Section 7.0: Torch Voltage and Current Characteristics

An important aspect of plasma torch operation is the variation of arc voltage for different current and gas flowrates. It is necessary to look at trends in how the torch responds to certain conditions to locate favorable operational configurations. Knowledge of such modes would allow more effective and longer torch operation. High levels of current quickly burn out the electrodes, but low levels produce poor arc stability. Consequently, high flowrates provide excellent global cooling for the electrodes, but also increase the pressure and narrow the arc, increasing the local heat flux to the anode. Therefore, it is important to determine when these tradeoffs become too expensive.

To accomplish this, tests were conducted to determine voltage and current behavior as the flowrate varied. Under normal circumstances, the voltage and current vary even while nothing is being changed. This is caused simply by normal unsteady plasma torch operation. However, it was hoped that trends could be discovered which would indicate stable operating modes and how the arc was affected both by changing the current and flowrate. As expected, the results had many fluctuations, but possible trends were discovered which provide insight into how the torch operates.

Some previous work done on methane arcjets resulted in voltage-current characteristics as seen in Fig. 7.1. Hruby concluded that voltage was insensitive to variations in current at the given mass flowrate of 87 mg/sec.

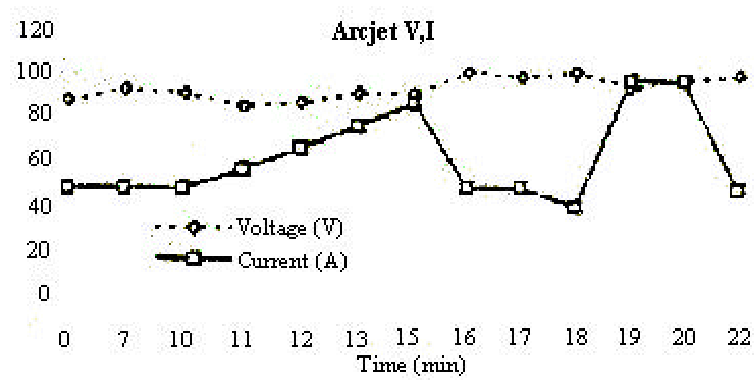

Figure 7.1: Hruby Arcjet V-I Characteristics (Hruby and Kolencik, 1997)

From Fig 7.1, it is clear that the voltage varies very little with changing current. This is because the voltage of an arc is mainly determined by the arc length. The current determines the arc width for a given pressure.

7.1: Testing Setup and Procedure

Testing began by setting the hydrocarbon flow controller at a flowrate of 30 SLPM for methane. The power supplies were set to 30% current (about 45A) and the HF starter was set to 5%. With the flowrate, current and HF set, the power supplies were turned on, and the HF starter was activated. As soon as the torch started, the HF starter was turned off and the power supplies were attached to the DAQ system. Immediately following connection, the DAQ system was activated. After 5 seconds, the current setting of each of the four power supplies was reduced 4%. The 5 second pause and 4% reduction was repeated until a 6% current setting was reached on the power supplies. These tests were designed to determine how the voltage is affected by changing the current at various flowrates.

The above procedure was repeated for a total of seven methane flowrates ranging from 30 SLPM to 12 SLPM in 3 SLPM increments. Five ethylene tests were completed ranging from 36 SLPM to 21.6 SLPM in approximately 3 SLPM increments. The odd testing increment for ethylene was due to a calibration factor that had to be multiplied to the output of the flow controller. Although the controller registered 30 SLPM, the actual ethylene flowrate was 30x1.2, or 36 SLPM.

Another series of tests were designed to determine how pressure (and hence flowrate) affects the voltage at constant current. For these tests only methane was used. The torch was operated with 30 SLPM of methane and a 27% current level. The flow was slowly reduced to 12 SLPM and then increased back up to 30 SLPM. Several tests were run to make sure the results were repeatable.

Finally, throughout the entire testing series, power data were collected for argon, methane, ethylene and propylene. Arc stability can be evaluated for each gas by analyzing those graphs. Rapid fluctuations in power indicate instability, while smooth curves indicate stable operation.

7.2: Results and Discussion

After the first set of testing was complete, the voltage and current data were plotted to see if any trends could be found. Figure 7.2 contains V-I graphs for methane at four flowrates. In all four graphs, the current is initially near 45A, which was consistent with the setting on the power supplies. In Fig. 7.2(a), the decrease in current setting over the first 20 seconds is not registered. However, there is a steady drop in voltage, which may indicate that the arc is more easily maintaining itself in a specific operating mode. Between 20 and 40 seconds, there is a continual drop in current to approximately 20A. At 40 seconds, the power supply settings had been reduced to 14%, resulting in a current of 21A. Over this range, the voltage returns to its high level near 80V. Beyond 40 seconds, the current remains in the 20A range, and the voltage is decreasing, again indicating a tendency to maintain an operating mode. This tendency for smooth operation for certain current levels was also reported by Barbi et al. (1989). He reported that torch operation with argon-hydrogen mixtures was smoothest for 20-30 amps. Although the current experiments do not include operation with argon-hydrogen mixtures, it is clear that different feedstocks should have smoother torch operation at certain levels of current.

There is more variation in the curves of Fig. 7.2(b) (methane @ 24 SLPM). The initial current is within the range of the setting on the power supplies, but the voltage is much lower than in the 30 SLPM run. As the current setting is decreased, there is an increase in current and a decrease in voltage. This was observed in the previous test where the current setting was decreased, but the current remained constant. The plasma torches was observed to attempt to draw the current it required from the power supplies to maintain an operating mode, even though a they were designed for constant current applications. This increase in current and decrease in voltage indicates that the torch may be trying to "jump" to a stable operating mode at a slightly higher current level, resisting the drop in current setting. As the second drop in current setting takes place, the current values drop down to the 40A range. This is similar to what occurred during the 30 SLPM case. The voltage also drops to 40 volts at about 20 seconds. As the current setting is decreased further, the 40A operating mode is maintained. The voltage once more remains low over this range indicating preference for this mode. At the 50-second mark, the current decreases with current setting towards the 20A-operating mode while the voltage increases. The increase in voltage may suggest difficulties continuing to operate at the 20A mode.

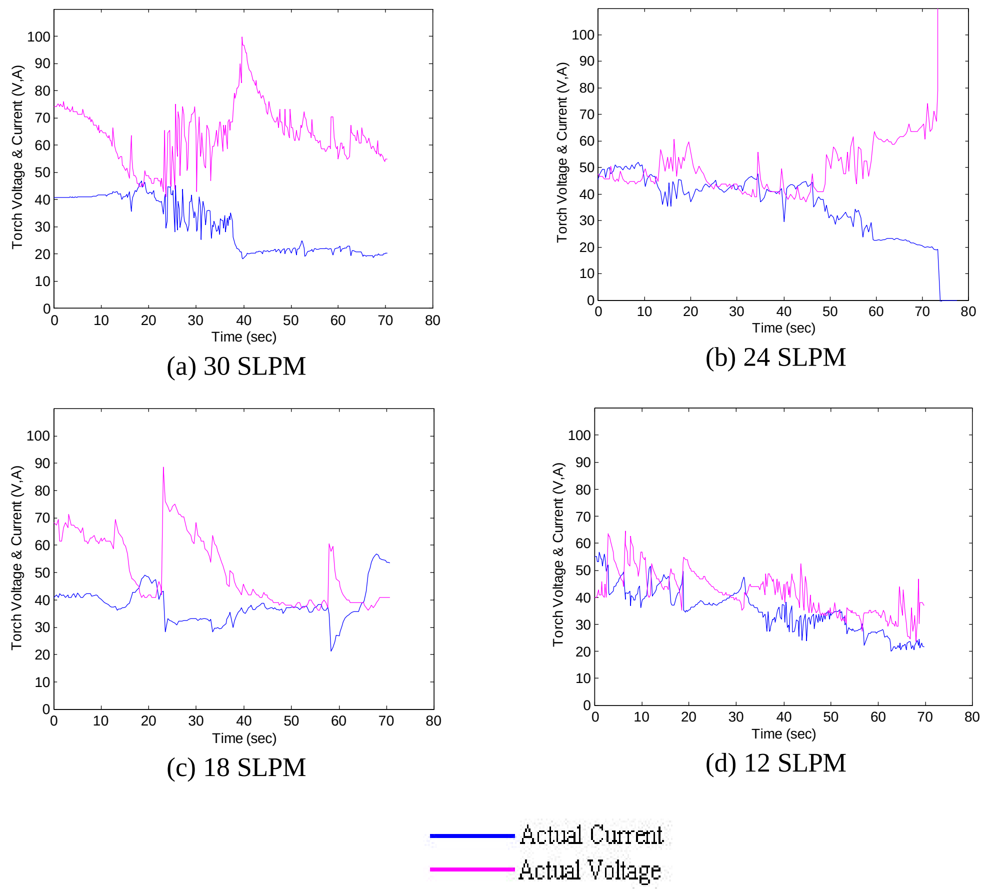

Figure 7.2: V-I Characteristics for Methane

Similar to the 30 SLPM run, Fig. 7.2(c), for 18 SLPM, starts out at the 40A-operating mode with a high voltage. As the current setting is decreased, the voltage drops, requiring less power to operate in that mode. Torch operation appears to become unstable as the arc tries to maintain the 40A mode with further decreases in power supply current setting. At 40 seconds, however, the voltage drops to 40 volts and the 40A mode is maintained. Rapid fluctuations in the current and voltage near 60 seconds may indicate an inability to operate at any stable mode.

At low flowrates (see Fig. 7.2(d)) current and voltage steadily decrease, with few fluctuations. It appears that the low flowrate may improve arc stability. This could explain the absence of the fluctuations experienced at higher flowrates.

The results of the ethylene tests are given in Fig. 7.3. Unlike the methane tests, the voltage and current data fluctuate over a wider range for ethylene. In the first run, Fig. 7.3(a), the 40A operating mode is again produced, but with large variations in voltage. As current setting is decreased, there is a current jump to near 55A, yet the voltage remains in the 40V range. It appears that the jump to the higher operating mode did not affect the voltage. Past 30 seconds, the current and voltage curves steadily decrease, possibly indicating smooth operation.

There is a higher starting current of 50A in the 32.4 SLPM run shown in Fig. 7.3(b). As the current setting is decreased, there is an increase in current to around 55 amps. Operation at this current level begins to drop off near 20 seconds, and current steadily decreases until 30 seconds to about 35 amps. From the 20 to 30-second point, the average voltage steadily rises, but with large fluctuations. The increase and fluctuations in voltage are indications of unstable operation. After 30 seconds, the voltage begins to drop and the current increases to near the 40A-operating mode. The decrease in power supply current setting near 60 seconds causes large current and voltage fluctuations, implying difficulty to maintain stable operation.

In Fig. 7.3(c), voltage and current vary widely over the first 10 seconds of the test. After 10 seconds, the current remains near the 40A-operating mode, until about 30 seconds, when the variations in current again become large. The voltage was maintained at a high and erratic value over the entire test, indicating that no stable operation was achieved.

At 25.2 SLPM, Fig. 7.3(d), current and voltage are steadily falling throughout the test. This effect was also observed for low flowrates of methane. Again, this could be an indication of stable operation. If so, it can be concluded that low flowrates beneficial for producing stable arcs.

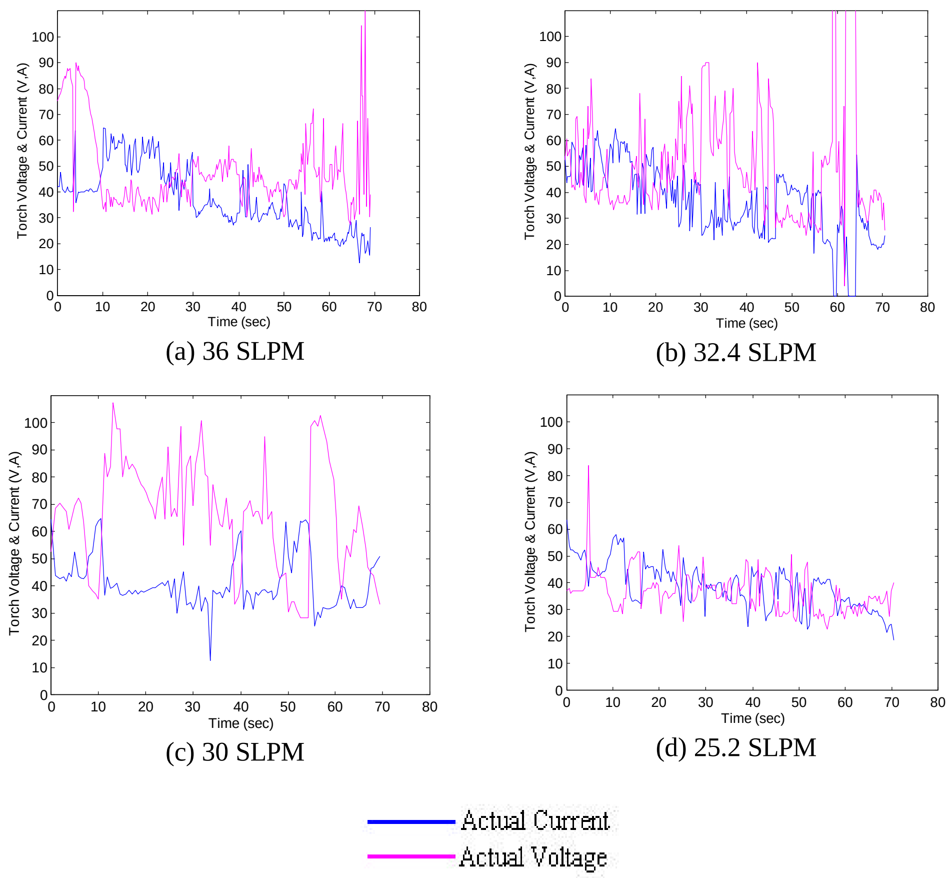

Figure 7.3: V-I Characteristics for Ethylene

7.2.1 Pressure Tests

The pressure tests provided conclusive evidence on how the torch voltage is affected by changes in flowrate. Figure 7.4 shows the results of one of those tests. During this test, current remained constant, hovering around 30-35 amps. The flowrate was reduced over a period of 90 seconds and was then maintained for a short period of time. It is clear that as the torch pressure drops, so does the voltage. This finding is supported by Costley et al. (1997) and Cobine (1941). Costley, by use of polynomial regression, showed that there was a strong relationship between current, arc length and pressure to voltage in a plasma torch. A graph of spark breakdown voltage for equal diameter spheres, Fig. 7.5, shows that for some common gases, the voltage requirement increases as pressure increases. Therefore, as far as flowrate conditions are concerned, it would be ideal to discover the minimum required flowrate for a particular application to keep power requirements down.

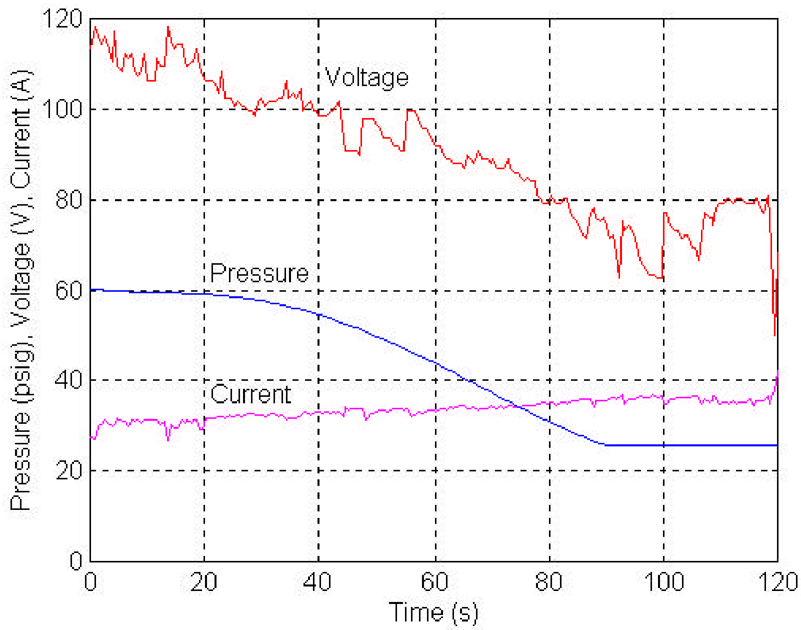

Figure 7.4: Pressure Effects on Voltage (Methane)

This result was expected, but the strength of the relationship between voltage and pressure was unknown. As the pressure decreases around an arc, the arc expands, increasing its cross-sectional area. Consequently, this reduces the electrical resistance of the arc, because of the area increase. For constant current, this effect produces a lower voltage. Dropping the pressure by 1 psi reduces the voltage by slightly more than a volt, but this slope is certain to change for different pressures and currents as shown in Fig. 7.5. Regardless, decreasing the pressure around an arc reduces the required voltage.

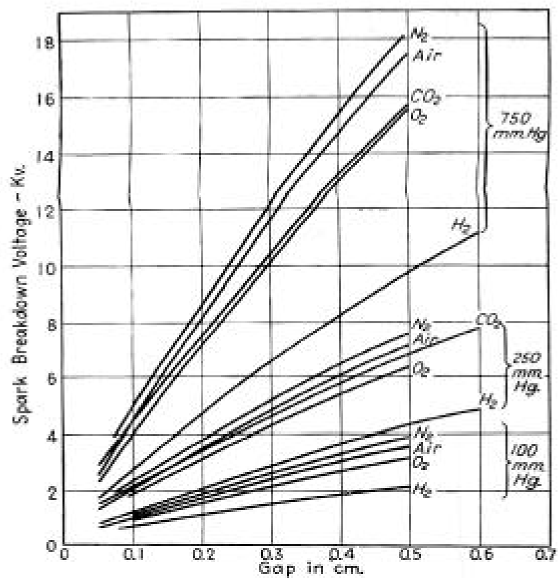

Figure 7.5: Spark Breakdown Voltage (Cobine, 1941)

<u>7.2.2: Effect of Feedstock Gas</u>

Finally, the power tests confirmed that stable operation was easier to maintain with simpler gases. For fixed current, the power will vary among different feedstock gases because of voltage requirements. Complex gases require more voltage than simple gases because of their higher electrical resistivity. The power curves for argon operation were very smooth under all test conditions, even at very low power. Methane power graphs exhibited a fair amount of fluctuations and spikes, but occasionally had smooth operation. Torch operation with ethylene was always rough and the power graphs never seemed to smooth out. This trend was similar to that of propylene, but the fluctuations were larger and more erratic. Voltage requirements increased for each gas in this order: Argon, methane, ethylene and propylene. This was expected since the chemical complexity of those gases also increases in that order. Not surprisingly, more current was needed to maintain stable operation for more complex hydrocarbons. Stable operating modes were found for methane at 20 and 40 amps. It is expected that stable-operating modes for both ethylene and propylene could be located at higher current levels, but these conditions were not tested.

7.3: Concluding Remarks

There appeared to be a correlation between the voltage and current of the torch. However, this conflicts with the results of the Hruby arcjet experiments shown in Fig. 7.1. For the Virginia Tech Plasma Torch, methane appeared to have two stable operating modes, 40A and 20A (27% and 14% respectively). For the ethylene tests, there did not appear to be any stable operating modes. It was observed that ethylene required a larger amount of current than methane to maintain stable operation.

Overall, methane appeared to have more potential operating modes than ethylene, but both had large fluctuations in the values of current and voltage at all flowrates. To more thoroughly determine voltage and current characteristics of each of these gases, a larger time interval between current setting reduction should be tested. Also, a large current reduction increment should be examined to more readily see the effect of changes in current. Due to the occurrence of large variations between actual current and current setting, the effects of decreasing and increasing current setting in a single test should be investigated. This would verify repeatability of the test results.

The voltage vs. pressure tests yielded more conclusive results. It was discovered that as the torch pressure decreases, the voltage also decreases, as expected. Changing the mass flowrate of the gases allowed control of the torch pressure. As the chamber pressure decreased, the arc was allowed to expand and increase its cross-sectional area. This reduced the electrical resistance of the arc and hence reduced the required voltage. By reducing the mass flow, the arc also experienced less elongation due to flow drag, also reducing the required voltage. To accurately determine quantitatively how pressure affects the voltage, without the influence of mass flowrate, anodes with different diameter constrictors should be used at a constant mass flowrate so that the operating pressure would be controlled by the diameter of the constrictor and not the mass flowrate. It appears that the chemical complexity of the feedstock determines where stable operating modes are found. Argon is a very simple gas and good electrical conductor. Stable operation with argon occurred under all current and flowrate conditions. Methane, the simplest of all hydrocarbon gases, had two stable operating modes at 20 and 40 amps. Stable operating modes for ethylene, and the more complex propylene, were not discovered. They are believed to be above 40 amps, if they exist at all. Regardless though, higher feedstock chemical complexity requires more current for stable operation. These effects are discussed more in depth in Section 10, Electrode Erosion.