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Plasma Torch for Biomass Pyrolysis

Abstract

Our world abounds in diffuse sources of energy, and the engineer’s challenge is to concentrate that energy, and convert it to a useful form. When America’s farmers grow corn, half of the non-root mass is left to decompose in the field. This corn stover (cobs, stalks and leaves) represents a convenient and plentiful source of energy. The scope of this paper describes undergraduate research into a key component of an apparatus which has the potential to make small- and medium-sized farms net exporters of energy.

Although large-scale gasifiers are already used to convert municipal solid waste to combustible synthesis gas (carbon monoxide plus hydrogen), system efficiencies do not scale well to the average farm operation. A common design is the up-draft gasifier, which partly combusts the feedstock while producing the syngas. Direct combustion is less efficient than complete gasification; and up-draft gasifiers further dilute the output gas with non-combustible nitrogen from the air. A different approach, pioneered by our company and patent pending, uses a novel apparatus to efficiently convert farm biomass to syngas, which can then be burned in a generator set to provide electrical power and heat. In order to achieve this efficiency, a plasma torch is used to rapidly pyrolyze corn stover, producing high BTU content syngas and a dry ash rich in soil nutrients.

A multidisciplinary team of four undergraduate researchers converted a commercially-available plasma cutter into a plasma torch for use in a farm-scale biomass syngas reactor. This hands-on research project combined the best available published literature on plasma cutters and torches with the accumulated experience of professional engineers from industry to create a working prototype. Following each major development, the student team reviewed their work, and near-term plans, with a review board. Fabricating the plasma torch required the use of computer-aided design tools, and close interaction with the model makers who ran the computer numerical controlled milling machine.

Anticipating the bizarre behavior of plasmas, the students integrated the ability to tweak their design after the first operational tests. After the lengthy design process, the test-and-refine phase proceeded quickly. Each student contributed to the understanding and improvement of the performance, engendering a spirit of teamwork, appreciation for diversity, increased problem solving ability, and an appreciation for the value of a thorough design phase. In this paper we briefly review the plasma torch biomass reactor concept, explain the lessons learned by the students, and address the value gained by the company.

Introduction

In December 2007, President Bush signed into law the 25x’25 Plan, with the aim to provide 25% of America’s energy needs from renewable sources by the year 2025. Carbon-neutral technologies for power production are needed to reduce overall greenhouse gas emissions to forestall global climate change. Biomass is emerging as a vital source of renewable, carbon-
neutral energy, as seen in the recent explosion of bio-ethanol plants across the US. However, using corn kernels for liquid fuels competes with the use of corn as food, which drives up market prices. After each bushel of corn is harvested, an equivalent mass of “crop waste” (straw, stover, stalks and bagasse) is left to decompose. The decomposition process adds humus and minor nutrients to the soil, but also emits carbon dioxide and methane into the atmosphere. If instead, post-harvest biomass can be efficiently converted to fuel, the price conflict with food vanishes, the amount of fossil fuels used is reduced, and a so-called waste product can acquire a net positive value.

Biomass-to-fuel systems have been designed, but suffer from the diffuse nature of their crop waste. There is a fundamental tradeoff between the efficiency of scale for the reactors, and the need to transport a low-value, low-density, geographically-distributed feedstock to a large reactor. To break this impasse, a new method of biomass gasification has been invented, and is now patent pending. With this fast pyrolysis method, crop waste is converted into a combustible gaseous fuel with a much higher heating value compared to direct combustion of the biomass. By shifting lignocellulosic material to a gaseous form, a great deal more heating value is available for combustion. This process is so efficient that a medium-sized farm (about 1000 acres) can produce more electrical and heat energy than they need with an apparatus operated on-site. The secret lies in efficiently heating the biomass, and our invention uses a plasma torch to do so. Four college interns were tasked with the design of this key component during the summer of 2007.

Using the corporate library, the student team researched the history of these devices. They found that plasma torches were first developed by NASA in the 1960s to simulate re-entry of space vehicles. A plasma torch consists of a gas (either air, or combustible gasses for even higher temperatures) greatly heated by passage through a miniature bolt of lightning created by applying a high voltage between two electrodes. Two types of torches are used in practice, the plasma cutter, which is commercially-available, and the less common plasma torch, as shown in Figure 1.

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![Figure 1. Plasma cutter (left) and plasma torch (right).](image-url)
On the left of Figure 1 is a transferred arc, where one electrode (+) is the working surface to be heated, cut, or melted. The right side shows a nontransferred arc, where the plasma tool contains both electrodes, and the gas flow carries the plasma (the lightning bolt) to the work surface. For biomass gasification, the nontransferred arc is used to heat the exterior of a syngas reactor. Spreading the plasma across a large surface was the task assigned to the team of undergraduate engineering researchers.

**Design and Fabrication**

As an aid to student motivation, each of the students was trained in the safe operation of a commercially-available plasma cutter, and allowed to conduct *ad hoc* experiments. Officially, they were instructed to develop safe work habits, and to develop an intuitive sense for the characteristics of a plasma tool. Unofficially, they had a great deal of fun cutting quarter-inch steel plate like gelatin, while showering white-hot sparks across the shop floor. They became very motivated.

![Figure 2. Student operating commercial plasma cutter.](image)

A key design variable was determined by testing. Given the voltage rating of the plasma cutter tool, there exists a maximum gap across which a spark can be generated, and the students set out to determine that critical dimension. Unique testing instrumentation was designed and assembled by the student team, allowing them to accurately adjust the gap distance of a transferred arc. After experimenting through a range of distances, they determined that a gap of 0.027 inches would spark intermittently. This set an upper limit to the electrode gap for the plasma torch. A nominal gap of 0.025 inches was chosen for the nominal design.

Next, the students were challenged with designing a custom head for the plasma torch, which would use the existing high voltage, gas regulation and hoses, and would produce not just a pencil of plasma, but a sheet. Figure 3 shows an early concept drawing where a roughly cylindrical reactor vessel is rotated past the sheet of plasma (3 flames shown) to heat the biomass inside. Figure 4 illustrates the concept for the sheet plasma torch head.
The four team members included undergraduate college students majoring in Mechanical, Electrical and Aerospace engineering. Two of the students were responsible for performing searches in the published literature and the US patent records, as well as to contacting established experts in academia. While there are quite a myriad of related publications and patents, they were unable to find specific designs for torch heads. University researchers either had no interest in such a mundane application, or demanded consulting fees for their services. Simultaneously, the other two team members performed product and manufacturer searches using industrial catalogs and web-based search engines. Several US manufacturers were identified and contacted for input or advice on a student research project. Without exception, these requests were denied. Apparently such designs are proprietary, or at the least, custom-designed for each application.

Lacking a working example of a sheet-shaped plasma torch head, the students queried practicing engineers within the company, and gathered the following guidelines and advice:

1) Plasmas do not last long at atmospheric pressure, so to transfer heat to the syngas reactor either a close spacing or a high gas flow rate is needed.
2) Electric arcs tend to concentrate in one spot, so spreading a single arc across a wide area will be challenging, and perhaps impossible.
The extremely high temperatures of a plasma (up to 15,000° C) will erode electrode materials, so material choice is important, and critical spacings should be either avoided, or compensated for.

The team then established a brainstorming design session to develop a range of approaches for initial review. These approaches ranged from simple to complex to silly, and under the guidance of the project mentor, were reduced to two competing concepts. The first was an annular orifice around which a concentrated spark could (somehow) be maneuvered to give the desired broad-area coverage in a time-averaged fashion. Although innovative and compelling, no facile means for manipulating such a traveling spark could be envisioned. The second design, which was eventually selected for fabrication and testing, was a sandwich of parallel flat plates equipped with internal air channels to distribute airflow evenly across parallel electrode surfaces. The students’ next task was to develop detailed CAD drawings, select materials and a fabrication method, and prepare for a detailed engineering design review.

Figure 4 shows a copper plate being milled to form the air channels and manifold of one half of the sandwich torch head design. A deep recess in the ¼” plate forms a pressure manifold, from which multiple channels, following a logarithmic progression of widths, direct air flow into a smaller manifold. From this second, smaller manifold, the air passes through the narrow electrode gap and out of the torch head.

Upon recommendations from a design review attended by three electrical engineers and a mechanical engineer (two having a professional engineering license), the electrode gap was scalloped to provide multiple regions having a small radius of curvature, intended to help initiate the sparks to form the plasma.

**Testing**

Wearing appropriate protective gear, and at this point in the project familiar with plasma torch operation, the students affixed their torch head design to the air hose and electrical cable of the
disassembled commercial plasma cutter tool. Built into the electrode sandwich was the ability to manipulate the gap along the electrode length, to make the gap as uniform as possible.

Operating at the maximum air flow and power setting, the electrode produced a stable arc on the first attempt. However, the plasma flame appeared only at one end of the electrode face, covering about 5-10% of its width. With continued operation, the flame suddenly jumped slightly further from the end, and this process continued until the flame appeared only in the center region of the 18 inch wide electrode face. After disassembly, oxidation was observed on those scalloped electrode edges where the arc had formed. The students deduced that the jumping occurred as oxide buildup increased resistance locally, and the spark jumped to a near neighbor with lower resistance.

Facing this result, the team was challenged to overcome what had been anticipated in advice point 2) above. An electronic or mechanical means to move the arc around, similar to the annular design, was discussed, and the team rigged up a mechanical fixture to do so. Using manual manipulation of the electrode gap, a localized plasma flame could be marched across the electrodes in a crude fashion. One daring (and clean-shaven) student discovered that by blowing air cross-wise to the electrode, the flame could be made to dance across the electrode edge. Both of these operations gave the students confidence that it is possible to design a moving arc with the desired properties in a time-averaged sense. However, creating a sheet of plasma remained elusive.

Lessons Learned and Company Value

In this summer research project, the students executed a complete design-and-test sequence on a key component to a high-value project with high societal relevance. The hands-on work at start and finish bracketed a substantial research and design phase which proved motivational and fun. The complementary nature of the disciplines required students to cooperate with one another in order to complete the project with minimal staff involvement. This, in turn, raised their self-confidence and demonstrated the value of diversity and teamwork.

Several insights realized from this project are helping in the development of the curriculum for next summer. Plasma cutting appears to be hugely fascinating for students. As part of their “practice”, the students created artwork and knick-knacks. While ostensibly off-task, three positive outcomes ensued: (1) other students grouped around, asking for a chance with the plasma cutter; (2) other student research groups, seeing the interest in this project, endeavored to make their own work more dramatic; and (3) the participants took home keepsakes which will remind them of this project, possibly helping to reinforce these lessons over the years. While in the past many student projects have been self-contained, this project was part of a larger effort. This helped focus the students’ efforts on a needed goal, while simultaneously allowing them to enjoy a larger sense of accomplishment. Their results became an important component of a major invited grant proposal recently submitted to the USDA by our company.
Summary

The ten week effort to design and improve a plasma torch heater for a biomass syngas reactor provided proof of concept feasibility. Because the task is to heat the exterior of a reactor (Fig. 2), the time-averaged heating behavior is acceptable. The high temperatures generated in a plasma allow fast pyrolysis of biomass inside the reactor. By heating biomass to 1250°C, intermediate byproducts such as tar, cyclic hydrocarbons and hydrogen sulfide are decomposed to the simple gasses hydrogen, carbon monoxide, and carbon dioxide. The ash remaining is dry, and replete with non-volatile minerals which can be spread over the fields to nourish next season’s crops. The synthesis gas produced can be combusted in a gas turbine without elaborate clean-up. Mechanical work from the turbine generates electricity for farm operations, and waste heat from the exhaust stack can be used to dry harvested grain in a silo, or to keep animal barns warm in the winter. Calculations of the economics of this process indicate economic payback is realistically attainable in just one year – a very attractive investment for a farm operation. The plasma torch is a key component, and the multi-disciplinary student research team has paved the way for further engineering development.

Bibliography

13. 2007 Iowa Farm Custom Rate Survey, Iowa State University, File A3-10, March 2007.