Section 6.0: Plasma Arc Stability

Arc stability tests were performed with the Virginia Tech Plasma Torch to discover its arc stability limits and causes of arc instability. Previously, it had been well proven that the torch could operate for large amounts of time on hydrogen, argon, nitrogen and mixtures thereof. Under current testing, the torch was operated with hydrocarbon feedstocks, methane, ethylene and propylene. The goal of these tests was to determine the operational feasibility of these gases and determine under what conditions the best torch operation occurred.

Arc stability can be characterized through torch parameters such as current level, electrode emission and plasma jet direction. The sound of the torch is also an indication of arc stability. Arc stability is a strong function of current level. The amount of current dictates the amount of "reinforcement" or strength the arc has to withstand disturbances. Arc fluctuation between two operating modes can be identified by fluctuations in the plasma jet and voltage. The plasma jet pulses between small and large jets as the arc jumps between low and high-voltage modes. The arc jumping from point to point around the anode can cause electrode emission. This "jumping" causes craters to form as the arc erodes pieces of electrode. A stable arc rotates smoothly around the anode, causing little or no electrode emission. Smooth arc rotation is aided by an effective flow swirler and smooth electrode surfaces. The jet direction is also a good indication of whether or not the arc is stable. Off-center jets are generally the result of deformities or misalignment of the electrodes, which will also adversely affect how the arc behaves. To an experienced torch operator, the tone of the torch is one of the best indications of how the torch is running. As an example, argon normally produces whisper quiet torch operation, but if the electrodes are grossly misaligned, the gap is too small, etc. then the pitch of the torch will be loud and sharp. Regardless of the cause, an unstable arc is more likely to blow off from disturbances than one that is stable.

One way of quantitatively evaluating the stability of an arc is by measuring its electrical resistance. Arcs with lower resistance tend to have a greater ability to resist fluctuations in the flow field. The resistance of an arc is inversely proportional to its length, just as with metallic conductors. The electrical conductivity is at a maximum in the center of the arc and drops off to almost zero at the outer edges (Stouffer, 1989). This is due to the high temperatures at the center and relatively low temperatures at the outer edges. Therefore, if the current increases and the arc diameter and length remain the same, conductivity within the arc column must also increase. Consequently, this will produce higher temperatures within the arc column. Ideally, it would be best to run a plasma torch with infinite current, but material limitations obviously forbid this. Therefore, simply increasing the current can usually solve any problems with arc stability.

It is important to have stability in the arc to insure consistent operation and less electrode wear. In addition, knowing how to promote stable arc operation can extend torch component life. A misdirected plume caused by arc instability can result in "hot spots" on the electrodes and cause premature failure. With that in mind, finding stable and avoiding unstable arc modes is very important.

6.1: Testing Setup and Procedure

For the first stage of arc stability tests the HF starter box was left on, with an intensity setting of 5%. Also, the DAQ system was disconnected from the torch so that the HF signal would not damage the components. Both methane and ethylene were tested using the same procedure. An initial current of 14% (about 21 A) was set on all four power supplies. The HF starter was set at 5%, and the hydrocarbon flow controller was run at a constant flowrate of 25 SLPM. The continuous run mode on the HF starter was turned on, which started the plasma torch. After one minute all four power supplies were reduced by 2%. The "one minute operation/reduce 2%" procedure was sequentially repeated until the torch ceased operation. Throughout the tests, notes were taken on the amount of electrode emission that occurred, plasma jet direction and plume size. These tests were mainly qualitative observations of electrode emission and plasma jet stability as the current was decreased.

Tests were also conducted on how the mass flowrate and current affect arc stability. Five tests were run: four with methane and one with argon. For methane, each test had four stages or steps. Each stage lasted approximately two minutes. In stage I, the current was set at 30% and the flowrate at 15 SLPM. The torch was ignited and the flow was slowly changed from 15 to 30 SLPM and slowly back to 15 SLPM. This step was designed to discover how the flowrate affected arc stability at high current levels. During stage II, the flow was kept constant at 15 SLPM and the current was adjusted from 30% down to 12%. Stage II was intended to find out how current affects arc stability at a given flowrate. Stage III was identical to stage I except that the current setting was 12% instead of 30%. In stage IV, the current was slowly decreased until the torch blew out. For this stage, the flowrate was kept constant at 15 SLPM. The single argon test was conducted in a similar manner except slightly lower flowrates and currents were used. Unlike the previous qualitative tests, the voltage, current and power signals were collected to observe any spikes or jumps that indicate the arc is operating in an unstable manner. Table 6.1 summarizes the stages, actions and their purposes.

Table 6.1: Arc Stability vs. Flowrate and Current Test Summary

	Steps	Purpose
Stage I	1) Set current at 30% and flowrate at 15 SLPM 2) Increase flow to 30 SLPM 3) Decrease flow to 15 SLPM	To discover how changing flowrate affects arc stability at high current levels.
Stage II	1) Keep flowrate constant at 15 SLPM 2) Decrease current from 30% to 12%	To discover how changing current affects arc stability at a constant flowrate.
Stage III	1) Current remains at 12% 2) Increase flow from 15 SLPM to 30 SLPM 3) Decrease flow to 15 SLPM	To discover how changing flowrate affects arc stability at low current levels.
Stage IV	1) Decrease current until torch extinguishes	To discover the lowest possible current setting for a given flowrate.

Arc stability was also measured as a function of arc gap. Eleven tests were conducted with methane, all at different arc gaps. The arc gap was initially set at 80° (0.141mm) and increased 30° (0.053mm) eight times ending at 290° (0.511mm). Three additional tests were conducted at 180°, 190° and 200° to provide clarity in the center of the test range. Each test was conducted with a 27% current setting and a methane flowrate of 30 SLPM. After each test, the gap was readjusted to account for electrode erosion.

6.2: Results and Discussion

The qualitative testing using methane and ethylene yielded clues as to how the torch operates with those feedstocks. Testing was first performed using methane. At a moderate current setting of 14%, there were small amounts of electrode emission (about 5 glowing particles per second). Near a 10% current setting, a cycling between operating modes began. This cycle initially had a 2cm long plasma jet that slowly reduced in size to approximately 1 cm over a period of 5 seconds. At that point, the jet would burst and reform to the 2cm initial size. Throughout the cycle, minimal electrode emission was present. This cycling indicates the arc was probably fluctuating between the high and low-voltage modes described in Section 3. Ideally, the torch should operate under the high-voltage mode because it reduces electrode wear and promotes cooling of the anode. After this current setting was passed, a very small (0.5 cm) stable jet was produced in the range of 7% current setting. At this point, the torch seemed to be operating purely in the low-voltage mode. Around 5% current setting the torch went out.

Ethylene had electrode emission of about 30 particles per second at a current setting of 14%. The rate of electrode emission was much higher than that experienced with methane. Despite the high emission, the arc appeared to be stable, with a steady jet and straight plume as shown in Fig. 6.1.

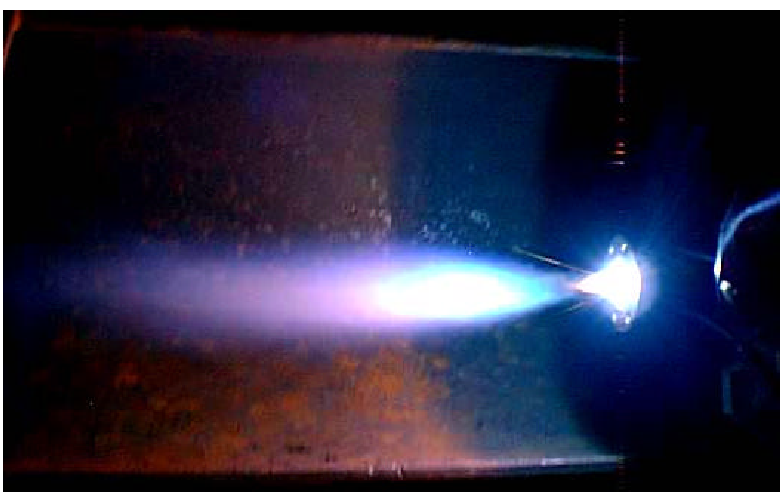

Figure 6.1: An Example of Stable Ethylene Operation

Again, the jet size decreased with decreasing current. The transition between high and low-voltage modes was almost instantaneous, unlike when the torch cycled through them with methane. At 8% current, there was approximately a 0.2cm long jet that was operating very unsteadily, but with less electrode emission. The jet direction was erratic and the flame plume was small and in bursts. As soon as the current was decreased past this point, the torch ceased operating.

From these qualitative tests it was clear that the torch operation was more stable with methane than ethylene. Methane produced smoother operation and lower electrode emission than ethylene. Throughout other tests, it was also discovered that methane had the ability to operate with less power (≈1.1 kW) than ethylene (≈1.3-1.4 kW). It is clear that the plasma torch operates better with simple gases. The simplest hydrocarbon gas is methane and hence should produce the smoothest operation of all hydrocarbon gases. Ethylene generally produces rough torch operation. Limited testing with propylene confirmed the fact that complex hydrocarbons reduced arc stability. Propylene tests ran roughly under all test conditions, even when mixed with large amounts of argon as a stabilizing gas.

The tests designed to determine how current and flowrate affect arc stability also uncovered important facts on how the torch operates. Increased flowrates were observed to decrease arc stability. This was seen in the current and power graphs of the tests. As the flowrate was increased, the current and power graphs were observed to fluctuate more often and with higher amplitude. Intuitively, this makes sense, because the flow passing through the torch is attempting to blow the arc off the anode. Increasing the flowrate, and hence the flow resistance, should increase the arc instability and was found to do so in this case. The power was also seen to increase slightly, by a few hundred watts at most, as the flowrate was changed from 15 to 30 SLPM. A decrease in power was also observed from 30 to 15 SLPM. This indicates that torch power is a weak function of flowrate. Higher flowrates will produce slightly higher power levels and more unstable operation. Higher levels of current restored stable operation, as expected. Large amounts of current passing through the arc widen the arc, stabilizing and reinforcing it. Larger currents also allow larger arc gaps to be used. Tests indicated that lengthening the arc gap had the most profound affect on arc stability and required much more current to maintain stable operation. In addition, voltage must increase to maintain the arc for larger arc gaps. Obviously, power supplies can only deliver so much voltage before the requirements exceed the supply. Operating well below this limit will prevent any surges or spikes from extinguishing the arc. From an arc stability perspective, there is an ideal arc gap, current, voltage and feedstock flowrate to produce the best operation for any particular feedstock. These tests indicate that a small arc gap (≈0.1-0.2mm), currents in the range of 30-40 amps and simple hydrocarbon feedstock flowrates around 20 SLPM are ideal for smooth stable operation with the Virginia Tech Plasma Torch.

6.3: Concluding Remarks

Overall, the arc appeared more stable at higher current settings, as expected, although methane did seem to have some stable operation near 7% current. Only tests conducted with ethylene experienced high amounts of electrode emission, particularly at the upper current settings. The electrode emission intensity was observed to decrease with decreasing current. However, lower current settings also reduced arc stability, increasing the chances for the arc to be blown out.

As a whole, the torch demonstrated stable operation with simple hydrocarbon gases at currents around 30-40 amps. Also, a small electrode gap shortens and widens the arc column, fortifying it. Flowrates around 20 SLPM provided enough cooling for the electrodes and did not seem to disturb the arc.