Section 3.0: Plasma Torch Design

A plasma torch is a device in which a flowing gas is passed through an electric arc, producing plasma. A plasma is a mixture of ions, electrons and neutral particles produced when stable molecules are dissociated (in this case by an electric arc). The electric arc is formed between two electrodes, the anode (+) and cathode (-).

Plasma torches vary widely in design and use. They have been used for waste management, metal cutters, flame stabilization, IC engine lean burn applications and exhaust emission control, among others. Plasma torches vary widely in power rating as well. Depending on their application and design, torches have been designed to operate with power consumption of a few hundred watts to several hundred kilowatts. Plasma torch designs are as diverse as the applications they are used for.

A schematic of a generic plasma torch is shown in Fig. 3.1. The gas enters the torch body through a tube, travels up the length of the cathode and out through the anode throat, meanwhile passing through the generated arc and becoming plasma.

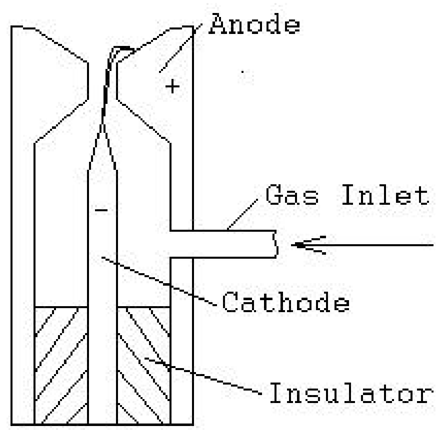

Figure 3.1: A Generic Plasma Torch Design

Many different types of gases have been used with plasma torches; Air, O_2 (Kato et al., 1996 and Mitani, 1995), N_2, H_2, Ar (Stouffer, 1989), CH_4, C_2H_4 and C_3H_6 (present study) to name a few. The first object the gas encounters when entering the plasma torch is the cathode. Typically, cathodes are thin, pointed rods made of tungsten or copper, although some are flat-ended depending on the application (Chan et al., 1980). They are electrically connected to the negative power supply of the torch. After travelling up along the cathode, the gas then encounters the electric arc, becomes plasma and passes out of the torch through the anode throat. The anode is generally constructed from copper or tungsten, like the cathode. It has a nozzle upstream of the throat to accelerate the flow, ejecting the gas-plasma mixture at high velocity out of the torch.

3.1: Heat Transfer Design Considerations

Perhaps the most difficult design consideration one must contend with when designing a plasma torch is heat transfer. Inadequate cooling of the electrodes can severely limit the operational life of the torch. High thermal gradients can produce high rates of electrode erosion, eventually leading to failure. The heat transfer into an electrode is the net sum of radiation, convection, conduction and electron heating. Both the anode and cathode exhibit different heating and cooling characteristics due to the geometry of the torch and electron path, so each will be examined separately. The following sections have been adapted from Stouffer (1989), the original designer of the Virginia Tech Plasma Torch, with extra sections describing recent modifications and discoveries.

3.1.1: Cathode Heat Transfer

Heat transfer to the cathode can occur through convection, conduction, radiation and electron interaction. Throughout the course of torch operation, the cathode is heated by the current passing through it (Joule heating). This is plainly seen in a common halogen bulb; as current increases, so does the temperature and brightness of the filament. Cathode heating in this manner is purely a function of cathode diameter and current. Another method of cathode heating is radiation. As the gas passes through the electric arc it is converted into plasma. This plasma radiates heat onto the electrodes and torch body, since they are at much lower temperatures. Radiation to the electrodes is known to increase as the current density increases (Finklnberg and Maecker, 1956). However, this radiative effect is rather small compared to the effect of Joule heating. Eberhart and Seban (1966), conducted an experiment with an argon arc at a pressure slightly above atmospheric. They found that only 2-8 percent of the total heat transfer to the anode was due to radiation. Likewise, the effect of radiation heating to the cathode will be small compared to other heating modes. Radiation is also a method of cooling for the cathode. Hot spots, especially the cathode tip, will radiate energy to the cooler gas surrounding it. Finally, the cathode can be heated by positive ion bombardment. Since the cathode is negative, it attracts positive ions, which collide with the cathode and convert their kinetic energy into thermal energy.

Convection, conduction and electron emission all serve to cool the cathode. Electron emission from the cathode occurs primarily at the tip. Electron emission from the cathode in a high-pressure plasma torch is thought to occur in two ways; field emission and thermionic emission (Hardy and Nakanishi, 1984). Field emission is the extraction of an electron from a material due to a large magnetic field. Thermionic emission is the emission of electrons from a material due to high temperatures (similar to sweat evaporation, this type of electron emission cools the material). The Richardson-Schotky equation predicts the current density at the cathode due to these two effects:

$$j = AT^2 \exp[\frac{-e}{kT}(f_c - \sqrt{\frac{Ee}{pe_o}})]$$

From this equation it is apparent that the current density, j, leaving the cathode is a strong function of temperature, T. Concurrently, since the highest temperature of the cathode is located at the tip, one can conclude that the current density is generally confined to that area.

Convection is another main source of cooling for the cathode. The flow geometry of the plasma torch is designed so that gas enters through the gas inlet ports, travels up the cathode body, through the electric arc and out through the anode throat. As the gas travels along the cathode body, it has not yet reached the electric arc and been converted into hot plasma. Therefore, it is still at ambient temperature and provides convective cooling.

Finally, conduction serves as another means of cooling the cathode. Since the cathode is one of the hottest elements in the plasma torch, second only to the anode, anything it is in contact with serves as a heat sink. A steel alignment sheath usually covers a majority of the cathode. This sheath is an excellent heat sink. Heat transfer also occurs through various electric insulators. However, electric insulators are usually good heat insulators as well (especially when compared to steel) and do not contribute significantly to help cool the cathode.

Curren (1985), studied the overall heat transfer to a cathode in a low power DC arcjet. He discovered that only 1 to 5 percent of the total arc power was lost to the cathode. In his experiments, as the power was increased, the percentage of power lost to the cathode actually decreased. This is an important consideration when improvements are needed in torch design. Apparently, power losses to the cathode are small when compared to the anode.

3.1.2: Anode Heat Transfer

The anode is the part of the plasma torch that receives the brunt of the thermal abuse. It is exposed to high temperature plasma, radiation, Joule heating, ion bombardment and electric arc impact. Unlike the cathode, which is cooled by convection, the anode is heated by convection. As the cool gases flow past the cathode and into the electric arc, they become ionized and extremely hot. The gases then flow through the anode throat, heating it by convection. This convection is a strong function of electrode geometry and alignment. If the plasma jet leaving the cathode tip is misaligned, instead of flowing through the center of the anode throat it may flow directly into the anode surface and severely increase the rate of convective heat transfer. Also, the diameter of the anode throat is important. As the diameter of the anode throat increases, convective heat transfer to the anode should decrease because of the increased distance between the anode wall and the centerline of the plasma jet. In fact, as the anode throat diameter and feedstock flowrate increases, a cool layer of gas may completely avoid the arc and follow the anode throat wall providing a cooling effect.

As with the cathode, the anode is both heated and cooled by radiation. The high temperature plasma flowing through the anode heats the anode by radiation. However, this radiation is generally quite small compared to other heating effects (Eberhart and Seban, 1966). Also, hot spots on the anode, especially portions exposed to the atmosphere, can radiate heat to the cooler gases surrounding them.

Joule heating is a significant source of heating to the anode, although not as severe as the cathode because of its larger mass. Current passing through any substance will tend to heat that substance proportionally to its electrical resistance. The rate of heat transfer for the anode is a function of electrical resistance, anode mass and the amount of current passing through it. Compared to the cathode, the anode has a lower electrical resistance because of its larger size and also has greater mass with which to dissipate heat. Therefore, Joule heating, although important, does not play as significant a role with the anode as it does with the cathode.

Perhaps the most important sources of heat transfer to the anode are ion bombardment and electric arc impact. Similar to the cathode, the anode attracts ions, in this case negative, which collide with the anode and convert their kinetic energy into thermal energy. The heat transfer to the anode is especially high at the point of arc attachment. Heat transfer occurs from the arc to the anode in several ways. First, the electrons have thermal energy, which they release upon contact with the anode. They also have kinetic energy, which partially gets converted to thermal energy as it passes through the anode. The heat transfer at the point of arc attachment is described by:

$$q_e = j[\frac{5kT_e}{2e} + U_a + f_a]$$

This equation, developed by Shih et al. (1968), demonstrates how the thermal energy (first term), kinetic energy gained by the electron acceleration through the arc (second term) and the kinetic energy given up by the electrons on impact (third term), relate to the heat transfer at the point of arc attachment, q_e. It is important to note that each term is multiplied by the current density, j. Therefore, the heat transfer to the anode due to the electric arc is largely dominated by the current density. This conclusion was also reached by Curren (1985). He determined that the heat transfer to the anode increased as current increased and decreased as feedstock flowrate increased.

The anode is primarily cooled by conduction, although convection and radiation do play minor roles. In most plasma torch designs, the anode is secured to the torch body by an anode cap, generally made of steel. This cap provides an excellent large body heat sink. Without it, the anode would quickly overheat. This anode cap is also connected to the torch body, another excellent heat sink. In most torch designs, the positive section of the torch comprises a majority of the torch mass. This is important in uncooled plasma torches to provide enough material to act as an effective heat sink for the anode.

3.2: Arc Mode Design Considerations

An anode, which has a constrictor, or throat, can operate in two different arc modes; high voltage and low voltage (also known as diffuse and constricted modes, respectively (Berns et al., 1996)). Both modes are shown in Fig. 3.2. The high voltage mode is characterized by an arc that passes completely through the anode throat and attaches on the downstream side of the constrictor. For the low voltage mode, the arc attaches somewhere before the anode throat. Of the two modes, the low voltage mode is more damaging to the anode. The high pressure upstream of the anode throat causes this high rate of electrode erosion. As pressure increases, an electric arc will tend to constrict. Because of the geometry of the anode, the pressure upstream of the anode throat is at a much higher pressure than the pressure downstream of the throat, which is roughly at atmospheric. Recall that the heat transfer rate to the anode at the point of arc attachment is a strong function of current density. Therefore, as pressure increases, current density increases and heat transfer at the point of arc attachment increases. This causes large thermal gradients, which generally result in high rates of electrode erosion. When designing a plasma torch anode, it is important to keep in mind in what arc mode the torch will operate.

High Voltage Mode

Low Voltage Mode

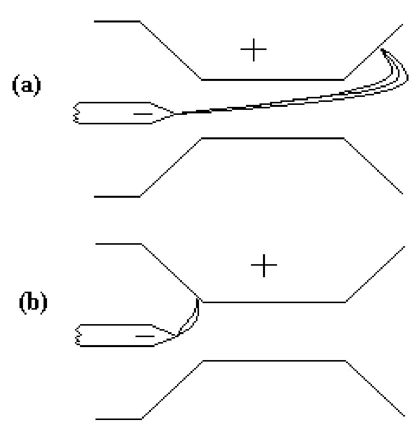

Figure 3.2: Arc Mode Operation

3.2.1: Regions of an Electric Arc

In addition to being able to operate in two different modes, there are also three different regions within an arc, each with unique characteristics. These regions are: the cathode fall region, positive column and anode fall region (Mahan, 1985).

Cathode Fall Region: The cathode fall region is located on the surface of the cathode. It is only about 0.001 mm thick, but depends on the pressure of the gas. The electric field strength in this area is very strong. Only electrons are found in this region, there is no plasma present. Also, the current density is highest in this section of the arc because the arc is narrowest at the cathode.

Positive Column: The length of an arc largely falls within the description of a positive column. In contrast to the cathode fall region, the electric field is very weak in the positive column. Also, this region is considered electrically neutral, so it is classified as a plasma.

Anode Fall Region: Like the cathode fall region, the anode fall region has a strong electric field and contains only electrons, no plasma. However, it is much thicker than the cathode fall region by several orders of magnitude and is located on the surface of the anode.

3.3: Effect of Gas Properties on Torch Design

Torch operation is highly dependent on the type of gases being used. Different gases have different specific heats, thermal conductivities, radical production and power requirements. The structure of an electric arc is dependent on the flowrate, specific heat and thermal conductivity of the gas being used. It has been shown, both in this study and in others, that monatomic gases behave very differently in a plasma torch than more complex gases. Even among gases in the same category (monatomic or diatomic), there are wide differences. Therefore, when designing a plasma torch, the feedstock with which the torch will operate is an important consideration.

The specific heats of monatomic and diatomic gases vary widely and behave differently over temperature ranges. Diatomic gases have translational, vibrational and rotational degrees of freedom, which generally lead to higher specific heats than monatomic gases which have only translational degrees of freedom. The thermal conductivity of a gas is directly proportional to its specific heat. Therefore, a diatomic gas will be more efficient extracting thermal energy from an electric arc. This characteristic results in diatomic gases requiring much larger amounts of energy for steady torch operation. Therefore, plasma torches designed to run on diatomic gases should be capable of channeling the electric current necessary to operate with the diatomic feedstock. Torches designed to run on argon, an electrically conductive monatomic gas, would be hard-pressed and subject to thermal damage if they were required to run diatomic gases which require much more power.

Also important in determining the structure of the arc is the way specific heat varies with temperature. The specific heats of monatomic gases generally decrease with increases of temperature because of their ability to store energy in only translational modes. However, diatomic gas specific heats generally increase with temperature until they become dissociated. At this point, they too can only store energy translationally. From the point of dissociation, their specific heats decrease as well. The result of this phenomenon is that the radial temperature profile of an arc in a diatomic gas will have a very narrow region where the arc is hot enough to dissociate the gas (Noeske and Kassner, 1962). This is caused by the ability of the diatomic gas to draw heat away from the arc very quickly without being ionized, except for a small region near the arc.

For diatomic gases, the electrical conductivity is highly dependent on temperature. Therefore, electric arcs in diatomic gases tend to be narrower because of their high rate of heat transfer. The electrical conductivities of monatomic gases vary little with temperature, so electric arcs in these gases tend to be much wider. Recall that narrow electric arcs have much higher heat fluxes at the anode surface than wider arcs. Therefore, torches designed to run on diatomic gases will need to account for this damaging effect. Noeske and Kassner (1962) conducted experiments on a bipropellant arcjet and found that the current carrying cross-section in a monatomic gas is nine times greater than in a diatomic gas with the same current. To pass the same amount of current in a smaller area, two things must be true. First, the electrical conductivity of the diatomic gas must be greater than the monatomic gas where the arc is present. Second, the temperature at the center of the arc must also be greater for the diatomic gas, because the current is confined to a much smaller area.

3.3.1: Ionization Processes

The goal of any plasma torch is to ionize and/or dissociate the feedstock gas passing through it. The energy necessary for ionization can be provided by electron collision, positive ion impact, absorption of radiant energy, or the gas may become so hot that ionization occurs thermally by the impact of neutral atoms (Cobine, 1941). All of these processes occur within a plasma torch, but the ionization processes in the region of the arc column are largely dominated by the first and fourth cases.

The ionization potential of electrons depends largely on their velocity, which is largely determined by the voltage. Slow moving electrons will not have sufficient kinetic energy to ionize an atom. Quickly moving electrons will pass through the sphere of influence of an atom before being able to remove an electron. Each particular element and compound have their own unique voltage at which ionization occurs most readily. As an example, mercury is most easily ionized into Hg^{+} at 40 volts, past which, this ability decreases steadily. Producing Hg^{+++} occurs most readily at just over 200 volts (Cobine, 1941). Two conclusions can be made from this. First, it is possible to produce different species from the same gas using different ionization voltages and second, producing a known, desired specie will best occur at a certain voltage.

Ionization occurring at extremely high temperatures is known as thermal ionization. It is the principal source of ionization in electric arcs. As the temperature of a gas increases, so do the velocities, increasing the likelihood that two or more neutral atoms will collide and ionize. At high temperatures, polyatomic molecules are also likely to dissociate, from which their simpler products can ionize.

3.4: Arc Stability

Arc stability is of utmost importance in maintaining smooth reliable operation of a plasma torch. Unfortunately, many of the forces present in a plasma torch tend to work against arc stability. However, several methods can be employed to increase the likelihood of stable arc operation. Increasing the arc diameter is perhaps the easiest way to produce a more stable arc. This is accomplished simply by increasing the current, or reducing the pressure. Aerodynamic stabilization can be accomplished through anode geometry or by inducing vorticity into the flow.

3.4.1: Arc Diameter

The diameter of an electric arc is directly related to how stable it is; the wider it is, the more stable it is. An arc with a wide cross-section is more likely to resist any sort of disturbances introduced by the gas flow or other means. Disturbances will generally be confined to the outer edges of the arc leaving a large straight path for current to travel through down the center. Thinner arcs do not have this type of buffer. Their current carrying path is much narrower. Once they are disturbed, their current path is displaced, creating a longer, unstable arc. Plasma torches operating with diatomic feedstocks generally suffer from this type of instability, because the arcs produced tend to be much narrower than arcs produced in monatomic gases. The underlying principle is that, given the same amount of disturbance, a narrow arc will be broken before a wider arc (Noeske and Kassner, 1962).

Pressure also affects the arc diameter. Increasing pressure will tend to constrict the arc and make it narrower. Another effect of increasing the pressure is to increase the temperature of the arc (Cobine, 1941). Changing the flowrate of the feedstock, or changing the diameter of the anode throat can change the pressure. In order to reduce the pressure in the torch body, the flowrate can be decreased, or the anode throat can be increased. However, decreasing the flowrate will limit the amount of convective cooling available to cool the electrodes. Also, increasing the diameter of the anode throat will reduce the amount of wall stabilization (discussed in the next section). Therefore, there is a tradeoff between arc stability and electrode cooling.

3.4.2: Wall Stabilization

Arc stability can be improved using wall stabilization. In the case of a plasma torch anode, wall stabilization occurs in the anode throat where the radial movement of the arc is constricted. Smaller throat diameters produce better wall stabilization, but also increase the pressure in the torch body, which constricts the arc. In this situation, a tradeoff occurs between which type of arc stabilization to use; low pressure or a small diameter throat. Ideally, the arc column would fill the entire anode throat, but because the melting temperature of every known solid material is much lower than the temperature of the plasma, a real arc will not completely fill the constrictor. Regardless, an arc in a smaller diameter constrictor will be more stable than one in a larger constrictor, given the same pressure.

The length of the constrictor is also important. If the constrictor is longer than the entry length of the arc column, the efficiency of the plasma torch suffers (Mahan, 1970). The entry length of an arc column is defined as the length for the arc to become asymptotic. At this point, all of the local power input is lost to the constrictor walls. If the constrictor is longer than this length, more power is needed for the arc to pass through, but with no added benefit.

3.4.3: Vortex Stabilization

Low power plasma torches operating at high pressures will generally have very thin arcs. From a wall stabilization perspective, this would force the anode throat to be small, which has the previously mentioned drawbacks. One way to overcome this drawback is to use vortex stabilization. Inducing swirl into the flow forces the arc to rotate about the anode, rather than remaining fixed in a single area. Arc rotation frequency is important when considering the thermal loading of the electrodes, according to Chan et al. (1980). Chan, hypothesized that too slow a rotation rate would result in too high a temperature during the time of contact and too fast a rotation rate would not allow for sufficient heat dissipation between rotations. Flow swirl can be produced either by the use of a flow swirler, or tangential gas inlets into the torch body.

A flow swirler is a device that receives the incoming axial flow and forces it into a vortex, much like inlet guide vanes in a turbojet. With tangential gas inlets, the gas enters the torch body with a tangential velocity component. Either method produces roughly the same results with different disadvantages. Flow swirlers are changeable pieces, which can easily be replaced with new designs, but also have large losses associated with them. Tangential injection does not suffer from these large losses, but in turn, once the torch is constructed, the tangential component of the inlets is permanently fixed.

For either method of vortex stabilization, as the gas passes into the anode nozzle the diameter of the anode nozzle decreases and the rate of tangential rotation of the flow must increase to maintain conservation of angular momentum. This produces two benefits. First, as the flow rotates, denser cooler gases are forced to the anode walls. This provides convective cooling for the anode (Wagner et al., 1987). Also, the hot, less dense gases are kept towards the center of the anode throat. Recall that the arc column tends to follow the path of least resistance, which is also where the gas temperature is highest. This tends to make the arc column remain in the center of the anode throat. Another added benefit is the variation of pressure with radius produced by the vortex in the anode throat. Mager (1961), analytically studied isentropic flow through a nozzle with swirl. He concluded that for ideal, isentropic flow, the pressure of the gas is zero at the centerline of the nozzle. This area of zero pressure increased as swirl strength increased. Naturally, the flow in a plasma torch is not ideal, but this does provide a convenient model. Due to the generated vortex, the pressure at the center of the anode throat is expected to be lower than at the walls. This will allow the arc column to increase its diameter and become more stable.

3.4.4: Magnetic Arc Rotation

Although not truly a form of arc stability, magnetic arc rotation provides many of the benefits of arc stability methods without many of the disadvantages. Magnetic arc rotation is accomplished by rotating a permanent magnet or producing a rotating electric field around the axis of the plasma torch by some other means. This rotating electric field causes the arc to rotate about the axis of the torch and greatly reduces the rate of electrode erosion, particularly on the anode (Chan et al., 1980). Electrode erosion is usually the cause of hot molten spots on the anode being flung off by the force of impact of the arc. By magnetically rotating the arc, portions of the anode are exposed to the arc for very short periods of time and are allowed to cool. One torch design that utilizes magnetic arc rotation is described by Harrison and Weinberg (1971). Their torch design forces the arc to rotate at 10^5 rpm by means of a field coil.

There are several disadvantages to this type of system. A plasma torch that uses magnetic arc rotation will be more complex than one that uses some form of vortex or wall stabilization, simply because of the addition of parts. Also, magnetic arc rotation does not provide any convective cooling to the anode like vortex stabilization does because it does not alter the characteristics of the flow, just the arc. However, even considering these effects, magnetic arc rotation allows one to control and change the frequency of arc rotation, unlike vortex or wall stabilization, which are basically hit-or-miss techniques. When designing a plasma torch, the advantages and disadvantages of each arc stabilization technique must be weighed and chosen to fit the particular type of plasma torch application.