Section 14.0: Torch Dynamic Startup Phenomena

Plasma torch startup processes are important for understanding how ignition in a design application will affect the performance of the torch and combustion chamber. The main purpose of a plasma torch in a combustor is to enhance combustion. Augmented mixing, hot metallic particle ejection and plasma jet oscillation can all improve combustion effectiveness. Tests were conducted at different flowrates to determine how methane and argon affect electrode emission rates, the intensity of the jet and startup time.

Electrode erosion occurs at high levels during startup and then tapers off as the torch warms up and reaches steady-state operation. The luminosity of the jet was found to be a function of flowrate, as was the time it took for full jet formation. Methane and argon were found to produce radically different effects on startup in all categories. Also, several wave phenomena (such as plasma wave propagation along the torch face) and evidence of vortices were observed. These aspects of the torch flow downstream of the anode indicate that the torch may provide good mixing characteristics as well as ignition and flameholding capability.

14.1: Test Procedure

A Reticon EG&R high-speed digital camera was used to take black and white photos of the torch during the startup process. The camera was capable of taking 1000 frames per second and storing 2048 frames. Seven tests were conducted at different flow conditions using both argon and methane. Table 14.1 summarizes the seven test conditions.

Table 14.1: High-Speed Digital Jet Examination Tests

Test #	Framerate	Frames Taken	Feedstock	Flowrate (SLPM)
1	500/s	230	Methane	25
2	1000/s	55	Methane	25
3	1000/s	75	Methane	15
4	1000/s	150	Methane	10
5	1000/s	105	Argon	20
6	1000/s	70	Argon & Methane	10 & 15
7	1000/s	900	Methane	15

The Reticon camera was fitted with a zoom lens to provide a closer look at the plasma jet. The frame size of all pictures taken was approximately 5.75cm x 5.75cm. Pictures were taken through the Lexan® window to protect the camera from the torch. The Lexan® window was thoroughly cleaned, but some dark spots showed up on the pictures. These are thought to be from dust on the zoom lens, or from some malfunction in the CCD array within the camera.

To start the test, the digital camera was triggered and several tenths of a second later, the torch was ignited using the HF starter box. All seven tests were conducted within a one-hour period using the same anode and cathode. Each test was run for no more than five seconds since only the startup processes were important. Finally, each of the seven tests were started and maintained at a 27% current setting so that only feedstock type and flowrate were variables.

14.2: Results and Discussion

The first methane test ran very smoothly. Startup showed little to no electrode emission. The first 15 ms of the test are shown in Fig. 14.1. The plasma jet took approximately 5-6 ms to fully form. Once formed, the jet began oscillating at 180 Hz, caused by the characteristics of the power supplies. The jet was large and intense. Also, due to electrode misalignment, or a small anode deformity, the plasma jet came out slightly off-center. Test #2, also run with 25 SLPM of methane, showed similar results. The test showed no electrode emission on startup and took approximately 5-6 ms to form a full jet. The jet was very bright and also formed off-center, as in test #1.

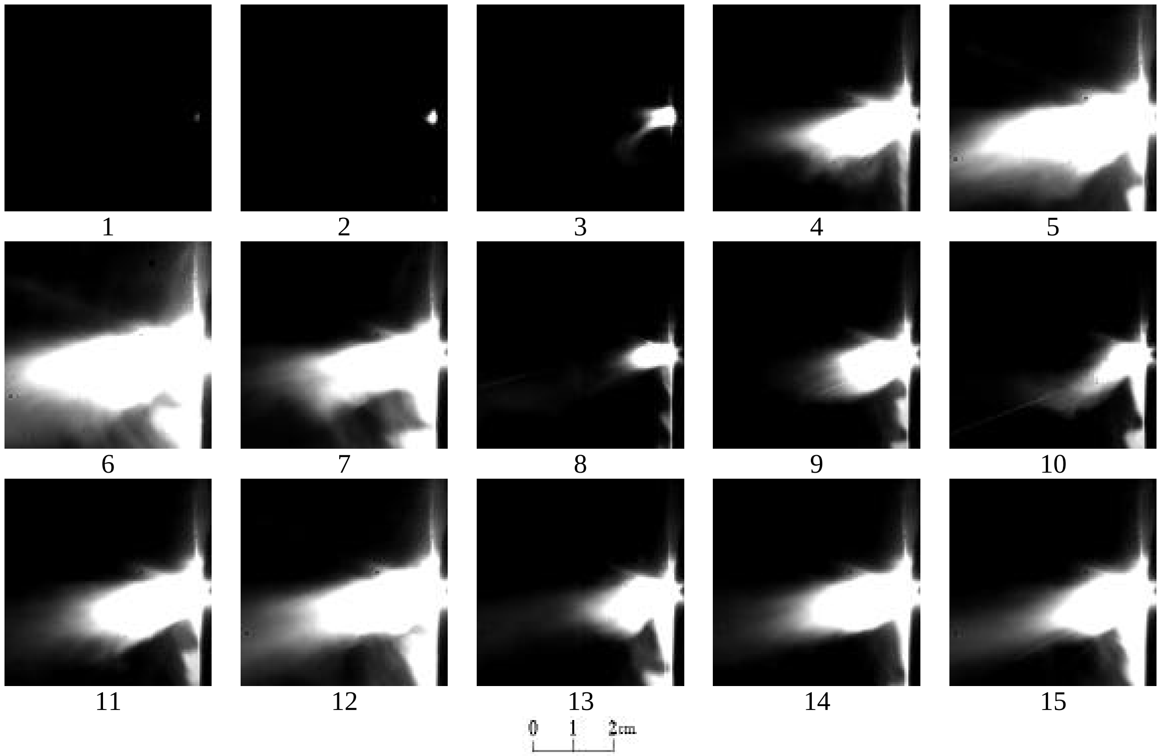


Figure 14.1: Pictures from Startup Test #1, Methane @ 25 SLPM
(Time between frames = 2ms)

Test #3 was run with 15 SLPM of methane to determine how lower feedstock flowrates would affect the startup conditions. Electrode emission began immediately upon initiating the arc. The emission was very heavy for about 20 ms and then tapered off. The electrode emission continued for approximately 50 ms. Figure 14.2 shows fifteen frames taken between 3-18 ms into the run.

It is apparent from Figs. 14.1 and 14.2 that lower feedstock flowrates will produce higher rates of electrode emission upon startup. The same trend occurred in test #4 with only 10 SLPM of methane. In that test, electrode emission was heavier and lasted longer. Therefore, to maximize torch life, the feedstock flowrate should be high upon startup and can then be reduced for steady-state operation, if necessary. This will reduce the amount of electrode mass lost during startup.

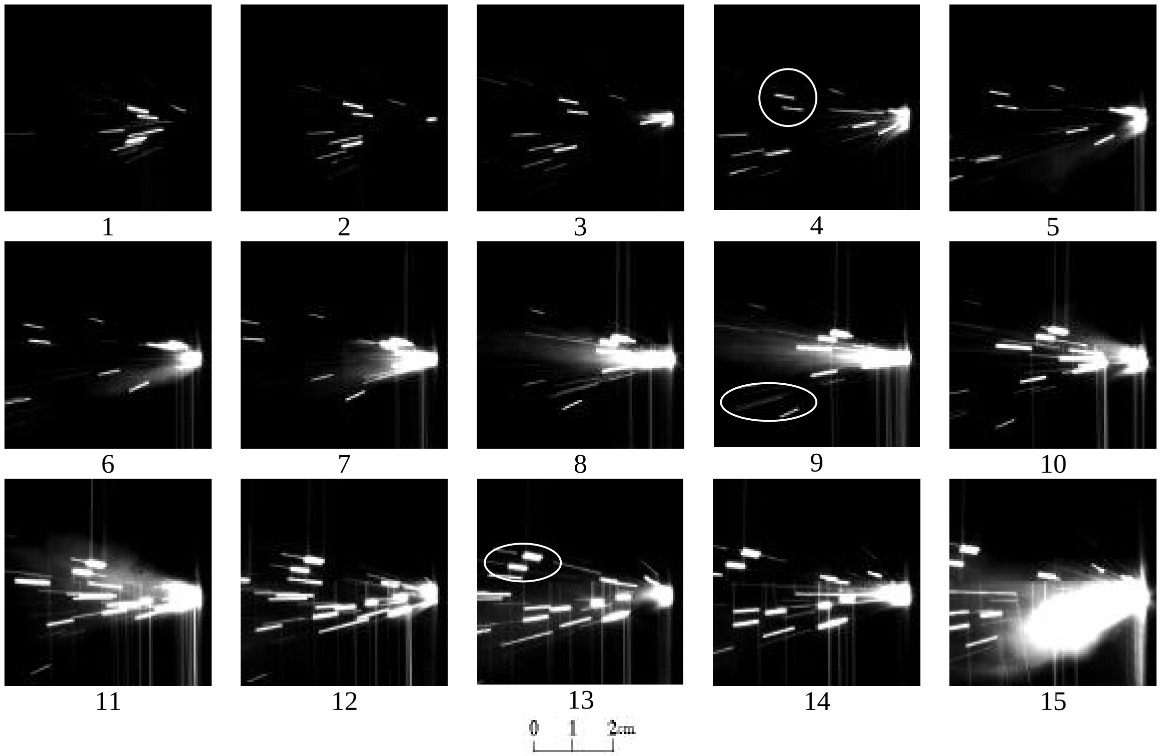


Figure 14.2: Pictures from Startup Test #3, Methane @ 15 SLPM
(Time between frames = 1ms)

The velocity of the electrode particles can be roughly calculated from Fig. 14.2 by tracking individual particles as they travel across the view of the camera. Three types of particles were tracked: heavy, medium and light. Large luminous spots on the photograph are assumed to represent heavy weight particles. Medium weight particles were assumed to be slightly smaller and light particles were very dim and small. An example of heavy weight particles is shown in frame 13 of Fig.14.2, medium particles in frame 4 and light particles in frame 9. From the data, the assumed heavy weight particles were calculated to travel at approximately 4.5 m/s, medium particles at 6.0 m/s and light particles at about 17.0 m/s. Conservation of momentum would support these conclusions that light particles would indeed travel faster than heavy particles, given the same, or roughly equal, gas ejection momentum. From an injection and combustor design viewpoint, these particles could perhaps act as flame-igniters in themselves if they are hot enough. Greater particle momentum would allow for greater flow penetration and should produce a more effective ignitor. Large particles would maintain higher temperatures for longer amounts of time because of their larger heat capacity. Applications that allow for short torch life may want to use increased rates of electrode emission purely for this benefit.

Another noteworthy observation from Fig. 14.2 is that the plasma jet did not fully form for at least 15 ms, three times longer than the tests run with methane at 25 SLPM. This slow formation was probably due to the effects of electrode emission. Electrode particles passing through the anode nozzle most likely disrupted the flow and prevented a smooth, steady jet from forming. Once the plasma jet reached steady operation (about 50 ms), the electrode emission stopped and normal jet oscillation began. The lower flowrate reduced the size and luminosity of the steady state jet during test #3.

During the fifth test, the torch was operated with 20 SLPM of argon. Figure 14.3 shows the first 15 ms of that test. As has always been the case, argon produces much less electrode emission than methane. A few small tungsten particles were ejected from the torch a short time after startup, (frames 11-15). Very light particles of tungsten were also observed during the test around 50 ms after startup, but were so insignificant that it can be concluded the test exhibited practically no electrode emission at all.

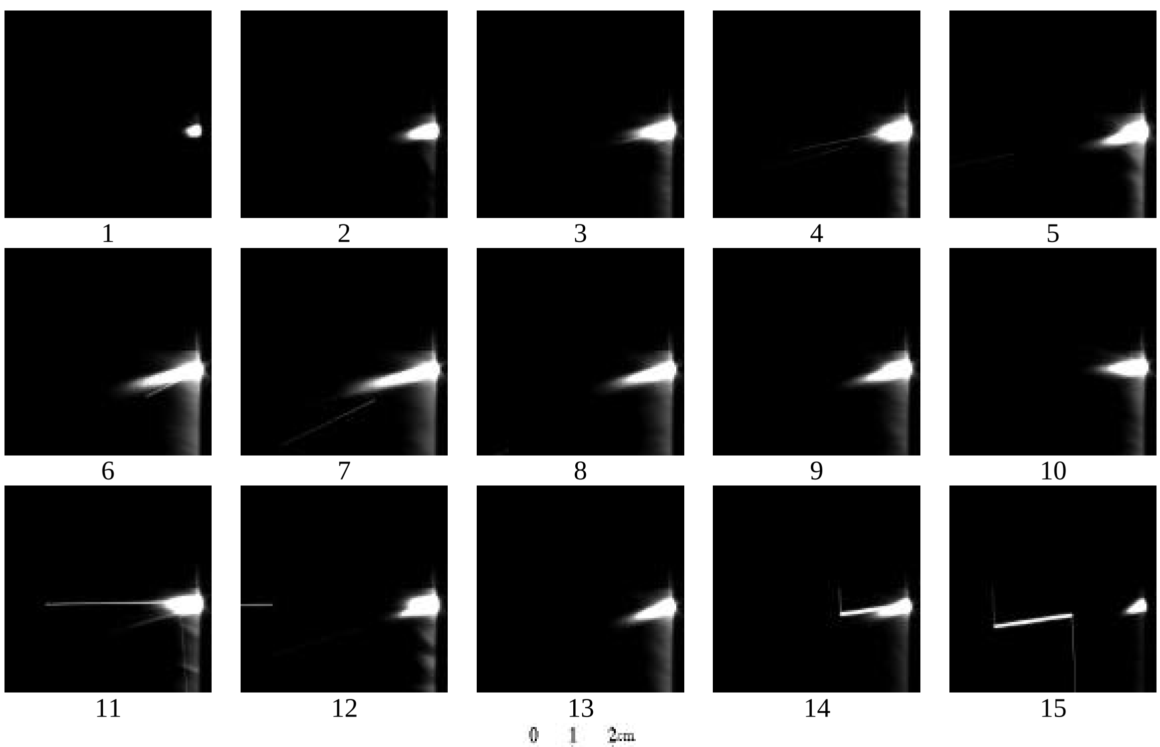


Figure 14.3: Pictures from Startup Test #5, Argon @ 20 SLPM
(Time between frames = 1ms)

A small, smooth jet formed about 6-7 ms after the arc was initiated. It fluctuated at the expected frequency of 180 Hz. The argon jet stayed relatively small compared to methane and also was not as bright. By observing how easily the torch started and operated with argon, it can be concluded that argon is indeed an ideal torch feedstock for increased torch life.

The first five tests provided useful information regarding how the torch starts with different feedstocks and feedstock flowrates. Lowering the feedstock flowrate will increase the amount of time required to form a steady-state jet. It will also drastically increase the amount of electrode emission. In addition, argon produces less electrode emission and also forms smaller, more stable jets than methane.

Test #6 was designed to observe how mixtures of methane and argon affect torch operation. A mixture of 10 SLPM argon and 15 SLPM methane was used for this test. Electrode emission was very light, but still heavier than for test #1 which was run with 25 SLPM of pure methane. A steady jet formed about 7 ms after the arc was initiated and the torch ran smoothly until the end of the test. The jet formed was a mixture of argon and methane jet characteristics. It was larger and brighter than an argon jet, but did not have the intensity of a pure methane jet.

Mixtures of argon and some hydrocarbon feedstock, such as methane or ethylene, tend to have higher rates of electrode emission, more stable operation and, in some unique cases, longer torch life than the pure feedstock. In general though, argon/hydrocarbon mixtures have been found to run for shorter amounts of time than simple pure hydrocarbon feedstocks because of the increased electrode erosion. The cause for this increased electrode erosion rate is unknown and goes against simple intuition. Adding argon to a flow reduces the voltage requirement, and hence should also reduce the electrode erosion rate, but the opposite has been observed. Reducing the required voltage stabilizes the arc. With the addition of argon, the torch has less tendency to extinguish due to arc instability, but more electrode wear is observed. For very complex hydrocarbons, the plasma torch runs for very short periods of time, because the voltage requirement is too high and the arc is blown off because of high instability. Adding argon in this situation is advantageous, because failure from arc instability is very likely. The argon will stabilize the arc and prevent failure from arc instability, but it still increases the rate of electrode erosion. In these cases, the tradeoff is a good one, but for simple hydrocarbons it generally is not.

The seventh test was used to collect data for a longer period of time after startup. The test lasted approximately 0.9 seconds, six times longer than the next longest test. The digital pictures taken during this test showed interesting startup and steady-state phenomena. Figure 14.4 shows a series of photographs depicting an off-center plasma jet several milliseconds after the arc was started.

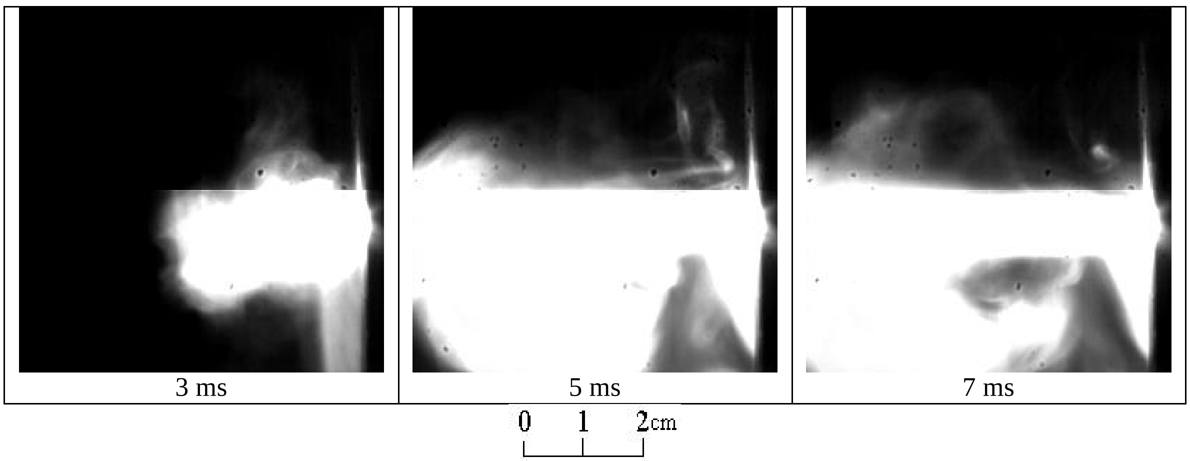


Figure 14.4: Off-Center Plasma Jet on Startup

In this test run, the plasma jet started highly off-center (first frame). Notice that the plasma jet quickly centers itself (second frame), but the plasma that came out of the torch off-center continues to propagate downstream. The final frame shows a perfectly centered jet with some residual swirling beneath it. In itself, this phenomenon is not very remarkable. However, residual plasma from the off-center startup allowed a very interesting phenomenon to be observed. Figure 14.5 shows the presence of a wave phenomenon, possibly a hemispherical shock wave, emanating from the torch nozzle. The pulsation of the plasma jet, the rapid rotation rate of the arc, or some other phenomenon may have caused these waves. The plasma left behind from the startup highlights the waves. The waves above the plasma jet are not as clear because there was no plasma to highlight the waves in that area. By analyzing the digital pictures in a picture animator, these waves were observed to propagate downstream. Unfortunately, they are not defined well enough in the photographs to be able to calculate their velocity.

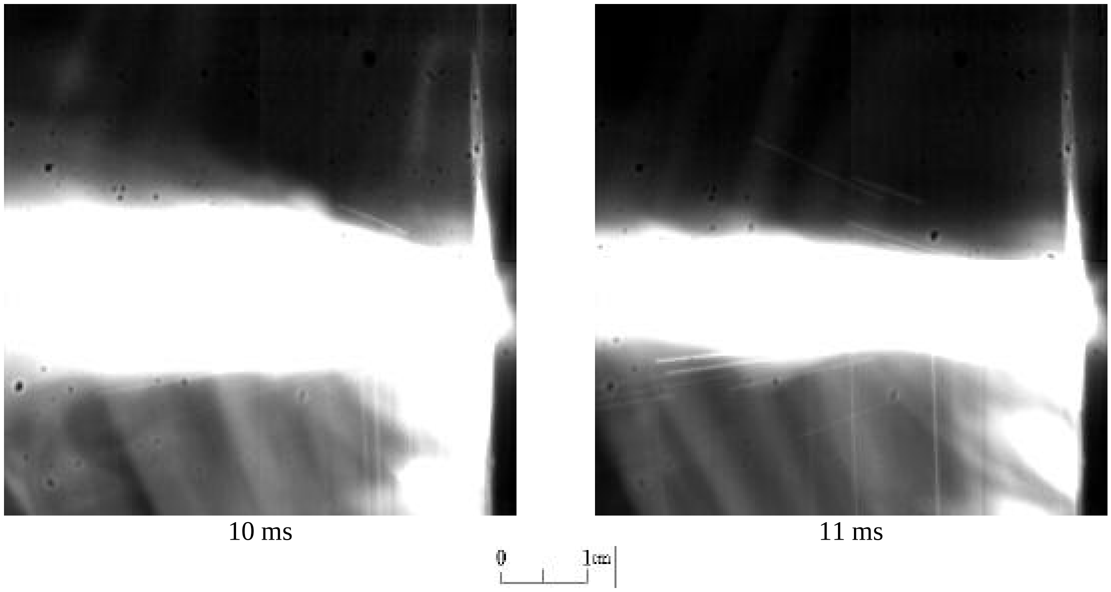


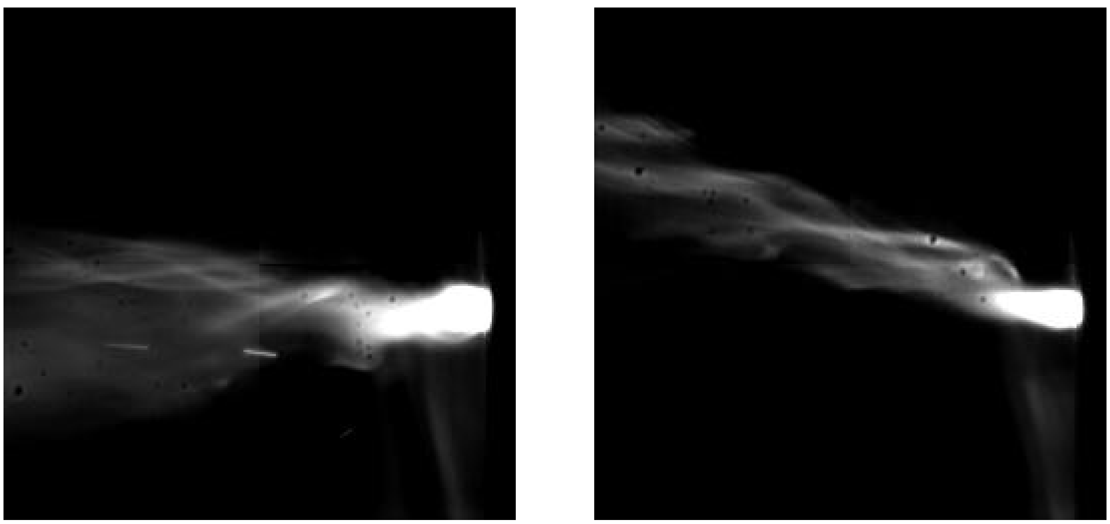
Figure 14.5: Plasma Jet Wave Phenomenon

An example of a verified shock wave is shown in Fig. 14.6. In this case, helium is being forced out of a 75-mm light gas gun. The wave is much more clearly defined because of the advanced equipment used to capture the phenomenon and the high clarity of helium density variations.


Figure 14.6: An Example of a Helium Shock Wave (Marcus, 1993)

Again it should be noted that the phenomenon shown in Fig. 14.5 may be the result of moving shock waves, but this can not be confirmed without equipment especially designed for that type of analysis.

Digital pictures of test #7 also showed conclusive evidence of swirling downstream of the anode nozzle. These vortices support two conclusions. First, the flow swirler is indeed swirling the flow inside the torch. Second, the vortex induced by the flow swirler is passing through the anode nozzle and remains intact at least five centimeters downstream of the torch face. Figure 14.7 shows two such photographs with flow vortices. Frame one was taken about 0.3 seconds into the test run. The plasma jet is well centered and the vortex is clearly defined from the torch face to the left edge of the picture. The second picture in Fig. 14.7 also shows a well-centered jet, but the vortex seems to be propagating downstream about 20° off-center. Analysis of the frames taken before this one showed that the plasma jet was off-center by about 20°. It then centered itself, leaving plasma behind to illuminate the swirling vortex.



291 ms 707 ms

0 1cm

Figure 14.7: Plasma Jet Vortices

These vortices show that the flow is still swirling even after it leaves the torch. These vortices will enhance the mixing rate of the plasma as it enters a fuel-air stream, also improving the combustion efficiency. Turbulent jets will mix faster than laminar jets. The vorticity in the plasma jet shown in Fig. 14.7 enhances the amount of turbulence in the jet, and hence the ability for mixing.

During the entire digital camera observation tests, glowing regions of plasma were observed to travel from the center of the plasma jet and across the face of the torch.

An example of this is shown in Fig. 14.8. The plasma regions are highlighted with black arrows, while the plasma direction is shown with the white arrows. This particular photograph was taken during test #2, while the torch was operating with 25 SLPM of methane, although the same event was observed to happen during most of the other tests as well. In this case, the plasma jet has just started contracting and is also quite off-center. The cause of the observation is not known, but may be linked to the plasma jet oscillation discovered earlier, or could be some sort of boundary layer effect. The plasma regions traveled anywhere from 5-10 m/s across the face of the torch, but exact speeds were difficult to calculate because the waves were constantly changing size and shape.

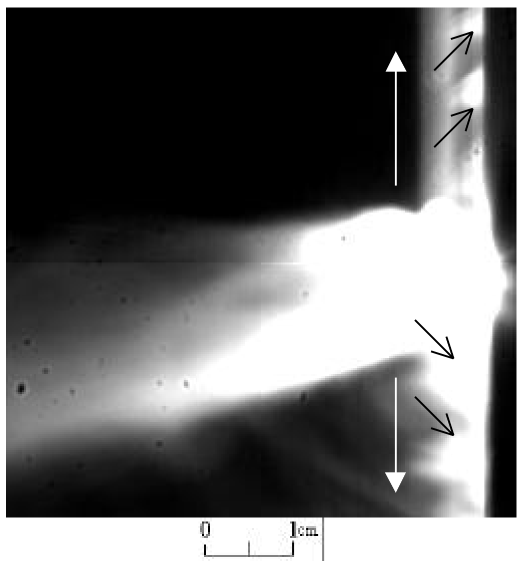


Figure 14.8: Plasma Region Propagation along Torch Face

This plasma propagation could be quite valuable if the torch was mounted in a fuel injector array. If the moving plasma is sufficiently energetic, it is possible that it could reach adjacent injectors and ignite them at their orifice, rather than waiting for the fuel and plasma streams to mix and ignite downstream. An effect similar to this was observed by Sato et al. (1992), who reported that plasma torches in his fuel injector experiments would ignite a fuel injector directly downstream of the plasma torch orifice. This fuel injector would then ignite adjacent parallel fuel injectors. It is possible that the plasma torch was responsible for igniting all the fuel injectors, but this is just a theory. However, the photographs taken during these tests clearly show that in an ambient environment the moving regions of plasma have enough strength to travel at least several centimeters away from the torch nozzle. Estimating from their speed and size, they may have sufficient strength to travel several times farther, but in a supersonic cross flow these phenomena would quickly be swept downstream. Regardless though, this plasma propagation phenomenon brings up some interesting design issues when integrating a plasma torch into a fuel injector scheme.

14.3: Recommendations and Final Remarks

Tests were conducted using an EG&G Reticon high-speed digital camera to photograph torch startup processes. The most visible startup effect was that of electrode emission. Electrode particles were seen to propagate downstream of the torch, characterized by blobs or streaks of light. Electrode emission was found to be heavier for methane than argon, as expected. Mixtures of argon and methane also produced high levels of emission. Lower flowrates of methane exhibited more electrode emission than higher flowrates. This was caused by quick, intense heating of the anode, without the cooling benefit of large volumes of methane. Electrode particle speeds were calculated by knowing the optical width of each frame, frame rate and tracking particles as they moved across the field of view. Particles categorized as “small” were observed to travel about 17.0 m/s while heavier particle velocities were around 4.5 m/s. This electrode emission can enhance ignition and flameholding. The hot metallic particles could possibly act as micro-flameholders as they travel downstream in the fuel-air mixture. Gasified metals, such as light alkali metals, could also prove effective and may even improve torch performance (Jahn, 1968).

Plasma jet formation as a function of feedstock type and flowrate was also studied. It was discovered that a fully developed plasma jet forms for both methane and argon in 5-7 ms, for flowrates between 20-25 SLPM. The flowrate affects the amount of electrode emission, which affects plasma jet formation. Tests conducted with less than 20 SLPM of methane showed severely increased development time because of electrode particles disrupting the jet formation. Depending upon the severity of the electrode emission, plasma jet formation time could be increased several times over. However, under all circumstances, the plasma jet was fully developed by 15-20 ms.

Jet intensity was measured simply by observing the size and apparent brightness of the jet. Black and white photographs provide very little information about the luminosity of the jet, but the jet could be observed quite easily through a welding mask. Methane consistently produced larger, brighter jets than argon. Argon jets were small and stable, with very little fluctuation. Overall, larger methane flowrates produced larger and brighter, but more unstable jets, as expected. This observation was also noted by Zhang et al. (1997). Using diode-laser absorption methods to analyze arcjet plasma, he discovered that the plume velocity and temperature were increased by both increased feedstock flowrate and specific input power. This finding also agrees with numerous other sources that state increased flowrate and pressure will constrict an arc column, increasing the temperature of the arc and hence, the plasma. Complimentary to these findings, Behbahani et al. (1982) reported that hot pockets of gas will be accelerated by pressure gradients much more quickly than cold pockets. He described their flow pattern as, "pellets from a shotgun, rather than in a uniform stream." Therefore, increasing the temperature of the arc column and plasma should also create a longer jet because of the increased velocity of the gases, as observed in these tests.

Several phenomena were observed by analyzing the digital photographs, which were not part of the original research plan. One of these phenomena was the presence of hemispherical waves observed propagating away from the torch nozzle. The wave speed could not be calculated from the digital photos, but they are clearly seen to be moving downstream. These waves were highlighted by slower moving plasma as the waves passed by. The waves are believed to be caused by the plasma jet oscillation or arc rotation. These waves, if they are indeed shock waves, could enhance the mixing of the plasma and fuel-air streams.

Vortices were also noticed downstream of the anode nozzle. These vortices were seen to travel at least five centimeters from the torch face, until they reached the edge of the field of view. The presence of vortices downstream of the torch face proves that the flow swirler inside the torch is indeed swirling the flow, and that these vortices are persisting through the anode constrictor and persisting some distance downstream. These vortices increase the turbulence of the jet and enhance the mixing of the plasma and fuel-air streams.

Another interesting observation was made when regions of glowing plasma were noticed to propagate away from the anode nozzle and across the face of the plasma torch. They traveled at about 5-10 m/s, but their velocity was difficult to estimate because they were constantly changing size and shape. These regions, if they contain enough momentum and energy, could possibly reach and ignite adjacent fuel injector orifices.

The high-speed digital camera used to analyze the torch startup processes yielded important results regarding how effective the plasma torch is expected to be as a flameholder and ignitor. Phenomena that are known to enhance mixing were observed as well as other torch characteristics that would augment the ignition capability of the torch. The electrode emission, turbulent vortex mixing and observed wave phenomena provide strong indications that the torch should be an excellent ignitor and flameholder, while also furnishing its own mixing enhancements.