Comparison of Thermal Performance of Rankine Cycle, Reheat Cycle, Regenerative Cycle & One Stage Regenerative & reheat Rankine Cycle with Same Initial & Final Parameters

Nitin Badhe[1], K.S. Gharge[2],

[1]*Student, Dept. of Mechanical Engineering, Government College of Engineering Karad, Maharashtra, India*
[2]*Ass. Professor, Dept. of Mechanical Engineering, Government College of Engineering Karad, Maharashtra, India*

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Abstract - *Vapor power cycles are used in steam power plants. In a vapour power cycle heat energy (released by the burning of fuel) is converted into work (shaft work), in which a working fluid repeatedly performs a succession of processes. In a vapour power cycle, the working fluid is water, which undergoes a change of phase. Among the various types of vapor power cycles is the Carnot cycle, which is theoretically the most efficient cycle and sets the limit for the efficiency of any vapor cycle. This limit is known as the Carnot limit. The Rankine cycle and its modifications are used widely and are theoretically the cycles best suited to steam power plants. By studying these cycles, we know practically what all must be done to increase the efficiency and cost effectiveness.*

Key Words: Vapor power cycle, Carnot cycle, Rankine cycle, efficiency, Steam power plant, water, heat energy

1. INTRODUCTION

The steam power cycle is a useful method for constantly converting heat energy into mechanical energy. The Carnot cycle has the maximum thermal efficiency of all cycles in a certain temperature range, in accord with the second law of thermodynamics. We have seen that Carnot cycle is not the theoretical/ideal cycle for steam turbine power plant because of the difficulty of pumping a mixture of water and steam and delivering it as saturated water only. However, this difficulty is eliminated in Rankin cycle by complete condensation of water vapor in the condenser, and then, pumping the water isentropically to boiler pressure. Rankine cycle is a theoretical/ideal cycle for comparing the performance of steam power plants.

Therefore, the Rankine cycle has become a basic cycle generally used in modern thermal power plants. Additionally, with the progress of science and technology, based on the Rankine cycle, there are reheat rankine cycle, regenerative rankine cycle and so on. At present, the actual cycles of steam power plants are very complex, but they are all improved based on the primary cycle. What are the economic differences of these improved steam power cycles? Let us compare them with specific examples.

2. Comparison

Example: In a power cycle, the initial parameters of fresh steam are p_1 = 87 bar, t_1 = 510˚C, The pressure of condenser is p_b = 0.1 bar. When the fresh steam expands to p_2 = 20 bar in the steam turbine, a part of the steam is extracted for regenerative heating, and the rest is sent to the reheater to be heated to 500˚C, and then return to the steam turbine to do work. Assume turbine efficiency = 65% and 100 TPH

2.1 Rankine Cycle (η_t = 65%)

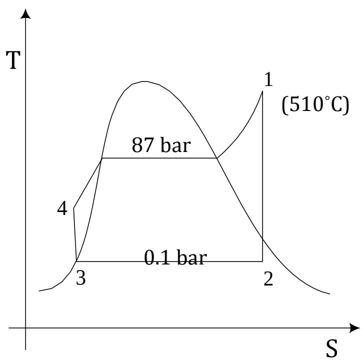

Fig. 1. T-s diagram of rankine cycle

From h-s diagram, the state parameters of the corresponding state point are as follows:

h_1 = 3414.3 kJ/kg = 3414.3* 0.23884 = 815.47 kcal/kg
$h_{2'}$ = 2119.99 kJ/kg = 506.34 kcal/kg ($S_1 = S_2$)
but η_t = 65%

$\eta_t = \frac{h1-h2}{h1-h2\prime} = 0.65 = \frac{815.47-h2}{815.47-506.34}$

h_2 =2573.01 kJ/kg = 614.54 kcal/kg

h_3 = 191.8 kJ/kg = 45.809 kcal/kg

h_4 = 200.57 kJ/kg =47.90 kcal/kg

Heat supplied (q_i)= $h_1 - h_4$
= 3213.72 kJ/kg = 765.565 kcal/kg

Turbine work (w_t)=$h_1 - h_2$

= 841.27 kJ/kg = 200.93 kcal/kg

Pump Work (w_p)= $h_4 - h_3$
=8.77 kJ/kg = 2.096 k cal/kg

Electricity generated = 200.93* 0.860*100/1000
= 17.34 MW=14909716.25 k cal/hr

Firing duty = $\frac{(815.47-47.90)*100*1000}{0.7}$
= 109652857.1 k cal/hr

$\eta_{thermal} = \frac{(200.93-2.096)}{765.565}$

= 25.9%

$\eta_{cycle} = \frac{14909716.25}{109652857.1}$

= 13.59%

2.2 Reheat Cycle

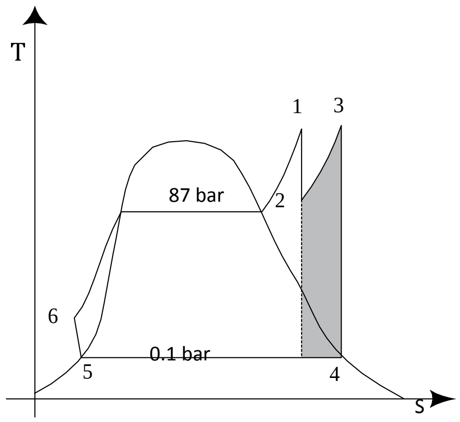

Fig. 2. T-s diagram of reheat rankine cycle

From h-s diagram, the state parameters of the corresponding state point are as follows:

h_1 = 3414.3 kj/kg = 815.47 kcal/kg
h_2 =3147.72 kj/kg = 751.80 kcal/kg (η_{HP} =60%)
h_3 = 3480 kj/kg = 831.16 kcal/kg
h_4 = 2745.5 kj/kg = 655.73 kcal/kg (η_{LP}=65%)
h_5 = 191.8 kj/kg = 45.80 kcal/kg
h_6 = 193.80 kj/kg = 46.28 kcal/kg

Heat supplied (q_i)= $(h_1 - h_6) + (h_3 - h_2)$
=3552.79 Kj/kg = 848.55 k cal/kg

Turbine work (w_t) =$(h_1 - h_2) + (h_3 - h_4)$
= 1001.08 Kj/kg = 239.1 kcal/kg

Pump Work (w_p) = $h_6 - h_5$
= 8.776 Kj/kg = 2.094 kcal/kg

Electricity generated = 239.1 * 0.860 * 100/1000
= 20.56 MW=17678417.88 kcal/hr

Firing duty = $\frac{848.55*(100*1000)}{0.7}$

= 121221428.6 kcal/hr

$\eta_{thermal} = \frac{(239.1-0.48)}{848.55}$

= 28.12%

$\eta_{cycle} = \frac{17678417.88}{121221428.6}$

= 14.58 %

2.3 Regeneration Cycle

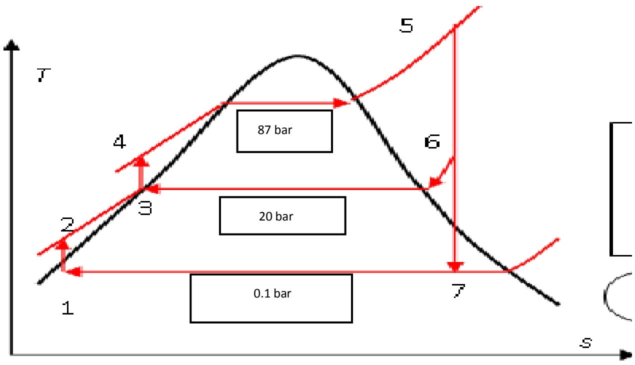

Fig. 3. T-s diagram of regenerative rankine cycle

From h-s diagram, the state parameters of the corresponding state point are as follows:

h_1 = 191.8 kj/kg = 45.80 kcal/kg
h_2 =193.80 kj/kg = 46.28 kcal/kg
h_3 = 908.5 kj/kg = 216.98 kcal/kg
h_4 = 916.38 kj/kg = 218.86 kcal/kg
h_5 = 3414.3 kj/kg = 815.47 kcal/kg
h_6 = 3121.41 kj/kg = 745.51 kcal/kg (η_{HP} =65%)
h_7 = 2472.35 kj/kg = 590.49 kcal/kg (η_{HP} =65%)

Energy balance of feed water heater
$mh_6 + (1-m)h_2 = h_3$

m = 0.2441 kg/kg of steam

Heat supplied (q_i)= $h_5 - h_4$
= 2497.92 kj/kg = 596.60 k cal/kg

Turbine work (w_t)= $(h_5 - h_6) + (1-m)(h_6 - h_7)$
= 783.50 kj/kg = 187.132 kcal/kg

Pump Work (w_p)= $(h_2 - h_1) + (h_4 - h_3)$
= 9.88 kj/kg = 2.35 kcal/kg

Electricity generated = 187.132* 0.860*100/1000
= 16.09 MW=13834909.72 kcal/ hr

Firing duty = $\frac{596.60*(100*1000)}{0.7}$
= 85228571.43 kcal/hr

$\eta_{thermal} = \frac{783.50 - 9.88}{2497.92}$

= 30.97%

$\eta_{cycle} = \frac{13834909.72}{85228571.43}$

= 16.20%

2.4 One stage regeneration and one reheat cycle

From h-s diagram, the state parameters of the corresponding state point are as follows:

h_1 = 191.8 kj/kg = 45.80 kcal/kg
h_2 =193.80 kj/kg = 46.28 kcal/kg
h_3 = 908.5 kj/kg = 216.986 kcal/kg
h_4 = 916.38 kj/kg = 218.86 kcal/kg
h_5 = 3414.3 kj/kg = 815.47 kcal/kg
h_6 = 3143.94 kj/kg = 750.89 kcal/kg (η_{HP} =60%)
h_7 = 3467.3 kj/kg = 828.129 kcal/kg
h_8 = 2744.29 kj/kg = 655.44 kcal/kg (η_{LP}=65%)

By energy balance of feed water heater

$mh_6 + (1 - m)\, h_2 = h_3$

m = 0.2422 kg/kg of steam

Heat supplied (q_i) = $(h_5 - h_4) + (1 - m)(h_7 - h_6)$
=2442.96 Kj/kg = 655.12 kcal/kg

Turbine work (w_t)=$(h_5 - h_6) + (1 - m)(h_7 - h_8)$
= 818.256 Kj/kg = 195.43 kcal/kg

Pump Work (w_p)=$(h_2 - h_1) + (h_3 - h_4)$
= 9.889 Kj/kg = 2.36 kcal/kg

Electricity generated = 195.43 * 0.860 * 100/1000
= 16.80 MW=144453399.83 kcal/hr

Firing duty = $\frac{655.12*(100*1000)}{0.7}$

= 93588571.43 kcal/hr

$\eta_{thermal} = \frac{818.256-9.889}{2742.96}$

= 29.47%

$\eta_{cycle} = \frac{14445399.83}{93588571.43}$

= 15.43 %

2.5 Calculation Result

Under the same initial and final parameters, we calculated the thermal efficiency and cycle efficiency of Rankine cycle, reheat cycle, regenerative cycle, and cycle with one stage regenerative and one reheat, respectively. The results are shown in Table 1, 2 and 3.

Table 1. Comparison of calculation results between reheat cycle and Rankine cycle.

	Rankine cycle	reheat cycle	
		result	Comparison with Rankinecycle
q_i kJ/kg	3213.72	3552.79	↑ 339.07
w_t kJ/kg	841.29	1001.08	↑ 159.79
w_p kJ/kg	8.776	8.776	→
$\eta_{thermal}$	25.90%	27.93%	↑2.03%
η_{cycle}	13.59%	14.58%	↑0.99%

Table 2. Comparison of calculation results between regenerative cycle and Rankine cycle.

	Rankinecycle	regenerative cycle	
		result	Comparison with Rankinecycle
q_i kJ/kg	3213.72	2497.92	↓ 715.8
w_t kJ/kg	841.29	783.507	↓57.783
w_p kJ/kg	8.776	9.88	↑ 1.11
$\eta_{thermal}$	25.90%	30.97%	↑5.07%
η_{cycle}	13.59%	16.20%	↑2.61%

Table 3. Comparison of calculation results between one stage regeneration and one reheat cycle and Rankine cycle.

	Rankine cycle	one stage regeneration and one reheat cycle	
		result	Comparison with Rankinecycle
q_i kJ/kg	3213.72	2742.96	↓ 470.76
w_t kJ/kg	841.29	818.25	↓23.04
w_p kJ/kg	8.776	9.889	↑ 1.11
$\eta_{thermal}$	25.90%	29.47%	↑3.57%
η_{cycle}	13.59%	15.43%	↑1.84%

3. CONCLUSIONS

From the above result it can be seen that thermal efficiency and cycle efficiency is higher in regenerative rankine cycle than reheat as well as one stage regeneration reheat rankine cycle compare with the same parameters.

Heat energy supplied to the boiler is higher in reheat rankine cycle and heat energy supplied to the boiler is lower in regenerative rankine cycle.

Work of turbine is higher in reheat rankine cycle i.e., electricity production is also high as compare to regeneration and as one stage regeneration reheat rankine cycle.

From the above result it can be seen that regeneration involves the utilization of heat within the system while reheating or superheating requires additional heat addition from outside. Thus, the suitable degree of regeneration may be better over reheating or superheating options.

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