The Fundamentals of Dry Ice Blast Cleaning

Today, CO₂ blasting is being effectively used in a wide array of applications from heavy slag removal to delicate semiconductor and circuit board cleaning. Imagine a process that can be used on-line without damaging equipment or requiring a machine “teardown”. Unlike conventional toxic chemicals, high pressure water blasting and abrasive grit blasting, CO₂ blasting uses dry ice particles in a high velocity air flow to remove contaminants from surfaces without the added costs and inconvenience of secondary waste treatment and disposal.

What Is Dry Ice?
Dry Ice is the solid form of Carbon Dioxide (CO₂) which is colourless, tasteless, odourless gas found naturally in our atmosphere.

With a low temperature of −78,5° (−190 °F), Dry Ice solid has an inherent thermal energy ready to be tapped. At atmospheric pressure, solid CO₂ sublimates directly to vapour without a liquid phase. This unique property means that the blast media simply disappears, leaving only the original contaminant to be disposed of. In addition, cleaning in water sensitive areas is now practical.

Carbon dioxide is a non-poisonous, liquefied gas which is both inexpensive and easily stored at work sites. Of equal importance, it is non-conductive and non-flammable.

Table 1. Carbon Dioxide (CO₂) properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight</td>
<td>44.01 g/mole</td>
</tr>
<tr>
<td>Density (Solid)</td>
<td>1.562 kg./mc at −78,5° C</td>
</tr>
<tr>
<td>Density (Liquid)</td>
<td>1.022 kg./mc at −18° C</td>
</tr>
<tr>
<td>Density (Gas)</td>
<td>1.977 kg./mc at 0° C</td>
</tr>
<tr>
<td>Melting Point</td>
<td>−56,5° C at 5,2 bar (triple point)</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>−78,5° C (sublimates)</td>
</tr>
<tr>
<td>Liquid-to-Snow Conversion Rate</td>
<td>0.46 kg. snow/kg. liquid at −17,6° C</td>
</tr>
<tr>
<td></td>
<td>0.57 kg. snow/kg. liquid at −47,8° C</td>
</tr>
</tbody>
</table>
**Media Manufacture**

In Dry Ice blasting, there are several methods used to manufacture the Dry Ice blasting media. One technique is to shave dry ice granules from solid Dry Ice block at the blasting machine. This generally produces sugar-crystal sized Dry Ice granules, which must be used quickly due to fast sublimation (due to their high surface area to volume ratio).

Another technique is to manufacture hard pellets of Dry Ice in a pelletizer then immediately blast with the pellets of store the pellets in an insulated container until the pellets are required. These pellets are generally on the order of 2–3 mm. in diameter, and 2.5–10 mm. in length.

In this method, Dry Ice is manufactured by flashing pressurized liquid CO₂ into snow, followed by compression of the snow into solid form. The snow is either directly nuggetized into pellets (mechanical compression) or is extruded into solid pellet form through a die under hydraulic pressure. The latter process allows for more efficient conversion from the liquid phase to the solid phase. Generally, it is desirable to have pellets which are well compacted, to minimize entrapment of gaseous CO₂ and/or air which may affect product quality.

As can be seen in Table 1, the yield achieved when flashing liquid carbon dioxide into snow increases as the temperature of the liquid CO₂ decreases, so it is important to pre-chill the incoming liquid CO₂ via heat exchangers with the outgoing CO₂ vapor. Figure 1 is a block diagram showing a basic pelletization process.

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**Figure 1.** Pelletization Process.

![Diagram of the pelletization process](image-url)
Several manufacturers make Dry ice pelletizers which may prove beneficial to have on-site for customers with high pellet demand. Facilities required for such an arrangement are generally as follows: a refrigerated liquid CO₂ tank, a pelletizer, and liquid CO₂ lines to reach the equipment. Some manufacturers make combined Dry Ice pelletizer/blast machines which manufacture Dry Ice and blast all in one operation. Facilities required for such an arrangement are: an air compressor (5 mc/min at 7 bar), a liquid CO₂ tank, a pelletizer/blast machine, compressed air hose and liquid CO₂ lines to reach the equipment, blast hose from the machine to the blasting operation, and the appropriate nozzle(s) for the application. This equipment is best suited to high volume, continuous blasting applications where the cost savings of manufacturing pellets on-site justifies the capital expenditure for the system.

**How Does Dry Ice Blasting Work?**

*The Basic Process*

Dry Ice particle blasting is similar to sand blasting, plastic bead blasting, or soda blasting where a media is accelerated in a pressurized air stream (or other inert gas) to impact the surface to be cleaned or prepared. With Dry Ice blasting, the media that impacts the surface is solid carbon dioxide (CO₂) particles. One unique aspect of using Dry Ice particles as a blast media is that the particles sublimate (vaporize) upon impact with the surface. The combined impact energy dissipation and extremely rapid heat transfer between the pellet and the surface cause instantaneous sublimation of the solid CO₂ into gas. The gas expands to nearly eight hundred times the volume of the pellet in a few milliseconds in what is effectively a “micro-explosion” at the point of impact. Because the CO₂ vaporizing, the Dry Ice blasting process does not generate any secondary waste. All that remains to be collected is the contaminate being removed.

As with other blast media, the kinetic energy associated with Dry Ice blasting is a function of the particle mass density and impact velocity. Since CO₂ particles have a relatively low hardness, the process relies on high particle velocities to achieve the needed impact energy. The high particle velocities are the result of supersonic propellant or air stream velocities.

Unlike other blast media, the CO₂ particles have a very low temperature of –78,5° C. This inherent low temperature gives the Dry Ice blasting process unique thermodynamically induced surface mechanism that affect the coating or contaminate in greater or lesser degrees, depending on coating type. Because of the temperature differential between the Dry Ice particles and the surface being treated, a phenomenon known as “fracking” or thermal shock can occur. As a material’s temperature decreases, it becomes embrittled, enabling the particle impact to break-up the coating. Refer to Figures 2 and 3.
Figure 2. Thermal shock induces micro-cracking in the surface coating

Also, the thermal gradient or differential between two dissimilar materials with different thermal expansion coefficients can serve to break the bond between the two materials. This thermal shock is most evident when blasting a non-metallic coating or contaminate bonded to a metallic substrate.

Quite often companies examining this process are concerned with the effect the thermal shock will have on the parent metal. Studies have shown that the temperature decrease occurs on the surface only, there is no chance of thermal stress occurring in the substrate metal. To illustrate this principle, an experiment was performed where thermocouples were imbedded into a steel substrate a varying depths (flush with the surface to 2 mm. deep). Refer to Figure 4.

Figure 3. CO₂ gas expansion and pellet kinetic effects break away and remove coating particles.
A CO₂ blast jet was constantly traversed across the test specimen for 30 seconds (a relatively long dwell time for this process) and the thermal couples recorded the changing temperatures at the various depths. As shown in Figure 5, the surface mounted thermocouple shows a temperature drop each time the blast jet impinged directly upon the thermocouple (50° C in about 5 seconds). In contrast, the thermocouples imbedded at various depths in the substrate recorded a slow gradual drop in temperature corresponding to the overall test plate temperature drop. The thermocouple 2 mm. deep only dropped 10° C after 30 seconds. This curve illustrates that the “Thermal Shock” occurs only at the surface where the coating or contaminate is bonded to the substrate (Reference 1) and has on detrimental effect to the substrate.
Another approach to looking at thermal stress is by studying the use of Dry Ice blasting in the molded rubber industry. Here, hot steel molds operating at 150° C are blasted with –78.5°C Dry Ice particles. The temperature difference between the hot mold and cold Dry Ice will not cause cracking. There are two reasons for this phenomenon. First, as seen above, the temperature gradient occurs at the surface. Secondly, the thermal stresses involved are much less than those encountered during normal heat treatment.

The thermal stress due to a temperature differential can be estimated using equation 1 where \( sy \) is stress, \( AT \) is temperature gradient, \( a \) is coefficient of expansion and \( Y \) is Poisson’s Ratio.

\[
\frac{(AT \times Exa)}{(1-y)}
\]

The corresponding parameter values are

\[
sy = \frac{((30 \times 10^6) \times (5 \times 10^{-6}) \times AT}{(1-0.33)}
\]

and the thermal stress (N/cmq) is

\[
sy = 224AT
\]
where the temperature differential will be about 57° C. This temperature leads to a low
tensile stress of 20,85 N/cm². Even if the mold temperature was brought down to the
temperature of the ice (an unrealistic extreme), the temperature gradient would be about
235° C. The corresponding tensile stress is 70,0 N/cm². This calculated stress is below
the yield point of steel in the hardened condition. Again, these thermal stresses would be
far less than those encountered during normal heat treatment where the temperature
differentials would exceed 260° C.

Even at high impact velocities and direct “head-on” impact angles, the kinetic effect of
solid CO₂ particles is minimal when compared to other media (grit, sand, PMB, etc.). This
is due to the relative lack of hardness of the particles and the almost instantaneous phase
change to a gas on impact which effectively provides an almost nonexistent coefficient of
restitution in the impact equation. Because CO₂ blasting is considered non-abrasive and
relies on the thermal effects discussed above, the process may be applied to a wide range
of materials without damage. Soft metals such as brass and aluminium cladding can be CO₂
blasted for the removal of coatings or contaminates without creating surface stresses
(pinging), pitting, or roughness (Reference 3).

**Blast Machine Types**

There are two general classes of blast machines as characterized by the method of
transporting pellets to the nozzle: two-hose and single-hose systems. In either type of
system, proper selection of blast hose is important because of the low temperatures
involved and the need to preserve particle integrity as the particles travel through the
hose.

In the two-hose system, Dry Ice particles are delivered and metered by various
mechanical means to the inlet end of a hose and are drawn through the hose to the nozzle
by means of vacuum produced by an ejector-type nozzle. Inside the nozzle, a stream of
compressed air (supplied by the second hose) is sent through a primary nozzle and
expands as a high velocity jet confined inside a mixing tube. When flow areas are properly
sized, this type of nozzle produces vacuum on the cavity around the primary jet and can
therefore draw particles up through the Ice hose and into the mixing tube where they are
accelerated as the jet mixes with the entrained air/particle mixture. The exhaust mach
number from this type of nozzle, in general, slightly supersonic. Advantages of this type of
system are relative simplicity and lower material cost, along with an overall compact
feeder system. One primary disadvantage is that the associated nozzle technology is
generally not adaptable to a wide range of conditions (i.e. tight turns in a cavity, thin-wide
blast swaths, etc.). Also, the aggression level and strip rate of the two-hose system is less
than comparable single-hose blast machines.

In a single-hose system, particles are fed into the compressed air line by one of several
types of airlock mechanisms. Reciprocating and rotary airlocks are both currently used in
the industry. The stream of pellets and compressed air is then fed directly into a single
hose followed by a nozzle where both air and pellets accelerate to high velocities. The
exhaust Mach number from this type of nozzle is generally in the 1.4 and 2.5 range,
depending on design and blast pressure. Advantages of this type of system are wide
nozzle adaptability and the highest available blast aggression levels. Disadvantages include relatively higher material cost due to the complex airlock mechanism.

Blast machines are also differentiated into Dry Ice Block Shaver blasters and Dry Ice Pellet blasters. The Block Shaver machines take standard 20 kg. Dry Ice blocks and use rotating blades to shave a thin layer of ice off the block. This thin sheet of Dry Ice shatters under its own weight into sugar grain sized particles. These particles then fall into a funnel for collection. A two-hose delivery system is used to transfer the particles at the bottom of the funnel to the surface to be cleaned. The low mass of these particles combined with the inefficient two-hose system limits the block shavers to light duty cleaning. Because the shaved ice machines deliver a particle blast with high flux density (Number of particles striking a square area of surface per second), they are effective on thin moderately hard coatings such as an air dried oil based paint. The disadvantage of the ice shaver is the particle size and flux density is fixed, as well as, the particle velocity.

In contrast, Pellet Blast machines have a hopper that is filled with pre-manufactured CO₂ pellets. The hopper uses mechanical agitation to move the pellets to the bottom of the hopper and into the feeder system. As stated earlier, the pellets are extruded through a die plate under great pressure. This creates an extremely dense pellet for maximum impact energy. The pellets are available in several sizes, ranging from 1.5 to 3 mm. in diameter. With a single-hose delivery system, the final pellet size and blast flux density exiting the nozzle is governed by the type of blast hose (hose diameter and interior wall roughness) and nozzle used. Because of its design, the single hose pellet blast units are capable of “dialling-in” the correct blast type needed for a wide range of individual coatings or contaminate removal.

For example, soft coatings such as rubber, silicone, foams and waxes, release agents, food ingredients, etc. need large pellets with low flux density for maximum strip rate and efficiency. These coatings require maximum thermal energy (i.e. pellets with large mss) and large spacing between pellets (i.e. low flux density) for optimum cleaning performance. In contrast, hard coatings such as paints, varnish, baked on sugars, carbon build-up, etc. require smaller particle size with high flux density and high particle velocity.

Blast machines are further differentiated into all-pneumatic and electro-pneumatic types. All-pneumatic machines have particle feed mechanism and controls operated pneumatically. This may include the use of air motors. The advantage of such a machine is the availability of compressed air at the blast locations, especially outdoors. One disadvantage is that the operation of the machine may be susceptible to disruption due to moisture or contamination in the compressed air supply. In addition, these machines are more prone to freeze-ups and are better suited for light duty spot cleaning applications. Also, if the machine is powered by an air motor, it will have a continuous exhaust of oily air. This same air motor can be easily flooded with water if the air system is not adequately dried.

Electro-pneumatic machines are truly “Environmentally Friendly” because there is no oily exhaust and these machines are more tolerant of moisture and contaminants in the air supply. The electro-pneumatic machines rarely freeze-up which makes them ideal for automated line applications where around-the-clock blasting is required. Also, these machines provide pulse free blasting for uniform cleaning and efficient use of the Dry Ice.
There is, however, a slight inconvenience factor associated with supplying both electrical power and compressed air to the machine at each blast location.

One of the most challenging technologies associated with either type of blast machine is the achievement of smooth, continuous pellet feed. One surprising property of Dry Ice is that it is not smooth or slippery like water ice nor smooth-flowing like sand or glass bead. Instead it is somewhat resistant to flow. Because of this, Dry Ice blast machines tend to have various agitators, augers and other devices in the hopper to improve pellet flow. Generally, the poorer the quality of dry ice, containing; for example, water ice build-up or a large percentage of CO₂ “fines” or snow, the more difficult it is to flow through a system. An additional property of Dry Ice is that it is extremely cold and will draw moisture out of the surrounding air in the form of frost. The machine, therefore, must be tolerant of repeated freeze-thaw cycles and the associated moisture accumulation that will take place over time.

Generally the difference between a high quality blast machine and a mediocre one lies in the units ability to do a cleaning job quickly, cost-effectively, and in the reliability of smooth and continuous pellet flow under real-world conditions.

Nozzle Technology
The nozzle is where the Dry Ice particles are accelerated to the highest velocity possible in order to create an effective blast stream. Figure 6 shows schematics of the two types of nozzles used for Dry Ice blasting. The science of two-hose ejector nozzles compared to single-hose convergent-divergent supersonic nozzles operating under the same conditions (i.e., air volume, pressure, temperature, CO₂ particle mass etc.), shows significantly higher efficiency capability for the described single-hose type nozzles. This difference in capability directly relates to the two-hose ejector nozzle’s overall supplied energy being used not only to accelerate the CO₂ particles, but also to create the vacuum pulling the secondary pellet flow through the secondary hose. Then more energy is drained to mix this low velocity particle flow with the high velocity jet flow in order to accelerate the particle through the two-hose nozzle. In simple terms, the net resultant energy available for pellet acceleration is inherently lower for two-hose systems because much of the available energy is lost simply in combining the CO₂ particle flow with the air-jet flow.

Figure 6. CO₂ Particle Blast Nozzle Types
Since the size of the Dry Ice particles effects the cleaning performance, a blast system should have the flexibility to “Dial-In” the correct particle size. This can be done a couple of different ways. First, the size of the pellet being produced by the pelletizer may be varied. Once the pellet is in the blast machine hopper, the size of the pellet reaching the surface to be cleaned can be varied several ways. The diameter and type of blast hose used will either keep the pellet intact or break the pellet up into smaller particles. Also, the nozzle may be intentionally mes-expanded to produce partially destructive shock waves in the nozzle. Both techniques are used independently or together to optimise the particle size, blast stream velocity, and flux density for any cleaning job.

When sand or any similar media with very small diameter is used in blasting, the size of the nozzle throat is very large compared to the blast media. In Dry Ice blasting, however, the nozzle throat may only be slightly larger than the dry ice particle being accelerated. Table 2 is a chart indicating the approximate size of a round nozzle throat for four different levels of blast pressure at a constant airflow of 200 Standard Cubic Feet per Minute (SCFM) and typical flow rate available for blasting operations. At higher pressures, the Dry Ice particle size needs to be smaller to correspond with the smaller throat size. The high pressure blast stream is described as high velocity small particles with high flux density. Again, this particle blast profile is suited best for removing hard coatings such as paint. The chart shows a larger nozzle throat diameter corresponding to low pressure operations. As stated above, large pellets impacting the surface with low flux density is ideal for cleaning soft coatings.