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EXERGO-ECONOMIC ANALYSIS OF A BATCH CHEMICAL PLANT

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Abstract. Exergy analysis, also known as *Thermodynamic Analysis*, is a tool that has been widely used to analyse the energy efficiency of continous processes. It is a powerful analysis tool that is based on the First and the Second Law of Thermodynamics but has a least two shortcomings related to process improvement. First, it provides a measure of process efficiency based on thermodynamics but does not point to ways to improve a process. Second, some results generated from an exergy analysis study may contradict economy. Both issues are addressed in this study. We introduce the term *exergo-economic analysis* to refer to the application of exergy analysis in conjuction with economic analysis. We apply exergo-economic analysis on a *batch* activated carbon plant to provide a complete guideline for process improvement. Calculations of the exergetic efficiencies along with the appropriate interpretations of the process performance based on the First and Second Law of Thermofynamics lead to a number of desirable parametric and design changes for the process. By means of exergo-economic analysis, we show that a modification case involving a *decrease* in the exergetic efficiency may actually be economically desirable. Thus, we emphasize that economy must be made a key consideration in any exergy analysis study.

Key Words: Exergy analysis, *exergo-economic* analysis, activated carbon plant, exergetic efficiency, retrofit

1.0 INTRODUCTION

Exergy can be defined as the maximum work potential of a system in relation to the environment [1]. Exergy analysis, as the name suggests is an analysis tool to assess the energy efficiency of a process. The *source of exergy* in a system is provided by a process stream that supplies heat, and is calculated as follows [2,3]

$$\Delta Ex_{\text{source}} = (H_{h,2} - H_{h,1}) - T_o (S_{h,2} - S_{h,1}) \qquad (1)$$

On the other hand, the process stream that receives the heat is termed as *exergy sink*,

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$$\Delta Ex_{\text{sink}} = (H_{c,s} - H_{c,1}) - T_o\ (S_{c,2} - S_{c,1}) \tag{2}$$

Unlike energy, exergy is never conserved. Exergy which is not harnessed will degrade and will be lost. Exergy loss reflects the irreversibilities in a process. Exergy loss can be calculated from an exergy balance as follows,

$$\Delta Ex_{\text{lost}} = \Delta Ex_{\text{source}} - \Delta Ex_{\text{sink}} \tag{3}$$

The *exergetic efficiency* can be defined as,

$$\eta_{Ex} = \frac{\Delta Ex \sin\ k}{\Delta Ex_{\text{source}}} \tag{4}$$

Exergy Analysis, however, provides no solution to improve a process. Our observation also reveals that some results generated from an exergy analysis study may contradict economy. For example, some processes assessed as inefficient, in fact, are economically advantageous. These are the issues addressed in the present work.

2.0 METHODOLOGY

In this study, exergy is coupled with economic analysis to assess the efficiency of an activated carbon plant and guide process improvement. The batch activated carbon plant under study [4,5] is designed to produce 13.5 kg activated carbon from 15 kg. of plant charcoal. The process is first decomposed into four main processing steps that include raw material heating (also called reactor preheating), steam superheating, activation reaction and product cooling. Each step which involves significant exergy potential and exergy loss is modeled as a system comprising of an exergy source and an exergy sink.

An exergy balance performed on the system indicates the amont of exergy loss and reflects the extent of irreversibility of the process. Apart from the modelling equations, we also provide graphical representations of the quality and quantity of exergy for the process (See Figures 3 to 14). This is done using an exergy analysis software, *Supertarget*$^{\text{TM}}$ [6].

Figure 1 and 2 show the raw material heating, steam superheating, activation reaction and product cooling on a process duration chart and a time-event chart respectively. The time-event chart is a type of Gantt Chart for batch processes and it represents the sequence and progress of each process step with respect to time.

The time-event chart is used to analyse and reschedule the process, thus enabling heat recovery and an increase in productivity. In Figure 15, we show that removing the product cooling stage allows operation of more than one batch within the same time frame. This leads to savings in energy and increased production rate for the modified activated carbon plant.

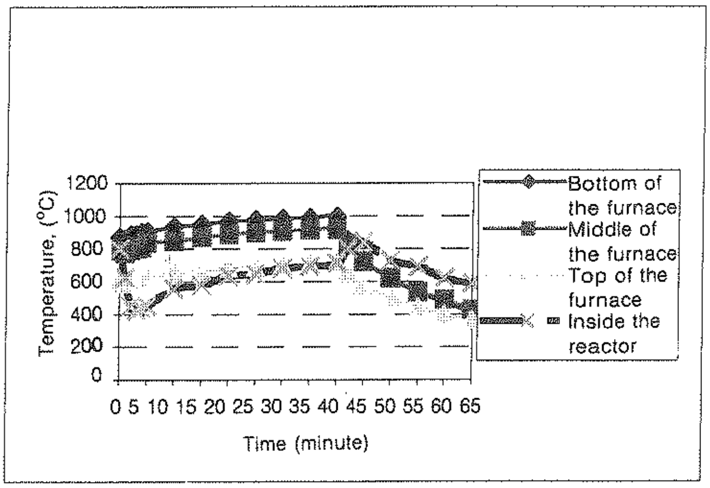

Figure 1 Temperature Change in the Reactor and Furnace During Activation Process (Mulop, 1991)

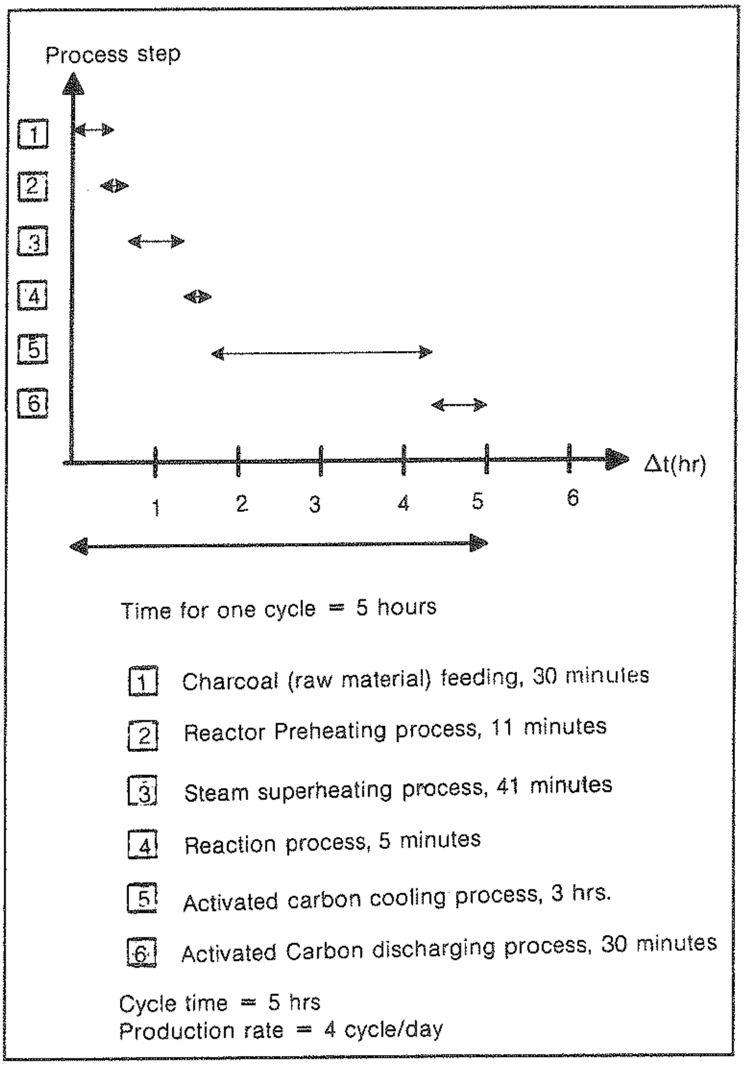

Figure 2 Time-Event Chart for Activated Carbon Plant

3.0 RESULTS AND DISCUSSION

Table 1 presents the results of the exergy analysis study on each of the process steps that are obtained through the application of equation (1) to (4). It is useful to have an overall picture of the quality and quantity of exergy for each of the given process, before and after process changes are made. Figures 3 to 14 provide graphical representations of the quality and quantity of exergy for the process, obtained using *Supertarget*^{TM} are presented in the form of Exergy Composite Curves (ECC) which is a plot of enthalpy versus Carnot factor. The areas under the upper and lower lines of the ECC represent the exergy source and exergy sink respectively. The difference between the two areas represents the exergy loss.

Result from the exergetic efficiency calculations shown in Table 1 show three areas of significant exergy losses that can be considered for efficiency improvement. They are:

(a) Exergy loss during heat transfer from hot gas to raw material in the reactor heating process.
(b) Exergy loss during mixing of hot gas with saturated water in superheating process.
(c) Exergy loss during product cooling.

In order to improve the exergetic efficiency of the plant, we recommend the reduction of steam flowrate and heat recovery from hot gas leaving the reactor to preheat either the incoming feed steam or air.

Table 2 compares the exergetic efficiencies of the main process steps before and after the proposed modifications. Reducing the steam flow rates from

Table 1 Result of Exergy Analysis for the Existing Plant

Process step	**Exergy Source (KW) Ex_{source}**	**Exergy Sink (KW) Ex_{sink}**	**Exergy Loss (KW) σT_o**	**Exergetic efficiency** η_{Ex}
Raw Material Heating	9.67	6.86	2.81	70.94%
Steam Superheating	486.13	340.38	133.6	69.90
Activation reaction	14.8	13.1	1.7	88.50%
Cooling of activated carbon	0.44	0	0.44	0%

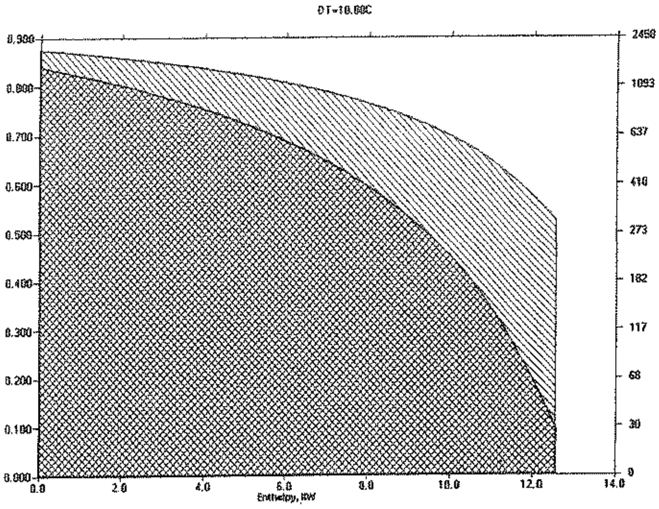

Figure 3 Exergy Composite Curve for Raw Material Heating (Reactor Preheating) Process

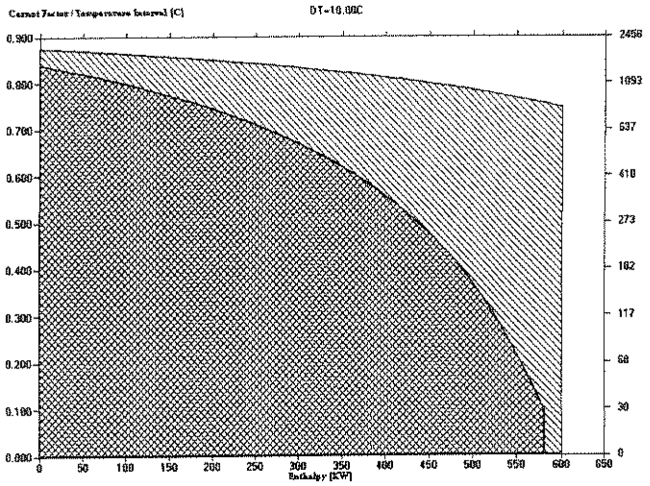

Figure 4 Exergy Composite Curve for Steam Superheating Process

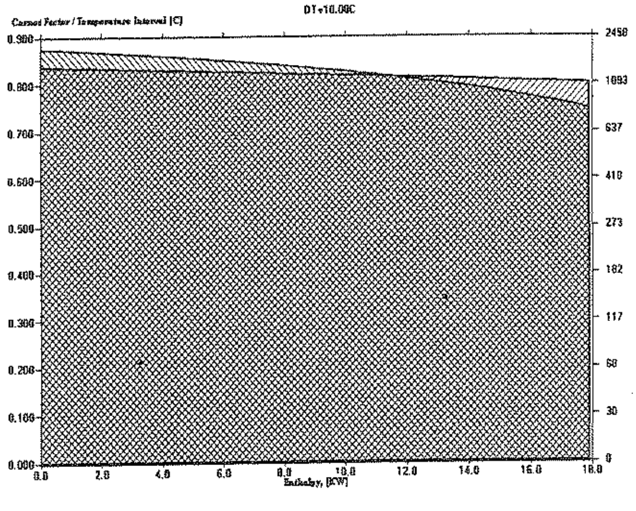

Figure 5 Exergy Composite Curve for Reaction Process

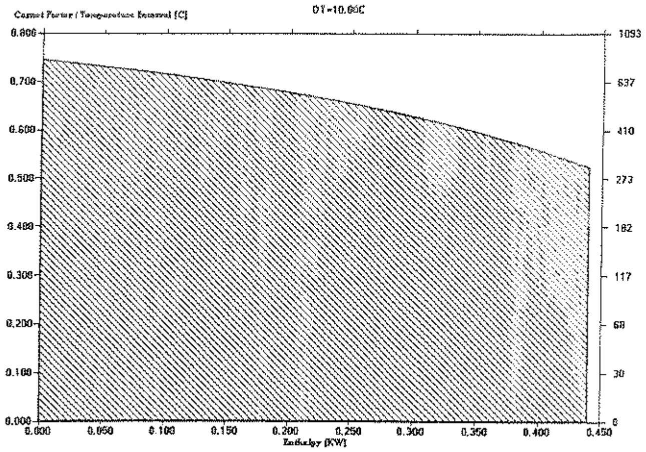

Figure 6 Exergy Composite Curve for Activated Carbon Cooling Process

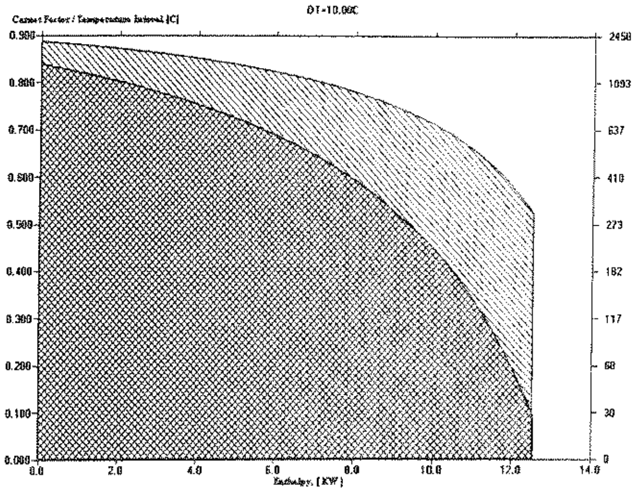

Figure 7 Exergy Composite Curve for Reactor Preheating Process (Modification - preheating air)

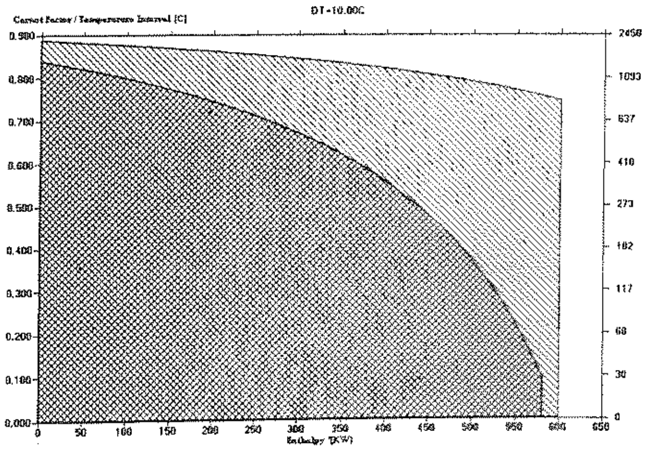

Figure 8 Exergy Composite Curve for Steam Superheating Process (Modification - preheating air)

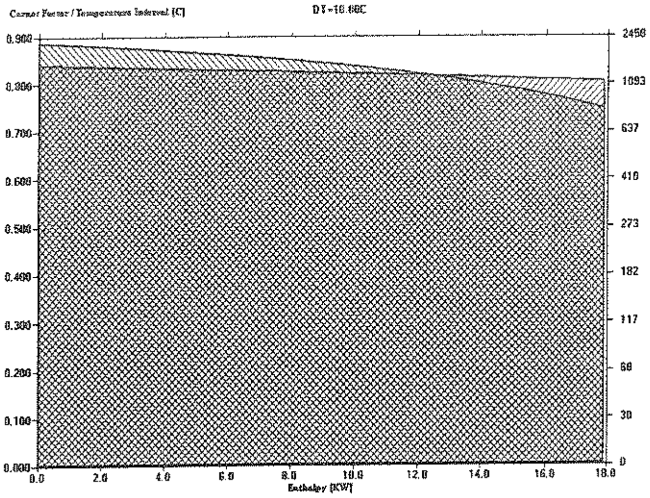

Figure 9 Exergy Composite Curve for Reaction Process (Modification - air preheating)

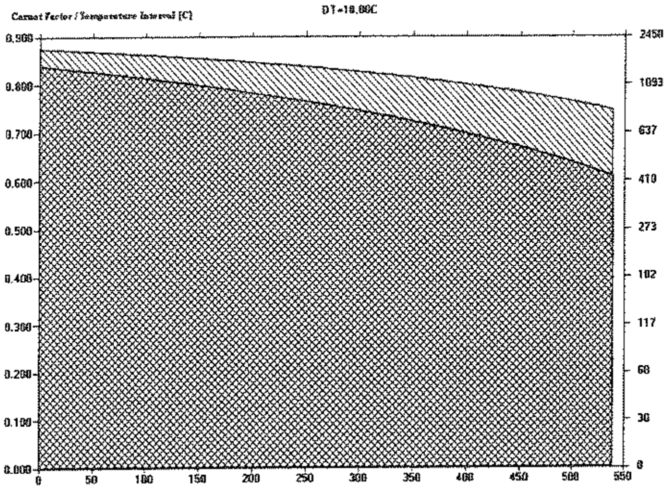

Figure 10 Exergy Composite Curve for Steam Superheating (Modification - preheating steam)

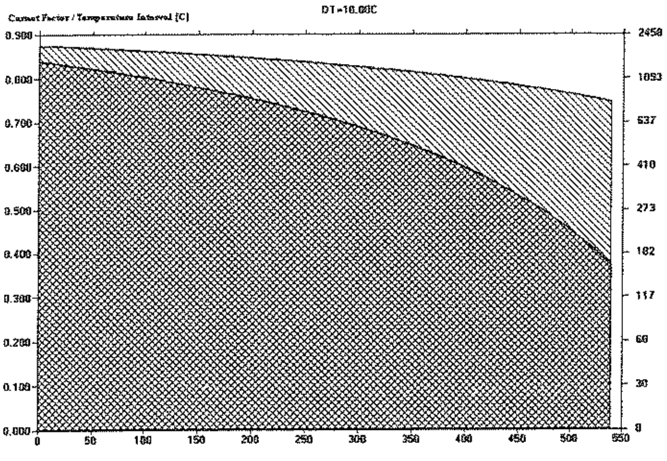

Figure 11 Exergy Composite Curve for Steam Superheating (Modification - steam flowrate

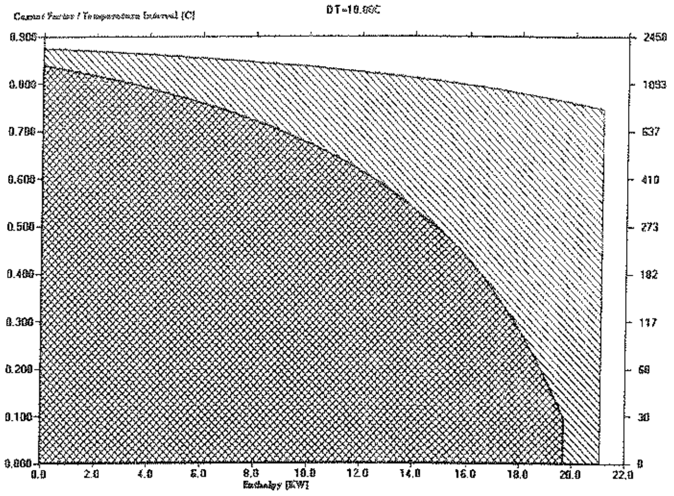

Figure 12 Exergy Composite Curve for Activation Process (Modification - steam flowrate)

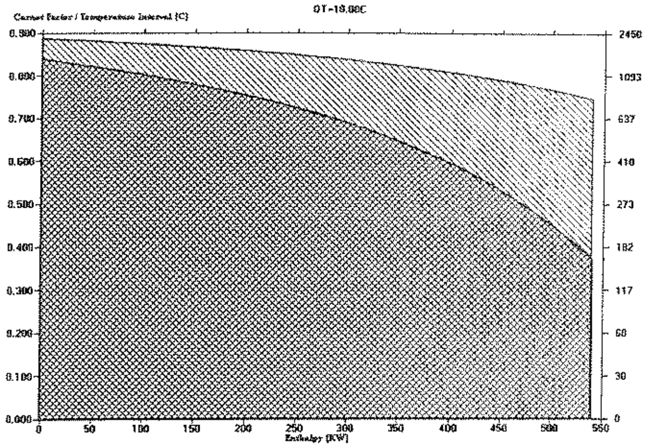

Figure 13 Exergy Composite Curve for Steam Superheating Process (Modification - air preheating & reduce steam flowrate)

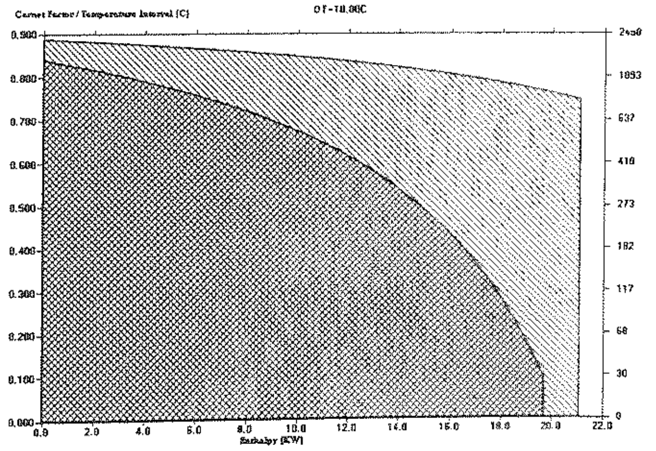

Figure 14 Exergy Composite Curve for Reaction Process (Modification - air preheating & reduce steam flowrate)

Table 2 Results of Exergy Analysis for Proposed Modified Plant

Process Step	**Exergetic Efficiency, η_{Ex}**				
	Existing Plant	**Modification Case**			
		Air preheating included	**Steam preheating included**	**Steam flow rate reduction**	**Steam flow rate reduction with air prehating**
Activated Carbon heating	70.94%	69.07%	NA	NA	NA
Steam superheating	69.90%	69.10%	79.20%	73.10%	72.20%
Activation reaction	88.50%	87.90%	NA	84.50%	84.50%

Table 3 Comparison for Air Preheating and Steam Preheating

	Heat recovery, 10^5 KW	**Exergetic Efficiency η_{Ex}**	**Capital Cost (RM)**
Air preheating	5.502	72.3%	280 000
Steam preheating	5.984	63.6%	27 400

0.103 m^3/s to the stoichiometric requirement of 0.006 m^3/s while maintaining the same amount of heat supply elevates the target temperature of the superheated steam. This measure increases the exergetic efficiency of the steam superheating process in the reactor by 3.2% (from 69.9% to 73.1%). Preheating the feed steam with hot gas leaving the reactor also increases the exergetic efficiency of the steam superheating process in the reactor by nearly 10% (from 69.9% to 79.2%).

Air preheating, however, is found to decrease the exergetic efficiencies of all process steps. This happens because air preheating increases the adiabatic flame temperature, leading to higher driving force for heat exchange in the reactor. With the sink (the reaction media) exergy remains constant, a bigger exergy loss results due to the higher driving force for heat transfer in the reactor. To prevent the loss of exergy and to reduce fuel consumption, we propose to maintain the highest reactor temperature to the same level as before the air preheating is included.

Table 3 compares the two preheating schemes in terms of exergetic efficiency, energy savings and capital investment. Clearly, steam preheating results in higher energy savings and significantly lower capital investment (the cost of heat recovery by steam preheating is 90.1% lower than that by air preheating) even though the exergetic efficiency for the steam preheating process is lower. Also, results in Table 2 suggest that steam preheating leads a higher exergetic efficiency for the reactor heating process. We thus consider steam preheating as the better scheme for heat recovery from the hot gas leaving the reactor.

The Exergy Composite Curve (ECC) for each modification is presented in Figure 7 to 13.

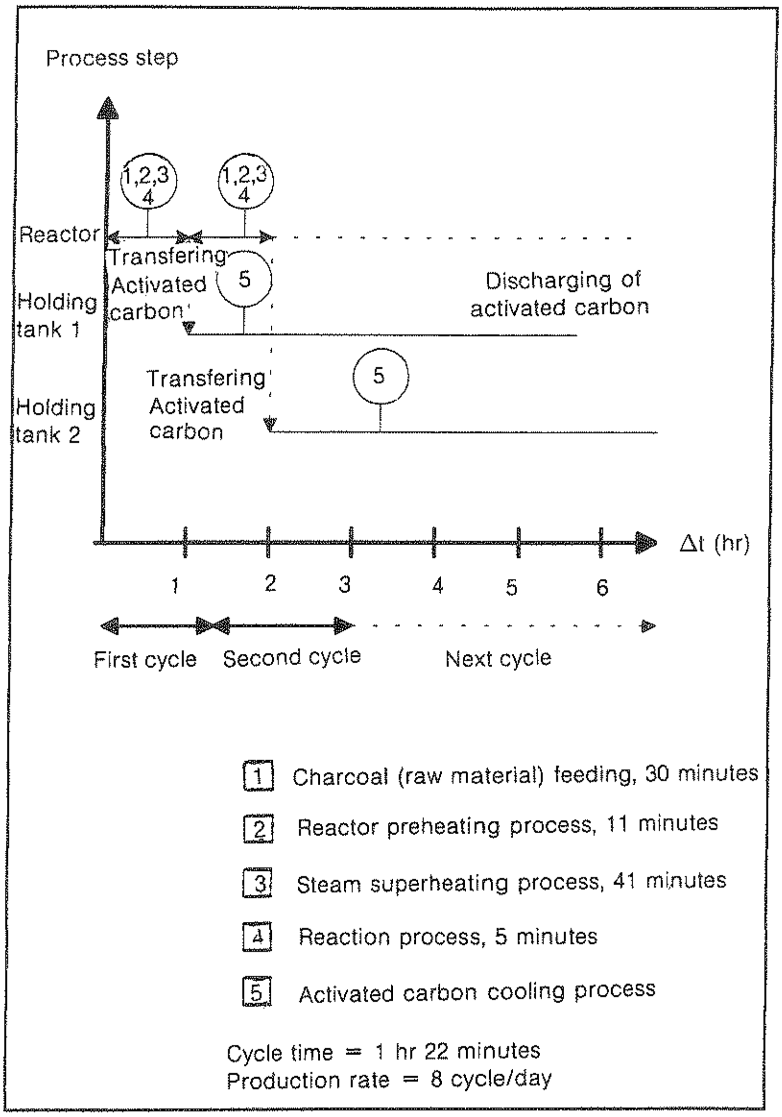

Figure 15 Time-Event Chart for Activated Carbon Process. Modification: Cooling Process in Holding Tank

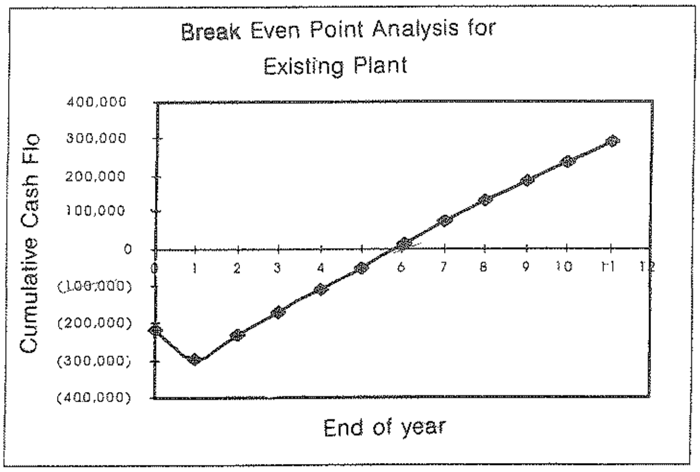

Figure 16 Break Even Point for the Existing Plant

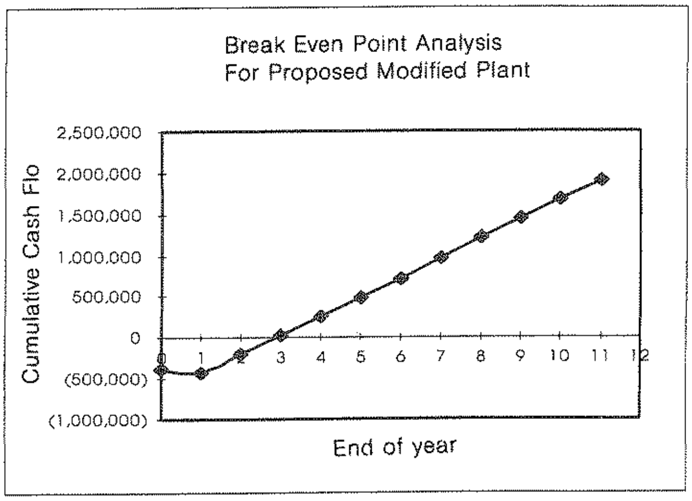

Figure 17 Break Even Point For Proposed New Plant

Finally, elimination of the cooling step from the batch cycle can increase the production rate of activated carbon to up to 60% per year. Figure 15 shows the proposed cycle which involves more than one process within the given time.

Two economic scenarios are analysed for the benefit of plant designers and operation engineers alike:

(i) The new design problem - This gives the projected cost of a new activated carbon plant. This scenario would be beneficial to plant designers.
(ii) The retrofit problem - This gives an estimated cost of the projected savings and the capital investment of the proposed modifications. This scenario would be beneficial to operation engineers.

The economic indicators are shown in Table 4. The internal rate of return (IRR) for the new plant is 72.0% compared to only 29.6% for the existing plant. The break even point is 3 years for the new plant and 5 years for the existing plant (see also Figure 15 and 16). On the retrofit project, the payback period on investment can be achieved after about 1 year operation. The estimated investment cost is around RM 47,000 and cost saving for steam and electric power is around RM 46,000 per annum.

Table 4 Economic Comparison for the Existing Plant and the Proposed New Plant

	Existing Plant	**Proposed Modified Plant**
Capacity (kg activated carbon/annum)	23 300	58 400
Economy		
Production cost	RM139 000	RM102 000
Break Even Point	5 years	3 years
Internal Rate of Return (IRR)	23.6%	72.0%

4.0 CONCLUSIONS

Exergo-economic analysis is applied to a batch activated carbon plant to identify the inefficiencies and to improve the plant's performance. The activated carbon process is first decomposed into four main processing steps, namely, raw material heating, steam superheating, activation reaction and product cooling. By focusing on the key processes, designers can identify the specific and meaningful potential changes to the plant operating parameters that can lead to process efficiency improvement. The results of the analysis show significant potential improvement through heat recovery from hot gas leaving the reactor, reduction in the steam flowrate and a modification of the cooling operation. Two economic scenarios representing new design and retrofit problems can benefit both new designers and operation engineers alike.

5.0 ACKNOWLEDGEMENT

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NOTATION

s	Entropy, Kj/kg.K
S	Entropy, KJ/s.K
h	Entaply, KJ
H	Entalpy, KW
T	Temperature, °C, K
W	Work, KW
Q	Heat, KW
m	Mass, kg/s
P	Pressure, KPa
n	Mol, mol
R	Gas constant

Greek letters

Δ	differential, e.g. ΔH is entalpi different
oT_o	Exergyloss
η_{Ex}	Exergetic efficiency
νA	stoichiometric coefficient for reactant or product A

Subscripts

Ex	Exergy
i	System input
e	System output