FIRST-TIME EXPERIENCE WITH ENGINE SIMULATION SOFTWARE IN AN INTERNAL COMBUSTION ENGINES COURSE

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Industry's development cycle of a new I-C (Internal Combustion) engine typically involves designing, building, and testing. When the cycle is carried out by undergraduate students during a one semester project, building and testing are omitted. Instead, focus is directed to the design process which is often characterized by endless streams of trial and error often resulting in engine geometries and performance that are more similar than they are different. To offset this inherent bias, students were introduced to GT-Power, industrial grade engine simulation software. The software was used in both a design and an analysis mode with particular emphasis given to combustion chamber design. By so doing students were able, for the first time, to determine the effects of changes in key variables on the performance of their respective designs. The purpose of this paper is to describe the experience of introducing engine simulation, an almost routine methodology in industrial engine research and design, into the classroom. The paper describes preparation on the part of the instructor and the students for the software's use and critical assessment of the software's benefits and limitations. Samples of student work and insights into their experience are presented. The paper shows that, despite the challenge of using advanced simulation software like GT-Power in a classroom, students and instructor clearly stand to benefit from the experience. Recommendations and some thoughts about future considerations are also presented.

BACKGROUND

Each offering of the senior-level elective Internal Combustion Engines course is accompanied by a student-team project involving a design of a single cylinder engine. Last fall, students were asked to design a 15-HP/3000-RPM engine for use on a ride-on mower. If the design process would evolve along traditional lines, students would initially focus on engine geometry, selecting parameters such as engine bore and stroke, connecting rod length, inlet and exhaust valve sizes, and compression ratio. Once defined, engine geometry would be combined with operating characteristics such as stoichiometric air/fuel ratio, combustion efficiency, and exhaust residuals, followed by a complete thermodynamic analysis of the engine using the air-standard Otto cycle at wide-open throttle. While simple and relevant, this approach rarely yields results that correlate well with actual engine geometry and operation. Thus a more comprehensive approach namely, computer simulation, was chosen for the student design project.

WHY SIMULATION?

With advancements in mathematical modeling of fluid flow and combustion, internal combustion engine simulation has in part replaced the costly and time-consuming cycle of building and testing engines every time a change to the engine or one of its components is made. Often, only after a component is optimized through simulation is a part actually constructed and tested. For a brief overview of the use of simulation models by engine manufacturing industry, consult the text by Pulkrabek.[1]

Whereas advanced mathematical modeling and simulation have made inroads into the industrial sector, their presence in academic circles is less pervasive except for FEA and CFD software which continue to be introduced into the undergraduate curriculum. Factors contributing to this development can be traced to ever-increasing computer skills of students and instructors, to the general availability of greater and faster computing in the public domain, to reformatting of complex simulation software to make it more user friendly, and to the perceived need by the technical community to use models and simulation to define and solve problems. In the area of engine development and design, educators were able to access an engine simulation program released by General Motors as early as 1987[2]. Today engine simulation software like GT-Power is used by educators, although evidence suggests that its primary use is in graduate research rather than in the undergraduate domain.

WHY GT-POWER?

A search of appropriate engine simulation software for use an undergraduate I-C engines course was conducted. The search led to numerous candidates; two are worth noting, namely:

(1) A virtual engine model described in ASME paper IMECE2004-61998, “The Development of a Computer-Based Teaching Tool for Internal Combustion Engine Courses”, by Pin Zeng and Dennis N. Assanis.

(2) A series of engine cycle models on the Colorado State University web link: http://www.engr.colostate.edu/~allan/thermo/page1/page1f.html

Although not a true simulation software, the latter was used in prior course offerings and is a worthwhile resource for general engine study. It features a simple engine model linked to the Otto cycle and provides analyses that are useful in the conceptual study of I-C engines. The model however yields results that do not correlate well with actual engine behavior. This shortcoming and the need to adopt an evaluation tool to better discriminate between student designs, led to venturing into the world of industry-grade simulation software such as GT-Power. The software is managed and distributed by Gamma Technologies of Westmont IL.

BRIEF DESCRIPTION OF GT-POWER

GT-Power is a mathematical tool that uses advanced methodology to simulate the thermodynamic, fluid mechanic, and chemical processes that define real I-C engine behavior. The heart of the software is designed around a series of icons and connectors that define engine components and a logical interface for their use. These are shown in a schematic of what is referred to by GT-Power as the Project Map. Icons in the Project Map can be energized to reveal related information such as assigned values, formulas, etc., and methodology to edit input data as needed. At the heart of the software are two operating domains called GT-ISE and GT-POST. GT-ISE builds, executes, and manages the simulation process while GT-POST, a post-processing tool, provides access to computed results and plots.

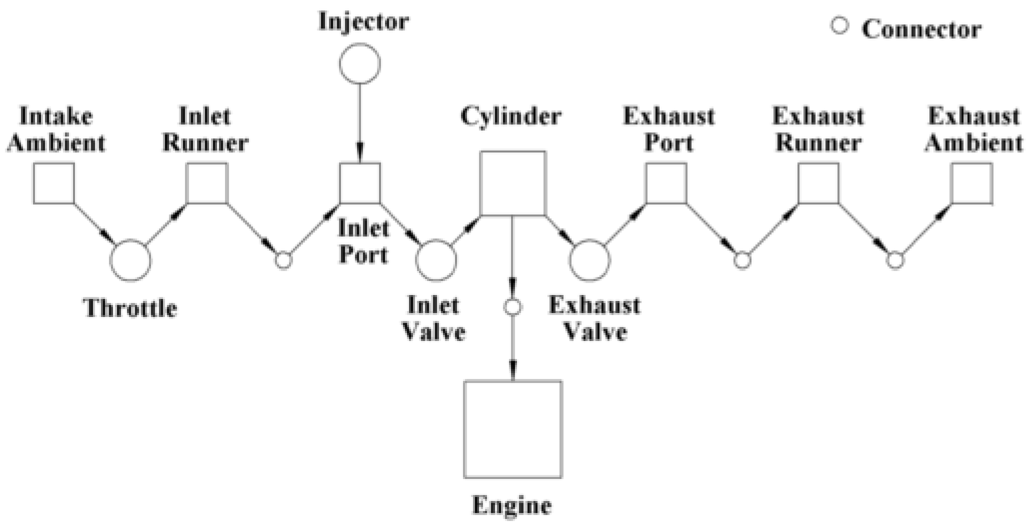

Figure 1.0 Schematic of GT-Power Project Map

Actual use of GT-Power involved simulation of two engine operating modes namely, non-predictive and predictive. Non-predictive is akin to “design” and predictive to “analysis”. In the non-predictive mode, students specified piston/cylinder geometry and compression ratio based on what can be described as “reasonable” values. Students then selected reasonable values of operating parameters such as spark timing, inlet and exhaust valve lift profiles, inlet and exhaust runner lengths and diameters, just to name a few. It should be pointed out that Gamma Technologies personnel were most helpful in providing reference data such as valve discharge coefficients and typical cylinder temperatures used in calculating heat transfer.

RESULTS OF GT-POWER SIMULATION

Figure 2.0 shows a summary of key engine design parameters for eight student teams using GT-Power in the non-predictive mode. The computed values represent students’ final effort at meeting the targeted output of 15 HP after completing a succession of “tweaks” and simulation runs. From Figure 2.0 one can readily see a thread of design commonality among the teams. This outcome is not unexpected considering that each design team was subjected to the same design constraints and used similar design methodology. However, the ability to make design changes and to analyze the effect of these changes rapidly, were clearly major benefits cited by the students in using GT-Power in the non-predictive mode. Figure 3.0 shows a plot of the coveted P-V diagram used to calculate indicated work by one of the student design teams. The diagram

Team #	Bore (mm)	Stroke (mm)	Conn-rd. Lgth. (mm)	V_d (mm^3)	Total V_c (mm^3)	Comp. Ratio	Diam. I-valve (mm)	Diam. E-valve (mm)	Brake Power (BHP)	BMEP (bar)	Squish (%)	BSFC (kg/kW-hr)	η_{brake} (%)	η_{ind} (%)	η_{mech} (%)	$\eta_{volumetric}$ (%)
1	85	78	136.5	442611	49204	9.99	30	27	15	10.1	41.5	0.2768	29	33	87.67	88.1
2	85	75.5	151	428424	47603	10	32.49	25.35	15	10.4	40	0.242	33.67	38.3	87.2	91.4
3	90	85	164.9	540746	67810	8.97	28	25.45	15	8.3	40	0.2576	31.5	37.3	84.69	79.8
4	95	80	160	567057	74529	8.6	27.5	25	15.2	8.02	40	0.2674	30.32	35.87	84.52	77.57
5	90	75	150	477129	54219	9.8	29.65	26.69	15.01	9.4	45	0.2436	33.3	38.45	86.2	82.9
6	90	75	131.25	477129	56132	9.5	29	27	14.98	9.36	41.22	0.2456	33	38.14	86.5	82.7
7	85	85	164.9	482332	53592	10	29	26.36	15	9.3	46.71	0.2492	32.83	38.46	85.32	82.4
8	95	80	164.9	567000	68425	8.86	28	23.1	15.1	9.96	54.61	0.2735	29.6	35.1	84.33	78.3

Figure 2.0 Student Engine Design Summary

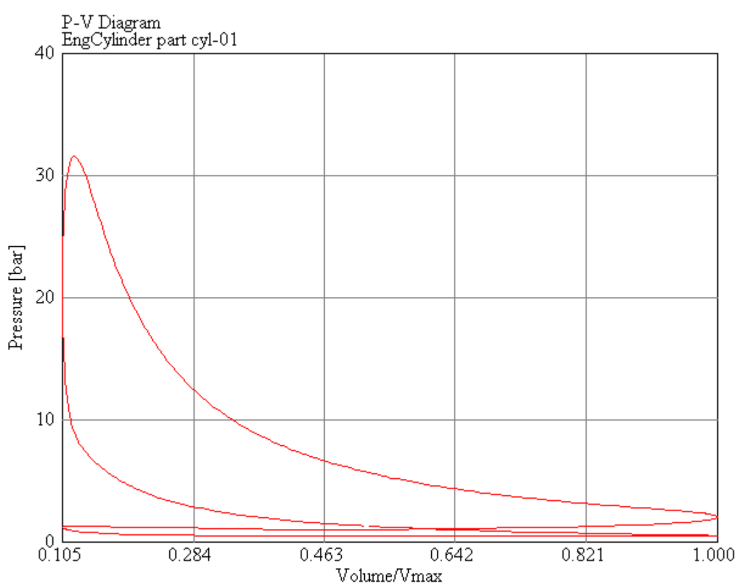

Figure 3.0 P-V Diagram

clearly shows the absence of the constant volume combustion process characteristic in Otto cycle analyses. GT-Power uses a combustion model based on Two-Zone[3] combustion methodology that computes cylinder and pressure in time increments as fuel from the unburned segment is consumed to satisfy a given burn rate.

Perhaps the most worthwhile experience of the entire project from both the instructor's and students' perspective was the ability of using GT-Power in the predictive or analysis mode. As mentioned, capability to do off-design analyses of engine performance was non-existent in past design projects. To be able to make these types of analyses was truly an exciting first-time experience for both instructor and students.

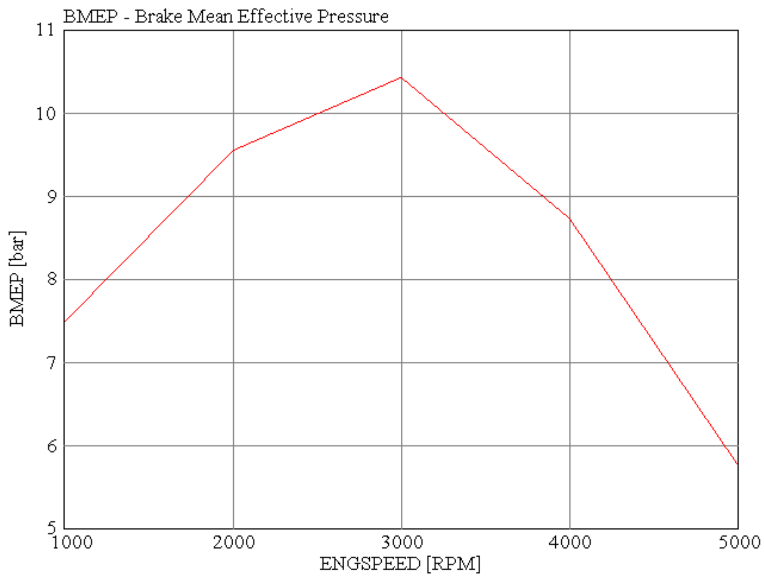

Figure 4.0 BMEP vs. Engine Speed

Figure 4.0 shows a sample plot of BMEP, brake mean effective pressure vs. Engine Speed. The shape of the plot is reasonable and supports expected behavior namely, that heat transfer losses dominate the low RPM region and friction losses dominate the high RPM region.

Figure 5.0 contains a partial list of additional calculated values for the GT-Power simulation run involving variation of engine speed in the predictive mode. Note the absence of EGR, Exhaust Gas Recirculation. This was done for simplicity. Engine speed increments of 1000 RPM were chosen to minimize simulation run-time. A smaller speed increment would yield a more accurate solution, but would also increase computation time. Trading off computation run-time for calculation accuracy is one of the inherent characteristics of simulation model.

It should be pointed out that use of GT-Power in the predictive mode required detailed definition of combustion chamber geometry. Whereas GT-Power is configured to accept any shape of combustion chamber defined by the more popular CAD systems, our application involved use of a so-called STL file, typically found in rapid prototyping, to define the shape of the cylinder head and the piston-cup cavities. For this first-time application, all combustion chambers were made to be cylindrical. This constraint was imposed to both simplify and speed up the combustion chamber geometry design process. However, the spatial X-Y-Z location of the sparkplug was left up to each design team. Students found this feature to be particularly useful and used GT-Power to find the optimum location of the sparkplug.

Engine Speed (RPM)	**1000**	**2000**	**3000**	**4000**	**5000**
BMEP (bar)	7.496	9.544	10.432	8.737	5.770
FMEP (bar)	0.968	1.227	1.511	1.733	1.909
Brake Efficiency	29.713	34.102	33.496	30.432	25.290
BSFC (g/kW-h)	272.851	237.736	242.037	266.403	320.577
Volumetric Efficiency	0.740	0.821	0.913	0.842	0.669
Percent EGR	0.000	0.000	0.000	0.000	0.000
Air Flow (kg/hr)	11.027	24.466	40.838	50.193	49.868
Fuel Flow (kg/hr)	0.730	1.620	2.704	3.323	3.302
Air-Fuel Ratio (trapped Air/Total Fuel)	15.099	15.100	15.100	15.100	15.100
Brake Torque (N-m)	25.556	32.540	35.567	29.787	19.674
Brake Power (HP)	3.588	9.139	14.984	16.732	13.814

Figure 5.0 Partial List of Additional Calculated Values

LESSONS LEARNED

Clearly, it can be stated that the experience gained from introducing a simulation package such as GT-Power into an undergraduate classroom was both a wholesome and worthwhile learning experience. Lessons learned can be summarized as follows:

- Engine simulation tools like GT Power are complex, all-encompassing, and made for general engine design applications. To fit the specific needs of a one-semester design activity, working features of the software's design and use required familiarization in a short period of time. This activity turned out to be most challenging.
- Training sessions and post-training user support provided by Gamma Technologies were invaluable. This was especially true in activities such as developing an appropriate model, selecting input parameters, and by-passing software routines that were either not relevant or not needed in the student project.
- Preparing a user manual to help students become acquainted with GT-Power reduced the time required to develop a level of user proficiency with minimum instructor

intervention. This instructor-centered activity turned out to be a most critical and contributed heavily to the successful use of GT-Power by the students.

- Outcome of challenging students with advanced software such as GT Power turned out to be an unexpected surprise. Once students realized that their efforts lead to a reasonably acceptable design, students began exploring limits for improving their designs, almost to the detriment of completing the project on time. This need to explore and "kick software's tires" has been observed in other first-time software applications. It suggests the presence of an inherent trait of today's students to want to learn more about new technology.

RECOMMENDATIONS AND FUTURE CONSIDERATIONS

It can be said clearly and unequivocally, that the experience gained from introducing simulation software such as GT-Power into an undergraduate engine design course, was both wholesome and worthwhile. Based on this experience, the authors submit the following recommendations:

- To ensure that students are provided with a most comprehensive and complete approach in the study of internal combustion engines, formally adopt use of GT-Power as a permanent computational design tool in the course.
- Introduce students to GT-Power earlier in the semester calendar. This will enable students to explore options in the design project segment of the course sooner. Also, current text has end-of-chapter problems that are excellent candidates for a solution using simulation.
- Upgrade user manual to include predictive analyses.
- Introduce theory and mathematical formulations used in GT-Power into class lectures and show how these compare with the expressions used in the class text. One such formulation involves the combustion process.

Using GT-Power in an undergraduate classroom environment provided an experience that fulfilled two new learning goals. These are:

1. the ability to create an almost limitless range of engine models that can mimic real engines with a high degree of confidence.

2. the ability to simulate and quantify engine performance at both design and off-design modes.

Whereas one cannot question the depth of knowledge and understanding gained from using simulation software in the study of internal combustion engines, one may want to consider the energy and effort expended in becoming reasonably proficient in using the software. Without question, GT-Power and similar complex problem solving software have an inherent learning curve often described as "steep". However, the steepness of the curve can be altered if one compares user needs with software capability. Clearly, the capability of GT-Power is beyond the design requirements of a single cylinder engine in a typical undergraduate engines course. However if the needs of the course and the capability of the software were to be realigned, the time and energy needed to become proficient in using the software would decrease. With that in mind, some thoughts for future consideration are presented. These include:

- Critically evaluate learning objectives of present engine design course and redefine the objectives assuming availability of simulation software like GT-Power.
- Suggest that Gamma Technologies, current owner and custodian of GT-Power, consider the development of an "academic" version of GT-Power with reduced capability and reduced cost of licensing.
- Extend to Gamma Technologies access to Purdue resources to aid in the development of the academic version of GT-Power.

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BIOGRAPHICAL AND CONTACT INFORMATION

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DISCLAIMER

The name "GT-Power" when referring to the software used in the course and that described in this paper is not intended to imply endorsement of the product by the authors, Purdue University, or ASEE.