Rankine Cycle Optimisation at Constant Boiler Temperature with Fuel Economy

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ABSTRACT

This work entails simulation, analysis and optimisation of a reheat-regenerative closed feed rankine cycle, regenerative rankine cycle and conventional rankine cycle using auto- generated steam table in MS excel. The steam table was programmed with some of the in-built functions in MS excel that includes **If Statement, Hlook up, Index and Match commands** to enable automatic update of enthalpy and entropy values in results computation as input parameters (temperatures and pressures) are varied. The results from graphical trends shows that the net work done and plant/cycle efficiency at constant boiler steam temperature increases with increase in steam pressure. Concurrently, the actual heat supplied by the boiler decreases as the steam pressure increases, thus saving boiler fuel energy.

Key Words: Rankine cycle; plant efficiency; optimisation; reheat cycle; regenerative cycle; auto generated steam table; steam pressure and fuel energy savings.

1.0 INTRODUCTION

This study looks at the simulation and analysis of the performance characteristic of a reheat regenerative, regenerative and conventional Clausius-rankine [1] cycles. Most research work on steam cycle dwelt on the theoretical/diagrammatic improvement of efficiency and work done based on reheating, regeneration, lowering condenser pressure and raising the boiler pressure and temperature. Reheating and regeneration are employed as this will help save fuel and cost hence reducing the green house effects that affect global warming. This includes the production of optimum power while operating at an optimised pressure and steam turbine (ST) inlet temperature. A 3-stage gas turbine [2] can readily supply the needed high exhaust thermal heat energy (up to 600 ºC) through a heat recovery steam generator (HGRS) to superheat the steam rankine cycle.

This work seeks to look at possible way to optimise (increase) the performance characteristic (net work done and efficiency) of a rankine cycle at constant boiler steam temperature. It also seeks to see how fuel energy can be saved during optimisation.

2.0 METHODOLOGY

This was carried out with respect to the schematic rankine cycle design, programming and results computations as follows:

2.1 Schematic Model Of The Rankine Cycles

The schematic diagram of the Rankine cycle is depicted in Figure 1. The fuel can be generated in the boiler by either electric heating, burning coal [3] natural gas [4] or through a HRSG (heat recovery steam generator) of a high exhaust energy from an upper cycle in a combined cycle [5] to produce super heated steam for expansion in the ST cycle. The high temperature steam (i.e. at a maximum of 600℃) is expanded in the first HP steam turbine and then reheated back to its initial temperature in the HRSG. It is subsequently expanded in the second LP steam turbine where some steam is extracted for closed feed water heating. The fully expanded gas from the second ST is condensed to a condenser pressure where the rejected heat energy is extracted as useful heat energy. Some make up water is supplemented and the condensed saturated water is pumped to a pipe line where it is reheated with the bled steam and finally rechanneled back to the boiler.

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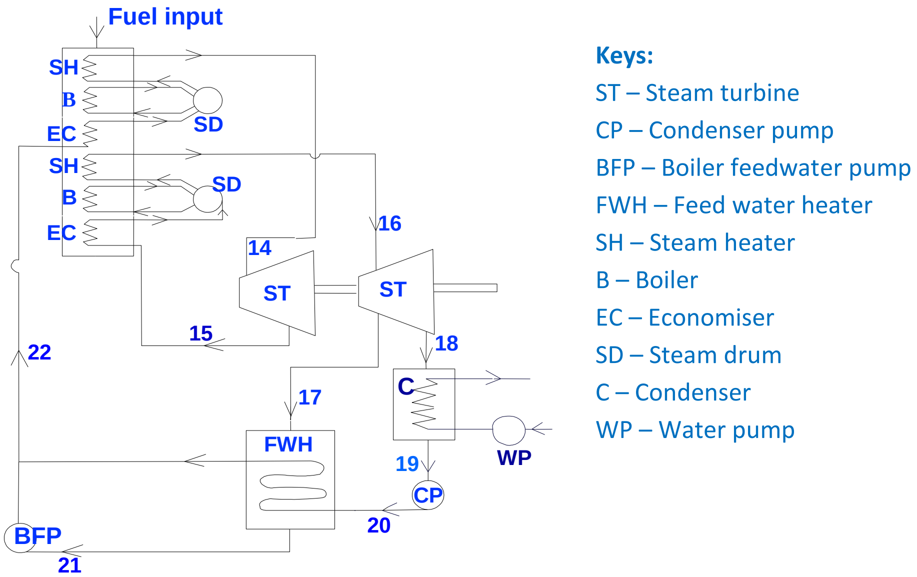


Fig. 1 Schematic diagram of the reheat regenerative rankine cycle with unfired HRSG as boiler

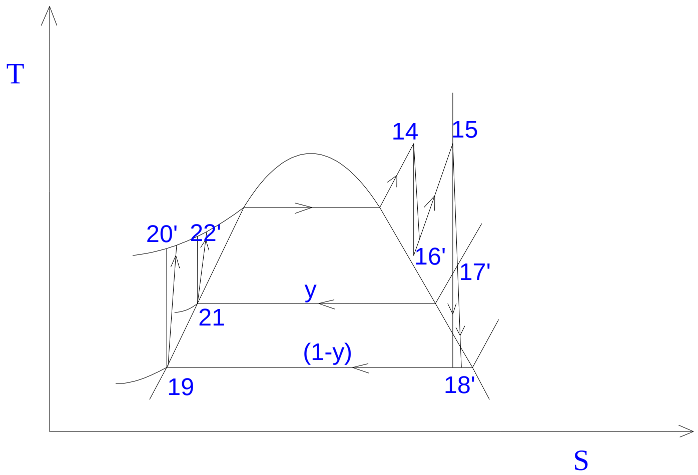


Fig. 2 Reheat regenerative rankine cycle T-S Diagram

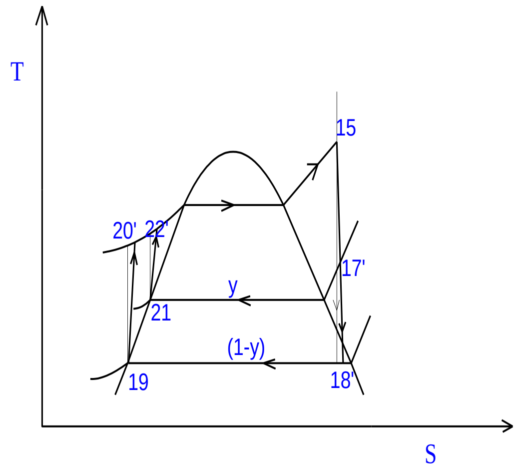


Fig. 3 Regenerative rankine cycle T-S Diagram

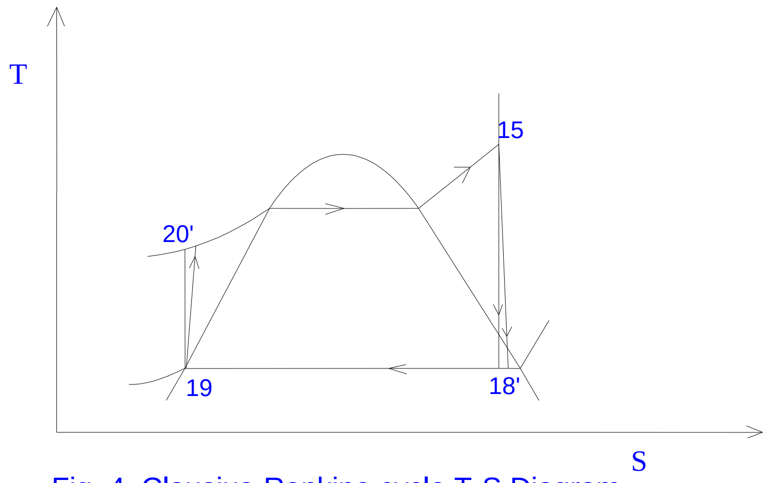


Fig. 4 Clausius-Rankine cycle T-S Diagram

2.11 Basic Assumptions of the Rankine Cycle

Some basic assumptions are made to ensure practicability of the simulated plant with the real plant. These are:

i. The boiler fuel should be generated either by electric heating, burning coal or through HRSG from exhaust gas of an upper cycle in a combined cycle. Gas turbine exhaust temperature could be as high as 500˚C to 600˚C for use by a steam turbine with an inlet (steam cycle) pressure as high as 165 bar [3]. Modern CC (combined cycle) power plants have inlet ST inlet pressure and temperature as high as 100 – 150 bar and 520 – 565˚C as a result of sequential stage combustion [6]
ii. Temperature ratio between the HP and LP steam turbines is taken to be unity i.e. LP steam turbine reheated to the initial steam inlet temperature.
iii. Pressure drop in the condenser and feed water heater are neglected.
iv. Steam turbine isentropic efficiency of 89% is assumed. Corresponding pumps isentropic efficiencies of 85% is taken.
v. Heat loss in the combustion chamber or recuperator is taken as 10% i.e. combustion chamber or recuperator efficiency of 90%.

2.2 Microsoft Excel Program Generation And Calculation

Microsoft Excel spread sheet was used in programming the Rankine cycle calculations. All the range of temperatures and pressures combinations corresponding to all possible values of enthalpies and entropies are tabulated in Table 2. An excel referencing function of HLOOKUP was used to pick up the ST inlet temperature and pressure. Reference functions of IF and HLOOKUP commands where used instantaneously to readjust or update the enthalpy and entropy of the reheat pressure as it changes. The INDEX command was used to look up the reheat temperature and its corresponding enthalpy. The IF and HLOOK UP referencing commands were again used to pick the appropriate extraction pressure enthalpy as it changes. Finally, the IF statement was used to look up the condenser pressure enthalpies at the corresponding volume of the saturated liquid levels.

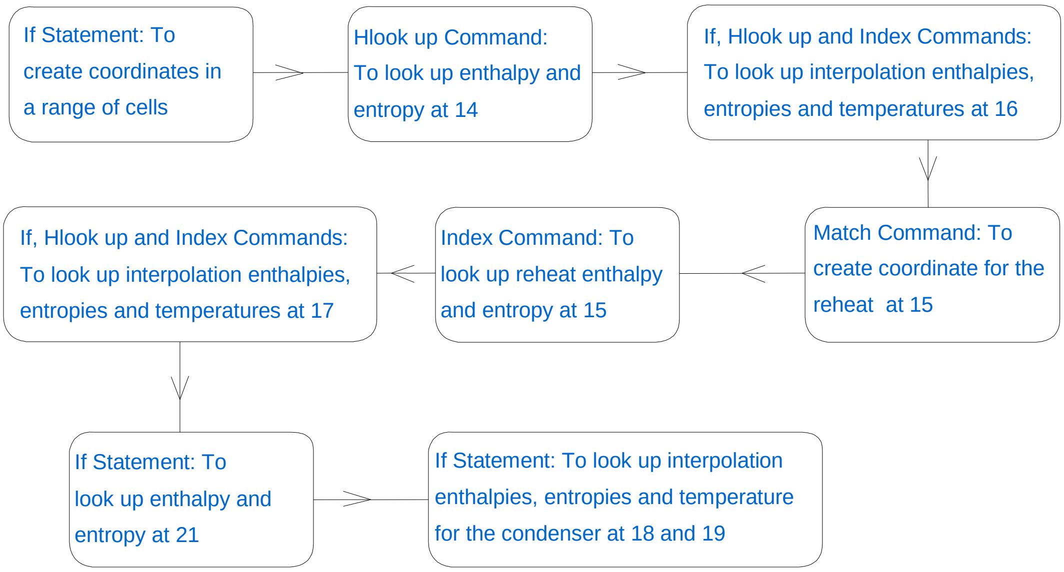


Figure 3: Flow Chart for the Excel Programming

The result's output comprising the cycle efficiency, energy utilisation factor, net work and net heat supplied is also displayed on the data sheet for prompt comparison with the varied parameters.

The range of input parameter values are carefully chosen with respect to realistic and practical viability of the plant. The analysis is subjected to varying input parameters such as boiler steam pressure and temperature as in table 1 below.

Notes: Items 1 – 5 in Table 1 can be varied. But items 3 – 5 are kept constant to simply analysis.

Table 1: Rankine Cycle Input Data

	RANKINE CYCLE DATA	**SYMBOL**	**UNIT**	**VALUES**	
1	Boiler Outlet Pressure	Pbo;	Bar	100	
2	Turbine Inlet Temperature	T15	C	400	
3	Pump &Turb. Isen. Efficiencies	ʃp; ʃt	%; %	85	89
4	1st Turb. Expansion Pressure and regenerative efficiency	$p_{x;}$ ʃr	Kpa	10	90
5	Extracted Steam & Cond. Pressure	Pex; Pc	Bar; Bar	3	0.05
6	Specific Volume at 19 & 21	V20; V21	m³/kg	0.0010052	0.001074
7	Enthalpy & Entropy at 14; P14 T14	h14; S14	KJ/Kg; KJ/kgK	3097	6.213
8	Int. Enthalpy & Entropy at 16; Pb, S16L	h16L; S16L	KJ/Kg; KJ/kgK	2607	6.211
9	Int. Enthalpy & Entropy at 16; Pb, S16H	h16H; S16H	KJ/Kg; KJ/kgK	2829	6.695
10	Int. Temperatures at 16: T16L, T16H	T16L; T16H	C; C	FALSE	200
11	Enthalpy & Entropy at 15; PT1, S15	h15f; S15f	KJ/Kg; KJ/kgK	3264	7.464

12	Int. Enthalpy & Entropy at 17; Pc, S17	h17L; S17L	KJ/Kg; KJ/kgK	2866	7.312
13	Int. Enthalpy & Entropy at 17; Pc, S17	h17H; S17H	KJ/Kg; KJ/kgK	2968	7.517
14	Int. Temperatures at 17: T17L, T17H	T17L; T17H	C; C	200	250
15	Enthalpy & Temperature at 21; Pex, S17	h21; T21	KJ/Kg; C	561	133.5
16	Int. Enthalpy & Entropy at Pc, S18	h18f; S18f	KJ/Kg; KJ/kgK	138	0.476
17	Int. Enthalpy & Entropy at Pc, S18	h18g; S18g	KJ/Kg; KJ/kgK	2561	8.394
18	Enthalpy & Temperature at 19; Pc, S17	h19g; S19g	KJ/Kg; C	138	32.9

The in-plant steam table is given below:

Table 2: The auto-generated Steam Table from MS excel

Pressure (Bar)			**Temperature (℃)**							
			200	**250**	**300**	**350**	**400**	**450**	**500**	**600**
100							3097	3241	3373	3624
							6.213	6.419	6.596	6.902
80							3139	3272	3398	3641
							6.364	6.555	6.723	7.019
60							3177	3301	3421	3657
							6.541	6.719	6.879	7.166
40							3214	3330	3445	3674
							6.769	6.935	7.089	7.368
30		6.180	6.186	6.289	6.541	6.744	**6.921**	**7.082**	**7.233**	**7.507**
		2710	2803	2858	2995	3117	**3231**	**3343**	**3456**	**3682**
20		6.200	6.340	6.547	6.768	6.957	**7.126**	**7.283**	**7.431**	**7.701**
		2731	2799	2904	3025	3138	**3248**	**3357**	**3467**	**3690**
15		6.210	6.452	6.711	6.919	7.102	**7.268**	**7.423**	**7.569**	**7.838**
		2681	2796	2925	3039	3148	**3256**	**3364**	**3473**	**3690**
10		6.211	6.695	6.926	7.124	7.301	**7.464**	**7.617**	**7.761**	**8.028**
		2607	2829	2944	3052	3158	**3264**	**3370**	**3478**	**3698**
9	**175.4**	6.623	6.753	6.980	7.176	7.352	7.515	7.667	7.811	8.077
	0.001121	2774.0	2835	2948	3055	3161	3266	3372	3480	3699
6	**158.8**	6.671	6.968	7.182	7.373	7.547	7.707	7.858	8.001	8.267
	0.001098	2757	2851	2958	3062	3166	3270	3376	3483	3701
3	**133.5**	6.910	7.312	7.517	7.702	7.874	8.032	8.182	8.324	8.588
	0.001074	2691	2866	2968	3070	3173	3275	3380	3486	3702
1	**99.6**	6.920	7.834	8.033	8.215	8.386	8.543	8.693	8.834	9.097
	0.001044	2516	2876	2975	3075	3177	3278	3382	3488	3703
0.15	**53.9**	214	2593	Enthalpy	(KJ/Kg)					
	0.0010140	0.7165	8.058	Entropy	(KJ/KgK)					
0.10	**45.8**	192	2584							
	0.0010102	0.649	8.149							
0.05	**32.9**	138	2561							

0.01	**0.0010052**	0.476	8.394
	7	29	2514
	0.0010002	0.106	8.974
	Enthapy		
	Spec. Vol.		

The analyses and computation of the GT are given below (Table 3): this is valid for only one simulation with inlet temperature of 400℃, pressure of 100 bars, with other respective data inputs from Table 1 (numbers 1 – 5) above. Items 6 – 18 from Table 1 linked with Table 2 are automatically updated to produce result in Table 3.

Table 3: Rankine Cycle Results Computation

	DATA FORMULATIONS/COMPUTATIONS	SYMBOL	UNIT	RESULTS	
1	Enthalpy at 16: h16 = (S14-S16L)/(S16H - S16L)×(h16H-h16L)+ h16L ; h16′ = (h16 -h14) X ∫t + h14	h16; h16′	KJ/Kg; KJ/kg	2607.92	2661.72
2	Enthalpy at 17: h17 = (S15-S17L)/(S17H - S17L)×(h17H-h17L)+ h17L ; h17′ = (h17 -h15) X ∫t + h15	h18; h18′	KJ/Kg; KJ/kg	2941.63	2977.09
3	Steam Dryness Fraction at 18: x =(S15 - S18f)/(S18g - S18f)	x		0.8825	
4	Enthalpy at 18: h18 = (1 - x)h18f + xh18g; h18′ = (h18 -h15) ×∫t + h15	h19; h19′	KJ/Kg; KJ/kg	2276.41	2385.04
5	Enthalpy at 20: h20 = h19f+ V19(Pb-Pc); h20′ = (h20 -h19)/∫p + h19	h20; h20′	KJ/Kg; KJ/kg	148.05	149.82
6	Enthalpy at 22: h22 = h21f+ V21(Pbo-Pb); h22′ = (h22 -h21)/∫p + h21	h22; h22′	KJ/Kg; KJ/kg	571.42	573.26
7	Heat supplied: Hs = (h14 - h22′) + (h15 – h16′)	Hs	KJ/Kg	3473.36	
8	Pump Work 1 & 2: WP1 = (1-y) × V20(Pbo - Pc); WP2 = yV22 (Pbo - Pex)	WP1; WP2	KJ/Kg; KJ/kg	8.54	1.55
9	Turb. Work Output: WST = (h14- h16′) + (h15- h17′)+ (1 - y)(h17′ - h18′)	WST	kJ/Kg	1225.95	
10	Steam Turb. Net Work in kJ & kW: WSN = WST - WP1 -WP2	WSN	kJ/Kg	1215.85	
11	Cycle and plant efficiency: ∫c = WST/ Hs	∫c; ∫p	%; %	38.89	35.00
12	Heat rejected by condenser: HC = (h18 – h19)	HC	KJ/Kg	2235.22	
13	Computation accuracy check: ratio of net work done and heat rejected by condenser to heat supplied = (WSN + HC)/ Hs		%	0.994	

Computation Accuracy Check: This is determined (in Table 3, item 15) as the ratio of the sum of net workdone and heat rejected by the condenser (and other losses due to isentropic expansion and compression, combustion chamber and regenerative efficiencies, pipe losses etc.) to the heat supplied in the combustion chamber that approximate to unity. Losses due to isentropic expansion and compression, combustion chamber and regenerative efficiencies are included in the accuracy check as in the Table 1 and 2. Pipe losses are neglected.

It can be seen from Table 3 (Item 14) that maximum energy loss occurs in the condenser (which is about 64.35% for the input parameters in Table 1). Amir et al [7] established that energy losses associated with the condenser represent about 60.86% of the total heat supplied to the plant though it is thermodynamically insignificant due to its low quality. Modern steam turbines with improved blade designs can be used to maximize workdone and efficiency of a steam power plant [8].

Extracted result output from the above computations (for only one simulation representing a single graphical coordinate point) is given in table 3. Similarly, all other graphical point coordinates are determined in a similar manner.

Table 4: Summarised Input/ Results Outputs

	INTPUTS	**VALUES**
1	Pressure (Bar)	100
2	Temperature (ºC)	400
	RESULT OUTPUTS	**RESULT VALUES**
1	Net Work done (KJ/Kg)	1215.85
2	Heat Supplied (KJ/Kg)	3473.36
3	Cycle Efficiency (%)	38.89
4	Plant Efficiency (%)	35

3.0 ANALYSIS AND OPTIMISATION OF RESULTS

3.1 Interpretation of Simulated Graphical Results:

The graph of net workdone and efficiency against temperature at constant boiler steam temperatures for the reheat regenerative cycle of Figure 2 is depicted in Figure 7.0. It can be seen that at all the constant boiler steam temperatures of 400 ºC, 450 ºC, 500 ºC and 600 ºC, a curvilinear trend is produced. Figure 7.1 shows that total heat supplied (plus reheat energy) increases as the boiler steam pressure increases. However we can exclude the reheat energy since it does not add in real term to additional fuel input energy, therefore the actual fuel input energy (heat supplied excluding reheat energy) is depicted in Figure 7.3. Figure 7.3 shows that the actual fuel heat input (supplied) decreases with increase in (steam boiler) pressure.

The cycle is modified to a regenerative rankine cycle as depicted in Figure 3. Corresponding boiler pressures are adjusted to 30 bars, 20 bars, 15 bars and 10 bars to enable the use of the adopted automatic steam table (Table 2), input data (Table 1) and computation table (table 3) with some minor adjustments. Simulation was conducted and the result is shown in Figure 8.0. Tthe work done and efficiency at constant boiler steam temperatures against boiler steam pressure also produces a curvilinear graph. Also, the actual fuel heat input (supplied) decreases with increase in (steam boiler) pressure (Figure 8.1).

Moreover, the cycle is modified to a conventional rankine cycle as depicted in Figure 4 with corresponding boiler pressures adjusted to 30 bars, 20 bars, 15 bars and 10 bars to enable the use of the adopted automatic steam table (Table 2), input data (Table 1) and computation table (table 3) with some minor adjustments to ease analysis. Simulation was conducted as shown in Figure 9.0 and the work done and efficiency at constant boiler temperature against boiler pressure also produces a curvilinear graphical

trend. Also, the actual fuel heat input (supplied) decreases with increase in (steam boiler) pressure (Figure 9.1). This decrease may be substantial if the actual kilogram of steam is known and included (i.e. multiplied accordingly).

Hence it can be established that the work done and efficiency of a conventional rankine cycle, regenerative rankine cycle and reheat regenerative rankine cycle are each proportional in a curvilinear manner to the boiler steam pressure at constant boiler temperature. Also, the actual fuel heat input (supplied) decreases with increase in (steam boiler) pressure. Hence optimisation at a particular boiler steam temperature saves fuel energy.

Figure 7.0: Effect of Maximum Temperature on the Net work and Efficieny

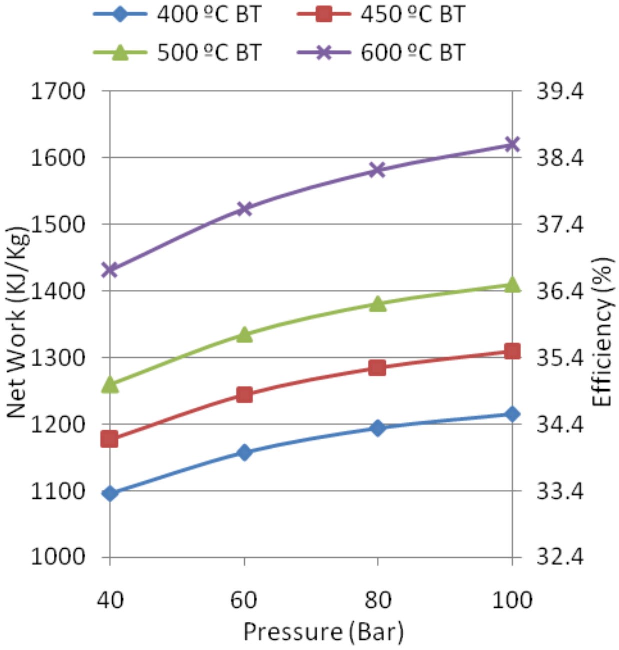
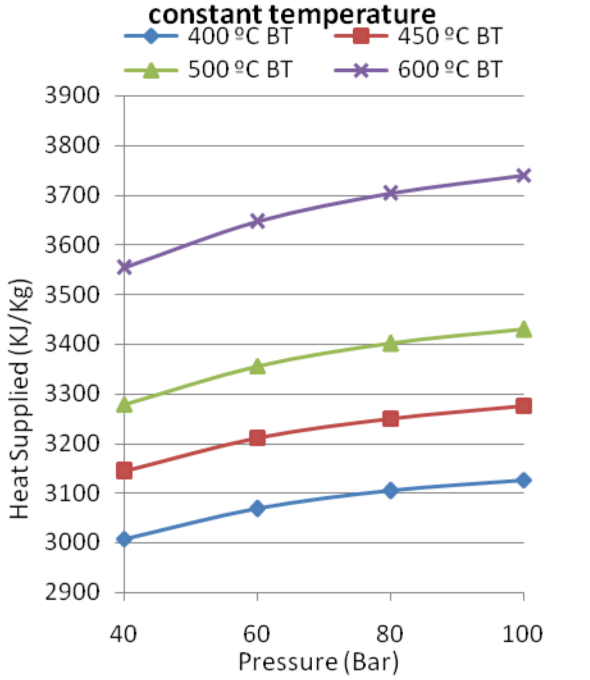


Figure 7.1: Effects of heat supplied on boiler steam pressure at constant temperature



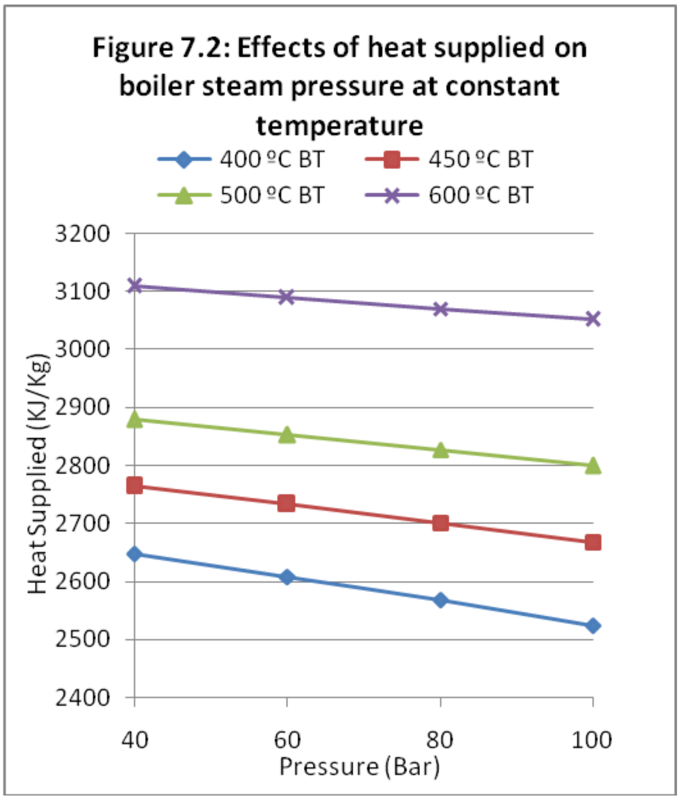


Figure 7.2: Effects of heat supplied on boiler steam pressure at constant temperature
400 ºC BT
450 ºC BT
500 ºC BT
600 ºC BT
Heat Supplied (KJ/Kg)
3200
3100
3000
2900
2800
2700
2600
2500
2400
40
60
80
100
Pressure (Bar)

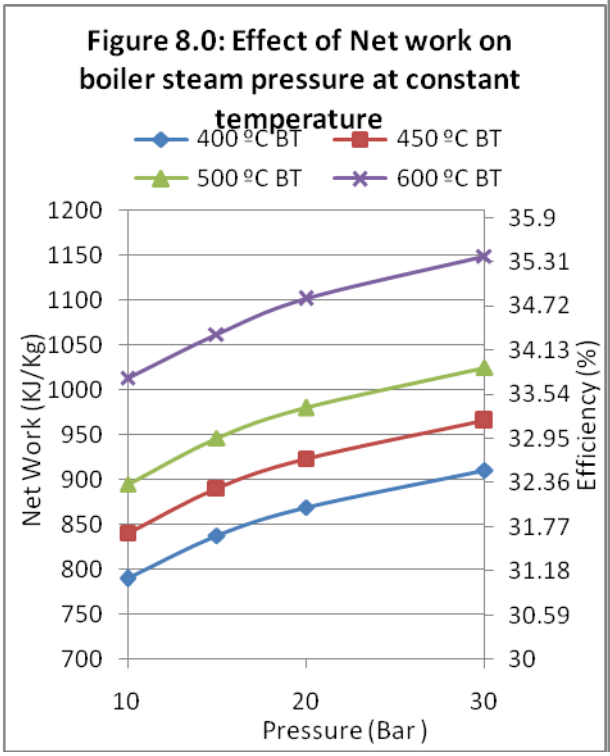


Figure 8.0: Effect of Net work on boiler steam pressure at constant temperature
400 ºC BT
450 ºC BT
500 ºC BT
600 ºC BT
Net Work (KJ/Kg)
1200
1150
1100
1050
1000
950
900
850
800
750
700
Efficiency (%)
35.9
35.31
34.72
34.13
33.54
32.95
32.36
31.77
31.18
30.59
30
10
20
30
Pressure (Bar)

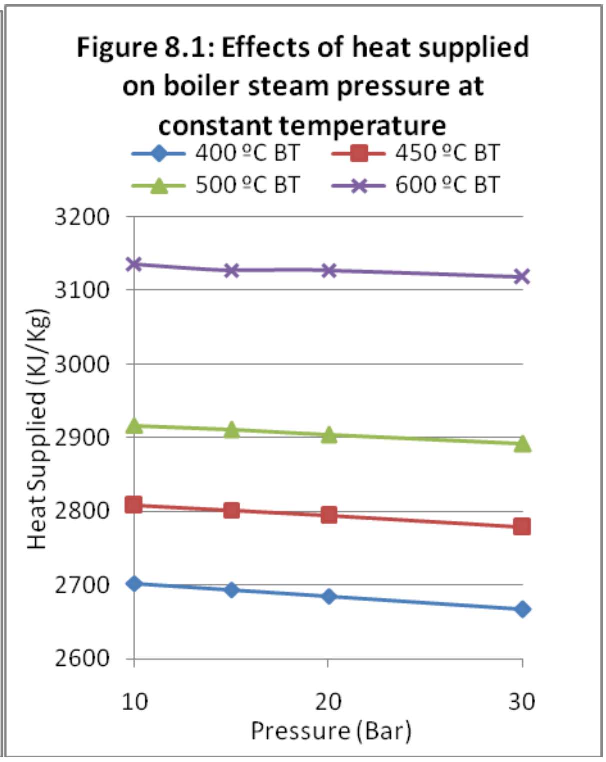
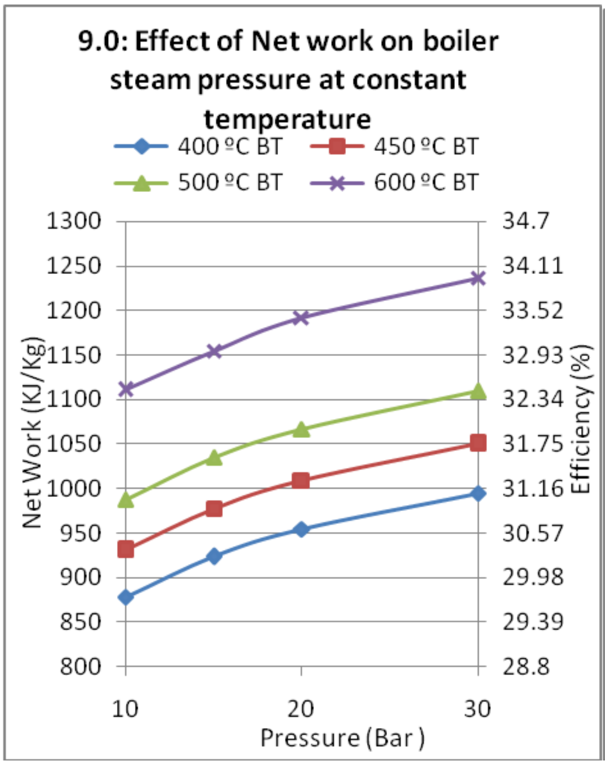
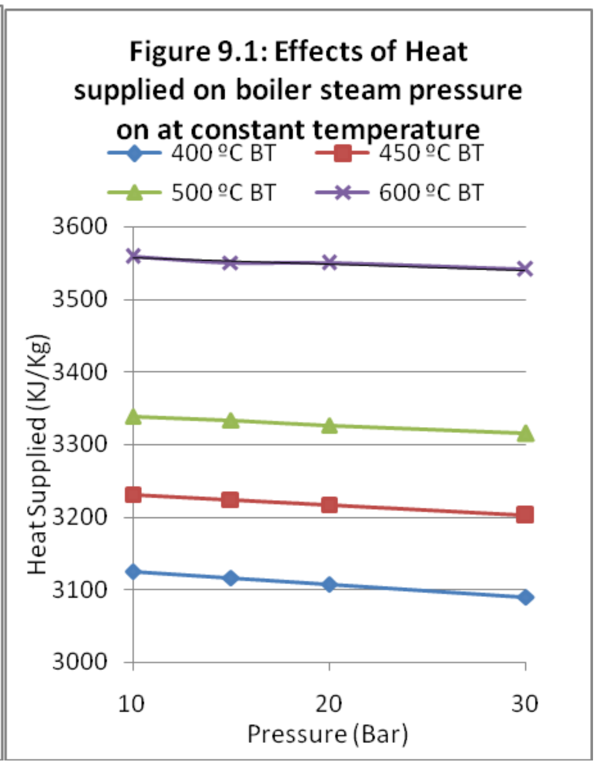


Figure 8.1: Effects of heat supplied on boiler steam pressure at constant temperature
400 ºC BT
450 ºC BT
500 ºC BT
600 ºC BT
Heat Supplied (KJ/Kg)
3200
3100
3000
2900
2800
2700
2600
10
20
30
Pressure (Bar)





4.0 CONCLUSION

A rankine cycle can be suitably simulated and analysed with instantaneous steam table updates using a simple Microsoft excel spread sheet. The accuracy of the work was confirmed by computation accuracy check as depicted in Table 3. The following conclusions were therefore made:

- The network work and circle efficiency at constant boiler temperature in a steam rankine cycle increases with increase in steam boiler pressure in a curvilinear manner
- Concurrently, the actual boiler energy (fuel) input decreases with increase in boiler steam pressure, thus saving additional fuel energy that might be used for optimisation at higher boiler temperature. Hence, further optimisation of the efficiency and network can be achieved at any constant boiler temperature
- Recent breakthrough have been made with steam turbine blades that can withstand high temperatures of up to and above of 600ºC [8], principally to optimise the power and efficiency of the plant. This work can therefore help to further optimise (increase) the power and efficiency at those temperatures and at the same time saves fuel energy.

REFERENCES

[1] Silvain, Q. and Vincent, L. (2011). The organic rankine cycle: thermodynamics, applications and optimisation. Encyclopaedia of life support systems (EOLSS). UNESCO-EOLSS Publishers, Oxford, UK.

[2] Dan-asabe, B. and Yawas, D. S. (2011). Design, simulation and optimisation of a three-stage gas turbine cycle using Microsoft excel. Nigerian Journal of Engineering, 18 (1), 145-152.

[3] Goswami, D. Y. and Kreith, F. (2008). Energy Conversion, CRC Press, New York.

[4] Meherwan, P. B. (1979). Handbook for cogeneration and combined cycle power plants.New York: ASME.

[5] Dan-asabe, B. (2009). Design, simulation and optimisation of a combined power to power and heating cycle. University of Hertforshire: Masters Project, UK.

[6] Kehlhofer, R. H., Nielson H., Warner, J. and Bachmann, R. (1999). Combined-cycle gas and Steam turbine power plants, PennWeell Publishing Company, Oklahama, US.

[7] Amir , V., Alireza, F., Sadegh, V., Hasan N. E., Azam B. and Roya N. R (2011). Improvement Power Plant Efficiency with Condenser Pressure. International Journal of Multidisciplinary Sciences and Engineering, 2(3), 38-43.

[8] Kolev, N., Schaber, K. and Klolev, D. (2001). A new type of a gas–steam turbine cycle with increased efficiency. Applied Thermal Engineering, 22(4), 391 – 405.