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Theoretical Analysis for Energy Consumption of a Circulation-Type Superheated Steam Degreasing System Applied to Oily Metal Waste Recycling

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Abstract: *Recycled waste material has recently become of interest because of the huge amount of natural resource consumption worldwide. It is necessary to introduce a material recycle system in municipal and industrial waste management. Quality improvement of oily metal waste disposed from metalworking factories as recycling materials is one of the issues. Here, the degreasing system plays an important role. In this paper, energy consumption of a circulation-type superheated steam degreasing system was applied to oily metal waste disposed from a metalworking factory. This system was compared to a once-through type superheated steam degreasing system. Flow rates of materials applicable to the degreasing system were estimated based on preliminary experiments, and heat and energy balances from the system were theoretically evaluated and compared between once-through and circulation type systems. As a result, a circulation-type superheated steam waste degreasing system that can process oily metal waste provides a promising energy-saving waste metal recycle system.*
Keywords: *Circulation, Degreasing, Energy balance, Material recycle, Once-through, Superheated steam*

I. Introduction

An increase in the world's population and an improvement in quality of human life cause natural resource depletion. Fossil fuel depletion has been of particular interest globally. However, material resource depletion has also become a serious issue. Generally, oily metal waste disposed from metalworking factories is melted directly by an electric steelmaking furnace or blast furnace, and recycled as low grade material, which includes impurities. Some removable methods, such as centrifugal separation or chemical dissolution, are introduced to remove oil from metal waste. A centrifugal separation method can not remove oil well enough from metal because metal waste has a complex shape. Oil gathering in a recess remains on a metal waste. On the other hand, if oil is removed with chemicals, the oil dissolves into a chemical substance and becomes difficult to separate from the chemical agent. In addition, it is also difficult to dispose of liquid waste that includes a chemical substance into the surroundings from an environmentally-conscious standpoint.

Superheated steam has been a very popular heat source for industrial and municipal applications, such as air conditioning and boilers. In particular, most of the electric power supply is generated by using superheated steam turbine systems in a power plant. Superheated steam is a gas generated by heating saturated steam until it exceeds the boiling point [1, 2]. For industrial application, the superheated steam is applied to drying several kinds of materials, like wood, coffee beans, vegetables, and waste materials, based on special characteristics such as inactive gas and condensation heat transfer [3-5]. A drying system using superheated steam plays an important role in high-moisture material drying procedures due to the steam's high thermal efficiency. This kind of steam creates several advantages, such as inactive gas and high specific enthalpy, for material processing systems. Accordingly, the system using superheated steam has been very useful in waste processing [6-8]. The superheated steam was introduced to improve the quality of metal waste disposed from metalworking factories as recycling materials [9-11]. The superheated steam evaporates waste oil and removes it from the metal. Nonetheless, in order to obtain a superheated steam, a large amount of latent heat for water evaporation is required. Generally, superheated steam is condensed after it passes through a processing section where the latent heat is exhausted into the surroundings, resulting in low thermal efficiency. In this paper, a practical circulation-type superheated steam degreasing system is proposed for oily metal waste recycling disposed from metalworking factories, and the system's energy consumptions are theoretically evaluated and compared to the results from a once-through type system.

II. CHARACTERISTICS OF SUPERHEATED STEAM FOR AN INDUSTRIAL APPLICATION

Superheated steam is an atmospheric vapor heated until it reaches 100 ºC or higher. Generally, superheated steam is available in a higher efficiency at around 170 ºC or more for an industrial application compared to the efficiency of hot air at the same temperature. This temperature is called the inversion temperature [12, 13]. The superheated steam can heat the materials by convection, radiation and condensation heat transfers, as shown in Fig. 1. The condensation heat transfer is a special feature of superheated steam heat transfer, especially for moisture materials, in which hot air heat transfer cannot be encouraged. When the material's surface temperature, which will be processed, is lower than 100 ºC, superheated steam can push large amounts of condensation heat into the material and the steam contains several prominent advantages, especially for waste processing, since the gas is an inactive gas. When the processing chamber is filled with the superheated steam, a chemical reaction, such as ignition, can be prevented since the steam does not contain O_2. Hence, fires or explosions cannot take place in the processing apparatus, and safety in the waste processing is finally ensured. Similarly, this gas also presents useful features for waste disposal, including sterilization, degreasing and deodorization.

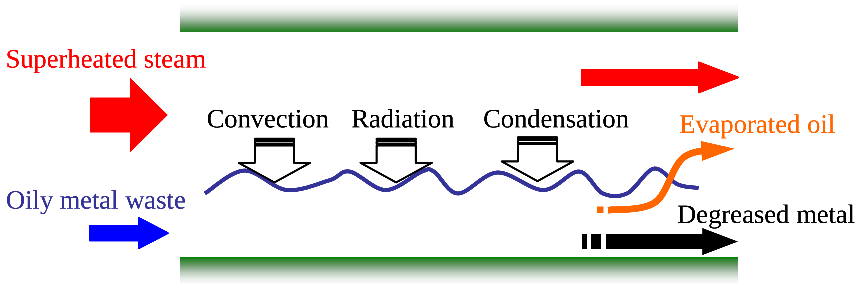


Fig. 1 Superheated steam and material flow in an open-type processing section applied to an oily metal degreasing system

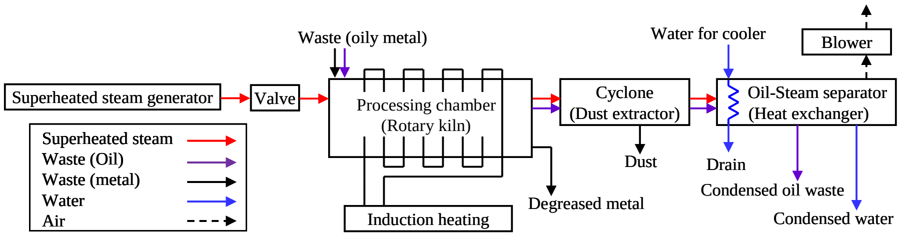
III. THEORETICAL ANALYSIS FOR HEAT AND ENERGY BALANCE

3.1. System Configuration of Superheated Steam Degreasing System

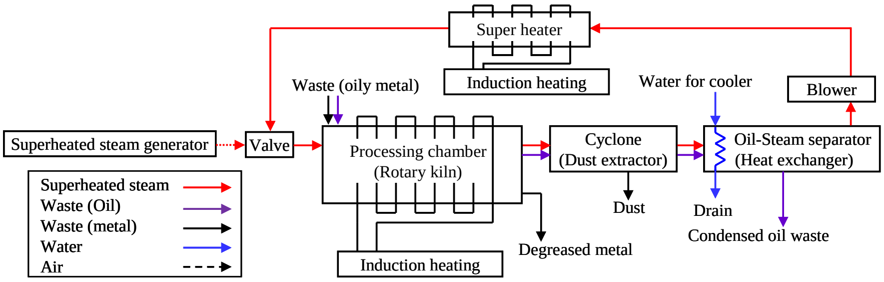
Figure 2 shows an oily metal waste degreasing system using superheated steam. Once-through type and circulation-type degreasing systems are assumed, and their heat and energy consumptions are compared. First, air in the processing chamber is displaced by superheated steam, which comes from the superheated steam generator. Next, oily metal waste is transferred into a chamber, and is processed. At the low oxygen concentration field, even in the high temperature field, the oily metal does not ignite. While the superheated steam passes through the processing chamber, the oily metal is stirred with superheated steam by use of the rotary kiln. Here, the induction heating is applied to heat superheated steam and waste materials. Oil is evaporated and mixed with steam, and the gas flows out from the chamber. On the other hand, degreased metal is discharged from the chamber. After that, superheated steam with evaporated oil passes through a cyclone for dust extraction, and flows into an oil-steam separator. If the system is a once-through type, evaporated oil and steam are simultaneously condensed by a cooling unit at the oil-steam separator, and these substances are collected in a liquid state, as shown in Fig. 2(a). A blower is introduced in order to promote the system's gas flow.

In contrast, only the evaporated oil is condensed at an oil-steam separator, and steam passes through the separator at the superheated steam state in a circulation type system, as shown in Fig. 2(b). The steam is pressurized by a blower and heated by a super heater again. After that, the heated steam flows into the processing chamber, while the steam that comes from the generator is closed in a steady state condition. Finally, the superheated steam is circulated in the degreasing system.

Figure 3 shows a demonstration of the superheated steam degreasing system and an example of waste material. The theoretical estimation in this paper was applied to this system. The system is composed of the equipment shown in Fig. 2. The system configuration can be changed for a once-through or a circulation-type system only by operation valves. The ducts and equipment were coated with a thick layer of heat-insulation material. Typical temperatures in the system were measured by K-type thermocouples and recorded by a multi-channel data logger.

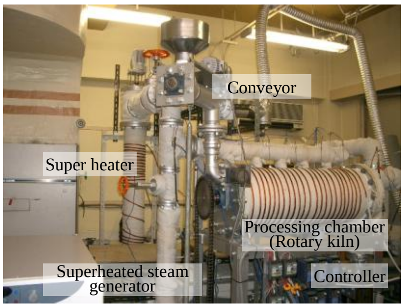


(a) Once-through type system



(b) Circulation-type system

Fig. 2 System configuration of degreasing system using superheated steam



(a) Demonstration system

(b) Oily metal waste

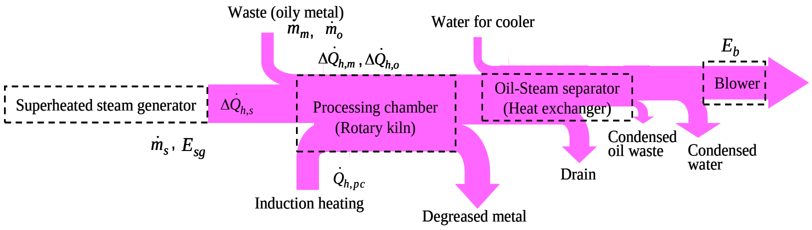
Fig. 3 Superheated steam degreasing demonstration system and example of waste material

3.2. Material Flow of Degreasing System

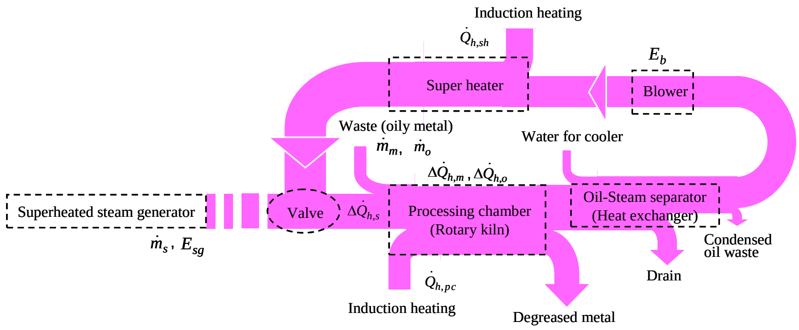
Material flow of this degreasing system was estimated based on the system shown in Fig. 2. Oily metal waste flowed into the processing chamber. The volume flow rate was assumed by defining 1/5 of the processing chamber capacity as filled by waste material, and the length of time for waste to pass through the processing chamber was assumed to be 10 minutes. The adhesion rate of oil was assumed to be 2.5 wt% of the metal waste. These assumptions were observed by a preliminary experiment. Oily metal waste was heated by the high temperature superheated steam and induction heating in the processing chamber. After processing, the degreased metal is discharged from the processing chamber, and superheated steam with evaporated oil flows out from the chamber. The volume flow rate of metal is $\dot{Q}_{v,m}$; thus, the mass flow rate becomes $\dot{m}_m$ = $\rho_m \dot{Q}_{v,m}$. The mass flow rate of oil is assumed to be $\dot{m}_o = 0.025\dot{m}_m$ in this estimation.

3.3. Energy Balance of Degreasing System

The heat balance and energy consumption of the once-through type and the circulation-type systems are estimated based on Fig. 4. Electricity was supplied to each type of equipment in order to operate the system. However, the electric consumption of the main apparatus was taken into account in this estimation.



(a) Once-through type system



(b) Circulation-type system in steady state condition

Fig. 4 Heat and energy balance of degreasing system using superheated steam

3.3.1. Once-through type system

The schematic heat and energy balance diagram of the once-through type system is presented in Fig. 4(a). Superheated steam enters the processing chamber in order to evaporate oil. Metal waste and oil temperatures at the processing chamber inlet and exit are $T_{m,1}$, $T_{o,1}$ and $T_{m,2}$, $T_{o,2}$, and the superheated steam temperature at the processing chamber inlet and exit are defined as $T_{s,1}$ and $T_{s,2}$, respectively. Oily metal waste must be heated to $T_{s,2}$ when it passes through a processing chamber. Therefore, heat added to the oily metal can be expressed as:

$$\Delta\dot{Q}_{h,m} = \dot{m}_m c_m \left(T_{m,2} - T_{m,1}\right) \qquad \text{(for metal)} \tag{1}$$

$$\Delta\dot{Q}_{h,o} = \dot{m}_o \left\{c_o \left(T_{o,2} - T_{o,1}\right) + L_o\right\} \quad \text{(for oil)} \tag{2}$$

where, $T_{m,1} = T_{o,1}$ and $T_{m,2} = T_{o,2} = T_{s,2}$.

On the other hand, heat supplied by the superheated steam generator is consumed to increase the temperature of the oily metal waste as follows:

$$\Delta\dot{Q}_{h,s} = \dot{m}_s \left(h_{s,2} - h_{s,1}\right) \tag{3}$$

If $(\Delta\dot{Q}_{h,m} + \Delta\dot{Q}_{h,o}) < \Delta\dot{Q}_{h,s}$, oil is evaporated and separates from the metal waste. However, additional heat $\dot{Q}_{h,pc}$ needs to be supplied by induction heating in the processing chamber if $(\Delta\dot{Q}_{h,m} + \Delta\dot{Q}_{h,o}) > \Delta\dot{Q}_{h,s}$. Steam with evaporated oil will be cooled by additional water at a temperature below evaporation and condensed to a liquid state in the oil-steam separator. Condensed steam and oil are separated by using the specific gravity separation method. Generally, heat loss from the equipment must not be neglected in this system. The additional heat will be supplied by the heater to the equipment and ducts.

3.3.2. Circulation-type system

The schematic heat and energy balance of the circulation-type system is shown in Fig. 4(b). For the circulation-type system, energy flow after the processing chamber is different from the once-through type system. After the waste materials pass through the processing chamber, the gas is cooled in the oil-steam separator. Only evaporated oil is condensed and steam remains in a superheated steam condition in the oil-steam separator. Following this, steam is pressurized by a blower and reheated by the super heater. The additional heat from the super heater is estimated as:

$$\dot{Q}_{h,sh} = \dot{m}_s\left(h_{s,4} - h_{s,3}\right) \tag{4}$$

If the steam temperature is increased by the super heater upon the inlet temperature $T_{s,1}$, high enthalpy steam can perform the oily metal waste processing. The steam flow rate is kept constant by using a high pressure blower, and the steam circulates without a superheated steam generator in a steady state condition, as shown in Fig. 4(b).

IV. Application for Demonstration System

The heat and energy flow described in Fig. 4 will be applied to the demonstration system to establish an energy balance. The theoretical conditions of the energy balance analysis are shown in Table 1. The size of the processing chamber in this system was 0.30 dia. × 1.0 m in length. Hence, the optimum volume and mass flow rates of metal are estimated as $\dot{Q}_{v,m}$ = 2.4×10^{-5} m^3/s and $\dot{m}_m$ = 7.0×10^{-3} kg/s, respectively. Here, the density of a waste metal is measured as ρ_m = 2.9×10^2 kg/m^3 by a preliminary experiment. In this case, the mass flow rate of oil is $\dot{m}_o$ = 1.7×10^{-4} kg/s, which corresponds to 2.5 wt% of the metal flow rate.

Table 1 Theoretical conditions of energy balance analysis based on preliminary experimental results

Temperature		
Metal and oil at the processing chamber inlet	$T_{m,1}$, $T_{o,1}$	15 ºC
Superheated steam at the processing chamber inlet	$T_{s,1}$	400 ºC
Metal, oil and superheated steam at the processing chamber exit	$T_{m,2}$, $T_{o,2}$, $T_{s,2}$	250 ºC
Superheated steam at the super heater inlet	$T_{s,3}$	150 ºC
Superheated steam at the super heater exit	$T_{s,4}$	400 ºC
Enthalpy of superheated steam		
at the processing chamber inlet at 0.1 MPa, $T_{s,1}$	$h_{s,1}$	3.28 MJ/kg
at the processing chamber exit at 0.1 MPa, $T_{s,2}$	$h_{s,2}$	2.97 MJ/kg
at the super heater inlet at 0.1 MPa, $T_{s,3}$	$h_{s,3}$	2.78 MJ/kg
at the super heater exit at 0.1 MPa, $T_{s,4}$	$h_{s,4}$	3.28 MJ/kg
Mass flow rate		
Superheated steam	$\dot{m}_s$	1.25×10^{-3} kg/s
Metal	$\dot{m}_m$	7.0×10^{-3} kg/s
Oil	$\dot{m}_o$	1.7×10^{-4} kg/s
Specific heat		
Metal (Aluminum)	c_m	0.9 kJ/(kg･K)
Oil (cutting oil)	c_o	2.1 kJ/(kg･K)
Evaporative latent heat of oil	L_o	320 kJ/(kg･K)

For the once-through type system, the energy balance is estimated based on Fig. 4(a). The evaporation temperature of the cutting oil has an observation range between 150 - 250 ºC. The exit temperature of material from the processing chamber is assumed to be $T_{m,2}$ = $T_{o,2}$ = 250 ºC. The initial temperature of the material and the evaporation temperature of oil are assumed to be 15 ºC and less than 250 ºC, respectively. The heat required to heat waste material is estimated as:

For metal:

$$\Delta\dot{Q}_{h,m} = \dot{m}_m c_m\left(T_{m2} - T_{m1}\right)$$
$$= 7.0\times10^{-3} \times 0.90\times10^{3} \times(250\text{-}15) = 1{,}480 \text{ W} \tag{5}$$

For oil:

$$\Delta\dot{Q}_{h,o} = \dot{m}_o\left\{c_o\left(T_{o2} - T_{o1}\right) + L_o\right\}$$

$$= 1.7\times10^{-4}\times\{2.1\times10^{3}\times(250\text{-}15) + 320\times10^{3}\} = 140\ \text{W} \quad (6)$$

Therefore, it is estimated for the waste material as:

$$\Delta\dot{Q}_{h,w} = 1{,}480 + 140 = 1{,}620\ \text{W} \quad (7)$$

The superheated steam generator employed in this demonstration system can produce 4.5 kg/h of steam at 450 ºC, 0.3 MPa, and its electric consumption is E_{sg} = 5.0 kW. Heat required to heat the waste material is supplied by the superheated steam generated by the superheated steam generator, $\Delta\dot{Q}_{h,s}$, and the induction heating through the processing chamber, $\dot{Q}_{h,pc}$. Heat supplied by superheated steam is estimated as:

$$\begin{aligned}\Delta\dot{Q}_{h,s} &= -\dot{m}_s\left(h_{s,2} - h_{s,1}\right)\\ &= -1.25\times10^{-3}\times\{2.97\times10^{6} - 3.28\times10^{6}\} = 390\ \text{W}\end{aligned} \quad (8)$$

It was found that only 390 W is available to heat waste material, even if the superheated steam generator consumes 5.0 kW. Residual energy, 4.6 kW, is exhausted and the superheated steam generator is inflected to replace air with steam inside a processing system. Therefore,

$$\begin{aligned}\dot{Q}_{h,pc} &= \Delta\dot{Q}_{h,w} - \Delta\dot{Q}_{h,s}\\ &= 1{,}620 - 390 = 1{,}230\ \text{W}\end{aligned} \quad (9)$$

has to be supplied by induction heating through the processing chamber. The inverter and conversion efficiency of induction heating are assumed to be 0.95 and 0.60 respectively. Electric consumption of the induction heating is estimated as:

$$E_{pc} = \frac{\dot{Q}_{h,pc}}{\eta_i\eta_c} = 2{,}160\ \text{W} \quad (10)$$

In addition, a blower is employed for the system. The electric consumption of the blower is measured by a preliminary experiment. The demonstration system employs a 750 W high pressure blower. The measured electric consumption of the blower is:

$$E_b = 600\ \text{W} \quad (11)$$

Consequently, the total energy consumption of the once-through type, E_{ot}, is estimated as:

$$\begin{aligned}E_{ot} &= E_{sg} + E_{pc} + E_b\\ &= 5.0 + 2.2 + 0.6 = 7.8\ \text{kW}\end{aligned} \quad (12)$$

$$e_{ot} = \frac{E_{ot}}{\dot{m}_m + \dot{m}_o} = 1.1\ \text{MJ/kg} \quad (13)$$

For the circulation-type degreasing system at a steady state condition, only energy consumed in a circulation area is estimated in Fig. 4(b). The required heat to increase the temperature of waste material was determined earlier using Eq. (7). The circulation-type system also supplies heat to the processing chamber by induction heating. Here, the steam mass flow rate is assumed to be the same as that of the once-through type system. The discharged steam with evaporated oil from the processing chamber is cooled in the oil-steam separator. Gas is cooled at a temperature between that of water evaporation and under that of oil condensation. The condensing temperature of oil is assumed to be 150 ºC in this estimation. Steam remains as superheated steam at 150 ºC. Therefore, the discharged steam from the oil-steam separator is superheated by the super heater. The required heat and electric consumption are estimated as:

$$\dot{Q}_{h,sh} = \dot{m}_s\left(h_{s,4} - h_{s,3}\right)$$
$$= 1.25\times10^{-3} \times(3.28\times10^{6} - 2.78\times10^{6}) = 625 \text{ W} \quad (14)$$

$$E_{sh} = \frac{\dot{Q}_{h,sh}}{\eta_i\eta_c} = 1.1 \text{ kW} \quad (15)$$

As a result, the total energy consumption of the circulation type, E_{ci} , is estimated as:

$$E_{ci} = E_{pc} + E_{sh} + E_b$$
$$= 2.2 + 1.1 + 0.6 = 3.9 \text{ kW} \quad (16)$$

$$e_{ci} = \frac{E_{ci}}{\dot{m}_m + \dot{m}_o} = 0.54 \text{ MJ/kg} \quad (17)$$

The energy consumption estimated from the circulation-type superheated steam degreasing system is smaller than the amount of the once-through type system.

It was also found that heat loss from the circulation-type system increases compares to the once-through type system because the path length of steam becomes longer. These results were obtained based on the main equipment of these systems. Therefore, additional energy, such as a duct heater or rotary kiln operation, should be added for each of the estimations. However, these results show the advantages of introducing a circulation-type decreasing system.

V. CONCLUSION

Energy consumption of the circulation-type superheated steam degreasing system is compared with the results of the once-through type system. Both system configurations are assumed and the heat and energy balance are estimated. The prototype processing system was constructed and the energy consumption with a heat balance was estimated. For the superheated steam processing system, the once-through type system consumes a sufficient amount of energy compared to the circulation-type system because the latent heat of water is higher than the electric consumption of additional equipment for the circulation-type system. As a result, the circulation-type superheated steam oily metal waste degreasing system serves as an adequate system for industrial application.

Acknowledgements

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NOMENCLATURE

c: Specific heat at a constant pressure [J/(kg・K)]
E: Electric consumption [W]
e: Specific electric consumption [J/kg]
h: Specific enthalpy [J/kg]
L: Latent heat [J/kg]
$\dot{m}$: Mass flow rate [kg/s]
$\dot{Q}_h$: Heat [W]
$\dot{Q}_v$: Volume flow rate [m^3/s]
T: Temperature [ºC]
η: Efficiency [-]
ρ: Density [kg/m^3]

Subscripts
1: processing chamber inlet
2: processing chamber exit
3: super heater inlet

4: super heater exit
b: blower
c: work coil
ci: circulation type
i: inverter
m: waste metal
o: waste oil
ot: once-through type
pc: processing chamber
s: steam
sg: superheated steam generator
sh: super heater
w: waste material

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