

Section 9.0: Analysis of Plasma Torch Coking

The reliability of a plasma torch in a supersonic combustion environment is of the greatest importance. Torch failure could result in loss of engine efficiency or even total engine failure, depending on the type of application. This section describes the conditions and effects of coking (carbon buildup or soot) in the Virginia Tech Plasma Torch over a period of several dozen test sequences. Heavy levels of coking can plug the anode orifice, which makes it impossible for the plasma torch to operate effectively. Emissions of carbon-based particulate matter in diffusion flames can result from either rich operation or fuel impurities. Plasma torch coking, where oxygen is not present, can occur from a process known as cracking and is dependent on torch power level, voltage frequency and intensity and type of feedstock. Qualitative measurements were made after each test run was complete to determine whether or not coking occurred.

9.1: Background, Testing Overview and Materials

Soot has long been recognized as a major pollutant. Regulations have been imposed to control soot emissions from various combustion devices including gas turbines. Also, burning soot particles can substantially increase the radiant heat transfer to engine components. Designs must be capable of withstanding higher temperatures depending on the amount of soot produced (Wirth, 1989). Particulate matter also poses a problem of clogging engine components such as injectors, or in the case of a plasma torch, the anode orifice.

In order to control the level of soot production, one must understand the chemistry behind soot formation. The first step of soot formation is nucleation. Nucleation occurs when fuel molecules dissociate into smaller hydrocarbon radicals upon heating. In a plasma torch this process is known as pyrolysis, the breakdown of hydrocarbon molecules in the absence of oxygen (also known as “cracking”). The radicals then polymerize into much larger chains and soot precursors. The second step is the growth stage. This stage is characterized by the bulk of soot production. Gas phase hydrocarbons condense onto the soot precursor molecules forming nearly spherical particles. During the

oxidation phase, these particles are burned and form the carbon deposits we recognize as soot. Soot production is dependent on the rate of reaction of all three stages (Wirth, 1989). In the case of a plasma torch, nucleation of the fuel would occur from the fuel-arc interaction. Polymerization and the growth stage should occur normally, but “burning” of the soot precursors could not occur until the plasma stream interacted with air. Therefore, any soot that was deposited on the inside of the plasma torch would either indicate that air was present or that the soot was formed with a different chemical process. Soot production is also dependent on the amount of several radicals that may be present during combustion. Radicals can increase or decrease the sooting tendency of diffusion flames depending on which radicals are formed. As an example, the presence of OH and O radicals can significantly increase the formation of soot (Hura and Glassman, 1989). However, without the presence of oxygen in the hydrocarbon feedstocks, these radicals could not be produced. The chemistry of soot formation in diffusion flames is well defined, but soot formed from hydrocarbon-arc interaction is not as well understood.

The plasma torch tests for coking were conducted using propylene, ethylene and methane. All three feedstocks were at least 99.5% pure with 0.5% being impurities such as nitrogen (an important fact in order to rule out fuel impurities as a cause for coking). Flowrates, current settings and electrode gaps were all changed to see how they influenced the production of soot. After a particular test series was finished, the Virginia Tech Plasma Torch was disassembled and simple inspections of the anode and cathode were made to determine whether or not coking occurred. After each test, the electrodes were cleaned using acetone to determine whether a blackened electrode was covered with soot or just discolored from the high temperatures present in the plasma torch. Earlier tests were started using an internal high-frequency starter provided with the Miller welders, while later tests were conducted with a variable external high-frequency starter.

9.2: Results and Discussion

While using the high frequency starter of the Miller welders to conduct tests, several conditions were present which affected whether or not coking occurred. In many of the tests, a flame plume was produced downstream of the plasma jet. On several occasions, the arc would be so unstable that it would blow out. A quick flame burst was then observed to come through the anode seal and out between the anode cap and torch body. The cause of this is unclear, since similar test conditions did not always produce this type of failure. The diffusion flame was extinguished by shutting off the feedstock supply. After each one of these tests, heavy coking was present. It is believed that the carbon buildup on the anode was produced during the last few seconds before the diffusion flame was fully extinguished. Air may have entered the torch as the torch pressure dropped and caused the coking, but the coking was not an effect of normal torch operation. Figure 9.1 shows a comparison between the downstream side of an anode with heavy coking and an unused anode. The upstream sides of the anodes show similar characteristics.



Figure 9.1: An Example of Anode Coking

Another condition that encouraged the production of soot was the voltage intensity of the high frequency current supplied by the Miller welding units. With an open circuit voltage of 270 volts, very little AC voltage was needed in order to ignite the plasma torch. The high frequency starter on the Miller welding units greatly exceeded this need. The tests that did not experience some sort of flame burst, failed due to a plug made from soot and pieces of electrode that formed in the upstream side of the anode throat. This mode of failure developed over the course of a few minutes as the plug slowly formed. Formation of the plug was thought to be related to the source of electrode erosion. Normally, electric current passes from the cathode to the anode, producing much higher rates of electrode erosion on the anode than cathode. By changing the arc

path back and forth, the cathode experienced a much higher rate of electrode erosion than normal and may have aided in the formation of a plug inside the anode constrictor.

Throughout the entire test series, the torch was run under many different conditions. Variations in current, torch pressure and feedstock flowrate had less effect on the production of soot than the use of high frequency current. It is possible that the voltage level of the high frequency current used in running the torch may affect the rate at which soot is formed. (i.e. higher voltage amplitudes increases nucleation-growth-oxidation reaction rate) Tests run with pure DC never showed any signs of coking. This conclusion was not reached by Hruby et al. (1997), who had severe problems with coking in methane DC arcjets. Operation in their experiments typically lasted less than a minute and ended when the constrictor filled with carbon deposits and shorted the arcjet. However, their torch design had a radically different electrode geometry than those conducted at Virginia Tech, which may explain the differing results.

The use of a Miller HF-251D-1 high frequency starter box alleviated all of the coking problems experienced during earlier tests. All tests run with the HF-251D-1 experienced minimal to no coking. This was mainly due to the ability of the HF-251D-1 to operate with very small amplitude settings. The HF-251D-1 did not change the frequency of the current, but rather allowed adjustment of the amplitude. Tests where the HF-251D-1 was used to ignite the torch, but then turned off to allow the torch to run on pure DC showed similar results. Also, a bluish discoloration of the downstream anode surface was observed during most tests. The cathode and upstream side of the anode showed no signs of discoloration. Clearly, the discoloration is an indication of the temperature reached by the tungsten anode and chemical interaction with the air on the outside surface of the plasma torch.

9.3: Recommendations and Final Remarks

Strong evidence indicates that the use of a variable high frequency starter box, operating with low intensity settings, can significantly decrease the amount of soot production in plasma torch operation. Coking appears to be dependent on the amplitude of the high frequency current present, fuel impurities and the type of hydrocarbon

feedstock being used. It is also noted that the sooting process, in the absence of oxygen within the torch, must be different than that for diffusion flames.

By plugging the anode orifice, soot and electrode particles can seriously impair the ability of a plasma torch to operate. The intensity of high frequency current used was determined to be the main cause of soot formation in the plasma torch, since fuel impurities were present in only minute amounts and there was no air in the plasma torch interior where some of the coking occurred. Although the use of high frequency current is needed only to ignite the torch, a small amount of continuous high frequency current is desirable in order to keep the electrodes cool and prevent excessive electrode wear. Future tests should concentrate on the specific effects that changing the voltage amplitude has on coking. If DC signals were to be augmented with AC signals to power the torch, this may become an issue.