Redesigning Blasting Nozzles to Improve Productivity

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In a previous article[1], Settles and Garg discussed the discrepancy between the low level of abrasive blasting technology and high-technology rocket propulsion, though the two have much in common. The importance of nozzle pressure and abrasive particle size in blasting productivity was also examined. Most important, a considerable opportunity to improve productivity by scientifically optimizing blasting nozzle design was identified. Since current nozzles are not very efficient, a doubling of productivity was judged to be possible. This, in turn, could have a considerable positive financial and environmental impact on the protective coatings industry.

Since Reference 1 was written, the Penn State Gas Dynamics Laboratory has undertaken such a nozzle optimization. Its success has depended on the availability of modern experimental and computational gas dynamic tools and technology transfer from the field of aerospace propulsion. The purpose of the present article is to describe how the nozzle optimization was accomplished and to examine the performance of the new abrasive blasting nozzle, which we call the Penn State Nozzle.

Nozzle Design Criteria

It is necessary at the outset to choose a design point for nozzle optimization because the range of abrasive particles, nozzles, and airflow rates in use for coatings removal is very broad. Following discussions with industry practitioners, we chose a No. 7 nozzle size (7/16-inch or 11.1 millimeter throat diameter), 100 psig (0.79 MPa) nozzle pressure, and G-40 steel grit as a design point representative of heavy-duty blasting of steel structures. The literature suggests that the typical load factor (the particle-to-air mass flux ration) is near unity for such blasting applications.[2-4]

An optical microgram of typical G-40 steel grit particles is shown in Fig. 1. Our measurements indicate that these particles are oblong with dimensions of 750 micrometers x 1,280 micrometers (30 mils x 51 mils) and a standard deviation of 20 to 25 percent of these dimensions. The specific gravity of the steel grit is 7, and a spherical particle of equivalent mass has a diameter of 820 micrometers (33 mils).

Characterization of Existing Nozzle Technology

Any blasting nozzle design improvement must be judged in comparison with present technology. The best current nozzle design is the so-called long-venturi nozzle (actually a converging-diverging Laval nozzle). The long-venturi blasting nozzle
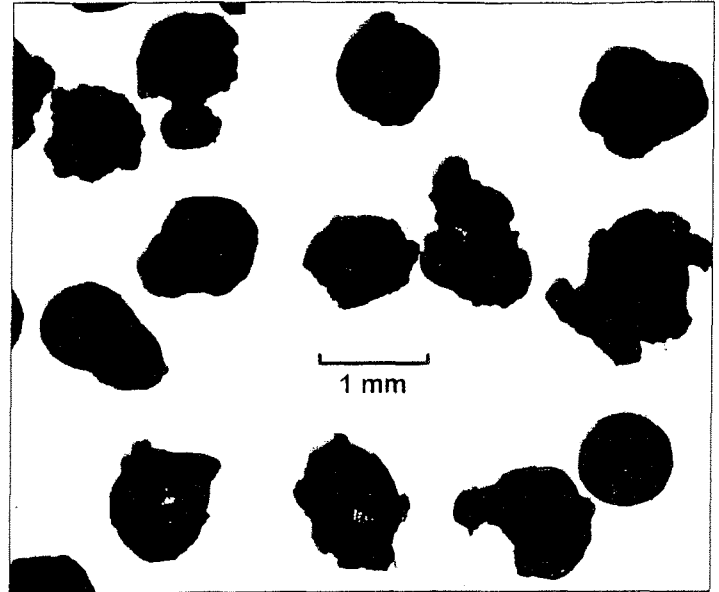

Fig. 1. Photo of a sample of G-40 steel grit (magnified). Figures courtesy of the authors.

appears to have been invented by G.D. Albert and W.H. Mead in 1955 as disclosed in British Patent 722464.[1,5] An off-the-shelf No. 7 long-venturi nozzle[6] with a tungsten carbide liner, shown in Fig. 2, was thus used to establish a baseline performance level.

Historically, the measurement of particle speed as it leaves an abrasive blasting nozzle appears only to have been attempted previously in work cited by Plaster.[5] Further, there is much confusion about this topic in the literature. It is often not understood that particle and gas speeds are different, and the gas
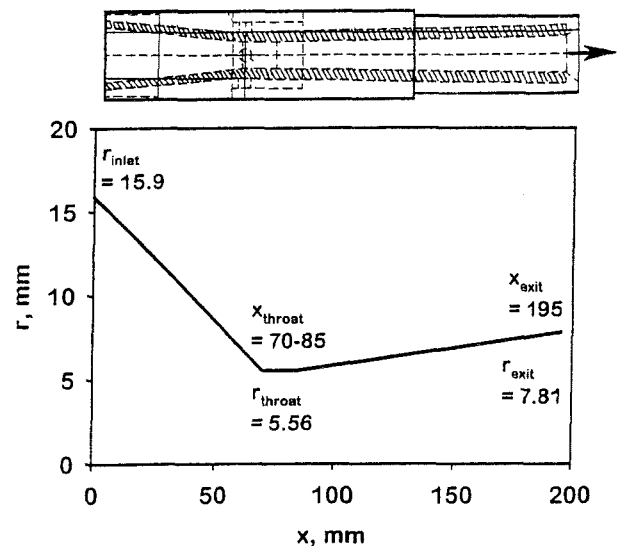

Fig. 2. Internal contour of #7 long-venturi nozzle (note r-axis is stretched for clarity)

speed is the larger— usually very much the larger—of the two. For present purposes, the gas speed can be calculated, but the particle speed at the nozzle exit must be measured, for it is the key to nozzle performance. In particular, the abrasive effect of a solid particle striking a surface is known to be generally proportional to the kinetic energy of the particle, $1/2mV^2$ where V is its speed and m is its mass.[7]

The long-venturi nozzle was mounted in a vertical test fixture and operated at a constant pressure of 100 psig (0.79 MPa), producing a mass flow rate of 0.18 kg/sec (0.40 lbs/sec) of air. A gravity-feed particle injection system controlled the mass flux of steel grit through the nozzle by releasing a weighed quantity of grit over a measured time interval.

A straightforward method, sometimes referred to as chrono-videography of streak velocimetry, was used to measure the speed of the steel particles.[8-10] The flight of grit particles exiting the nozzles is captured on videotape using a special camera with a variable electronic exposure gate that is read precisely in microseconds on an oscilloscope. The moving particles appear as streaks in each video frame. The length of these streaks can be measured from a known reference scale in the field of view. Particle speed is determined by dividing the streak length by the gate time. Many such streaks are measured using image-processing software to obtain useful particle-speed statistics. The accuracy of this approach is in the range of ±6 to 11 m/sec (±13 to 25 mph).

Particle speeds of G-40 steel grit were measured 38 mm (1.5 in.) beyond the exit of the long-venturi nozzle under conditions of very low particle loading as well as at the 1:1 particle load factor typical of actual blasting. The measured speed and standard deviation are 133 m/sec ±15 m/sec (or about 300 mph), with no significant effect from particle loading. The lack of this effect is at variance with Plaster's[5] assertion and indicates that particle collisions with other particles and with the nozzle wall are not significant up to a 1:1 particle loading for present nozzle.

Computer Prediction of Nozzle Performance

Next, we applied a one-dimensional computer model of airflow through a Laval nozzle and the resulting acceleration of grit particles through the nozzle due to the aerodynamic force of the airflow.[1] A single spherical particle is tracked through the nozzle flowfield by this model using Newton's second law of motion, commonly written as F = ma (Force = mass x acceleration) and the isentropic relationships of gas dynamic theory. This step is important to compare with the experimental data of particle speeds produced by the long-venturi nozzle and to verify the usefulness of the computer model as a predictive tool for blasting nozzle design.

Figure 3 shows the combined results of the computer model and particle-speed measurements of the long-venturi nozzle. While measurements could be made only outside the nozzle exit, the computer model predicts both the air and particle speeds along the entire nozzle length and beyond. Several key observations can be made from these results.
- The computed and measured particle speeds at the nozzle exit agree within about 7 percent.
- The steel grit particles lag far behind the speed of the gas throughout the nozzle.
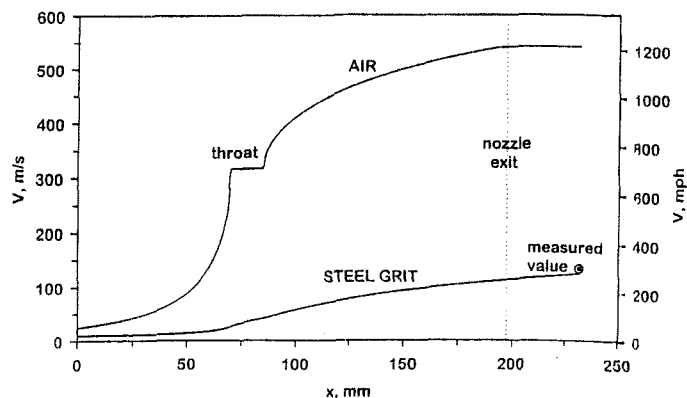

Fig. 3. Computer prediction of air and steel grit speeds through long-venturi nozzle, compared with experimental

- The acceleration of the grit particles before the nozzle throat is negligible.
- The nozzle-exit kinetic energy of the steel grit is only about 5 percent of that of the airstream under conditions of equal air and grit mass flow rates.

Thus, the No. 7 long-venturi nozzle, though representing the best current nozzle technology, still wastes 95 percent of the energy of the compressed air it uses. The opportunity to design a better nozzle is clear, and the good agreement of measurement and computation for the long-venturi nozzle convinces us that we have valid tools at hand for optimizing the nozzle.

Underlying Physical Principles

For a more efficient blasting nozzle to be designed, the underlying physics of the process must first be recognized.[1] Compressed air, expanding through the nozzle, reaches the speed of sound (Mach 1) at the throat and typically twice the speed of sound (Mach 2) at the exit. In other words, the air accelerates from a low speed in the blasting hose to perhaps 1,200 mph (1,930 km/h) while passing through a nozzle only a few inches or centimeters long. Being much more massive than air molecules, abrasive particles have too much inertia to keep up with such acceleration. They do accelerate, although at a slower rate, because of the drag force imposed by the airstream flowing over them. Their acceleration, a, is governed by Newton's second law of motion (F = ma). The drag force F "pushes" the particles to higher speeds. Drag is often seen in a negative context, such as the force resisting the forward motion of an airplane, a car, or a downhill skier. Here, however, drag is everything, for without it a blasting nozzle cannot function.

The sketch of an abrasive particle in a supersonic airstream emphasizes this point (Fig. 4). Although both the particle and the airstream are in motion, it is the relative speed V_{rel} between the two that determines the particle acceleration. In this sketch, V_{rel} is greater than the local sound speed, c, so the relative Mach number ($M_{rel} = V_{rel}/c$ of the air with respect to the particle is supersonic, and a shock wave forms ahead of the particle. This is also the case downstream of the throat of an abrasive blasting nozzle.

The drag force F on a particle accelerating through a blasting nozzle is given by following simple formula.

$F = C_d . A . (1/2\rho V_{rel}^2)$ where A is the (average) cross-sectional area of the particle, C_d is the particle drag coefficient,

Supersonic Airflow → with respect to Particle → F
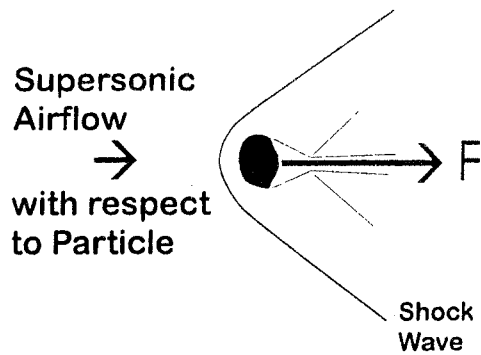
Shock Wave

Fig. 4. Sketch of nozzle air flow past an abrasive particle at a supersonic relative Mach number

and $1/2\rho V_{rel}^2$ is the dynamic pressure of the airstream relative to the particle. With G-40 steel grit selected, A is already fixed.

One may then influence the particle drag force only by way of the drag coefficient and the dynamic pressure. Maximizing these two parameters maximizes particle drag and thereby particle acceleration, producing the fastest possible particle speed at the nozzle exit. As discussed earlier, this is exactly what we wish to accomplish.

The drag coefficient of a particle in flight cannot be predicted easily but must be measured. The best available data comes from the experiments of Bailey and Hiatt, who fired steel balls down a U.S. Air Force ballistic range.[11]

Our abrasive particles are of such a size the C_d is only a weak function of the Reynolds number* (diameter x velocity x density ÷ absolute viscosity) of their flight, but is a strong function of the Mach number, as shown in Fig. 5. Beginning with a value of about 0.45 at low speeds, C_d rises dramatically in the transonic zone, finally leveling off around a value of unit for Mach numbers greater than about 1.4. Coincidentally, gas-dynamic theory (Fig. 6) requires the dynamic pressure also to peak around Mach 1.4, when the pressure upstream of the nozzle is fixed.

Thus, within a certain level of approximation, $M_{rel} = 1.4$ is a "magic number" for the optimization of an abrasive blasting nozzle. (Probably the most serious approximation here is the representation of oblong grit particles as equivalent spheres. It is
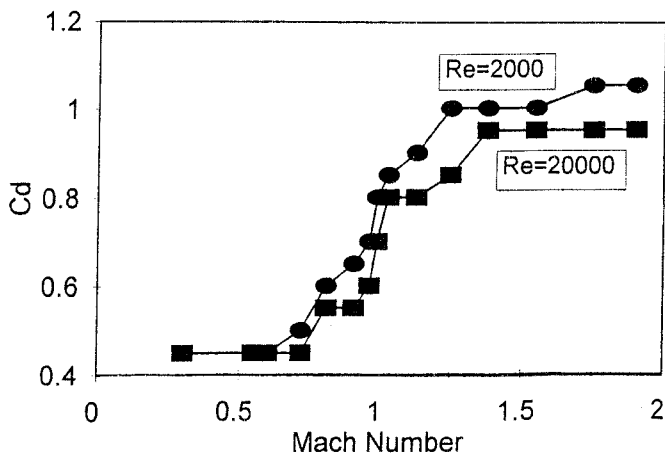

Fig. 5. Sphere drag coefficient vs. Mach number at two different Reynolds numbers (from the data of Bailey and Hiatt)
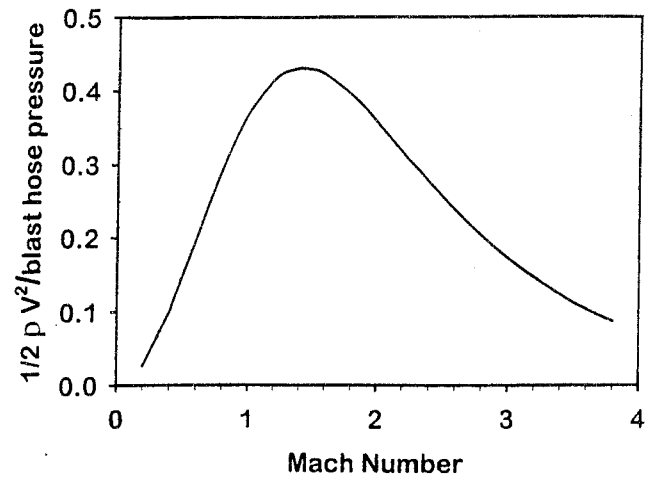

Fig. 6. Ratio of nozzle dynamic pressure to upstream blast hose pressure as a function of nozzle Mach number

justified by the good agreement stated earlier between actual grit data and our computer model in the case of the long-venturi nozzle, and by ballistic range data for rotating steel cubes, cited by Hoerner[12], which are similar to the data of Fig. 5.)

* *The Reynolds number is a dimensionless parameter describing the ratio of inertia to viscous forces of a flow. It is usually important in aerodynamics, but it is not very important in this particular application.*

Nozzle Optimization Design Rules

Based on the above, we can now state for the first time a series of scientific design rules for an efficient, high-productivity abrasive blasting nozzle.

• Within reasonable limits, minimize the convergent-nozzle section length leading up to the throat to bring the relative Mach number between air and particles to unity as soon as possible.

• Make the constant area throat region no longer than necessary to avoid its wearing open to a larger diameter during extended nozzle use.

• After the throat, diverge the nozzle contour rapidly until the relative Mach number between air and particles reaches a value of about 1.4.

• From there, diverge the nozzle contour gradually to maintain the relative Mach number at about 1.4.

• Extend the length of this diverging nozzle section as required, within reasonable limits, to achieve the desired particle speed at the nozzle exit.

• Finally, for a given upstream pressure, the ratio of nozzle exit to throat areas should be chosen according to basic gas dynamic theory to be near perfect expansion.[1]

Recalling the role of particle drag discussed earlier, these nozzle design rules may be concisely summarized as follows: Push early, push hard, and keep pushing for as long as it takes.

The Penn State Nozzle

Using the same design point described earlier for the long-venturi nozzle, we have applied these new rules to design an improved blasting nozzle. Our goal was to double the productivity achieved by the current nozzle technology. To do

so, the G-40 steel grit particles must have twice the kinetic energy at the nozzle exit compared to a long-venturi. Since kinetic energy is $1/2mV^2$, this requirement means their average speed should be $\sqrt{2}$ or 41 percent faster. Our computer model was run, using the above design rules, with the length of the nozzle's diverging section taken as a variable. The result is a new No. 7 nozzle with a shorter converging section but an overall length of 345 mm (14 in.), which is 150 mm (6 in.) longer than the 195-millimeter (8-inch) length of the No. 7 long-venturi.

This increased length is a natural and unavoidable consequence of the need to maintain the accelerating aerodynamic drag force on the grit particles for as long as possible to achieve maximum exit speed. The increased length is necessary to extract energy efficiently from the compressed air for the purpose of accelerating the abrasive. In terms of basic physics, short blasting nozzles can never be efficient.

Figure 7 shows the results of the computer model prediction of air and particle speeds along the length of the Penn State Nozzle. Compared to Fig. 3, particle acceleration is seen to begin earlier, to be higher, and to last longer than in the case of the long-venturi nozzle. A sketch of the corresponding nozzle contour is given in Fig. 8.

An initial experimental prototype of the Penn State Nozzle was fabricated by casting acrylic resin around a mandrel machined to the proper nozzle contour. Such a prototype is limited in its usefulness: it wears out very quickly and, as we discovered, behaves differently than a hard ceramic nozzle at realistic particle loading values. Near-elastic collisions between particles and a hard ceramic nozzle wall cause little loss of particle momentum. Thus, as described earlier, for the ceramic long-venturi nozzle, the particle load factor had no effect on particle exit velocity. This is not the case with a soft plastic nozzle, where inelastic collisions absorb much of the particle momentum. The hardness of the nozzle wall ceases to be an issue only at very low particle loading.

Nonetheless, the prototype served our purpose of allowing an experimental test of the computer model prediction of Fig. 7. Compared to the long-venturi nozzle, a 35 percent higher exit speed of G-40 steel grit particles was measured. While this early result falls somewhat short of our goal, it nonetheless proves the concept. The productivity of the Penn State Nozzle is thus expected to approach twice that of the best current blasting
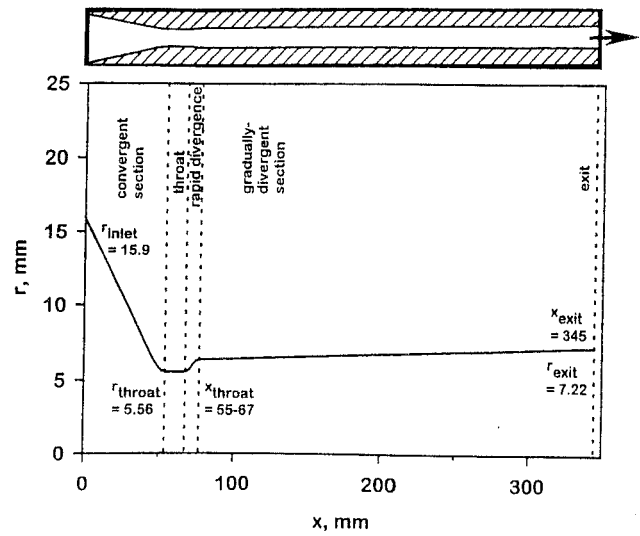

Fig. 8. *Internal contour of #7 Penn State Nozzle (note r-axis is stretched for clarity)*

nozzle technology. Further testing is required, including both laboratory tests of a hard ceramic nozzle and field tests of blasting productivity, to accurately determine the degree of improvement.

The design point of the Penn State Nozzle has been doubling blasting productivity of a No. 7 nozzle with 100 psig (0.79 MPa) hose pressure and G-40 steel grit, conditions of great importance to the coatings removal industry. However, many other abrasives and a range of different hose pressures may be used in specific blasting applications. How will the Penn State Nozzle perform under these conditions? It was shown that an increase of hose pressure or a reduction of abrasive grit size improves blasting productivity regardless of nozzle design.[1] This clearly holds true for the Penn State Nozzle as well. Moreover, the scientific design principles stated earlier result in improved nozzle performance regardless of pressure or choice of abrasive. For example, our computer model also predicts a substantial productivity improvement when 680-micrometer (27-mil) sand is used as the blasting media. Of course, higher particle velocities may also cause increased fracturing and reduced recyclability of sand and other frangible abrasive media.

The value of doubling blasting nozzle productivity in bridge paint removal nationwide was estimated to be as much as $100 million/year.[1] In addition to this potential, the Penn State Nozzle also interferes less with the environment than conventional nozzles because it requires less abrasive to clean a given area. Finally, its use requires only a quick and relatively inexpensive nozzle replacement, with no other change of blasting equipment, abrasive, or pressure.

A patent application has been filed for the Penn State Nozzle as the first abrasive cleaning nozzle designed by scientific methods to achieve a desired productivity goal. Short nozzles, bazookas, and especially long-venturis were never designed scientifically.[1] The application of the modern technology of nozzle design in the protective coatings industry is, in our opinion, long overdue.
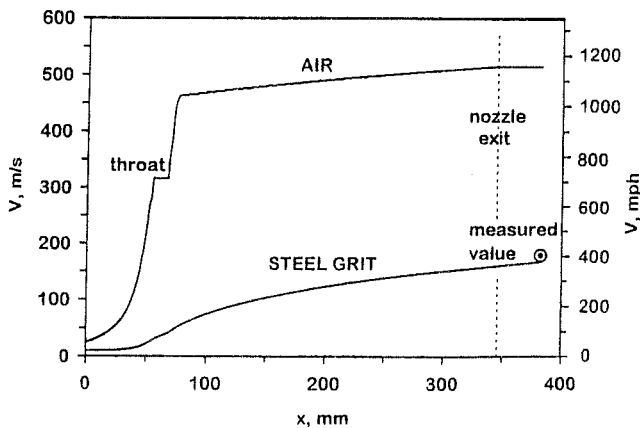

Fig. 7. *Computer prediction of air and steel grit speeds through the Penn State nozzle, compared with experimental measurement*

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