AC 2008-1569: ALTERNATIVE FUELS RESEARCH WITHIN A MULTIDISCIPLINARY CAPSTONE DESIGN PROJECT

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Abstract

This paper will describe the results of recent activities concerning the development of a hydrogen-diesel farm tractor test bed used within a capstone design project. The project, part of a "Wind to Hydrogen" program funded by the Department of Energy, received the support of a regional electric cooperative and equipment supplier to take a medium sized row crop diesel tractor and convert it to a dual fuel vehicle with minimal modifications. Performance results from the proof of concept phase will be reported.

Besides presenting experimental results, insights and experiences gained in the process of establishing a multidisciplinary student team will be described. The significant communication role played by web-based organizational tools and the impact of student skills on team effectiveness will be discussed. Future efforts will be described.

Overview

The purpose of this paper is to serve as an illustrative example of how a senior level capstone design experience can be utilized to conduct funded research in a new growing area. Results of the experimental work are presented as a way to demonstrate the quality of the research obtainable through the student team's efforts. The project took advantage of a nexus situation of an existing design course, a new funding opportunity, unique participants' skills and available or donated resources. Each of these components and the project will be described in detail below, followed by results obtained to date, perceived impact on educational outcomes and desired follow on activities.

The Course

The Mechanical Engineering department at North Dakota State University (NDSU) has had a two semester, six credit (three per semester) senior design capstone course for more than 12 years. Although technically two courses the sequence is really handled as though it were a single course flowing through 30 weeks of academic time, exemplified by a single student team, one project and planning timeline for that entire period. Instructional guidance is provided through two department faculty members. Each faculty member is responsible for unique aspect of the course. One, which could be considered the "Instructor" is responsible for the administration of the course, assembling design project for the students, entering grades and other system requirements. The instructor has primary responsible for educating the students on the theoretical process of design. The second faculty member serves as a content specialist for the student team on their project. This faculty member is considered to "Mentor" the student team on the application of design theory to practice. Several texts have taken the same approach for design education, one of which is that by Ulmen[1]. Until recently the typical sequencing for the two semesters was fall-spring or spring-summer, but in the last year a spring-fall cycle has also been tried. For each sequencing, between eight and 15 three-person teams (and the occasional four-or five-person team, in special circumstances) selects from a list of available projects. The projects have an associated mentor and the project team and mentor than stay together for the entirety of that sequence. The projects come from various sources, some are the result of national student design competitions from such organizations as ASME or SAE. Other projects come from the community or local businesses and provide services under the aegis of community development. Additional projects as needed come from faculty or department to address research or teaching needs. Occasionally projects are proposed by students returning from cooperative educational experiences and are sponsored by the companies for which they were. All projects are reviewed by the Instructor to ensure that they contain sufficient design content for the course and to keep the students engaged (three hours/ credit/week, three credits, three students, 30 weeks equals approximately 810 student hours).

During the first semester of the course students are required to attend a one hour a week lecture given by the instructor to discuss the major facets of design, i.e. team building, design approach, problem identification, concept generation, evaluations, analysis, modeling (numeric and/or physical) and testing. A budget is also constructed for each project as it is a timeline for planning purposes. Additional weekly meetings are held as needed in the second semester. Throughout the second semester scratch that throughout both semesters the student team meets with the mentor on a weekly basis to discuss the details of the project and assure that it's being completed in a timely fashion. The grading is accomplished by inputs from both the instructor and the mentor on: end of semester written reports, oral, presentations posters and weekly meeting contributions. The weighted contributions are 65% 35%, respectively, for the mentor and the instructor with typical 90, 80, 70, etc., A, B, C contract grading applied. During the course of the sequence, extensive use is made of a web-based educational support tool, blackboard. The tool is used for administrative functions such as attendance, announcements, homework assignments as well as communication functions, particularly e-mail. Additional details about the course are available upon request.

The Opportunity

In the fall of 2006, a unique opportunity for a project in this design course appeared as a result of the intersection of three situations, namely national concerns about energy, unique resources available in the local region and people willing to combine the two. Specifically, a local energy cooperative, Basin Electric Power Cooperative, Bismarck, ND, was able to acquire some resources from a Department of Energy pilot grant to study the opportunities available to lessen US dependence on petrochemical oil. The DOE project, titled "Wind to Hydrogen"[2], was to utilize the abundant wind sources of North Dakota[3] to address the large US consumption of transportation energy[4] through the transformation of that energy to another form more easily usable in vehicles. The electric co-op decided to transform the wind energy to hydrogen through commercial electrolyzer technology using electricity supplied to the grid from local wind farms. The hydrogen gas (H2, or H2G) thus produced would be used in some example vehicles representing typical local usage. A commercially converted multiple-fuel pickup truck was one type of test vehicle used[5]. The converted truck was capable of using hydrogen, natural gas or gasoline. Because the extensive agricultural activity in the area, the co-op decided to also convert a tractor to burn hydrogen, which presented a problem because no commercial conversion was available for the diesel power plant typically used on these vehicles. The cooperative decided that the value of working with this type of tractor would be of great interest to most of its members who had comparable tractors on their own farms. As a result the cooperative decided to set aside a moderate amount of funding for exploratory activity with local commercial or educational institutions.

The Resources

Once the electric cooperative decided to press ahead with the conversion of a diesel powered tractor, they contacted local tractor suppliers. As a result of those talks the local Caterpillar dealer entered into an agreement with the co-op to lease a moderately sized row-crop wheeled tractor. The tractor used was a 2004 MT525B Caterpillar Challenger wheeled row crop model. This tractor has a 5.98 liter displacement Perkins in line 6 cylinder diesel engine rated at173 brake hp. It is turbocharged with an air to air after-cooler, see Fig 1. Although part of the lease agreement required that the tractor be returned in the same condition in which it was received, it made a fine test bed for the ensuing project.

North Dakota State University Prof. Robert Pieri, front, displays the tractor converted to partial hydrogen fuel operations with his student team, seniors Mitch Helleen, top, Ted Wald, hand on hydrogen tank, and Temi-Tope Akingboye. (Photo by Jen Swanson, Basin Electric Power Cooperative)

Fig 1: Tractor Used

The second major resource made available was the easy availability of hydrogen gas resulting from the presence of the electrolyzer itself. The unit was a Hydrogenics model HySTAT-30 refueling station[6] which consists of a generation and compression module, storage ability and a dispenser module. This system is capable of producing about 30 kg of hydrogen per day and is able to dispense the gas at controllable pressures up to 5000 psi. The water supplied to this unit was filtered from the local municipal source. The electrical energy supplied came from the local electrical utility, a member of the sponsoring co-op. The grid supplied energy originated from three wind farms the co-op operates within the state.

The final resource needed to complete the project was an entity that had the people equipment and motivation to do the conversion and demonstrate its utility. For that the co-op turned to

NDSU for support because of its role as the state's land-grant institution and its tradition of technical excellence. Another contributing factor was the well-known reputation of the University students' strong work ethic and hands-on abilities.

The Skills

Upon being contacted by the co-op through NDSU's Agriculture Extension services, the school's engineering faculty decided that the best fit for the project was with the Mechanical Engineering Department (ME) with support from Electrical and Computer Engineering (ECE) and Agricultural and Biosystems Engineering (ABEN) departments. Because of several factors including traditional interest area, existence of the design sequence, available resources etc. And ME department took the lead function in the project. A project mentor was appointed with two associate mentors. The timing dictated that spring summer semesters would be used for the project. Because of the interdisciplinary nature of the project, faculty support from the other two departments was secured, making for a faculty leadership group of five people. These five faculty had leadership and administrative skills, technical expertise in agriculture, mechanics, material selection, manufacturing, thermodynamics, gas and cryogenic handling, instrumentation and electronics.

The project plan was to use student design teams from each department. ABEN had a bit of a problem because their design sequence was out of phase with the spring start for this project but they were able to find three students who would be interested in participating in the project although all students may not be available for both semesters. The other two departments were able to utilize normally scheduled design sequences to enlist interested students for the project. The resultant student group had a maximum number of eight members that dropped to four during the summer because of prior commitments, jobs and co-ops etc.. Although all student teams brought particular skills to the project, the student team from the ME department took advantage of a particularly unique situation by enlisting a student with prior training as a diesel engine mechanic. It also turns out that one of this particular student's parents was on the staff at the sponsoring electrical co-op. All but two of the eight students had prior experience with local agricultural activities, and three of the students were part-time employees of ABEN, providing them trusted access to tools and materials.

During the first semester of the project, the faculty and student teams conducted a weekly design meeting, as most ME design projects would do. During the second semester the prime mentor and the reduced student group held more infrequent meetings for reasons described below. Each student design team was responsible to their own academic unit for completion of their course required items. All faculty members involved with the project tried to facilitate these activities. Also during the second semester and opportunity arose for the inclusion of a visiting scholar to participate in many of the activities.

The Project

The basic objective for the project was to provide a diesel powered tractor (compression ignition, IC engine) that would be able to be operated in a "normal" mode while displacing traditional petrochemical diesel fuel with hydrogen gas. The "normal" operating mode would imply conditions as-safe-as or safer-than normal agricultural equipment operation. The sponsors wanted this tractor to be seen doing typical activities in the region neighboring be electrolyzer station, for public awareness issues. As the project was being formulated, the mentors conducted research into possible options for the tractor conversion. Design considerations included; safety, cost, ease of execution and use, lack of permanent modifications, gas storage and effectiveness toward overall objectives. Consultations were conducted with research engineers at Caterpillar engines division. The result of this activity determined that the typical method of IC engine conversion to hydrogen was to replace the diesel fuel with H2 gas and add a spark plug, effectively making it a spark ignition (SI) engine. In the application currently under consideration those modifications would require extensive rework of the engine head. The project had neither the time nor the money to accomplish this. Fortunately one source[7] was found to have considered fumigating the engine inlet air with hydrogen gas and using the burning injected diesel as a flame source. After consideration from the design team and discussing alternatives, it was decided that the project would focus on this inlet fumigation technique.

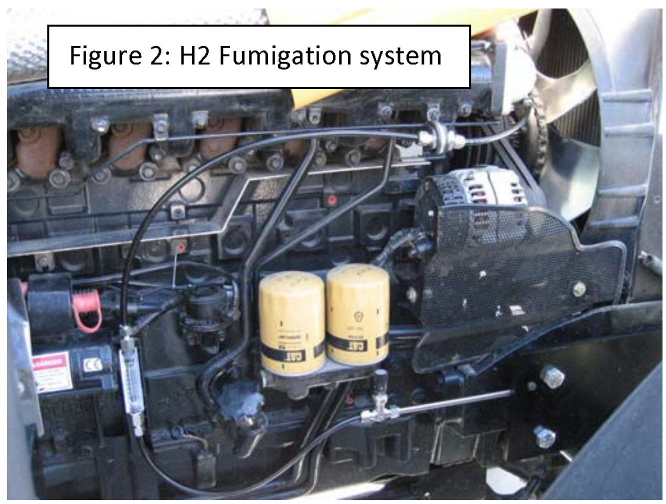
All activity focused about the safe handling of the hydrogen gas. All project members were required to read on the Organization site instruction about safety concerns. All hardware considered was either already used in H2 applications or need to be H2 certified. As part of this indoctrination, the team quickly became aware of the physical properties of H2 gas that caused some of the difficulties with the CI conversion. Although hydrogen gas has a very low ignition energy (20 j, 1/10 that of gasoline vapor)which accounts for its high flame speed, its autoignition temperature is 1085^0F, compared to diesel temperature of about 470^0F, i.e compression alone will not ignite H2!

Once the general direction of the project was decided, the team was able to focus on the steps required to enable the work to begin. Because of safety considerations and to facilitate the design procedures, it was decided to take advantage of the truck commercial conversions mentioned above and use the same hardware where feasible. The design teams broke out areas of responsibility, pretty much following the disciplines. The ECE team would work on controls, sensing and operating functions. The ME team would focus on gas flow and hardware, engine modifications and performance testing. The ABEN team would focus on basic additions to the tractor to support modifications, provide expertise in performance measurement and would act as a final certification of acceptable operating methods. The general timeline was of that additional research, hardware ordering, installation and testing and baseline measurements would be accomplished in the first semester. The primary objective of the second semester was intended to be field operation of the tractor, data gathering and analysis. Instrumentation of the engine was required; it was minimized to recording cylinder pressure since it was agreed that pressure was the most critical item to monitor for safety. An advanced optically based gauge was used on the first and sixth (last) cylinder, going through the head to the top of the cylinder between the valves. Two were used to monitor H2 mixing. All reading for H2 were to be compared to those for conventional diesel fuel.

To facilitate communication among the scattered participants in the project, a newly available aspect of Blackboard was applied i.e. "Organizations". The organizational intent of the Organizations feature is to differentiate itself from course organization. The purpose for this Organization feature is to provide web-based lateral communication, in a synchronous or asynchronous mode. It also provides good functionality as a repository for information crucial to the organization. During the course of the project this site has received contains copies of research papers, modification drawings, hardware supplier quotes, tentative calendars, posters, schedules, etc. Besides its use as a storage site, this feature was actually displayed during weekly project meetings to ensure that all participants in the project were up to speed. Students and faculty seem to adapt well to its utilization.

Several interruptions to the schedule occurred because of sponsors desire to display the work-in –progress to members of the energy industry and the general public. This provided excellent exposure of the program, university and students, but it did move the schedule around.

Figure 2: H2 Fumigation system



The following picture, Figure 2, shows the final plumbing set-up for the infusion system. Two metering vales were used with an inline flow meter to confirm rates. Although SST tubing was used for most rigid lines, some H2 approved plastic tubing was incorporated to isolate vibrations. This set-up would only provide for manual adjustment of H2 flow into the system. Figure 3 shows the arrangement of the gas storage tank and pressure regulation system.

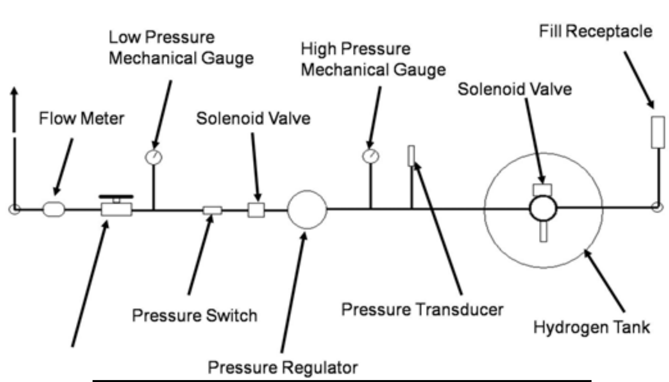


Figure 3: Figure of the H2 Flow system

The Results

The project was able to get the engine to run with the H2 infusion, and was therefore successful in meeting fundamental objectives. By using a PTO dynamometer, the students proved that infusion of 10%

energy density of H2 caused a 10% increase of power, see the Summary in Figure 4. However, because automation of the valve control was not accomplished, extensive use experience was not gathered. Also, because of the extensive electronic control of the diesel fuel dispensing system,

Figure 4: Summary of Results

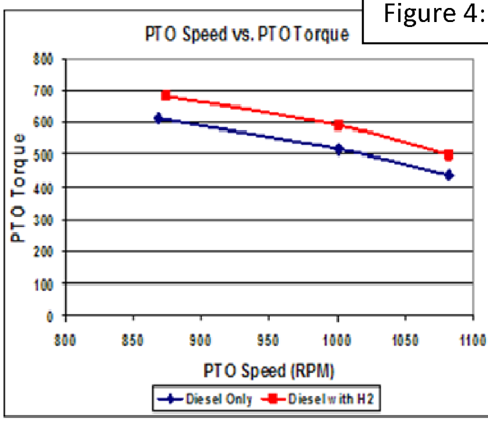


Figure 19. PTO Speed vs. PTO torque results

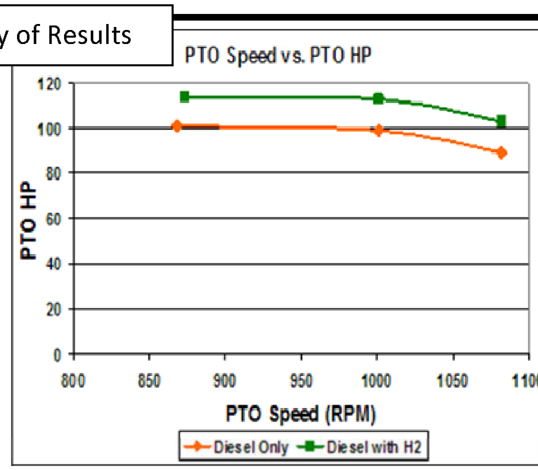


Figure 20. PTO Speed vs. PTO HP results

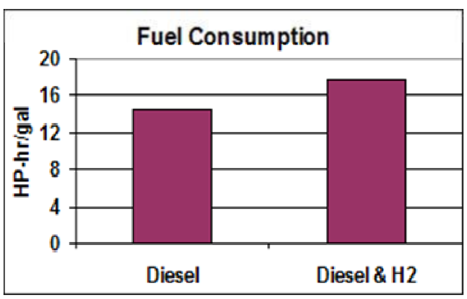


Figure 21. Fuel consumption data gathered during the dynamometer tests

Average Exhaust Emissions Data			
Measurement	Diesel only	Diesel/H2	% Diff
%O_2	12.12	11.4	6.12%
%CO	0.096	0.096	0.00%
%CO_2	7.32	7.28	0.55%
ppm HC's	4	4.2	4.88%
ppm NO	422	466.2	9.95%
ppm NO_2	27.8	30.4	8.93%

Table 1. Exhaust emissions data

relative metering of diesel and H2 couldn't be accomplished.

The Impact

The impact of this project on the students, faculty and departments was large. As stated above opportunity for visibility was high. The mentor was invited to speak at several occasions and the students received extensive exposure to the public policy decision making process.

The Future

The H2-Tractor project continues for a second design sequence in the ME department to address problems identified above and to extend a broadened research program. Although the skill set of the current team is not quite as serendipitous as the first team, these students are quite capable in the right. An added feature to the current project is a graduate student to facilitate the research program. This graduate student is currently involved with a more in-depth exploration using a single cylinder engine of the engine performance parameters with the infusion of hydrogen gas into a diesel engine.

The Commercial

The participants of this design program wish to thank those providing support, without their efforts this worthwhile experience would not have come to pass.

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