International Journal of Technology (2015) 6: 938-945
ISSN 2086-9614

OPTIMIZATION OF ORGANIC RANKINE CYCLE WASTE HEAT RECOVERY FOR POWER GENERATION IN A CEMENT PLANT VIA RESPONSE SURFACE METHODOLOGY

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(Received: June 2014 / Revised: August 2015 / Accepted: October 2015)

ABSTRACT

A cement plant that produces 8,300 tons per day releases 265,000 Nm^3/h of flue gas at 360°C from its Suspension Preheater (SP) and 400,000 Nm^3/h of hot air at 310°C from its air quenching cooler (AQC). It is imperative to recover the waste heat emitted by the plant for power generation, i.e., Waste Heat Recovery Power Generation (WHRPG). This paper aims to optimize waste heat recovery from the cement plant using Response Surface Methodology (RSM), for which an Organic Rankine Cycle (ORC) is applied for electric power generation. The working fluid of an ORC power generation system was selected among candidates of organic working fluids (i.e., isobutane, isopentane, benzene, and toluene) by using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a Multi-Criteria Decision Analysis (MCDA) method. The ORC power generation system configuration and the corresponding operating conditions employing the selected working fluid (i.e., pressures and temperatures) are optimized by applying RSM. Based on TOPSIS evaluation and considering factors of health, safety, environment impacts, cost, and power generated, isopentane was selected as the working fluid for the ORC WHRPG, which was configured to consist of a boiler, two expansion turbines, a reheater, and a recuperator. Implementation of RSM attained optimum operating conditions of high pressure turbine, low pressure turbine, and condenser at 11.3 bar-a saturated vapor, 4.3 bar-a and 184°C, and 1.8 bar-a, respectively. Finally, the gross electric power generated of 5.7 MW at 12.5 percent of energy conversion efficiency is generated by the pertinent ORC WHRPG.

Keywords: Cement plant; Optimization; RSM; ORC; TOPSIS; WHRPG

1. INTRODUCTION

The energy consumption per capita per annum has been asserted by economists to be one of the prosperity indicators. Developed countries consume as much as 300 GJ of energy per capita per annum, whereas developing countries consume as little as one-eighth of that of developed countries (Anonymous, 2014). The discrepancy in energy consumption has led to a fierce competition in exploitation of energy resources. Accordingly, energy conversion efficiency improvement is deemed a prudent avenue worth of pursuing.

A waste heat recovery system generating electrical power is essential to enhance the overall energy conversion efficiency. A cement plant releases waste heat from two sources, preheating

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Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v6i6.1695

and quenching processes. At present, a heat recovery steam generator (HRSG) is widely applied to generate steam by recovering the thermal energy from waste heat. Then, the steam generated is expanded to power a turbo-generator producing electricity, i.e., a Waste Heat Recovery Power Generation (WHRPG) (Kawasaki Plant Systems, Ltd., 2007). An alternative to employing a steam power plant to recover thermal energy of waste heat is an Organic Rankine Cycle (ORC) power plant that employs organic fluid or refrigerant for its working fluid. ORC is superior to the Claussius (steam) Rankine cycle when the heat source is of low temperature, i.e., below 400°C (Legmann, 2014). Furthermore, there are various types of organic working fluid, thereby the organic working fluid and the Rankine cycle operation conditions to be imposed in regard with the cement plant waste heat must be carefully designed and optimized (Quoilin et al., 2013).

2. METHODOLOGY

A cement plant that produces 8,300 tons per day releases 265,000 Nm^3/h of flue gas at 360°C from its Suspension Preheater (SP) and 400,000 Nm^3/h of hot air at 310°C from its air quenching cooler (AQC) (Tjahajana, 2012), see Figure 1. In this cement plant, the flue gas is also being used for a drying process with a minimum gas temperature requirement of 225°C. Therefore, it is imperative to recover the waste heat emitted by the plant for power generation through a WHRPG system. The thermal energy of waste heat releases by SP and AQC in the cement plant is calculated using Cycle Tempo 5.0 accompanied with FluidProp 2.4, which is a database of properties of working fluids. These two sources of thermal energy are recovered by generating steam through HRSGs.

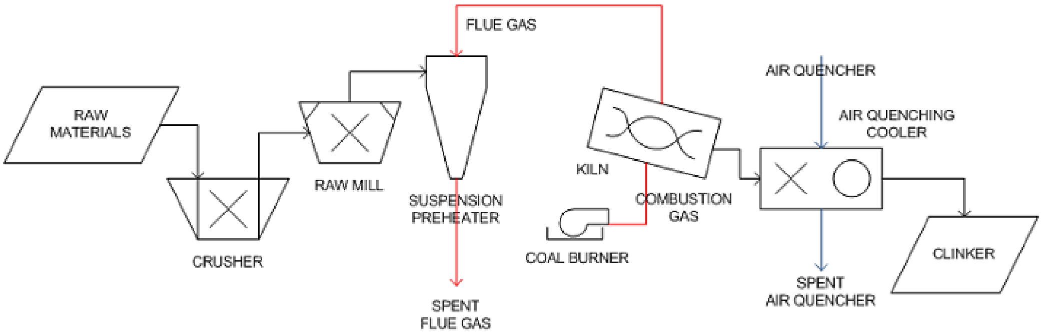

Figure 1 Sources of waste heat in a cement plant (Tjahajana, 2012)

In implementing ORC WHRPG, the working fluid for an ORC power generation system ought to be selected judiciously according to the availability of waste heat temperature. Bahaa and Koglbauer (2007) had shown a procedure on how to select the best-suited working fluid with regard to waste heat temperature. Based on that study, isobutane, isopentane, benzene, and toluene were selected as four candidates of working fluid to be applied in ORC WHRPG in a cement plant. By using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang & Yoon, 1981), a Multi-Criteria Decision Analysis (MCDA) method, the best-suited working fluid is selected based on criteria of health, safety, environment, cost, and power generation. Here, the power generated by ORC for a certain working fluid was calculated using Cycle Tempo 5.0 and the FluidProp 2.4 database.

The ORC power generation system configuration and the corresponding operating conditions employing the selected working fluid, i.e., pressures and temperatures, are optimized by applying Response Surface Methodology (RSM), which was conceived by Box and Wilson

(1951). In this method, sets of decision (independent) variables are sampled, and experiments (or, in this case, simulations) were conducted to produce sets of corresponding objective functions in terms of dependent variables (Bradley, 2007). The response surface generated, which represents the objective function for the optimization, is then evaluated to obtain the optimum point, e.g., by using the steepest ascends method.

The Central Composite Design (CCD) sampling method (Montgomery, 2001) was applied to generate variation of decision variables. Then Cycle Tempo and FluidProp 2.4 were applied for the thermodynamic simulations of the ORC WHRPG, which is configured to consist of a boiler (AQC boiler), two expansion turbines [high pressure (HP) and low pressure (LP) turbines], a reheater (SP reheater), and a recuperator. This configuration is constructed considering there are two sources of waste heat having different thermal power and temperature (see Figure 2) and by setting turbine internal efficiencies of 0.85, electric generator efficiency of 0.98, and pump internal efficiencies of 0.75. Moreover, Design Expert v.8 and Minitab 16 were used in RSM implementation for optimization of the ORC WHRPG.

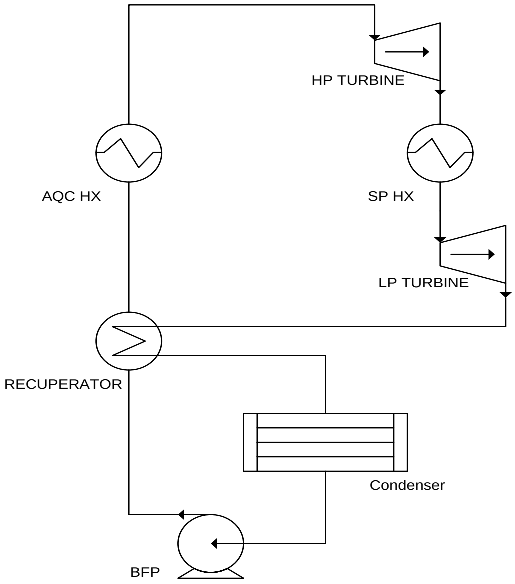

Figure 2 ORC WHRPG configuration

In this study, decision variables, i.e., independent variables applied for optimization, are the HP turbine inlet pressure, pHPT, at saturated vapor; the LP turbine inlet pressure, pLPT, at superheated vapor; and the condenser pressure, pC. The gross electrical power output, Pe, is regarded as the objective function, i.e., dependent variable, to be optimized as this is the desired tangible output parameter in a waste heat recovery scenario compared to that of energy conversion efficiency. The formal formulation of the optimization problem is presented by Equation 1 as follows.

$$\max P_e\,(p_{HPT}, p_{LPT}, p_C) \qquad \text{(kW)} \tag{1}$$

Subject to:

$9.66 \leq p_{HPT} \leq 11.34$ (bar-a)

$2.66 \leq p_{LPT} \leq 4.34$ (bar-a)

$1.83 \leq p_C \leq 2.17$ (bar-a)

$T_{sat}(p_{HPT}) \leq T_{PHT,out} \leq T_{sat}\,(p_{HPT}) + 2^oC$ (^oC)

$q_{AQC} \leq 28.0$ (MW_{th})

$q_{SP} \leq 17.5$ (MW_{th})

3. RESULTS AND DISCUSSION

The waste heat thermal power from SP, qSP, and AQC, qAQC, of 17.5 MWth of flue gas and 28 MWth of hot air, respectively, were calculated using Cycle Tempo 5.0. Table 1 shows the composition of the flue gas from SP, which is used to evaluate the thermal power available from the SP.

Table 1 SP flue gas composition

No	Composition	Mass Fraction (%)
1	CO_2	40.72
2	N_2	50.45
3	O2	3.06
4	H_2O	3.01
5	CO	0.02
6	SO_2	0.0006
7	Balance of Mass	2.74

By applying Carnot's heat engine efficiency formulation, Equation 2, at hot temperature, TH, of 360°C and 310°C, and cold temperature, TC, of 30°C, the maximum available mechanical energy attained from the waste heat sources are therefore 8.5 MW and 13.4 MW, respectively. These figures are set to be the measuring stick of energy conversion efficiency.

$$\eta_{\mathrm{Camot}} = 1 - \frac{T_C[K]}{T_H[K]} \tag{2}$$

Based on TOPSIS evaluation and by considering factors of health, safety, environment impacts, cost, and power generated, isopentane was selected as the working fluid for the ORC WHRPG, because it is ranked the highest (see the resulting TOPSIS working fluid rank in Table 2).

Table 2 TOPSIS rank of ORC working fluid

Working Fluid	Distance to Ideal Solution	Rank
Isobutane	0.67	2
Isopentane	0.74	1
Benzene	0.25	4
Toluene	0.51	3

Table 3 Design of experiment level code

Code Level	-1.682	-1	0	+1	+1.682
p_{HPT} (bar)	9.66	10.00	10.50	11.00	11.34
p_{LPT} (bar)	2.66	3.00	3.50	4.00	4.34
p_C (bar)	1.83	1.90	2.00	2.10	2.17

The CCD sampling level code of 20 experiments by thermodynamic simulation is chosen for each independent variable (i.e., decision variable, pHPT, pLPT, and pC) is shown in Table 3, and the corresponding power generations resulting from Cycle Tempo 5.0 and FluidProp 2.4 simulations are shown in Table 4. The number of simulations is by no means exhaustive; however, it is statistically justified by applying p-test and ANOVA methods.

Table 4 Design of experiment simulation runs

Run #	p_{HPT} (bar-a)	p_{LPT} (bar-a)	p_C (bar-a)	P_e (kW_e)
1	11.00	4.00	2.10	5,259
2	10.50	3.50	2.00	5,152
3	10.00	4.00	2.10	5,006
4	10.50	3.50	2.00	5,152
5	10.50	3.50	2.16	4,951
6	10.50	3.50	2.00	5,152
7	10.50	3.50	2.00	5,152
8	10.50	2.65	2.00	4,937
9	10.00	3.00	2.10	4,783
10	11.00	3.00	2.10	5,034
11	11.34	3.50	2.00	5,352
12	11.00	4.00	1.90	5,498
13	10.50	3.50	2.00	5,152
14	10.50	3.50	2.00	5,152
15	10.50	4.34	2.00	5,317
16	11.00	3.00	1.90	5,257
17	9.66	3.50	2.00	4,933
18	10.00	4.00	1.90	5,151
19	10.00	3.00	1.90	5,031
20	10.50	3.50	1.83	5,366

Thus, from Table 4, the objective function of dependent variable gross electric power, Pe, in terms of the first-order approximation of response surface function is constructed by applying the least square regression capability of Minitab 16, and is formulated by Equation 3 as follows.

$$P_e = 3931.69 + 260.91p_{HPT} + 212.06p_{LPT} - 1137.11p_C \tag{3}$$

The first-order response surface function, Equation 3, is statistically confirmed by a sequential p-value test of less than 0.0001. In addition, the results of ANOVA carried out by using Design Expert v.8 show that the coefficients and the independent (decision) variables pHPT, pLPT, and pC are proved to be statistically significant in determining the corresponding objective function of power generation, Pe.

Implementation of RSM via Design Expert v.8 on the objective function, Equation 3, attains optimum operating conditions of HP turbine, pHPT, LP turbine, pLPT, and condenser pressure, pC, at 11.3 bar-a saturated vapor, 4.3 bar-a and 184°C superheated vapor, and 1.8 bar-a, respectively. The corresponding temperature–entropy diagram for the ORC WHRPG is shown in Figure 3 . In the figure, process 14-1 depicts the heating process in the AQC boiler, process 1-2 denotes the expansion process in the HP turbine, process 2-5 represents the reheating process in the SP reheater, process 8-6 denotes the second expansion process in the LP turbine, process 6-7 and process 13-14 show the heat exchange in the recuperator, and process 2-8 prevails in the condenser. In addition, the HP turbine and the LP turbine produce 2.67 MWe and 3.14 MWe, respectively. Finally, the gross electric power generated of 5.7 MWe at 12.5 percent energy conversion efficiency is produced by the ORC WHRPG.

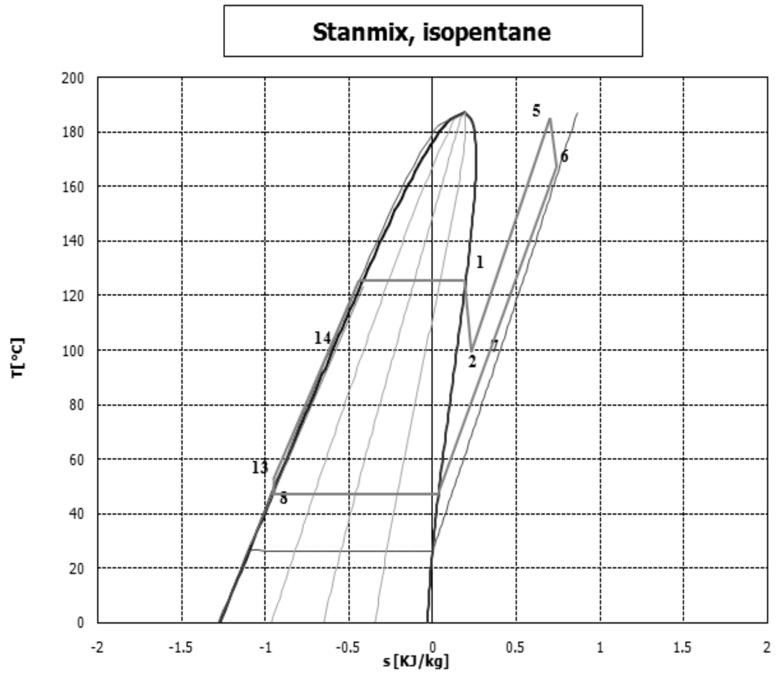

Figure 3 Temperature–entropy diagram for ORC WHRPG

The low energy conversion efficiency of 12.5 percent to that of the thermal power input from AQC and SP waste heat may seem unfavorable; however, comparing the power output generated of 5.7 MWe to that of the maximum available mechanical energy yielded by Carnot heat engine cycle of 21.9 MW, the ORC WHRPG prevails in harvesting 26 percent of the available mechanical energy from the waste heat energy.

Another performance baseline of WHRPG in a cement plant is its power generated per ton of cement production (Tjahajana, 2012). From 1980–2009, WHRPGs in cement plants in the world produced 0.38–2 kWe per ton of cement production. The ORC WHRPG in a cement plant of 8,300 ton per day capacity (using isopentane as the working fluid and configured to consist of two turbines, two waste heat recovery heat exchangers (AQC boiler and SP reheater), a recuperator, and a condenser) yields 0.69 kWe per ton of cement production.

It is worthy to note that by using isopentane as the working fluid of the ORC WHRPG, in terms of thermal power, all 28 MWth waste heat from AQC and 17.2 MWth out of 17.5 MWth waste heat from SP are transferred to isopentane through AQC and SP heat exchangers. At present, as far as exergetic losses in heat exchangers are concerned, this current endeavor has not reached that aspect.

4. CONCLUSION

RSM was capable of optimizing ORC WHRPG in a cement plant. In a cement plant of 8,300 ton per day production capacity, 5.7 MWe is generated at 12.5 energy conversion efficiency. The electric power generated was 26 percent out of the maximum available mechanical energy potential possessed by the waste heat from AQC and SP. In addition, the ORC WHRPG produced 0.69 kWe per ton of cement, which is in the lower quartile of current WHRPGs in cement plants.

The highest pressure of 11.3 bar-a at the HP turbine and the highest temperature of 184°C at the LP turbine were relatively low compared to that of the steam Rankine cycle power plant, which then dictated less stringent mechanical and thermal strength of materials. This study, of course, still can further be improved. Future study should consider second-degree approximations of response surface, employing additional dependent variables such as energy conversion efficiency, considering heat exchanger exergetic losses by including consideration of heat exchangers pinch points, and applying supercritical ORC, which will be more closely match the waste heat temperatures.

5. ACKNOWLEDGEMENT

We would like to thank to Renewable Energy Integration Network (REIN) FTUI Laboratory which always provide convenient access and enlightenment to us in this research.

6. REFERENCES

Anonymous, 2014. List of countries by energy consumption per capita. Available online at http://en.wikipedia.org/wiki/List_of_countries_by_energy_consumption_per_capita. Accessed on July 17, 2014

Bahaa, S., Koglbauer, G., Wendland, M., Fischer, J., 2007. Working Fluid for Low-temperature Organic Rankine Cycle. *Energy*, Volume 32(7)

Box, G.E.P., Wilson, K.B., 1951. On the Experimental Attainment of Optimum Conditions. *Journal of the Royal Statistical Society*, Volume 13, pp. 1–45

Bradley, N., 2007. *The Response Surface Methodology*. Thesis. Graduate Faculty, Indiana University South Bend

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

JFE Engineering Corporation, 2014. Cement Waste Heat Recovery Power Generation. Available online at www.jfe-eng.co.jp/en/foreign/int03.html. Accessed on July 17, 2014

Kawasaki Plant Systems, Ltd., 2007. Waste Heat Recovery Power Generation (WHRPG) for Cement Plant. Available online at https://www.jetro.go.jp/mexico/topics/20071017878-topics/Kawasaki_Waste_Heat_Recovery_Cement_Plant.pdf. Accessed on July 17, 2014

Legmann, H., 2002. *Recovery of Industrial Heat in the Cement Industry by Means of the ORC Process*. Ormat Technoloies Inc

Montgomery, D.C., 2001. *Design and Analysis of Experiments*, New York: John Wiley & Sons, Inc.

Quoilin, S., Broek, M.V.D., Declaye, S., Dewallef, P., Lemort, V., 2013. Techno-economic Survey of Organic Rankine Cycle (ORC) Systems. *Renewable and Sustainable Energy Reviews*, Volume 22, pp. 168–186

Tjahajana, A., 2012. A Thermo-economic Study on Waste Heat Recovery Power Generation in a Cement Plant. Directorate General of International Industrial Relations, Industrial Ministry of Republic of Indonesia (in Bahasa)