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

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Contents:

Introduction

- Efficiency of power generating cycle improves, if the heat rejection occurs at lowest feasible temperature
- Achieved by generating power in a combined cycle mode
- Improving gas turbine efficiency does not necessarily improve the combined cycle efficiency
- 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

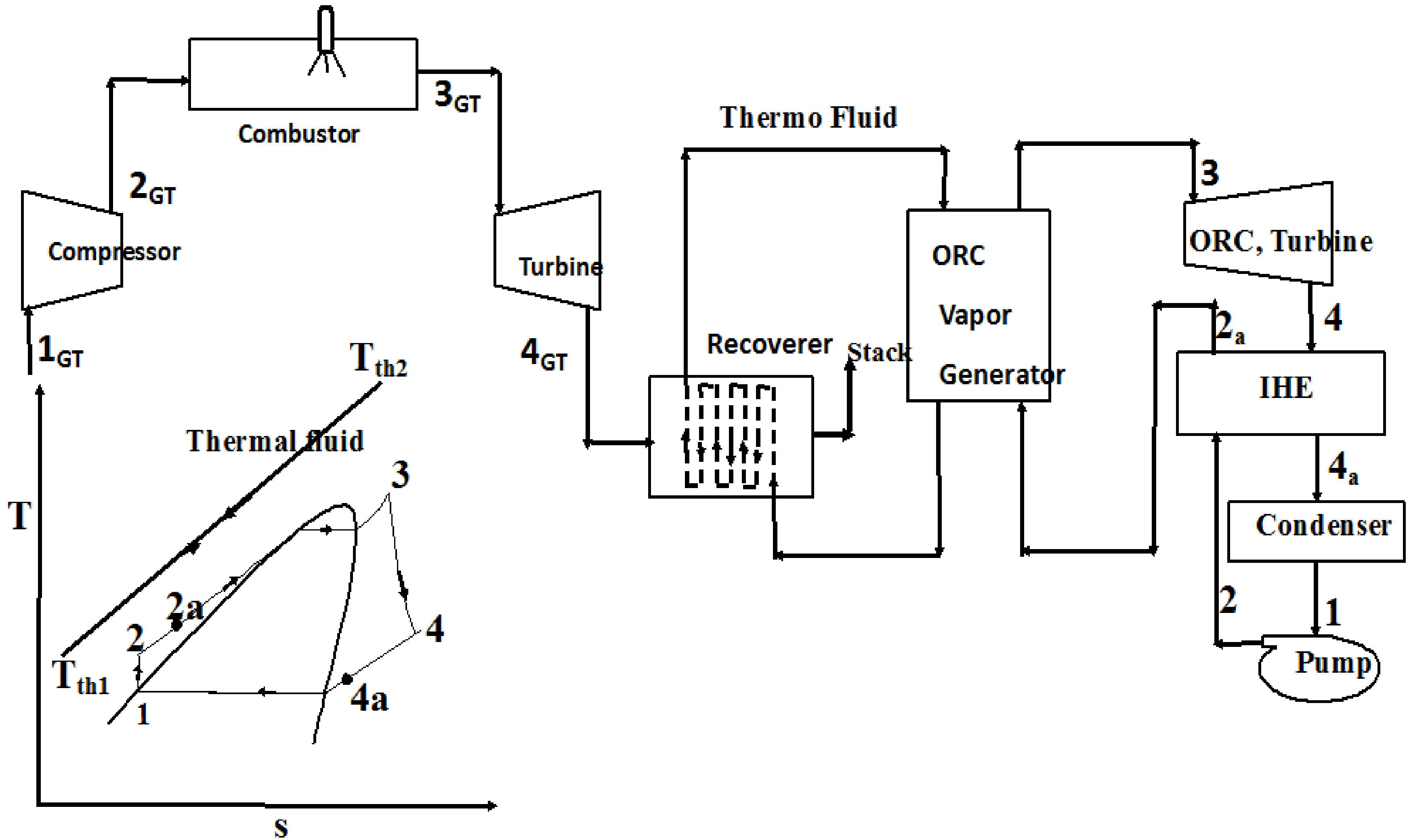
- Saturated Toluene, cyclopentane, butane, MM, MDM, MD_2M, D_4, D_5 are studied parametrically to understand energy recovery potential from the gas turbine exhaust

- To avail the advantage of internal regeneration using IHE, another bottoming cycle in conjunction with MM bottoming cycle has been discussed

- Multi pressure evaporative scheme is developed to understand the complete power recovery potential from MM

- Thermodynamic properties of working fluids calculated using Peng-Robinson cubic equations

Description of combined cycle



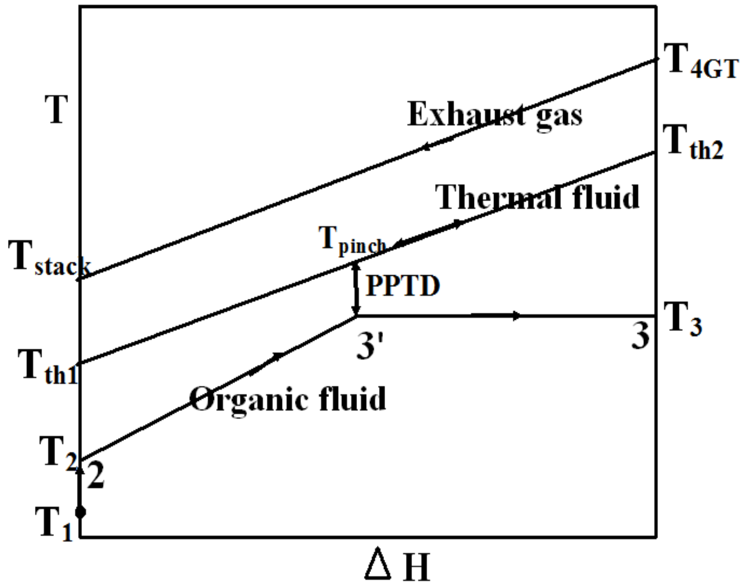
A) Description of Toping Cycle

- High efficiency, intercooled and recuperated toping gas turbine cycles produce exhaust gas temperature in the range 355 to 450^{o}C

Specifications of different gas turbine models

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

Description of ORC Bottoming Cycle



Operating temperatures of exhaust gas, thermo oil & working fluid

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

INTEGRATION OF SATURATED ORC BOTTOMING CYCLE WITH TOPING GAS TURBINE CYCLE

- Isentropic efficiency of turbine and pump are assumed as 0.88 and 0.80
- The effectiveness of IHE is 0.8
- PPTD $\geq 10^{o}C$

Thermodynamic analysis of the cycle

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

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

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

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

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

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

$$PPTD = T_{pinch} - T_3{}'$$

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

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

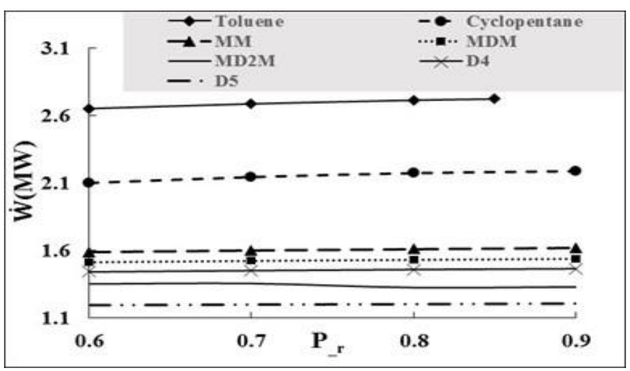
Integration of Toping Cycle SGT200 with Bottoming ORC Saturated Cycles

- Saturated ORC schemes with small capacity gas turbine SGT200 is studied parametrically
- 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 integration with gas turbine cycle for all working fluids considered are studied parametrically at various reduced pressures (P_r) (0.6-0.9).

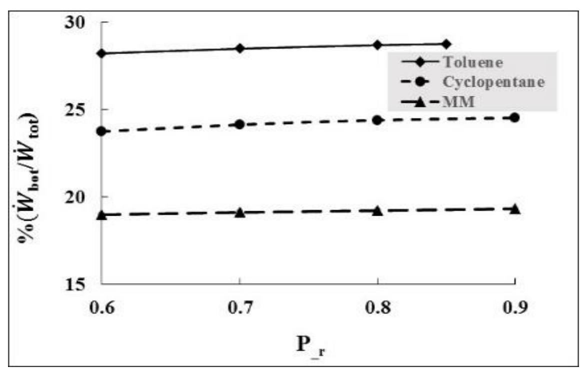
Results for saturated ORC cycles for all working fluids at 0.9P_r

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

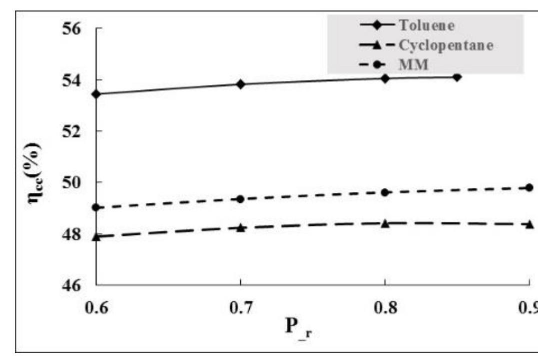
$$\eta_{cc} = \eta_{GT} + \eta_{ORC} - (\eta_{GT} \cdot \eta_{ORC})$$



Total power recovered



% $\dot{W}_{bot}/\dot{W}_{tot,}$



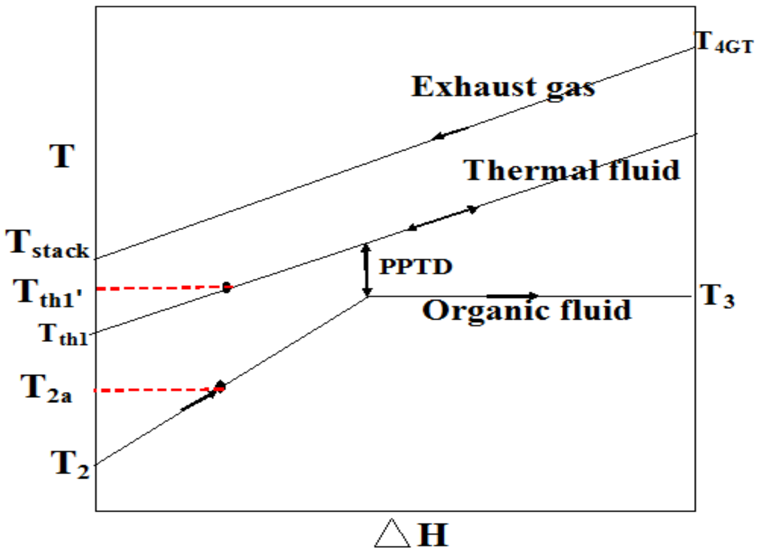
η_{cc}

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

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

Impact of Internal Heat Exchange on Power Recovery

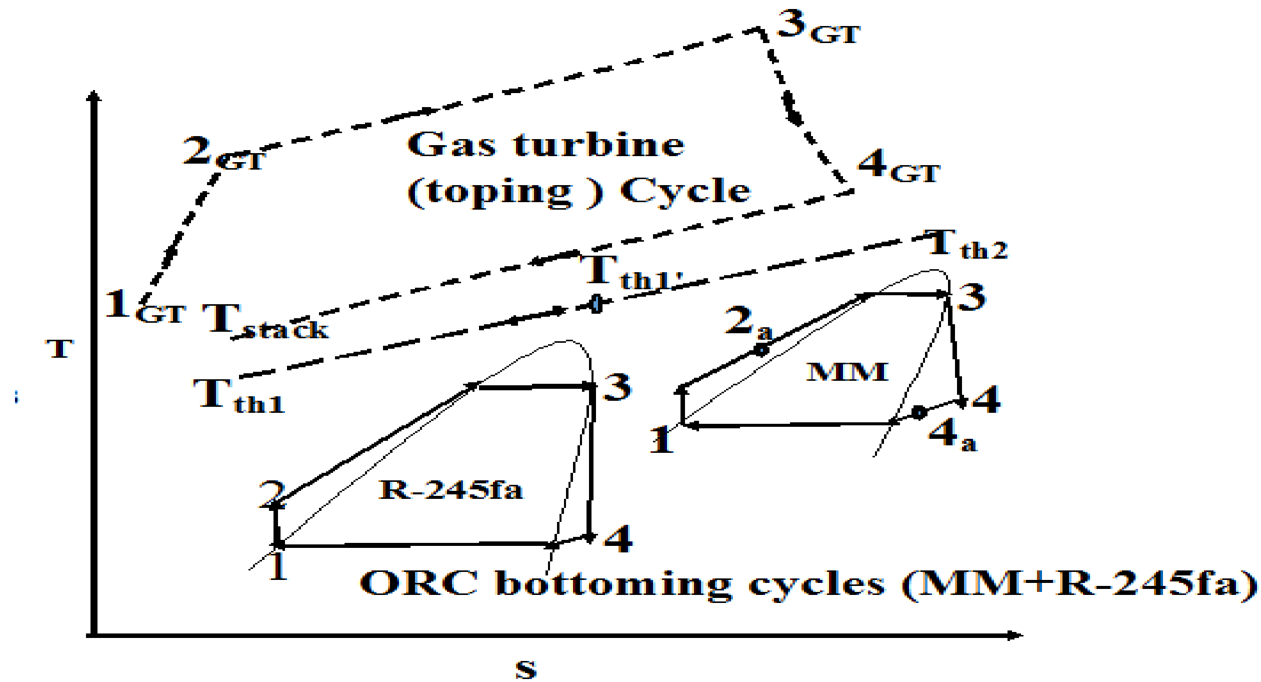


IHE effect on thermal oil circuit

- 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 oi circuit also, the thermo oil leaves the vaporizer $T_{th1'}$ instead of T_{th1}
- This potential generated due to IHE effect, can 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
- 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}

Integration of MM+R-245fa bottoming cycles

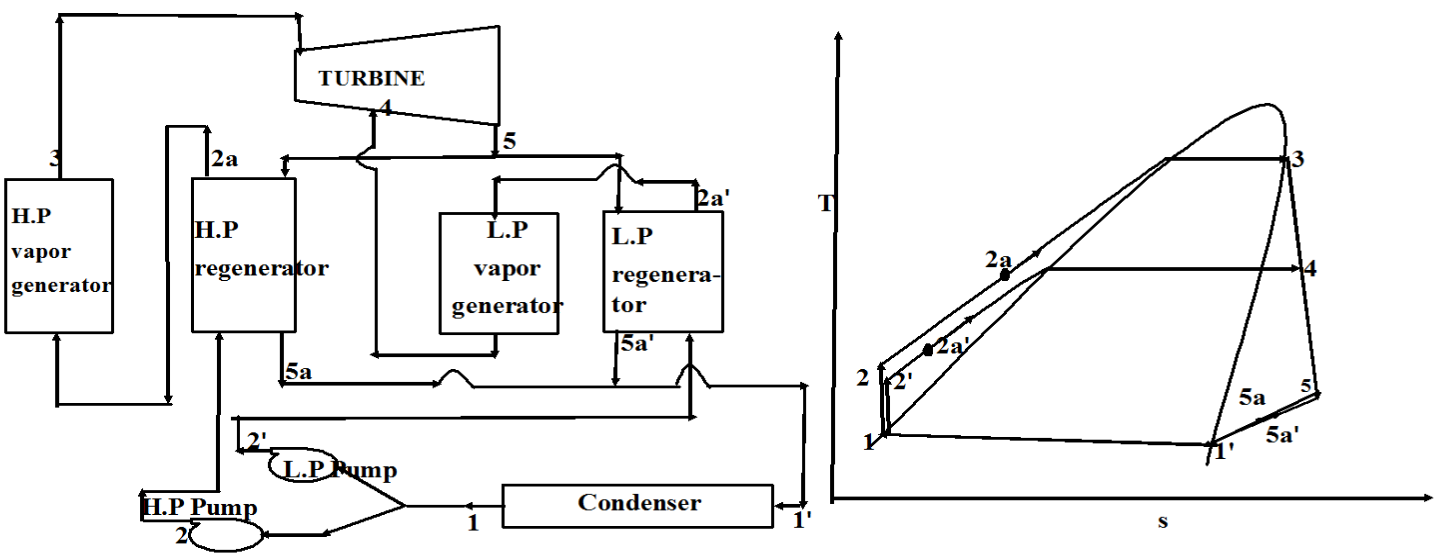


Results for parametric optimization of R-245fa bottoming cycle used in conjuction with MM at 0.9P_r for integration with GE LM-6000

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

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



Block and T-s diagram for multi pressure evaporation

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

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: $x_h = \frac{\dot{m}_{wf1}}{\dot{m}_{wf}}$

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

Hence temperature of the mixed stream is approximated as:

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

Thermodynamic analysis of the cycle

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

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

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

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

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

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

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

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

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

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

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

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

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

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
- Even though multi pressure evaporation of MM produces less power but it reduces complexity of the cycle.

Thank You