UTILIZATION OF WASTE HEAT FROM INTERCOOLED, REHEAT AND RECUPERATED GAS TURBINES FOR POWER GENERATION IN ORGANIC RANKINE CYCLES

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ABSTRACT

Organic Rankine cycle (ORC) is a very attractive technology for the conversion of low-grade thermal energy into electrical and/or mechanical energy. As the ORC has a wide range of power, it can recover the waste heat from power cycles such as turbines and/or microturbines of gas. The ORC bottoming cycle is currently incorporated into the exhaust of recuperative gas turbines to further lower the temperature of the exhaust gas, yielding similar overall efficiency to that of conventional gas turbine and steam combined cycles. However, a certain amount of thermal energy in the intercooler is not effectively utilized in the intercooled gas turbine cogeneration cycles. The temperature of the compressed air at the intercooler inlet could be found about 120 ℃-250 ℃. This is an ideal energy source to be used in an ORC for power generation.

In this investigation, a thermodynamic analysis was carried out on combined cycles comprising recuperated, intercooled and reheat gas turbines and two ORCs (recuperated ICRHGT-ORCs) to recover waste heat from the intercooler and the exhaust of recuperated gas turbine. Three existing gas turbines were performed as the topping cycles with appropriate modifications. The following organic fluids were considered as the working fluids in ORCs: R123, R245fa, toluene and cyclohexane. A computer program was then designed for computations of system performance. Thermodynamic analyses were performed to study the effects of parameters including evaporator temperatures and degrees of superheat at the ORC turbine inlet on the combined cycle performance. These parameters were then optimized with thermal efficiency as the objective function by means of a genetic algorithm. It was found that all the three modified gas turbines with bottoming ORCs had higher performance, with thermal efficiency increase of 7.8% to 15.2%, in comparison to their original values.

1. INTRODUCTION

In the low-grade waste heat recovery field, the organic Rankine cycle (ORC) gives a good performance to convent low and medium temperature heats such as renewable energies like solar, wind and geothermal power, low enthalpy heat rejected by industry and exhaust gas of gas turbines into electrical or/and mechanical energy. Much work has been carried out on the application and performance of ORCs (Angelino *et al.*, 1998, Hung, 2001, Wei *et al.*, 2007, Tchanche *et al.*, 2011, Vélez *et al.*, 2012). Typically, the ORC as a bottoming cycle in combined power plants is a promising process to enhance the system efficiency and reduce the fossil fuel consumption. For gas turbine applications, the combination of an ORC bottoming cycle can reduce design and development cost.

The modularity and wide range of power of the ORC system allow repowering of the existing gas turbines to use the thermal power of the exhaust gases typically available in the temperature range of 250 – 300 ℃ and produce electricity by acting a bottoming cycle. Najjar and Radhwan (1988) proposed a cogeneration system by combining a gas turbine cycle with an ORC bottoming cycle. The results showed that a global combined cycle efficiency slightly below 45.2% with an efficiency improvement of about 54% by using R22 as the organic fluid. Invernizzi *et al.* (2007) investigated the performance of a 100 kW size micro-gas turbine and ORC combined cycle. They reported that the micro-gas turbine could obtain an additional 45 kW of electricity and an efficiency improvement of 30% to 40%. Yari (2008) conducted parametric analysis and comparison of the micro turbine ORC with or without internal heat exchanger combined cycles. The effects of several parameters on the combined cycle performance were also discussed. Clemente *et al.* (2013) studied a number of different expanders for ORCs with the aim to design a bottoming cycle for a 100 kW recuperated gas turbine. A careful review of these numerous works shows that the bottoming ORC cycle is designed to recover waste heat from the flue gases of a small recuperative gas turbine. However, combined cycles comprising high efficiency heavy duty gas turbines and ORCs in the medium and large scale power generation have not been carefully analyzed. Chacartegui *et al.* (2009) found this shortage and then studied the use of ORC bottoming cycles incorporated into the exhaust of recuperated gas turbines or very high pressure ratio gas turbines, which are characterized by their very high efficiency but low exhaust temperature. Moreover, they modified the topping gas turbines by adding intercooled compression and reheat, showing that the efficiency of the modified combined cycle was up to 3% points higher than conventional single pressure steam combined cycles, depending on the working fluid.

By adding an intercooled compression to the modern high efficiency gas turbines, the low pressure compressor (LPC) outlet temperature varies from 120 ℃ to 250 ℃, depending on the LPC pressure ratio (Bhargava *et al.*, 2002). This amount thermal energy currently is rejected to the coolant like atmospheric air, cooling water or sea water. It is noticed that there may be a continuous increase of efficiency improvement of the current gas turbine and ORC combined cycle by designing an additional ORC bottoming cycle to recover the heat from the intercooled compression. In addition, a limited amount of work has been done on the evaluation of a combined cycle comprising a recuperated, intercooled and reheat (ICRH) gas turbine and two ORC bottoming cycles in cogeneration applications.

This paper investigated the possibility of increasing the performance of recuperated ICRH gas turbines by combining two ORCs which recover the waste heat from the intercooler and the exhaust of recuperated gas turbine. Three existing gas turbines with appropriate modifications were performed as the topping cycles. For the ORC bottoming cycles, the following organic fluids were considered as the working fluids: R123, R245fa, toluene and cyclohexane. A computer program was designed for computations of system performance. Four key parameters in the bottoming cycles including evaporator temperatures and degrees of superheat at the ORC turbine inlet were evaluated to analysis their effects on the combined cycle thermal efficiency. These parameters were then optimized with thermal efficiency as the objective function by means of a genetic algorithm (GA).

2. RECUPERATED ICRHGT-ORCS COMBINED CYCLE DESCRIPTION

In this section, two ORC bottoming cycles are incorporated into the exhaust and two successive compression stages, respectively, of a recuperated ICRH gas turbine cycle, as shown in Figure 1. The purpose of such analysis is to evaluate the interest of the proposed bottoming cycles when integrated with the recuperated ICRH gas turbines. In order to use the exhaust waste heat, an ORC is employed through an evaporator to further decrease the exhaust temperature. Additionally, a second ORC is designed through a suitable evaporator 2 to recover waste heat from the compressed air leaving the LPC.

For the topping cycle, three existing gas turbines are selected and modified to be converted into the recuperated ICRH gas turbine cycles. The selected gas turbines include a modern heavy duty gas turbine Alstom GT 24, a high efficiency aeroderivative gas turbine GE LM-6000 (dry) and a recuperated and intercooled gas turbine Rolls-Royce WR 21. The examples give a large power range from 25 MW to 179 MW. This study converted each of the selected gas turbines into a recuperated ICRH cycle system using the design methodology presented in Bhargava *et al.* (2002). Note that for the Rolls-Royce WR 21 gas turbine, a low pressure turbine (LPT), which is not presented in Figure 1, is included between the high pressure turbine (HPT) and the combustion chamber 2 (CC2). The calculated main performance of each modified gas turbine is presented in Table 1.

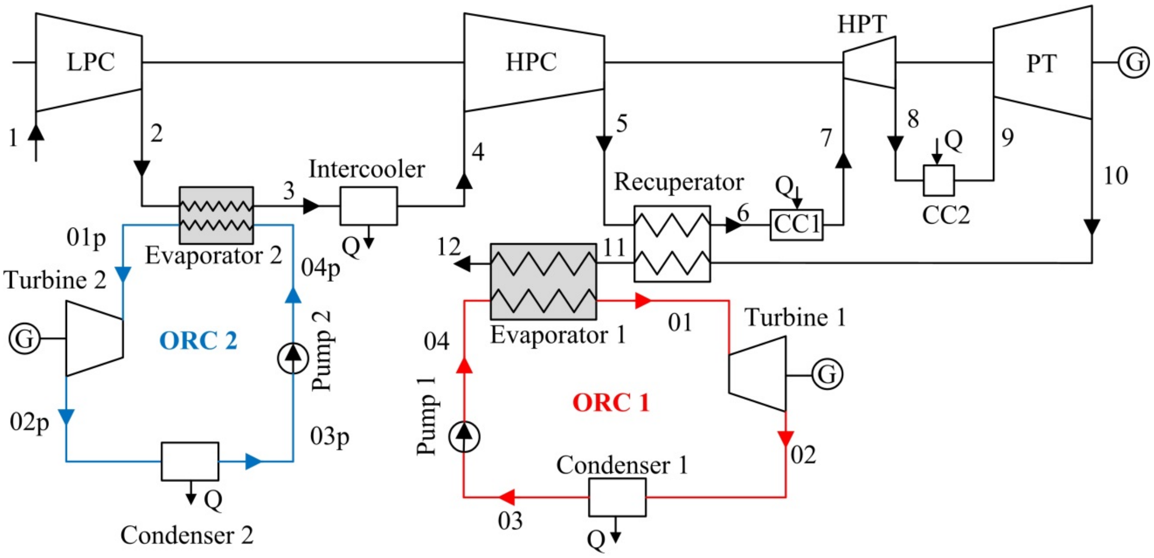


Figure 1: Schematic diagram of reference combined recuperated ICRH gas turbine with two ORC cycles

Table 1: Recuperated ICRH Gas turbines main characteristics

Parameter	GE LM-6000	Alstom GT 24	RR WR 21
Power Output (MW)	96.84	249.75	35.76
Overall Efficiency (%)	47.59	47.32	47.5
Turbine Inlet Temperature (℃)	1260	1260	982
Exhaust Temperature (℃)	462	384	307
LPC outlet temperature (℃)	117	211	152
Exhaust Gas Flow (kg/s)	148.7	391	73.1
Overall Pressure Ratio	34.1	31	16.2
LPC Pressure Ratio	2.65	4.48	3.3
HPT Pressure Ratio	3.44	2.03	1.97
LPT Pressure Ratio	-	-	1.64
PT Pressure Ratio	9.88	15.27	4.94

Data in Table 1 show that each of the recuperated ICRH cycle had impressive efficiency and power output. The modified LM-6000 machine achieved efficiency and power of 47.59% and 96.84 MW, respectively. For the modified GT 24 gas turbine, the efficiency and power were 47.32% and 249.75 MW, respectively. Additionally, the recuperated ICRH cycle derived from WR 21 machine attained efficiency and power of 47.5% and 35.76 MW, respectively. Although the value of exhaust temperature for modified gas turbines is not particularly high due to the presence of the recuperator, it can further drop by addition of an evaporator to transfer its heat to the bottoming cycle. For the modified LM-6000, GT 24 and WR 21 the LPC outlet temperatures were 117, 211 and 152 ℃, respectively. The difference in values of LPC outlet temperature for modified gas turbines is due to the fact that the optimum LPC pressure ratio varies.

For the bottoming cycle, two simple configuration of ORC are considered. The ORC uses organic working fluids with low boiling points to recover heat from low- and medium temperature heat sources. The selection of the working fluid substantially affects the performance of the ORC. Table 2 presents a list of some common working fluids considered in this paper along with their critical properties and maximum operating temperatures. The limitation of maximum operating temperature for each working fluid guarantees that fluid degradation is avoided. The working fluid at the ORC turbine inlet can be either saturated or superheated. The effect of degree of superheat on the combined cycle thermal efficiency will be later discussed.

Table 2: Properties of working fluids used in this study

Working fluid	T_c (℃)	P_c (MPa)	T_{max} (℃)
R123	183.68	3.66	175
R245fa	154.05	3.64	140
Toluene	318.6	4.13	300
Cyclohexane	280.45	4.075	270

3. THERMODYNAMIC ANALYSIS

In this section, the thermodynamic model of combined cycles that use commercially modified gas turbines and ORC bottoming cycles was developed on the basis of available resource in literature (Bhargava *et al.*, 2002, Chacartegui *et al.*, 2009, Yari and Mahmoudi, 2010). It must be noted that the same working fluid is used in both bottoming ORCs for certain recuperated ICRHGT-ORCs combined cycle.

3.1 Assumptions

The following assumptions for the combined cycle are considered in this study:
(1) The system operates in a steady-state condition; kinetic and potential energy changes are neglected.
(2) The pressure drops throughout the pipes and heat exchangers are negligible.
(3) The general assumptions of ORC are listed in Table 3. Saturated liquid is supposed at the condenser outlet with a conservative temperature of 40 ℃.
(4) In thermodynamic calculations special attention is paid to the values of pinch point in evaporator which is not below 2 ℃.
(5) The effectiveness of 0.9 was considered for the intercooler and the recuperator.

Table 3: ORC data assumption

Pump Efficiency (%)	Turbine Efficiency (%)	Evaporator Efficiency (%)	Condensation Temperature (℃)
80	85	90	40

3.2 Performance evaluation

The net power output of the recuperated ICRHGT-ORCs can be expressed as:

$$\begin{aligned}\dot{W}_{net} &= \dot{W}_{net,\ REC\ ICRHGT} + \dot{W}_{net,\ ORCs} \\ &= (\dot{W}_{HPT} + \dot{W}_{PT} - \dot{W}_{LPC} - \dot{W}_{HPC})_{REC\ ICRHGT} + (\dot{W}_{T} - \dot{W}_{P})_{ORC,\ 1} + (\dot{W}_{T} - \dot{W}_{P})_{ORC,\ 2}\end{aligned} \tag{1}$$

The overall efficiency of the combined cycle is given by

$$\eta_I = \frac{\dot{W}_{net}}{\dot{Q}} = \frac{\dot{W}_{net}}{\dot{m}_{air}(h_7 - h_6) + \dot{m}_{mix,1}(h_9 - h_8)} \tag{2}$$

The power ratio is defined as the ratio of bottoming cycles to combined cycle power, which is given as follows

$$\text{Power Ratio} = \frac{\dot{W}_{net,ORCs}}{\dot{W}_{net}} \tag{3}$$

3.3 Optimization method

In order to recover as much waste heat as possible, it is necessary to optimize the combined cycles. The parameters chosen for optimizing recuperated ICRHGT-ORCs combined cycle are evaporator temperatures, pitch point temperature difference and degrees of superheat at the ORC turbine inlet.

The equation of the mathematical model reveal that the optimum value for overall efficiency (η_I) can be expressed as a function of these five operating parameters, as shown in the equation:

$$\text{Maximize} \quad \eta_I \left(T_{e,\,1}, T_{e,\,2}, \Delta T_E, \Delta T_{\text{sup},1}, \Delta T_{\text{sup},2}\right) \tag{4}$$

Subject to:

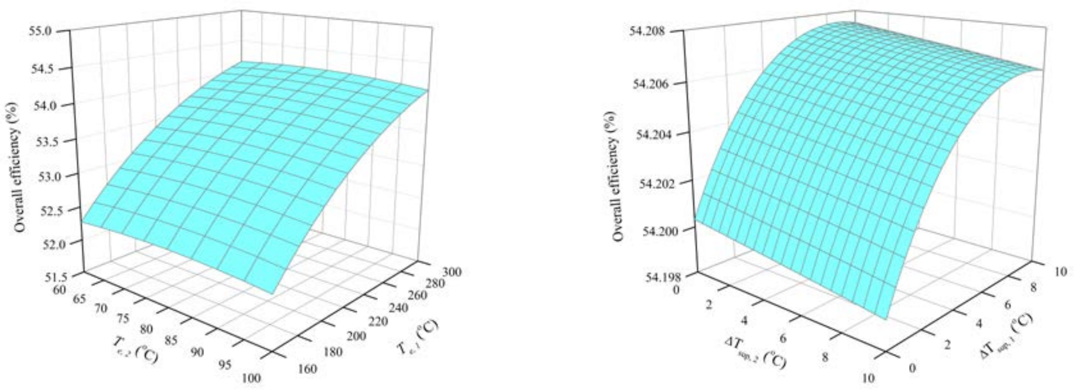
$$\begin{aligned} & 90 \le T_{e,\,1} \le T_{\max} \\ & 60 \le T_{e,\,2} \le T_2 - 10 \ \text{ or } \ T_{\max} \\ & 2 \le \Delta T_E \le 15 \\ & 0 \le \Delta T_{\text{sup},\,1} \le 10 \\ & 0 \le \Delta T_{\text{sup},\,2} \le 10 \end{aligned} \tag{5}$$

where $T_{e,\,1}$ is the evaporator temperature of the organic fluid in ORC 1, $T_{e,\,2}$ is the evaporator temperature of the organic fluid in ORC 2, T_2 is the LPC outlet temperature, ΔT_E is the pitch point temperature difference in the evaporator, $\Delta T_{\text{sup},\,1}$ is the superheat degree at the ORC 1 turbine inlet, $\Delta T_{\text{sup},\,2}$ is the degree of superheat at the ORC 2 turbine inlet, $T_{\max}$ is the maximum operating temperature of the organic fluid.

The constraints as listed in Equation (5) were applied by setting the bounds on each variable. Note that the upper bound of $T_{e,\,2}$ was limited to either LPC outlet temperature subtracted 10 ℃ or maximum operating temperature of the organic fluid. This is because the critical temperature of the organic working fluid like R245fa may below the LPC outlet temperature. In the present study, the genetic algorithm (Holland, 1992) is applied to the optimization process to obtain the maximum overall efficiencies for each combined cycle.

4. RESULTS AND DISCUSSION

The results of parametric analysis of the recuperated ICRHGT-ORCs combined cycles are presented in this section. Reference data from the NIST REFPROP database (Lemmon *et al.*, 2007) are used to calculate the working fluid thermodynamic properties. In addition, a code of the recuperated ICRHGT-ORCs combined cycles was developed to perform the simulation of these combined cycles. As toluene has higher critical properties and turbine specific enthalpy than R123, R245fa and cyclohexane, it is used as the working fluid of the bottoming cycles to evaluate effects of key parameters of ORCs on the performance of three modified gas turbine and ORCs combined cycles. Optimizations of recuperated ICRHGT-ORCs combined cycles for different organic working fluids were then conducted.

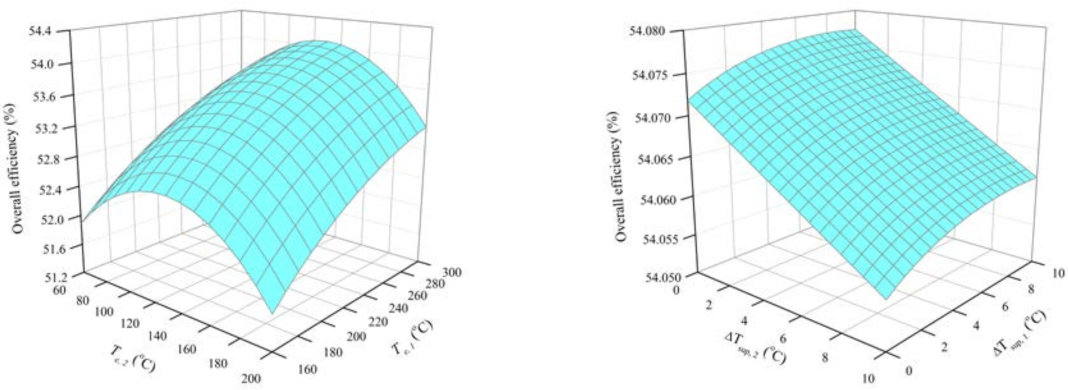


(a) **(b)**

Figure 2: Overall efficiency versus evaporator temperatures (a) and degrees of superheat (b) with toluene as the organic working fluid and the recuperated ICRH LM-6000 gas turbine as the topping cycle

The effect of the evaporator temperatures and degrees of superheat on the overall efficiency of toluene LM-6000-ORCs combined cycle is shown in Figure 2. It can be seen that the overall efficiency strongly increased with an increase in the evaporator temperature $T_{e,\,1}$. It seems that a greater overall efficiency can be obtained by a higher evaporator temperature in the evaporator 1. This result is understandable because the exhaust temperature of LM-6000 was as high as 465 ℃. However, the evaporator temperature $T_{e,\,2}$ had slight effect on the overall efficiency. It can be seen from Figure 2(b) that there is an optimum value of superheat degree at the ORC 1 turbine inlet with which the efficiency is found to be maximum.

Figure 3 shows the variation of modified GT 24-ORCs combined cycle with evaporator temperatures and degrees of superheat in bottoming cycles with toluene as the working fluid. It can be observed that an increase in evaporator temperature 1 ($T_{e,\,1}$) led to an increase in overall efficiency. However, an increase in evaporator temperature 2 ($T_{e,\,2}$) led to an increase and then a decrease in the combined cycle efficiency. These results indicate that the ORC 2 plays an important role in the enhancement of the overall efficiency. This is expected because the LPC outlet temperature of GT 24 was up to 211 ℃, and, as a result, the heat recovery from LPC exhaust in evaporator 2 section increased significantly. From Figure 3(b) it can be seen that the overall efficiency decreased with an increase in degree of superheat at ORC 2 turbine inlet. An increase in degree of superheat at ORC 1 turbine inlet, however, led to an increase in the overall efficiency.

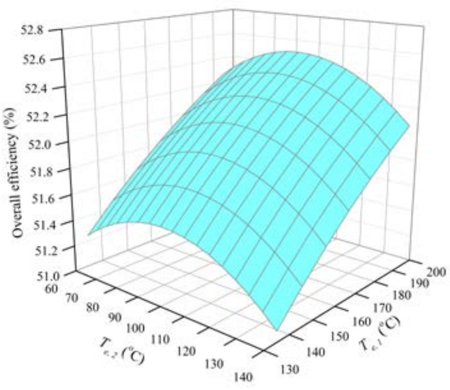


(a) **(b)**

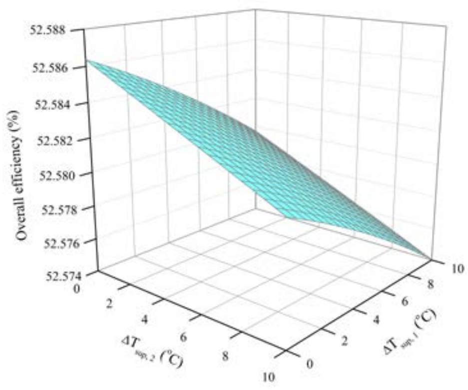
Figure 3: Overall efficiency versus evaporator temperatures (a) and degrees of superheat (b) with toluene as the organic working fluid and the recuperated ICRH GT 24 gas turbine as the topping cycle

Figure 4 presents the effects of evaporator temperatures and ORC turbine inlet vapour superheating on the toluene WR 21-ORCs combined cycle efficiency. It can be seen from Figure 4(a) that an optimum evaporator temperature 2 ($T_{e,\,2}$) existed and could be found by parameter optimization of the combined cycle. For a higher evaporator temperature 1 ($T_{e,\,1}$), greater waste heat is transferred to the ORC 1 resulting in an increase of power generation in ORC turbine and therefore the combined cycle efficiency. Figure 4(b) shows that by increasing the degrees of superheat at the turbine inlet both in the ORCs the overall efficiency decreased. It appears that saturated vapour of the organic working fluid is expected at the turbine inlet in both ORCs for the WR 21 and ORCs combined case.

In order to investigate the interest of combining low temperature bottoming cycle with low exhaust temperature intercooled gas turbines, a parametric optimization of the bottoming cycles is now presented depending on the modified gas turbines as described in Table 1 and working fluid in the bottoming cycles. Results are shown in Tables 4, 5 and 6 for different topping gas turbines.



(a)



(b)

Figure 4: Overall efficiency versus evaporator temperatures (a) and degrees of superheat (b) with toluene as the organic working fluid and the recuperated ICRH WR 21 gas turbine as the topping cycle

Table 4 shows the optimization results of the recuperated ICRH LM-6000-ORCs combined cycle for different organic fluids. It is found that the modified LM-6000-ORCs combined cycle had higher performance, with thermal efficiency increase of 8.75% - 15.18% depending on the organic fluid, in comparison to the original value of stand-alone recuperated ICRH LM-6000. Note that the efficiency enhancement is the overall efficiency of the combined cycle relative to the efficiency of single modified gas turbine. The maximum overall efficiency was obtained by using toluene as the ORC fluid, i.e., 54.81%. Moreover, the toluene REC ICRHGT-ORCs had an overall power output of 111.54 MW with a power ratio of 13.18%. These findings are understandable because the turbine specific work or enthalpy drop of toluene in ORCs is higher when compared with R123, R245fa and cyclohexane. The net additional power produced by the ORCs was about 8.5 - 14.7 MW. The R123 and R245fa ORCs combined cycles demanded mass flow rates of about 231 and 216 kg/s in ORC 1, respectively, which were almost 3 times greater than that the toluene or cyclohexane ORCs combined cycle demanded. The ORC 2 recovering waste heat from the intercooler produced electricity of about 0.5 MW on average for each organic fluid. This amount of power is relatively smaller than the power generated by the ORC 1 due to the limitation of LPC outlet temperature. The optimum operating parameters using the GA are also presented in Table 4. It can be seen that the pitch point temperature difference approached a value of 2 ℃ for all the organic working fluids, which means that the evaporator size would be large or the evaporator should be well designed to meet the demand of heat transfer. On the other hand, the degree of superheat at the ORC 1 turbine inlet was as high as 10 ℃ using R123 as the organic fluid, while the degree of superheat at the ORC 2 turbine inlet was relatively small for each organic fluid.

Table 4: Summary of optimization results for maximum overall efficiency of the modified GE LM-6000-ORCs cycle

Parameter	**R123**	**R245fa**	**Toluene**	**Cyclohexane**
Overall Efficiency (%)	52.62	51.75	54.81	53.89
Efficiency Enhancement (%)	10.57	8.75	15.18	13.24
ORC 1 Power Output (MW)	9.72	7.95	14.21	12.33
ORC 2 Power Output (MW)	0.52	0.53	0.49	0.49
Overall Power Output (MW)	107.08	105.32	111.54	109.66
Power Ratio (%)	9.56	8.05	13.18	11.69
$T_{e,1}$ (℃)	169.9	140	299.7	263.8
$T_{e,2}$ (℃)	80.3	78.1	80.3	75.6
ΔT_E (℃)	2.3	2.1	2.2	2.9
$\Delta T_{sup,1}$ (℃)	10	8	5.7	1.4
$\Delta T_{sup,2}$ (℃)	0.7	2.1	1.2	3.4
ORC 1 Mass Flow Rate (kg/s)	231.4	215.7	72.8	76.7
ORC 2 Mass Flow Rate (kg/s)	31.6	31.4	12.1	14.1

Table 5 shows the optimization performance of the recuperated ICRH GT 24-ORCs combined cycle. It is found that the modified GT 24-ORCs combined cycles had efficiencies of 52.13% - 54.07%, with thermal efficiency increase of 10.17% - 14.26%, in comparison to the original value of stand-alone recuperated ICRH GT 24. The maximum overall efficiency was obtained by using toluene as the ORC fluid, i.e., 54.07%, which is close to the overall efficiency of toluene REC ICRH LM-6000-ORCs combined cycle. Moreover, the toluene REC ICRH GT 24-ORCs had a maximum overall power output of 284.47 MW. The net additional power produced by the ORCs was about 25.4 - 35.6 MW. Furthermore, the power ratios were 9.96%, 9.23%, 12.48% and 10.6% for R123, R245fa, toluene and cyclohexane combined cycles, respectively. The ORC 2 could produce electricity of about 9 MW by using R245fa as the ORC fluid. This amount of power is more than a half of the power generated by the ORC 1 due to the high inlet temperature of ORC turbine 2. Correspondingly, large amount of R245fa is desirable to run the R245fa REC ICRH GT 24-ORCs combined cycle, which, however, may increase the system capital cost. Conversely, organic fluids with high turbine specific enthalpy like toluene and cyclohexane had few mass flow rates in ORCs. The optimum operating parameters using the GA are also presented in Table 5. It can be seen that, similar to the case of modified LM 6000-ORCs combined cycle, the pitch point temperature difference approached a value of 2 ℃ for all the organic working fluids. On the other hand, the degree of superheat at the ORC 1 turbine inlet ranged from 0.2 ℃ to 8.2 ℃, while the degree of superheat at the ORC 2 turbine inlet was close to zero for all the organic fluids.

Table 5: Summary of optimization results for maximum overall efficiency of the modified Alstom GT 24-ORCs cycle

Parameter	R123	R245fa	Toluene	Cyclohexane
Overall Efficiency (%)	52.55	52.13	54.07	52.93
Efficiency Enhancement (%)	11.06	10.17	14.26	11.85
ORC 1 Power Output (MW)	19.83	16.34	28.99	23.13
ORC 2 Power Output (MW)	7.78	9.06	6.63	6.48
Overall Power Output (MW)	277.36	275.15	284.47	279.36
Power Ratio (%)	9.96	9.23	12.48	10.60
$T_{e,1}$ (℃)	175	140	297	225.7
$T_{e,2}$ (℃)	139	129.4	126.1	150.6
ΔT_E (℃)	2.2	2.2	2	2
$\Delta T_{sup,1}$ (℃)	6.6	8.2	4	0.2
$\Delta T_{sup,2}$ (℃)	0.4	0	0.7	0
ORC 1 Mass Flow Rate (kg/s)	477.6	442.7	150.3	161.9
ORC 2 Mass Flow Rate (kg/s)	230.9	280.9	82.1	68.2

Table 6 shows a summary of optimization performance of the recuperated ICRH WR 21-ORCs combined cycle for different organic working fluids. It is found that the modified WR 21-ORCs combined cycles had efficiencies of 51.19% - 52.62%, with thermal efficiency increase of 7.77% - 10.76%, in comparison to the original value of single recuperated ICRH WR 21. The maximum overall efficiency was obtained by using cyclohexane as the ORC fluid, i.e., 52.62%, which is slightly higher than that by using toluene as the ORC working fluid. Moreover, the cyclohexane REC ICRHGT-ORCs had an overall power output of 39.61 MW with a power ratio of 9.72%. The minimum power ratio was obtained by using R245fa, i.e., 7.21%, where the overall power output was equal to 38.55 MW. The ORC 2 produced electricity of about 0.5 MW on average for each organic fluid. This amount of power is relatively smaller than the power generated by the ORC 1 due to the limitation of LPC outlet temperature and minimum pitch point temperature difference. The optimum operating parameters using a GA are also presented in Table 6. It can be seen that the pitch point temperature difference approached a value of 2 ℃ for all the organic working fluids. On the other hand, the degree of superheat at the ORC 1 turbine inlet could be as high as 7.8 ℃ using R123 as the organic fluid, while the degree of superheat at the ORC 2 turbine inlet was relatively small for all the organic fluids in absence of cyclohexane. It can be noticed that the mass flow rate of the working fluid in ORC 1 in this case was much lower than that of corresponding working fluid in ORC 1 in LM-6000 and GT 24 combined cases as given in Tables 4 and 5. This is because both of the exhaust temperature and the exhaust flow rate of the WR 21 gas turbine were relatively lower, i.e., 307 ℃ and 73.1 kg/s, respectively, which leads to a decrease in heat transfer to the ORC 1. Compared to the other two high efficiency gas turbines, the modified WR 21 is more suitable to couple ORC bottoming cycles with reasonable operating conditions.

Table 6: Summary of optimization results for maximum overall efficiency of the modified RR WR 21-ORCs cycle

Parameter	R123	R245fa	Toluene	Cyclohexane
Overall Efficiency (%)	51.77	51.19	52.55	52.62
Efficiency Enhancement (%)	8.99	7.77	10.61	10.76
ORC 1 Power Output (MW)	2.68	2.2	3.3	3.34
ORC 2 Power Output (MW)	0.53	0.56	0.5	0.51
Overall Power Output (MW)	38.97	38.55	39.56	39.61
Power Ratio (%)	8.25	7.21	9.59	9.72
$T_{e,1}$ (℃)	170.6	140	205.8	235.7
$T_{e,2}$ (℃)	98	104	95.3	92.7
ΔT_E (℃)	2.2	2	2	2
$\Delta T_{sup,1}$ (℃)	7.8	5.6	0.9	0.8
$\Delta T_{sup,2}$ (℃)	0	0.4	0.4	2.9
ORC 1 Mass Flow Rate (kg/s)	64.8	61.4	23.4	22.5
ORC 2 Mass Flow Rate (kg/s)	23.9	22	9.2	10.1

5. CONCLUSIONS

The main conclusions drawn from this study are the following:

- The analysis of combined cycles based on commercial gas turbines and two ORCs shows that ORCs are an interesting and impressing option when combined with high efficiency gas turbines with low exhaust temperatures. Among the organic fluids in the bottoming cycles, toluene ORC combined cycles for each modified gas turbines present a very attractive overall efficiency.
- The efficiencies of recuperated ICRH gas turbines when coupled with two ORC bottoming cycles were improved by about 7.8% to 15.2% depending on the exhaust temperature and LPC outlet temperature of the topping gas turbine cycle and organic working fluid in ORCs. The use of different organic fluid in the two bottoming cycles may further improve the combined cycle efficiency.
- The heavy duty gas turbines like modified LM-6000 and GT 24 are not preferable to be used in combined cycles with R123 or R245fa ORC as the bottoming cycles resulting from the demand for large amount of mass flow rate in bottoming cycles and further high system capital cost. Gas turbine with relatively small power like WR 21 is more suitable to combine bottoming ORCs with reasonable mass flow rate of the organic fluid.
- The ORC 2 yielded about 0.5 and 0.53 MW on average of the power output for LM-6000 and WR 21 gas turbine combined cycles, respectively. The power could be further increased by using a high pressure ratio LPC and a newly designed HPC of the topping recuperated ICRH gas turbine.

NOMENCLATURE

CC	combustion chamber
G	generator
GT	gas turbine

HPC	high pressure compressor	
HPT	high pressure turbine	
LPC	low pressure compressor	
ORC	organic Rankine cycle	
PT	power turbine	
Q	heat transfer rate	(kW)
REC	recuperator	
T	temperature	(℃)
$\dot{W}$	power generation	(kW)
$\dot{m}$	mass flow rate	(kg/s)

Greek letters

η_I	first-law efficiency	(%)

Subscript

1,2,3…	cycle locations
c	critical
E	evaporator
I	first law
max	maximum
mix	mixture
sup	superheating

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