Case Study that Integrates Thermodynamics with Engineering Economics

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Abstract

This paper presents a case study that is a practical example for use in second semester thermodynamics, air conditioning or engineering economics courses. It integrates the students exposure to thermodynamics and engineering ecomomics.

There is tremendous pressure to purchase the equipment with the lowest possible initial cost. However, if energy prices increase dramatically the choice of a low initial cost system may create unbearably high operating costs which could drive the owner of the equipment out of business. This is not good for future business. The goal of this paper is to equip students with a tool they can use to make optimum choices when selecting the level of efficiency for a piece of equipment. This tool uses life cycle cost analysis applied to thermodynamic systems (thermoeconomics) as the objective function in the optimization of a chiller. Thermo-economics will help the manufacturer determine what level of efficiency is best for the market. It will help the engineer determine the appropriate sizes for the components of a system. It will help the suppliers convince the building owner whether or not the additional cost for a high efficiency system is worth the additional investment.

How do we then trade off between the coefficient of performance (COP) and the initial costs? Thermo-economics gives us a tool we can use to balance these two opposing forces and determine the optimum COP of a piece of equipment for a particular application. In this paper thermo-economics was applied to the selection of a 400 ton (1400 kW) chiller operating 2500 hours/yr. In this example an investment in a high efficiency chiller produced a rate of return of 20 %. The thermoeconomic model (return on investment analysis) was simple for ease of use and understanding. It assumed the purchasing power of the currency was constant over the life of the equipment. It did not account for salvage value, depreciation or fuel price escalation since these variables increase the complexity of the analysis and have a high degree of uncertainty. The uncertainty was addressed through the use of sensitivity and breakeven analyses. The effects of changes in seven independent variables upon the return on investment were explored. The rating of the low efficiency equipment would need to decrease below .663 kw/ton (COP=5.30) or that of the high efficiency equipment would need to increase above .627 kw/ton (COP=5.61) for the return on investment to drop below 10%. The initial investment in high efficiency equipment would need to exceed $91,000, electricity costs would need to drop below $.042/kwh, the operating time would need to drop below 1500 hours a year, the cooling load would need to drop below 240 tons(840 kW) or the life of the equipment would need to drop below 6.5 years before the high efficiency equipment will not provide an adequate return on investment

Thermo-economics is essential in the optimization of chillers or other energy consuming devices. It balances the opposing forces of initial cost and efficiency on equal footing: dollars. A user-friendly, easy to understand, return on investment analysis has been applied to a practical application. Sensitivity and breakeven analyses have been used to address the uncertainty that economic variables introduce into the problem. Students will want to add this tool to their professional portfolio so they are able to make wise choices that meet customer needs.

Introduction

The educational experience for an undergraduate student is often compartmentalized. In thermodynamics there is little time to present economics into an already full syllabus and in engineering economics the experience of the instructor limits the range of applications they can present. This case study is designed to integrate the information the students receive from these two courses. The economics are simplified so it can be used in a course on thermodynamics. The thermodynamics are explained sufficiently so someone without a background in thermodynamics can understand the application.

"Things should be made as simple as possible, but not any simpler." Einstein. Most engineers are comfortable with quantities that can be calculated with a high degree of certainty. Quantities such as coefficient of performance (COP), a measure of efficiciency, and irreversibilites, a measure of inefficiency, can be measured and predicted with high accuracy, usually within 5%. When economics are introduced into the equation engineers become uneasy because of the high degree of uncertainty in costs and prices. However, economics are essential in the analysis though if the optimum piece of equipment for an application is to be determined. If the optimum is based on maximizing the COP then the equipment will require infinite heat exchangers. Likewise if the optimum is based on minimizing irreversibilities then again infinite heat exchangers are required. In order to determine a realistic size of the heat exchangers one must consider the trade off between operating costs (which are a function of the COP and irreversibilities) and the initial cost (which is a function of the size of the equipment).

How do we integrate the costs into the analysis without making the analysis overly complex? The simplest method is to calculate the payback that determines the length of time required for the savings to pay back the initial investment. However, there are two drawbacks to this method. First, payback does not account for the fact that a dollar today is more valuable than a dollar in the future. Therefore, the value of future savings are inflated which may cause you to spend too much today on high efficiency equipment. Secondly, it is difficult to set a target value for an acceptable payback. We know it is somewhere between immediately and before the end of the life of the equipment. The method of thermo-economics applied in this study addresses these two issues without making the problem overly complex. The time value of money is taken into consideration using the present worth factor for a uniform series (e.g., annual energy savings). The target value is determined by comparing the rate of return for an investment with rates of return for other investments available to the owner of the equipment.

Baseline conditions

Whenever you make a choice it is based on a specific set of conditions you are aware of at the time of the decision. Some of these conditions are known with more certainty than others. Intially though you must decide upon a set of conditions which are most likely to occur. These conditions are called the baseline conditions. The following paragraphs provide the reasoning for the baseline conditions selected for this example.

The annual cost for operating a chiller is directly proportional to the number of hours it runs in order to meet the comfort requirements of the facility. There are many variables that influence operating hours. Outdoor temperature, solar radiation, number of occupants, lights, equipment, wind speed, control system setpoint and building materials are a few of the variables that affect operating hours. There are several energy analysis tools available that account for all these variables and provide a reasonable estimate of these operating hours. For this paper a typical office building located in Atlanta, Georgia was selected for analysis. The operating hours for a typical year were estimated to be 2500 hours.

Until the summer of 2000 energy prices had been stable for more than two decades. Since that time prices have changed dramatically. This is a good reason why we cannot depend on the results of the baseline analysis alone. We need to evaluate how each of the variables influences our decision through a sensitivity analysis. The EIA[1] reports on their web site that the average retail price for electricity in the United States for commercial customers was $ 0.0726/kwh in 1999. For this analysis the electricty price was rounded off to $ 0.07/kwh for the baseline case.

There are several variables that influence the performance of the chiller. The size and type of heat exchangers, fluid temperatures and flow rates, compressor type and expansion device are just a few of the variables. For this study two different chillers were evaluated at the same design cooling load of 400 tons (1400 kW). Manufacturer's performance data were used for the baseline. Both chillers had centrifugal compressors and shell and tube heat exchangers with copper tubes. Both use R134a for the refrigerant. The primary difference between the two systems is the size of the heat exchangers. The high efficiciency unit has an evaporator that is 135% larger and a condenser that is 173% larger than the low efficiency unit based on weight. In order to keep the same capacity even though the heat exchangers were much larger the compressor's impeller size and speed are reduced accordingly. The performance data were based on the Air-Conditioning and Refrigeration Institute (ARI) Standard[2] 550/590 which specifies the operating conditions displayed in Table 1.

Table 1. Operating Conditions

Operating Variable	Value
Water Temperature Leaving Chiller	44 ºF (7.0 ºC)
Evaporator Waterside Field Fouling Allowance	.0001
Chilled Water Flow Rate	960 gpm (61. liters/s)
Water Temperature Entering Condenser	85 ºF (29. ºC)
Condenser Waterside Field Fouling Allowance	.00025
Condenser Water Flow Rate	1200 gpm (76 liters/s)

For the operating conditions contained in Table 1 the high efficiency chiller required .560 kW of compressor power per ton of cooling (COP = 6.28) while the low efficiency unit required .732 kW/ton (COP = 4.80). The initial cost for the high effiency unit was assumed to be $175,000 while the low efficiency unit only cost $120,000. The life of the chillers is assumed to be the same at 15 years. This is based on estimates of service life of various heat and cooling systems and components given by ASHRAE[3] (1999). Fifteen years is the life listed for water-cooled air conditioners.

Thermo-economics

Thermo-economics is essentially the application of life cycle costs to thermal systems. It allows us to weigh the opposing effects of initial costs and operating costs. It converts engineering units (e.g., kwhs, btus, etc) into business units or dollars. It is a tool that can be used to persuade a customer to invest in high efficiency equipment when appropriate.

Assumptions

The following four assumptions were made in order to keep the analysis as simple as possible but not too simple. First the purchase power of a dollar was assumed constant with respect to time. This means that any inflation in energy costs was equal to the inflation in income used to pay for the energy. The sensitivity analysis presented later could be used to estimate the impact of any disparity between rate of change in energy costs and income.

In addition to constant purchasing power the maintenance costs were assumed equal for the two chillers. This was a particularly valid assumption for the case considered in this paper since the only difference between the two chillers is the size of the heat exchangers. In other cases this may not hold since increases in efficiency may reduce reliability. When this is the case the increased maintenance costs can be directly subtracted from the annual energy savings.

The third assumption was the salvage value is negligible at end of life. Although accounting for salvage value would not add much complexity to the economic model it also would not add much information either. For example, assume the salvage value was 10% of the original value of the equipment at the end of its useful life of 15 years. Also assume the owner expected to receive a 10% per year return on investment. Then in today's dollars the salvage value would be only worth 2.4% of the original equipment cost. Under these conditions the salvage value is negligible and can be overlooked.

The fourth and final assumption was the effect of taxes was not considered. Riggs[4] (1977) states, "When alternatives being compared are to satisfy a required function and are affected identically by taxes, the before-tax comparison yields the proper preference." In our example both chillers were satisfying the required function of keeping the occupants of a building comfortable and were subject to identical tax rates and depreciation schedules. Therefore, it was unnecessary to complicate the analysis by considering taxes.

Time Value of Money

Benjamin Franklin once said, "A bird in the hand is worth two in a bush." This is also true with money. If someone were to offer you a $100 today or $104 a year from now which would you choose? A responsible person would choose the $100 today because it could be invested and then generate more than $104 a year from now. That is because money changes in value over time. Over the life of a piece of equipment future savings become less valuable on a per dollar basis. If this is not taken into consideration you will spend too much money on your initial investment. For example: Assume a 10% return on an investment and an equipment life of a 15 years. If the time value of money is not factored into the analysis the energy savings for the high efficiency equipment would be overvalued by nearly twice its real value in today's dollars. In today's competitive environment you cannot afford to make too many mistakes like that.

The equation that relates an annual payment, in this case energy cost savings, to its present value was given by Riggs[4] (1977) below in Equation 1.

$$P = A\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right) \quad (1)$$

where,

P = Present value of the annual payment ($)

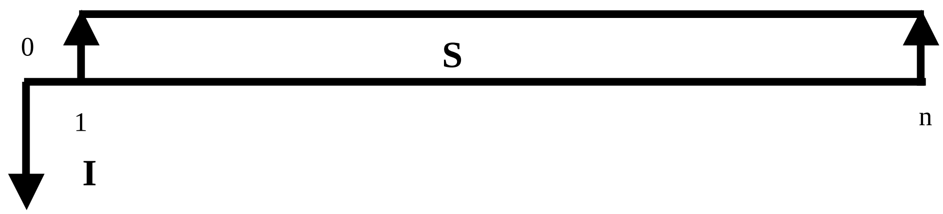
A = Amount of annual payment ($/yr)

i = Time value of money (fraction/yr)

n = Expected life of equipment (yrs)

After translating future energy savings into current dollars this equation was used to perform a rate of return analysis. Please refer to the cash flow diagram for our problem given in Figure 1. At year 0 "I" dollars was invested in a high efficiency piece of equipment. This investment was the difference in initial costs between the high efficiency equipment and the low efficiency equipment. During years 1 through n, a savings (S) in energy costs was realized each year.

Figure 1. Cash Flow Diagram for an Investment in High Efficiency Equipment



To determine the rate of return on the investment set the investment equal to the present worth of your annual savings as shown in Equation 2 and solve for the time value of money (i). Even though this equation is in implicit form there are several software tools available to solve this type of equation.

$$I = S\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right) \quad (2)$$

where,

I = Investment in high efficiency equipment over low efficiency equipment ($)

S = Savings in energy costs ($/yr)

The only task that remains to complete the analysis was to determine the annual energy cost savings. This was done using Equation 3.

$$S = L \times t \times c(r_l - r_h) \quad (3)$$

where,

L = Design cooling load (tons)(kW)

t = Annual operating time (hours/year)

c = Cost for electricity ($/kwh)

r_l = Inverse efficiency rating of low efficiency equipment (kw/ton)(1/COP)

r_h = Inverse efficiency rating for high efficiency equipment (kw/ton)(1/COP)

Results

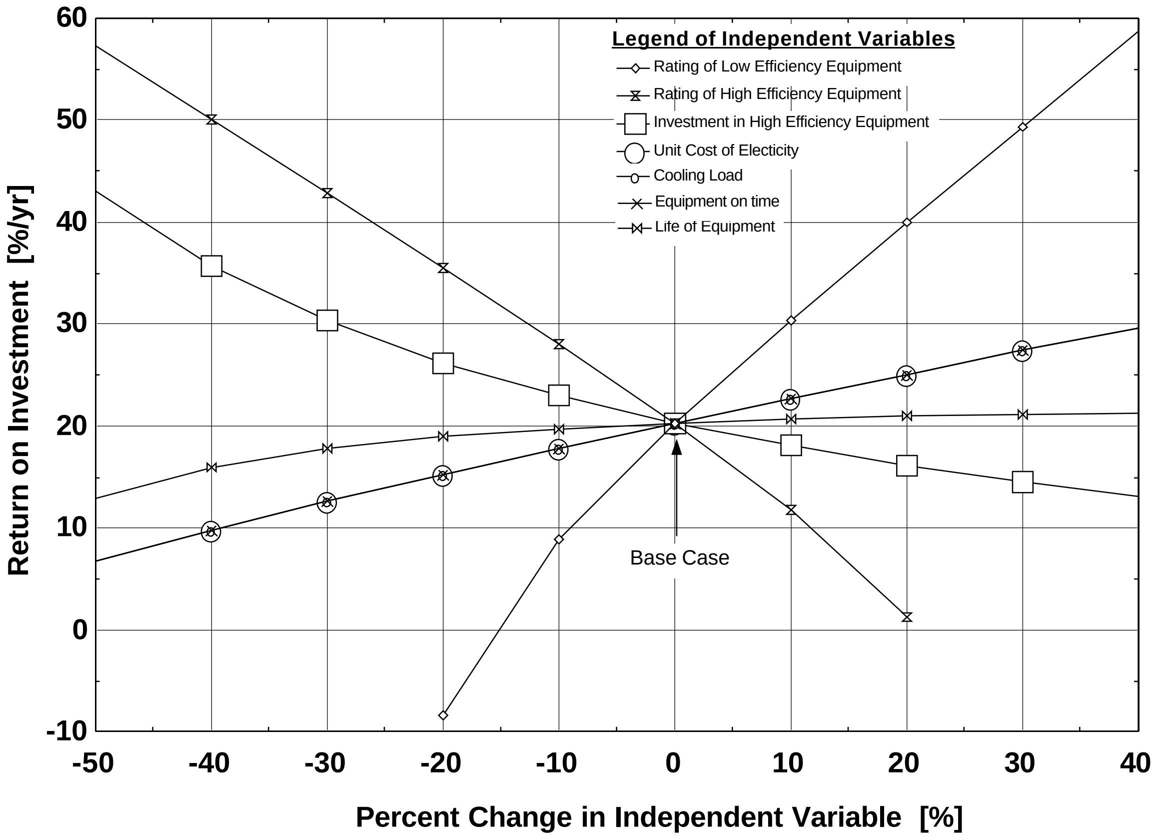
The input data needed for the analysis have been compiled and the tools necessary to perform the economic analysis have been developed. Next, the results of the baseline case will be presented. The baseline case was composed of the most likely senario and will lead to the outcome with the greatest probability. For the baseline case given the specifications for the chillers noted earlier the return on investment is 20%.

However, we live in uncertain times and it is difficult to predict how any of the seven variables considered in this analysis will change with time. For this reason a sensitivity analysis was also performed. A sensitivity analysis is an excellent tool to handle uncertainty because it shows how changes in the input variables influence the result. Another useful tool that complements the sensitivity analysis is breakeven analysis. This quantifies the change required in each of the independent variables before the decision changes.

Sensitivity Analysis

Each of the seven fundamental variables in this analysis were varied individually from 50% below their baseline values to 40% above their baseline values while holding the other variables constant. The only exceptions to this occur in the ratings of the equipment where they become nearly equal to one another after changing by only 20%. The results are contained in Figure 2.

Figure 2. Sensitivity Analysis Results



To help interprete the data presented in Figure 2 it is useful to show the range of the independent variables in dimensional form rather than in percentage form. Table 2 contains this information.

Table 2. Ranges of Independent Variables in Dimensional Form

Independent Variable	50% Below Baseline	Baseline	40% Above Baseline
Low efficiency rating (kw/ton) [COP]	(-20%) 0.584 [6.02]	0.73 [4.80]	1.022 [3.43]
High efficiency rating (kw/ton) [COP]	0.28 [12.6]	0.56 [6.28]	(+20%) 0.672 [5.23]
Investment in high efficiency equipment ($)	27500	55000	77000
Unit cost of electricity ($/kwh)	0.035	0.07	0.098
Cooling Load (tons) [kW]	200 [700]	400 [1400]	560 [2000]
Equipment "on" time (hrs/yr)	1250	2500	3500
Life of equipment (yrs)	7.5	15	21

Breakeven Analysis

In the breakeven analysis each of the independent variables was changed until the rate of return equals the minimimum acceptable rate of return (MARR). For this analysis the MARR was assumed to be 10%. Table 3 lists the dimensional values of each independent variable at the breakeven point. They are listed in order of importance from the variable requiring the smallest change to the one requiring the largest change on a percentage basis.

Table 3. Results of Breakeven Analysis
Minimum Acceptable Rate of Return 10%

Independent Variable	Value at Breakeven Point	Change from Baseline (%)
Rating of Low Efficiency Equipment	.663 kw/ton [COP = 5.30]	-9.4
Rating of High Efficiency Equipment	.627 kw/ton [COP = 5.61]	12.0
Unit Cost of Electricity	$0.042/kwh	-40.0
Cooling Load	240 tons [840 kW]	-40.0
Equipment On Time	1500 hours/year	-40.0
Life of Equipment	6.5 years	-56.7
Investment in High Efficiency Equipment	$91,000	65.5

Discussion

The baseline case results in a return on investment of 20%. Is this a good return on investment? That depends on the owner of the equipment. What other investment options do they have? What is the level of risk they are willing to accept? If we use the stock market as a barometer, it has produced a rate of return averaging 12% per year over 15 year periods since 1932. A more conservative investor may use a 10-year government bond, which returns an average of 5% per year since 1798, as their guideline for making an investment choice. The raw financial data were extracted from GFD[5,6] (2001).

How do we know if the chiller will last 15 years? Will energy prices hold steady over the next 15 years or will they change? What happens if I can find a supplier that will give me a great deal on the high efficiency equipment so that my initial investment is reduced? Or what if I can find a more efficient piece of equipment at the same price? These questions and more can be answered by the sensitivity analysis.

Since all the independent variables were non-dimensionalized on a percentage basis they could be plotted on the same graph. This increased the usefulness of the sensitivity analysis significantly because now the effects of the independent variables on the dependent variable, in this case the rate of return, could be interpreted relative to one another. For example it is clear that the rating of the low efficiency equipment has a much stronger effect on the rate of return than the life of the equipment. A 40% increase in this rating will increase the return on investment from 20% to nearly 60% while the same percentage increase in the life of the equipment increases the return on investment by a miniscule 1%. The independent variables have been listed in order of importance in the legend in Figure 2.

The sensitivity analysis also was used to predict the level of uncertainty that can be tolerated in each of the independent variables. Assuming a minimum acceptable rate of return of 10%, all but two variables can tolerate 40% uncertainty without risking a change in the decision to purchase the high efficiency equipment. The remaining two variables (equipment ratings) can only tolerate an uncertainty of 10%.

It is interesting to note in Figure 2 that the unit cost of electricity, cooling load and equipment on time have an identical influence on the rate of return. This is supported by Equation 3 that shows that the energy savings is directly proportional to each of these three variables.

Another valuable way the data from the sensitivity analysis were interpreted was to determine, in dimensional form, how much each of the independent variables need to change before the decision changes or breakeven analysis. This gave target values of the independent variables that help determine when to change the decision. For example if a new technology were developed to create electricity at less than $0.042/kwh then it would no longer be cost effective to purchase the high efficiency equipment.

Conclusions

A practical case study has been presented which integrates the subjects of thermodynamics and engineering economics. The integration of these two subjects is essential since thermo-economics is the only way to properly account for the tradeoffs between efficiency and initial costs. Objective functions using irreversibilites or COP yield unrealistic optimums.

Realistic assumptions have been made to provide a simple thermo-economic analysis that has broad application. This tool can be applied using many of the software packages that are readily available to most engineering students. The tool can be applied not only to air conditioning systems but also heating and refrigeration systems in the selection of equipment. It can be used by engineering students to assist manufacturers, engineers, suppliers and building owners justify the additional investment in high efficiency equipment by determing the rate of return on that investment.

A nondimensional sensitivity analysis is a powerful tool to help you deal with the uncertainty that is introduced in the analysis by the cost data. It quantifies the uncertainty that can be tolerated in each of the independent variables. Then data collection efforts can be prioritized so that more accurate data are collected for the variables that produce the greatest change in the rate of return.

For the case studied in this paper there is a high degree of certainty that investing in the high efficiency equipment is the wisest choice. This decision would change only if the following changes in the independent variables occurred. The rating of the low efficiency equipment would need to decrease below .663 kw/ton (COP = 5.30) or that of the high efficiency equipment would need to increase above .627 kw/ton (COP = 5.61) for the return on investment to drop below 10%. The initial investment in high efficiency equipment would need to exceed $91,000, electricity costs would need to drop below $.042/kwh, the operating time would need to drop below 1500 hours a year, the cooling load would need to drop below 240 tons (840 kW) or the life of the equipment would need to drop below 6.5 years before the high efficiency equipment will not provide an adequate return on investment. Use this case study to introduce your students to a powerful economic tool to aid them in helping their employer make decisions that maximize their return on investment.

This case study was introduced to students as a part of a junior level laboratory class for mechancial engineers. The student feedback was favorable. They appreciated the practical aspects of applying life cycle costs when making design choices.

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Biography

DAVID CHARLES ZIETLOW, PH. D., P.E. is an assistant professor of mechanical engineering at Bradley University in Peoria, IL. His professional objective is to promote the wise use of energy resources through discovery and transmittal of the thermal sciences. He has twelve years of industrial experience in the thermal science area to complement his four years of academic experience.