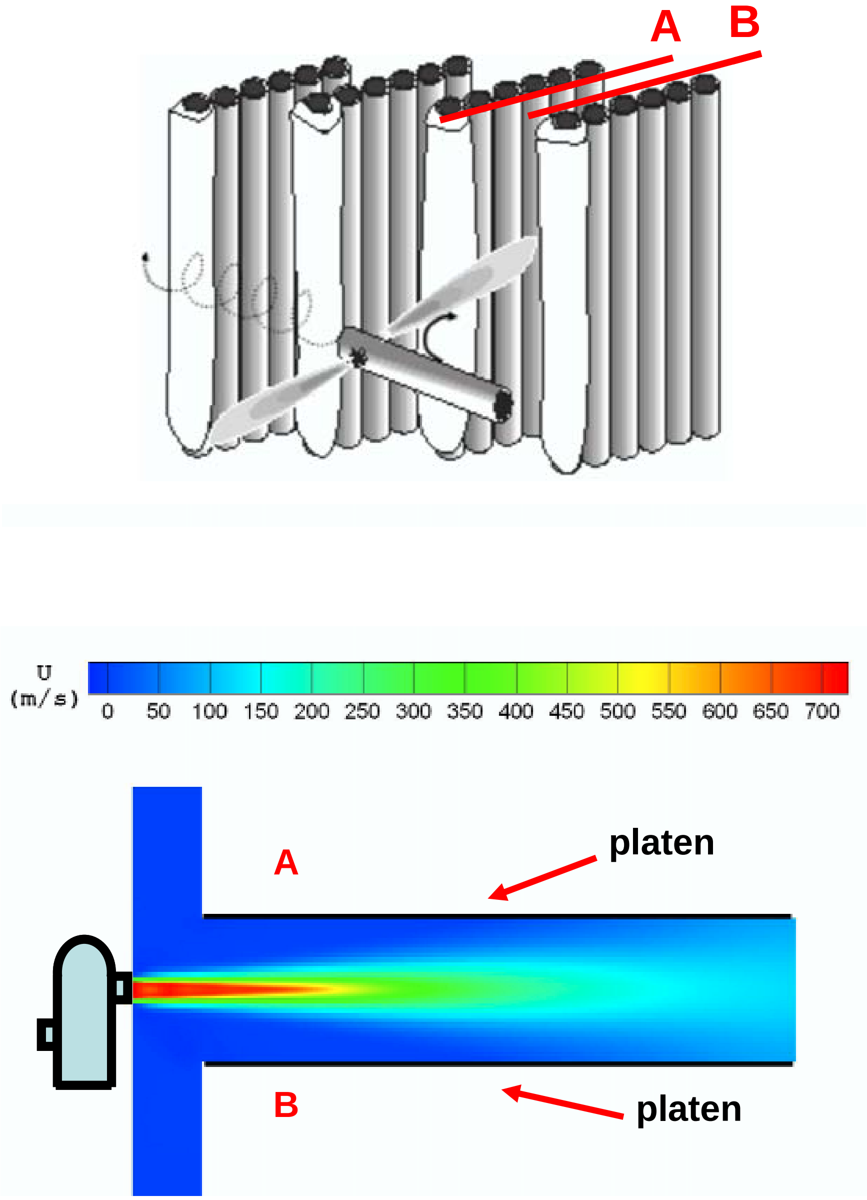

**Figure 8.** Schematic view of a sootblower jet between superheater platens (top), an axial velocity contour from the simulation (bottom).

Figure 9 shows simulation and test results obtained at lance pressures of 8 bar (top) and 17-18 bar (bottom). The simulation results are in surprisingly good agreement with the measurements, given the complexity of the experiments and the uncertainly associated with the data. It is important to appreciate that these results are an integration of data over a region that encompasses flow within 24 mm of the centerline of the jet; this smooths the fluctuations in pressure associated with an off-design jet, and is also the reason why the jet force decreases dramatically, beginning almost immediately downstream of the nozzle exit. The results clearly illustrate the very limited distance over which a sootblower jet exerts appreciable force.

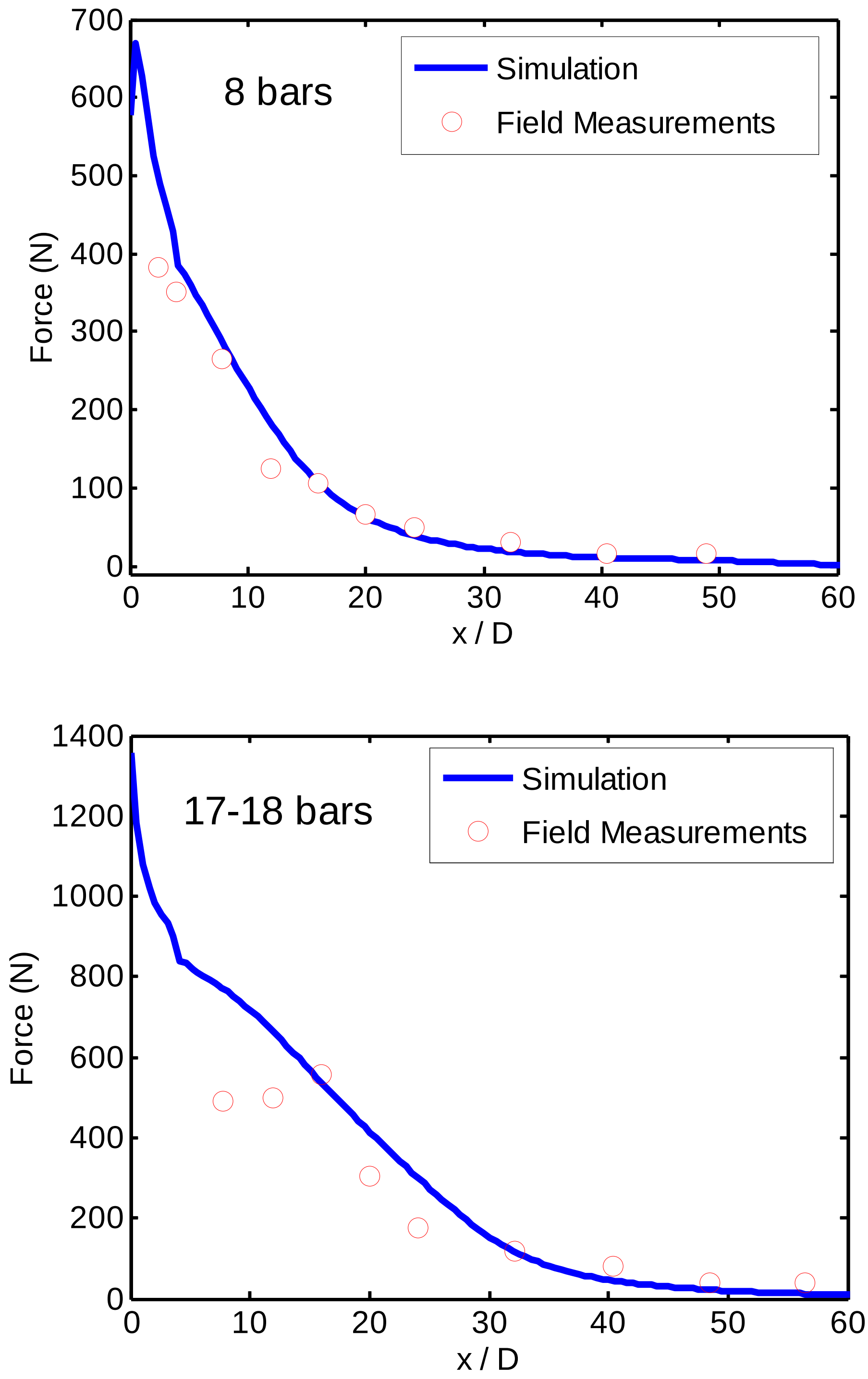

**Figure 9.** Results for lance pressures (from top to bottom) of 8 and 17-18 bar (gauge). Nozzle exit diameter, *D*=3.7 cm.

## SUMMARY

A CFD model has been developed to accurately predict the flow physics of a turbulent supersonic sootblower jet, by incorporating various corrections into the standard $k-\varepsilon$ turbulence model. The model yields accurate predictions for a wide range of flow behavior, from "fully-expanded" jets to the much more complicated "off-design" jets that are characterized by multi-cell shock structures that decay with distance from the nozzle exit due to turbulent mixing. The model has been validated by comparison with experimental data obtained in our own lab and data available in the scientific literature, and by comparison with data obtained via tests conducted in an actual boiler. The predictions are in some cases surprisingly good, given the uncertainty associated with some of the data, and demonstrate that the model is well-suited to predict a wide range of sootblower jet behavior.

## ACKNOWLEDGEMENTS

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