APPLICATION OF GENETIC ALGORITHM OPTIMIZATION FOR ORGANIC RANKINE CYCLE WASTE HEAT RECOVERY POWER GENERATION

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Abstract

Waste heat recovery for power generation has lately been widely practiced in process industries. A cement plant of 8,300 ton per day capacity releases 17.5 MW_{th} of flue gas at 360°C to 225°C from its suspension preheater (SP) and 28.0 MW_{th} of hot air at 310°C to 122°C from its air quenching cooler (AQC). The temperature of waste heat from a cement plant is in the lower bound of performace criteria to employing Claussius Rankine cycle (steam power cycle), therefore, organic Rankine cycle (ORC) can alternatively be applied for power generation. Finding the optimum solution of the design pressure and temperature of the ORC for waste heat recovery for power generation (WHRPG) corresponding to the most suitable working fluid is the aim of this study. Genetic algorithm (GA) is being considered for the method to determine the optimum solution. In addition, the technique for order of preference by similarity to ideal solution (TOPSIS) is applied to select the best matched working fluid for the ORC. According to TOPSIS evaluation, amongst four working fluid considered, i.e., isobutane, isopentane, benzene, and toluene, isopentane is ranked at the top in terms of health, safety, environment, power output, and cost critera. The optimum ORC WHRPG design is capable of producing 6,094 kW of electric power with AQC boiler pressure of 11.09 bar-a, SP reheater pressure and temperature of 3.68 bar-a and 184°C, and recuperator and condenser pressure of 1.27 bar-a. The highest pressure of 11.09 bar-a at HP turbine and the highest temperature of 184°C at the LP turbine are relatively low compared to that of steam Rankine cycle power plant, thereby dictate less stringent mechanical and thermal strength of materials requirement.

Keywords: Genetic algorithm, Optimization, Organic rankine cycle, Waste heat recovery

Introduction

Waste heat recovery for power generation has lately been widely practiced in process industries for there is a large amount of wasted thermal energy at mostly low temperature is expelled to the environment by various thermal processes. In a cement process plant, thermal energy in forms of hot air from air quenching cooler (AQC) and flue gas from suspension preheater (SP) at temperature of 300°C to slightly less than 400°C are wasted, therefore, useful form of energy can be attained from these waste heat through the application of power plant via heat recovery steam generator (HRSG). At present, electric power generation via Claussius Rankine cycle (steam Rankine cycle) using HRSG for the steam generation recovering waste heat from the SP and AQC is able to generate from the lowest of 0.38 kW_e/ton cement to the highest of 2.0 kW_e/ton cement [1]. It is worth mentioning that the temperature of waste heat from a cement plant is in the lower bound of performance criteria to employing Claussius Rankine cycle, therefore, organic Rankine cycle (ORC) can alternatively be applied for power generation purpose [2]. Furthermore, various working fluid to be employed for ORC has been meticulously studied as to select the most suitable working fluid in regard to the waste heat temperature and the efficiency of energy conversion [3, 4].

A pertinent cement plant with a production capacity of 8,300 ton of cement per day releases 17.5 MW_{th} of flue gas (q_{SP}) at 360°C to 225°C from its SP and also 28.0 MW_{th} of hot air (q_{AQC}) at 310°C to 122°C from its AQC [1]. In this study, instead of implementing steam Rankine cycle for recovering the waste heat, ORC is to be applied for the waste heat recovery for power generation (WHRPG). Finding the optimum solution of the design pressure and temperature of the ORC for WHRPG corresponding to the most suitable working fluid is the aim of this study.

In this study, Genetic algorithm (GA) [5, 6, 7] is being considered for the method to determine the optimum solution in terms of output power. Moreover, particular constrained GA optimization function embedded in MatLab 2010 was applied to solve the constrained optimization problem. In addition, the technique for order of preferency by similarity to ideal solution (TOPSIS) is used to selecting the working fluid for the ORC [8].

Methods

The ideal power that can be extracted from the waste heat is evaluated by using Carnot efficiency formulation, Equation (1), with the hot temperature, T_H, of hot air from AQC and of flue gas from SP, and the cold temperature, T_C, of the surrounding.

$$\eta_C = 1 - \frac{T_C}{T_H} \tag{1}$$

The challlenge of optimizing ORC for WHRPG lies in designing the configuration of ORC, and in selecting the working fluid to closely match the waste heat temperature. For this purpose, ORC consisting of an AQC boiler, a high pressure (HP) turbine, a SP reheater, a low pressure (LP) turbine, a recuperator, a condenser, and a boiler feed pump, (see Figure 1), is specified. A recuperator was inserted between the LP turbine and the condenser due to the fact that the organic working fluid being considered for the ORC is of dry type, where expansion process leads to superheated vapor, therefore, the superheated vapor enthalpy is appropriately transferred to the subcooled working fluid exiting from the condenser through the recuperator.

Moreover, four working fluid were preselected considering that their critical temperatures are close to the available waste heat temperature [3]. Figure 2 shows the temperature – entropy diagram of benzene, toluene, isobutane, and isopentane which are considered for the ORC working fluid. The selection of the most suitable working fluid is carried out through the application TOPSIS method per criteria of health, safety, environment, power output, and cost. The decision matrix for multi criteria decision analysis (MCDA) using TOPSIS is presented in Table 1. It should be empashized here that the power output for each working fluid in Table 1 is calculated via Cycle Tempo 5.0 based on the ORC configuration depicted by Figure 1.

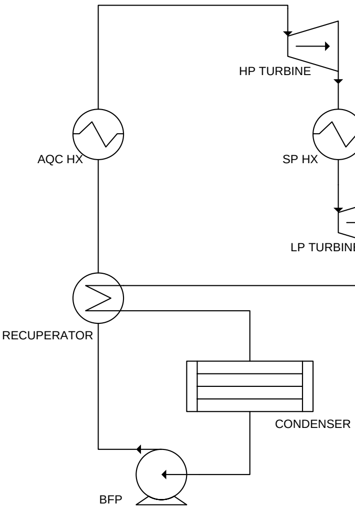

Figure 1. ORC configuration with AQC boiler, HP turbine, SP reheater, LP turbine, recuperator, condenser, and boiler feed pump

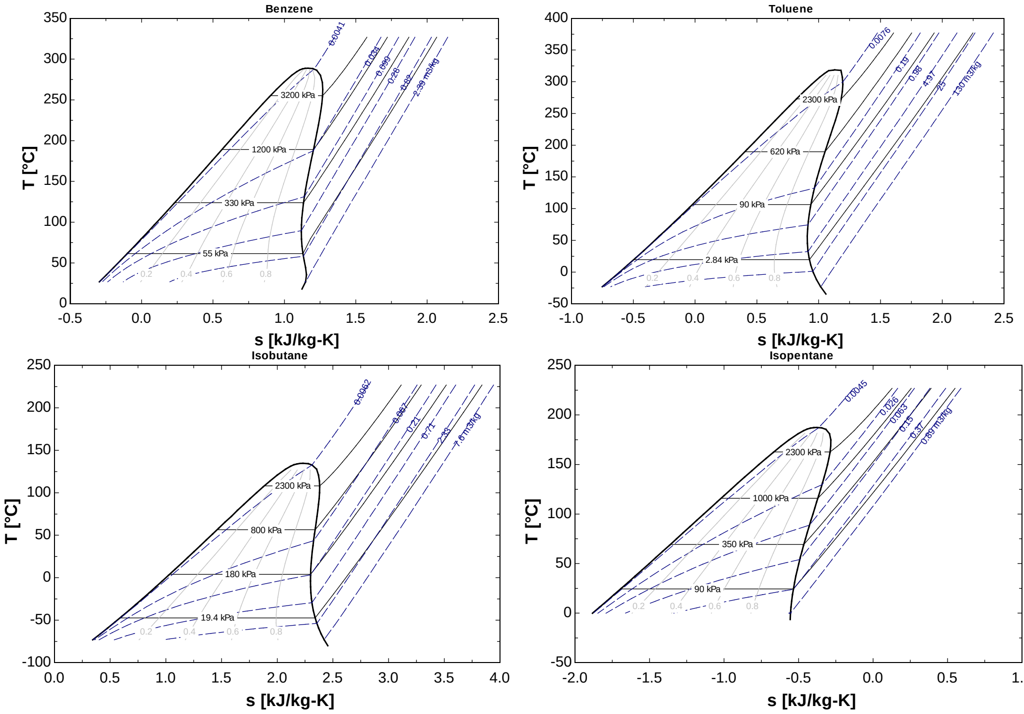

Figure 2. Temperature – entropy diagrams of benzene, toluene, isobutane, and isopentane (in clockwise fashion from top left)

Table 1. MCDA Decision Matrix

Working Fluid	Flammability [relative]	Toxicity [relative]	GWP [CO_2 eq.]	Price [US$/kg]	Power [MW]
Isobutane	4	1	4.52	1 – 5	5.13
Isopentane	4	1	1.09	1 – 2	6.40
Benzene	3	4	1.76	1.2 – 1.6	5.55
Toluene	3	2	1.47	2 – 3.5	3.94

Following the selection of the most matched working fluid for the corresponding ORC configuration, the constrained optimization formulation is specified as in Equation (2) with output power as the objective function and the AQC boiler pressure (p_{AQC}), the SP reheater pressure (p_{SP}), and the condenser pressure (p_C) as the decision variables.

$$\max P_e(p_{AQC}, p_{SP}, p_C) \qquad [\mathrm{kW}] \qquad (2)$$

subject to

$10.5 \le p_{AQC} \le 14.0$ [bar-a]
$2.0 \le p_{SP} \le 5.0$ [bar-a]
$1.27 \le p_C \le 2.0$ [bar-a]
$T_{sat}(p_{AQC}) \le T_{AQC,out} \le T_{sat}(p_{AQC}) + 2^{o}C$ [^{o}C]
$q_{SP} \le 17.5$ [MW_{th}]
$q_{AQC} \le 28.0$ [MW_{th}]

The constrained GA capability of MatLab, however, requires that the objective function to be optimized is in the form of a mathematical function thereby preprocessing of sample population generation to be imposed in GA is carried out by simulating the ORC for power generation via Cycle Tempo 5.0 along side with FluidProp 2.4 providing the working fluid properties for the selected working fluid. And, a regression function of sample population is then generated via Minitab 16. Otherwise, a function linking MatLab and Cycle Tempo must be created in order to communicate and exchange data, which is a tall order.

Assuming turbines internal efficiency of 0.85, pump internal efficiency of 0.8, and heat exchangers effectiveness of 1.0, a population of 58 samples of ORC with AQC boiler pressure (p_{AQC}) from 10.5 bar to 12.4 bar, SP reheater pressure (p_{SP}) from 2.8 bar to 4.4 bar, and condenser pressure (p_C) from 1.27 bar to 1.30 bar was generated via Cycle Tempo 5.0 resulting in power generated (P_e) from 6.00 MW to 6.13 MW. The objective function to be optimized by GA is then generated using Minitab 16 by first order regression to the population with independent variables of p_{AQC}, p_{SP}, and p_C, and dependent variable of P_e. The resulted first order regression is in forms of Equation (3).

$$P_e = a_0 + a_1 p_{AQC} + a_2 p_{SP} + a_3 p_C \qquad (3)$$

In implementing constrained GA in MatLab 2010, the following parameters are specified [6, 7] (see Table 2). It must be noted that the working fluid exit temperature in AQC boiler ($T_{AQC,out}$), the maximum heat available in AQC boiler (q_{AQC}) and SP reheater (q_{SP}) have been eliminated from the constrained GA optimization formulation considering that they have been taken into account during the population samples generation using Cycle Tempo 5.0.

Results and Discussion

The ideal power that can be generated by the waste heat from AQC and SP with the surrounding temperature of 30°C are 13.4 MW and 8.5 MW, respectively. Then, the sum of these figures (21.9 MW) is used as the measuring stick of ORC performance.

Selection of working fluid carried out by applying TOPSIS proves that isopentane is superior compare to those other working fluids being considered (see Table 3).

Table 2. Constrained GA Set of Parameters in MatLab

Parameter	Description
# of independent variables	3
Population type	Double precision vector
Population size	100
Selection type	Roulette wheel
Crossover type	Single point
Crossover rate	0.8
Elitism	2
Mutation type	Uniform
Mutation rate	0.01
Total generation	100
p_{AQC} lower bound	10.5
p_{AQC} upper bound	14
p_{SP} lower bound	2
p_{SP} upper bound	5
p_C lower bound	1.27
p_C upper bound	2
# of iteration	5

Table 3. TOPSIS Results of Working Fluid Rank

Working Fluid	Relative Similarity to Ideal Solution	Rank
Isobutane	0.67	2
Isopentane	0.73	1
Benzene	0.25	4
Toluone	0.51	3

The objective function of maximizing electric power output, P_e [kW], as a function of AQC boiler pressure, p_{AQC} [bar-a], SP reheater pressure, p_{SP} [bar-a], and condenser pressure, p_C [bar-a], resulted from Minitab 16 using first order approximation of regression is presented by Equation (4).

$$P_e = 6911.85 + 114.182 p_{AQC} + 203.24 p_{SP} - 2224.83 p_C \tag{4}$$

The constrained GA optimization via MatLab 2010 results are shown in Table 4. The net power output of 6.09 MW is 27.8% that of ideal power output. In terms of cement production capacity, the design of ORC for WHRPG is amount to 0.73 kW/ton cement, which is in the lower quartile of current WHRPG in cement plants, i.e., in between 0.38 kW/ton and 2 kW/ton. The corresponding temperature – entropy diagram of the ORC for WHRPG in cement plant of 8,300 ton/day capacity is shown by Figure 3.

Table 4. Constrained GA Optimization Results

Output	Value
Net Power Output [kW]	6094.75
AQC Boiler pressure [bar-a]	11.091
SP Reheater pressure [bar-a]	3.679
Condenser pressure [bar-a]	1.273

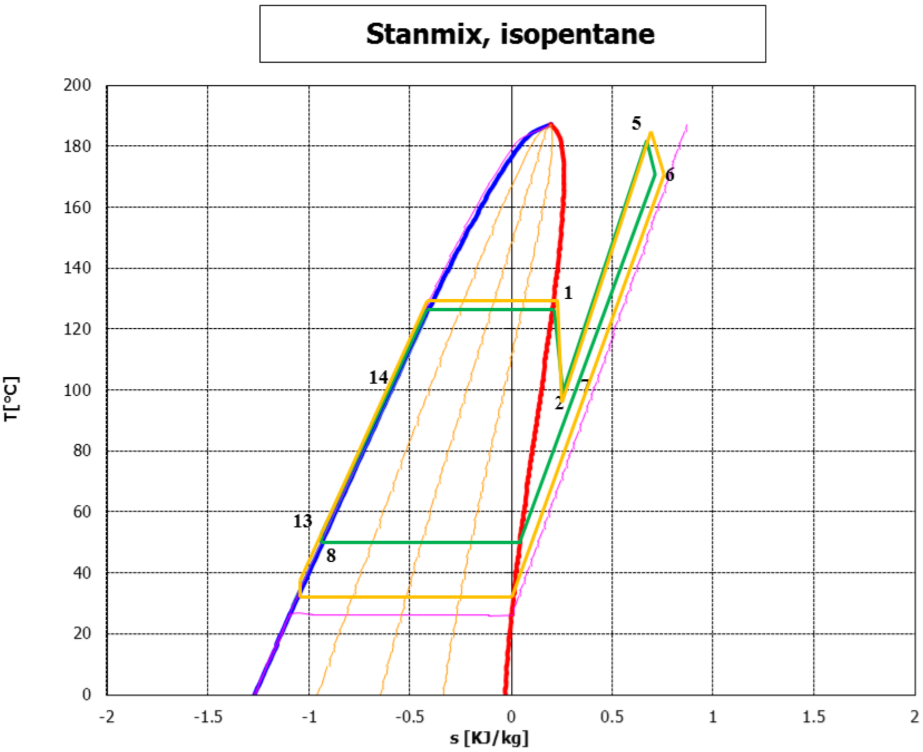

Figure 3. Temperarature – entropy diagram for the ORC for WHRPG

This optimum power generation of 6.09 MW, however, was resulted from assuming that steady state operation at designed load prevails. Discrepancy of power load to that of designed load has not been simulated in this study.

In addition, it is worth mentioning that the available thermal energy of 28 MW_{th} in hot air from AQC is all converted into working fluid thermal energy (enthalpy) in AQC boiler; whereas, 17.2 MW_{th} out of 17.5 MW_{th} of thermal energy in flue gas from SP is converted into working fluid enthalpy in SP heater. This study, however, has not included exergetic losses due to heat transfer in heat exchangers nor optimizing the pinch point of the heat exchangers (AQC boiler and SP reheater).

Conclusions

The implemented constrained GA using MatLab embedded function has resulted in optimum design of ORC WHRPG in a cement plant. In a cement plant of 8,300 ton per day production capacity, 6.09 MW_e is able to be generated at 12.5 percent of energy conversion efficiency. The electric power generated is 27.8 percent to that of maximum available mechanical energy potential possessed by the waste heat from AQC and SP. In addition, the ORC WHRPG produces 0.73 kW_e per ton of cement which is in the lower quartile of current WHRPG's in cement plants.

The highest pressure of 11.09 bar-a at HP turbine and the highest temperature of 184°C at the LP turbine are relatively low compared to that of steam Rankine cycle power plant thereby dictate less stringent mechanical and thermal strength of materials requirement.

This study, however, can still further be delved and improved. Future investigations that can be pursued are: (1) considering second degree approximation to objective function, (2) employing additional dependent variables such as energy conversion efficiency, (3) taking heat exchanger exergetic losses into account by considering heat exchangers pinch points, and (4) the possibility of applying supercritical ORC to more closely matched waste heat available temperatures. Even further, instead of applying single

ORC configuration, two separate ORC waste heat recovery power generations can be compared to that of single ORC configuration in terms of investment cost.

References

[1] A. Tjahajana, "Kajian tekno-ekonomi teknologi waste heat recovery power generation pabrik semen," Direktorat Jendral Kerjasama Industri Internasional Kementrian Perindustrian, Republik Indonesia, 2012.

[2] I. Vabkeirsbilck, B. Vanslambrouck, S. Gusev, and M. De Paepe, "Organic rankine cycle as efficient alternative to steam cycle for small scale power generation," In: *Proceeding of 8th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*, Pointe Aux Piments, Mauritius, July 11-13, 2011.

[3] L.J. Brasz, and W.M. Bilbow, "Ranking of working fluids for organic rankine cycle applications," In: *Proceeding of International Refrigeration and Air Conditioning Conference*, Purdue, July 12-15, 2004.

[4] Y. Dai, J. Wang, and L. Gao, "Parametric optimization and comparative study of organic rankine cycle (ORC) for low grade waste heat recovery," *Energy Conversion and Management 50*, pp. 576–582, Elsevier Ltd., 2009.

[5] S.S. Rao, *Engineering Optimization Theory and Practice*, 4th Edition, John Wiley & Sons, New Jersey, 2009.

[6] G. Mitsuo, and C. Runwei, *Genetic Algorithms and Engineering Optimization*, John Wiley and Son, 2000.

[7] S.N. Sivanandam, and S.N. Deepa, *Introduction to Genetic Algorithms*, Springer, 2008.

[8] C.L. Hwang, and K. Yoon, *Multiple Attribute Decision Making: Methods and Applications*, Springer-Verlag, New York, 1981.