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Optimal Green Facility Planning - Implementation of Organic Rankine Cycle System for Factory Waste Heat Recovery

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***Abstract*—**As global industry developed rapidly, the energy demand also rises simultaneously. In the production process, there's a lot of energy consumed in the process. Formally, the energy used in generating the heat in the production process. In the total energy consumption, 40% of the heat was used in process heat, mechanical work, chemical energy and electricity. The remaining 50% were released into the environment. It will cause energy waste and environment pollution. There are many ways for recovering the waste heat in factory. Organic Rankine Cycle (ORC) system can produce electricity and reduce energy costs by recovering the waste of low temperature heat in the factory. In addition, ORC is the technology with the highest power generating efficiency in low-temperature heat recycling. However, most of factories executives are still hesitated because of the high implementation cost of the ORC system, even a lot of heat are wasted. Therefore, this study constructs a nonlinear mathematical model of waste heat recovery equipment configuration to maximize profits. A particle swarm optimization algorithm is developed to generate the optimal facility installation plan for the ORC system.

***Keywords*—**Green facility planning, organic rankine cycle, particle swarm optimization, waste heat recovery.

I. INTRODUCTION

LARGE amount of energy and fuel are consumed by factories during the manufacturing process. According to a recent survey in Taiwan, the industrial department accounted 38.56% with total energy, and 50% of carbon dioxide emissions with total national emissions [1]. The energy is used in the form of heat energy and 90% of it is accounted for the total energy consumption. Among the heat generated, only 40% of heat energy is converted into useful process heat, mechanical work, chemical energy, and electricity. The rest of 50% heat is released as waste heat form into environment and causing energy waste and environmental pollution [2]. According to the detailed analysis, the temperature of most industry waste heat discharge is between 130℃ to 650℃. Two million kiloliter oil equivalent (KLOE) of waste heat below 250℃, accounting for as high as 62.72% of the total waste heat, belongs to the low temperature of waste heat discharge [3].

Today for low-temperature waste heat recovery power generation system, the Organic Rankine Cycle (ORC) system is the advanced technology with high power generation efficiency. The ORC system is widely used in industrial waste heat, geothermal hot springs, bio-mass heat and waste heat power generation purposes [4]. In addition, the ORC system almost has no fuel consumption during it running period, it can also reduce carbon dioxide and sulfur dioxide emissions and other pollutants [5]. The ORC system uses organic working fluid as a medium of pick up thermal power generation [6]. It can choose suitable low boiling point substances as the working fluid (such as refrigerant, ammonia, etc.) by different heat source temperature range, and makes low temperature heat energy converted into electricity or brake horsepower output. For the medium and the low temperature heat source, converted to electricity, is more efficient than converting into water [7]. The main loop circuit of an ORC system include: pump, evaporator, expander, generator and the condenser. Working fluid circulating in the circuit model starts from: 1) a booster pump, 2) being evaporated into vapor, 3) promoting the expansion machine and generators, 4) then condensing to liquid water and completing the cycle [8]-[10].

However, as in Taiwan the environment of tariffs is generally low, invest of ORC generator have high risk of too long investment recovery period and return on investment. The industry executives still maintain hesitated, even if the factory has lots of waste heat. Only few factories are willing to invest in ORC generator to conduct waste heat recovery power generation [6]. Therefore, the goal of this study is using ORC power generation units to construct a nonlinear mathematical model of waste heat recovery equipment configuration to maximize profits. The factory will convert the low temperature waste heat into electric power via the ORC system. A particle swarm algorithm to find out the suitable generator set number and model, will be an effectively method for a factory to improve its waste heat recovery

II. MODEL CONSTRUCTION

A. Background

This study focuses on the factory's low temperature waste heat with recycling value, and implementing an ORC system for waste heat recovery. With the condition of maximum output power, only heat source temperature and discharge temperature, heat source mass flow rate and specific heat, the

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working fluid evaporation temperature, and the condensing temperature, are considered by waste heat of heat capacity [11]. It includes the loss of power transmission and the generator efficiency. Without discussing each element thermal efficiency, the overall optimization cycle thermal efficiency is achieved [6], [12]. In the cost analysis of investment of ORC generator, the most important issue is the equipment costs of ORC unit itself. The other factors considered include: installation cost of the generating set surrounding the production facility, and the time value of the investment [13]. In addition, the operation and maintenance costs of waste heat recovery equipment operation will increase yearly, must through constant-escalation-levelization-factor to the cost of the time value of money considerations [13], [14].

In this study, the objective function is to maximize the annual net profit which includes the annual sell electricity income, annual investment cost, annual operation and maintenance costs, government subsidies and annual salvage value. Then a particle swarm optimization algorithm is developed to find out the suitable number of ORC units from the waste heat recovery equipment configuration optimization. Then it can be learned that all of the waste heat source in factory should be parallel configuration of those generators model

B. Nomenclature

I	Total number of heat source in factory
J	Total number of generators model of ORC
HT_i	Temperature of the heat source i (°C)
LT_i	Discharge temperature of the factory requirements (°C)
M_i	Total mass of the heat source i (kg/hr)
S_i	Specific heat of the heat source i (cal/g°C)
ET_j	Evaporation temperature of the working fluid in ORC model j (kelvin, K)
CT_j	Condensing temperature of the working fluid in ORC model j (kelvin, K)
RH	Running hours of ORC model j of ORC in a year (hr)
EP	electricity price per kWh
EGR	electricity growth rate
PEC_j	purchased equipment cost of ORC model j
SV_j	salvage value of ORC model j
A_j	each generator government grants of ORC model j
CI_j	cost of installation of ORC model j
CP_j	cost of piping of ORC model j
CEE_j	cost of electrical equipment of ORC model j
CC_j	cost of civil and structural work of ORC model j
CS_j	cold source of ORC model j
DPC_j	design and planning costs of ORC model j
MC_{ij}	maintenance costs of ORC model j installation at the heat source i
PRC_{ij}	plant repair costs of ORC model j installation at the heat source i
$GRMC$	growth rate of the maintenance costs
B	factory budget
FPB	payback required by the factory
$MARR$	minimum acceptable rate of return
n	assessment of useful life
x_{ij}	the number of ORC model j installation at the heat source i
m_{ij}	the mass diverted to ORC model j from the heat source i (kg/hr)

$$y_{ij} = \begin{cases} 1 \text{ , the heat source } i \text{ has installed the model } j \text{ of ORC ;} \\ 0 \text{ , the heat source } i \text{ has not installed the model } j \text{ of ORC} \end{cases}$$

$$Y_j = \begin{cases} 1 \text{, the factory has installed the model } j \text{ of ORC} \left(\sum_{i=1}^{I} y_{ij} \geq 1\right) \text{ ;} \\ 0 \text{, the factory has not installed the model } j \text{ of ORC} \left(\sum_{i=1}^{I} y_{ij} \geq 0\right) \end{cases}$$

C. Mathematical Model

Objective function is to optimize the waste heat recovery equipment configuration profits (annual sell electricity income annual investment cost annual operation and maintenance costs + government subsidies + annual salvage value) as in (1).

$$\begin{aligned} P = & \left\{ \begin{array}{l} \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J} \left(\begin{array}{l} \left[m_{ij} \times S_i \times \left(HT_i - LT_i \right) / 860 \right] \\ \times \left(1 - \sqrt{CT_j / ET_j} \right) \times RH \end{array} \right) \right\} \times EP \\ \times \left[\frac{(1+EGR)^n - 1}{(1+EGR) - 1} \right] \times \left[\frac{MARR \times (1+MARR)^n}{(1+MARR)^n - 1} \right] \end{array} \right\} \\ & - \left\{ \begin{array}{l} \left\{ \sum_{j=1}^{J} \left[\sum_{i=1}^{I} \left[\left(\begin{array}{l} PEC_j + CI_j + CP_j \\ + CEE_j + CC_j + CS_j \end{array} \right) \times x_{ij} + DPC_j \times Y_j \right] \right] \right\} \\ \times \left[\frac{MARR \times (1+MARR)^n}{(1+MARR)^n - 1} \right] \end{array} \right\} \\ & - \left\{ \begin{array}{l} \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \left(MC_{ij} + PRC_{ij} \right) \times x_{ij} \right] \times \left(\frac{1+GRMC}{1+MARR} \right) \\ \times \left\{ \left[1 - \left(\frac{1+GRMC}{1+MARR} \right)^n \right] \Big/ \left[1 - \left(\frac{1+GRMC}{1+MARR} \right) \right] \right\} \\ \times \left[\frac{MARR \times (1+MARR)^n}{(1+MARR)^n - 1} \right] \end{array} \right\} \\ & + \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J} A_j \times x_{ij} / n \right\} \\ & + \left\{ \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \left(SV_j \times x_{ij} \right) \right] \times \left\{ MARR \Big/ \left[(1+MARR)^n - 1 \right] \right\} \right\} \end{aligned} \quad (1)$$

$$ET_j \times y_{ij} \leq HT_i \text{ , } \forall i \text{ , } \forall j \quad (2)$$

$$y_{ij} \leq x_{ij} \leq M \times y_{ij} \text{, } \forall i \text{ , } \forall j \quad (3)$$

$$Y_j \le \sum_{i=1}^{I} y_{ij} \le M \cdot Y_j,\ \forall j \tag{4}$$

$$\sum_{j=1}^{J} m_{ij} \le M_i\ ,\forall i. \tag{5}$$

$$\left\{ \begin{matrix} \left[m_{ij} \times S_i \times \left(HT_i - LT_i \right) / 860 \right] \\ \times \left(1 - \sqrt{CT_j \div ET_j} \right) \end{matrix} \right\} \Big/ x_{ij} \le GC_j\ ,\forall i\ ,\forall j \tag{6}$$

$$\sum_{j=1}^{J} \sum_{i=1}^{I} \left(\begin{matrix} \left(\begin{matrix} PEC_j + CI_j + CP_j \\ +CEE_j + CC_j + CS_j \end{matrix} \right) \times x_{ij} \\ +DPC_j \times Y_j \end{matrix} \right) \Big/ P \le FPB,\ \forall i\ ,\forall j \tag{7}$$

$$\sum_{j=1}^{J} \sum_{i=1}^{I} \left(\begin{matrix} \left(\begin{matrix} PEC_j + CI_j + CP_j \\ +CEE_j + CC_j + CS_j \end{matrix} \right) \times x_{ij} \\ +DPC_j \times Y_j \end{matrix} \right) \le B,\ \forall i\ ,\forall j. \tag{8}$$

$$\left\{ P \Big/ \sum_{j=1}^{J} \sum_{i=1}^{I} \left(\begin{matrix} \left(\begin{matrix} PEC_j + CI_j \\ +CP_j + CEE_j \\ +CC_j + CS_j \end{matrix} \right) \times x_{ij} \\ +DPC_j \times Y_j \end{matrix} \right) \right\} \ge MARR, \forall i\ ,\forall j \tag{9}$$

$$x_{ij} \ge 0, x_{ij} \in Z, m_{ij} \ge 0, y_{ij} \ge 0, y_{ij} \in \{0,1\}, Y_j \ge 0, \forall i, \forall j \tag{10}$$

Equation (2) represents the heat source i with ORC model j, the evaporation temperature of ORC can't be higher than the temperature of that source. Equation (3) denotes for the generator heat source if not installed, the installation decision number is 0. If factory installs the j generator, then (4) represents at least one heat source will install the generators, which must considers the generator design and planning costs. The big M's in (3) and (4) are infinite large values. Equation (5) represents the sum of mass diverted to ORC model j from heat source i, and the mass cannot be greater than the total mass of that source. Equation (6) is the available generating capacity of the heat source i installed ORC model j. It cannot be greater than the generating capacity of that model. Equation (7) is the constraint of payback period. Equation (8) is the constraint of budget. Equation (9) is the constraint of return on investment. Equation (10) indicates all variables must be greater than or equal to zero.

III. Model Validation

This study discusses the illustrative real case for a steel works factory within the two color coating line, in the process of production will produce waste heat. The heat source data is shown in Table I. The conditions of ORC generator power generation, and the relative of investment cost, according to the literature and the case data which company provided, the simulation parameters set as in Table II [2], [6], [10], [13]. This case company for investment restrictions: $MARR$ is 10(%), FPB is 5(year), B is 50,000,000(NT). And assuming RH is 8000(hr/year), EP is 3.01(NT/kWh), EGR is 2(%), n is 20(year), and $GRMC$ is 1(%).

This study uses particle swarm optimization (PSO) algorithm to simulate the flock foraging, through global search and particle search, then find the optimal solution after iterative update [15]. This research uses linear decreasing weighting method [16] and the related parameters are as in Table III. Use MATLAB 7.10 to write a program, get the results in Table IV.

The planning results show that one model 1 ORC equipment is installed for heat source 1, one model 2 ORC equipment is installed for heat source 1, one model 1 ORC equipment is installed for heat source 2, and one model 2 ORC equipment is installed for heat source 2, respectively. The optimal total annual profit is NT dollar $14,845,764.

TABLE I
Heat Source Basic Data

Heat source	M_i (kg/hr)	S_i (cal/g℃)	HT_i (℃)	LT_i (℃)
$i = 1$	23,760	0.31	320	170
$i = 2$	23,280	0.31	332	170

TABLE II
ORC Basic Data

Model of ORC	GC_j (kW)	ET_j (K)	CT_j (K)	PEC_j (NT)	SV_j (NT)	A_j (NT)	CI_j (NT)
$j = 1$	50	381.15	313.15	4,500,000	450,000	2,000,000	270,000
$j = 2$	125	394.15	294.15	11,250,000	1,125,000	5,000,000	675,000
Model of ORC	**CP_j (NT)**	**CEE_j (NT)**	**CC_j (NT)**	**CS_j (NT)**	**DPC_j (NT)**	**MC_j (NT)**	**PRC_j (NT)**
$j = 1$	405,000	180,000	135,000	225,000	225,000	225,000	225,000
$j = 2$	1,012,500	450,000	337,500	562,500	562,500	562,500	562,500

TABLE III
PSO Algorithm Parameter Settings

Generations	Particle No.	Max weight (w_{max})	Min weight (w_{min})	Studying factor 1 c_1	Studying factor 2 c_2
500	100	0.9	0.4	2	2

TABLE IV
ROC Implementation Results

Heat source i with ORC model j	$i = 1$, $j = 1$	$i = 1$, $j = 2$	$i = 2$, $j = 1$	$i = 2$, $j = 2$
Number of installation x_{ij}	1	1	1	1
Mass m_{ij} (kg/hr)	6,715	16,920	7,494	15,662
Annual net profit (NT/year)	14,845,764			

IV. Conclusions

This study constructed a nonlinear mathematical model of waste heat recovery equipment configuration to maximize implementation profits of the ORC system, with the illustrative real case of painting process of waste heat emissions in a steel company. A particle swarm algorithm is developed to find out the best green configuration of company's color coating process for optimal installation of the ORC waste heat recovery equipment. The results show promising application of the analytical model and the solution PSO algorithm.

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