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Selection of the Optimum Working Fluids in Organic Rankine Cycles Using TOPSIS

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Organic Rankine Cycles (ORC) can be used to convert low-grade waste heat to electricity. The working fluid employed in the ORC has a strong influence on the thermal efficiency of the system. Until now, methods for the selection of working fluids have been based on trial and error approaches which are not very effective. As a result, the motivation for the work reported in this paper is to remedy this using decision-making techniques such as TOPSIS (technique for order preference using similarity to ideal solution), which can help identify an optimal working fluid at the preliminary stage

1. Introduction

One of the most important discussions in waste heat recovery concerns the Organic Rankine Cycle (ORC) due to its ability to convert low-grade waste heat into electrical power. We define low-grade waste heat as that with a temperature in the range 90 ^{o}C to 250 ^{o}C. The conventional ORC consists of a pump, an evaporator, a turbine and a condenser. Figure 1 shows the main components of the cycle, which uses organic fluid as a working fluid in the system.

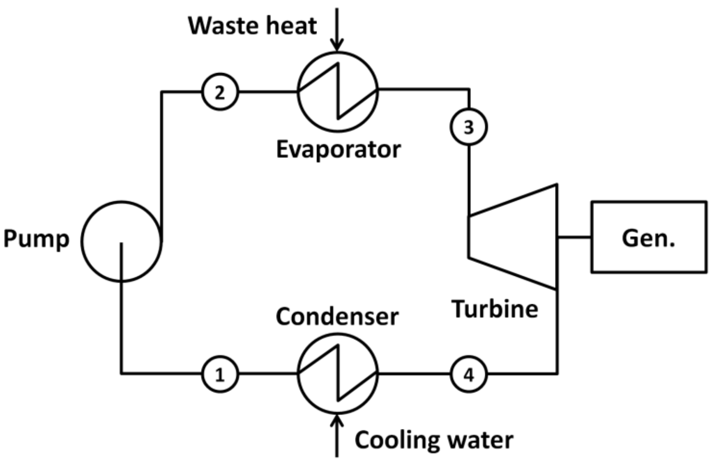

Figure 1. ORC diagram

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A major challenge is to find a fluid that has a good range of thermodynamic, environmental, safety and economic properties. To date the selection of working fluids has been based on trial and error, where a potential working fluid is tested and then the system output parameters are calculated. This approach consumes a lot of time and resources. Thermodynamic attributes such as thermal efficiency (Chen et al. 2010; Lai et al. 2011) and exergy efficiency (Li et al. 2012; Sun et al. 2012) are often the only criteria used for evaluation.

A Multiple-Attribute-Decision-Making (MADM) approach is used to analyse working fluid properties at a level before they are tested in ORC. MADM techniques obtain an optimal solution based on a weighted compromise between attributes. Sen et al (1998) provide a decision tree to choose MADM methods. This shows that TOPSIS is useful when expert opinion is available for weighting attributes. The TOPSIS method prefers alternatives closest to an ideal design and furthest from a non-ideal design (Hwang et al. 1981). This method was chosen because it can efficiently compare working fluid attributes such as thermodynamic properties, environmental capabilities, safety and cost.

2. Attributes of working fluids

Table 1 shows the attributes of ORC working fluids to be evaluated. The four main criteria are thermodynamic, environmental, safety and economic.

Table 1. Evaluation criteria for ORC working fluid (Tchanche et al. 2009)

Criterion	Attribute	Description	Objective
Thermodynamic	Liquid density	Should be as high as possible to increase mass flow rate and reduce equipment size.	High
	Latent heat vaporization	Should be as high as possible to absorb heat in evaporation process.	High
	Liquid heat capacity	Should be low to maintain the amount of waste heat required in process heating.	Low
	Viscosity	Should be low to reduce pump power consumption.	Low
	Thermal conductivity	Should be high to achieve high heat transfer coefficient in condensers and evaporator.	High
	Boiling point	Should has a low temperature difference from the critical temperature.	Low
	Critical temperature	Should be higher than the waste heat temperature, (for a subcritical cycle).	High
Environmental	Ozone depletion potential (ODP)	Should be as low as possible. As it damages the ozone layer. ODP range (0 to 4).	Low
	Global Warming potential (GWP)	Should be as low as possible. GWP calculation based on 100 years.	Low
Safety	Flammability	Should be as low as possible, as it can cause an explosion in the plant. Range (0 to 4).	Low
	Toxicity	Low as possible to maintain the safety of the plant. Range (0 to 4).	Low
Economic	Working fluid price	Should be low in price to maintain low operating costs of the ORC	Low

3. Technique for order preference using similarity to ideal solution (TOPSIS)

TOPSIS (developed by Hwang et al. 1981) selects alternatives desings based on their nearness to an ideal design solution. The TOPSIS method briefly consists of the following:

i) Develop a normalised decision matrix of the candidate working fluids properties; fluids numbered $A_{1..m}$ and the attributes $X_{1..n}$ including the idealised design choices, A^* and A^-.

iii) Obtain a weighted decision matrix (V) by multiplying the normalized working fluids (r_{ij}) by the corresponding weight matrix (Wi) obtained by expert opinion.
iv) Extract the ideal working fluid properties (A*) and non-ideal working fluid properties (A^-) from the weighted matrix (W). The ideal solution is the desired value of working fluid properties in the weighted matrix (W) in the same column.
v) Determine the distance from the ideal and non ideal solutions for all fluids.
vi) Calculate the relative closeness of each alternative (Ci*) to ideal solution and non ideal solution.
vii) Find the preference order by arranging the Ci*. The closer Ci* is to 1, the closer it is to the ideal solution.

These steps are shown in more detail with the following case study.

4. Case Study

The Decision matrix software (Dalton 2009) developed at Newcastle University was used to obtain the results. The simulation consisted of 6 working fluids. The properties are shown in Table 2 in the form of a Decision Matrix. It should be noted that the ozone depletion potential (ODP) for all six working fluids is zero therefore ODP has been excluded from consideration. The indexes $C_{1..11}$ represent liquid density, latent heat of vaporization, liquid heat capacity, viscosity, thermal conductivity, difference between boiling point temperature to waste heat, critical temperature, global warming potential (GWP), toxicity, flammability and price. The boiling point difference, C_6 was calculated using equation 1:

$$\text{New Bp } (C_6) = \text{Waste heat source temperature} - \text{normal boiling point} \quad (1)$$

Table 2. Properties of the working fluids (Calm et al. 2007) as a working fluids matrix

Working fluid name	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
Ammonia	483	1371	6	0.07	0.31	123	132	0	3	2	780
R600a	451	367	3	0.08	0.02	101	135	20	1	4	924
R134a	84	216	3	0.07	0.05	116	101	1300	1	0	1135
R152a	678	324	3	0.07	0.07	114	114	124	0	4	406
R245fa	1133	197	2	0.19	0.07	75	154	1030	2	0	1550
R236ea	1178	218	1	0.16	0.06	84	139	710	1	0	1550

Table 3 shows the normalized matrix.

Table 3. Normalized Matrix

Working fluids	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
Ammonia	0.217	0.671	0.598	0.199	0.676	0.422	0.359	0.000	0.600	0.298	0.243
R600a	0.202	0.180	0.297	0.219	0.044	0.346	0.366	0.009	0.200	0.596	0.288
R134a	0.038	0.106	0.264	0.207	0.116	0.397	0.274	0.584	0.200	0.000	0.354
R152a	0.304	0.159	0.258	0.207	0.153	0.390	0.309	0.056	0.000	0.596	0.127
R245fa	0.508	0.097	0.148	0.539	0.153	0.257	0.418	0.462	0.400	0.000	0.483
R236ea	0.528	0.107	0.141	0.454	0.129	0.287	0.378	0.319	0.200	0.000	0.483

Criteria weightings were obtained using pair-wise comparisons from three different experts in the ORC field. Their opinions, in the form of relative weightings, are shown in Table 4.

Table 4. Attribute weightings matrix from experts 1, 2 and 3

Expert	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
1	6.59	29.56	6.59	6.59	1.32	1.32	22.97	2.42	1.32	1.32	20
2	21.33	22.69	5.19	23.12	13.86	2.27	2.19	2.19	2.19	2.19	2.19
3	14.99	18.63	2.24	2.07	2.07	9.70	7.20	1.077	1.077	1.077	1.077

The un-normalised data from Table 4 highlights that while most opinion is broadly similar, differences between opinions occur. Once normalized this is used to weight the decision matrix to give Table 5.

Table 5. Working fluid properties with normalised weighting from expert 1

Working fluids	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
Ammonia:	0.0143	0.1984	0.0394	0.0131	0.0089	0.0056	0.0824	0.0000	0.0079	0.0039	0.0486
R600a:	0.0133	0.0531	0.0196	0.0144	0.0006	0.0046	0.0841	0.0002	0.0026	0.0079	0.0576
R134a:	0.0025	0.0312	0.0174	0.0137	0.0015	0.0052	0.0629	0.0141	0.0026	0.0000	0.0708
R152a:	0.0201	0.0469	0.0170	0.0137	0.0020	0.0052	0.0710	0.0013	0.0000	0.0079	0.0253
R245fa:	0.0335	0.0286	0.0098	0.0355	0.0020	0.0034	0.0960	0.0112	0.0053	0.0000	0.0967
R236ea:	0.0348	0.0315	0.0093	0.0299	0.0017	0.0038	0.0868	0.0077	0.0026	0.0000	0.0967

The distance for all candidate fluids from the ideal and non-ideal fluids is determined and shown in Table 6.

Table 6. Distance from ideal and non ideal solution

Working fluids	Ideal solution (a*)	Non ideal solution (a-)
1. Ammonia	0.05	0.18
2. Isobutane (R600a)	0.15	0.06
3. R134a	0.18	0.04
4. R152a	0.15	0.08
5. R245fa	0.19	0.05
6. R236ea	0.18	0.05

Table 7 shows the preference order of the working fluids using TOPSIS based on opinions from each expert. Ammonia has the highest rank, followed by R152a, isobutene, R245fa and R236ea.

Table 7. Ranked solutions from experts 1,2 and 3

Working fluids	Expert 1	Working fluids	Expert 2	Working fluids	Expert 3
Ammonia	0.80	Ammonia	0.71	Ammonia	0.60
R152a	0.35	R152a	0.41	R152a	0.46
Isobutane	0.29	R236ea	0.41	R236ea	0.46
R245fa	0.23	R245fa	0.38	Isobutane	0.41
R236ea	0.22	Isobutane	0.35	R245fa	0.41
R134a	0.19	R134a	0.30	R134a	0.31

Figure 2 shows that ammonia has the highest ranking among the working fluids. R152a and isobutene are second after ammonia. R245fa and R236ea are in third place and R134a last.

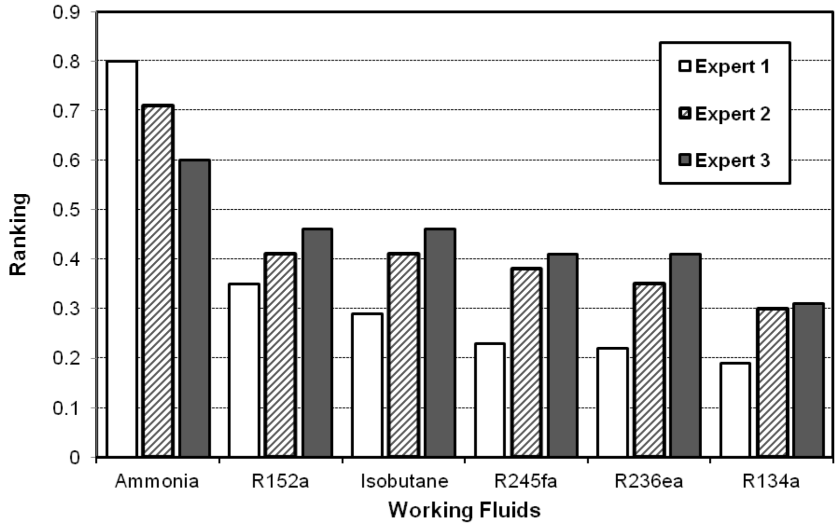

Figure 2. Working fluid rankings based on three expert opinions

5. Working fluid thermodynamic analysis

IPSEPRO software was used to calculate net power output, efficiency, pump power and heat exchanger area. The scenario chosen was an evaporating temperature of 90 ^{o}C while cooling water at 10 ^{o}C. The minimum approach temperature was assumed to be 10 ^{o}C for each working fluid and the waste heat mass flow rate to be 10 kg/s.

The following method was used to determine the ORC parameters:

$$\eta = \frac{(h_3 - h_4)}{(h_2 - h_1)} \quad (2)$$

$$\bar{Q}_{eva} = \dot{m}\,(h_3 - h_2) \quad (3)$$

$$\dot{W}_{in} = \dot{m}\,(h_2 - h_1) \quad (4)$$

$$\dot{W}_{out} = \dot{m}\,(h_3 - h_4) \quad (5)$$

$$\bar{Q}_{con} = \dot{m}\,(h_4 - h_1) \quad (6)$$

$$\dot{W}_{net} = \dot{W}_{out} - \dot{W}_{in} \quad (7)$$

where:

η : thermal efficiency and h_1,h_2,h_3,h_4 are enthalpy at each point shown in Figure 1
Q_{eva} : heat from evaporator to heat the working fluids,
m : working fluid mass flow rate.
W_{in} : power pump consumption,
Q_{con} : cooling duty needed by the condenser,
W_{net} : net power of the cycle between the turbine, W_{out}, and the pump, W_{in}.

6. Discussion

The objective of this work was to investigate the usefulness of the TOPSIS in the selection of ORC working fluids. In this section we compare the main results from TOPSIS and IPSEPRO.

Table 8. Results show that the highest thermal efficiency is provided by isobutane and ammonia

Working fluid	Gross power (kW)	Pump power (kW)	Net power (kW)	Thermal efficiency	Evaporator UA value (kW/K)	Condenser UA (kW/K)	Refrigerant mass (kg/s)	Cooling water mass (kg/s)
Ammonia	55	4	51	0.11	26	28	0.4	9.6
Isobutane	54	4.6	50	0.11	37	18	1.1	9.6
R152a	53	6	47	0.10	29	28	1.6	9.7
R245fa	50	2	48	0.10	26	17	2	9.7
R236ea	49	2.6	47	0.10	26	17	2.4	9.7
R134a	51	8	42	0.09	26	28	2.5	9.8

Ammonia is the optimum working fluid for all experts due to its high value of latent heat vaporization, liquid capacity, thermal conductivity and it also has the lowest global warming potential of all the working fluids investigated here. The disadvantage of ammonia is that it has the highest toxicity compared to the others. However all the experts weighted toxicity low. The IPSEPRO simulation showed that thermal efficiency of ammonia and isobutene are the highest due to its high enthalpy of evaporation. R152a is second-ranked by TOPSIS because it has a relatively high latent heat of vaporization. However it has lower critical temperature than both the above fluids despite being low in price.

7. Conclusion

This work has used Multi-Attribute Decision Making (MADM) method (TOPSIS) for the selection of working fluids for ORCs. The optimal working fluid was defined as that which can fulfil thermodynamic, safety, environmental and economic requirements. This study considered six working fluids: ammonia, R236ea, R152a, R600a, R245fa and R134a, and found that:

- TOPSIS can be effectively used to find an optimum working fluid , which fulfils requirements.
- Ammonia is the optimum working fluid recommended by TOPSIS due to its high latent heat, liquid heat capacity, thermal conductivity and critical temperature, and acceptable price.
- Ammonia and isobutane have the highest thermal efficiency among other working fluids, based on the ORC simulation result by IPSEPRO (a thermodynamic simulation software).
- R134a proved most expensive with the lowest thermal efficiency according to IPSEPRO.

This study only considered one case, that of a 90 ^{o}C evaporation temperature using conventional ORCs, with cooling water at 10 ^{o}C. It also only used weighting attribute assessments from three experts with different levels of experience, which limiting the overall value of the case study. Future work will investigate a wider range of scenarios, i.e. ORC configuration, source and sink temperatures and comparison of these results with those of other MADM techniques.

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