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Development of a Combined Cycle Gas Turbine/Steam plant for Training Marine and Power Engineers

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ABSTRACT

The integration of micro turbine engines into the engineering programs offered at Maine Maritime Academy (MMA) has created a dynamic, hands-on approach to learning the theoretical and operational characteristics of a turbojet engine. Maine Maritime Academy is a fully accredited college of Engineering, Science and International Business located on the coast of Maine and has over 850 undergraduate students. The majority of the students are enrolled in one of five majors offered at the college in the Engineering Department. MMA already utilizes gas turbines and steam plants as part of the core engineering training with fully operational turbines and steam plant laboratories.

As background, this paper will overview the unique hands-on nature of the engineering programs offered at the institution with a focus of implementation of a micro gas turbine trainer into all engineering majors taught at the college. The training demonstrates the effectiveness of a working gas turbine to translate theory into practical applications and real world conditions found in the operation of a combustion turbine.

This paper presents the efforts of developing a combined cycle power plant for training engineers in the operation and performance of such a plant. Combined cycle power plants are common in the power industry due to their high thermal efficiencies. As gas turbines/electric power plants become implemented into marine applications, it is expected that combined cycle plants will follow. Maine Maritime Academy has a focus on training engineers for the marine and stationary power industry. The trainer described in this paper is intended to prepare engineers in the design and operation of this type of plant, as well as serve as a research platform for operational and technical study in plant performance.

This work describes efforts to combine these laboratory resources into an operating combined cycle plant. Specifically, we present

efforts to integrate a commercially available, 65 kW gas turbine generator system with our existing steam plant. The paper reviews the design and analysis of the system to produce a 78 kW power plant that approaches 35% thermal efficiency. The functional operation of the plant as a trainer is presented as the plant is designed to operate with the same basic functionality and control as a larger commercial plant.

INTRODUCTION

Maine Maritime Academy is situated on eastern Penobscot Bay and is home to approximately 850 students. (Figure 1) Over fifty percent of the students attending the college are enrolled in one of five Engineering Department's majors that ultimately lead to a B.S. degree. Requirements for graduation range from 131 to 177.5 semester hours depending upon which of the five academic majors a student will complete. Students generally take eight semesters to complete the program requirements with the exception of the Marine Systems Engineering program that requires two additional semesters of classes. Of the 850 students attending the college, 55% are members of the Regiment of Midshipmen and are part of the U.S. Coast Guard licensing program. The remaining 45% of the student body is made up of non-regimental students who do not intend to obtain a U.S. Coast Guard marine license upon graduation. Approximately 16% of the students are female. [1] Other professional licenses may be obtained and will be discussed later in the paper. In addition to the core academics, students in each of the regimental engineering majors are required to participate in two training cruises aboard the Academy's training ship and at least one cadet shipping assignment aboard a commercial vessel. Students in the non-regimental programs are required to complete at least two industrial cooperative assignments at industrial facilities or power plants across the country.

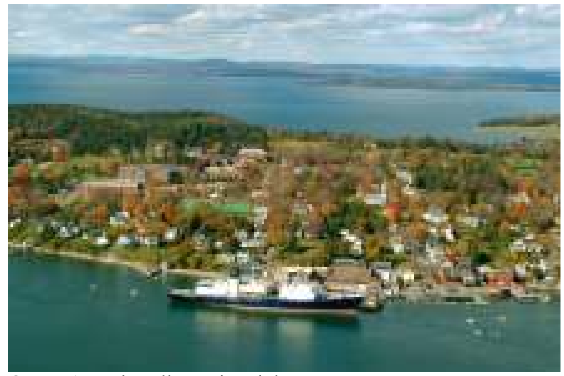

Figure 1: MMA campus and training ship

During the past ten years nearly 85% of new power plant construction, within the electric power industry, has been combined cycle combustion turbine plants. Power plants utilizing combustion turbines and steam turbines are quicker to install, require low manpower, and are less detrimental to the environment than traditional alternatives. The trend toward building combined cycle power plants began in the 1980s and peaked around 2000 with the deregulation of electric utilities in the U.S. Newer combined cycle power plants offer higher thermal efficiencies approaching 60%, which is far superior to conventional fossil fuel plants that are usually in the range of 40%. In the marine field, currently the power plant of choice is the slow speed diesel engine; but there are numerous ships currently in service powered by simple cycle gas turbines. The turbo electric propulsion system utilizing a combustion turbine prime mover is currently receiving lots of attention from the U.S. Navy. Because of the added weight and size associated with combined cycle power plants, it is unlikely that the next generation of large merchant ships will be powered by combined cycle combustion turbine plants. Because we train both marine and stationary power engineers, our programs and laboratory facilities must be flexible and applicable for all engineering majors.

Another area of potential growth and development lies with micro turbine technologies in the form of combined heat and electric power generation (CHP) as shown in figure 2. Application engineers in training need to be introduced to this emerging technology. Numerous businesses across the country have installed micro turbines with heat exchangers to capture waste heat from the exhaust of these tiny turbo-generators. It is the intention of this paper to examine the unique, hands-on educational opportunity provided by the engineering programs offered at Maine Maritime Academy and show how a working turbojet engine has been integrated into each of the engineering majors offered at the college. In addition, the paper will present the efforts and work toward developing a combined cycle power plant for training engineers in its operations and performance characteristics.

Figure 2: (Capstone 60 kW, CHP unit installed at Quirk auto dealership in Bangor, Maine)

NOMENCLATURE

ABET	Accreditation Board of Engineering and Technology
CHP	Combined Heat and Power
EIT	Engineer-In-Training
EMD	Electro Motive Division
IMO	International Maritime Organization
LHV	Lower Heating Value
MEO	Marine Engineering Operations
MET	Marine Engineering Technology
MMA	Maine Maritime Academy
MSE	Marine Systems Engineering
NEASC	New England Association of Schools and Colleges
PE	Professional Engineer
PET	Power Engineering Technology
STCW	Standards of Training Certification and Watch Keeping
TAC	Technology Accreditation Commission
USCG	United States Coast Guard

PROGRAM OVERVIEWS

Marine Engineering Operations (MEO)

MEO forms the foundation of all programs within the Engineering Department. Students learn to operate and maintain the power generation and propulsion systems, electrical, hydraulic, and auxiliary systems associated with shipboard machinery. This major leads to a U.S. Coast Guard engineering license and requires participation in the Maine Maritime Academy Regiment of Midshipmen. MEO students must meet all requirements for international STCW certification. In 1978, the International Maritime Organization began developing industry standards for training and watch keeping for maritime professionals. The US Coast Guard has endorsed these standards and each of the Maritime Academies has adopted the standards within their engineering programs. The program's STCW requirements are audited every five years for compliance with applicable international standards onboard ships. Most graduates of this program will find employment as engineering officers on commercial ships upon graduation; however, many chose to work in offshore oil exploration, shore-side power generation or business. [2] Gas Turbines (Eg431) is required of this major, and successful completion results in a gas turbines endorsement on the USCG marine engineers license.

Marine Engineering Technology (MET)

MET incorporates many courses from the MEO program with additional courses in science, mathematics, communication, technical science, and laboratory testing methods. Students entering this major are interested in working at sea with the option of becoming a shore-based technologist. This program is accredited by the Technology Accreditation Commission (TAC) of the Accreditation Board for Engineering and Technology (ABET). This major leads to a U.S. Coast Guard engineering license and requires participation in the Maine Maritime Academy Regiment of Midshipmen. Graduates of this program are also qualified to take the fundamentals of engineering exam which is the first step in obtaining the PE license. Graduates in this program that complete Eg431, Gas Turbines will also receive the gas turbines endorsement of their USCG marine engineer license. [3]

Power Engineering Technology (PET)

This non-seagoing major includes most MEO courses, plus detailed study of stationary power plant operations and management. Career opportunities as a power engineering technologist lie in utility power plants, biomass operations environmental compliance and cogeneration systems. Graduates of this program are qualified to take the fundamentals of engineering exam, the first step in becoming a registered professional engineer. Gas Turbines, Eg431 is also a required course for this major. The PET program is accredited by the TAC of ABET. [3]

Marine Systems Engineering (MSE)

Within this program, there are two degree options available to students, the MSE license track (5 years) and the non-license track (4 years). Students in the MSE five-year program are required to be members of the Regiment of Midshipmen for the first four years and the fifth year is optional. Students in the four year program are not required to participate in the Regiment; however, it is recommended. Both of these programs are math-intensive enabling the graduate to work as a design engineer, engineering consultant, or manager in maritime, industrial, or general technical fields. Both of these majors incorporate higher level science, mathematics, engineering science, and power plant technologies. Graduates of this program are qualified to take the Engineer in Training (EIT) exam the first step in becoming a registered professional engineer (PE). Students of this program combine extensive hands-on experience with rigorous analytical and design skills, and several go on to a graduate program in engineering after completion of the B.S. degree. [3]

Program	Total Credits
MEO	137.5-139.5
MET	144.5
PET	131
MSE 5-year	175.5-177.5
MSE 4-year	138-141

Table 1: MMA Semester Hour Requirements [4]

SEA TIME & CO-OP TRAINING

All candidates seeking a 3rd Assistant Engineers license from the U.S. Coast Guard are required to complete a minimum of 180 days of sea time. This is accomplished through specialized laboratories, simulators, and three distinct training cruises at sea, two aboard our ocean-going training ship and one aboard a commercial vessel. Engineering majors impacted by these training requirements include: MEO, MET, and MSE five-year students. Each of these programs must fulfill STCW International Standards as identified by the International Maritime Organization (IMO). [4]

Training Cruise

At the conclusion of the first and third academic years, students gain sea time experience aboard the college's *T.S. State of Maine*. Scheduled during May and June, for at least 60 days, training cruises typically include foreign and domestic ports-of-call. Our training ship is a 500 foot, 16,000 ton diesel-powered automated vessel and is one of the most sophisticated and modern training ships in the U.S. Maritime Academy fleet. When not on cruise, the vessel is the largest dynamic lab available for students and is used by several of the faculty to enhance academic classes. During the school year, students also perform all maintenance tasks and prepare the vessel for the upcoming training cruise.

Cadet Shipping

The second cruise experience, completed at the conclusion of the sophomore year, places cadets aboard a commercial merchant ship such as a tanker, bulk carrier, container ship, tugboat, supply boat, LNG carrier or cruise liner. The cadet shipping program is a vital element of the undergraduate education experience and requires the completion of an extensive sea project covering all major power plant systems onboard. This 60 day assignment involves the creation of system drawings and daily reports of ship board activities and work experiences. The cadets are immersed in this dynamic industry and are given a chance to test their knowledge, learn first hand from professional maritime officers, see the world, and earn income in the process.

Co-Ops

All PET and MSE four-year students gain hands-on training in summer cooperative work experiences in power plants and large industrial settings nationwide. Co-op assignments are at least one semester in duration during the summer. MSE five-year students must also complete a cooperative industrial field experience at the end of the fourth year of the program. [4]

Figure 3: MMA Lab Steam Plant

Engineering Laboratories

Maine Maritime Academy maintains a variety of engineering laboratories which provide a foundation for much of the hands-on training in the engineering curriculum. These laboratories include:

- Small scale operating steam plant (figure 3)
- EMD and Caterpillar diesel engine lab (figure 4)
- Power plant simulators for coal & combined cycle combustion turbine power plants
- Machine tool lab
- Welding & material testing lab
- Control room simulator (diesel)
- Electrical power lab
- Thermodynamics/fluids lab
- Machinery vibration fault trainer
- Micro turbine lab with data acquisition
- 500 foot training ship *T.S. State of Maine* (Figure 1)

Figure 4: Diesel Lab Cutaway Caterpillar Engine

Course Integration of the SR30 Micro turbine

In 2003, through the generous donation of an MMA alumnus, the college acquired its first operational gas turbine for inclusion into the engineering programs. Figure 5 shows the SR30 turbojet engine manufactured by Turbine Technologies LTD in Chetek, Wisconsin which was selected for its turnkey operation, data collection and its reputation and usage at numerous colleges around the U.S. The unit was soon used in several of the courses and became very popular among students and faculty. The SR30 has also been very effective as a recruiting tool and is demonstrated to hundreds of Maine high school students annually during Discovery Voyage visits, an MMA program in which Maine high school students spend a day visiting and operating equipment in MMA labs.

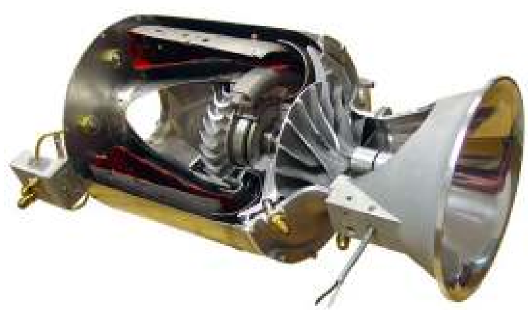

Figure 5: SR30 Cutaway view of Micro-turbine (Illustration from www.turbinetechnologies.com)

The SR30 is a single shaft, centrifugal compressor, axial turbine with a reverse flow annular combustion chamber design. The unit is 12.5 inches long and 7.5 inches in diameter and weights about 12 pounds. The turbine shaft is supported by precision, ceramic high speed bearings, and is pressure lubricated by synthetic turbine oil. The unit operates at an idle speed of

45,000 rpm and at over 80,000 rpm at full power and generates 30 pounds of thrust. The engine mass flow rate is between 0.4 and 0.9 pounds/second which simplifies venting of the high velocity exhaust gasses. The engine can operate on a wide variety of fuels, such as home heating oil, diesel, kerosene or jet fuels without reconfiguration of the fuel delivery system. The unit consumes about 1.8 gallons/hour at idle and just under 5 gallons/hour at full power. [5]

Gas Turbine Related Courses at MMA

All students of the engineering majors are exposed to gas turbines through a variety of engineering courses. All MEO and PET students are required to take Eg431 Gas Turbines. This course involves the study of principles, descriptive classifications, structure and accessories of marine and stationary gas turbine power producers. The course focuses on the operation and maintenance requirements associated with combustion turbine power plants from simple open cycle aero derivative units to heavy industrial frame units configured in a combined cycle mode. The SR30 with its data acquisition system is used to translate theory into hands on experience of the operation of a dynamic engine. Students are required to conduct pre-start checks, start up and run the engine, and collect operating data that can later be used in class and for homework assignments to determine engine performance, efficiency, fuel consumption and heat rate calculations. Eg431 students also participate in a field trip to a working high efficiency combined cycle power plant or visit a marine gas turbine powered vessel.

Et212, Thermodynamics II is a course taken by all MET, PET and MSE students. The course covers power and refrigeration cycles, heat transfer, and energy conversion devices. Students in this course will operate the SR30 turbine and take operational data using the data acquisition system. They use this data to analyze the performance of the engine, including component efficiencies. As a class project, former students completed a feasibility study of creating a combined cycle power plant using the SR30 turbine and the MMA steam plant. This project laid the groundwork for the study outlined in this paper.

All PET and MET students also take Et351 Thermo/Fluids Lab, a laboratory course in which students measure and analyze performance of energy conversion devices. In this lab, students operate and take data from an air turbine, the SR30 gas turbine, a heat pump, and several types of heat exchangers. They use this data to analyze effectiveness and efficiency of the devices. After running the SR30 turbine at varying fuel flow rates, students can determine the efficiencies of the compressor, combustor, and turbine, and see how these efficiencies change as engine speed changes. PET students also take Capstone I & II which involves extensive use of computers in the operation of combined cycle power plants and conventional fossil power plant operations.

MMA Steam Plant

MMA currently utilizes a fully operational steam plant as part of its engineering laboratories. A key part of this paper is a conceptual analysis to couple a commercially available Capstone C65 micro-turbine generator with this steam plant to create a small scale combined cycle training plant for use in the engineering curriculum. Figure 6 shows the existing lab boiler for the MMA steam plant with associated control system and instrumentation. This boiler can produce up to 0.139 kg/s of steam flow at pressures exceeding 9 bar.

Figure 6: MMA Steam Plant Lab Boiler

The Curtis turbine obtained its name from the original inventor of the velocity compounded impulse stage and is common in small auxiliary steam turbines. Our plant is coupled to a velocity compounded impulse single stage turbine shown in figure 7. The turbine is attached to a 3 phase 3600 rpm generator. In addition, the analysis included replacing the single stage turbine with a multi-stage turbine of higher efficiency.

Figure 7: Curtis turbine and Generator

In order to implement the combined cycle plant the C65 micro-turbine exhaust would need to be plumbed to the burner inlet of the MMA boiler in the area shown in figure 8. Proper balancing of exhaust backpressure will be required to ensure proper operation of the micro-turbine.

Figure 8: Boiler Burner Assembly

The micro-turbine exhaust would be connected in parallel with the existing burner assembly. This will allow for operation of the steam plant in either combined cycle or pure steam plant mode.

Combined Cycle Analysis

The Capstone C65 gas turbine generator system was chosen to couple with the existing steam power plant at MMA for the following reasons:

- Low capital cost (~$50,000)
- High overall efficiency (29% based on LHV)
- Turnkey system
- Size compatible with the MMA steam plant

The relevant characteristics of the Capstone turbine are listed in table 2. The important performance parameters for the analysis were: efficiency, power output and exhaust gas temperature. From these parameters the inputs for the steam plant analysis were computed.

Electrical power output (kW)	65 kW
Overall efficiency (Electrical to LHV)	29%
Exhaust Gas temperature	309 ºC
Full power heat rate kW (LHV)	224.2 kW
Total exhaust heat rate available	143 kW
Estimated exhaust flow rate kg/s	0.485 kg/s

Table 2: Capstone turbine specifications and computed outputs [6]

Table 3 lists the inputs and assumptions used for the steam plant analysis. The analysis assumed that the exhaust gas was air standard, so the combustion product composition and its effects were neglected. Given the high air-fuel ratios typical of micro-turbines, this was considered a good approximation. The electrical efficiency of all electrical generators in the system was assumed at 93%.

Electrical Generator efficiency	93%
Exhaust gas composition	100% standard air
Boiler external heat loss (% of input heat)	5%
Max. superheat steam temperature	289 ºC
Steam turbine efficiency	50% & 80%
Condenser coolant inlet condition	Water @ 20 ºC
Condenser effectiveness	0.80
Condensate pump efficiency overall	50%
Piping pressure losses	Neglected

Table 3: Steam plant analysis assumptions

Losses typical of the MMA steam plant were used for the analysis including a 5% boiler heat loss and condenser effectiveness of 0.8. Two different steam turbine efficiencies were analyzed. The isentropic turbine efficiency of 50% represented the performance of the current velocity compounded turbine. Replacement of the existing turbine with a multi stage axial flow turbine could achieve an estimated isentropic turbine efficiency of 80%. A typical steam cycle analysis was performed for a simple cycle steam plant and the results are listed in Table 4. The boiler pressure was chosen at 800 kPa, which is a typical operating pressure for the MMA boiler. Also the system can be run to a vacuum pressure in the condenser of about 20 kPa. Given these conditions, with the existing Curtis turbine, and a computed steam flow of 0.0279 kg/s it was found that the current boiler turbine would operate at a steam plant efficiency of 11.4 % with 8.21 kW of electrical output. If the turbine were replaced with a multistage unit, the steam plant efficiency would 18.55% with 13.32 kW of electrical output.

Boiler		
Steam mass flow (kg/s)	0.0279	0.0279
Boiler pressure (kPa)	800	800
Condensate inlet temp	63	63
Saturation temp ºC	165	165
Superheated steam exit temp ºC	289	289
Boiler enthalpy rise kJ/kg	2767	2767
Total Boiler heat rate kW	77.2	77.2
Boiler exit stack air temp ºC	149	149
Boiler pump enthalpy rise kJ/kg	<15	<15
Turbine	One stage (Curtis)	Multistage Axial
Turbine Efficiency	$\eta_{isen} = 0.5$	$\eta_{isen} = 0.8$
Turbine steam exit press. (kPa)	20	20
Turbine steam exit temp. ºC	110	60.1
Turbine steam exit quality	superheated	0.955
Turbine enthalpy drop kJ/kg	331	528.4
Overall Performance		
Net shaft power (kW)	8.82	14.32
Steam plant efficiency (%)	11.4	18.55
Steam plant elec. power kW	8.21	13.32

Table 4: Simple cycle steam plant analysis results

Table 5 shows the resulting performance estimates when the gas turbine and steam plants are operated as a combined cycle plant. Using the current Curtis turbine, the overall combined cycle electrical output was estimated as 73.2 kW and the overall combined cycle plant efficiency was 32.7 %, resulting in a 12.75 % increase in both plant output and plant efficiency. With a high efficiency multi-stage turbine, the overall combined cycle electrical output was estimated as 78.4 kW and the overall combined cycle plant efficiency was 35 %, resulting in a 20.7 % increase in both plant output and plant efficiency as compared to the stand alone micro-turbine.

	Single Stage Turbine	Multi Stage Axial turbine
Combined cycle electrical power output (kW)	73.2	78.4
Overall Combined cycle plant efficiency (%)	32.7	35
Power output increase (kW)	8.2	13.32
Power output and efficiency increase (%)	12.75	20.7

Table 5: Overall estimated combined cycle plant performance

SUMMARY AND CONCLUSIONS

Maine Maritime Academy, established in 1941, is known for the quality of its undergraduate engineering programs and provides a unique hands-on approach to learning. There are potential advantages to learning in a small college community where everyone knows your name. With the acquisition of an actual micro turbine engine as a trainer, the college's engineering programs have obtained a powerful tool for the conversion of gas turbine theory into actual operating experience and understanding. The successful integration of the SR30 turbojet into MMA's engineering programs has led to efforts outlined in this paper to combine a commercially available micro-turbine with an existing laboratory steam plant to produce a combined cycle training plant. This power plant will address the anticipated need of training marine and stationary power engineers in the theory and operation of this important type of power plant. Calculations show that the combined cycle plant can increase the electrical efficiency of an existing gas turbine generator by 13-21%. The Academy is currently in the initial design phase of a new education building that will accommodate engineering laboratories. The incorporation of a CHP micro turbine power plant into the design of this new facility is being considered along with other green energy systems.

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Mostly we are grateful and proud of the engineering students who have contributed time, energy, and enthusiasm into researching the feasibility of a micro gas turbine and steam turbine combined cycle plant. Our students make it enjoyable to strive for continued improvement in our engineering programs at Maine Maritime Academy.

We also thank Quirk Auto Park for access to their Capstone C60 micro-turbine as well as Capstone Turbines Inc. and Turbine Technologies LTD. for their technical assistance regarding their products.

REFERENCES

1. Registrar's Report, October 2006, Maine Maritime Academy, Castine, Maine.
2. STCW Standards, International Convention of Standards of Training, Certification and Watch Keeping for Seafarers, 1978, as amended in 1995 and 1997. International Maritime Organization, London, 1996
3. Engineering Accreditation Commission, 2005-2006, "Accreditation Policy and Procedures Manual;" pp. 1-6 Accreditation Board for Engineering and Technology, Inc. 111 Market Place, Suite 1050, Baltimore, Maryland 21202; www.abet.org

4. Maine Maritime Academy 2005-2007 Undergraduate Catalog. By MMA, Castine, Maine 04420
5. Turbine Technologies Ltd. 410 Phillip's Street, Chetek, Wisconsin 54728 Product Spec. Sheets
6. Capstone Turbines Inc. capstoneturbine.com, product data sheets for C65 & C65-ICHP micro-turbines (866)422-7786