Generation of Air-Blast Shot Velocity

by David Kirk

Introduction

Air-blast shot peening is well-established as the principal technique employed for precision peening. Shot particles are accelerated by a stream of compressed air fed into a nozzle. The maximum velocity of the air stream in the nozzle is the speed of sound, which is about $340ms^{-1}$ at 20˚C. Particles can be introduced into the air stream by any one of three techniques: suction-, gravity- or direct-feeding. Induced shot velocities are normally up to about $100ms^{-1}$.

Shot velocity dominates its kinetic energy, $½mv^2$, which in turn dominates peening intensity. Effective peening therefore requires that we control, amongst other things, the velocity of the shot particles. That control depends upon regulating the several factors that affect the shot velocity. Air streams and induced particle velocities are aspects of fluid dynamics and ballistics. Rows of textbooks in university libraries bear silent witness to the complexities of those subjects! We have a practical need, however, to consider, quantitatively, the factors that affect the generation of shot velocity.

The generation of air-blast shot velocity is considered in three stages:

1 - Air stream,
2 - Introduction of shot into the air stream and
3 - Acceleration of the shot particles by the air stream.

A general equation is presented that can be used to predict the effects of size, shape, density and nozzle air pressure on shot velocity.

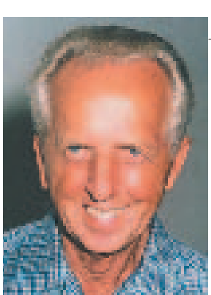
1 AIR STREAM

1.1 Compressed air

Our primary need is to have an adequate supply of compressed air. Nozzle manufacturers publish tables of the compressor capacity requirements for nozzles of different diameters. These give information about the rate at which air has to be compressed in order to maintain a stated range of nozzle pressures. Unfortunately the rate is often quoted using an ambiguous unit – such as "CFM". Industrial examples of unambiguous units are "SCFM" – Standard Cubic Feet per Minute – which is the flow of air corrected to 'standard' conditions - such as 1.0 atm (14.7 psi), 20˚C and 36% humidity - and "ACFM" which means Actual Cubic Feet per Minute – being the actual volume of compressed air put into a pipe per minute, regardless of its compression ratio. As an example: if a compressor takes in 100 CFM of air at 1 atm and compresses it to 5 atm then we have 100 SCFM input and 20 ACFM output.

Pressure gages normally indicate 'relative (to atmospheric)' rather than 'absolute' pressures. That means that without any compression we would have a zero reading. The compression ratio, CR, is given by: CR = (1 + P) to 1 where P is the 'relative' gage reading in atmospheres.

Air at atmospheric pressure has a density of about $1.2kgm^{-3}$. If we compress it by applying an outside additional pressure of one atmosphere (14.7 psi) we halve its volume (P = 1 so that CR = 2) and thereby double its density. At a typical peening pressure of seven atmospheres (100 psi) we have multiplied its density by a factor of eight. In general, air density = CR times $1.2kgm^{-3}$. It is this 'heavy air' that we force through air supply pipes. Fig.1 illustrates 'heavy air' production.



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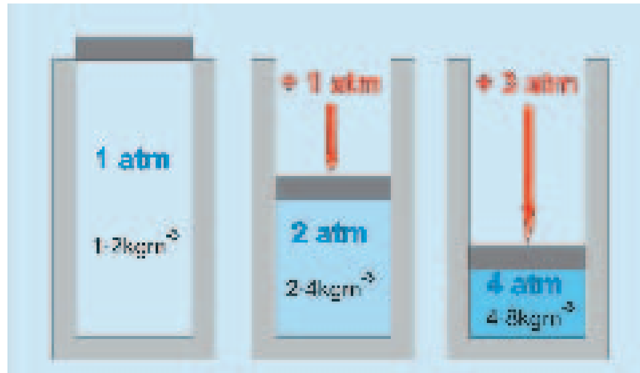

Fig.1 External compression producing 'heavy air'.

1.2 Pipe flow

The outlet from an air compressor goes into a ballast tank and thence to an air supply pipe, preferably via a drying unit. The compressed air flows as a stream through the pipe. This can then be connected to a shot feed and nozzle system. Ballast tanks even out pressure fluctuations from the compressor and provide a reservoir of compressed air. One or more pressure control valves, **PCV**, will be present in the air supply line. The compressed air, at a pressure, $\mathbf{p_1}$, is fed into a blast hose of length L, at the other end of which is a nozzle where the pressure will then be $\mathbf{p_2}$, see fig.2.

Fig.2 Schematic representation of air stream component elements, not to scale.

Pressure control valves are our primary control mechanism. As we increase the pressure we expect that the air flow rate through the hose will also increase. An important practical consideration is the capacity rating of the air compressor system. The air compressor must be capable of pumping air into the ballast tank faster than we are taking it out. A simple analogy is an auto's alternator/battery system. If the battery output is continually greater than the alternator's input then we end up with a flat battery!

A useful analogy when considering air flow rates is that of electricity. Just as we need a potential difference between the ends of a wire for electricity to flow so we need a pressure difference between the ends of a pipe for air to flow. For example, $(p_1 – p_2)$ is the pressure difference between the ends of the air supply pipe which induces a corresponding air flow rate, **Q**, through that pipe. $(p_1 – p_2)$ is useful as a process control parameter. Changes in $(p_1 – p_2)$ can be either abrupt or gradual. For example if $(p_1 – p_2) = p_1$ we have a burst pipe! If $(p_1 – p_2)$ approaches zero then the pipe has become blocked with shot at the nozzle. A common example of gradual change is that caused by nozzle wear. As the nozzle diameter increases $(p_1 – p_2)$ increases (assuming that p_1 is maintained at a constant value – which is normal industrial practice).

It is worth noting that the pressure drop $(p_1 – p_2)$ also represents 'wasted energy'. The work, W, being done in pushing air at a constant rate through the air supply pipe is given by **W = p.V** where V is a given volume of air. The 'useful energy' is that being used at the nozzle end of the pipe, p_2.V. The 'wasted energy' is therefore $(p_1 – p_2)$.V.

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It follows that we can save energy by reducing ($p_1 - p_2$). To a first approximation energy loss increases linearly with pipe length, **L**. Excessive pipe lengths should therefore be avoided. A far more important factor is the internal diameter, **D**, of the supply pipe. The pressure drop for a given flow rate is inversely proportional to D^4 (very approximately). Doubling the pipe diameter will reduce ($p_1 - p_2$) by a factor of about sixteen whereas halving the length only halves the pressure drop.

1.3 Nozzle flow

Our second requirement is to accelerate the air stream at the nozzle. One mechanism for fluid velocity increase is very familiar. A garden hosepipe has low-velocity water flowing through it until it reaches a nozzle. If that nozzle has a cross-sectional area that is a quarter of the cross-section of the hose then the velocity of water would, normally, be increased four-fold at the nozzle. We can apply the same principle to air stream acceleration, up to a certain critical velocity – the speed of sound. Fig.3 illustrates the basic geometry that is involved.

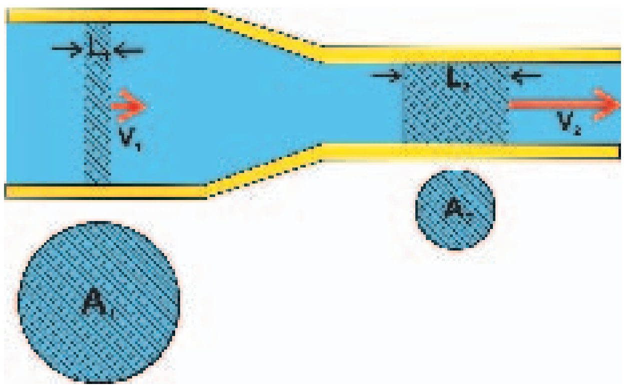

Fig. 3. Velocity change as air in supply pipe reaches nozzle.

Consider an imaginary cylinder of air, shown in fig.3, having a volume $A_1.L_1$ and travelling at a velocity v_1. When this cylinder reaches the nozzle it has the same volume (assuming no density change) but different dimensions, A_2 and L_2 and now has a velocity v_2. Now since $A_1.L_1 = A_2.L_2$ it follows that v_2, must then be A_1/A_2 times greater than v_1. In general: $v_2 = v_1.A_1/A_2$. Now since $v_1.A_1 = Q$ we have the important relationship that:

$$v_2 = Q/A_2 \qquad (1)$$

Using Q as 10 litres per second and a nozzle cross-sectional area of $40mm^2$, equation (1) gives us v_2 as $250ms^{-1}$. That value is for the average velocity across the nozzle section. In practice the velocity varies across the section.

Equation (1) only applies up to a limiting value of v_2. That is because practical nozzle air pressures are always high enough to produce what is termed "choked flow". Fig.4 is a simplified schematic representation of how the nozzle air velocity changes with increase of nozzle air pressure (assuming that the nozzle vents to 1 atm pressure in a peening unit). A "sonic barrier" exists at the narrowest part of the nozzle, caused by the difference in pressure in the nozzle as compared with that in the peening unit. This barrier occurs when the air pressure difference is about 1.9 atm. Because all practical peening involves a pressure difference of more than 2 atm (29.4 psi) we have a fixed limited air velocity in the nozzle - regardless of nozzle pressure and nozzle diameter. The only proviso is that an adequate supply of compressed air is maintained.

The constancy of air velocity in the nozzle begs the question: "What effect does air pressure have if it does not affect air velocity?" The answer is that at higher pressures the air is more compressed so that it has a greater density - but has the same velocity. Increasing the nozzle pressure increases the 'mass flow' of air. Alternatively we could say **"As we increase nozzle air pressure we are firing heavier air - but at a constant velocity".**

The *average* 'fixed limited' nozzle air velocity depends on the nozzle design and can be inferred from 'nozzle performance tables' supplied by manufacturers. For one set of tables, the derived average

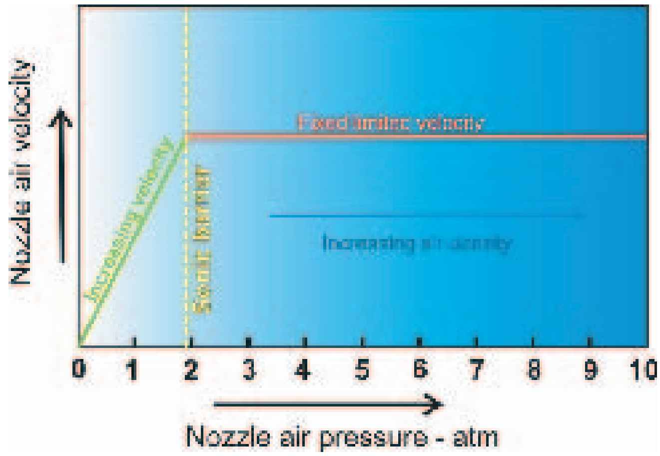

Fig. 4 Schematic representation of velocity variation with air pressure.

nozzle air velocity values were always 207±1 ms^{-1} (678±2 fps) regardless of nozzle pressure or diameter. Average nozzle air velocity estimation simply involves dividing the air flow by both the compression ratio (to give ACFM) and the nozzle cross-sectional area.

Table 1 shows specimen calculations obtained using an Excel spreadsheet and manufacturer's data. The Excel columns are shown as A, B, C and D in the table and the "9" is simply the row number that was being used for entering values.

Table 1 Specimen Calculations of Average Air Velocity in Nozzle.

Nozzle pressure - atm (psi)	Compressor air flow - litres/s (scfm)	Nozzle diameter - mm (inch)	Average air velocity – $m.s^{-1}$ * (feet/second)
6.8 (100)	204 (432.6)	12.7 (0.5)	206 (678)
3.4 (50)	115 (243.6)		206 (676)
6.8 (100)	51 (108.2)	6.35 (0.25)	206 (680)
3.4 (50)	29 (61.2)		208 (680)
A	B	C	D

* - =(B9*1000/((A9+1)*(3.142*C9^2/4)))

The air velocity across the nozzle varies from a maximum of 340 $m.s^{-1}$ (speed of sound in air) to zero at the nozzle wall. An average value of 207 $m.s^{-1}$ reflects this variation.

It is worth noting that in both pipes and blast nozzles we always have what is termed "turbulent flow" – as opposed to "streamline flow" – because the corresponding Reynolds's numbers are very large. Turbulent flow is illustrated in fig.5. Air moves in three dimensions following sinuous pathlines but with an average forward velocity.

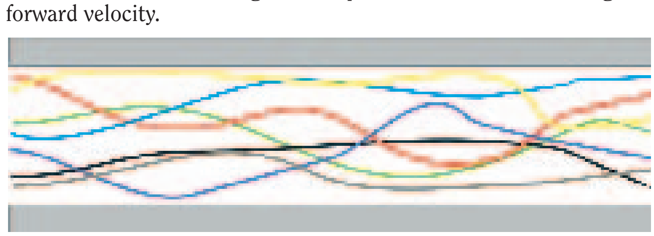

Fig. 5 Pathlines followed by air during turbulent flow through pipes or nozzles.

2 INTRODUCTION OF SHOT INTO THE AIR STREAM

The three common systems for introducing shot into the air stream are suction-, gravity- and direct-feeding.

2.1 Suction feed

This system is illustrated, schematically, in fig.6 on page 28.

Air is sucked up the shot feed tube at a velocity v_1 (which is much lower than the air blast velocity, v_2) hence the term "suction feed". Because the velocity v_1 is less than v_2 the air pressure in the shot feed tube is higher than that in the nozzle. This phenomenon was explained by Bernoulli (hence "Bernoulli's Principle"). If p_1 is the pressure in the shot feed tube and p_2 is the pressure in the nozzle then we have that:

$$(p_1 - p_2) = ½.\rho_A.(v_2^2 - v_1^2) \qquad (2)$$

where ρ_A is the density of the air.

$(v_2^2 - v_1^2)$ is very large so that the predicted pressure difference $(p_1 - p_2)$ must also be substantial.

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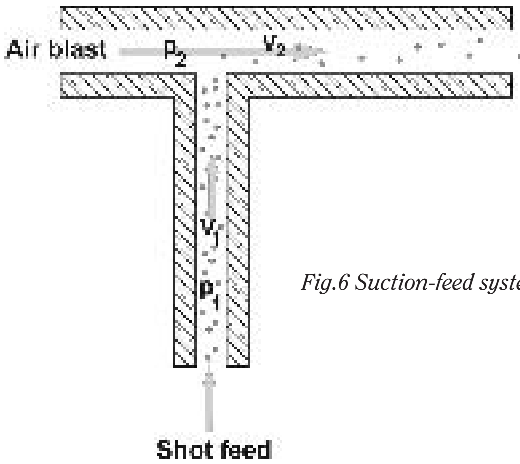

Fig.6 Suction-feed system.

The induced shot feed pipe velocity, v_1, is sufficient to drag shot particles into the nozzle. Turbulent air flow in the nozzle aids mixing of shot and air.

2.2 Gravity feed

Gravity feeding is very similar to suction feeding in that shot is introduced into, or close to, the nozzle. The difference is that the entry point is above the nozzle - so that we have a combination of gravitational and suction forces encouraging the shot particles to enter the nozzle. We would therefore expect that we can achieve higher shot feed rates than with suction feeding. Fig.7 is a schematic representation of a gravity feed nozzle. Shot is shown as entering at a 45° angle, which is found to facilitate air/shot mixing.

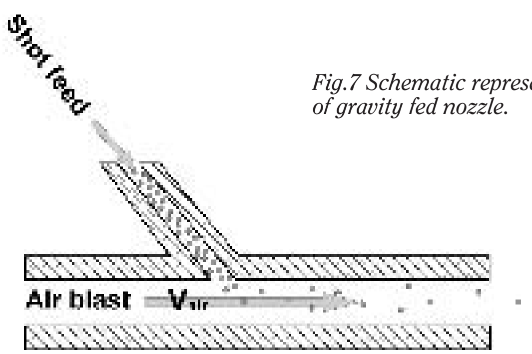

Fig.7 Schematic representation of gravity fed nozzle.

2.3 Direct feed

With direct fed systems, shot and air are mixed before entering the blast hose pipe. The mixture of shot and low velocity compressed air travel together before entering the nozzle. This system is illustrated schematically in fig.8. Turbulent air flow throughout the system aids uniform mixing of air and shot.

3 VELOCITY OF SHOT PARTICLES ACCELERATED BY AN AIR STREAM

3.1 Acceleration

Our fast-flowing air stream exerts a force on each shot particle that has been introduced. Acceleration occurs when we have an imbalance of forces. One form of Newton's Second Law is that "Force is equal to mass times acceleration" or:

$$F = m.a \qquad (3)$$

where **F** is the magnitude of the imbalanced force, **m** is mass and a is the consequent acceleration in the direction of **F**.

Fig.9 represents a model of the air/shot situation in a straight-bore nozzle. On the central axis we have the maximum air velocity with lower velocity as we move towards the bore surface. The average (mean) air velocity is that calculated in section 1.1, being about 200m.s^{-1} (656ft/sec) for a straight nozzle. Shot particles will move about in the nozzle bore, because the air flow is "turbulent". We can

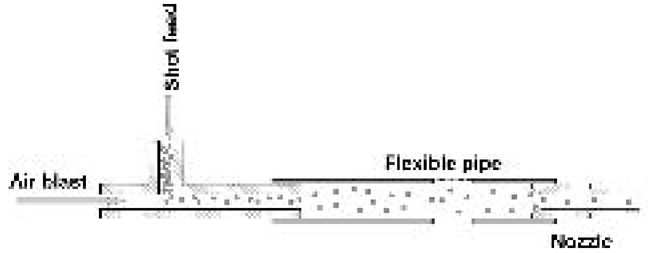

Fig.8 Direct feed system (not to scale).

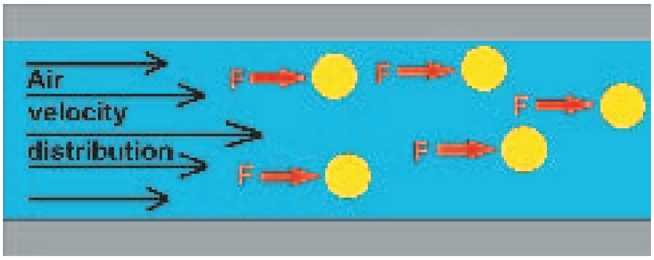

Fig.9 Model of air/shot situation in a straight-bore nozzle.

therefore assume that there is an average axial force, **F**, that is virtually the same for each particle.

With suction- and gravity-feed systems we have a limited distance, **s**, in which to accelerate the particles. Direct-feed gives us much more distance in which to generate shot velocity, v_s. The greatest acceleration will occur within the nozzle (where the air velocity is greatest).

If we assume that the acceleration remains constant then we have a simple relationship between the three parameters **a**, **s** and v_s:

$$v_s^2 = 2.a.s \qquad (4)$$

In order to increase the velocity we can either increase the acceleration or increase the length or both. Shot peening nozzles have a length of the order of 100mm so that the acceleration has to be very high in order to produce velocities in the region of 50m.s^{-1}. Substitution of 0.100m and 50m.s^{-1} into equation (4) gives us that the required acceleration would be 12,500m.s^{-2} or 1,250 times normal gravitational acceleration!

We can re-write equation (3) as **a = F/m** and substituting that into equation (4) gives us:

$$v_s^2 = 2.F.s/m \qquad (5)$$

The force, **F**, on a particle in fast-flowing fluids is given by the equation:

$$F = ½.C_D.A.\rho_A.(v_a - v_s)^2 \qquad (6)$$

where C_D is the "drag coefficient" (a dimensionless number that depends upon the shape of the object and for a smooth sphere $C_D \approx 0.5$), A is the cross-sectional area of the object, ρ_A is the density of the **compressed** air (1.2kgm^{-3} times the compression ratio), v_a is the velocity of the air stream and v_s is the velocity of the shot particle. $(v_a - v_s)$ is termed the "relative velocity" of the particle compared with that of the air stream.

3.2 Shot velocity development

Combining equations (5) and (6) gives that:

$$v_s = (C_D.A.\rho_A.s/m)^{0.5}\ (v_a - v_s) \qquad (7)$$

Equation (7) can be expressed in more familiar terms, for spherical shot, by substituting $\pi.d^2/4$ for **A** and $\rho_s.\pi.d^3/6$ for **m**, where d is shot diameter and ρ_s is the density of the shot. That gives:

$$v_s = (1{\cdot}5.C_D.\rho_A.s/\pi.d.\rho_S)^{0.5}\ (v_a - v_s) \qquad (8)$$

All we have to do now is to solve equation (8) for v_s, using known peening parameters. The simplest approach is to set up an

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Excel spreadsheet that includes a formula that is a re-arranged form of equation (8). Table 2 shows how the required shot velocity (cell C11) is evaluated using the following (in Excel format):

=C9*((1.5*C3*C5*C4*C8)/(C6*C7))^0.5/(1+((1.5*C3*C5*C4*C8)/(C6*C7))^0.5)

With a spreadsheet it is a simple task to enter specific values for the variables. A range for a given variable can also be used to plot a graph of that variable against induced velocity.

Table 2 Specimen calculation of nozzle-induced shot velocity using Excel.

1	B	C	D
2	Parameter	Value	Units
3	Cd	0.5	
4	Air density	1.2	kgm^{-3}
5	Air pressure	9	atm
6	Shot density	7860	kgm^{-3}
7	Shot diameter	0.25	mm
8	Length	50	mm
9	Air velocity	200	$m.s^{-1}$
10			
11	Shot v elocit y	48.6	$m.s^{-1}$

Fig.10 is an example of curves produced using equation (8).

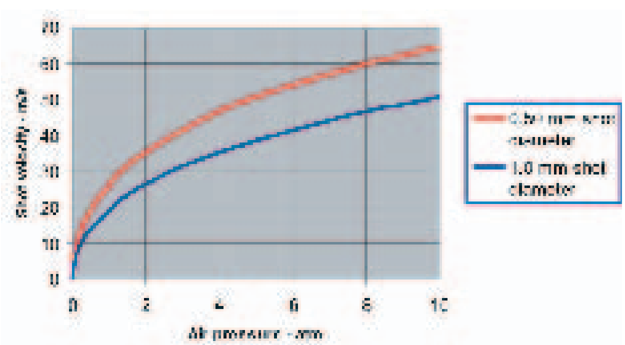

Fig.10 Curves of nozzle-induced shot velocity versus nozzle air pressure.

There are, however, three stages in which shot particles can increase their velocity. These are in the:

(i) feed pipe,
(ii) nozzle and
(iii) post-nozzle air/shot cone.

Feed pipe velocity increase only occurs with direct-feed systems.

(i) feed pipe
The direct-feed pipe length is huge compared with that of the nozzle. Air velocity in the pipe is, however, much smaller than that in the nozzle. The air velocity is estimated by dividing the compressor air input by the product of compression ratio and pipe cross-sectional area. For example, using the Table 1 spreadsheet and substituting 6.8 atm (100psi) and 204 litres/s (432.6 scfm) for a 25.4mm (1") I.D. pipe gives 51.5 $m.s^{-1}$ (170 feet/second) for feed pipe air velocity. Substituting a length of 4000mm for Length, 6.8 atm (100psi) for Air pressure and 51.5 $m.s^{-1}$ for Air velocity into the Excel spreadsheet used for Table 2 gives an induced shot velocity of 11.2 $m.s^{-1}$. That can be regarded as a 'pre-nozzle velocity increase' - to be added to subsequent nozzle acceleration. This pre-nozzle velocity increase is attractive when we have large shot and/or a requirement to maximise shot velocity.

(ii) nozzle
Equation (8) was used to predict the variation of nozzle-induced shot velocity with air pressure for two shot sizes - as shown in fig.10. The advantage of pre-nozzle velocity increase for large shot becomes apparent. The equation can also be used to predict the effects of nozzle length and shot material (through change of shot density).

(iii) post-nozzle air/shot cone
As the shot particles exit from the nozzle they are travelling much more slowly than the air stream – as evidenced by the examples in the preceding section. Fig.11 illustrates the situation where shot acceleration occurs in the nozzle from A to B with a constant air velocity. A rapid reduction of air pressure occurs at B. From B to C the relative air velocity reduces, so that at C both air and shot are travelling at the same speed. Thereafter the shot is travelling faster than the air stream so that a reduction in shot velocity occurs.

Fig.11 Combined acceleration within nozzle, A-B, and after leaving nozzle, B-C.

Theoretical analysis of shot velocity changes in the expanding cone, BC, is very, very complicated. There is some experimental evidence that the maximum shot velocity occurs at about 200mm from the nozzle. As a rough example, substitution of 200mm for Length,100$m.s^{-1}$ for Air velocity (as an average value) and 1 atmosphere for Air pressure would indicate a post-nozzle shot velocity increase of 17.6$m.s^{-1}$. Nozzle type will also be a factor, convergent-divergent nozzles, for example, have a larger air velocity at exit than have straight nozzles.

3.3 Final shot velocity
Shot velocity at the nozzle exit will be the sum of (i) and (ii) for direct feed systems and just (ii) for suction and gravity feed systems. Post-nozzle shot velocity will depend upon the distance from the nozzle – being a maximum at some distance from the nozzle (of the order of 200mm).

DISCUSSION and CONCLUSIONS
This article is based on a simple model of air flow and shot acceleration. The small effects of temperature and humidity have been ignored. Very accurate values for predicted shot velocities cannot, therefore, be expected. On the other hand the equations presented can be used to explain experimentally-observed variations.
Several significant conclusions can be drawn from the analyses contained in the article. These include:

- An adequate air supply will induce a virtually-constant nozzle air velocity that is a large fraction of the speed of sound and is independent of both nozzle air pressure and diameter.
- Increasing the nozzle air pressure increases induced shot velocity because of the corresponding increase in air density.
- A general equation has been presented that allows quantitative prediction of induced shot velocity and the effects of shot size, shot density, nozzle length and nozzle pressure.