System Analysis of Wastewater Treatment by Separation Process of Oil and Suspended Solids

January 2017

Eriko ANKYU

System Analysis of Wastewater Treatment

by Separation Process of Oil and Suspended Solids

A Dissertation Submitted to

the Graduate School of Life and Environmental Sciences,

the University of Tsukuba

in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy in Agricultural Science

(Doctoral Program in Appropriate Technology and Sciences for Sustainable Development)

Eriko ANKYU

Contents

Chapter 1 Background

1.1 Wastewater including the large amount of oil and SS

There are some cases of wastewater including the large amount of oil and SS (Suspended Solids) such as a food processing factory, a cafeteria and a biomass refinery process factory. Here, SS is defined as insoluble material with below 2 mm of particle size floating in water. To treat wastewater including the large amount of oil and SS, huge amount of cost and energy are required. Figure 1.1 shows a boiling tank in a food processing factory where chicken bones are boiled for production. Wastewater after boiling includes the large amount of chicken oil and SS mainly composed of protein. If this wastewater is drained into river without treatment, water pollution would happen downstream or if it drains into public sewerage, functional disorder of wastewater treatment facility would happen. In wastewater treatment system in Japan, wastewater flows into wastewater treatment facilities including grease trap. Generally, it is said that workers clean up the grease trap everyday by their hand to recover oil sludge and discard it as industrial waste, and vacuum vehicle absorb oil sludge in 1 or 2 month to maintain its treatment ability. In average, it cost 20000-30000 JPY per once to absorb oil sludge by vacuum vehicle.

Figure 1.2 shows wastewater from a cafeteria in a university. Much oil is attached with the dishes, and to clean off it huge amount of water was required. Wastewater after washing the dishes includes large amount of oil with fine food particles. Then, regular maintenance for the grease trap are required same as a food

Fig. 1.1 Biling tank in a food processing factory

Fig. 1.2 Wastewater from caferetia

processing factory. In the food restaurant industry and the food processing industry, unrecovered and unused animal and vegetable oil are estimated 200 thousand ton per year. It is roughly equivalent to 9.70×10^3 TJ of heat energy, 628,000 t of CO_2 reduction, 17.9 billion yen (179 million USD) of economic effect[1)].

Figure 1.3 shows wastewater from a biomass refinery process factory of palm oil production. From harvest of palm oil fruit to production of palm oil, many processes are required. During these processes, much wastewater including huge amount of oil and SS is exhausted. Wastewater from biomass refinery process especially in Southeast Asia is currently treated by methane fermentation at open pond. So, it causes emission of methane as greenhouse gas into the air. To recover oil from wastewater and decrease emitted methane are expected from the viewpoint of preventing global warming.

Wastewater exhausted from daily life at household and industrial such as a factory and a restaurant, and classified two; organic wastewater and inorganic wastewater. Water Pollution Control Act in Japan set the effluent standards (Table 1.1)[2)] for the target of soluble organic matter, oil, heavy metal and so on to wastewater exhausted from industrial. Especially, wastewater including organic oil such as animal and vegetable oil and fat from industrial offices that exhaust wastewater over 50 m^3 per day is restricted to subject to the effluent standards. The index of effluent standard for oil is normal hexane extract substance (n-Hex), below 30 mg/L (Table 1.1)[2)].

On the other hand, because industrial offices that exhaust wastewater below 50 m^3 per day and household are exempt from this standard, wastewater from these

Fig. 1.3 Wastewater from biomass refinery

Table 1.1 Effluent standard [1)]

Index	Arrowed concentration
Hydrogen ion concentration (pH)	Except sea area5.8～8.6 Sea area 5.0～9.0
Biochemical oxygen demand (BOD)	160 mg/L (Daily avelage 120 mg/L)
Chemical oxygen demand (COD)	160 mg/L (Daily avelage 120 mg/L)
Suspended solids (SS)	200 mg/L (Daily avelage 150 mg/L)
Normal hexane extract substance (including mineral oil and so on)	5 mg/L
Normal hexane extract substance (including animal and vegetable oil and fat)	30 mg/L
Content of phenols	5 mg/L
Content of copper	3 mg/L
Content of zinc	2 mg/L
Content of soluble iron	10 mg/L
Content of soluble manganese	10 mg/L
Content of chrome	2 mg/L
Number of colitis germ legions	Daily avelage 3000/cm^3
Content of nitrogen	120 mg/L (Daily avelage 60 mg/L)
Content of phosphorus	160 mg/L (Daily avelage 8 mg/L)

offices and household is sometimes released to the river and the sea without proper treatment. Wastewater from industrial offices that exhaust wastewater below 50 m^3 per day and household sometimes includes the large amount of oil and SS. Oil flowed out to the sea rapidly spreads on the water surface and cut the supply of oxygen into water. It causes to decrease dissolved oxygen concentration and prevent breathing of underwater aquatic organism. More, organic substances such as animal and vegetable oil and fat become putrid and cause water pollution, odious smell, and harmful insect occurrence. Moreover, when wastewater including the large amount of oil was flow into sewage, it causes blocking of drainage pipe (Fig. 1.4) and sometimes consolidated oil produced oil ball to draft to the sea (Fig. 1.5). Additionally, functional disorder of wastewater treatment facility would happen to cause the decrease of treatment ability and deterioration of water quality after treatment.

Wastewater from industrial offices that exhausted wastewater below 50 m^3 per day and home that is out of this regulation also affect to these problems. Especially, wastewater from industrial offices that exhaust wastewater below 50 m^3 per day has a large environmental load because the large amount of wastewater was exhausted per one industrial office. Therefore, it is necessary to consider the effective treatment of organic wastewater not only the target of the regulation but also the target out of the regulation and provide the motivation of concerning proper wastewater treatment including the large amount of oil even if the target is out of the regulation.

SS is wastewater was mainly composed by protein and starch. The index of the effluent standard for SS is below 200 mg/L, daily average 150 mg/L (Table 1.1) [2). It

Fig. 1.4 Blocking of sewage pipe [3)]

Fig. 1.5 Oilball floated to coast [3)]

is well known that SS also causes water pollution, odious smell, and harmful insect occurrence by mixing and connecting oil. Then, not only oil but also SS should be collected upstream before flowing into wastewater treatment facilities

1.2 Oil-water separation equipment and SS recovery equipment

Oil-water separation technology is widely used to recover oil from wastewater treatment in food related facilities. Organic wastewater including huge amounts of animal and vegetable oil and fat are drained from food related facilities such as a food processing factory, a ramen shop, a school cafeteria, and energy related facilities such as biomass refinery process factory.

The food processing factory (Naoetsu-Yushi Co. Ltd. Japan) (Fig. 1.6) produced wastewater including animal oil on the process of boiling chicken and it causes the decrease of treatment ability of wastewater treatment facilities. A ramen shop and a school cafeteria also have some problems of wastewater treatment caused by oil. To wash off oil from the dishes and the cooking equipment, much amount of dishwashing detergent is required which decrease the water quality. Oil mass can be the cause of the obstruction and the blocking of the drain pipeline of wastewater treatment facilities, and it causes to give out a bad smell to the neighbor. To prevent these problems, they need to increase the number of staff to clean up it. Recovering oil upstream before flowing into wastewater treatment facilities enables to reuse the recovered oil and increase treatment ability of wastewater treatment facilities. As for energy related facilities, wastewater from the refinery of biomass energy such as palm oil still includes considerable amount of vegetable oil (Fig. 1.7) and it was disposed as industrial waste or treated at open pond by methane fermentation (Fig. 1.8). Then, recovering biomass oil from wastewater brings more profit and reduces the load on wastewater treatment.

To prevent these problems and to improve these strengths, there are many technologies to separate oil and water, for example, centrifugation, floatation, flocculation, and absorption. Recovering oil from wastewater prevents the blocking of the drain pipeline and the decreases of processing ability of wastewater treatment facilities[4-7]. Moreover, in a food processing factory under proper sanitary condition, the recovered oil can be used as food and the oil-removed wastewater can be used as a water resource. Then introducing oil-water separation technology into a food processing factory offers the opportunity to produce a profit from wastewater. Furthermore, significant cost reduction of wastewater treatment facilities in a factory is expected by decreasing scale size of wastewater treatment facilities. However, in actual factories, it is judged based on their feelings to introduce oil-water separation technology and SS recovering technology into the factory. One of reason why oil-water separation technology and SS recovering technology are not widely used is considered that the advantage and disadvantage of introducing them are multiple and difficult to overview whole system.


Fig. 1.6 Wastewater including oil from the food processing factory


Fig. 1.7 Wastewater from the palm oil factory

Fig. 1.8 Open pond for methane fermentation using wastewater from the palm oil factory

Therefore, technical evaluation based on economics is required to judge its effect objectively.

1.3 Wastewater treatment system in Japan

Fig. 1.9 shows outline of wastewater treatment system in Japan. Wastewater from each source flows into public sewerage and sends to purification plant including grease trap. In this system, wastewater including the large amount of oil causes blocking of drainage pipe (Fig. 1.4) and oil ball is produced and drift to the sea (Fig. 1.5). To prevent these problems, Japan has Water Pollution Control Law which determines effluent standard for factory, store and restaurant with over 50 m^3 wastewater per day. Household, factory, store and restaurant with blow 50 m^3 wastewater per day are out of consideration in this law. Among effluent standard, oil related standard is normal-hexane extract below 30 mg/L and SS related standard is blow 200 mg/L (daily average 150 mg/L). To keep these standards, purification tank including grease trap is generally used.

However, purification tank including grease trap is very expensive. More, to keep its treatment ability, daily and monthly maintenance is required. In addition, there is no motivation to subject the effluent standard because there is no penalty of breaking the standard. To prevent these problems, introducing oil-water separation technology and SS recovering technology upstream is developed. By introducing oil-water separation equipment (Fig. 1.10) and SS recovering technology, cost of purification tank including grease trap can be lower and maintenance time and cost

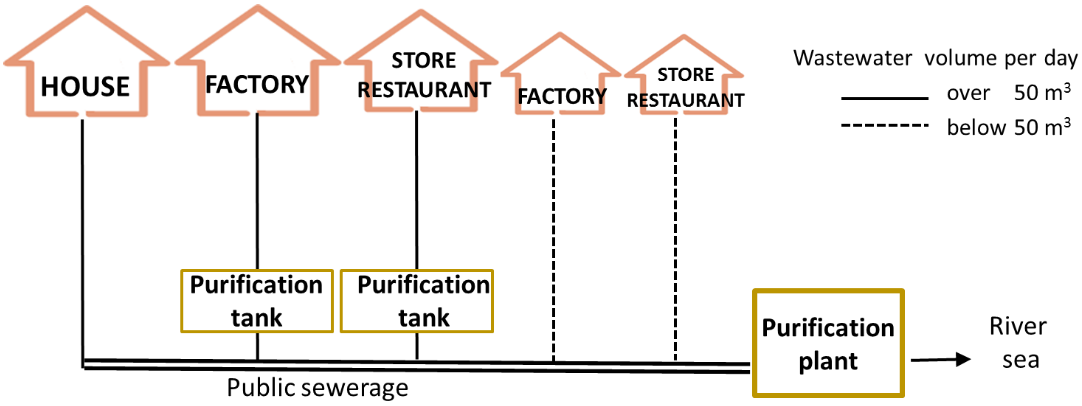

Fig. 1.9 Outline of wastewater treatment system in Japan

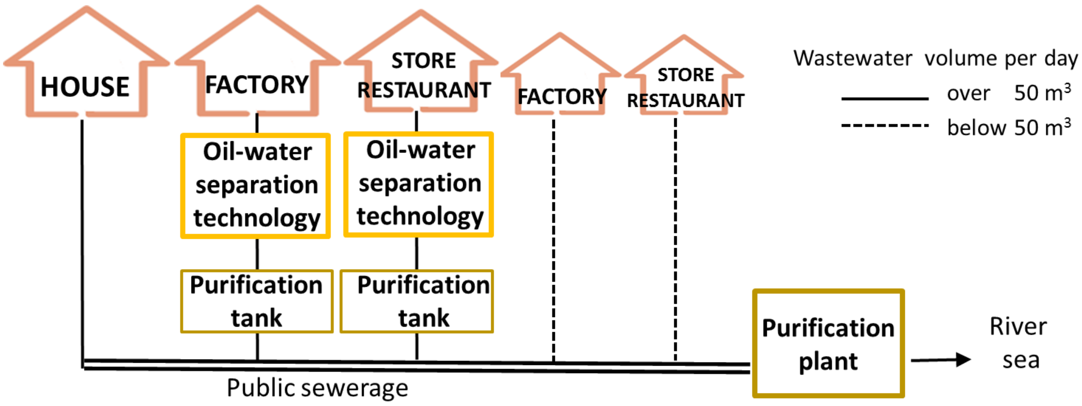

Fig. 1.10 Outline of wastewater treatment system in Japan
with oil-water sepatation technology

will be decrease. Not only observation of regulation but also downsizing of wastewater treatment facilities are expected. In addition, the recovered oil and SS can be used as resource under proper condition.

1.4 Objective

This research aimed to propose energy and economic evaluation for wastewater treatment system including oil-water separation equipment and SS recovery equipment. First, the overview about wastewater including the large amount of oil and SS exhausted from a food processing factory, cafeteria, and biomass refinery process was shown in Chapter 1. Second, economic evaluation method for introducing oil-water separation equipment into wastewater treatment system to attain energy recycling system in a food processing factory using Value Function (VF) and Separative Work Unit (SWU) of separation engineering was proposed in Chapter 2. Next, Filtration experiments representing SS recovery equipment were conducted using artificial wastewater to clarify the relationship between the separation ability of oil-water separation and the recovery rate of SS recovery equipment according to oil concentration at 20°C and 60°C in Chapter 3. Based on the characteristics of oil and SS by the filtration experiments, an economic evaluation method for a wastewater treatment system was proposed for two cases: using oil-water separation equipment without SS recovery equipment (single use), and using oil-water separation equipment with

SS recovery equipment (combination use) from the view of separation engineering using the separative work unit (SWU).

Chapter 2

Economic Evaluation for Energy Recycling System by Oil-Water Separation Equipment in Food Processing Factory

2.1 Introduction

From the viewpoint of reduction of environmental load and efficient use of biomass, food waste recycling attracts more attention. Hyde *et al.* [8] reported that the East Anglian Waste Minimisation project in the food and drink industry demonstrated 12 % of raw materials reduction to achieve significant contribution to company profitability, and Khoo[9] conducted environmental evaluation of the food waste recycling facilities in Singapore using life cycle assessment (LCA). In Japan, Food Waste Recycling Law was established in 2000. Tanaka[10] conducted environmental and economical evaluations toward some recycling facilities for food waste using LCA and LCC (Life Cycle Cost).

The vegetable and/or animal oils in wastewater are often discharged from food processing factories and restaurants. The oil in wastewater causes degradation of drainage water quality and deterioration of performance for the wastewater treatment facility. Additionally, it increases the management cost for cleaning and maintenance of a sewer pipe and wastewater treatment facilities as social problem. Recently, wastewater management cost is increased and it brings serious problems to the food processing and restaurant companies due to the environmental policy of the government. Therefore, these companies pay close attention to wastewater that is contaminated by the oil.

Oil-water separation is one of the key technologies to solve the wastewater management problems. There are many technologies for separating oil and water, including centrifugation, floatation, flocculation, and/or absorption. Therefore, selection and design for appropriate oil-water separation equipment to wastewater management is an important issue. Finally, recovery of the oil from wastewater would increase not only performance level of the wastewater treatment facility without plumbing blockages, but also profit from the recovered oil in energy recycling system[4-7]. That is, installing oil–water separation equipment to wastewater treatment system offers an opportunity to generate a huge profit of energy and cost from wastewater that would otherwise be wasted. In addition, improved efficiency of factory’s wastewater treatment facilities is expected to result in substantial cost reduction.

In most previous research about oil-water separation as energy recycling, the amount of recovered oil or CO_2 reduction is the center of interests. On the other hand, from the macro perspective, oil removed water as water resource has significant value. Then, the evaluation method that consider wider range of oil-water separation as system was required.

When a decision-maker of a food processing factory attempts installing oil-water separation equipment, an economic evaluation method is required for management because low cost and high performance of oil-water separation equipment shows trade-off relation, generally.

The purpose of this study is to propose an economic evaluation method for installing oil-water separation equipment into the oil containing wastewater to attain energy recycling system in a food processing factory using Value Function (VF) and Separative Work Unit (SWU) of separation engineering.

2.2 Method

2.2.1 Flow of Oil-Water Separation

Separation equipment generates valuable resources (products) and valueless resource (wastes) in downstream from feedstock of upstream. In the concept of oil-water separation in a food processing factory (Fig. 2.1), oil-water separation equipment separates the recovered oil and the oil removed water in downstream using wastewater treatment system from the oil containing wastewater in upstream. Economic value of the recovered oil and the oil removed water depends on their amount and purity (concentration). Then, effective and economical separation equipment should be selected to a food processing factory.

Where, O_{out} [kg/day], W_{out} [kg/day] and W_{in} [kg/day] are, respectively, the amount of the recovered oil per day, of the oil removed water per day, and of the oil containing wastewater per day. X_{Oout} [-], X_{Wout} [-] and X_{Win} [-] are defined as the oil mixing ratio in the recovered oil, the oil removed water and the oil containing wastewater, respectively. Higher mixing ratio of oil and other contaminants in

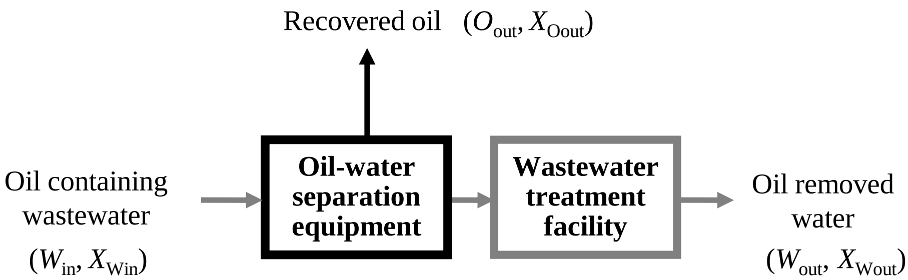

Fig. 2.1 Concept of oil-water separation and SS recovery in a wastewater treatment system

wastewater brings the increase in the workload required for water purification. The relation between the six variables is expressed by the following equation.

$$O_{\mathrm{out}} \cdot X_{\mathrm{Oout}} + W_{\mathrm{out}} \cdot X_{\mathrm{Wout}} = W_{\mathrm{in}} \cdot X_{\mathrm{Win}} \tag{2.1}$$

2.2.2 Value Function and Separative Work Unit

SWU is the scale of treatment ability of separation process, widely used in the field of nuclear power engineering and so on[11)]. VF is the function used to calculate SWU and convert concentration *X* to the economic value. Generally, *V*(*X*) of VF is decided based on entropy change in separation engineering, as below[11)12)].

$$V(X) = (2X - 1)\ln\left(\frac{X}{1-X}\right) \tag{2.2}$$

Equation (2.2) is used only for the case that separation produces a product and a waste from feedstock in separation engineering. However, oil-water separation of this research produces both oil and water as valuable resources without waste. Thus, eq. (2.2) is not suitable for this research. More, eq. (2.2) expresses the value of separation on the assumption of physically ideal condition based on theory of informational entropy. However, oil-water separation is not categorized to using eq. (2.2) because it is not on ideal condition and applicative evaluation should count the additional values of oil as combustion energy and water as decreasing of wastewater treatment cost.

Therefore, VF of oil-water separation in a food processing factory should be defined for each product with single unit. Then, $f(X_{\mathrm{Oout}})$ [JPY/kg], $g(X_{\mathrm{Wout}})$ [JPY/kg] and $h(X_{\mathrm{Win}})$ [JPY/kg] are assumed as VF of the recovered oil, the oil removed water and the oil containing wastewater respectively, which was defined by the economic value of oil and water considering with mixing ratio of them.

SWU, δU, is used as the measure of the economic value produced by the separation[11-13]. Then SWU per day in a food processing factory, δU_{s}, was defined as the following equation. The positive value of δU means the profit generated by the separation and the negative value means the spending lost by the separation.

$$\delta U_{\mathrm{S}} = O_{\mathrm{out}} \cdot f\left(X_{\mathrm{Oout}}\right) + W_{\mathrm{out}} \cdot g\left(X_{\mathrm{Wout}}\right) - W_{\mathrm{in}} \cdot h\left(X_{\mathrm{Win}}\right) \qquad (2.3)$$

2.2.3 Material and Energy flow

The food processing factory, Naoetsu-Yushi Co. Ltd., was taken as the experimental site to apply the calculation of VF and SWU. The factory produced boiled chicken from culled chicken, and high temperature steam was used for boiling, and abundance of chicken oil flown out with the wastewater after boiling process. In an attempt to solve these problems of wastewater treatment by this abundance of chicken oil, the oil–water separation equipment was installed into the wastewater treatment system of the factory.

The oil–water separation equipment operated on the basis of the specific gravities of oil and water, and on the speed control of wastewater flowing inside the equipment without chemical and biological treatments. As a result, there were no quality changes in the water and no seasonal changes in the treatment volume. The energy and material flow of the factory is shown in Fig. 2.2. The recovered oil was used as fuel for the steam boiler. The oil removed water was purified by the wastewater treatment facility, and the purified water was used for melting snow inside the food factory in winter season. In other seasons, part of the purified water was used for water of plants and most of it was released into the river. As other possible way, hot-air heating within the factory or indirect heat source by purified water is under consideration.

Most of contaminant in wastewater from chicken boiling process except oil was suspended solids (SS) that consists mainly of protein and starch. From the field investigation, the concentration of SS (1,100 mg/L) was revealed to be small compared to the concentration of oil (19,000 mg/L) in the wastewater. More, our investigation showed that SS was recovered easily from wastewater after applying oil-water separation equipment. Then, on the assumption that contaminants except oil could be removed easily, the wastewater was treated as containing only oil and water, and the separation of these resources was the focus of the calculation. The pressure and temperature of the wastewater were assumed to be same before and after the separation.

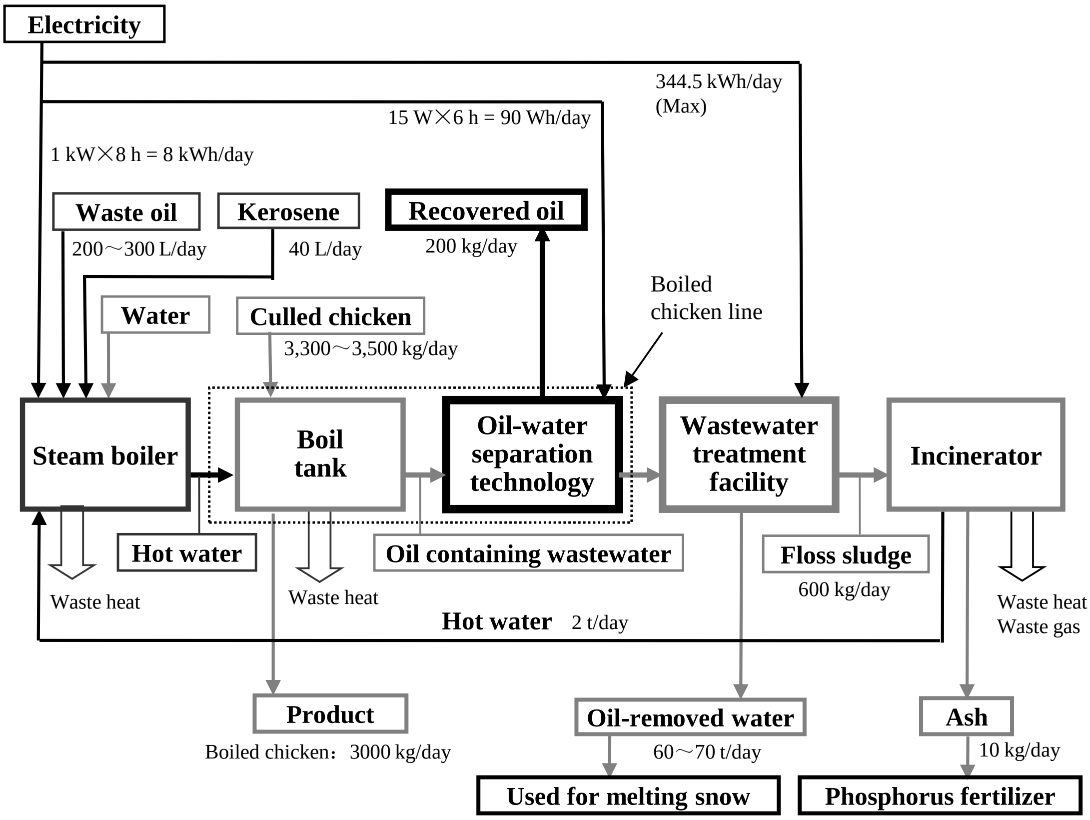

Fig. 2.2 Material and Energy flow of the food processing factory (Naoetsu-Yushi Co. Ltd.[14-15])

2.2.4 Value Function for the food processing factory

The VF was determined by the field investigation at the food processing factory. As the recovered oil was used as fuel to the steam boiler, the VF of $f(X_{Oout})$ was determined by the heating value and can be expressed as follows.

$$f(X_{Oout}) = V_{heat} \cdot \{X_{Oout} \cdot H_{oil} - (1 - X_{Oout})H_{wat}\} \tag{2.4}$$

Where V_{heat} [JPY/J] is the conversion factor from heating value to economic value. H_{oil} [J/kg] and H_{wat} [J/kg] are the heating value of oil and water respectively.

When X_{Oout} was not 100% that meant the recovered oil contained water, total evaporating energy of water in the recovered oil should be considered for estimating the heating value of the oil. As a result, the VF of $f(X_{Oout})$ increased linearly from the negative heating value at 0% of X_{Oout}.

The initial cost and the running cost of the wastewater treatment facility are traditionally determined by the permissible amount of wastewater per day because the wastewater treatment facility could treat only oil-less or low oil containing wastewater, not much oil containing wastewater from a food processing factory. Then, the standard for these costs of the wastewater treatment facility that should treat the oil containing wastewater is not clear. Therefore, P_i, the initial cost of the wastewater treatment facility that should treat oil containing wastewater, and P_r, the running cost of the wastewater treatment facility that should treat oil containing wastewater were assumed to be determined by its scale for the maximum permissible concentration of the n-hexane extracts N [mg/L] [16-19], and expressed as following.

$$P_\mathrm{i} = p_\mathrm{i} \cdot \frac{a}{A \cdot N} \cdot A = p_\mathrm{i} \cdot \frac{a}{N} \tag{2.5}$$

$$P_\mathrm{r} = p_\mathrm{r} \cdot \frac{a}{A \cdot N} \cdot A = p_\mathrm{r} \cdot \frac{a}{N} \tag{2.6}$$

Where N [mg/L] is the maximum permissible concentration of the n-hexane extracts, a [kg] and A [L] are the amount of the oil in the oil containing wastewater per day and the amount of the oil containing wastewater per day, respectively. p_i [JPY/L] and p_r [JPY/L] are the standard initial and running costs of the wastewater treatment facility per the total amount of wastewater that is treated over a lifetime of wastewater treatment facility, respectively.

Recovering oil from the oil containing wastewater contributes to the cost reduction of the wastewater treatment facility. ρ_w [-] is the specific gravity of the wastewater that changes with the X_Win or X_Wout, P_sep [JPY/L] is the initial cost of the oil-water separation equipment per the amount of treated wastewater over a lifetime of it. E_sep [kWh/L] is the input energy (electricity) of the oil-water separation equipment per the total amount of treated wastewater over a lifetime of it and η [JPY/kWh] is the conversion factor between cost and energy.

Considering the initial and running costs of the wastewater treatment facility, $h(X_\mathrm{Win})$ [JPY/kg] as the VF for the wastewater treatment facility without the oil-water separation equipment, and $g(X_{\mathrm{Wout}})$ [JPY/kg] as the VF for the wastewater treatment facility with the oil-water separation equipment were determined as below. The VFs of $h(X_{\mathrm{Win}})$ and $g(X_{\mathrm{Wout}})$ decrease almost linearly with an increase of X_{Win} and X_{Wout}.

$$h(X_{\mathrm{Win}}) = -\frac{P_i + P_r}{A\rho_w} = -\frac{(p_{\mathrm{i}} + p_{\mathrm{r}})}{\rho_w \cdot N} \cdot X_{\mathrm{Win}} \tag{2.7}$$

$$g(X_{\mathrm{Wout}}) = h(X_{\mathrm{Wout}}) - \frac{P_{\mathrm{sep}}}{\rho_w} - \frac{E_{\mathrm{sep}} \cdot \eta}{\rho_w} \tag{2.8}$$

2.3 Results and discussion

2.3.1 SWU for general factory and objective factory

The specific data to decide VFs in the food processing factory, Naoetsu-Yushi Co. Ltd., is listed in Table 2.1 and the determined VFs based on Table 2.1 is shown in Figs. 2.3-2.5 expressed by the following equations, $f'(X_{\mathrm{Oout}})$, $h'(X_{\mathrm{Win}})$ and $g'(X_{\mathrm{Wout}})$. The difference between $h'(X_{\mathrm{Win}})$ and $g'(X_{\mathrm{Wout}})$ were relatively small, because the initial cost and input energy of the oil-water separation equipment was small compared with the wastewater treatment facility.

$$f'(X_{\mathrm{Oout}}) = 92.6X_{\mathrm{Oout}} - 5.3 \tag{2.9}$$

$$h'(X_{\mathrm{Win}}) = -124.0X_{\mathrm{Win}} \tag{2.10}$$

$$g'(X_{\mathrm{Wout}}) = -124.0X_{\mathrm{Wout}} - 0.059 \tag{2.11}$$

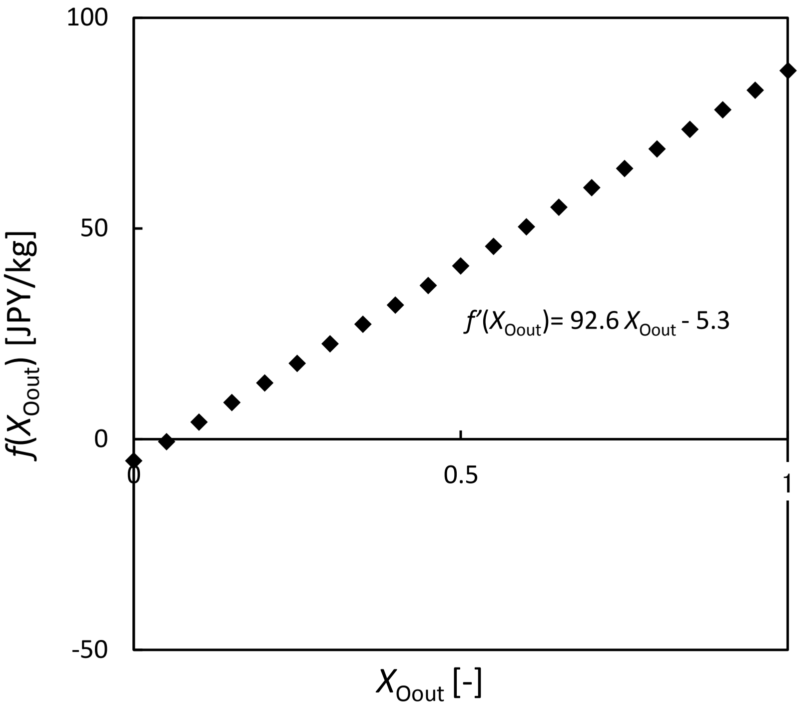

Fig. 2.3 Value Function (VF) for the recovered oil

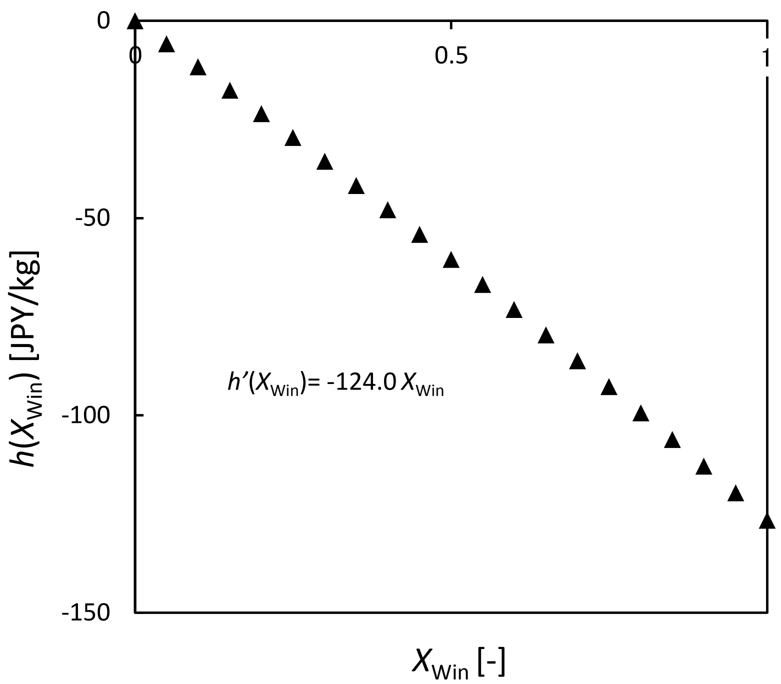

Fig. 2.4 Value Function (VF) for the wastewater treatment facility without the oil-water separation equipment

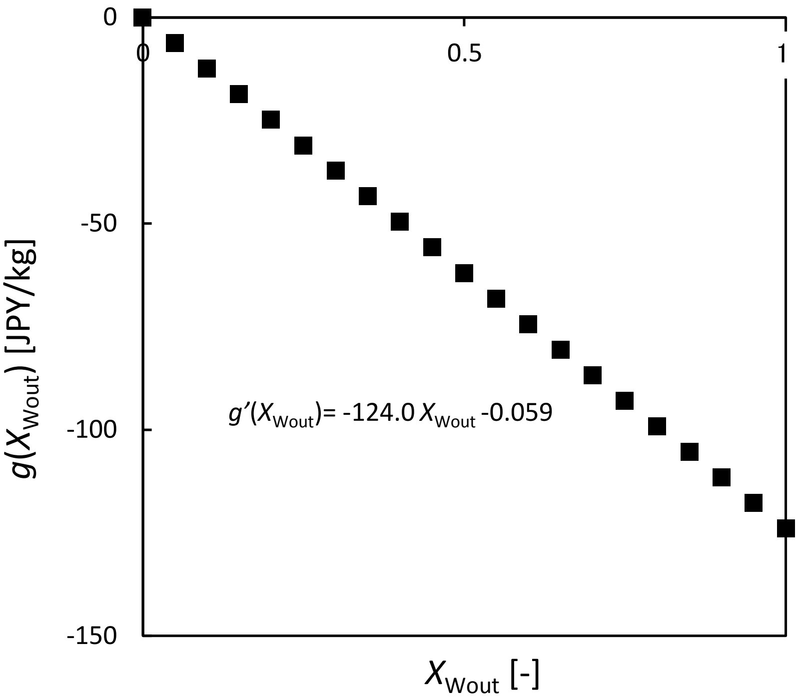

Fig. 2.5 Value Function (VF) for the wastewater treatment facility with the oil-water separation equipment

Table 2.1 Specific data to decide VFs in the food processing factory (Naoetsu-Yushi Co. Ltd.)

Variable	Value	Unit
Heating value of fuel oil A	39.1 [20]	MJ/L
Price of fuel oil A	90.7 [21]	JPY
V_{heat}	0.00000232	JPY/J
Heating value of chicken oil	9,000 [22]	kcal/kg
H_{oil}	37,656,000	J/kg
H_{wat}	2,270,000 [23]	J/kg
a	183 *	kg
A	40,000 *	L
N	0.00003 [24]	kg/L
E_{sep}	0.00000225 *	kWh/L
η	15.53 [25]	JPY/kWh
Specific gravity of animal oil	0.915 [26]	-
Specific gravity of water	1 [26]	-
Wastewater treatment facility		
Lifetime	15 *	year
Initial cost	60,000,000 *	JPY
Running cost	307,205 *	JPY/month
Oil-water separation equipment		
Lifetime	15 *	year
Initial cost	13,000,000 *	JPY

Marked *: Obtained in field investigation

SWU for generalized oil-water separation, δU_{s}, was expressed by eq. (2.3) and VFs for generalized oil-water separation were expressed by eqs. (2.4), (2.7) and (2.8). Using the decided VFs (eqs. (2.9), (2.10) and (2.11)), SWU for oil-water separation in this objective factory, $\delta U'_{s}$, was expressed as below.

$$\begin{aligned}\delta U'_{S} = {} & O_{out} \cdot (92.6 X_{Oout} - 5.3) \\ & + W_{out} \cdot (-124.0 X_{Wout} - 0.059) - W_{in} \cdot (-124.0 X_{Win})\end{aligned} \tag{2.12}$$

SWU for this food factory was calculated from 0% to 100% of X_{Oout} by increments of 5% with 0.0046 as fixed value of X_{Win} (oil 183 kg, wastewater 40,000 L) using *a* and *A* (Fig. 2.6). The value of X_{Wout} was automatically decided by the fixed value of X_{Win} and the variable, X_{Oout} using eq. (2.1). Horizontal line of Fig. 2.6 shows the purity of the recovered oil, which is equal to the separation ability of the oil-water separation equipment. The calculated result was approximated by the following equation.

$$\delta U'_{S} = 39600 X_{Oout} - 3300 \tag{2.13}$$

If X_{Oout} was 0, the oil-water separation equipment was not required for the wastewater treatment system. Positive value of SWU meant that profit by the recovered oil and the oil removed water was larger than cost for the oil-water separation equipment and the wastewater treatment facility. Therefore, over 0 of SWU

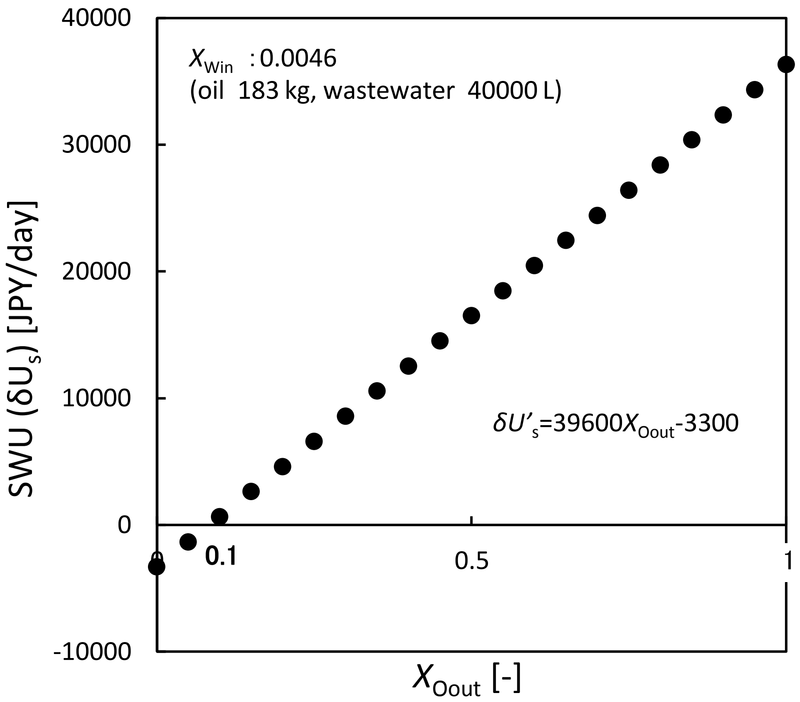

Fig. 2.6 Separative Work Unit (SWU) in the food processing factory

by changing the value of X_{Oout} showed a profit by using the oil-water separation equipment. In this simulation, at least 10 % of the separation ability was required to attain positive value of SWU (Fig. 2.6).

2.3.2 Recovery period (payback time)

The initial cost, the running cost, and the required periods for recovery of the initial cost of the oil-water separation equipment and the wastewater treatment facility are listed in Table 2.2. The SWU calculation for the food processing factory gave a result of 722,282 JPY/month (20 days operation per month) using 0.0046 of X_{Win} and 99.5% of the separation ability of the oil-water separation equipment. Profit of SWU was used for the running cost and recovering the initial cost. Recovery period (payback time) for the oil-water separation equipment and the wastewater treatment facility was 162.6 months (13.5 years) at 0% of discount rate. Lifetime of the oil-water separation equipment and the wastewater treatment facility was estimated to be 15 years (Table 2.2). The results indicated that surplus recovered SWU had profit after recovery of the total initial cost until the lifetime (13.5 years to 15 years after installing). In this case, installing the oil-water separation equipment into the food processing factory at 0% of discount rate was revealed to be economically feasible.

On the other hand, discount rate affected the recovery period (Fig. 2.7). Under 2 % of discount rate, the recovery period for the oil-water separation equipment and the wastewater treatment facility was shorter than the lifetime of them that means economic feasibility (Table 2.3). Over 2 % of discount rate, payback could be difficult

Table 2.2 Initial and running costs of the oil-water separation equipment and the wastewater treatment facility and calculation results of recovery period

	Oil-water separation equipment	Wastewater treatment facility
Initial cost [JPY]	13 million	60 million
Running cost [JPY/month]	1.35	307,205
Recovery period for initial cost [month]	18.0	144.6
Total recovery period [month]	162.6	
Lifetime [month]	180	

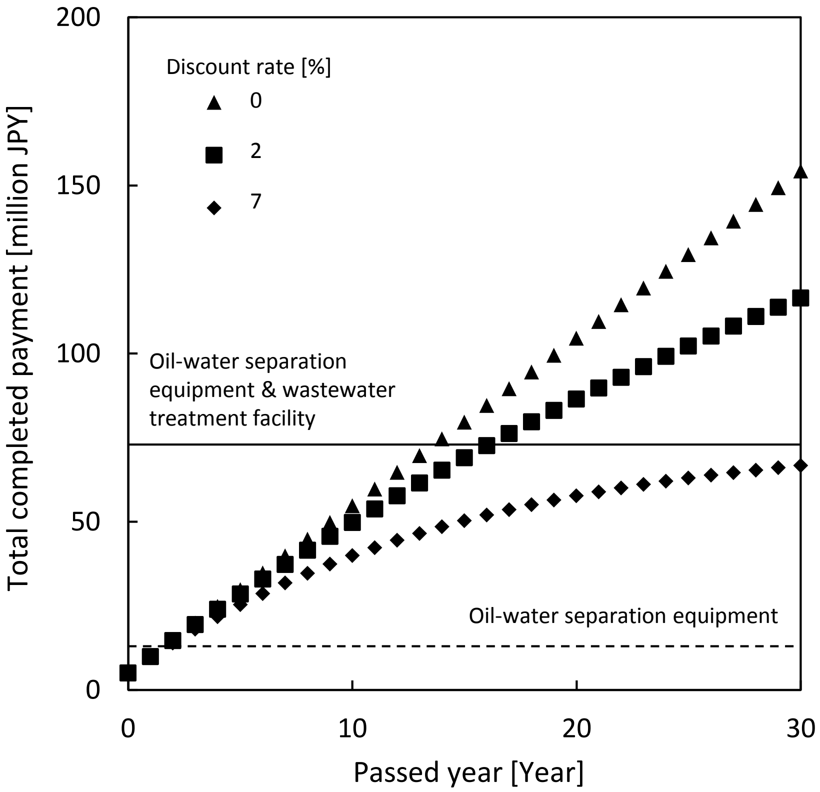

Fig. 2.7 Cumulative SWU considering discount rate
(Solid line: total payback cost of the oil-water separation equipment and the wastewater treatment facility, dotted line: total payback cost of the oil-water separation equipment)

within the lifetime. However, considering some cases that effective oil-water separation equipment is installed to an existing wastewater treatment facility, the recovery period only for the oil-water separation equipment was below 2 years (Table 2.3), shorter enough to payback within lifetime, even at 10 % of discount rate.

2.3.3 Required separation ability for payback

On the other hand, in the case where the lifetime of the current oil-water separation equipment are 15 years, surplus of 405,556 JPY/month were required to recover the total initial cost, 73 million JPY of the oil-water separation equipment and the wastewater treatment facility. Added the total monthly running cost of 307,206 JPY, the required total profit are 712,762 JPY/month (35,638 JPY/day). The result shows over 98.3% of the separation ability was required in operation to recover the initial cost within a lifetime of the oil-water separation equipment and the wastewater treatment facility (Fig. 2.6) at 0% of discount rate.

2.3.4 Comparision of different technologies

As an example, the SWU of the current equipment (initial cost: 13 million JPY) and an alternative equipment (initial cost: 6 million JPY[27)28)]) are shown in Fig. 2.8. In this simulation, the two were assumed as having same specs except for the initial cost and the separation ability (X_{Oout}). If the two have same separation ability and different initial cost, the SWU of the alternative equipment that had lower initial cost shows higher SWU than the current equipment. However, the initial cost and the separation

Table 2.3 Recovery period of the oil-water separation equipment and the wastewater treatment facility considering discount rate

Discount rate [%]	Recovery period [Year]	
	Oil-water separation equipment and Wastewater treatment facility	Only oil-water separation equipment
0	13.7	1.7
1	14.8	1.7
2	16.2	1.7
3	17.9	1.7
4	20.2	1.7
5	23.6	1.8
6	29.4	1.8
7	46.2	1.8

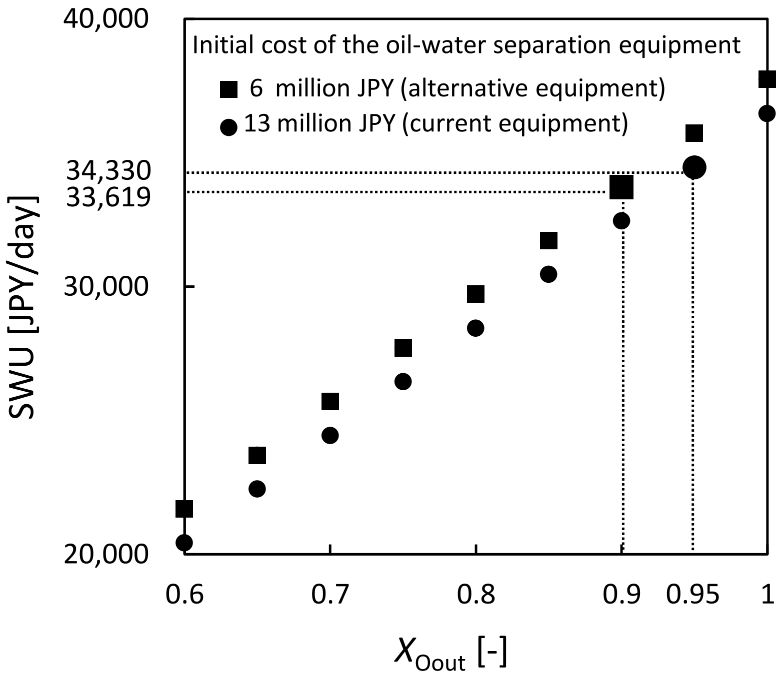

Fig. 2.8 Comparison of Separative Work Unit (SWU) between two types of oil-water separation equipment with different initial cost under 0% of discount rate

ability of oil-water separation equipment have a trade-off relation, generally. When the expensive and high performance current equipment (initial cost 13 million JPY, X_{Oout} 0.95), and the cheaper and lower performance alternative equipment (initial cost 6 million JPY, X_{Oout} 0.90) were compared, the SWU were 34,330 JPY/day and 33,619 JPY/day, respectively. This result shows that even if the initial cost was decreased by more than half by installing the alternative equipment, the decrease by 5 % in the separation ability indicated lower SWU, the reduction of total profit, which was not suitable for the alternative.

The comparison of the payback time for each equipment was shown in Fig. 2.9. Except 0% of discount rate, payback time of them was longer than the lifetime. Payback time of the alternative based on lower SWU and initial cost is shorter than the current equipment based on higher SWU and initial cost. More, the difference between them was increasing progressively according to increased discount rate. Therefore, when discount rate is at 0% or low, the current equipment was desirable, and when the discount rate increases, the alternative would be selected. Therefore, SWU of this method could achieve the comparison of the different technology or different conditions with trade-off relation for total performance improvement of a food factory.

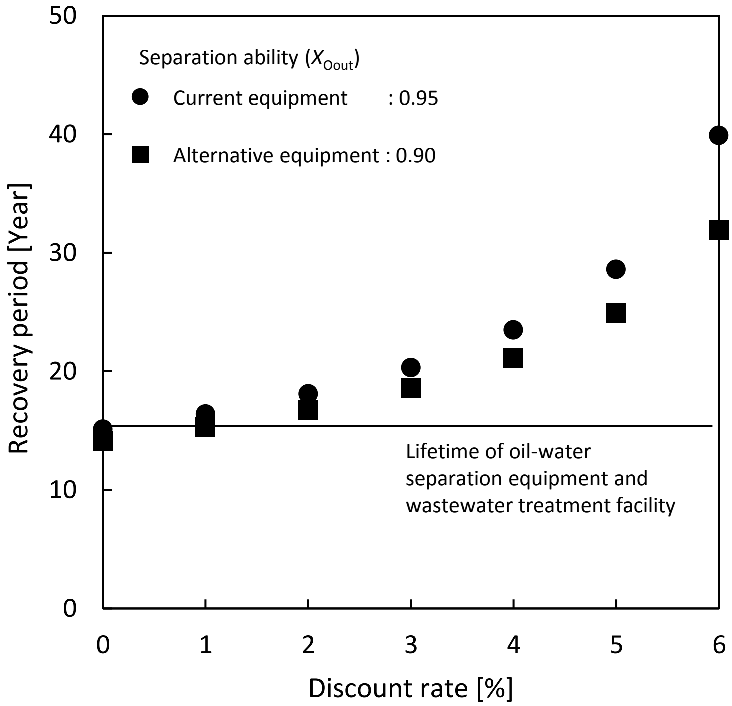

Fig. 2.9 The comparison of recovery period
for the current equipment (X_{Oout} 0.95) and the alternative equipment (X_{Oout} 0.90)

2.4 Conclusion

1) Value Function (VF) and Separative Work Unit (SWU) were applied to the economic evaluation for the wastewater management system using the oil-water separation equipment in the food processing factory, Naoetsu-Yushi Co. Ltd.

2) Required ability of the oil-water separation equipment to obtain a profit was determined as at least 10% in this simulation for the food processing factory with 0.0046 of the oil mixing ratio in oil containing wastewater X_{Win} (oil 183 kg, wastewater 40,000 L).

3) Initial cost recovery period for installing the oil-water separation equipment and the wastewater treatment facility was calculated as 162.6 months for the food processing factory at 0% of discount rate.

4) The proposed method could achieve the comparison of different equipment or different conditions with trade-off relation for total performance improvement of a food factory.

Chapter 3

Economic Evaluation of Wastewater Treatment System based on Recovery Characteristics of Oil and SS by Filtration

Wastewater from food processing factories, restaurants, and food shops includes not only oil but also large volumes of suspended solids (SS) such as food residue, composed mainly of protein and starch. If high performance oil and SS recovery can be achieved, the total workload and running costs of wastewater treatment facilities would be dramatically reduced. Furthermore, recovered oil and SS can serve as significant sources of additional profit if oil and SS can be collected with no chemical change. Thus, the separation ability of oil-water separation equipment and the recovery rate of SS recovery equipment affect the economics of the treatment process.

This study aims to evaluate the economics of installing oil-water separation equipment and SS recovery equipment on a wastewater treatment system using the results of filtration experiment about the recovery characteristics of oil and SS, and evaluation method, Separative Work Unit (SWU).

First, filtration experiments representing SS recovery equipment were conducted using artificial wastewater to identify the relationship between the separation ability of oil-water separation and the recovery rate of SS recovery equipment for oil concentration. Since high performance SS recovery can be achieved empirically by reducing oil contamination in wastewater through filtration, artificial wastewater with changing concentrations of oil and SS was used in the filtration experiments to calculate the recovery rate of oil and SS. Second, an economic evaluation method was proposed to evaluate the introduction of oil-water separation equipment and SS recovery equipment on a wastewater treatment system based on Chapter 2. To explain the effect of introducing oil-water separation equipment and SS recovery for wastewater treatment at a restaurant or a food shop, an economic evaluation by SWU was conducted for two cases; one is a case named single use which is introducing only oil-water separation equipment without SS recovery equipment explained on Chapter 2 and the other is a case named combination use which is introducing oil-water separation equipment with SS recovery equipment.

Filtration experiments determined relationship between the input amount of SS in the oil-removed water and the recovery rate of oil and SS by filtration, R [-], at 20°C and 60°C. From this relationship, the separation ability of oil-water separation equipment determined oil concentration in oil-removed water, then R [-] of SS recovery equipment. Based on these results, the SWU for combination use at 20°C and 60°C was higher than the SWU for single use. The SWU for combination use at 60°C was higher than that at 20°C. At 60°C, combination use increases the SWU by 562 JPY/day compared to single use, at 45% separation ability of oil-water separation equipment according to the results of our filtration experiments[29].

Chapter 4 Overall conclusions

This research aimed to propose energy and economic evaluation for wastewater treatment system including oil-water separation equipment and SS recovery equipment upstream of wastewater treatment facility based on separation engineering and evaluate the effectiveness of introducing oil-water separation equipment and SS recovery equipment in wastewater treatment system.

First, the overview about wastewater including the large amount of oil and SS exhausted from a food processing factory, cafeteria, and biomass refinery process was shown in Chapter 1. Wastewater including the large amount of oil and SS caused s various problems for wastewater treatment, such as decreasing treatment effectiveness of the wastewater treatment facility, and increasing facility running costs

Second, economic evaluation method for installing oil-water separation equipment into wastewater treatment system to attain energy recycling system in a food processing factory using Value Function (VF) and Separative Work Unit (SWU) of separation engineering was proposed in Chapter 2. VF for calculating SWU was determined by the field investigation at the food processing factory, Naoetsu-Yushi Co. Ltd. The results showed the required ability of the oil-water separation equipment to obtain a profit as at least 10% in this simulation for the food processing factory. More, the recovery period (payback time) of the initial cost for installing the oil-water separation equipment and the wastewater treatment facility at 0% of discount rate was calculated as 162.6 months, which was shorter than the lifetime of them and it shows the economic feasibility of installing the oil-water separation equipment. The proposed method could achieve the comparison of different equipment or different conditions for total performance improvement, and help the selection of the alternative equipment or the implement of the surrounding condition.

Third, Filtration experiments representing SS recovery equipment were conducted using artificial wastewater to clarify the relationship between the separation ability of oil-water separation and the recovery rate of SS recovery equipment according to oil concentration at 20°C and 60°C in Chapter 3. Based on the characteristics of oil and SS by the filtration experiments, an economic evaluation method for a wastewater treatment system was proposed for two cases: using oil-water separation equipment without SS recovery equipment (single use), and using oil-water separation equipment with SS recovery equipment (combination use) from the view of separation engineering using the separative work unit (SWU). The separation ability of oil-water separation equipment could determine the required recovery rate of SS recovery equipment. SWU for combination use at 20°C and 60°C was higher than SWU for single use. SWU for combination use at 60°C was higher than that at 20°C. At 60°C, combination use increases SWU by 562 JPY/day (treatment amount 3000 L/day) compared to single use, at 0.45 separation ability of oil-water separation equipment by using the result of our filtration experiments.

Therefore, the advantage of introducing oil-water separation equipment and SS recovery equipment to wastewater treatment system for wastewater including the large amount of oil and SS was clarified. More, the effectiveness and versatility of the proposed evaluation method was shown.

Reference

1) Noguchi, Y.; Sekine, C., *Japanese Society of Agricultural Informatics*, 19 (4), 86-94 (2010)
2) Ministry of the Environment, http://www.kankyo. metro.tokyo.jp/water/pollution /regulation/emission_standard/general.html, (Last access: 2015.03.08)
3) Bureau of Sewerage Tokyo Metropolitan Government, http://www.gesui.metro.tokyo.jp/onega/tomin_all.htm, (Last access: 2015.03.08)
4) Asakawa, S.; Noguchi Y.; Suzuki, A.; Yamagishi, T.; Sudo, R., *Japanese Journal of Water Treatment Biology* (30), 74 (2010)
5) Sato, H., *Environmental Management*, 45 (6), 528-534 (2009)
6) Noguchi, Y.; Nishimura, O.; Asakawa, S.; Yamagishi, T.; Ootsuka, T., *Journal of Water and Waste*, 54, 849-859 (2012)
7) Tsukii, S.; Nakamori, H.; Hirano, K., *J. Jpn. Inst. Energy*, 87, 291-296 (2008)
8) Hyde, K.; Smith, A.; Smith, M.; Henningsson, S., *Journal of Cleaner Production*, 9, 57-64 (2001)
9) Khoo, H.H.; Lim, T. Z.; Tan, R. B.H., *Science of the Total Environment*, 408, 1367-1373 (2010)
10) Tanaka, M.; Fukushima, K.; Nagao, N.; Niwa, C.; Toda, T., *Science of the Total Environment*, 432, 309-317 (2012)
11) Fuchs, K.; Peierls, R., "Separation of Isotopes, Selected Scientific Papers of Sir Rudolf Peierls: With Commentary (Dalitz, R.H. and S. R. Peierls). World Scientific series in 20th century physics", World Scientific, 19, 303-320 (1997)
12) Takeda, K., "Mechanism of separation –Latest separation", Kyoritsu Shuppan Co.

Ltd., 1988

13) Bernstein, J., “SWU for U and ME”, Cornell University Library, 2009

14) Noguchi, R.; Tofael, A.; Takigawa, T.; CIGR2011, CIGR International Symposium on "Sustainable Bioproduction - Water, Energy, and Food", 19-23 September 2011 (Tower Hall Funabori, Tokyo, Japan)

15) Otsuka, T., Ankyu, E., Noguchi R., The society of Eco-Engineering 2013, 29-30 June 2013 (Tamagawa University, Tokyo, Japan)

16) FUJI CLEAN Co., LTD., http://www.fujiclean.co.jp/fujiclean/product/wq_1.html, (Last access: 2014.06.16)

17) Tadokoro, M.; Sakurai, T., *Journal of Water and Waste*, 36(9), 10-17 (1994)

18) Matsumura, H., Pollution load of animal and plant oil, Monthly Journal of Johkasou, 442, 29-31(2013)

19) The Japan Association of Rural Solutions for Environmental Conservation and Resource Recycling, http://www.jarus.or.jp/villagedrain/ 03lowcost /01-14.pdf, 3pp, (Last access: 2014.10.03)

20) Ministry of Economy, Trade and Industry, http://www.enecho.meti.go.jp/statistics /total_energy/pdf/stte_012.pdf, (Last access:2015.03.08)

21) Ministry of Economy, Trade and Industry, http://www.enecho.meti.go.jp/statistics /petroleum_and_lpgas/pl007/results.html#headline3, (Last access: 2015.03.08)

22) USDA National Nutrient Database for Standard Reference Release 27, http://ndb.nal.usda.gov/ndb/ foods/show/675, (Last access:2015.03.08)

23) Japan Society for Food Engineering, Eds., “Food Engineering”, Asakura

Publishing Co., Ltd., 2012, pp. 110

24) Ministry of the Environment, http://www.kankyo. metro.tokyo.jp/water/pollution /regulation/emission_standard/general.html, (Last access: 2015.03.08)

25) Hokuriku Electric Power Company, http:// www.rikuden.co.jp/ryokin/syoutenkoujyou.html, (Last access: 2015.03.08)

26) AS ONE Corporation, http://www.as-1.co.jp/ academy/5/5.html, (Last access:2015.03.08)

27) Mekatoronet, http://www.mekatoro.net/mechatro _parts/vol3/pdf/p10-113.pdf, (Last access: 2015.04.20)

28) NAC FEEDING CO., LTD., http://www.nacweb. co.jp/products/industrial4, (Last access: 2015.04.20)

29) Ankyu, E.; Otsuka, T.; Noguchi, R., *Journal of the Japan Institute of Energy*, 95(3), 275-282 (2016)

Acknowledgement

This study for doctoral degree thesis was accomplished under the supervision of Associate Professor Ryozo Noguchi. His wide knowledge and his logical way of thinking have been of great value of me. His understanding, encouraging and personal guidance have provided a good basis for the present thesis.

I wish to express my warm and sincere thanks to Professor Tomohiro Takigawa, Professor Mitsutoshi Nakajima, and Professor Yutaka Kitamura for their helpful and constructive comments, and for their important support throughout this work.

I would like to express my thanks to Associate Professor Ahamed Tofael and Assistant Professor Takuma Genkawa for their valuable support in my research life.

As for filed investigation and collecting some important data, I am deeply grateful to Mr. Hideo Sato, in Daitogiken. Inc., Mr. Takayoshi Sato, in Naoetsu-Yushi Co. Ltd., Mr. Yuji Noguchi, Mr. Susumu Asakawa and Mr. Toshihiko Otsuka, in Saitama-Ken environmental analysis & research association. Without their kind support, this work would have not been achieved.

I wish to extend my warmest thanks to whole members of the Agricultural Machinery and bio systems engineering Lab for spending a lot of grateful time together in our lab. And I wish to thank my friends for their encouraging words and activity.

I would especially like to thank my family. Without their constant support and understanding, it would have been impossible for me to finish this work.