ANALYSIS OF SMALL HIGH SPEED CO\textsubscript{2} PARTICLES USING LOW-COST VIDEO IMAGING SYSTEMS

Stephen G. Pothier, Laurie A. Meade, and Chris B. Rogers

Department of Mechanical Engineering
Tufts University
Medford, MA 02155

David Parekh
McDonnell Douglas Aerospace
St. Louis, MO

Abstract

Introduction
Stripping the paint from aircraft surfaces can be a difficult job. Traditional chemical removal techniques use caustic, environmentally unfriendly substances, generate toxic waste, require workers to wear breathing apparatus and protective clothing, are generally difficult to automate. McDonnell Douglas Corp. developed an innovative technology that eliminates most of these problems. This procedure uses a high intensity pulsed xenon lamp and a continuous spray of carbon dioxide solid particles. The high intensity lamp, which is focused on a roughly 100 cm\textsuperscript{2} area of the aircraft surface, flashes and instantly burns a layer of paint that is a few microns thick. Small (100 micron to 1.5 mm diameter size) high speed solid CO\textsubscript{2} particles, which are driven by compressed air, are simultaneously swept across the vaporized area. This process cools the surface, preventing heat from transferring to the sublayers, and sandblasts away the paint soot. A vacuum system then sucks up the paint particulate.

There are many benefits of this system compared to chemical stripping. For example, the aircraft surface is instantly left clean, dry and free of any chemical residues. It is easy to automate and the process is rapid. Rather than breathing apparatus and protective clothing, worker only need to use UV eye protection and hearing protection. Paint layers as thin as one micron can be removed at a time. And, the only toxic substance generated is the paint that was actually removed from the aircraft surface, which is ported to a storage bag by the vacuum system.

The most expensive part of operating this system is creating and driving the carbon dioxide particles. To make the process more cost effective, the focus of our research is to understand the
CO₂ flow in order to make use of the CO₂ particles as efficient as possible. The research is aimed at several unknowns such as particle velocities, sizes, and loading (number of particles per time). This paper covers a preliminary examination at the McDonnell Douglas research facility in St. Louis.

**Experimental Facility**

The experimental facility consists of a Pelletizer that produces the CO₂ pellets (about 5 mm nominal diameter), a Jet nozzle, and the Xenon lamp. High pressure air entrains the CO₂ pellets and then transports them through about 30m of hose before exiting in a near 2 dimensional jet.

Figure one shows the orientation of the jet to the substrate and Xenon lamp. The robotics head is positioned above the substrate using three laser-diode positioners. This distance and the speed of the head are paint dependent and independently determined for each paint removal process. Figure one also shows a photograph of the actual nozzle. It is important to note the two rectangular sections connecting the hose to the two nozzles. These connectors convert the cross-sectional area from the round tube to the rectangular cross-section of the jet very abruptly. In this connector, the particles most likely collide with internal walls and shatter. Currently we are looking into what sort of dynamics are taking place in this region.

The nozzle flow has a few interesting properties. First, the flow is choked about half-way down the nozzle, exiting the nozzle at about 150 m/s and about -60°C. The particles enter the connector at about 10 m/s, collide with the walls, and enter the 2-D nozzle with a large variation in diameter and lateral velocity. They exit the nozzle in essentially a uniform, 2-D sheet with a concentration of roughly 400 particles per square centimeter (based on image analysis). Diameters vary from about 100 micron to 1.5 mm.

**Particle Velocity**
The first step in understanding the process was to estimate the particle velocities. Initial estimates based on the exit speed of the carrier fluid put the particles moving at approximately 150 m/s. In order to make accurate velocity measurements of the particles, we developed a two-camera system, where the synchronization of the two camera images is offset by 8 µs. Results from this system demonstrated much slower velocities and so we replaced the two camera system with a streak technique to estimate the velocities. Both techniques are presented below.

**Two Camera System**

The camera setup, shown in figure 2, consists of two laboratory grade CCD video cameras, which both frame at the standard 30 frames per second rate, and are set 90° apart. Both cameras are aimed at a cube beam splitter, and through the beam splitter both cameras see at the same image. The initial triggering is done when a phototransistor senses the flight from a flashlamp (strobe light). Each camera has the ability for external triggering, and the output of each camera is ported to one of two computer-mounted frame grabbing boards. Using a custom designed electronic triggering device, one camera can grab an image eight microseconds before the next. Both images are then sent to their respective frame grabbing boards, and are stored as pairs. Later, velocity analysis is performed by using standard digital particle image velocimetry (DPIV) techniques, or visually by looking at pixel displacement. Figure 3 shows a schematic of the full setup. Although the cameras are synched to each other, they still frame at 30 Hz (it is just that the individual images are 8µs apart). Thus, 30 times per second we can get an instantaneous map of the particle velocity field.

**Figure 1:** Setup of two camera particle imaging system. The cube beam splitter separates an incoming image of particle flow, sending the same image to the two CCD cameras. An electronic circuit shutters the first camera (camera 0) and then 8 µs later shutters the second camera (camera 1). The two images are then sent to individual...
frame grabbing boards. The phototransistor starts the cameras with the flash of a strobe light.

**Figure 2:** Two-camera high-speed imaging system. The cameras are focused on a 4 cm$^2$ area of CO$_2$ particle flow. When the flashlamp (strobe) fires, half the incoming image is sent to camera 0, and the other half to camera 1. These cameras are synchronized so they frame 8 microseconds apart. Shortly after, each image is sent to its respective frame grabbing board in the computer for analysis.

**Streak System**

The streak system relies on a well-documented strobe pulse to image a streak on the video camera (or film). We let a CCD camera run normal (30 frames per second), and then set the strobe to run at 30 frames per second. Therefore, although not synchronized, we were guaranteed to get one strobe flash per camera frame. The camera output was ported to a Hi8 recorder. We used a 40 µs strobe as a time base for the velocity measurements. We could also estimate particle diameters from these images.

Using this technique, we could measure particle velocities from 25 m/s to 120 m/s, with about a 10% accuracy. Difficulty arises in defining the end of a streak because the light from the strobe decays exponentially. For slow particles, the error arose from lack of spatial resolution. The current data imply that the CO$_2$ particle had a diameter of 0.15 mm, and the average particle
velocity is 65 m/s. These results were compared with standard photography imaging using the 40µs strobe (photographic film has a pixel resolution 15 times greater than CCD imaging), with the same results. Figure 3 shows a sample streak photograph. One can see the exponential decay in the strobe intensity field, limiting the accuracy of the velocity measurement. Diameter measurements are diffraction limited at the low end (less than 20µm) where the particle will appear to be larger than reality.

![Figure 3: Particle Streaks](image)

**Particle / Surface Collision**
The second process of interest was the collision of the CO$_2$ particles with the substrate. Figure 4 shows a single particle impinging on a surface. At this point we are not even certain of the state of the particle upon collision. The energy required to change the phase of the pellet to liquid is substantially greater than the kinetic energy of the particle, yet the image appears to be very similar to a liquid drop. Notice the uniformity in the shard (or droplet) diameters. The apparent spray patterns also are reminiscent of a fluid droplet. We are currently developing a substrate where we can measure surface temperatures, taking advantage of the increase in heat transfer of a colliding liquid to determine the phase.

![Figure 4: Particle Collision](image)
Conclusions
In conclusion, in this article we have presented the beginnings of an examination of CO₂ particles in a high speed jet. We have developed two different image-based techniques to estimate the particle velocities and diameters. Our techniques are currently being refined to improve the uncertainty in the velocity measurements. We have also just began to examine the collision mechanism, in order to better understand how the particles remove heat and the soot from the painted substrate. With a proper understanding of the particle behavior, one could, most likely, redesign the system so that it would no longer require the large compressors it currently uses, as well as improve the paint removal uniformity.

References