INNOVATIVE ORC SCHEMES FOR RETROFITTING ORC WITH HIGH PRESSURE RATIO GAS TURBINES

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ABSTRACT

Combined cycle mode of power generation is one of the efficient ways of generation of power. Combined cycles generally use gas turbine in the toping cycle. However, steam is a standard working fluid in bottoming cycle in present units. Recent studies show that Organic working fluids are most suitable for bottoming cycles under certain range of exhaust gas temperatures. Gas turbines with retrofits like intercooling between the compressor stages and regenerator are not suitable for conventional combined cycle operations. Tapping higher amounts of gas turbine exhaust thermal energy for power generation for high pressure ratio, recuperative gas turbine are feasible with organic working fluids.

Present research work aims at introduction of organic Rankine cycle (ORC) as a bottoming cycle in a conventional combined cycle unit. Commercially available gas turbine models like SGT200 (small capacity) and GE LM -6000 (medium capacity) have been considered for the toping cycle. Saturated Toluene, cyclopentane, butane, MM, MDM, MD_2M, D_4, D_5 are studied parametrically to understand energy recovery potential from the gas turbine exhaust. The working fluid with higher potential for power generation is best suited for ORC.

Use of dry working fluids can achieve the same efficiency as that of other organic working fluids, as they create a scope for use of Internal Heat Exchange (IHE). The advantage of IHE can be understood with reduced condenser loads and enhanced potential for waste heat recovery from the source fluid. It can be either used for thermal applications or power applications depending upon its availability. As siloxanes are deep dry working fluids, their internal regeneration capability is good and hence another bottoming cycle can be thought of with lower boiling point organic working fluid in conjunction with primary bottoming cycle. A very innovative scheme with R-245fa and butane bottoming cycles are studied in conjunction with MM saturated cycle. The power recovery potential by using both the bottoming cycle schemes is studied. This scheme increases complexity of the combined cycle. Hence a dual pressure bottoming cycle scheme is developed using MM as the working fluid. Saturated MM is injected with expanding vapor in the turbine (which is in superheated state). Studying the potential of energy recovery in this arrangement is very creative.

1. INTRODUCTION

Efficiency of power generating cycle improves, if the heat rejection occurs at lowest feasible temperature. This is better achieved by generating power in a combined cycle mode. The commercial combined cycles generally use gas turbine in the toping cycle. The exhaust gas from the toping cycle is used to generate steam for the generation of power in the bottoming cycle. Heavy duty gas turbines with higher exit temperatures from the turbine are techno-economically viable for combined cycle applications.

Combined cycle efficiency depends upon the optimal selection of the gas turbine efficiency. Improving gas turbine efficiency does not necessarily improve the combined cycle efficiency. It is useful only if it does not cause high reduction in steam cycle efficiency. For the same gas turbine inlet conditions, the toping cycle attains higher efficiency at higher pressure ratio. But the efficiency of combined cycle with moderate pressure ratio toping cycle is better than the high pressure ratio toping cycle. This is because steam turbine operates with higher inlet pressure and temperature and contributes greater output. Chacartegui *et al.* (2009a) observed that, gas turbines with retrofits like intercoolers and regenerators are not found suitable in conventional gas and steam combined cycles. Jaheeruddien (2004) observed that steam and gas combined cycles with triple pressure bottoming cycle achieve highest efficiency.

Nazzar *et al.(*2003) carried out review of cogeneration opportunity using gas turbine exhaust. Tapping gas turbine exhaust heat to power for a high pressure ratio, recuperative gas turbines needs organic working fluid. It can perform better in the given exhaust temperature range. The integration of ORC with high efficiency, recuperative turbines is carried out by Chacartegui *et al.* (2009b). Bianchi *et al.* (2011) carried out study of different alternative waste heat recovery arrangements like ORC, Stirling engine, inverted Bryton cycle for low to moderate temperature heat sources. Srinivasan *et al*. (2010) and Vaja and Gambarotta (2010) studied integration of ORC with I C engine exhaust.

Colonna *et al. (2006a) (2008a)* developed multi parameter Span and Wagner equations for determination of thermodynamic properties of selected siloxanes. The same authors recommend siloxanes for high temperature ORC applications. Drescher and Bruggemann (2007a) and Fernández *et al*. (2011a) suggested use of intermediate thermo oil (recoverer) circuit to exchange energy with source fluid and organic fluid.

This paper presents introduction of ORC as a bottoming cycle in a combined cycle mode. Commercially available gas turbine models of medium to small power capacity are selected for the toping cycle. Saturated toluene, cyclopentane, butane, MM(Hexamethyldisiloxane), MDM(Octamethyl trisiloxane),MD_2M(Decamethyaltetrasiloxane),D_4(Octamethylcyclotetrasiloxane),D5(Decamethylcyclopentasiloxane) are studied parametrically to understand energy recovery potential from the gas turbine exhaust. Thermodynamic analysis of the cycle is carried out with the help of software program developed in C++.Thermodynamic properties of the working fluids calculated using Peng Robnsion cubic equations, the constants required to calculate vapor pressure and ideal gas isobaric heat capacity taken from Colonna *et al.* (2006b) (2008b) and Nanan and Colonna (2009) for siloxanes. For toluene, cyclopentane and butane the constants have been referred using Lai Ngoc Anh (2009).

To avail the advantage of internal regeneration using IHE, another bottoming cycle in conjunction with MM bottoming cycle has been discussed in sections to follow. A creative multi pressure evaporative scheme is developed to understand the complete power recovery potential from MM

2. DESCRIPTION OF COMBINED CYCLE

Retrofitting high pressure ratio gas turbine toping cycle with ORC bottoming cycle is certainly a challenging task. An intermediate thermo oil circuit (recoverer) circuit is preferred over direct exchange of energy from gas turbine exhaust to the organic working fluid, keeping the safety aspect in focus. Siemens, SGT 200 and high efficiency aero derivative GE LM -6000 are considered for toping cycle. The energy recovery potential for the bottoming ORC cycle using different working fluids is studied for saturated turbine inlet conditions of the bottoming cycle.

2.1 Description of Toping Cycle

The modern heavy duty gas turbine models are not preferred for integration with ORC. The specifications of the gas turbine toping cycles used in this work are provided in Table 1 High efficiency, intercooled and recuperated toping gas turbine cycles produce exhaust gas temperature in the range 355 to 450^{o}C. When there is no process steam requirement, taping this potential could be possible effectively through organic working fluids.

Figure 1. represents block and *T-s* diagram for combined cycle power plant with gas turbine toping cycle and ORC bottoming cycle with intermediate thermal (thermo) oil circuit. The atmospheric air enters the compressor at point 1_{GT} and it is pressurized to 2_{GT} and then enters the combustor, where it helps to combust the fuel. The hot gases from the combustor 3_{GT} enter the gas turbine, after passing

through the turbine it leaves at 4_{GT} and enter the recoverer (known as heat recovery steam generator HRSB in steam based combined cycle). Dow therm A, thermo oil is used to exchange energy with turbine exhaust. After exchanging energy to the thermo fluid the exhaust gases move to stack and is let out to the atmosphere at prescribed conditions. Thermo fluid after receiving energy from the hot exhaust gases enter the vapor generator of ORC circuit.

Table 1: Specifications of different gas turbine models [Siemens web page, Chacartegui *et al.* (2009c)]

Parameter	SGT200	GE LM-6000
$\dot{m}_{ex}$(kg/s)	29.3	127
PR	12.2	29.1
TIT(K)		1533
TET(K)	739.15	711
$\dot{W}$(MW)	6.75	43.4
η (%)	31.5 (ele)	41.8

2.2 Description of ORC Bottoming Cycle

For high pressure ratio recuperative gas turbine toping cycles, steam based bottoming cycle is least efficient. In this scenario, using an organic working fluid in bottoming cycle is a novel idea. The organic working fluid enters the pump at point 1 and it is pressurized to turbine pressure at point 2. Then it flows through the internal heat exchanger (if provided in the circuit) and receives energy from the turbine exhaust of bottoming cycle and leaves at point 2a. It enters the vapor generator and leaves at point 3. After expansion in the turbine point 4, it is in superheated state and made to pass through internal heat exchanger (IHE). It leaves IHE at 4a and passes through condenser; after condensing it enters pump at point 1.

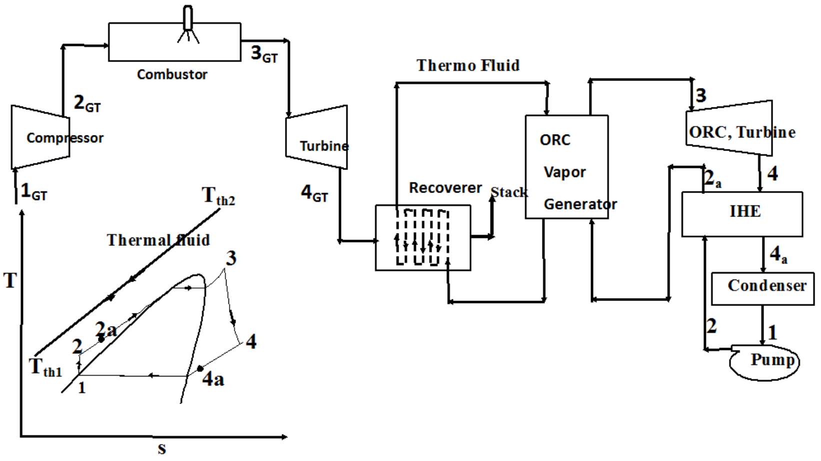


Figure 1: T-s and block diagram for combined cycle power plant

Figure 2. shows temperature T-ΔH diagram for the generalized combined cycle for bottoming cycles without IHE. It represents heat exchange between exhaust gas to intermediate thermo oil as well as thermo oil to the organic working fluid. The exhaust gas and intermediate thermo oil temperatures for different working fluids is given in Table 2 for SGT 200 integration with organic working fluids. It also explains the operating conditions of the condenser of the ORC circuit. The exhaust gas inlet temperature to the recoverer circuit is denoted by T_{4GT}, it is the exit temperature of the flue gas from the toping cycle. The exhaust gas outlet temperature from the recoverer circuit (T_{stack}) is taken as 423.15 K (150°C) based on the suggestions by Meherwan (2002).The inlet and outlet temperature of the thermo oil at the recoverer circuit is denoted by T_{th1} and T_{th2}. T_{th2} is the inlet temperature of the thermo oil to the vaporizer section of ORC and it leaves the vaporizer at a temperature T_{th1}. The maximum temperature of the working fluid is governed by stability and safety criterion of the working fluid. It is given by T_3 in the Figure 2. Since we have carried out a parametric study it is not presented in Table 2. The minimum

temperature of the working fluid is given by condenser conditions. Minimum condenser pressure of 5kPa is recommended by Drescher and Bruggemann (2007b) and Fernández *et al*. (2011b). The condenser temperature (T_{con}=T_1) of 323.15K (50°C) is selected for toluene, cyclopentane, butane and MM as their saturation pressure i.e. condenser operating pressure (P_{con}=P_1) is above 5kPa. For the working fluids MDM, MD_2M, D_4, D_5 the condenser temperatures (T_1) is elevated to maintain the minimum acceptable condenser pressure.

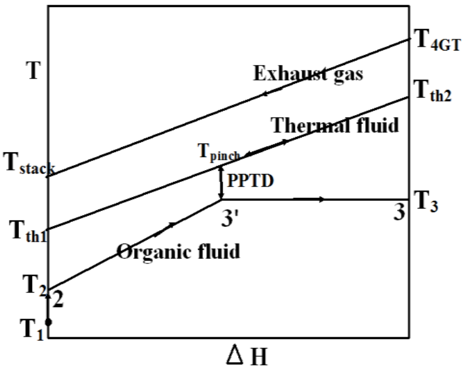


Figure 2: T-ΔH diagram for recoverer and vaporizer

Table 2: Operating temperatures of exhaust gas, thermo oil & working fluid [Refer Figure 2]

Working fluid	T_{4GT} (K)	T_{stack} (K)	T_{th1} (K)	T_{th2} (K)	T_1 (K)	P_1 (kPa)
Toluene	739.15	423.15	343.15	648.15	323.15	9.19
Cyclopentane	739.15	423.15	343.15	648.15	323.15	103.92
Butane	739.15	423.15	343.15	648.15	323.15	494.27
MM	739.15	423.15	343.15	648.15	323.15	17.72
MDM	739.15	423.15	363.15	648.15	343.15	5.83
MD_2M	739.15	423.15	393.15	648.15	375.15	5.00
D_4	739.15	423.15	383.15	648.15	363.15	5.68
D_5	739.15	423.15	410.15	648.15	390.15	5.29

3. INTEGRATION OF SATURATED ORC BOTTOMING CYCLE WITH TOPING GAS TURBINE CYCLE

Saturated ORC schemes are widely accepted schemes in ORC technology in various applications. These are simple and show good efficiency and preferred over superheated and supercritical schemes for dry working fluids. Different dry type of working fluids like toluene, cyclopentane, butane, MM, MDM, MD_2M, D_4, and D_5 are studied parametrically to understand the energy recovery potential from gas turbine exhaust. The condition of the vapor leaving the turbine is superheated for dry type working fluids. Hence cycles with internal heat recovery using IHE is also studied. An innovative R-245fa bottoming cycle in conjunction with MM bottoming cycle is also studied to understand total recovery potential from gas turbine exhaust. The following assumptions are made in the analysis of the cycle.

- Isentropic efficiency of turbine and pump are assumed as 0.88 and 0.80
- The effectiveness of IHE is 0.8
- PPTD ≥10°C

3.1 Thermodynamic analysis of the cycle

Selection of pinch point is one of the important parameters in the combined cycle analysis. It can be defined as the temperature difference between the exhaust gas (thermo oil in this case) leaving the evaporator section and saturation temperature of the working fluid at the turbine inlet pressure. It is the lowest temperature difference existing in the evaporator. The calculation of the pinch point and mass flow rates of working fluid is carried out by conducting energy balance. Refer Figure 2. For the notations.

A) Energy exchange in recoverer to calculate mass flow rate of thermal fluid:

Energy lost by the exhaust gas= Energy gained by the thermal fluid

$$\dot{m}_{ex} \times C_{p,ex} \times (T_{4GT} - T_{stack}) = \dot{m}_{th} \times C_{p,th} \times (T_{th2} - T_{th1}) \tag{1}$$

B) Energy exchange in vaporizer section of ORC bottoming cycle to calculate mass flow rate of working fluid:

Energy lost by thermal fluid=Energy gained by the working fluid

$$\dot{m}_{th} \times C_{p,th} \times (T_{th2} - T_{th1}) = \dot{m}_{wf} \times (h_3 - h_2) \tag{2}$$

C) Energy exchange in the evaporator section of the vaporizer to calculate PPTD

$$\dot{m}_{th} \times C_{p,th} \times \left(T_{th2} - T_{pinch}\right) = \dot{m}_{wf} \times (h_3 - h_3{}') \tag{3}$$

$$PPTD = T_{pinch} - T_3' \qquad (4)$$

D) The first law efficiency for heat engine can be expressed as:

$$\eta_{th} = \frac{Net\ work\ output}{Heat\ input} = \frac{\dot{m}_{wf} \times (w_t - w_p)}{\dot{Q}_{in}} \qquad (5)$$

3.1 Integration of Toping Cycle SGT200 with Bottoming ORC Saturated Cycles

In this section integration of different ORC schemes with small capacity gas turbine SGT200 is discussed. Toluene, cyclopentane, butane, MM, MDM, MD_2M, D_4, D_5 working fluids have been studied parametrically to understand the potential for power generation, when connected with gas turbine exhaust. The working fluid with higher potential for power generation is best suited for ORC integration.

The integration with gas turbine cycle for all working fluids considered are studied parametrically at various reduced pressures (P_$_r$) (0.6-0.9). Initially cycles without internal regeneration have been studied followed by cycles with internal regeneration.

Table 3 shows the results obtained for saturated cycles at the maximum permissible temperature limit for individual fluid, expressed in the form of reduced temperature T_$_r$ (T_{max}/T_c). The corresponding saturation pressure is also expressed in the form of reduced pressure P_$_r$ (P_{max}/P_c). $T_{max} = T_3$, is permissible maximum inlet temperature for the working fluids for integration with SGT200. Toluene is considered at 0.85 P_{max}/P_c, understanding its safe limit of evaporation for saturated cycles as provided by Chacartegui *et al.* (2009d).

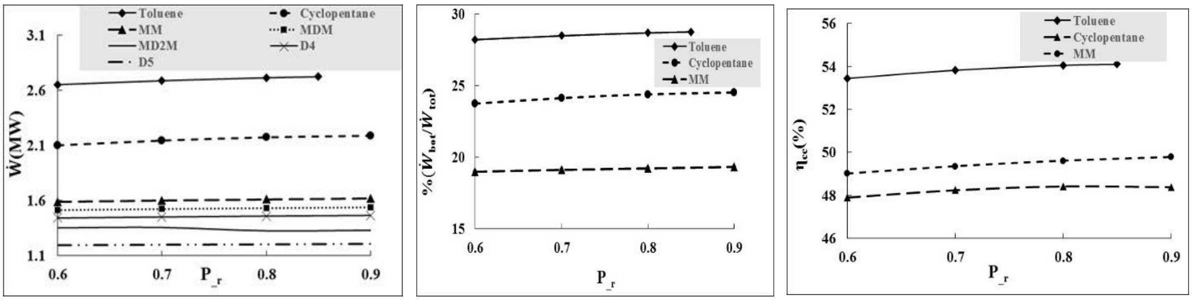
Power produced by any power generating cycle is a function of the mass flow rate of the working fluid and the specific net work output ($w_{net}=w_t- w_p$) of the working fluid. It can be observed that mass flow rate of toluene cycle is less compared to other working fluids, but specific net work output is considerably high over other working fluids. This can be shown with higher level of power recovery from integration with a particular heat source. After toluene, cyclopentane and MM show better exhaust heat to power conversion capabilities. The efficiency of the cycle without IHE is studied initially. Except for butane the potential for internal heat exchange using turbine exhaust is good for all the working fluids considered and hence cycles with IHE have been studied for other working fluids. It can be observed that toluene shows highest efficiency of 25.75% and D_5 exhibits lowest efficiency with a value of 11.38%. The combined cycle efficiency is calculated for gas turbine and ORC integration. The efficiency of the toping gas turbine cycle is referred from Siemens web page and its value is taken as $\eta_{GT} = 0.334$. Highest combined cycle efficiency of 54.11% is observed for toluene with integration with SGT 200.

$$\eta_{cc} = \eta_{GT} + \eta_{ORC} - (\eta_{GT} . \eta_{ORC}) \text{ [Murugan and Subbarao (2010)]} \qquad (6)$$

Table 3: Results for saturated ORC cycles for all working fluids at 0.9P_$_r$

Working fluid	T_$_r$	P_$_r$	$\dot{m}_{wf}$ (kg/s)	w_{net} (kJ/kg)	$\dot{W}$ (MW)	$\eta_{(-IHE)}$ %	$\eta_{(+IHE)}$ %	η_{cc} %
Toluene	0.978	0.850	14.847	183.401	2.723	25.75	31.09	54.11
Cyclopentane	0.984	0.900	18.622	117.574	2.189	20.71	22.49	48.38
Butane	0.985	0.900	25.601	57.082	1.461	13.82	----	42.60
MM	0.988	0.900	20.656	78.364	1.619	15.31	24.59	49.78
MDM	0.990	0.900	20.196	76.060	1.536	14.53	27.44	51.68
MD_2M	0.989	0.900	21.035	63.105	1.327	12.55	25.53	50.41
D_4	0.988	0.900	23.191	63.058	1.462	13.83	26.53	51.07
D_5	0.989	0.900	22.908	52.552	1.204	11.38	24.11	49.46

Parametric study of all the working fluids is done for the P_$_r$ range 0.6-0.9. Figure 3(a). shows power recovery potential of all the working fluids. Toluene shows highest power recovery at all the reduced pressures and power recovered by the D_5 is least. This makes toluene most competent working fluid for the integration at all inlet conditions of the turbine. The contribution of bottoming cycle to the total power produced by the combined cycle is expressed by ratio of % $\dot{W}_{bot}/\dot{W}_{tot}$. Figure 3(b) shows % $\dot{W}_{bot}/\dot{W}_{tot}$ for toluene, cyclopentane and MM the top three power recovery working fluids. As toping cycles for all the working fluids is same it is obvious that toluene shows higher ratio compared to other two. Similarly combined cycle efficiency at various reduced pressures is shown in Figure 3(c). The combined cycle efficiency with toluene as the bottoming cycle is highest at all the reduced pressure ranges and it is followed by MM and cyclopentane.



(a) (b) (c)

Figure 3 (a, b, c): Total power recovered, % $\dot{W}_{bot}/\dot{W}_{tot}$, η_{cc}

3.2 Integration of Toping Cycle GELM-6000 with Bottoming ORC Saturated Cycles

The integration of the saturated ORC with different working fluids with medium capacity gas turbine GE LM- 6000 is done in a similar way to SGT 200. The exhaust gas enters the recoverer at 711K at a mass flow rate of 127kg/s and enters the stack at a temperature of 150°C. Thermo fluid is maintained at a temperature of 343.15K and 648.15K at the inlet and out let of the recoverer. Table 4 shows the results obtained for the parametric integration of GE LM- 6000 with different working fluids at $0.9P\_{r}$. Power recovery potential of toluene is highest as compared to other working fluids, similar to SGT 200 integration.

Table 4: Results for the parametric integration of GELM-6000 with different working fluids

Working fluid	T_{r}	P_{r}	$\dot{m}_{wf}$ (Kg/s)	$\dot{W}$ (MW)	$\eta_{(-IHE)}$ %	$\eta_{(+IHE)}$ %	η_{cc} %	$\%(\dot{W}_{bot}/\dot{W}_{tot})$
Toluene	0.978	0.85	58.43	10.72	25.07	30.10	59.32	19.80
Cyclopentane	0.984	0.9	73.28	8.62	20.70	22.49	54.89	16.56
MM	0.988	0.9	81.28	6.37	15.31	24.59	56.11	12.80
MDM	0.990	0.9	79.47	6.04	14.53	27.44	57.77	12.22
MD_2M	0.989	0.9	82.77	5.22	12.55	25.53	56.66	10.74
D_4	0.988	0.9	91.26	5.75	13.83	26.53	57.24	11.70
D_5	0.989	0.9	90.15	4.74	11.38	24.11	55.83	9.84

3.3 Impact of Internal Heat Exchange on Power Recovery:

The advantage of IHE can be understood with reduced condenser loads and enhanced potential for waste heat recovery from the source fluid. It can be either used for thermal applications or power applications depending upon its availability.

Figure 4. shows the advantage of using IHE to the circuit. The temperature of the working fluid increases from T_2 to T_{2a}. And due to this heat addition in a constant pressure process is h_3-h_{2a} instead of h_3-h_2 as represented in the diagram. The effect of this can be observed in thermo oil circuit also, the thermo oil leaves the vaporizer at $T_{th1'}$ instead of T_{th1}. This potential generated due to IHE effect, can be availed either by utilizing it for thermal application or else for power generation. This potential is very small for toluene and cyclopentane and it can be used for small process heat requirement of the industry. As siloxanes are deep dry working fluids, their internal regeneration capability is good and hence another bottoming cycle can be thought with lower boiling point organic working fluid. For the sake of analysis, MM cycle at $0.9P\_{r}$ is considered to integrate with another bottoming cycle. R-245fa and butane bottoming cycles are studied in conjunction with MM saturated cycle at $0.9P\_{r}$ by using the potential $T_{th1'}$-T_{th1}. As R-245fa produces higher power with the integration and it is presented in the next section.

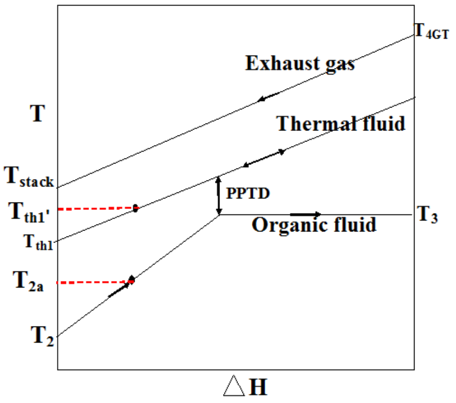


Figure 4: IHE effect on thermal oil circuit

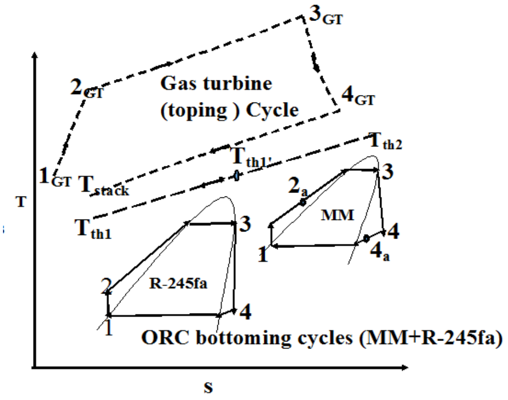


Figure 5: Integration of MM+R-245fa bottoming cycles

3.4 Saturated R-245fa Bottoming Cycle in Conjunction with MM at 0.9P_$_r$ for Integration of GE-LM 6000

A very innovative cycle has been developed by understanding the extra potential created due to IHE effect. Figure 5. Shows T-s diagram for saturated R-245fa bottoming cycle which is used in conjunction with MM cycle. The thermo oil leaving the vaporizer of the MM circuit ($T_{th1'}$) is made pass through another vaporizer in which it interacts with low boiling point working fluid R-245fa. After exchanging energy it leaves the vaporizer of R-245fa at T_{th1}, which is the inlet temperature to the heat recoverer. The saturated R-245fa vapor enters the turbine at point 3 after expansion in the turbine the state of the working fluid is slightly superheated. Hence the use of internal heat exchanger is eliminated. The turbine exhaust vapor enters the condenser at point 4.After condensing at point 1 it is pumped to turbine pressure. As this bottoming cycle uses two ORC circuits, it increases complexity of the design, it also adds extra capital investment on all ORC components. The cost associated with this arrangement is not being discussed in this work.

Table 5 shows the parametric study carried for R-245fa cycle for the reduced pressure range of 0.6 to 0.9 P_$_r$. It can be observed that saturated R-245fa at a reduced pressure of 0.9 P_$_r$ contributes power of 1.76MW, it is the maximum power obtained from the arrangement. Total power obtained by the two bottoming cycles (MM+R-245fa) is 8.13MW. The efficiency of the combined cycle improves considerably by converting this potential into power. A combined cycle efficiency of 69.57 % is reached by the combination of MM at 0.9 P_$_r$ and R-245fa also at 0.9 P_$_r$. The contribution of the bottoming cycle to the combined cycle power is also improved by incorporating this scheme.

Table 5: Results for parametric optimization of R-245fa bottoming cycle used in conjuction with MM at 0.9P_$_r$ for integration with GE LM-6000

P_$_r$	$\dot{m}_{wf}$ (kg/s)	$\eta_{(\text{-IHE})}$ %	$\dot{W}$ (MW)	$\dot{W}_{bot}$ (MM+R245fa)	η_{cc} (%)	%($\dot{W}_{bot}/\dot{W}_{tot}$)
0.90	58.22	12.63	1.76	8.13	69.57	15.77
0.80	57.24	13.27	1.72	8.09	70.16	15.72
0.70	57.10	13.73	1.67	8.04	70.58	15.63
0.60	57.36	13.99	1.58	7.95	70.82	15.49

4. MULTI PRESSURE EVAPORATION FOR ORC BOTTOMING CYCLES

In this section multi pressure evaporative scheme for bottoming cycle ORC plant is being studied for MM as the working fluid. A very innovative case has been developed and analyzed by using MM as the working fluid.

Due to internal heat exchange between turbine exhaust vapor and exit liquid from pump, the temperature of the thermo oil leaving the vaporizer section of the ORC is increased. This potential has been utilized by running another bottoming cycle (R-245fa in conjunction with MM cycle). The total power produced by the bottoming cycle by both MM and R245fa is 8.13MW at 0.9P_r as discussed in previous section. It is the maximum power recovery from the combination. Of course it increases the power recovery potential of the bottoming cycle, but it also increases complexity and cost of the cycle by adding one more ORC cycle (components) to the circuit.

4.1. Discussion of Dual Pressure Evaporative MM Cycle

The idea of generating MM vapor and injecting it in the turbine, instead of R-245fa was futile because the condition of MM at lower pressures is superheated and it is not supported by thermodynamics. Therefore a new idea is developed in which instead of generating superheated vapor at the lower pressure (pressure of injection), saturated vapor is being generated and injected in MM turbine. It does lead to slight reduction in exergy of expanding vapor, but it is important that it should produce power comparable to MM and R-245fa combination. After studying feasibility of evaporation at different pressures, it is decided to evaporate MM at 0.3269P_r (0.639MPa) for injection into the turbine.

The block and T-s diagram for the scheme is shown in Figure 6.The condensate from the condenser with flow rate $\dot{m}_{wf}$ at point 1 is divided into two streams: mass $\dot{m}_{wf1}$and $\dot{m}_{wf2}$. The mass $\dot{m}_{wf1}$is pressurized to high pressure in high pressure pump, (2). It is internally regenerated by using the vapor from the exit of the turbine to point, (2a). The regenerated high pressure fluid then enters the high pressure vapor generator at point 2a. It leaves the vapor generator in a saturated state with respect to the turbine inlet pressure, (3). At the same state it enters the turbine and expands till point 4. The condensate $\dot{m}_{wf2}$ is pumped through low pressure pump at 2', the fluid leaving the low pressure pump is internally regenerated using turbine exhaust in the low pressure regenerator to point 2a'. It then enters the low pressure vapor generator and heated till point 4. It is injected into the turbine at the same state. The state of low pressure vapor at point 4 is saturated and the state of the expanding vapor is superheated at point 4. It leads to small amount of exergy destruction of expanding vapor. The temperature of the mixed stream is calculated by this approximation.

Mass flow rate of vapor expanding in turbine at high pressure: $\dot{m}_{wf1}$ =81.284kg/s

Mass flow rate of low pressure vapor: $\dot{m}_{wf2}$ =10.8kg/s

Total mass:$\dot{m}_{wf} = \dot{m}_{wf1} + \dot{m}_{wf2}$ = 92.084kg/s (7)

Temperature of the expanding vapor at point 4:$T_{4,sup}$=480K

Temperature of the low pressure saturated vapor:$T_{4,sat}$=451.98K

Mass fraction high pressure expanding vapor: $x_h = \frac{\dot{m}_{wf1}}{\dot{m}_{wf}}$ (8)

Mass fraction of low pressure vapor:$x_l = \frac{\dot{m}_{wf2}}{\dot{m}_{wf}}$ (9)

Hence temperature of the mixed stream is approximated as:

$$T_4 = x_h \times T_{4,sup} + x_l \times T_{4,sat} \approx 477\text{K} \tag{10}$$

As both the streams mixing at the same pressure, P_4=0.639MPa

The further expansion of the mixed stream is considered from P_4, T_4 to condenser condition till point 5. At point 5 the total mass flow rate of working fluid is divided into two steams. $\dot{m}_{wf1}$ goes to high pressure regenerator and $\dot{m}_{wf2}$ enters low pressure regenerator. After exchanging energy with feed fluid in IHE, both the streams mix together and enter the condenser at point 1' and the cycle continues.

4.2. Thermodynamic analysis of the cycle

Rate of work obtained from high pressure vapor before mixing (3-4) in the turbine:

$$\dot{W}_{t1} = \dot{m}_{wf1} \times (h_3 - h_4) \tag{11}$$

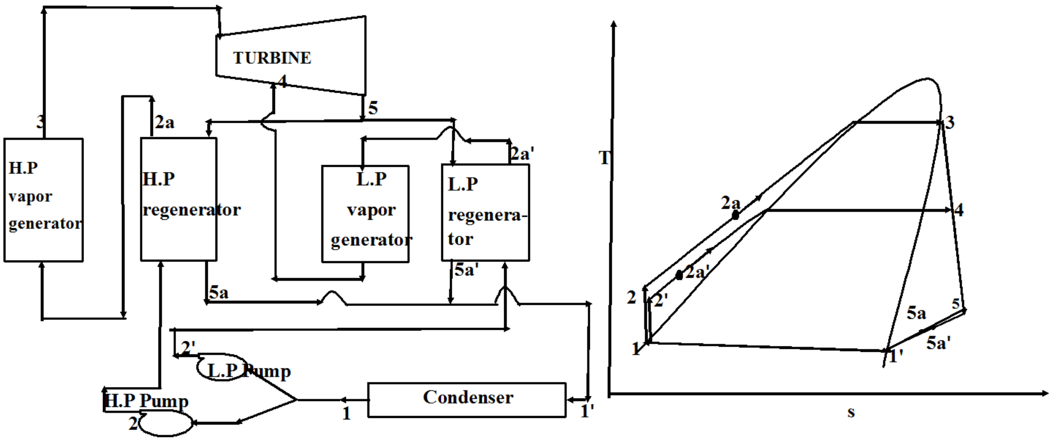


Figure 6: Block and T-s diagram for multi pressure evaporation

Rate of work obtained from the mixed stream (4-5) the turbine:

$$\dot{W}_{t2} = \dot{m}_{wf} \times (h_4 - h_5) \tag{12}$$

Total rate of work obtained: $\dot{W}_t = \dot{W}_{t1} + \dot{W}_{t2}$ (13)

Rate of work in put to high pressure pump: $\dot{W}_{p1} = \dot{m}_{wf1} \times (h_2 - h_1)$ (14)

Rate of Work in put to low pressure pump: $\dot{W}_{p2} = \dot{m}_{wf2} \times (h_2{}' - h_1)$ (15)

Total rate of pump work: $\dot{W}_p = \dot{W}_{p1} + \dot{W}_{p2}$ (16)

Net rate of work obtained : $\dot{W}_{net} = (\dot{W}_t - \dot{W}_p)$ (17)

Rate of energy input to the cycle: $\dot{Q}_{in} = \dot{m}_{wf1} \times (h_3 - h_{2a}) + \dot{m}_{wf2} \times (h_4 - h_{2a}{}')$ (18)

Efficiency of the cycle: $\eta_{th} = \frac{Net\ rate\ of\ work\ obtained}{Total\ rate\ of\ Energy\ input} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$ (19)

Table 6: Results for multi pressure evaporation for MM

T_r3	P_r3	T_r4	P_r4	$\dot{m}_{wf1}$ (kg/s)	$\dot{m}_{wf2}$ (kg/s)	$\dot{W}_t$ (kW)	$\dot{W}_p$ (kW)	$\dot{W}_{net}$ (kW)	$\dot{Q}_{in}$ (kW)	η (%)
0.98	0.90	0.87	0.33	81.28	10.80	7540.50	251.48	7289.00	28526.44	25.55

Table 6 shows the results obtained for multi pressure evaporation. It can be observed that net power produced from the multi pressure evaporation is 7.289 MW and the total power produced by bottoming cycle of saturated MM and saturated R245fa at 0.9P_r is 8.13 MW. There is a reduction of power by 841kW by injecting MM saturated vapor in to the turbine, but this cycle is less complicated and simple as it consists only single ORC in the bottoming cycle.

5. CONCLUSIONS

The potential for power recovery using different organic working fluids for saturated ORC schemes is studied for high pressure ratio recuperative gas turbine toping cycles. The cycles are studied for both without IHE and with IHE schemes. Toluene shows highest recovery potential over all the working fluids considered. It generates a power of 2.723MW for integration with SGT200. The advantage of using IHE not only improves efficiency but also creates opportunity for extra power generation using low boiling point working fluid. MM bottoming cycle in conjunction with another low boiling point working fluid (R245fa) recovers a power of 8.13MW(MM+R245fa) for integration with GE-LM 6000. This is lower than toluene bottoming cycle which produces 10.72 MW of power from integration .A multi pressure cycle using MM as the working fluid is discussed at the end for the integration of GE-LM 6000. The advantage of IHE is utilized to generate saturated vapors of MM and injected into the expanding vapor of MM bottoming cycle. The power recovery capability of this innovative idea is compared with (MM+R245fa) combined bottoming cycle. Even though multi pressure evaporation of MM produces less power but it reduces complexity of the cycle.

NOMENCLATURE

List of Symbols			**Subscripts**	
$\dot{m}$	Mass flow rate	kg/s	cc	Combined cycle
PR	Pressure ratio	(-)	GT	Gas turbine
h	Enthalpy	kJ/kg	th	Thermo
P	Pressure	MPa	wf	Working fluid
T	Temperature	K	sup	Superheated
s	Entropy	kJ/(kg-K)	sat	Saturated
TIT	Turbine inlet temperature	K	bot	Bottoming
TET	Turbine exit temperature	K	tot	Total
IHE	Internal heat exchanger	(-)	t	Turbine
$\dot{W}$	Power	MW	p	Pump
w	Specific work output	kJ/kg	c	Critical
C_p	Specific heat	kJ/(kg-K)	sup	Superheated
T_{r}	Reduced temperature	(-)	sat	Saturated
P_{r}	Reduced pressure	(-)		
Greek Symbols				
η	Efficiency	(%)		

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