Criteria for optimizing the process of motor oil regeneration

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Abstracts. Ways to increase economic efficiency during motor oil recovery are presented in the paper. The engine oil regeneration involves the use of internal energy resources. The methodology of motor oil regeneration system assessment is given in the paper. The exergy is taken as a main study source of the analysis. Thus, this method allows figuring out the ways and levels of the energy use and its distribution on the individual level. Besides that, the most efficient parts of the regeneration system could be described. Thermodynamical optimization based on the proposed methodology grants the possibility to find the beneficial way of motor oil recovery. Hence it is also the most energy and economically efficient solution. Thermo-economic analysis provides information about the feasibility of the engine oil regeneration in general.

1. Introduction

The properties of motor oils are usually changing in time. The main reasons of motor oil deterioration are oxidation, thermal decomposition, mechanical pollution, water and gasoline dilution [1-3]. In most cases, such changes do not influence the possibility of motor oils reuse after the cleaning and recovery process [4]. There are two ways of the subsequent use of motor oils. First method is to use oil in the house heating by burning it in burning furnaces. The second way is a reuse of the old motor oil after its cleaning. However, the continuous growth of the prices on the hydrocarbons and the development of the ecological standardization make the recycle is an advantageous method. The use of the regenerative oils has a great impact on the economy, leads to the sustainable use of the oil products and reduce the amount of wastes and as a result, minimize the impact on the environment.

The methodology of the oil regeneration is based on the physical, chemical or physico-chemical process of polluted materials extraction from the used oil [5]. The physical methods of engine oil regeneration include mechanical cleaning and removal of water, asphaltenes, petroleum coke and other solid particles. The chemical regeneration is good for bitumen, water, acidic and hetero-organic compounds extraction. The physico-chemical removal is also useful in removal of distilled and emulsified water and acidic compounds. The multi-component structure of motor oils limits the applicable regeneration methods. Moreover, for the same reason, there is a difficulty in determination of the suitable regimes for the engine oil purification and amount of oil extraction. The best-fitted method for engine oil improvement should take into account the quality requirements and also allowable
number of contaminants in motor oils.

2. Materials and methods

Based on the literature analysis and review [6-8], it could be stated that currently, the approach of motor oil recovery efficiency assessment is absent. Since all modern methods of engine oil recovery are based on the multiple heating and cooling of the solution and as a result requires a lot of energy the questions of the secondary use of energy should be stated as priority. Moreover, the reuse of thermal energy could be done by warming input flows with the outgoing streams of previously cleaned oil. Thus, it could save a lot of energy on the stages of preliminary warming and also during the process of regeneration.

The practice of energy and technological systems optimization shows the significance of the thermodynamical analysis. So that assessment allows describing difficult chemical and thermodynamical process with the language of equations.

Consider to use the thermodynamical efficiency as a main parameter of the energy and technological features of motor oil regeneration installations during the profitability assessment. Moreover, the most promising way of the analysis is to check out the exergy concept based on the second law of thermodynamics. Exergy study allows studying the degree of energy use and its losses, besides that the distribution of the losses among the individual units of the system and the less efficient parts could be also clarified [9-11].

During the assessment and physico-chemical optimization of motor oil recovery process, the exergy and energy of the thermal flow are used as the main parameters [12]. Physical exergy (E) is the difference between temperature and pressure of the studied compounds from the temperature (T₀) and pressure (P₀) of the environment. Chemical exergy is related to the equality of the chemical potentials between compounds and the environment.

Then the molar exergy could be described by the following formula.

\[ E_m = H(T, P) - H_0(T_0, P_0) - T_0 \left[ S(T, P) - S_0(T_0, P_0) \right] - \sum_{i=1}^{n} x_i \left( \mu_i - \mu_{0i} \right) \]  

(1)

where \( E_m \), H, S – molar exergy, enthalpy and entropy of flow of the matter, KJ/mol, KJ/m³;
\( \mu_i, x_i \) – chemical potential and molar part of the i-th component in the mixture;
\( n \) – number of components; index "0" shows the parameters related to the environment.

Exergy of the warm flow is shown in the equation 2.

\[ E_q = Q(T - T_0)/T, \]

(2)

where \( T \) is the temperature of the flow, °K.

Physical and chemical parts of the exergy should be also taken into account during the analysis of the engine oil regeneration process. Then, in general, the increment of the molar exergy of the substance with the shift in temperature, pressure and composition has the following form:

\[ dE_m = \left( \frac{\partial E_m}{\partial T} \right)_{P, x_1, \ldots, x_n} dT + \left( \frac{\partial E_m}{\partial P} \right)_{T, x_1, \ldots, x_n} dP + \sum_{i=1}^{n} \left( \frac{\partial E_m}{\partial x_i} \right)_{T, P, x_1, \ldots, x_{i-1}} dx_i \]

\[ = \bar{E}_T dT + \bar{E}_p dP + \sum_{i=1}^{n} \bar{E}_x_i dx_i, \]

(3)

Results after integration are shown in equation 4:

\[ E_m = \int_{T_0}^{T} \bar{E}_T dT + \int_{P_0}^{P} \bar{E}_p dP + \sum_{i=1}^{n} \int_{x_{i,0}}^{x_i} \bar{E}_x_i dx = E_T + E_P + E_{ch} = E_f + E_{ch}, \]

(4)
where $E_T$ – isothermal energy, related to the pressure difference between technological flow and the environment, KJ/m³; $E_p$ – isobaric exergy, calculated as a difference in the temperature between environment and the flow, KJ/m³.

Isobaric component of the physical exergy is calculated by the following equation

$$
\left( \frac{\partial E_m}{\partial T} \right)_{p,x} = \left( \frac{\partial H}{\partial T} \right)_{p,x} - T_0 \left( \frac{\partial S}{\partial T} \right)_{p,x}.
$$

Consider using the following equations (6) for the enthalpies and entropies evaluation [13]:

$$
\left( \frac{\partial H}{\partial P} \right)_{T,x} = C_p \quad \text{and} \quad \left( \frac{\partial S}{\partial P} \right)_{T,x} = C_p/T,
$$

where $C_p$ - mass flow rate with the constant pressure, KJ/kg·K; $T$ – temperature of the technological flow, °K.

Thus, considering $C_p$ to be constant, the equation has changed (7).

$$
E_T - E_{T_0} = C_p[T - T_0 - T_0ln(T/T_0)].
$$

The change in exergy during the engine oil cleaning process under the constant pressure could be represented by the following equation (8).

$$
E_T - E_{T_0} = \Delta H(1/T/T_0).
$$

Isothermal part of the physical exergy is based on the current equation (9)

$$
\left( \frac{\partial E_m}{\partial P} \right)_{T,x} = \left( \frac{\partial H}{\partial P} \right)_{T,x} - T_0 \left( \frac{\partial S}{\partial P} \right)_{T,x}.
$$

Consider using equation 8 and 9, so the result of the evaluation could be seen in the equation 11

$$
\left( \frac{\partial H}{\partial P} \right)_{T,x} = V - T \left( \frac{\partial V}{\partial P} \right)_{T,x} \quad \text{and} \quad \left( \frac{\partial S}{\partial P} \right)_{T,x} = -\left( \frac{\partial V}{\partial T} \right)_{T,x},
$$

$$
\left( \frac{\partial E}{\partial P} \right)_{T,x} = V - (T - T_0) \left( \frac{\partial V}{\partial T} \right)_{T,x}.
$$

If the gas mixture or vapor phase is not ideal and described by the equation of state with the second virial parameter $\beta$ [9], then the following formula (12) could be used.

$$
V = \frac{RT}{P} + \beta,
$$

where $\beta$ is the second virial parameter and is the function of temperature and pressure. The calculation of the virial coefficient ($\beta$) is based on the Berthelot or Redlich-Kwong equations [14, 15].

After the differentiation of the equation (12), the change of the isothermal exergy could be described by the equation 14.

$$
\left( \frac{\partial V}{\partial T} \right)_{P,x} = \frac{R}{P} + \left( \frac{\partial \beta}{\partial T} \right)_{P,x}.
$$

$$
E_p - E_{p_0} = RT_0ln(P/P_0) + T_0(P - P_0) \left( \frac{\partial \beta}{\partial T} \right)_{P,x}.
$$
While assessing the chemical exergy, the ideal gas is taken as an environment. Then the work of the chemical compounds’ alignment is evaluated by the sum of the energy needed for the substance transformation to the equilibrium state with the environment. Thus, the state and exergy of the compounds are ideal.

So, the transformation could be represented in the following way. First, the water-oil parts are evaluated during its transition from the liquid to the vapor, and later from the vapor to the liquid state. The equation describing the changes in the exergy with the $P_d$ and $T_d$ parameters looks as follows:

$$E_{ch} = E_p' + E_p'' + E_{id},$$

(15)

where $E_p'$ is the exergy of the changing from the liquid to the vapor phase with the constant structure and parameters ($P=\text{idem}, T=\text{idem}, \sum n_i=\text{idem}$), KJ/m$^3$; $E_p''$ – exergy of the transition from the vapor to the liquid with the constant parameters and structure, KJ/m$^3$; $E_{id}$ – exergy of the ideal gas vapor composition, KJ/m$^3$.

The $E_p'$ is calculated empirically taken into account that phase transition is happening under the temperature of boiling ($T_{\text{boil}}$). Only after that the energy used for evaporation is evaluated and brought to the standard state of the substance with the $T_0$.

The $E_p''$ during the isothermal spreading is calculated using the following equation:

$$E_p'' = H_{\text{in}} - H_{\text{out}} + T_0 \Delta S_{\text{irrev}}.$$  

(16)

The $E_{id}$ is the minimal work that needed to be done during the reversible separation of the ideal vapor mixture [9]:

$$E_{id} = -RT_0 \sum x_i n \gamma_i x_i,$$

(17)

where $\gamma_i$ is the coefficient of the $i$-th component activity.

Then the chemical exergy that happened as a result of the difference between environment and the compounds could be described by the current equation.

$$E_{ch} = E_p' + \Delta H + T_0 \Delta S_{\text{irrev}} - RT_0 \sum x_i n \gamma_i x_i.$$  

(18)

So, the chemical exergy of the technological flow of engine oils could be determined by the following equation. The analysis of the thermodynamic efficiency usually is based on the exergy balance equation.

$$\sum E_{\text{con}} = \sum E_{\text{out}} + \sum E_{\text{loss}} = \sum E_{\text{out}} + \sum E_{\text{in}}^{\text{loss}} + \sum E_{\text{out}}^{\text{loss}},$$

(19)

where $\sum E_{\text{con}}$ – connected to the system exergies of different types, KJ/m$^3$; $\sum E_{\text{out}}$ - different exergies coming out of the systems, KJ/m$^3$; $\sum E_{\text{loss}}$ – losses of exergy, KJ/m$^3$; $\sum E_{\text{in}}^{\text{loss}}$ – inner losses of exergy correlated with the irreversibility inside the system (losses from hydraulic connection, differences in heat and mass transfer etc.), KJ/m$^3$; $\sum E_{\text{out}}^{\text{loss}}$ – outer losses of exergy related to the system interaction with the environment (unused exergy of the flows etc), KJ/m$^3$.

Thus, the equation of the exergy coefficient of performance (COP) characterized by the thermodynamic properties of the installation has the following type:

$$\eta_{e} = \frac{\sum \Delta E_{\text{useful}}}{\sum \Delta E_{\text{used}}},$$

(20)
where $\Delta E_{\text{useful}}$ – useful exergy developed through the technological process, KJ/m$^3$; $\Delta E_{\text{used}}$ – total used exergy, KJ/m$^3$.

Thus, in the process of engine oil regeneration, the COP of exergy could be described by the following equation.

$$
\eta_e = \frac{\sum \Delta E_{i,p}^{\text{useful}} + \sum \Delta E_{i,T}^{\text{useful}}}{\sum \Delta E_{i,p}^{\text{used}} + \sum \Delta E_{i,T}^{\text{used}}},
$$

where $\Delta E_{i,p}^{\text{useful}}$, $\Delta E_{i,T}^{\text{useful}}$, $\Delta E_{i,p}^{\text{used}}$ and $\Delta E_{i,T}^{\text{used}}$ are describing changes of the useful and used exergies and the components of the engine oils; $E_{el}$ – exergy of the electric energy, KJ/KW; $\Delta E_0$ – total exergy used for the input and output, KJ/m$^3$.

So, to make a better COP and future exergy assessment, it is necessary to evaluate the parameters from the equations (15) in explicit way as technological coefficients functions. Then the determined equation (21) would allow substantiating the thermodynamic scheme of the installation for the engine oil regeneration in a faster and more advantageous way.

Thermo economic analysis is of great importance too, as it allows finding the best-fitted solution between thermodynamic efficiency of the process and the value of the non-energy costs during the implementation. The main goal is minimizing the costs per unit of exergy. Criteria for the optimization could be described by the following equation:

$$
R_i = \min C = \min \left[ \sum C_i E_i + \sum K_i \right] / G_y,
$$

where $C_i$ – cost of the exergy unit flow of engine oils and energy, KJ/m$^3$rub.; $E_i$ – exergy of the engine oil, KJ/m$^3$; $K_i$ – capital and operating costs, rub.; $G_y$ – regenerative installation productivity, m$^3$/hour.

3. Conclusion
Thermodynamic optimization allows finding the best approach to motor-oil regeneration. The method of analysis helps achieving the balance between costs and the amount of energy spent on the engine oil recovery.

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