

A THERMOECONOMIC ANALYSIS FOR HOME AIR CONDITIONING SYSTEM

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Abstract

The application of thermoeconomics to the optimization of a home air conditioning system will be presented in this paper. The method is well suited for application to thermodynamic process and exergy destruction. The exergetic efficiency of the compressor, condenser, evaporator, expansion valve and electric motor are chosen as the decision variables to be optimized. The total cost for the component system can also be calculated.

Introduction

Thermoeconomic analysis combines economic and thermodynamic analysis by applying the concept of cost (economic property) to exergy (energetic property). Most analysts agree that exergy is the most adequate thermodynamic property to associate with cost since it contains information from the second law of thermodynamics accounting for energy quality (Wall G, 1986). An exergy analysis locates and quantifies the irreversibilities in a process. Exergy based thermoeconomic methods are also referred as *exergoeconomics* (Tsatsaronis *et. al*, 1985).

The purpose of the thermoeconomic analysis of an air conditioning system is to minimize the overall product cost which can be expressed in terms of exergy variables and system variables (temperature and pressure)(Tozert R *et. al*, 1996).

System Model

The system configuration is defined in Figure 1 which consists of a compressor, a condenser, an expansion valve, an evaporator and an electric motor.

Table 1 shows a set of data identifying one possible operating condition for this plant. This will be assumed as the base-case state for the numerical example to be developed later in the paper.

Exergy Analysis

The first law of thermodynamics states that energy cannot be destroyed. However, the first law of thermodynamics does not recognize any waste in an adiabatic process.

The second law of thermodynamics shows a part of the flow energy such as the enthalpy of a flow stream, is useless. An exergy analysis based on the first and second laws of thermodynamics calculates the useful energy associated with each flow stream in a process (Lozano *et. al*, 1994) Exergy analysis accurately identifies and evaluates the true exergy destruction of an energy system. This analysis shows that useful energy are being destroyed during any step of the energy-conversion (Tsatsaronis *et. al*, 1994).

Exergy is not only an objective measure of the thermodynamic value of energy but it is also closely related to the cost of the energy because users pay for the useful part of energy.

Total exergy of a system are divided into four major components, which are the physical, E^{PH} , kinetic E^{KN} , potential E^{PT} and chemical E^{CH} exergy (Lozano *et. al.*, 1993). The total exergy can be calculated as follows.

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \tag{1}$$

Economic analysis

Cost estimates should be made during all stages of the design. This provides a basis for decision making at each stage. The cost of main product can be calculated through the following four steps (Bejan *et. al.* 1996, Blank L.T *et. al.*, 1989 and Burmiester *et. al.*, 1997): -

- estimate the total capital investment,
- determine the economic, financial, operating and market input parameter for the detailed cost calculation,
- calculate the total revenue requirement,
- calculate the leveled product cost.

Thermoeconomic Analysis

For an overall system operating at steady state, the cost balance is given by (Tsatsaronis *et. al.*, 1997):

$$\dot{C}_{p,tot} = \dot{C}_{f,tot} + \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} \tag{2}$$

The cost balance expresses that the total cost for the product of the system (\dot{C}_p) is equal to the combination of the fuel cost rate (\dot{C}_f) and the cost rates associated with capital investment (\dot{Z}^{CI}), and operating and maintenance (\dot{Z}^{OM}). The sum of these two variables can be replaced as: -

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{3}$$

Equations 2 and 3 show that the variable \dot{C} associated with the exergy stream and variable \dot{Z} represents all functions cost.

For a simple system, when the system operates at the state level there may be a number of entering and exiting streams as well as work or heat interactions with the surroundings. Exergy costing which involves cost balance is usually formulated for each component separately. For the entering and exiting streams of matter with associated rates of exergy transfer \dot{E}_i , \dot{E}_e , power \dot{W} , and the exergy transfer rates associated with heat transfer \dot{E}_q can be written as below:

$$\dot{C}_i = c_i \dot{E}_i = c_i (\dot{m}_i e_i) \tag{4}$$

$$\dot{C}_e = c_e \dot{E}_e = c_e (\dot{m}_e e_e) \tag{5}$$

$$\dot{C}_w = c_w \dot{W} \tag{6}$$

$$\dot{C}_q = c_q \dot{E}_q \tag{7}$$

where c_i, c_e, c_w and c_q are the average cost per unit of exergy in Ringgit Malaysia per gigajoule (RM/GJ). For example, the cost balance applied to the k th system component, by using Equations 4, 5, 6 and 7 will result in the following:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \quad (8)$$

When generated by using Equations 4 to 7, Equation 8 becomes:

$$\sum_e (c_e \dot{E}_e)_k + c_{w,k} \dot{W}_k = \dot{C}_{q,k} \dot{E}_{q,k} + \sum_i (c_i \dot{E}_i)_k + \dot{Z}_k \quad (9)$$

In this part, we will discuss the concept generation of fuel and product in the thermal stream. Both the product and fuel are expressed in terms of exergy and as we know, the fuel represents the resources in generating the product (Valero A. *et. al*, 1986)

After introducing the cost rates with the fuel (\dot{C}_F) and product (\dot{C}_P), we can define the average cost per unit of fuel and product for every component by using these equations:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \quad (10)$$

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \quad (11)$$

where $c_{F,k}$ and $c_{P,k}$ represent the average costs at which each exergy unit of fuel and product for the k th component.

The cost associated with the exergy destruction in a component is a hidden cost but it is very useful in thermoeconomic analysis. The cost rate balances with consideration of the exergy loss and exergy destruction are given as: -

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{L,k} + \dot{E}_{D,k} \quad (12)$$

$$c_{P,k} \dot{E}_{P,k} = c_{F,k} \dot{E}_{F,k} - \dot{C}_{L,k} + \dot{Z}_k \quad (13)$$

The cost rate associated with exergy loss, represents the monetary loss associated with the rejection of exergy loss from the system to its surroundings. For the simple approach, the cost rate of exergy losses will be set as zero, $\dot{C}_{L,k} = 0$ (Tsatsaronis *et. al*, 1994). Eliminating $\dot{E}_{F,k}$ and using Equation 11, Equation 13 that can be re-written as:

$$c_{P,k} \dot{E}_{P,k} = c_{F,k} \dot{E}_{P,k} + (c_{F,k} \dot{E}_{L,k} - \dot{C}_{L,k}) + \dot{Z}_k + c_{F,k} \dot{E}_{D,k} \quad (14)$$

eliminate $\dot{E}_{P,k}$ result in

$$c_{P,k} \dot{E}_{F,k} = c_{F,k} \dot{E}_{F,k} + (c_{P,k} \dot{E}_{L,k} - \dot{C}_{L,k}) + \dot{Z}_k + c_{P,k} \dot{E}_{D,k} \quad (15)$$

Assuming that the product is fixed and the unit cost of fuel is independent of the exergy destruction, Equation 10 can be rewritten as:

$$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \quad (16)$$

Similarly if we assume that the fuel is fixed and the unit cost of fuel is independent of the exergy destruction, Equation 11 can be re-written as:

$$\dot{C}_{D,k} = c_{P,k} \dot{E}_{D,k} \quad (17)$$

The values of the rates of exergy destruction \dot{E}_D and exergy loss \dot{E}_L provide thermoeconomic measures of the system inefficiencies. The component exergy destruction rate can be compared to the total exergy destruction rate within the system, $\dot{E}_{D,tot}$ giving the ratio:

$$y_D = \frac{\dot{E}_{D}}{\dot{E}_{D,tot}} \tag{18}$$

The exergetic efficiency ε is the ratio between product and fuel. The exergetic efficiency is defined by

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} \tag{19}$$

and the exergy rate balance for the system is,

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \tag{20}$$

Thermoeconomic Optimization

Conventional technique for optimization procedures may suffice for relatively simple air conditioning system, even though for such system cost and performance data are seldom in the form required for optimization (D’Accadia *et. al*, 1998). However, with increasing system complexity these conventional methods can become unwieldy, time consuming and costly.

The objective function for the case studies is shown below: -

$$\text{Minimize } \dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} \tag{21}$$

The cost-optimal exergetic efficiency is obtained for a component from the remaining system component based on the following assumptions:

- The *k*th component exergy flow rate of the product \dot{E}_p and the unit cost of the fuel $c_{F,k}$ remain constant, the investment costs increase with increasing capacity and exergetic efficiency of the component,
- the annual carrying charge associated with *k*th component is obtained by multiplying the total capital investment for this component by the capital recovery factor
- the annual levelized operating and maintenance costs for the *k*th system component has a constant that accounts for the variable operating and maintenance costs.

This objective function may be expressed as

$$\text{Minimize } c_{P,k} = \frac{c_{F,k}}{\varepsilon_k} + \frac{(\beta + \gamma_k)B_k}{\tau \dot{E}_{P,k}^{1-mk}} \left(\frac{\varepsilon_k}{1 - \varepsilon_k} \right)^{nk} + \varpi_k + \frac{R_k}{\tau \dot{E}_{P,k}} \tag{22}$$

The minimum cost per exergy unit of product is obtained by differentiating Equation 22 with respect to exergetic efficiency and setting the derivative to zero.

$$\frac{dc_{P,k}}{d\varepsilon_k} = 0 \tag{23}$$

Results And Discussion

Figure 2 is a bar chart showing the exergy destruction for the case study at pressure of 2 bar. Comparison was made when the system was operating at the optimum condition. Exergy destruction for the evaporator constitutes over more than 50% of the total losses of the system for the study case. Expansion valve accounts for a larger fraction of the total exergy losses in the optimum system. Further research and development must be made for the component to improve it (Wall G, 1991).

Figure 3 shows the situation where the condenser and expansion valve have a high cost rate when compared to the other components in the system. This situation is due to the high exergy losses which mean growth cost per exergy fuel for both components. So condenser and expansion valve will be less effective components. Figure 4 shows that the increase in efficiency in the optimum system is mostly affected in the evaporator. From the case study for the use of 2.0 bar, we can say that, at the optimum operation the cost value and exergy can be reduced.

Figure 5 shows the graph of the exergetic efficiency as a function of the compressor pressure. Generally the graph shows how the exergetic efficiency increases as the entering pressure of compressor increases. The rate of the exergy product to exergy fuel will decrease due to the exergy destruction for these components that causes this situation. At the same time, the evaporator has a lower exergetic efficiency when compared with the other components. This is caused by a high value of exergy fuel.

Figure 6 shows the total cost of the main components at the normal and optimum condition. The graph shows that the total cost decreases at the optimum condition. The shape of the graph is a straight-line and shows that the cost of the product value increases when the pressure increases. From Figure 6, we can also see that for the optimum rate of process, the cost saving will increase about 11% as compared to the actual working condition.

The result also indicates that the operation of the condenser and expansion valve are more expensive when compared to the other components. When the pressure increases from 1.0 to 2 bar for the total system, the operation of the compressor and electric motor will be more efficient, but not necessarily for the other components. Figure 7 shows that within a total increase of component cost and efficiencies, it is more economical to choose a less expensive compressor and electric motor.

Figure 8 shows the cost difference percentage between actual working conditions with optimal condition system at various pressures. From the curve, it is observed that the maximum value of the total cost component can be achieved when a system operates at 1.5 bar. From the optimum value of 1.5 bar, the following values of the cost can be obtained: compressor RM/hr 0.34, condenser RM/hr 0.76, expansion valve RM/hr 0.75, evaporator RM/hr 0.10 and electric motor RM/hr 0.49 by inserting the values from Table 1 into Equation 1 to 23.

Conclusion

Optimization, in a general sense involves the determination of the highest or lowest value over some range. In engineering, the usual consideration is for economic optimization, which usually means minimizing the cost of a given process or product.

The approach taken this paper is to combine the economic and thermodynamic analysis and applying it to a home air conditioning system. The results show that the compressor and evaporator are the components with the highest exergy losses. After the optimization, 11% of cost saving can be achieved. When the system operates at a pressure of 1.5 bar, the system will achieve the optimum level of efficiency for the various component as follow: compressor RM/hr 0.34, condenser RM/hr 0.76, expansion valve RM/hr 0.75, evaporator RM/hr 0.10 and electric motor RM/hr 0.49 where the total cost for the overall system is RM/hr 2.40.

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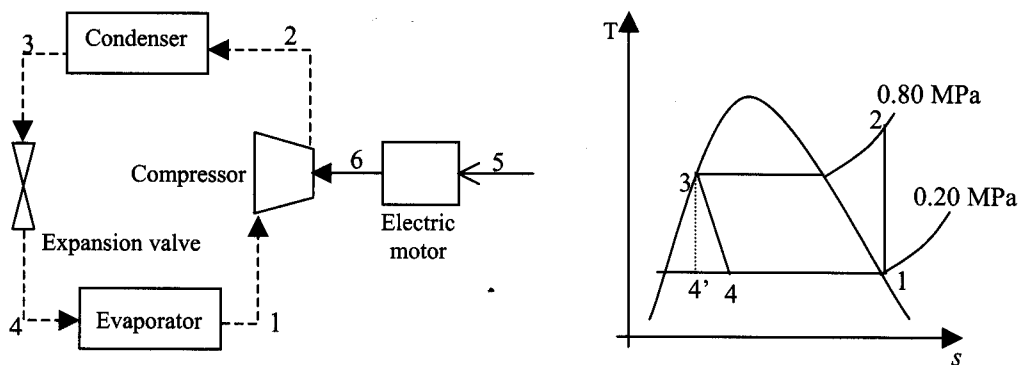


Figure 1 Schematic and T-s diagram for an air conditioning system

Table 1 The Summarized Data For A Typical Home Air Conditioning System

Refrigerant	R-134a
Saturated vapor condensing temperature	304.48 K
Saturated vapor evaporating temperature (altered) – 2 bar	262.25 K
Cold room internal temperature	298.15 K
Ambient temperature	303.15 K
Reciprocating compressor: assumed efficiency	
- Isentropic efficiency	0.8
- Electric motor's efficiency	0.9

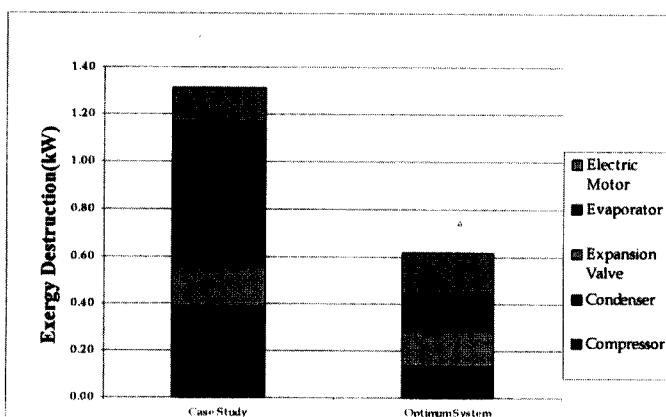


Figure 2 Exergy Destruction For The Case Study And The Optimum System

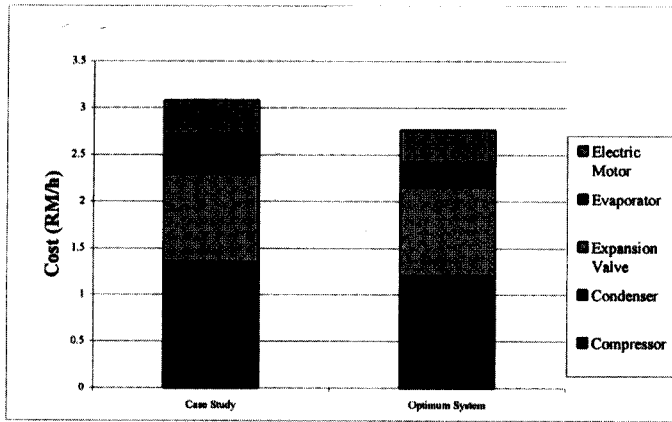


Figure 3: Cost For The Case Study And The Optimum System.

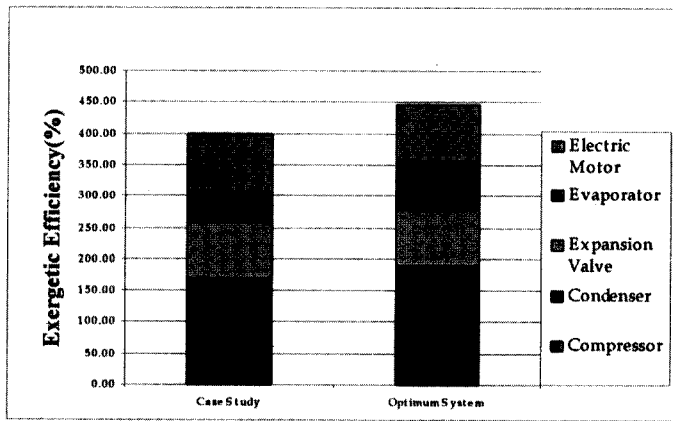


Figure 4 Exergetic Efficiency For The Case Study And Optimum System

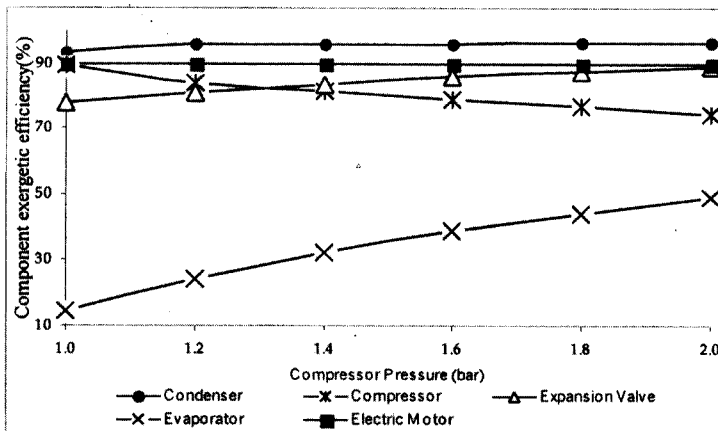


Figure 5 Exergetic Efficiency As A Function Of Pressure

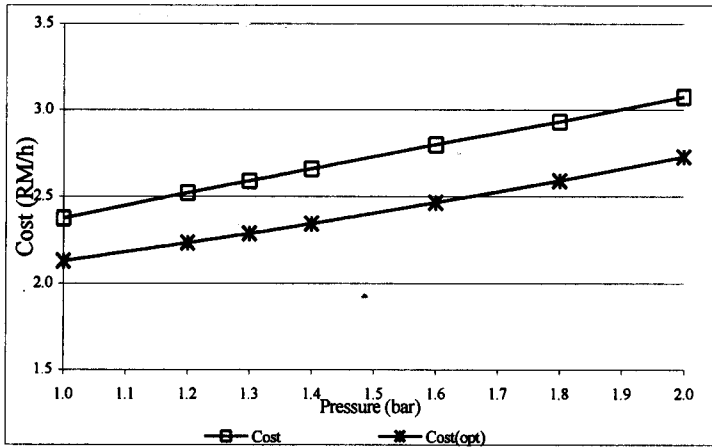


Figure 6 Component Cost As A Function Of Pressure

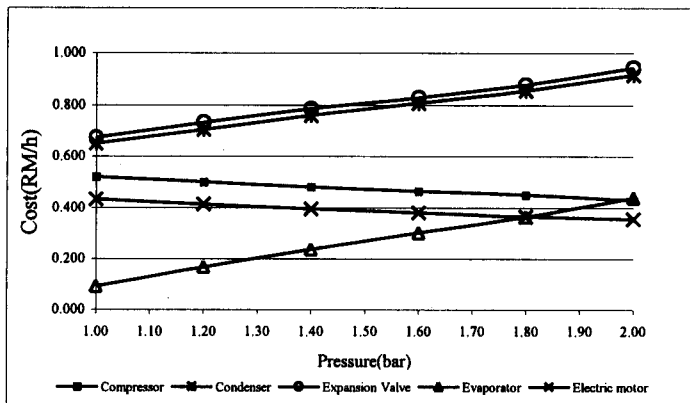


Figure 7 Cost Product Of Component As A Function Of Pressure

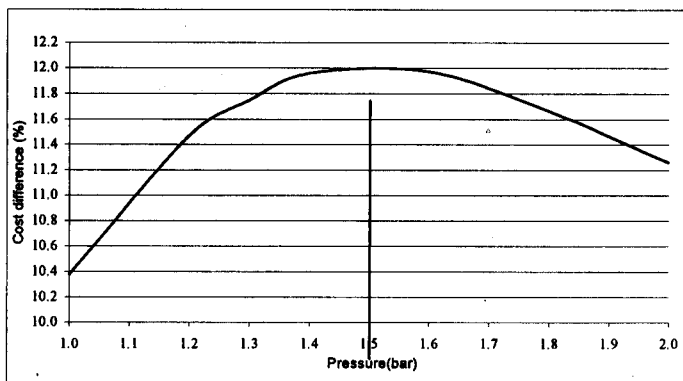


Figure 8 Cost Difference As A Function Of Pressure