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An Analysis of Capital Cost Estimation Techniques for Chemical Processing

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by

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We, the undersigned committee, hereby approve the attached thesis, “An Analysis of Capital Cost Estimation Techniques for Chemical Processing” by Omar Joel Symister.

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Abstract

Title: An Analysis of Capital Cost Estimation Techniques for Chemical Processing

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This research serves to compare the use of the capital cost estimation software, Aspen Capital Cost Estimator (ACCE), with other capital cost estimating methods specifically the module costing technique outlined by Richard Turton *et al.* and also a factorial costing technique outlined by Gavin Towler and Ray Sinnott. This study will compare popular process equipment found in the chemical process industries. The relationship between the capacities of the equipment, as it relates to the cost as well as operational pressures and materials of construction (MOC), will also be obtained and compared. The results of this study may be used by professionals in their decision of which method of capital cost estimation they may want to employ.

The results and comparison varied a great deal based on the equipment being costed, but for most of the equipment tested, the costs went up in a linear fashion. For all of the methods studied, when the cost of the installed equipment is plotted versus the capacity on a log-log scale a linear relationship is achieved. The slopes of these lines (or capacity exponents) are presented in the work showing how the economy of scale varies for the different cases studied. In general slopes of less than unity are obtained with consistently different slope values for the three methods. The ACCE usually had the lowest cost of the three methods. Another

thing to note is that the factorial method had the least equipment data available, while ACCE was the most diverse.

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Chapter 1
Introduction

According to Perry's Chemical Engineering Handbook [1], the total capital investment includes funds required to purchase land, design and purchase equipment, structures, and buildings, as well as to bring them into operation. This may be a daunting task for the cost engineer depending on the scope and size of the process being built. This study aims to compare different methods of calculating the equipment capital cost for major process equipment found inside many process plants. Furthermore, a comparison to Aspen Capital Cost Estimation (ACCE) software package will be done as well.

A major factor in deciding whether or not to build or expand any chemical/process plant is the capital cost estimation. The capital cost is the investment that is put in to build or expand the plant. During the design process, it is nearly impossible to know the exact quantity of this investment. This is why it is important for the engineers and project managers to get as close to the actual value as possible.

Usually, methods proposed by authors have bases from correlations of actual vendor data. Couper *et al*. mentions that there will be a certain amount of scatter in price data. This may be due to variations among manufacturers, quality of construction among other factors. The authors continue to say that the accuracy of the correlations cannot be better than ± 25% [2]. The methods below shall be used in study estimates.

Several sources classify capital cost estimates into the same five classifications. These classifications are as follows: detailed estimates, definitive estimates, preliminary estimates, study estimates, and order-of-magnitude estimates. Each classification requires a different level of information and preparation to do. Table 1 shows an example of this classification in a matrix. Turton *et al*. also gave a brief description of each classification in Table 7.1 of Turton [3].

Table 1: Cost estimate classification matrix for process industries [4]

	Primary Characteristic	***Secondary Characteristic***		
Estimate Class	**Percent of project Completion**	**Purpose of estimate**	**Methodology**	**Expected Accuracy range**
Class 5	0% to 2%	Concept Screening	Capacity factored, parametric models, judgement, or analogy	L: -20% to 50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to 30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to 20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to 15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to10% H: +3% to +15%

According to AACE International, process technology, cost data, and many other risks affect the accuracy range. The range typically represents a 50% confidence interval[4].

Order-of-magnitude estimates usually rely on cost information for a complete process. This information is usually taken from previously built plants. This cost information is scaled using scaling factors for capacity and inflation. This estimate is also called the ratio or feasibility estimate and usually requires a block flow diagram.

Moving along in increasing order of complexity and detail is the study estimate. The study estimate uses a list of the major equipment included in the process, such as pumps, compressors and turbines, columns and vessels, heat exchangers, etc. After sizing is done, the cost is determined for each piece of equipment. Also called the major equipment or factored estimate, the study estimate usually needs cost charts and process flow diagrams [3]. Only these two estimates will be looked at for the most part in this thesis.

Chapter 2
Objective of Study

The objective of this research is to compare the use of the capital cost estimation software, Aspen Plus Capital Cost Estimator (ACCE), with methods proposed by Turton *et al.* [3] and also Towler and Sinott [5]. Using these methods, this study compares the capital costs of ten types of equipment, including various types of mixers, pumps, heat exchangers, compressors, and pressure vessels. The equipment type chosen was limited to those common to each of the three methods. The relationship between the capacities of the equipment as it relates to the cost as well as operational pressures and materials of construction (MOC) was obtained and compared where possible.

Equipment Scope – equipment supported by all three methods was:

- Mixers: Propeller
- Compressors: Centrifugal; Reciprocating
- Exchangers: U-tube shell and tube; Floating head shell and tube; U-tube kettle reboiler
- Pressure Vessels: Vertical; Horizontal
- Pumps and Drivers: Single stage centrifugal; Explosion proof motor

Chapter 3
Review of Literature

Although the most accurate way to estimate the purchase cost of a piece of equipment is to get a current price quote from the appropriate vendor, this may sometimes prove difficult to obtain based on the vendor's policies. The next best alternative would be to use cost data from previously purchased equipment of the same type. Based on previous cost data, the current cost of equipment could change based on differences in the equipment capacity and also differences in time.[3]

Turton *et al.*, and other authors in various texts, give this relationship between purchased cost and an attribute related to units of capacity:

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^n \qquad (eq. 3.1)$$

where A is the equipment cost attribute; C is the purchased cost and n is the cost exponent. Subscripts ‘a’ and ‘b’ refer to equipment with the required attribute and equipment with the base attribute respectively. The value of the cost exponent varies based on the equipment. The value for n, however, is often around 0.6. Using this common value for n is referred to as the six-tenths rule [1,3,5,6]. Ereev and Patel mentions that this relationship illustrates an economy of scale[6]; therefore, equipment at twice the capacity of another is less than twice the cost.

If cost data is collected from previous years, the cost forecast for current year and years to come will be different due to factors such as inflation. To account for this change, cost indexes are used. Turton also gives the following relationship:

$$C_2 = C_2\left(\frac{I_2}{I_1}\right) \qquad (eq. 3.2)$$

where C is the purchased cost, I is the cost index. 1 and 2 refer to the base time when cost is known and the time when cost is desired, respectively.

There are several indices used in the chemical industry to adjust for inflation. These include:

The Nelson-Farrar Refinery Index [7,8]

The Marshall and Swift (M&S) Index [8]

The Engineering News – Record Construction Index [8,9]

The Chemical Engineering Plant Cost Index (CEPCI) [8,10]

Turton uses CEPCI to account for inflation in the literature.

Turton *et al.* also covers the total capital cost of a plant. The authors go through methods of calculating the total module cost (total capital cost), such as the Lang factor technique [3,5,11] and the module costing technique.

For the Lang factor technique, the total capital cost is determined by the product of the total purchased cost and a constant known as the Lang factor. The equation is as follows:

$$C_{TM} = F_{Lang} \sum_{i=1}^{n} C_{p,i} \qquad (eq. 3.3)$$

where C_{TM} is the capital cost of the plant; $C_{p,i}$ is the purchased cost of the major equipment units; n is the total number of units and F_{Lang} is the appropriate Lang factor.

The Lang factor is given in Turton for three types of chemical plants – plants that process only fluids (F_{Lang} = 4.74); plants that process only solids (F_{Lang} = 3.10); and plants that process both solids and liquids (F_{Lang} = 3.63).

This technique, unfortunately, does not account for special changes in the process such as materials of construction and high operating pressures.

Module Costing Method proposed by Turton *et al*.

The module costing technique, however, does factor in these changes based on specific equipment type, system pressure and materials of construction.

Equation 3.4 is used to calculate the bare module cost which is the sum of the direct and indirect costs. Direct costs entail the equipment free on board (f.o.b.) cost and the materials required for installation (piping, insulation and fireproofing, foundations and structural supports, instrumentation and electrical, and painting) and also the labor to install equipment and material. Indirect costs entail freight, insurance, taxes, construction overhead, and contractor engineering expenses.

$$C_{BM} = C_p^0 F_{BM} \qquad (eq. 3.4)$$

where C_{BM} is the bare module equipment cost; F_{BM} is the bare module cost factor (looked up in tables in the appendix of Turton's text) that is based on material of construction and operating pressure; C^0_p is the purchased cost for base conditions (common materials and near-ambient pressures). In order to incorporate the equipment material and pressure, a modification to the equation above can be used. Equation 3.5 adds additional constants such as a material factor (F_M) and a pressure factor (F_P) (see equations A.3 and A.5). From correlations, the constants B_1 and B_2 are material specific and may be found in tables in Turton.

$$C_{BM} = C_p^0 F_{BM} = C_p^0 (B_1 + B_2 F_M F_P) \qquad (eq. 3.5)$$

Furthermore, the data for the purchased cost of equipment, at ambient temperature and using carbon steel, were fitted to the following equation:

$$\log(C_p^0) = K_1 + K_2 \log(A) + K_3 [\log(A)]^2 \qquad (eq. 3.6)$$

where K_1, K_2 and K_3 are equipment specific constants also found in the appendix of Turton.

Turton's method does not offer much flexibility for calculating just a direct cost or indirect cost as with the factorial method. Material, labor and installation costs as a function of other factors are given, but actual values for these factors are not given.

Another thing to note about the data in Turton is that they are based on a survey of equipment manufacturers during May to September of 2001. The average CEPCI value during this period was 397. According to Turton *et al*., this method was first proposed by Guthrie and modified by Ulrich [3].

Factorial Method proposed by Towler and Sinnott

In Towler and Sinnott, the Fixed Capital Investment (FCI) is given as an inside battery limits (ISBL) – which is the cost of the plant itself including:

- Equipment purchase cost

- Equipment erection, including foundations and minor structural work
- Piping, including insulation and painting
- Electrical, power and lighting
- Instruments and automatic process control (APC) systems
- Site preparations

Also, the FCI consists of the outside battery limits (OSBL), the construction and engineering costs, offsites and contingency charges (not studied in this thesis). Towler and Sinnott agree with Turton *et al*. when it comes down to the classification of cost estimates as both literature sources used the classifications put forward by the Association for the Advancement of Cost Estimating[4] (AACE Intenational, see Table 1). They also agree on how one goes about doing the order-of-magnitude calculations for changes in capacity [equation (3.1)].

Towler and Sinnott, however, puts forward a different correlation in order to calculate purchased equipment costs. These correlations are in the form of the following equation.

$$C_e = a + bS^n \qquad (eq. 3.7)$$

where C_e is the purchased equipment cost; a and b are constants found in Table 7.2 in Towler and Sinnott[5], S is the size parameter, and n is the exponent for that type of equipment.

The purchased equipment cost uses a US Gulf Coast basis in January 2010. This period has a CEPCI of 532.9 and a NF refinery index of 2281.6. Prices are all for carbon steel. Towler and Sinnott also mentioned that this method is more for a preliminary design estimate.

For more detailed estimates that account for the type of material used other than carbon steel and also installation costs (C_{ISBL}), Towler and Sinnott uses what is called the Factorial Method. The C_{ISBL} is somewhat similar to the C_{BM}. The C_{ISBL} used in Towler and Sinnott is a direct cost, whereas C_{BM} has direct and indirect.

This is calculated using an expansion of the Lang factor equation:

$$C = \sum_{i=1}^{i=M} C_{e,i,CS}\left[\left(1+f_p\right)f_m + \left(f_{er}+f_{el}+f_i+f_c+f_s+f_l\right)\right] \qquad (eq. 3.8)$$

This equation should be used when the purchase cost has been found on a carbon steel basis. If found on a basis other than carbon steel, the following equation should be used with the installation factors corrected.

$$C = \sum_{i=1}^{i=M} C_{e,i,A}\left[\left(1+f_p\right) + \left(f_{er}+f_{el}+f_i+f_c+f_s+f_l\right)/f_m\right] \qquad (eq. 3.9)$$

where $C_{e,i,CS}$ is the purchased equipment cost of equipment i in carbon steel, $C_{e,i,A}$ is the purchased equipment cost of equipment i in alloy, M is the total number of pieces of equipment. The other factors are for piping (f_p), equipment erection (f_{er}), electrical, instrumentation and control (f_i), civil engineering work (f_c), structures and buildings (f_s), lagging, insulation and paint (f_l) and a materials factor (f_m)[5].

The list of process equipment information Towler and Sinnott is not as diverse as the one given in Turton and does not account for different design pressures or type of equipment.

Computer Program Use in Cost Estimation as evaluated by Ying Feng (2011)

An article published in the August 2011 edition of *Chemical Engineering Journal* by Feng and Rangaigh compares five capital cost estimation programs. Some of these programs use the same methods proposed by authors in the texts covered above. The five programs evaluated were as follows: CapCost, EconExpert, AspenTech Process Economic Analyzer (Aspen Tech PEA), Detailed Factorial Program (DFP), and Capital Cost Estimation Program (CCEP). The authors used case studies to evaluate the five programs at the equipment and plant levels.

The first program evaluated was CapCost. This program uses the module costing method as discussed in Turton *et al*. This is available with the process design book written by Turton *et al*.; furthermore, the program is written in Visual Basic and is able to handle preliminary process cost. The second program evaluated by Feng is the Detailed Factorial Program (DFP). This program uses the detailed factorial estimate as laid out in the book by Towler and Sinott. However, in the article, the constants correspond to a January 2007 CEPCI of 509.7 (instead of 532.9 in 2010 as discussed above).

The third program was Capital Cost Estimating Program (CCEP). This used a correlation presented in Seider [11] for estimation of free on board (FOB) cost of equipment. According to Feng, Seider developed these purchased cost correlations for common process equipment based on available literature sources and vendor data. The program also uses material factors and Guthrie's bare module factors thereafter to estimate equipment costs. These correlations may be found in the book written by Seider *et al*. using a CEPCI of 500 (2006 average). The equation used for is similar to the equation used by Turton *et al*. to calculate C^0_p:

$$C_p^0 = \exp\{A_1 + A_2\,log(S) + A_3[log(S)]^2 + \cdots\} \qquad (eq. 3.10)$$

EconExpert is the fourth program evaluated. According to Feng, it is a Web-based interactive software for capital cost estimation [12]. It also uses the equipment module costing method. The data for this program may be found in “Chemical Engineering Process Design and Economics by Ulrich and Vasudevan [12]. Ulrich and Vasudevan present the data in plots and graphs. EconExpert represents these plots in polynomial form using multiple regression. EconExpert uses a CEPCI of 400 (2002 average).

The last program is AspenPEA (predecessor to ACCE), which is designed to generate both conceptual and detailed estimates. AspenPEA claims to have time-proven, field tested, industry-standard cost modeling and scheduling methods. Feng used AspenPEA version 7.1, which follows 2008 data with a CEPCI of 575.

This article covered an adequate amount of process equipment including compressors, heat exchangers, mixers, pumps, towers, and vessels among others. Also covered were the total purchase and module costs. Feng found that all programs were user-friendly. The author also found that AspenPEA had the most equipment types available, while DFP was the most limited. Furthermore, the overall plant cost does not differ by much; however, the programs differed significantly for the equipment costs. This wasn’t the case for all equipment, but for certain equipment types.[12]

ASPEN Capital Cost Estimator (formerly AspenPEA)

Economics in Aspen involves two software systems: The process simulator (Aspen Plus) and the economic evaluation software (Aspen Capital Cost Estimator[13]). Both are integrated by having the economics software embedded in the process simulator. Aspen Capital Cost Estimator (ACCE) is a model-based estimator which, according to AspenTech, employs a sophisticated "volumetric model" rather than a factor-based model as discussed earlier. ACCE uses cost models to prepare detailed lists of costs of process equipment and bulk materials. AspenTech claims that these models have been tested and improved over time with feedback from organizations that use the ACCE [14,15]. However, obtaining the actual model or data used to come up with this model isn't easy due to Aspen Plus being a proprietary software. ACCE v8.8 uses a 1st Qtr. 2014 pricing basis (CEPCI 576.1).

The pricing changes in Aspen Icarus Evaluation Engine for V8.6 (2013 basis) to V8.8 may be found in the help menu of the software[16]. The changes included:

- a 2.7% decrease to a 0.8% increase in equipment costs
- a 3.3% decrease to a 5.6% increase in piping costs
- a 0% to 4.4% increase in civil engineering costs
- a 1.3% decrease to a 3% increase in steel costs
- a 7.5% to 13.8% increase in instrumentation costs
- a 0.3% to 2.3% decrease in electrical costs
- a 3.1% decrease to 1.7% increase in insulation costs
- a 0.5% to 0.9% increase in paint costs
- Carbon steel plate pricing had an approx. 8% increase
- 304 stainless steel plate pricing had an approx. 2% decrease while tubing had a 17% decrease

Some changes shown were dependent on location. According to the software, "these results were obtained by running a general benchmark project containing a representative mix of equipment found in a gas processing plant. In addition to pricing changes, model enhancements and defect corrections have affected overall percentage differences."[16] The software also noted, "…the costs may include quantity or design differences, since various models and methods have been updated or fine-tuned based on client feedback and defect resolution."[16]

Chapter 4
Method of Research

This study employed the use of the Aspen Capital Cost Estimator (ACCE) to evaluate the equipment used in the study. Aspen Plus Process Simulator also has the ability to estimate capital costs based on these simulated processes using what is called Active Economics. Active Economics ultimately uses the ACCE to do this. By using ACCE directly, the dependency on which raw materials are used as inputs in the process is eliminated. The cost of each piece of equipment, at each scenario, was estimated using Turton's Module Costing Method (first proposed by Guthrie and modified by Ulrich), Towler and Sinnott's Factorial Method (assumed a fluids processing plant), and using the ACCE. Calculations outside of Aspen were done using Excel. Using these tools, a comparison of equipment capital costs was made among these different techniques. Furthermore, feasible capacity ranges (low, middle, high) and materials of construction (carbon steel and 304 stainless steel) were modified and compared for each piece of equipment looked at in this study. All final costs are brought to 2014 final values by the use of the Chemical Engineering Plant Cost Index (CEPCI) obtained from the Chemical Engineering Magazine. For a look at the ACCE user interface and a general procedure, see Appendix B. However, for a detailed description of how to use the ACCE software, refer to the user guide[13].

Process/Pressure Vessels

For the vertical pressure vessels, the capacities chosen were based on feasible ranges laid out in the methods studied. Each method also required different specifications. For a list of additional equations used for the pressure vessels, see Appendix A. For Turton's method, the capacity ranges are from 0.3 to 520 m^3. For Towler and Sinnott, the capacity ranged from 160 to 250,000 kg of shell mass. ACCE was more flexible and required either the diameter with the tangent to tangent height, or just the liquid volume. The former option was used in Aspen. With these constraints in place, it was decided to keep the diameter fixed at 3 meters and change only the length of the vessel. Lengths between 10 and 30 meters suited both feasibility ranges resulting in volumes between 70 and 212 m^3 (see equation A.4). Furthermore, this also resulted in shell masses ranging between 8,800 and 36,000 kg by using the densities of carbon or stainless steel where applicable (see equation A.2). A high and a low design pressure were chosen between feasibility ranges laid out in Turton. In this case, the low pressure was 1 bar, and the high was 10 bar. In the case of Towler and Sinnott's method, which does not account for pressure in the cost equations, the wall thickness was used based on the pressure chosen (equation A.1). This circumvents that problem as wall thickness is a function of pressure. The wall thickness is also needed to find a shell mass. This study also assumed an operating temperature of 30 degrees Celsius. This assumption is needed due to the maximum allowable stress for stainless steel decreasing as temperature increases. A weld efficiency, which also affects the wall thickness, was assumed to be 100% for simplicity. For horizontal vessels, the lengths chosen to meet the constraints were between 1 and 4 meters.

Other Process Equipment

The three heat exchangers chosen were treated the same, except for the capacity ranges. The U-tube and floating head shell and tube heat exchangers had capacities between 50 and 1000 m^2; whereas, the U-tube kettle reboiler had capacities of 15 and 100 m^2. The shell and tube sides were either CS/CS or SS/SS, and the pressures were the same on both sides as well.

The pumps and compressors were sized in Aspen Plus v8.8 in order to obtain the different capacities requirements for each method to get as best a comparison as possible. For example, the pump capacity in Towler and Sinnott's method requires a flow rate while Turton's method requires a shaft power; so, in order to make sure the same specification pump is being costed, a flow rate and a pressure increase was specified in the process simulator using water at 25^{o}C and 1 bar as the input. After the simulation is complete, the design pressure and head required can also be specified along with the flow and power into the ACCE.

For the compressors, a little mathematical manipulation was necessary to obtain a fluid power to be used with Turton's method (see equation 4.1).

$$Fluid\ Power(kW) = Brake\ Power\ (kW) * Efficiency \qquad (4.1)$$

An efficiency of 78% suggested by table 11.10 of Turton[3] was used . Towler and Sinnotts's method used brake power as the capacity. An inlet flow was specified in Aspen.

Mixers and motors were costed as outlined in Towler and Sinnott and Turton. For mixers, the range chosen was between 5 and 75 kW; for the explosion proof motor a range of 200 to 2500 kW was chosen.

Chapter 5
Results and Discussion

By linearizing the six-tenths rule (equation 3.1), one gets equation 5.1 below.

$$\log(C_a) = n log(A_a) + \mathrm{k} \qquad (5.1)$$

where the constant 'k' is $\log(C_b/A_b^n)$. According to Perry, the data is most accurate in the narrow middle range of capacity, and that the error is large at both ends of capacity (high or low) [1]. Table 9-50 in Perry's Chemical Engineering Handbook[17] has a list of cost data which includes the exponent for various pieces of equipment.

When compared to ACCE, Towler and Sinnott's method was generally the highest of the two other methods, with exceptions in some cases. This may be due to each method including different contributors to cost and also how these contributors are accounted for. As for Towler and Sinnott's factorial method, which covers only the direct capital cost and also site preparation, the percent differences were about the same for carbon steel and stainless steel values, which shows the errors are consistent between the two methods.

Stainless steel is approximately four times more expensive than steel according to MEPS International – an independent supplier of steel market information and trends[18]; so it is expected to see an increase in price going from carbon steel to stainless steel. All three methods are consistent with their costs.

As capacity increases there is an economy of scale displayed in the results. Looking at the cost per unit capacity graphs below, one can see that as capacity increases, the price per unit decreases, and in some cases the cost per unit capacity actually starts to increase again.

If the design pressure increases, then the design engineer would have to make adjustments accordingly, especially for wall thickness. Increasing the wall thickness for the vessels would, intuitively, increase the amount of material needed to fabricate the vessels and increase its cost. This is also reflected in the results for each process vessel. The cost exponents obtained for the elevated pressures were similar.

Pressure Vessels

Vertical Vessels

The exponents obtained for the vertical pressure vessels were n = 0.90, 0.76, 0.60 for Turton's Method, Towler & Sinnott's method and ACCE, respectively. Observation of Figure 1 shows that the points behaved well in this range for the most part with ACCE having a bit more scatter along the line. Figure 2 and Figure 3 shows the cost per capacity plot. For the carbon steel plot, the cost per length starts increasing between 25 to 30 meters or approximately after 200 m^2. For the stainless steel plot, that point is between 20 and 25; which is around 150 m^2. In Figure 3, Turton's method behaves a little strange crossing over from being the highest at the start and the lowest at the end. This error may be due to the different capacity requirements or due to the fact that Towler and Sinnott uses a completely different set of factors to calculate the purchased equipment cost for stainless steel vessels as opposed to carbon steel.

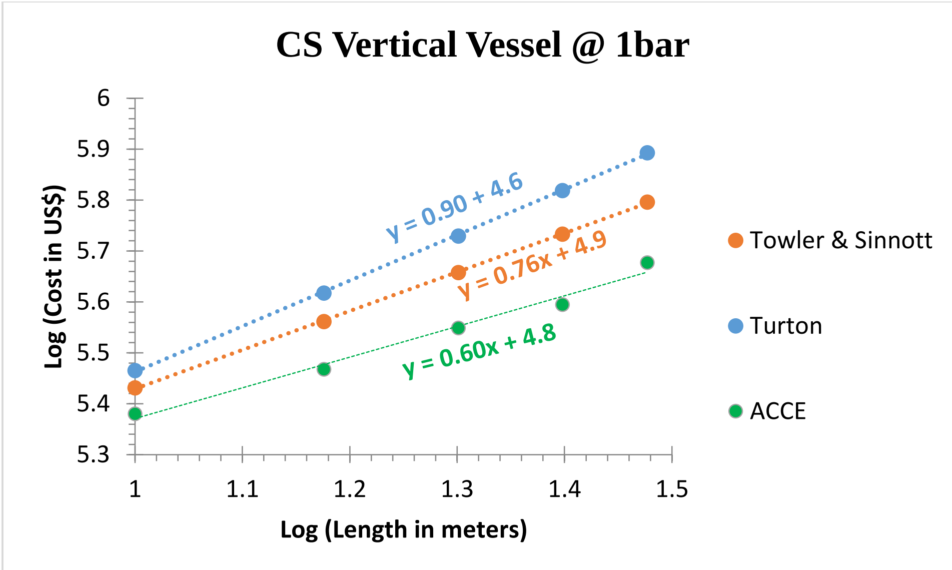

Figure 1: Cost vs. Capacity plot of a carbon steel vertical vessel at 1 bar

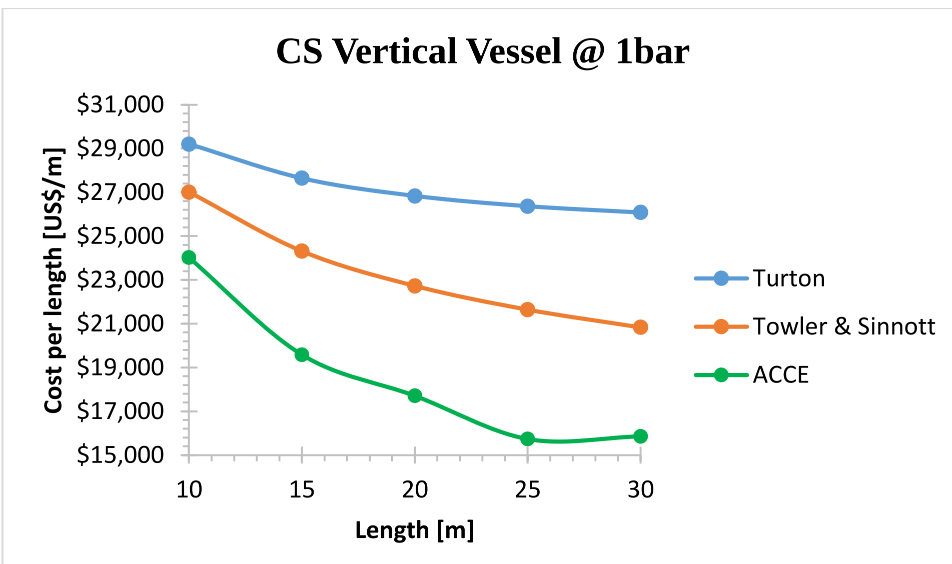

Figure 2: Cost per unit capacity plot for a carbon steel vertical vessel at 1 bar

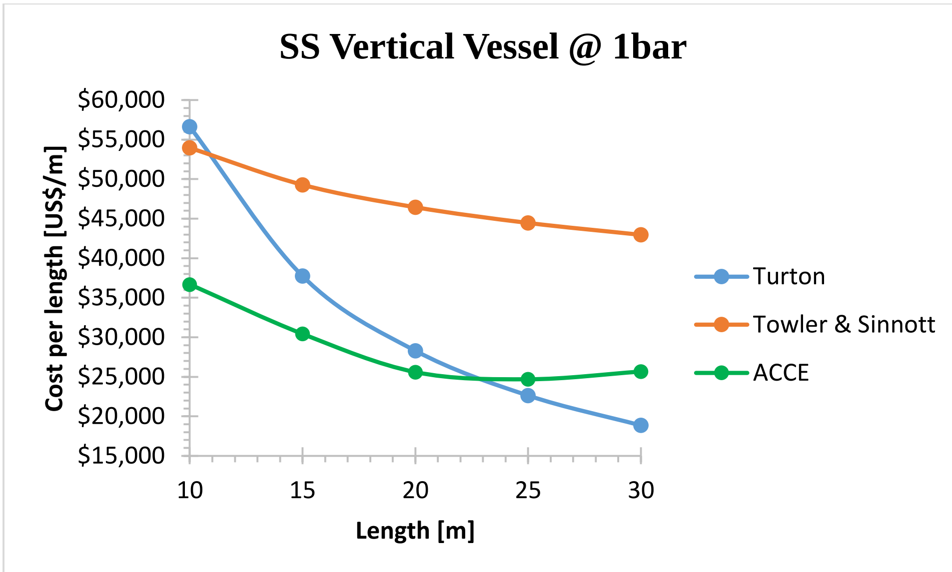

Figure 3: Cost per unit capacity plot for a stainless steel vertical vessel at 1 bar

Horizontal Vessels

The exponents obtained for the horizontal pressure vessels were n = 0.58, 0.50, and 0.30 for Turton's Method, Towler & Sinnott's method and ACCE, respectively for carbon steel (Figure 4). Figure 4 also showed ACCE having a bit more scatter along the line than the other methods. Figure 5 and Figure 6 show the cost per capacity plot. ACCE gives the highest cost per length in this case while Turton's method give the lowest values. As mentioned before in the methodology, the capacity ranges were chosen based on the valid feasibility region for each method. While 10 to 30 meters satisfies the region in Turton's method (in terms of volume), it is out of the valid range for Towler and Sinnott's method (in terms of shell mass). Therefore, the range chosen was 1 to 4 meters.

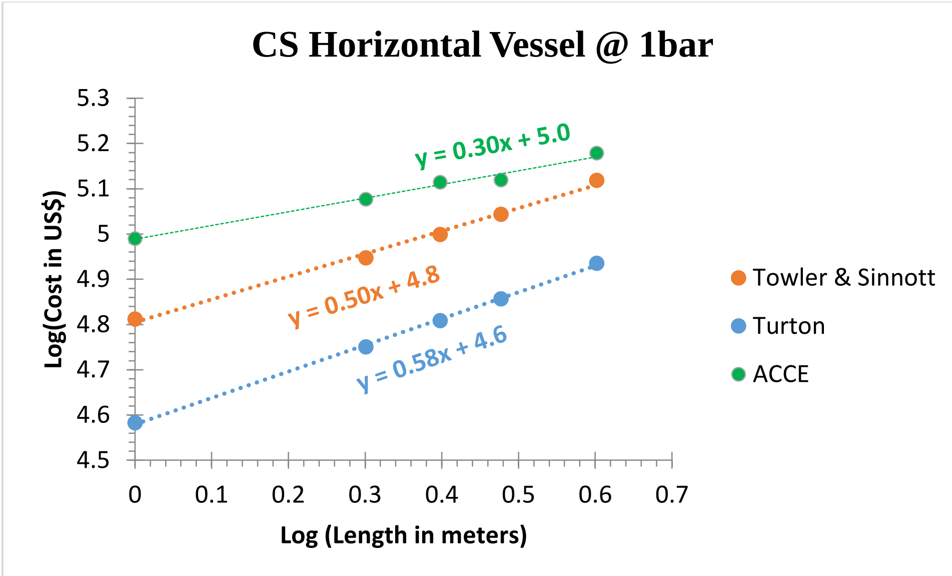

Figure 4: Cost vs. Capacity plot of a carbon steel horizontal vessel at 1 bar

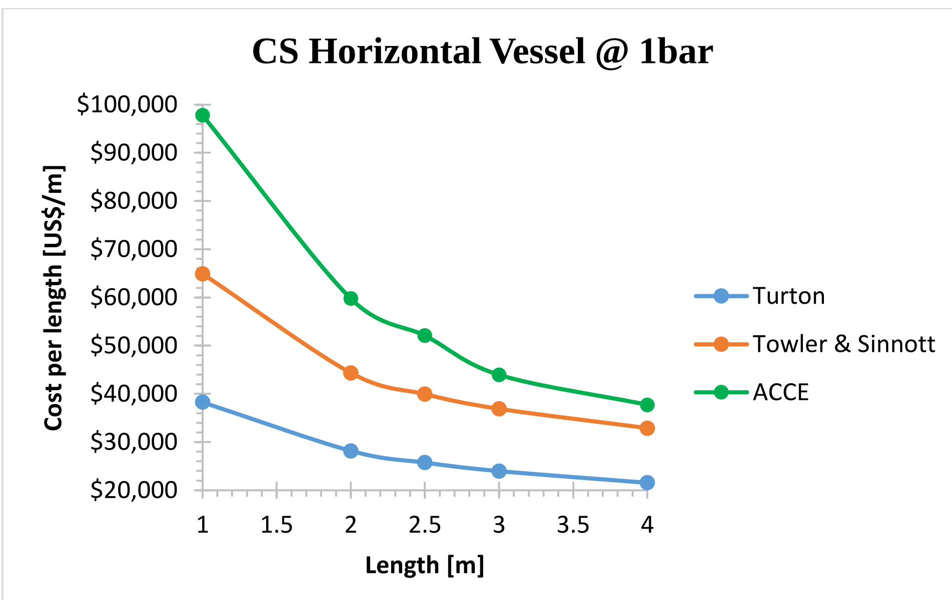

Figure 5: Cost per unit capacity plot for a carbon steel horizontal vessel at 1 bar

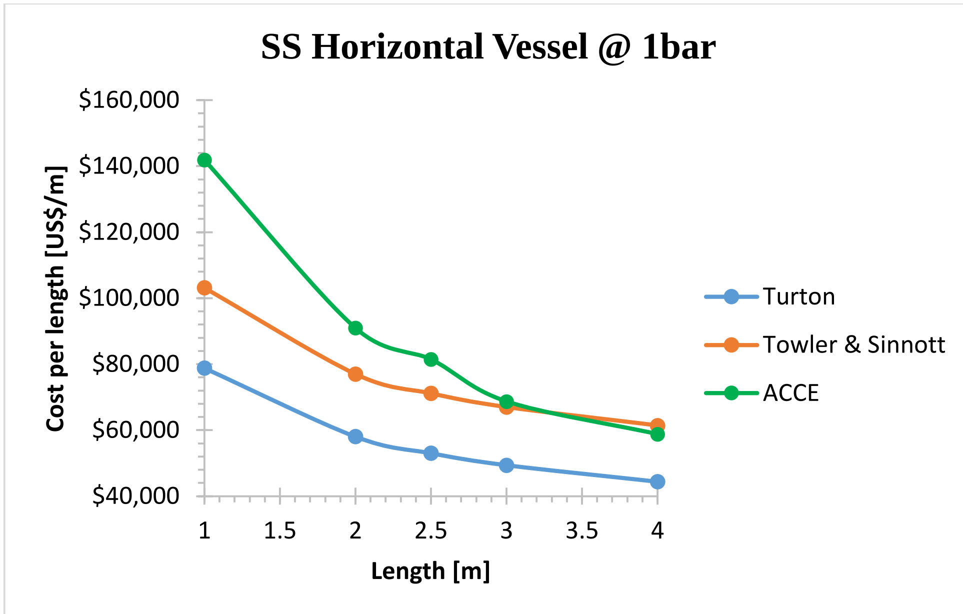

Figure 6: Cost per unit capacity plot for a stainless steel horizontal vessel at 1 bar

Heat Exchangers

The exponents obtained for the shell and tube type heat exchangers were n = 0.67, 0.65, and 0.41 for Turton's Method, Towler & Sinnott's method and ACCE, respectively for the U-tube (Figure 7) and the floating head (Figure 10). For the U-tube kettle reboiler n = 0.73, 0.25, and 0.21 for Turton's Method, Towler & Sinnott's method and ACCE, respectively (Figure 13). There was a lot more scatter among all the methods. Towler and Sinnott's method seem to level out on the cost per area graphs for the floating head and U-tube heat exchangers.

U-tube Shell and Tube

Figure 8 and Figure 9 show the cost per capacity plot. ACCE gaves the lowest cost per length of the three methods. Turton's method gave the largest values although in Figure 8, Towler and Sinnott's method was very close to Turton's method.

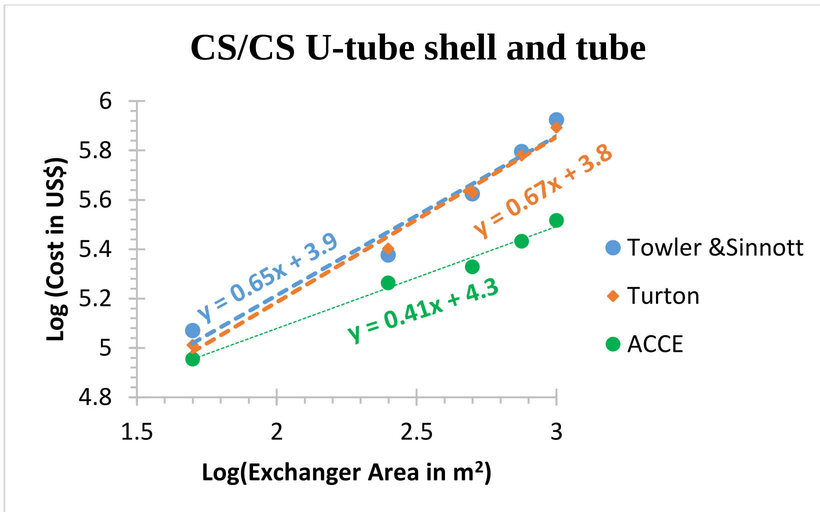

Figure 7: Cost vs. capacity plot for a carbon steel U-tube shell and tube heat exchanger

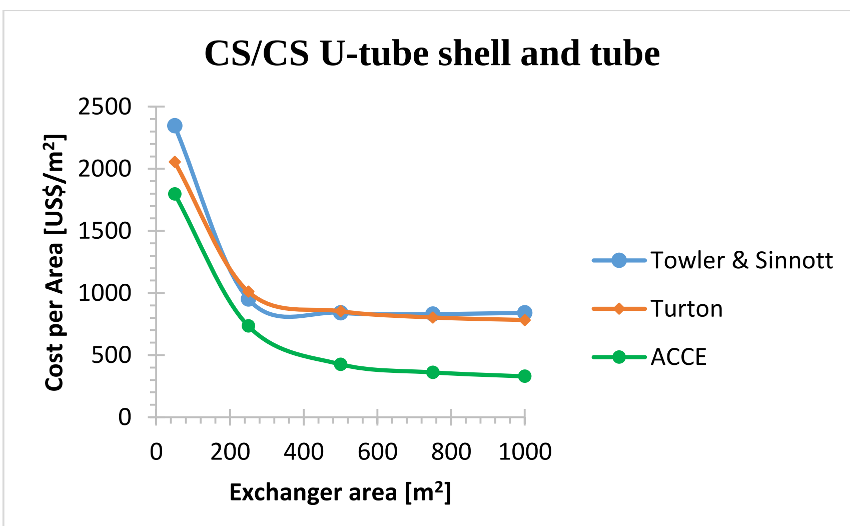

Figure 8: Cost per unit capacity plot for a carbon steel u-tube shell and tube heat exchanger

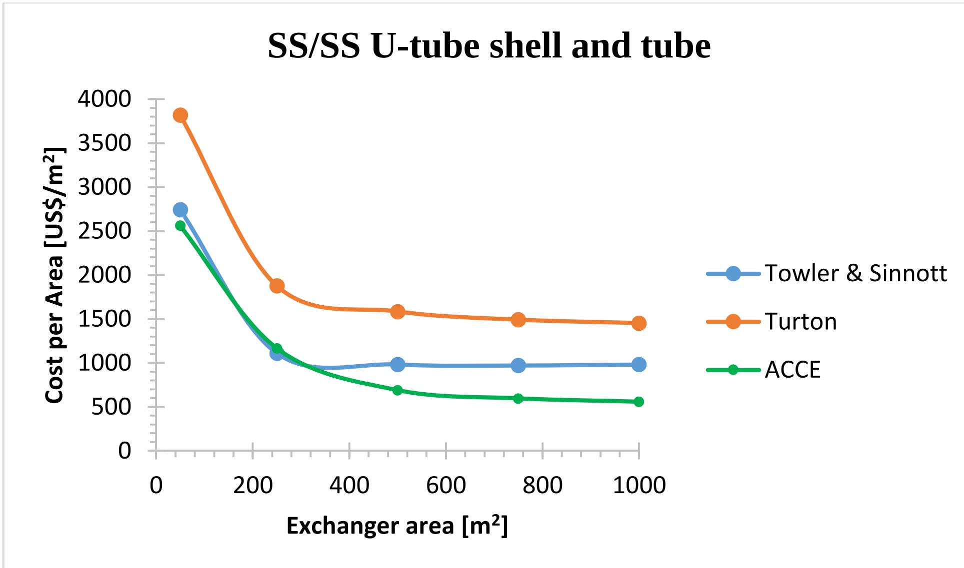

Figure 9: Cost per unit capacity plot for a stainless steel u-tube shell and tube heat exchanger

Floating Head

Figure 11 and Figure 12 show the cost per capacity plot. ACCE gave the lowest cost per length of the three methods. Towler and Sinnott's method gave the largest values for carbon steel while the values were quite close to Turton's method for stainless steel. Turton's method can be seen leveling off as well in both figures.

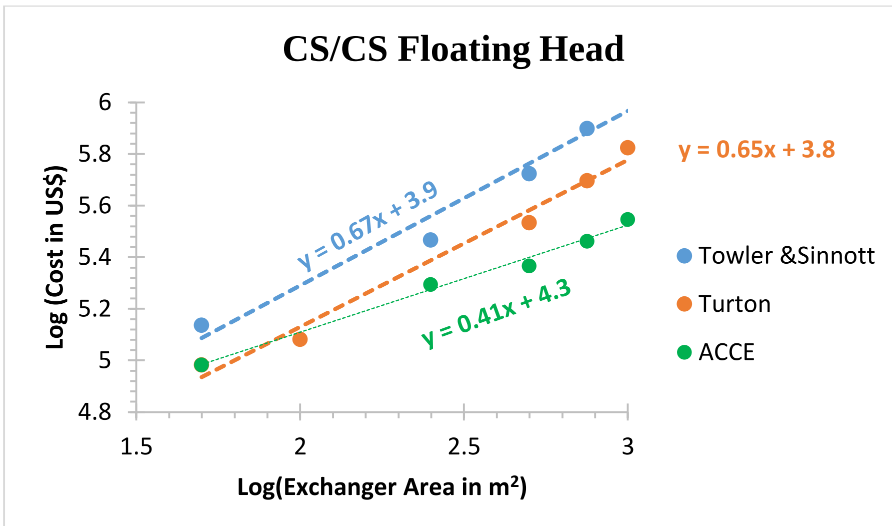

Figure 10: Cost vs. capacity plot of a carbon steel floating head shell and tube heat exchanger

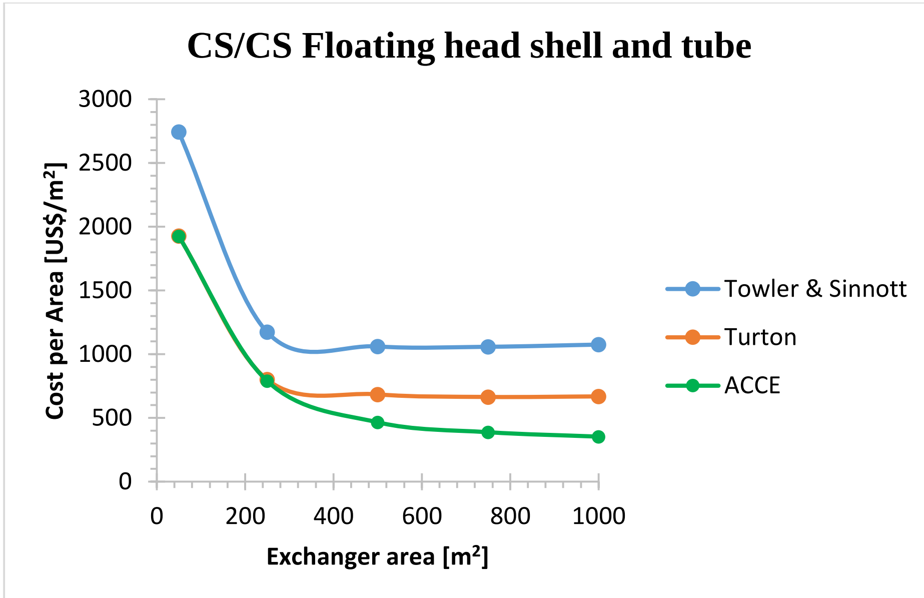

Figure 11: Cost per unit capacity plot for a carbon steel floating head shell and tube heat exchanger

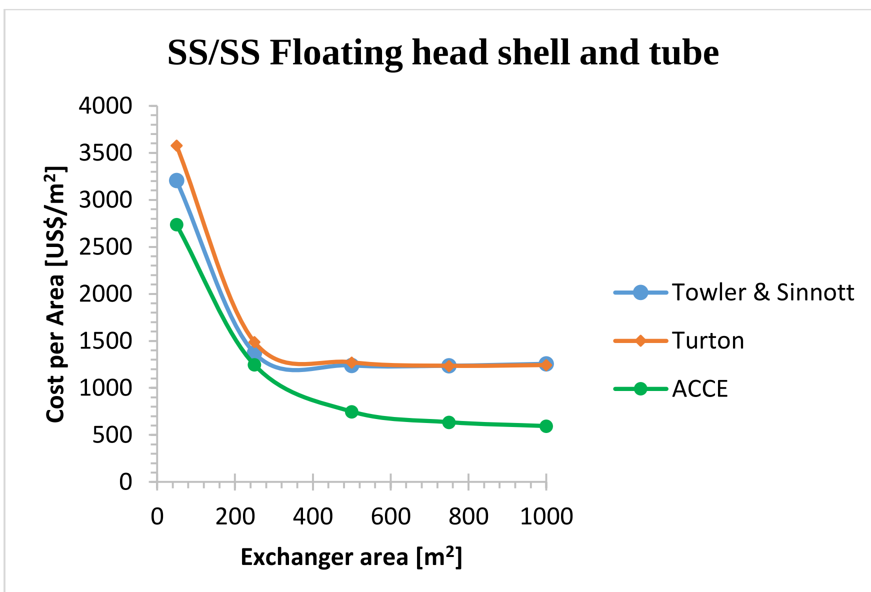

Figure 12: Cost per unit capacity plot for a stainless steel floating head shell and tube heat exchanger

Kettle Reboiler

Figure 13 and Figure 14 show the cost per capacity plot on a dollar basis and a dollar per square meter basis, respectively for carbon steel. Figure 15shows the cost per capacity plot for the U-tube kettle reboiler on a dollar per square meter basis for stainless steel. Turton's method can be seen leveling out for both materials.

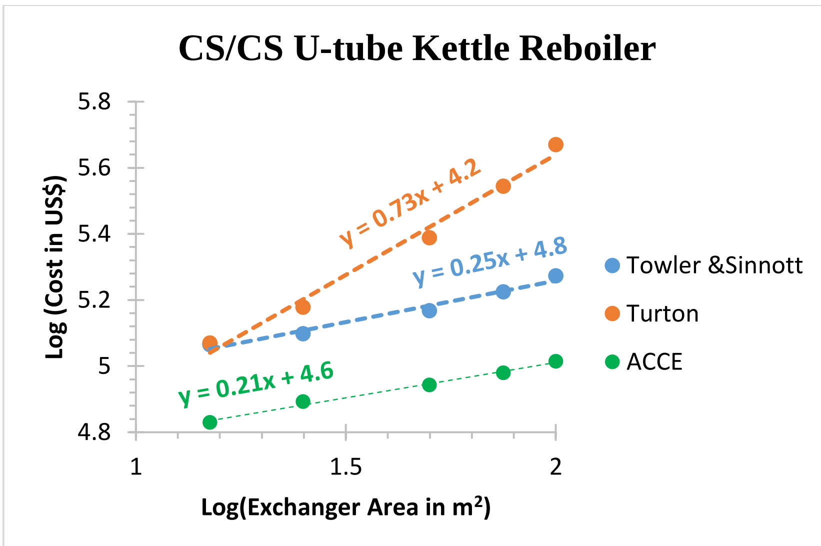

Figure 13: Cost vs. capacity plot for a carbon steel U-tube kettle reboiler

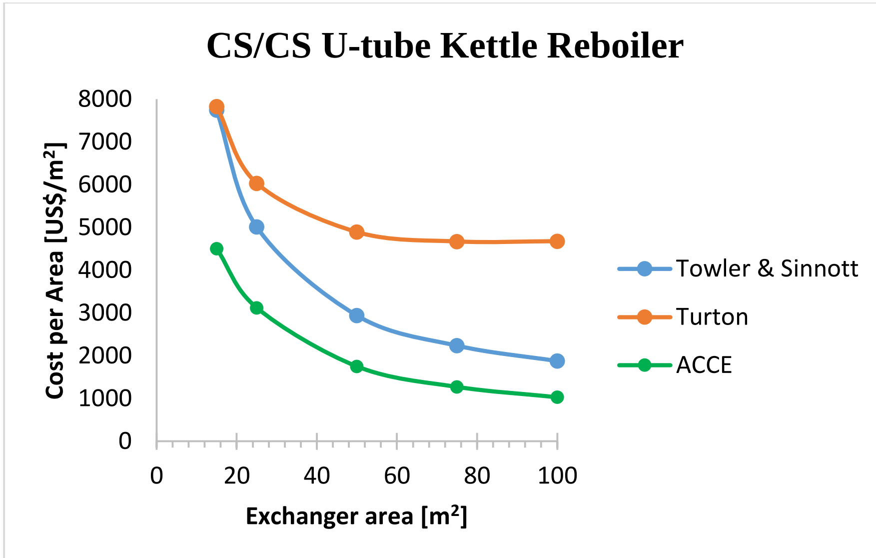

Figure 14: Cost per unit capacity plot for a carbon steel U-tube kettle reboiler

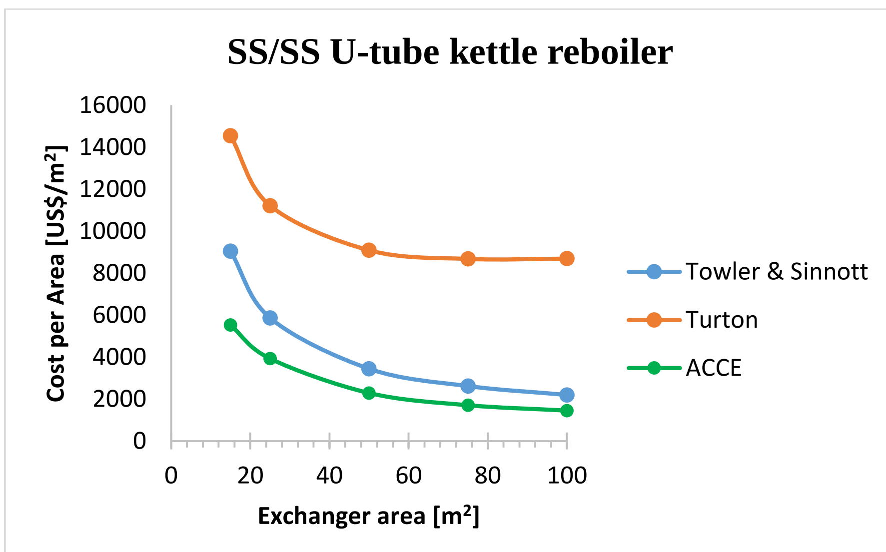

Figure 15: Cost per unit capacity plot for a stainless steel U-tube kettle reboiler

Pumps and Drivers

Centrifugal Pump

The exponents obtained for the centrifugal pump were n = 0.58, 0.50, 0.53 for Turton's method, Towler & Sinnott's method and the ACCE method, respectively. Observation of Figure 16 shows that the points behaved well in this range for the most part with ACCE having a bit more scatter along the line. Figure 17 and Figure 18 shows the cost per capacity plot, whereas Towler and Sinnott's method is observed giving the largest values. The stainless steel plot has Towler and Sinnott's method showing very similar results to Turton's method.

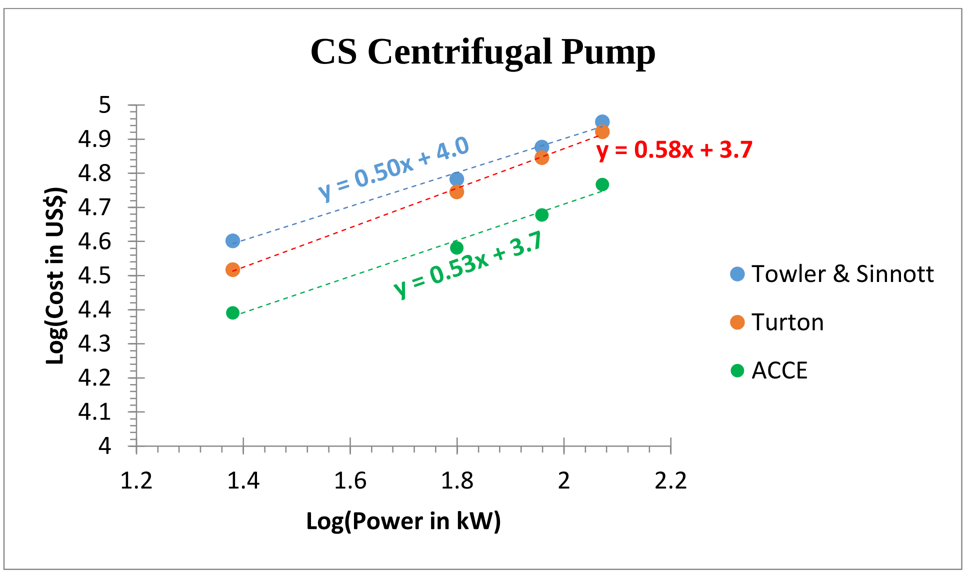

Figure 16: Cost vs. capacity plot for a carbon steel centrifugal pump

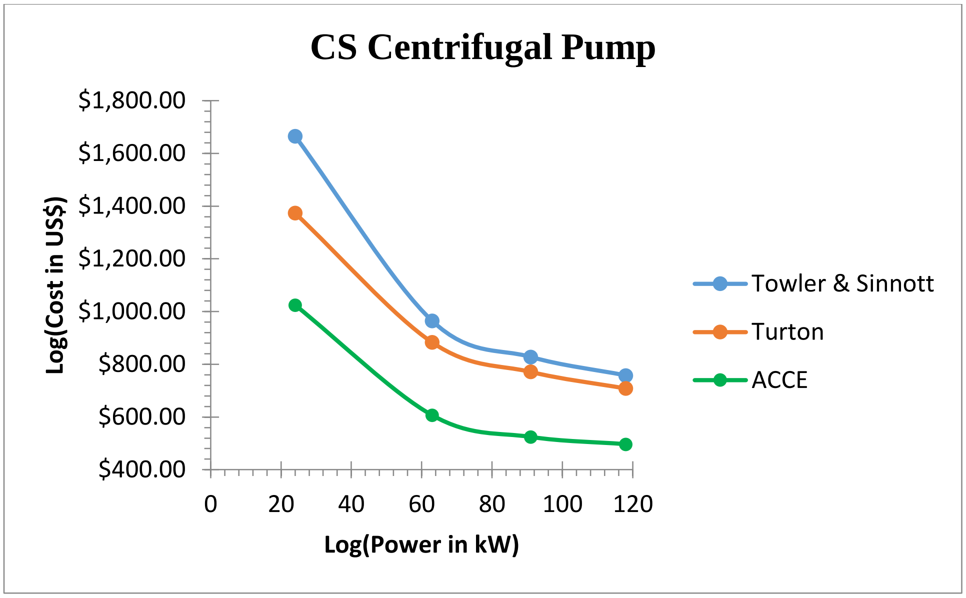

Figure 17: Cost per unit capacity plot for a carbon steel centrifugal pump

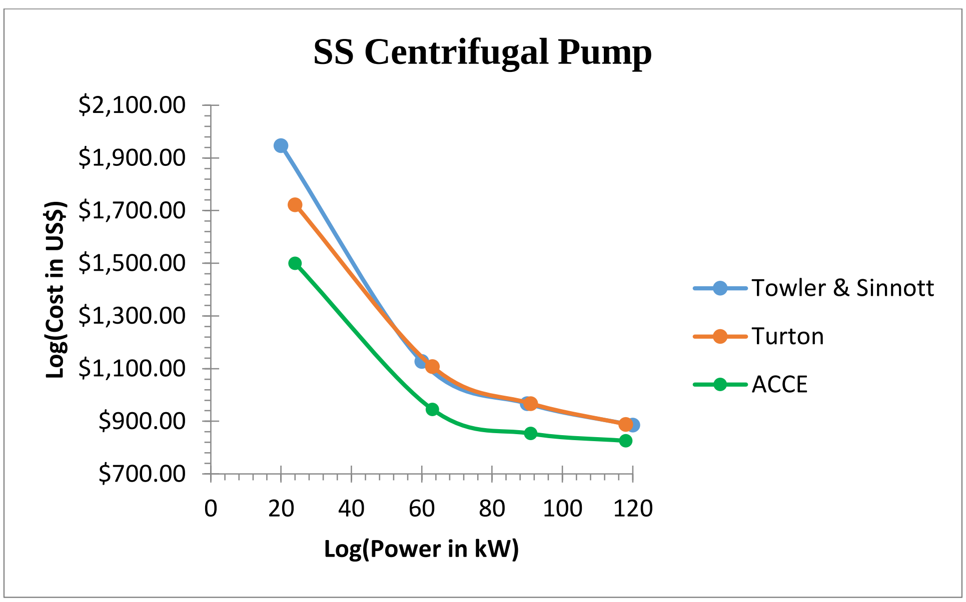

Figure 18: Cost per unit capacity plot for a stainless steel centrifugal pump

Explosion Proof Motor

The exponents obtained for the explosion proof motor was n = 0.39, 0.61, 0.66 for Turton's method, Towler & Sinnott's method and the ACCE method, respectively. Observation of Figure 19 shows that the points behaved well in this range for Towler and Sinnott's values; however, the other two methods had a bit more scatter along the line. Figure 20 shows the cost per capacity plot. Turton's method starts off being the largest, and as capacity increases, this method became the lowest. The methods are closer together in value for this piece of equipment.

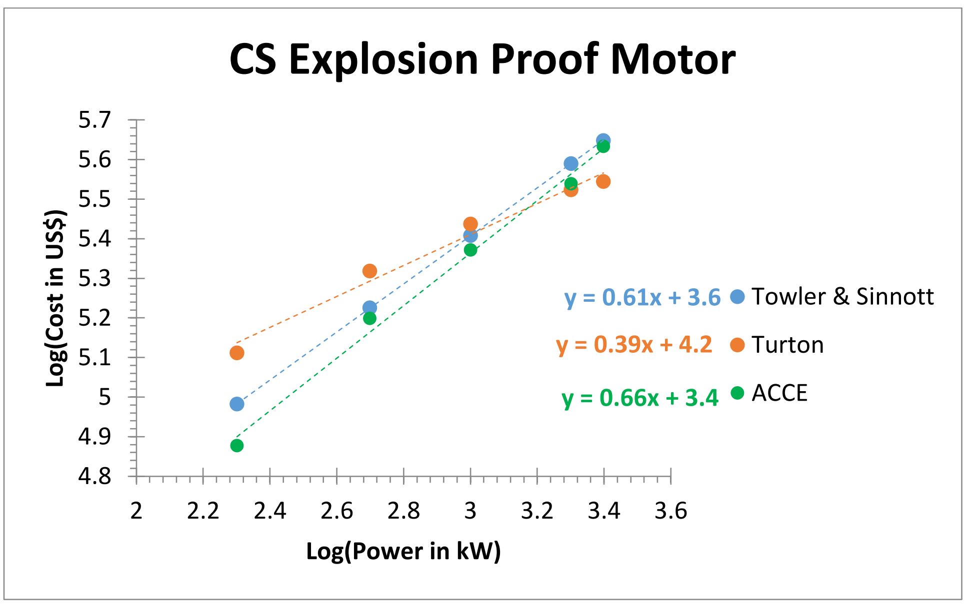

Figure 19: Cost vs. capacity plot of a carbon steel explosion proof motor

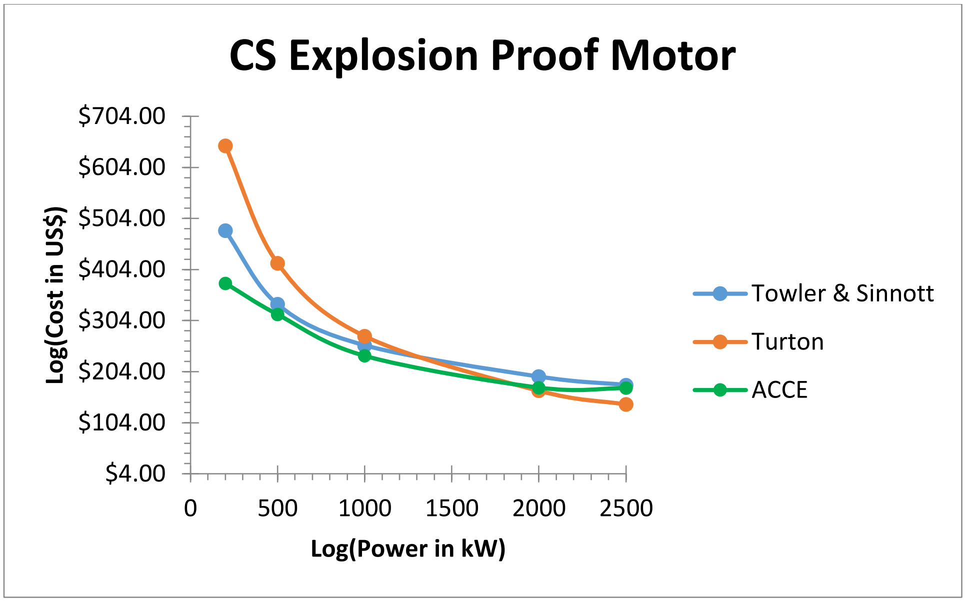

Figure 20: Cost per unit capacity plot for a carbon steel explosion proof motor

Compressors

Centrifugal

The exponents obtained for the centrifugal compressor was n = 0.72, 0.45, 0.27 for Turton's method, Towler & Sinnott's method, and the ACCE method, respectively. Observation of Figure 21 shows that the points behaved well in this range for the two factor based methods; however, ACCE had a bit more scatter along the line. Figure 22 and Figure 23 shows the cost per capacity plot. Towler and Sinnott's method is unusually high in comparison. Turton's method is also unusually low. Towler and Sinnott method may, in fact, contain drivers as well as the authors do not doesn't specify if the cost included drivers for the compressor or not. Turton *et al*. do mention in the tables that the cost is without drivers.

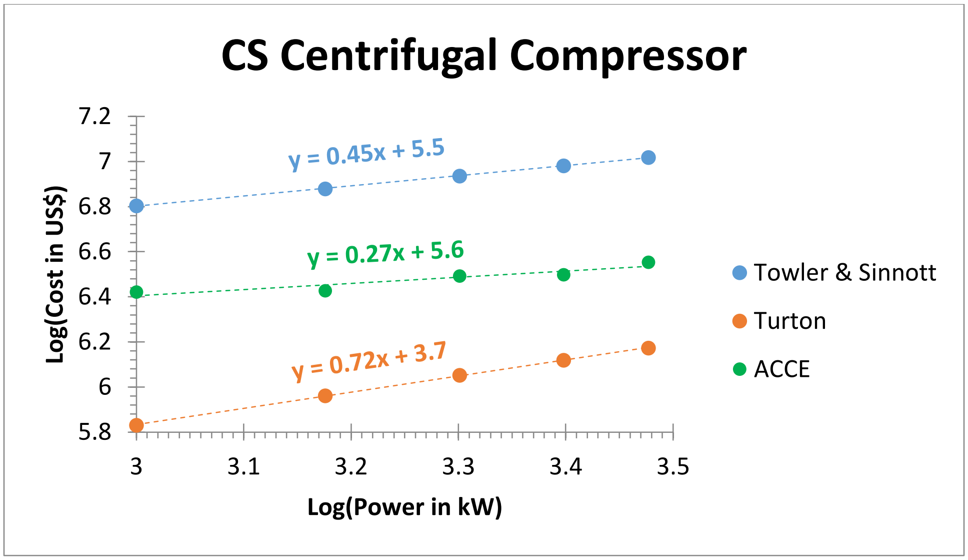

Figure 21: Cost vs. capacity plot for a carbon steel centrifugal compressor

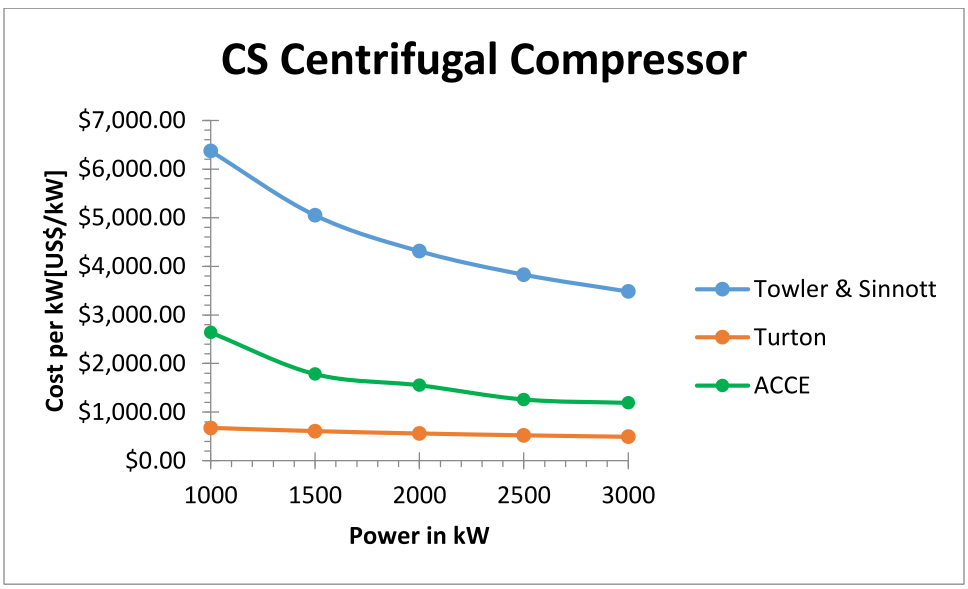

Figure 22: Cost per unit capacity plot for a carbon steel centrifugal compressor

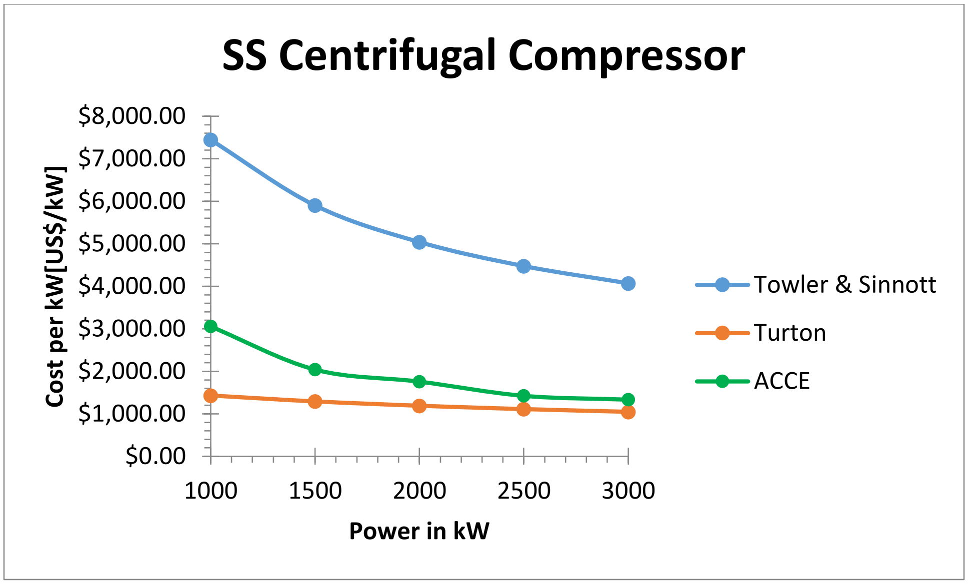

Figure 23: Cost per unit capacity plot for a stainless steel centrifugal compressor

Reciprocating Compressors

The exponents obtained for the reciprocating compressor was n = 0.72, 0.55, and 0.18 for Turton's method, Towler & Sinnott's method and the ACCE method, respectively. Observation of Figure 24 shows that the points behaved well in this range for the all the methods. Figure 25 shows the cost per capacity plot. Towler and Sinnott's method and Turton's method behaved the same as they did with centrifugal compressor.

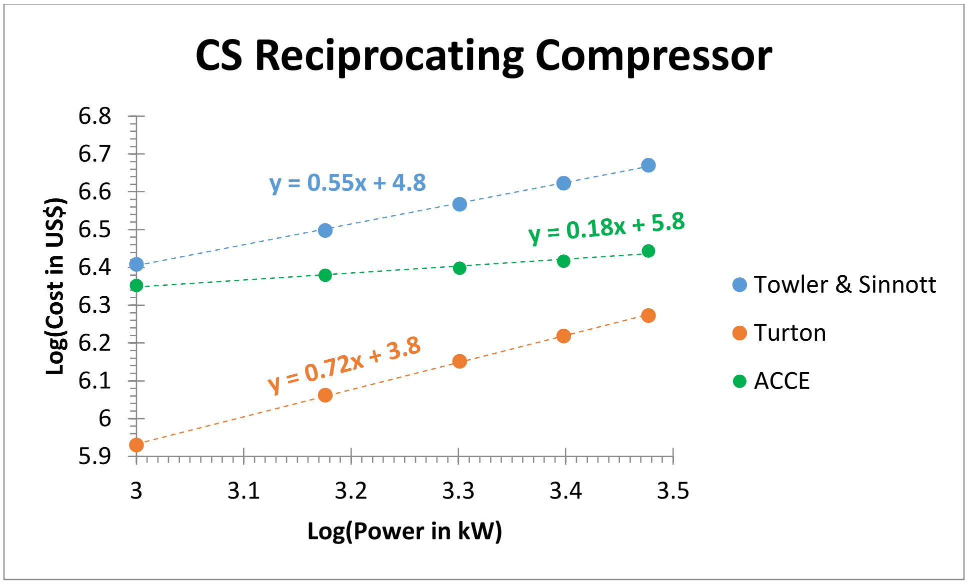

Figure 24: Cost vs. capacity plot of a carbon steel reciprocating compressor

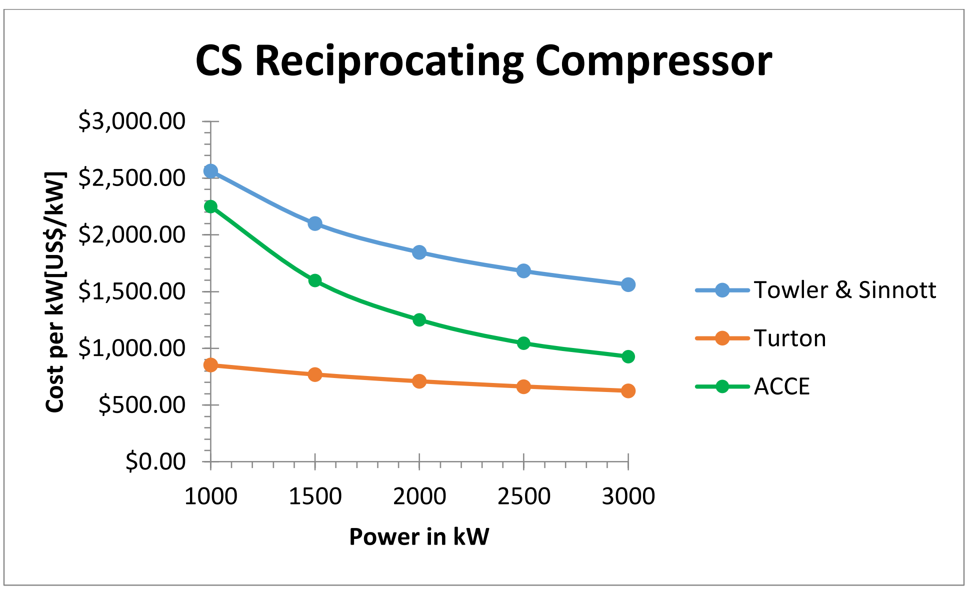

Figure 25: Cost per unit capacity plot for a carbon steel reciprocating compressor

Mixers

Propeller

The exponents obtained for the centrifugal compressor was n = 0.38, 0.61, and 0.57 for Turton's method, Towler & Sinnott's method and the ACCE method, respectively. Observation of Figure 26 shows that the points behaved well in this range for the two factor-based methods; however, ACCE had a bit more scatter along the line. Figure 27 shows the cost per capacity plot. Towler and Sinnott's method was the largest, although this time, the values were close to the ACCE values. Turton's method was the lowest.

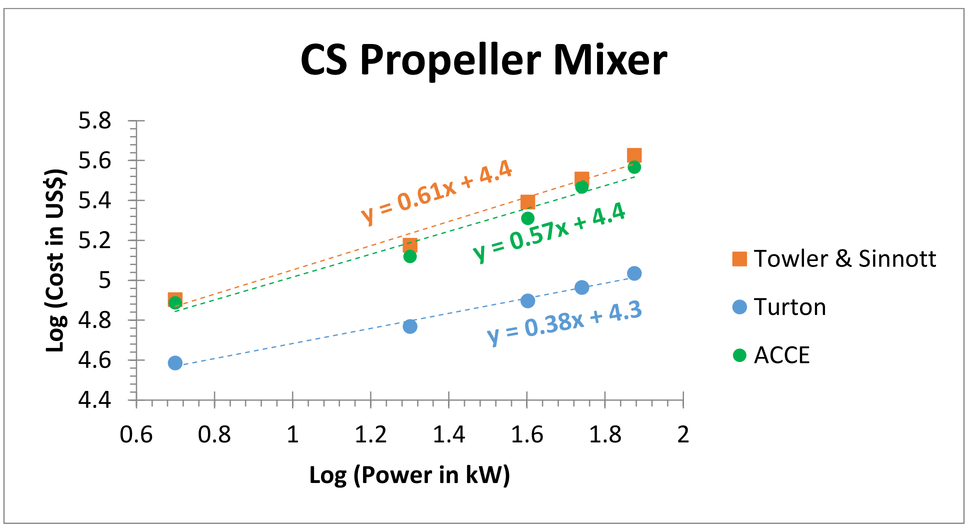

Figure 26: Cost vs. capacity plot of a carbon steel vertical propeller mixer

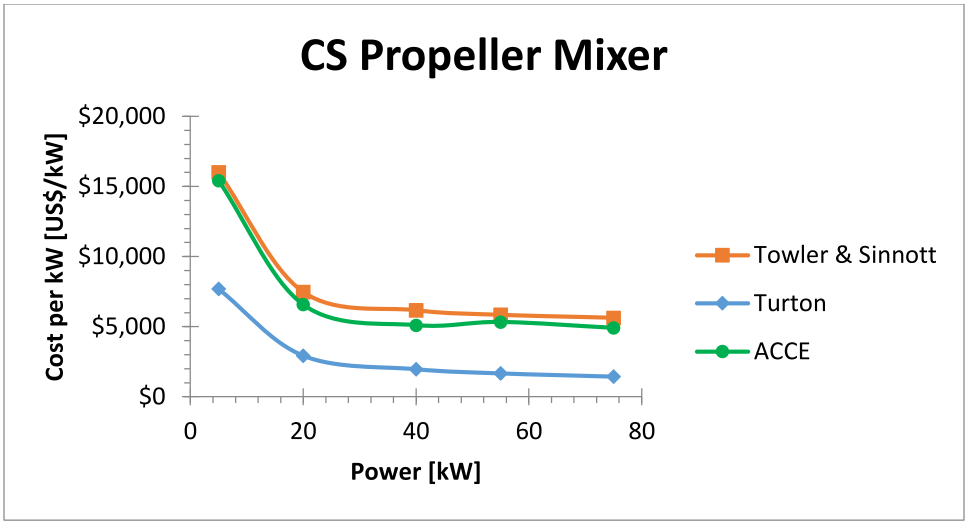

Figure 27: Cost per unit capacity plot for a carbon steel propeller mixer

Validation of Results

The Aspen Capital Cost Estimator is so detailed in its cost reports that using it as a benchmark is the other methods is justified. ACCE provides a detailed breakdown of each individual item that contributes to the cost of the piece of equipment. The program is also able to account for more detailed specifications which, consequently and intuitively, will make the estimate more precise than the factor-based methods. A sample report is shown in Appendix C. It shows all the design data used in the cost engine as well as a summary of all the installation costs and estimated man hours needed and the cost for those man hours.

The six-tenths rule may be used as another tool for validation of the results as it is based off of actual vendor data as well. According to Brown[19], this is one of the most useful relationships in cost engineering as it is valid for both equipment purchase and plant and process costs. However, he also goes on to say that the charts should be used with caution as the cost data for these charts were 20 to 45 years old[19]. This data is, of course, even older now. Brown[19] also has a list of data with exponents in the appendix of his text as well, some of which are taken from *Perry's Chemical Engineers' Handbook*[17]. The results obtained above hardly matched up to the exponents given in Table 9-50 in *Perry's Chemical Engineers' Handbook*[17]. Observation of this table also shows that the size ranges studied above are also outside of the given size ranges in the text. Brown[19] goes on to say that these errors happen when one independent variable is used to correlate cost data when more than one variable is needed to represent the data, or when pressure, temperature and materials of construction vary significantly[19]. An article in the *Encyclopedia of Chemical Processing and Design* by Remer and Chai[20], also includes cost exponents from a number of different sources as well. However, the authors noted that this method (six-tenths rule) is only for the purchase price of equipment and that additional installation and labor costs, as well as other expenses, make the final costs much higher; these extra costs may go as high as 90% of the purchased cost[20].

Erwin (2014) gives sample equipment costs for common process application in his text, *Industrial Chemical Process Design*. According to Erwin (2014), the values are to give a novice designer an idea of the approximate prices of common types of plant equipment [21]. The cost, given by Erwin, for a centrifugal, motor-driver compressor rated for 2000 brake hp (1492 kW) is $880,000; a reciprocating motor-driven compressor rated also at 2000 brake hp is $1,120,000. When brought up from 2001$ to 2014$, the centrifugal type comes to $1,280,000 and the reciprocating type comes to $1,625,000. Erwin did not specify whether the material of construction and further said that these were only purchased costs. For the scenarios that involve the compressors above, the purchase costs are not shown. ACCE, however, gave a value of $2M for the CS centrifugal compressor at 1500 kW. Using the same case for the reciprocating compressor, ACCE gave a value of

$2M also, which is within the limits of error. This price, in ACCE, could be larger or smaller based on the specified inlet and outlet flow rates.

Chapter 6
Conclusions and Recommendations

Error! Not a valid bookmark self-reference. summarizes the results obtained by each method. Turton's method had an average exponent of 0.63, while Towler & Sinnott's method and ACCE had average exponents of 0.55 and 0.41, respectively.

For most of the equipment, both Turton's module costing method and Towler and Sinnott's factorial method, when compared to the ACCE, was within the -30 to 50% margin of error as laid out by the AACI for class 4 estimates[4]. The heat exchangers, however, were on the high side with the factorial method showing differences as high as 100% of the ACCE value for the floating head type; these same differences are seen also for the kettle reboiler with the module costing method. This trend was also seen in comparisons done by Feng in which the DFP program's costs (based on the factorial method) were also really high in comparison[12]. Major differences in the results come down to the availability of pricing data and the accuracy with which cost curves are made. As mentioned before, Towler and Sinnott's factorial method does not take into account the type of equipment being costed. The result of this is every piece of equipment being multiplied by the same factors, similar to the Lang factor method, with the addition of the material factors. This method does not account for design pressures either. Turton's method, on the other hand, accounts for pressure and materials of construction in most of its equipment. However, some equipment like mixers and compressors do not account for changes in these factors.

Table 2: A summary of the cost exponents obtained for each method

	Cost Exponent, n		
Equipment Type	**Turton's Module Costing Method**	**Towler & Sinnott's Factorial Method**	**Aspen Capital Cost Estimator**
Vertical Vessel	0.90	0.76	0.60
Horizontal Vessel	0.58	0.50	0.30
U-Tube Shell and Tube Heat Exchanger	0.67	0.65	0.41
Floating Head Shell and Tube Heat Exchanger	0.67	0.65	0.41
U-tube Kettle Reboiler	0.73	0.25	0.21
Centrifugal Pump	0.58	0.50	0.53
Explosion Proof Motor	0.39	0.61	0.66
Centrifugal Compressor	0.72	0.45	0.27
Reciprocating Compressor	0.72	0.55	0.18
Propeller Mixer	0.38	0.61	0.57

Future work in the area of cost estimation should include, but not limited to updating the cost curves to reflect the current year. Moreover, in the case of the module costing method, work should be done on finding the factors for each piece of equipment so that a proper breakdown of the direct and indirect costs can be made. This would greatly help engineers in the case where a capital cost program cannot be afforded. As mentioned before, the equipment chosen was based on the support of all three methods; more equipment could be added even to get a comparison of at least two methods. If possible, one could try to correlate only purchased cost. Work could also be done to get factors out of Aspen by way of reverse engineering the costs or by another method. Other methods, such as, Seider and Seader's[11] module costing method could also be incorporated into the study.

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Appendix A
Additional Equations used for Pressure Vessels

Process Vessels

$$t_w = \frac{P_i D_i}{2SE - 1.2P_i} \qquad A.1$$

$t_w: wall\ thickness;$

$P_i: Internal\ pressure;$

$D_i: Internal\ diameter;$

$S: Maximum\ allowable\ stress;$

$E: Weld\ efficiency$

$$shell\ mass = \pi D_c L_c t_w \rho \qquad A.2$$

$D_c: Column\ diameter;$

$L_c: Column\ length;$

$\rho: Density\ of\ material$

$$F_{P,vessel} = \frac{\frac{(P+1)D}{2SE-1.2P} + CA}{t_{min}} \qquad A.3$$

$F_P: Pressure\ factor;$

$CA: Corrosion\ allowance\ (assumed\ to\ be\ 0.00315\ m)$[3]

$t_{min}: Minimum\ wall\ thickness\ (assumed\ to\ be\ 0.0063\ m)$[3]

$$Volume\ (V) = \frac{\pi DL}{4} \qquad A.4$$

F_P for other Equipment

$$log_{10}F_P = C_1 + C_2log_{10}P + C_3(log_{10}P)^2 \qquad A.5$$

Appendix B
The Aspen Capital Cost Estimator user interface

1. After opening the software, left-click on new project.
2. Enter a the name of your project in the window that pops up then click ‘ok’
3. You may choose whether to use metric or imperial units in the next window that pops up then click ‘ok’
4. On the next window you may choose the options as seen in Figure 28. Click ‘ok’ when done.

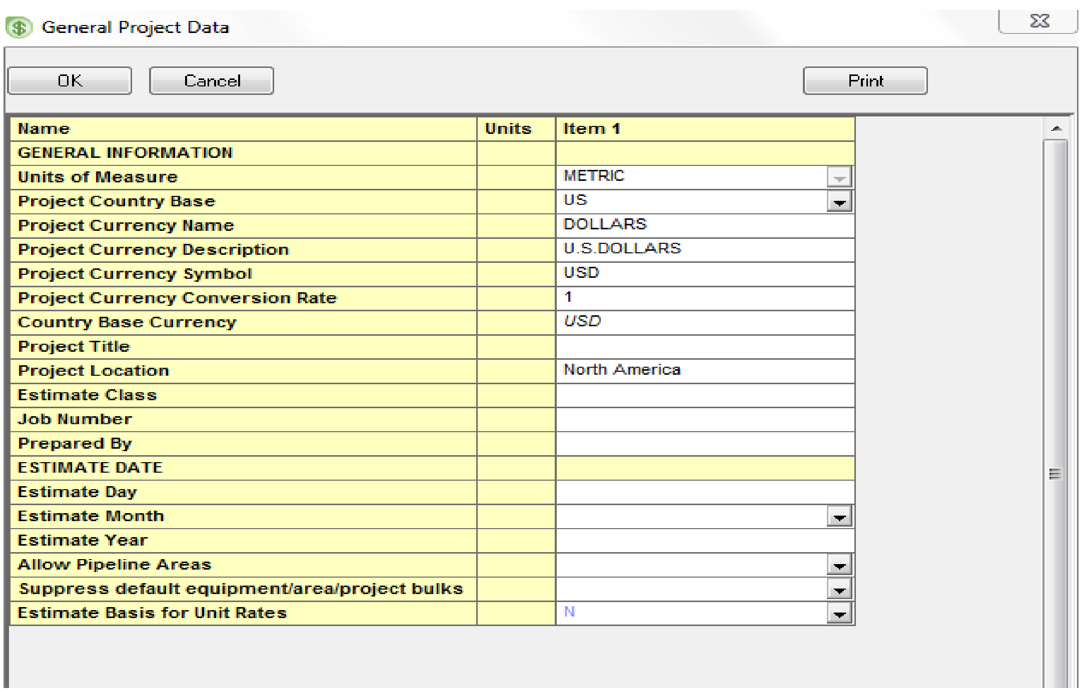

Figure 28: Geneal project data window

5. In the upper left hand corner of the screen, one will see your project; right-click on the name of one's project area and choose 'Add Project component'
6. From there, one may choose what items one wants to cost (Figure 29)

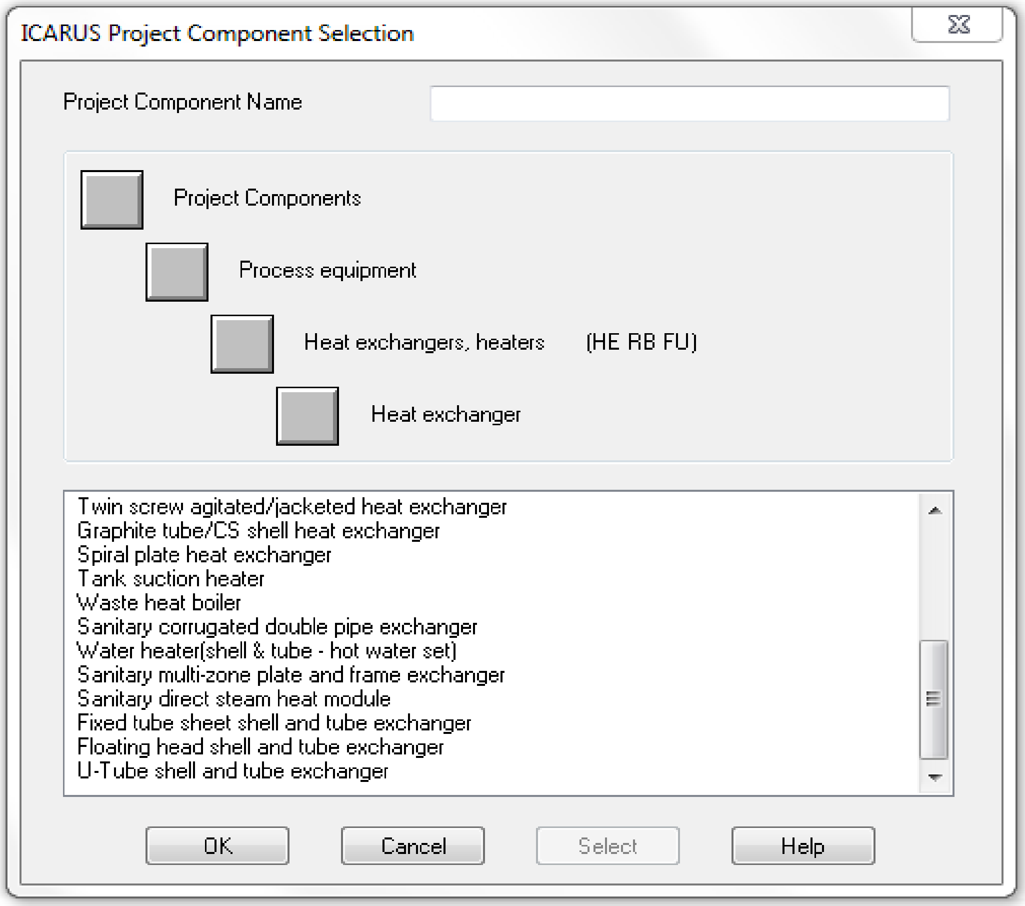

Figure 29: Project component selection window

7. After choosing the item, one may add/change the specifications of the chosen item (Figure 30).
8. To cost the item, left-click on the evaluate button above the equipment specification screen.

Name	Units	Item 1
Item Reference Number		1
Remarks 1		
Remarks 2		
Item description		PV
User tag number		
Structure tag		
Component WBS		
Quoted cost per item	USD	
Currency unit for matl cost		USD
Source of quote		VB
Number of identical items		1
Installation option		
Code of account		
Icarus/User COA option		
Application		CONT
Shell material		SS304
Liquid volume	M3	
Vessel diameter	M	3
Vessel tangent to tangent height	M	30
Design gauge pressure	KPAG	1,100
Vacuum design gauge pressure	KPAG	
Design temperature	DEG C	30
Operating temperature	DEG C	
Skirt height	M	
Skirt thickness	MM	
Vessel leg height	M	
Wind or seismic design		
Fluid volume	PERCENT	20
Manhole diameter	MM	450
Number of manholes		1
Allowance for internals	PERCENT	0
Demister thickness	MM	
Demister area	M2	
Base material thickness	MM	
Corrosion allowance	MM	
Number of body flange sets	PAIR	
Weld efficiency	PERCENT	100
Stress relief		
Cladding material		
Cladding thickness	MM	
Stiffening ring spacing	MM	
Head type		
Head thickness Top	MM	
Head thickness Bottom	MM	

Figure 30: Equipment specification screen

Appendix C
ACCE Sample Item Report

By right-clicking the item one costed and selecting "item report", a report like the one below is generated. All the values you specified (Figure 30) as well as the default (or calculated) values needed are shown under design data. The equipment, installation and labor costs are shown under summary cost. The following item report (taken directly from the program) is for a 304 stainless steel vertical process vessel at 1100 KPAG with a diameter of 3 meters and a height of 30 meters.

ITEM REPORT

Processing Date : Wed Dec 23 10:36:05 AM 2015
Version : Aspen Capital Cost Estimator 34.1.0(Build 3457)

List of Items :

Project : Thesisequipment
Scenario : Process vessels
PV

Project : THESISEQUIPMENT
Scenario : PROCESS VESSELS

PV

Item Code: DVT CYLINDER
Internal Name : DVT CYLINDER PV

Sizing Data
Design Data
Summary Costs

Sizing Data

Description	Value	Units

Design Data

Parameter	Value	Units
Item type	CYLINDER	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Application	CONT	
ASME design basis	D1NF	
Liquid volume	211.982	M3
Design gauge pressure	1100.000	KPAG
Design temperature	30.000	DEG C
Operating temperature	30.000	DEG C
Fluid specific gravity	1.0000	
SHELL DATA		
Shell material	SS304	
Diameter option	ID	
Vessel diameter	3.0000	M
Vessel tangent to tangent height	30.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Fluid volume	20.000	PERCENT
Weld efficiency	100.000	PERCENT

Base material thickness	13.000	MM
Corrosion allowance	0.000000	MM
Head thickness Top	7.0000	MM
Head thickness Bottom	8.0000	MM
THICKNESSES REQUIRED		
Circumferential stress thickness	12.831	MM
Long tensile stress thickness	6.6875	MM
Long compressive stress thick	7.0744	MM
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	4.5000	M
Skirt thickness	13.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	SS304	
Nozzle A Quantity	1	
Nozzle A Diameter	400.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	1	
Nozzle B Diameter	450.000	MM DIAM
Nozzle B Location	S	
Nozzle C Quantity	1	
Nozzle C Diameter	350.000	MM DIAM
Nozzle C Location	S	
Nozzle D Quantity	1	
Nozzle D Diameter	200.000	MM DIAM
Nozzle D Location	S	
Nozzle E Quantity	8	
Nozzle E Diameter	50.000	MM DIAM
Nozzle E Location	S	
Number of manholes	1	

Manhole diameter	450	MM
WEIGHT DATA		
Shell	29600	KG
Heads	1700	KG
Nozzles	310	KG
Manholes and Large nozzles	160	KG
Skirt	4400	KG
Base ring and lugs	900	KG
Ladder clips	140	KG
Platform clips	300	KG
Fittings and miscellaneous	70	KG
Total weight	37600	KG
VENDOR COST DATA		
Material cost	191861	DOLLARS
Shop labor cost	71551	DOLLARS
Shop overhead cost	75566	DOLLARS
Office overhead cost	57626	DOLLARS
Profit	55497	DOLLARS
Total cost	452100	DOLLARS
Cost per unit weight	12.024	USD/KG
Cost per unit liquid volume	2132.724	USD/M3

Summary Costs

Item	Material(USD)	Manpower(USD)	Manhours
Equipment&Setting	452100.	11629.	368
Piping	244064.	63931.	2103
Civil	9339.	8236.	328
Structural Steel	29488.	5262.	183
Instrumentation	55450.	5678.	182
Electrical	4590.	2703.	90
Insulation	0.	0.	0
Paint	555.	775.	35
Subtotal	**795586**	**98214**	**3289**

Total material and manpower cost = USD 893800.