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Developing Relevant and Practical Projects for a Senior Capstone Thermal Fluids Design Course

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ABSTRACT

This paper starts with the description of the subject course from the Academic Register.

"A capstone, project-oriented course in the thermal-fluids area of mechanical engineering that applies engineering techniques to the design of thermal/fluid processes and systems. Students work in teams on projects that involve design of piping systems, heat exchangers, thermodynamic cycles, and other thermal fluid system."

It is a required course, taken mostly by graduating seniors, but sometimes by juniors. The prerequisites are two courses in Thermodynamics and a course in Heat Transfer Analysis and Design. Students have also completed a course in Fluid Mechanics.

The subject school is on a trimester system with relatively intense 10 weeks per terms, rather than the more typical semester system of 15 weeks per term, that is less intense, and can provide more opportunity for reflection. Whereas semester courses are typically defined in terms of credit hours, the courses at this trimester college are defined by three courses per trimester for a minimum of 36 full courses for graduation. The subject counts as one course.

However, the five project format that will be described, with students working in teams, can be a reasonable fit for either academic calendar. The instructor reviews the success of each project after each term. Some are repeated with some modifications, while new projects may be inspired by current events, such as controversies over construction of new oil and gas pipelines. This paper describes the projects that were performed in the fall of 2015.

I. Introduction to the Course Philosophy, Approach and Organization

Although some of the following projects may appear too simplistic for a senior capstone course, the detailed descriptions will identify fundamental concepts and approaches that are emphasized and reinforced, along with some important and interesting nuances. An interesting practical example is that the students do the calculations to learn that the pump or compressor energy required per fuel energy transferred is substantially more for natural gas than it is for oil that has the much higher density.

The course also evolves from the author's experience over many years of preparing hundreds of students and working engineers for the Fundamentals and Practice parts of the Professional Engineering Licensing Exam. Most have successfully completed courses and degrees. However, if they are given a liquid mass flow rate, density and pressure increase of a pump, they don't remember how to calculate the ideal power requirement.

The instructor must then choose between directing the student to a formula in a handbook, or alternatively to figure it out by thinking, with the assistance of physical dimensions. This course is developed in a manner in which students are encouraged to solve problems by thinking. What a student only knows can be forgotten, whereas what is understood conceptually will not diminish with time.

Some understanding of some problems takes additional thinking and reflection. An example is the transport of a liquid versus gas on a long pipeline, where intermediate pumps or compressors are used. The purpose of the pumps for a liquid is simply to produce a pressure increase equal to the pressure drop between stations, whereas in a gas pipeline the purpose of the compressor is to increase the absolute pressure and thus increase the density, which decreases power requirements.

Thus, there is a motivation to design gas pipelines for the highest pressure that the technology allows, whereas there is no incentive for high pressure in an oil pipelines. The maximum pressure in the oil pipeline only has to be as high as the frictional pressure drop between pumping stations. An infinite number of pumping stations, which means no distance between pumping stations, would result in the need for no additional pressure above atmospheric in the pipes.

II. Projects and Organization

The five projects were 1) the design of a long crude oil pipe line with multiple pumping stations, 2) re-designing this pipeline to transfer natural gas with multiple compressor stations, 3) design of a liquefied natural gas (LNG) plant and specification of the ocean going fleet of LNG carriers required for transfer from plant to customer, 4) design of ice rinks for hockey and a municipal park with the evaluation of a photovoltaics for electric power, and 5) the design, construction and competition of solar powered boats, supplemented with a guest lecturer by the builder of a solar powered cargo barge.

Students work in teams with a leader, analysts and economist. Assignments are rotated for each project, in a manner in which each student has the opportunity to serve in each position, and also to work with other students. The final grade is a combination of how the students evaluate the performance of other students via a questionnaire after each project, and the instructor's grading of presentations, participation and written reports.

Along with selecting the projects, the other challenge becomes how best to introduce, perform and report each project within the allotted two weeks. It helps that each project has significant similarities, and thus the next project can build upon and extend ideas and methodologies from prior projects.

Project Number 1 Oil Pipe Line

This was inspired by the 24 inch diameter pipeline, called The Big Inch, that was constructed during the emergency conditions of World War II, to deliver crude oil overland for a distance of 1250 miles from the wells in Texas to the refineries in New Jersey (reference 1). The emergency was that German submarines had destroyed 60 coastal oil tankers, that carried about 60,000 barrels of oil each, during the first months of the war in 1942.

The Big Inch expanded upon previously existing pipeline technology. It was significantly longer and higher capacity. It was designed with a peak operating pressure of 650 psi. The nominally straight route was surveyed by air. It passed through wilderness, under rivers and streams and over mountain ranges. It would have 26 intermediate pumping stations, each of which required 9000 kw of electric power. It would reach a capacity of 325,000 barrels of crude oil per day.

The introductory assignment for this project is for each student to start thinking about pipe lines by researching and making a Power Point slide describing an existing pipeline, and another Power Point slide summarizing a pipeline accident. In addition, students are required to watch a vintage video that is available on U-Tube. It shows the surveying, the trenching equipment, the dynamite blasting under a river and the startup ceremony.

Students are then tasked with trying to confirm the reference design conditions of The Big Inch by means of a spread sheet based calculations. The analysis requires several assumptions, such as the temperature, and the temperature dependent viscosity, along with a myriad of conversion factors.

Using the barrels per day as the input or independent variable, the flow velocity is calculated. The pressure drop between pumping stations is calculated from a friction head that is calculated with the Darcy equation, which requires a Moody friction factor, which is a function of the Reynolds number and assumed roughness of the pipe.

It is noted that the established technique students and engineers now use to estimate the friction factors, that define both the attainable flow rates and the corresponding pumping power requirements, were developed during World War II by Princeton engineering professor Lewis Ferry Moody (Reference 2) in the form of equations and charts.

The friction head and density provides the pressure drop, and multiplying by the volumetric flow rate yields the ideal power requirement for each pumping station. Finally, the actual electric power is calculated by dividing the ideal power by the product of assumed pump and electric motor efficiencies.

This calculation also requires working back and forth between English and SI units. Since it is highly improbable that any team will get the correct answer the first time through, we proceed in small steps, and check by assuring that each team gets the same answer before proceeding further. This means that each team will be in exact agreement on the assumptions, equations and resulting reference case mass flow rate and power requirements.

Once there is reference case agreement, we are then prepared for evaluating other operating conditions such as flow rates, and then graphing, interpreting and explaining the results. Neglecting the second order differences, the pressure drop between pumping stations is shown to be proportional to the square of the flow rate, and the power requirement is proportional to the cube of the flow rate.

Students can then calculate the total energy required for pumping, and the total electric cost per barrel, to deliver oil through the 1250 mile long pipeline as a function of flow rate.

At the end of two weeks, each team prepares a Power Point presentation, and writes a report. The suggested method for the report is to start by laying out the appropriately ordered tables and figures as attachments. The writing then becomes mostly a matter of sequentially explaining these tables, figures and attachments.

Project Number 2 Natural Gas Pipeline

The next project is motivated by the conversion of this crude oil pipeline to natural gas after WWII. This should be appreciated as one of the most important advances in the history of energy system technology (reference 3). It is noted that regional natural gas pipelines had been developed earlier in Pennsylvania in the 1870s, but the shallow sources of the gas had been mostly depleted. Thus, prior to WWII most gaseous fuels for heating were produced by highly polluting and inefficient coal gasification plants, called gas houses, while the natural gas from the oil wells in the south was being wastefully flared at the well heads.

Coal companies, miners and railroads benefitted from the status quo, and resisted the introduction of major gas pipelines via legislation, including blocking lobbying the use of eminent domain that would allow construction of pipelines through private land. After much resistance, the Federal Power Commission in 1947 allowed for the conversion of the Big Inch pipeline to the delivery of natural gas. This also involved the selling by auction of the government owned pipeline to a private company (reference 4).

With the advent of pipelines, heating systems for homes and commercial buildings were rapidly converted to natural gas or low viscosity heating oil. It replaced coal, that had been dumped from a truck, stored in a cellar, and shoveled into the furnace, and followed by carrying out of the ash. The time consuming and labor intensive chore of keeping warm became unnecessary. Gas, propane and oil furnaces that required virtually no attention, and with temperature automatically controlled by thermostat, rapidly became the new normal.

Eminent domain was extended to new pipelines. Within a decade virtually all coal gasification plants were shut down. New York City first received pipeline natural gas in 1952. Seattle became the last major US city to get natural gas in 1956. A historic preservationist succeeded in saving the Seattle coal gasification plant from demolition. It remains as a towering artifact on a scenic Puget Sound peninsula that is called Gas Works Park.

The first assignment for this gas pipeline analysis project is for each student to research and make a Power Point poster of coal gasification plants and coal heating systems, and another poster with a map of existing gas pipelines and gas and oil heating systems.

The next assignment involves the challenge of identifying the requirements to convert a pipeline from oil to natural gas, including replacing pumps with compressors, and then analyzing the power requirements as a function of maximum allowable pipe pressure and mass flow rate.

They learn an importance difference between the capability and the analysis of oil versus gas pipelines results from the relatively high and constant density of oil as compared to the much lower density of gas, and also where the density is also proportional to the pressure. Since the power requirement varies inversely with the density, the motivation is to operate a gas pipeline at the maximum allowable pipe pressure.

However, the analysis for gas pipelines gets much more complicated. The maximum pressure and density is at the discharge of each compressor, which was 650 psi for the Big Inch. As the gas flows from the compressor, the frictional pressure drop decreases the density, which increases the velocity, which results in the pressure drop per distance as a function of flow increasing by the velocity squared. Thus, the pressure will rapidly deteriorate, and further limit the mass flow rate capability, and increase the required power.

The analysis requires students to develop a finite element type of analysis. The actual distance between compressors is divided by the number of elements that are chosen. We start with the somewhat arbitrary assumption that for the reference case the pressure will drop from 650 psi to 450 psi between 50 mile spaced compressor stations. The subsequent analysis requires a finite element method, of modeling 10 sections of 5 miles each between the compressors. Then a trial and error or iterative method is required to determine the mass flow rate that can be achieved for these constraints and conditions.

This analysis is performed on a spread sheet, while the instructor assures that each team calculates the same mass flow rates for these conditions. Students are then advised to change parameters one at a time, such as the maximum allowable pipe pressure as the independent variable, and then calculate the corresponding mass flow rate, power and energy requirement.

It is challenging, but necessary to quantify the principle of why higher pressure results in more mass flow rate, and a corresponding lower compressor power and lower energy per unit mass energy requirements. A useful, but imprecise, analogy can be made to our electric power systems, where higher voltage allows for lower current, and thus more efficient electric energy transmission.

As a historic note, we explain that the engineer and industrialist George Westinghouse pioneered the design and construction of compressor powered regional gas pipelines in the 1870s (reference 5). A decade later he pioneered long distance electric transmission by means of using high voltage for efficient transmission, and then reduced to lower voltage for safe use. It can be speculated that he applied the principle that he had learned from gas pipelines to pioneer our modern day multiple voltage electric power system.

While the class gas pipeline analysis had been based upon converting the WWII Big Inch to natural gas, there is now again a major expansion of pipeline capacity as a result of increased supplies from hydro-fracking, and the related conversion of electric generation from coal to more efficient and cleaner natural gas fueled electric power plants.

There have also been major objections and protests against expanding pipelines based upon safety, land use and calls for elimination of all carbon fuels. The lead agency for the hearings and licensing is the Federal Energy Regulating Agency. Each student is asked to identify and make a Power Point poster of a proposed pipeline expansion that is currently under review.

A final Power Point presentation is performed by each team, while all other students rate the presentations in terms of content and delivery. Each team is once again required to prepare a final report.

Project Number 3 Analyze Liquefied Natural Gas Plant and Ocean Going Carriers

Oil tankers were developed soon after the first oil wells in the 1860s, and have been increasingly used on rivers, coasts and oceans. However, the transport of natural gas in tanks at atmospheric pressure was not practical, since 120 cubic feet at atmospheric pressure is required for the energy equivalent of a gallon of liquid fuel. Pressuring the gas to 1800 psi can reduce the volume to 1 cubic foot for the equivalent of a gallon of gasoline. This can be practical for an automobile, but the high pressure is impractical for large tanks on ocean going ships.

The alternative for transporting natural gas across oceans is to liquefy it, and the result is known as Liquefied Natural Gas, or LNG. It requires lowering the temperature to -259 F at atmospheric pressure. This was first demonstrated around 1960 (Reference 6). There is now a dramatic growth in LNG as a result of increased gas demand in island counties like Japan, with no significant domestic source, from producing countries like Australia, that have a surplus. The United States has been importing moderate amounts of LNG, but with the recent and unexpected increases from hydro-fracking, the United States is preparing to be a major LNG exporter.

Liquefying can be performed with a three stage compression refrigeration system, with ammonia cycle at the highest or ambient temperatures, and with its evaporator receiving the rejected heat from the condenser of an intermediate temperature ethylene cycle, and the evaporator of the ethylene cycle, receiving heat from the condenser of a natural gas or methane cycle. The discharge of the methane throttle is at atmospheric pressure and -259 F, and is about half saturated vapor and half liquid. This mixture goes to a separator with the LNG drained to storage tank, and the -259 F vapor leaving at the top, and then mixing with the makeup or feed supply at atmospheric pressure and ambient temperature, and then on the methane compressor.

The reference case assumes a 20 F temperature difference between the condensing and evaporating temperature of each heat exchanger, and a 70 % isentropic efficiency of each compressor. The corresponding property table is created for each cycle, using the Computer Aided Thermodynamics Tables, CATT. Assuming the design production rate of LNG, the corresponding flow rate of ethaline and ammonia is found via an energy balance on each heat exchanger. The corresponding power is found for each compressor, and the total compressor power. Dividing the production rate by the total power will produce the work required per unit of LNG produced. The units of production per unit energy are calculated in (lb LNG /hp hr), (lb LNG /kw hr), and (Kg LNG /K Joule).

These calculations are performed and the tables created on a spread sheet. The property tables of pressure vs enthalpy, pressure vs specific volume and absolute temperature vs entropy diagrams are hand sketched, which is found to provide a better understanding than computer based drawing.

Diagrams showing temperature (F) vs rate of heat transfer (Btu/hr) for the de-superheating and condensing hot stream, that releases its heat, and for the evaporating cold stream that receives the heat, are also hand sketched. The instructor oversees each team to assure each gets the same and correct results for the property tables, the 1st law process and cycle tables, and for the heat exchanger diagrams.

Once there is perfect agreement between each team on the reference case, variations on the reference are prescribed. This includes changing the temperature differences on the heat exchangers, changing the assumed isotropic efficiencies of the compressors and replacing the irreversible throttle valves with power producing expanders.

Once again the practice is to start with a reference that is examined and understood. Then change only one thing at a time. It is also noted that all systems in general, and the LNG plant in particular are systems comprised interconnected system components. Thus, a change in one parameter or condition will result in a change of all others.

Another point of emphasis is to take a good look and reflect on the results. Get a better grasp of the relative importance of each variation such as heat exchanger temperature differences, compressor efficiency and expanders, and what is required to implement each on the actual plant.

For example, decreasing the temperature difference on the heat exchangers increases the efficiency and lowers energy requirements, but at the cost of more heat transfer surface. Thus, there is an economic optimal amount of heat exchanger area, and further increases in heat exchanger area will result in diminishing returns in term of compressor energy savings.

The reference for this analysis is a floating LNG plant called the Prelude (Reference 7). It has been designed to liquefy natural gas in Australia, and supply a fleet of LNG tankers to ship a distance of 4400 miles or 7100 km to Japan. Students are asked to research the rate of LNG production, along with the capacity, speed, propulsion type, power and fuel consumption, loading and unloading time, and the investment capital and operating costs of a reference LNG carrier.

From these assumptions, students estimate the time for a round trip voyage, the number of tankers required, and the cost of transportation per metric tonne of LNG. They also research the capital cost and the operating cost of the LNG plant, and the cost of the natural gas at the well head in Australia. The resulting calculation is the total cost of the delivered LNG in Japan in terms of dollars per metric tonne, and dollars per energy unit. Finally, they convert these delivered LNG costs to barrels of oil equivalent (BOE) and compare with the current market cost of refined oil in Japan.

Project Number 4 Design Ice Rinks for Hockey and Park Playground

The preliminary for this project is for each student to research and make a poster of the history and technology of artificial or engineered ice skating rinks, as compared to natural frozen rivers and ponds, and another poster describing the size and requirements for a standard ice or hockey rink, including the enclosing structure and facilities (reference 8).

We then take an inspection tour of the campus rink, that is typical of contemporary systems (reference 9 and reference 10). We start by looking at the ice from above, and then going below to see the chilled brine circulating loop, the chiller skid on which is installed the evaporator that cools the brine, the compressor and throttle, and condenser that is cooled by circulating water, that is cooled by an outside forced air heat exchanger, similar to a large car

radiator. The circulating pumps for the brine and for the cooling water are also identified. We also talk to the rink engineer about the operational and maintenance requirements.

The class then travels to the facilities building from which the operation of the rink is monitored via a menu of block diagrams on a computer monitor. The campus facilities engineer provides printouts which show the real time temperatures, pressures and flow rates throughout the system.

Back in the class room we construct an energy flow diagram using units of Btu/hr. The energy flow starts with heat flow from the inside air to the ice, then the flow of this heat from the ice to the concrete floor, followed by heat flow from the concrete floor to the circulated brine that get heated by a few degrees, and finally this heat from the brine is rejected to the refrigerant in the chiller evaporator. The compressor work then adds energy and increases the temperature of the refrigerant to the condenser. The condenser then rejects the sum of the evaporator heat and the compressor work to the cooling water. The heat from the cooling water is transferred to the outside air via the outside water to air heat exchanger.

This entire energy flow throughout the system starts with and is proportional to the free convection heat transfer coefficient defined by h (Btu/hr ft^2 F) for the horizontal surface between the warmer air above the rink to the ice. Empirical correlations exist to determine to determine this value. However, the better method, which is presented, is to calculate this coefficient h from the measured operating conditions. The product of the measured ice surface area and the difference between the air and ice temperature times this unknown convection heat transfer coefficient, is equal to the product of the measured mass flow rate, heat capacity and temperature increase of the brine as it circulates from inlet to the outlet headers of the circulating brine. The calculated value of h is about 1 (Btu/hr ft^2 F).

While the college has an ice rink, there is no rink available to the community, Thus, half of the teams are assigned to design a standard size hockey rink facility for the city central park, and another team designs a smaller rink for a neighborhood park. The electric power requirement is calculated, which can be provided by the existing public utility, or by solar panels, or some combination. Each team selects an area and efficiency of solar panels to be installed, and estimates the portion of the rink energy that can be supplied by this renewable source of energy.

Power Point presentations and reports are prepared. Two teams were selected to make a presentation and proposals at a City Council Meeting, with an audience of the mayor, recreational committee members, reporters and television (reference 11). This was followed by a front page newspaper article, with pictures of the students at the college ice rink. Students also volunteered to help with the city park program, and several citizens and companies communicated enthusiasm and support.

Project Number 5 Design and Competition with Solar Powered Boats

This final project is the only one that requires additional materials, equipment and cost beyond what is available the modern class room with video and computers. The additional requirements for this project are access to a shop and a 3D printer to fabricate the hulls, small motors and photoelectric panels, and a test basin with overhead sun lamps.

This final project is to design, manufacture and compete with prototypes of toy electric motor boats powered by photovoltaic cells. Maximum boat dimensions are 8 inch length, 3.4 inch beam and 4.5 inch height. Each cell is a 4 inch by 3 inch rectangle. The competition is for the fastest speed, followed by a tugging or pushing competition between two boats.

For introduction each student researches and makes a poster of the history of hull designs and the analytical, semi- empirical and towing tank experimental methods of predicting drag vs speed for hull shapes, and then performing the required scaling between the model size and the actual hull.

Students also research the performance of photovoltaic devices. They are taught about selecting a motor to produce the maximum power. It is a complicated challenge. Power is the product of current and voltage. A lower equivalent resistance of the motor will result in higher current and lower voltage. Alternatively, a higher resistance will result in higher voltage from the solar cell, but less current. While the system can operate over a wide range of equivalent motor resistances, the optimal match is best determined experimentally (Reference 12).

Each team is required to suggest three candidate hull shapes, such as double hull, rectangular and curved single hull, and rate each on a scale of 1 to 5 with a decision matrix for properties such as drag, stability and manufacturability. They pick a best choice hull from the decision matrix, make a solid works drawing and then construct it on a 3D printer.

Propulsion options are a paddle wheel or propeller, with size and shape that should be the best match for the hull and the photovoltaic powered electric motor output. The propeller or paddle wheel is also produced on a 3D printer or fabricated separately.

After fabrication and connecting of the parts and wiring, a substantial amount of testing and adjustments is required. Each team selects a name for their boat. The final competition is performed with an audience of invited faculty and students, which is followed by a Power Point presentation by each team.

Guest Lecture about the Design and Performance of a Solar Powered Cargo Barge

In lieu of a final exam for the mostly graduating seniors, we invited a presentation by an engineering professor, who has for many years been designing and installing energy efficient

buildings and renewable energy systems. A recent project by this Professor David Borton has been the construction of a solar powered cargo barge. It was built under his supervision by high school and college students, to transport cargo on the Erie Canal (Reference 13). This solar powered barge was named SOLAR SAL, in recognition of the barge hauling mule named Sal that is celebrated in a famous canal song.

The presentation to the class including details of construction, the maximum and average solar power, the storage batteries, and a description of educational and publicity stops along the 330 mile route. Dr Borton also suggested a variety of conservation and renewable energy career opportunities and challenges for the graduating student.

IV Evaluating and Summary Comments

Interim and final exams have been given in previous years for this course. However, exams cannot be crafted to realistically cover the wide range of information and analysis required for the myriad of projects in this course. The performance of the projects by teams further complicates the individual grading. Exams could detract from the flow of the learning.

The alternative method that was developed was a combination of students grading each other via a questionnaire, and the instructor grading each student on the quality of their posters, and their written portion of each team report.

Assignments are rotated so every student is a team leader, an analyst and an economist. The team membership also rotates, so each student gets to work with most of the others. At the end of each project, students evaluate each team member in terms of their contributions in ability to work together, contributions, and their overall performance from starting with the Most Valuable Player at the top of the scale. While students can be somewhat uncomfortable rating others, it is explained that is a preparation for their future careers where honest and conscientious judgements of the performance of others is often required.

A grade for each student is based upon the ratings of their classmates, and the instructor's evaluations based on posters, presentations and reports. The results of the two methods are usually remarkably close. The instructor makes a final grade judgement based on the average of the two techniques.

The author believes, and comments confirm, that these carefully considered projects lead to an excellent and memorable capstone course experience. These projects provide a bridge between the theory and equations from the prerequisite courses, and show the application to a variety of interesting engineering projects.

The course also shows the value of basic spread sheets, tables and graphs to structure, calculate and display the performance of systems with many interconnections. The development of a well-defined reference case or design is emphasized as the first mission. Once this is established, the changing of one input assumption at a time, can allow for the

creation of more meaningful tables and graphs, and to better understand the sensitivity of the results to input assumptions.

An initial challenge and frustration was the need to find many conversion factors and to correctly perform many conversions. Many required conversions are between the metric system in which students are most familiar, and the commonly used units within the English system such as BTU, feet, degree F, barrels, and gallons. The students became better and more comfortable with these required conversions as the course progressed, which should be recognized as an important outcome, since it is a vital requirement for every practicing engineer.

The author invites readers to contact him with their comments, and for further information or discussion.

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