An Analytic Hierarchy Process (AHP) Approach for the Selection of Working Fluid in an Organic Rankine Cycle (ORC) System

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Abstract: Organic Rankine Cycle (ORC) is a thermodynamic cycle which is usually applied for low-grade waste heat utilization. ORC uses organic fluids, instead of water, as the energy carrier medium, due to its low operating temperature conditions. This technology can potentially reduce the energy requirement in process systems, because waste heat can be transformed into other forms of useful energy such as mechanical and electrical energy. However, the evaluation and ultimate selection of the most appropriate ORC working fluid is a multi-level, multi-criteria decision problem. This study thus utilizes the Analytic Hierarchy Process (AHP) for problem structuring and eventual ranking of working fluid alternatives. For the selection of appropriate working fluid, the following criteria are considered: boiling point, exposure limits, % ORC thermal efficiency, thermal conductivity, and cost. The working fluids considered are refrigerants namely Difluoromethane (R32), Pentafluoroethane (R125), 1,1,1-Trifluouroethane (R143a), Propene (R1270), Propane (R290), 1,1,1,2-Tetrafluoroethane (R134a), and 1,1-Difluoroethane (R152a). A case study on the application of ORC technology for a food manufacturing company in the Philippines is utilized to demonstrate the methodology. Based on the results of the case study, 1,1-Difluoroethane is the appropriate working fluid as it dominates the other alternatives with respect to the most important criterion in the decision structure, i.e. % ORC Efficiency.

Key Words: Organic Rankine Cycle; Analytic Hierarchy Process; Refrigerants; Working Fluid.

1. INTRODUCTION

Presently, most industrial flue gases are emitted into the atmosphere. The heat coming from these flue gases are usually wasted during exhaustion into the atmosphere. In order to utilize these waste heats, strategies like alternative energy source conversion, are commonly used. One source of flue gas emissions is the combustion of fossil fuels (coal and bunker fuel oil) which results in environmental problems such as air pollution and greenhouse gas emission. In order to recover waste heat, various heat engines and processes are utilized. The recovered heat is practically of low temperature and of low grade. However, it is still suitable for space heating, water heating, greenhouses, water preheating, and others (Tchanche et al., 2011). Using the Rankine Cycle (RC) is one way to maximize the utilization of waste heat. RC is one of the most important ways of transforming heat into mechanical or electrical energy. Water is a common working fluid for RC because it is chemically and economically stable and has a relatively low viscosity which facilitates good energy transfer (Chen et al., 2010). However, water has also some disadvantages. High working temperature is one of the requirements in order to produce superheated steam. When saturated steam is generated, the presence of condensate droplets can corrode the turbine blade (Toffolo et al., 2014). However, water is not suitable due to the high fuel requirement for superheating. When water is used for low temperature applications, limited heat recovery can be achieved (Brasz et al., 2004). Due to these conditions, Organic Rankine Cycle (ORC) has been used (Shu et al., 2014; Quoilin, 2011). The working fluids that are typically used in ORC are refrigerants. The high relative density of refrigerants prevents turbine blade corrosion. ORC can be utilized within a Combined Heat and Power (CHP) plant in order to recover condenser heat for other purposes, such as heating water (Nouman, 2012). However, just like water used in RCs the use of refrigerants also have disadvantages including issues on its toxicity, safety, explosion limits, flammability, and, environmental impact, among others (Saleh et al., 2007).

The problem encountered is the emission of flue gas in the under-commissioned source equipment, coded as Boiler 1. Then, ORC is to be designed after the flue gas line of Boiler 1, as adapted from the study of Anake et al. (2012) where ORC is applied in a potato chips manufacturing plant in order to recover waste heat for evaporation purposes and energy production as well. In this study, the Analytic Hierarchy Process (AHP) is used in the selection of the appropriate ORC working fluid for a food manufacturing company situated in Pasig City. AHP is one of the most widely used multiple criteria decision analysis which has been applied in various problem domains (Vaidya and Kumar, 2006). An AHP-based decision model was thus used to evaluate the appropriate working fluid incorporating the value judgment of the decision maker.

2. METHODOLOGY

2.1. Organic Rankine Cycle

Figure 1 shows the ORC setup for this study. Since the exhausted flue gases from the heating equipment are still hot, heat recovery can be done by using the flue gas as heating medium for some cogeneration plants. This power cycle is very unique because it is powered by waste heat fed to the heating equipment, such as an evaporator, instead of regular hot gases coming from the combustion of fossil fuels, such as coal and bunker fuels (Shu et al., 2014).

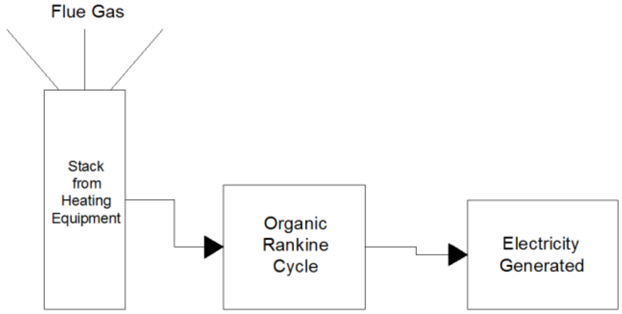

Fig. 1: ORC Setup

The schematic flow of the ORC is shown in Figure 2. Like RC, ORC is mainly composed of several equipments. The first component is the heat source, where isobaric evaporation takes place (steps 1-2). Boilers and evaporators are typically used as heating source. Followed by the turbine where the electricity generation and isentropic expansion takes place (steps 2-3). Then, it is in the condenser that isobaric condensation happens and condenser heat is also recovered (steps 3-4). Finally, the pump is installed to drive the liquid refrigerants to the heating equipment and this is where isobaric compression takes place (steps 4-1) (Linke et al., 2010; Linke et al, 2012).

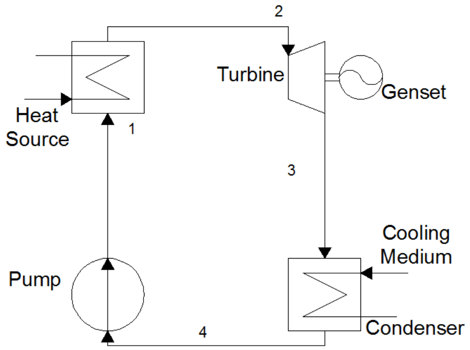

Fig. 2: Schematic Flow of ORC

Working fluid is also one of the very important factors in ORC operations due to its characteristics and properties as the energy carrier medium. Table 1 summarizes the desirable characteristics of the identified criteria in the selection of appropriate working fluid for ORC applications. For example, adequate chemical stability at the desired working temperature is one of the key criteria in the selection of working fluid for ORC applications.

Table 1: Criteria for the Selection of Appropriate Working Fluid

Criterion	Condition	Reason
BP	Low	Low operating temperature
EL	Low	Low risk involvement
Eff	High	More efficient for ORC application
TC	High	High heat conduction
RMC	Low	Less expensive for RM

2.2. Analytic Hierarchy Process

The Analytic Hierarchy Process consists of three main steps to rank the alternatives. First is the decomposition of the complex problem into hierarchical structure. The second step is computation of priority weights from the pairwise comparative judgment matrix using the eigenvector method (Saaty, 1977). The third step is the computation of the overall or global priority weights using hierarchical composition or simply known as additive weighting.

Figure 3 describes the decision structure used in this study. The goal of this study is to determine the appropriate ORC working fluid based on the following criteria: Boiling Point (BP), Exposure Limit (EL), % ORC Thermal Efficiency (Eff), Thermal Conductivity (TC), and Raw Material Cost (RMC). The alternative working fluids considered are the refrigerants namely Difluoromethane (R32), Pentafluoroethane (R125), 1,1,1-Trifluouroethane (R143a), Propene (R1270), Propane (R290), 1,1,1,2-Tetrafluoroethane (R134a), and 1,1-Difluoroethane (R152a).

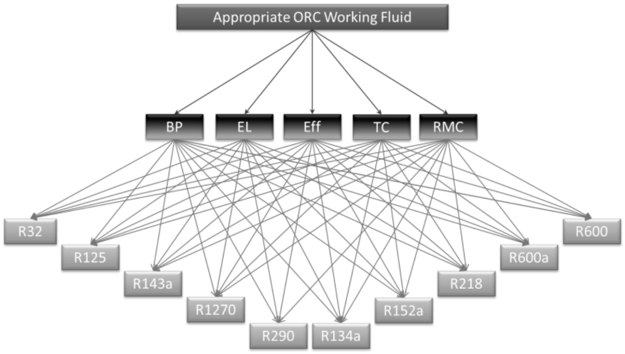

Figure 3: AHP Diagram for Working Fluid Selection

The pair-wise comparison was done for criteria to determine their relative importance with respect to the goal of selecting the most appropriate working fluid. In this study, the value judgment was provided by one of the authors who is the Engineering and Maintenance Manager of URC-BCFG. Table 2 is an example of a positive reciprocal pairwise comparison matrix incorporating the value judgment to derive the ratio-scale weights. The value judgment is based on the 9-point scale which expresses the intensity of importance of one criterion over the other. In other words, an intensity of "9" suggest an extreme importance of one criterion over the other whereas an intensity of "1" suggests equal importance. Note that it is a reciprocal matrix as the element in the matrix, a_{ij} is equal to $1/a_{ji}$. As shown in Table 2, the importance weights of criteria with respect to goal (W_{CG}), i.e., a matrix or column vector of priorities were derived using eigenvector method. The consistency ratio (CR) is also determined to check the inconsistency of the value judgments. Note that a CR of less than 0.1 is considered tolerable.

Table 2: Pair-wise comparison matrix for the criteria

	BP	EL	Eff	TC	RMC	Eigenvector, W_{CG}
BP	1	1/4	1/9	1/3	1/4	0.03872
EL	4	1	1/6	4	1/3	0.14264
Eff	9	6	1	5	4	0.54002
TC	3	1/4	1/5	1	1/2	0.08074
RMC	4	3	1/5	2	1	0.19790

λ_{max} = 5.44 CR = 0.09987

As for the priority weights of alternatives with respect to each criterion, these were derived from the normalization of the quantitative data. Note that for the smaller-the-better criteria such as BP, normalization was done for the reciprocal of the data. Appendix A describes the raw data used for the computation of priority weights. Equation 1 is then used to compute the global priority weights of these alternatives with respect to the goal.

$$W_{AG} = W_{AC}W_{CG} \qquad (1)$$

where W_{AG} is matrix containing the global priority weights of alternative with respect to goal. In this study, it is a column vector of order 10 which corresponds to the number of alternatives in the decision structure. The W_{CG} is the matrix containing the importance weights of criteria with respect to goal which is a column vector of order 5 which corresponds to the number of criteria in the decision structure. The W_{AC} is the matrix containing the priority weights of alternatives with respect to each criterion which is an array of 10 rows and 5 columns representing the number of alternatives and criteria, respectively.

3. RESULTS AND DISCUSSION

Table 3 summarizes the priority weights derived for the decision structure. Note that ORC thermal efficiency (Eff) is the most important criterion and has the highest criteria weight (0.54) based on the value judgment provided in Table 2.

Table 3: Priority weights of alternatives with respect to each criterion, W_{AC}

	BP (0.04)*	EL (0.14)	Eff (0.54)	TC (0.08)	RMC (0.20)
R32	0.15190	0.12500	0.00907	0.03281	0.07857
R125	0.14981	0.12500	0.09754	0.03008	0.12347
R143a	0.14894	0.12500	0.10086	0.04169	0.03087
R1270	0.14927	0.25000	0.10782	0.28254	0.14286
R290	0.14559	0.12500	0.18930	0.23707	0.28810
R134a	0.13617	0.12500	0.22686	0.13440	0.14405
R152a	0.11831	0.12500	0.26854	0.24142	0.19207

* Importance weights of criterion as shown in Table 2

Table 4 shows the ranking of the working fluids based on their computed global priority weights using Equation 1. This is simply the overall scores of the alternative from additive weighting of the priority weights of the alternative with respect to each criterion. R152a was the most preferred among the alternative refrigerants with a score of 0.22493. Therefore, R152a is selected as the appropriate working fluid for ORC in this study.

Table 4: Over-all scores of the alternatives, W_{AG}

Refrigerants	W_{AG}
R152a	0.22493
R290	0.20185
R134a	0.18497
R1270	0.15075
R125	0.10317
R143a	0.08754
R32	0.04681

4. CONCLUSION

AHP allow us to select the appropriate working fluid in ORC applications in a systematic and transparent manner. An illustrative case study is presented for the food manufacturing company incorporating the value judgment of a decision maker. The working fluid known as 1,1-Difluoroethane or R152a is ranked first as it dominates the other alternatives with respect to the % ORC Thermal Efficiency which is the most important criterion in the decision structure.

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Appendix A. Quantitative data used for priority weight calculation of alternatives with respect to each criterion

Refrigerants	Chemical Name	Chemical Formula	Boiling Point (K)	Exposure Limit (ppm)	% ORC Efficiency	Thermal Conductivity (k, W/m/K)	Raw Material Cost (PhP/kg)
R32	Difluoromethane	CH_2F_2	221.55	1000	0.68390	0.01641	239.36
R125	Pentafluoroethane	C_2HF_5	224.65	1000	7.35224	0.01504	152.32
R143a	1,1,1-Trifluoroethane	$C_2H_3F_3$	225.95	1000	7.60253	0.02085	609.28
R1270	Propene	C_3H_6	225.45	500	8.12694	0.14129	131.648
R290	Propane	C_3H_8	231.15	1000	14.26882	0.11856	65.28
R134a	1,1,1,2-Tetrafluoroethane	$C_2H_2F_4$	247.15	1000	17.09942	0.06721	130.56
R152a	1,1-Difluoroethane	$C_2H_4F_2$	284.45	1000	20.24122	0.120739	97.92