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Identification for Thermal Energy Optimization in the Process of Esterification Through the Evaluation of Combustion Reactions in Thermal Oil Heater

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Abstract: The optimization of energy has been conducted in the process of esterification. The energy for the process sourced from fuel gas combustion in thermal oil heater. The process optimization was conducted by identifying the products of combustion that in the reactor. The result shows for set point 150 and 200 ºC, the CO concentrations were 5182 and >10,000 ppm. However, the thermal efficiencies obtained at set point 150 and 200 ºC were 73.6 and 53.4%, which below the design value (80%). Therefore, this paper recommends combustion tuning to improve the efficiency. Finally, the potential saving also obtained through this improvement.

Keywords: Thermal energy, optimization, combustion, thermal oil heater

1. Background

The climate change has become a global issue and the growth of greenhouse gaseous (GHGs) emissions[1–7] was believed to be the main cause. Many countries concern with this issue, and they have developed policies toward to Net Zero Emission (NZE). The sector of energy dominates this issue, since the GHGs mainly produced from the activities within this sector.

Conserving energy is a part of the policies, and it is aimed to reduce the fuel consumption without reducing the products' quality [8–13]. In terms of economic literatures, the energy conservation means of reducing greenhouse gas emissions and the way of achieving the energy policy goals[14]. A recommendation obtained from the study conducted by *Tenrini et al.*, whereas the policy of energy efficiency has a positive impact to the environmental sustainability as well as economic growth[15]. Through this concern, it can be associated that obtaining better efficiency in energy usage will potentially give benefit on cost of production and environmental impact (reduce GHG emission).

This paper is aimed to show the effect of improvement in combustion performance to increase energy efficiency usage and how it potentially gains the cost benefit. The study is obtained from a case of improving efficiency in the process of producing a chemical product, named ester. Ester is a chemical compound, and derived from an acid (can be organic or inorganic) whereas at least one of the –OH hydroxyl group replaced by a group of an –O– alkyl (can be alkoxy).[16] Ester is mostly used as fragrances or perfumes and food flavoring; however, they can also be turned into polymers dubbed as polyesters. This can be used to make cans or plastic bottles. Around 11% of the world's market for specialty chemical in 2020 was made up of esters[16]. The global esters market is estimated to be worth around US$ 89.36 Billion in 2022. Owing to the rising demand for esters from diverse and end-use industries such as chemical, food, and automotive, the overall sales are projected to grow at a Compound Annual Growth Rate (CAGR) of 5.2% from 2022 to 2029, totaling US$ 127.41 Billion by 2029[17].

This growth indicates an increasing need of ester within the industries, not only in Indonesia, but also abroad. This situation attracts some manufacturers to produce ester as their main products and sell them as a raw material to the user industries[18].

Esterification is a general name of a chemical reaction, in which two reactants (an acid and alcohol) form an ester as their product. The formula of carboxylic acid esters is RCOOR' (whereas R and R' are any organics combining groups) that prepared from the reaction of alcohols and carboxylic acids in the presence of hydrochloric acid or sulphuric acid as a catalyst[19]. During the process of production, some parameters such as temperature, pressure, mixing process, and raw material composition become major consideration. Therefore, the esterification should be supported with main equipment that could provide sufficient condition for mixing, reacting and providing heating-cooling to obtain a required product. For providing a prompt heat to the process, a thermal energy sources can be considered obtained from hot water heaters, steam heaters, or recirculating hot oil systems. The process of heating preferred through an indirect heating, whereas a heat transfer medium from a liquid phase is heated and circulated to one or more heat or energy users within a closed-loop system[20].

The investigation is focused on the equipment of thermal oil heater (TOH). TOH is used to provide heat for esterification process, and controlling the heat level very important to obtain accepted quality of ester products. This study is taken from a case of using TOH in the esterification process with the data obtained from a plant that located in Indonesia. The flow process of heat from TOH to ester reactor can be seen in Fig. 1. The heat sourced from natural gas combustion in TOH, and transferred to reactor. There is a heat exchanger inside the reactor to transfer heat needed for esterification process.

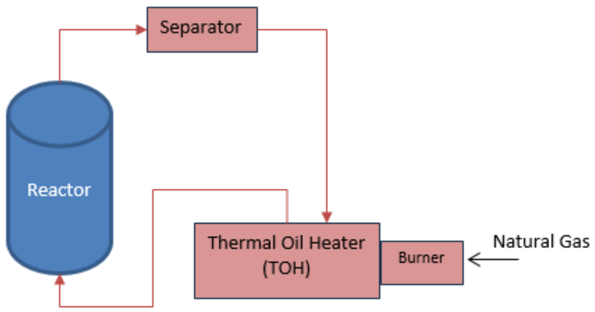

Fig. 1: Schematic diagram TOH and Ester Reactor

The objective of this study is to increase the energy efficiency in TOH by improving the combustion performance. The identification was conducted during the process of heat production for esterification process. The identification includes the combustion reactions occurred in the TOH. Optimizing the process of combustion reactions[21–28] within the TOH have important roles for obtaining the more efficient process. The study conducted by Ataei *et al* has provided a systematic method in designing the hot oil systems. This method accounts the interactions and identify the constraint occurred in the process, referred to a combination of mass pinch analysis and thermal to improve the efficiency of energy[29]. However, the study within this paper focus on the combustion process occurred in TOH, and includes the identification for obtaining the cost benefit potency after the improvement.

2. Thermal Oil Heater in The Process of Esterification

The esterification process used a case in this paper runs in a batch system using steam from the thermal oil heater (TOH) where the heated hot oil is flowed to an ester reactor with a capacity of 5 tons or 10 tons. The process flow can be seen in Fig. 2.

According to the procedure, the TOH is set at 20 °C above the target reaction temperature in order to maintain the products within the required specification. During the production process, the TOH output temperature can reach temperature up to about 250 – 260 °C.

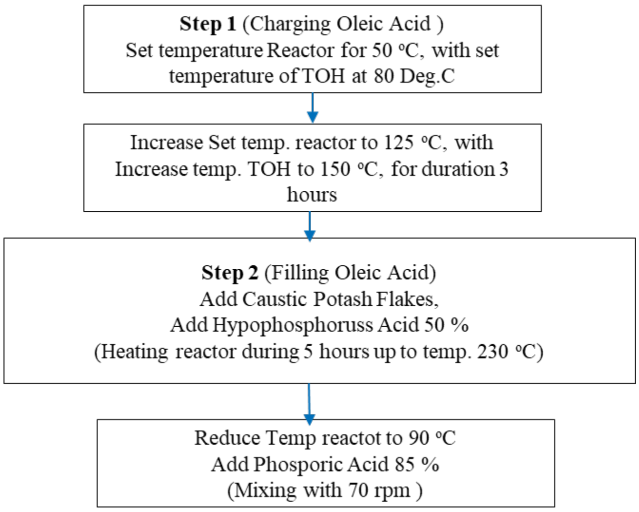

Fig. 2: The processes flow for operating TOH in the process of esterification.

The TOH uses gas fuel with a modulated burner type, where gas consumption adjusts the set point of output temperature. Hot oil is supplied to two reactors which are used to produce esters with capacities of 5 tons and 10 tons. The specification of TOH can be seen in Table 1.

Table 1. The specification of the TOH.

Parameter	Unit	Value/Description
Manufacturer		Basuki
Fuel		Natural Gas (CH_4 89.11%; C_2H_6 3.77%; C_3H_8 1.17%)
Burner		WM-GL20
Temperature Max	°C	300
Oil Flowrate	m^3/hour	94
Heat Output	kcal/hour	1,200,000

3. Test Performance on Thermal Oil Heater

The burner on TOH has modulation control specification, whereas the gas consumption will be adjusted to gain the output temperature of TOH reach the set point temperature. When the output temperature of TOH closer to the set value, the gas consumption will be reduced until stop. During this test, the temperature output of TOH were set at 150 °C and 200 °C, respectively. The data obtained through a recording device can be seen in Fig. 3.

(a)

(b)

Fig. 3: Burner for TOH profile at set point (a) 150 ºC and (b) 200 ºC

The reason why the temperature set on 150 and 200 ºC, because it follows the operational procedure as seen in Fig. 2. It is based on experiences that at these level of temperature the better esterification products will be obtained. Fig. 3 (a) shows the profile of TOH burner at set point 150 ºC, and Fig. 3 (b) for set point of 200 ºC. The trend of gas flowrate for each set of temperature also can be seen in this figure. As seen in Fig. 3, the profile of temperature in the TOH burner agree with the gas fuel flow. However, in order to identify the performance level of combustion process in the burner, the gas products measurement need to be measured and calculated.

4. Performance Results

The results of test performance in the combustion within TOH are presented in Table 2. Energy Performance Indicator of TOH is represented by the Efficiency within the TOH Burner, and represented with the calculation as stated in Eq. 1.

$$\eta_{TOH} = \frac{m_{ho} c_{pho} \Delta T_{ho}}{m_{gas} GHV} x\ 100\% \ \ldots\ldots\ldots\ (1)$$

With, η is efficiency, m_{ho} is oil mass flowrate, Cp is specific heat capacity of hot oil, and ΔT is the difference temperature initial and final of hot oil. Meanwhile, $\dot{m}_{gas}$, and GHV indicates the Gross Heat Value for fuel gas. The resume of calculation for identification process occurred in the TOH burner are provided in Table 2.

Table 2. Result of measurement.

Parameter	Unit	Value	
Temp Set Point	ºC	*150*	*200*
Fuel Gas Flow	Nm^3/h	**20**	**34**
GHV	BTU/SCF	1035.96	1035.96
	kJ/m^3	38558.43	38558.43
Heat from Gas	Kw	**214.21**	**364.16**
	MMBTU/h	**0.73**	**1.24**
Inlet Hot Oil Temp	ºC	139.60	181.70
Outlet Hot Oil Temp	ºC	149	193.3
Hot Oil Flow	m^3/h	**34**	**34**
Hot Oil Heat Gain	kW	**157.6**	**194.5**
	kCal/hr	**135644.65**	**167391.27**
Excess O_2	%	**0**	**0**
CO_2	%	**8.29**	**9.13**
CO	Ppm	**5182**	**>10000**
Excess Air, O_2	%	**0**	**0**
Flue Gas Temperature	ºC	**128**	**136.2**
EnPI: Thermal Efficiency	%	**73.6**	**53.4**

According to equation of efficiency above (Eq. 1), and as the values are presented in Table 2, the thermal efficiency obtained in TOH at the set point of 150 ºC and 200 ºC is 73.6% and 53.4%, respectively. However, these values are below their design, which was at 80%. Since the efficiency in TOH obtained below their design, therefore a potency of improvement. From the gas emission obtained in Table 2, it also can be seen that the excess of O_2 were zero, meanwhile the CO value for each set temperature were high (5182, and >10000 ppm). This condition indicates the rich combustion occurred during the combustion, and it means the excess fuel supplied into the combustion reactor. Therefore, the more efficient process can be obtained by reducing the fuel within the combustion process in TOH. And, this fuel reduction causes the potency of fuel cost reduction.

The condition occurred in the TOH are potentially to be improved with process of combustion optimization. Controlling the air and fuel ratio into the combustion reactor of TOH should be conducted to optimize the process. Therefore, by conducting the set of combustion process, it is expected the TOH efficiency can be increased and a potential of saving gas fuel can be obtained. The illustration in Fig. 4 can be considered used to improve the efficiency combustion of TOH reactor.

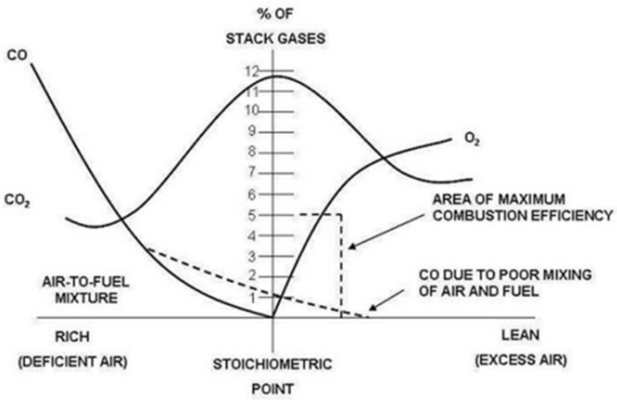

Fig. 4: Area of Rich and Lean Combustion[30].

Fig. 4 shows a reference that in line with the way to improve combustion efficiency in TOH. The combustion process can be optimized by reducing the gas fuel and controlling the O_2 and CO values. The less CO values should be obtained in order to gain the better combustion efficiency.

5. Energy Optimization Analysis

According to the operational data obtained during the test, to obtain one batch process of esterification (about 3800 kg), it consumes about 11 MMBTU (Million British Thermal Unit) of gas fuel. In average, the consumption of gas fuel to produce ester was about 3.31 MMBTU/ton. This value will be used as a reference to analyze the need for gas fuel in TOH combustion.

In order to optimize process combustion in the TOH, this paper uses flue gas emission analyses, as the products of combustion. As seen in Fig. 4, a good combustion occurs at an optimal excess air condition. In the combustion process, air is required to obtain stoichiometric condition, which also depends on the chemical species of the fuel, as well as the fuel feed rate[31,32]. At the condition of rich combustion, the air supply is below of it's need to achieve the stoichiometric combustion, and at this condition incomplete combustion occurred. It is indicated by a high concentration of CO gas emission. The combustion on the TOH should be set to shifts at the condition of the 10% excess air, as it is referred to the design. Some value of excess air that can be used as a reference for optimized combustion for several fuel can be seen in Table 3. It is expected, at this condition the heat energy produced from the combustion could optimally transferred to the working fluid.

Table 3. Typical Optimum Value of Excess Air and Oxygen for several fuel[33,34]

Fuel	% Excess Air	% O2
Gas	5-10	1-2
Coal	20-25	4-4,5
Oil	5-15	1-3
Biomass	20-40	4-6

With an average measured air rate was 160 m^3/hour, and the gas fuel consumption for TOH should be about 1.86 MMBTU/ton, however from the design document of TOH, the thermal efficiency should be at 80% and excess air should be at 10%, so the value can be adjusted to 2.48 MMBTU/ton. With reference of gas fuel consumption in the year of 2021 in the existing plant, so the potential for gas savings could be about 784.18 MMBTU/year or equivalent with about 107,335,000.00 IDR/year. If, it is assumed to conduct the optimization process of combustion needs cost about IDR 75,000,000.00, hence it requires about 0.7 years to achieve the break event point of optimization cost. The resume of calculation can be seen in Table 4.

Table 4. Saving Potential for TOH.

Parameter	Unit	Value
Total MMBTU Gas 2021	MMBTU	6871.6475
	IDR	940,554,557
Ester Gas Consumption	MMBTU/ton	3.31
Total MMBTU Gas Ester 2021	MMBTU	3136.71
	IDR	429,336,104
Average Air Flowrate	m^3/h	160
Ester Gas Consumption 10% of EA	MMBTU/ton	2.48
Gas Savings 2021	MMBTU/year	**784.18**
	IDR/year	**107,335,000**
	% Gas	**11.4**
Combustion Tuning	IDR	**75,000,000**
BEP	Year	**0.7**

It needs to be noted that savings gas fuel used during the combustion effect directly to the reduction of gas CO_2 emission. With an assumption that the greenhouse gas emission factor for natural gas about 56.1 tCO2/TJ[35], so the potency of gas emission reduced to about 46.42 tCO_2/yr

6. Conclusion

The data obtained from the measurement in TOH reactor shows a very limited of excess air (O_2) and higher of CO (see Table 2). In the same time, the performance (thermal efficiency) of TOH obtained as seen in Table 2, were 73.6% and 53.4%, respectively. These values were below the design value of TOH. Therefore, this study identifies the potency of saving by improving the combustion performance in TOH reactor. By increasing the excess air (O_2) in TOH up to 10%, as stated in the design, it is potentially to reduce the fuel cost. According the calculation as seen in Table 4, the potential saves up to about 107,335,000.00 IDR/year. However, by reducing the fuel amount, it also potential to reduce of GHG emission.

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Nomenclature

η_{TOH}	Efficiency in TOH
c_p	specific heat capacity (J kg^{-1} K^{-1})
m_{ho}	Mas flowrate (kg/s)
ΔT	Temperature difference
m_{gas}	Mass flowrate of the gas (kg/s)
s_0	specific enthalpy of the dead state (J kg^{-1} K^{-1})
GHV	indicates the Gross Heat Value
MMBTU	A thermal unit of measurement for Natural Gas (Million British Thermal Unit)

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