Thermal Efficiency Improvement to an Existing 420 MW Reheat–Regenerative Sub-critical Rankine Cycle by Rearrangement and Addition of Feedwater Heater System

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Abstract

This paper presents a systematic method to improve the thermal efficiency of an existing 420 MW reheat–regenerative steam power plant by adding a closed feedwater heater. The power plant employs 1 high pressure turbine, 1 intermediate pressure turbine, 1 set of low pressure turbine, 3 high pressure closed feedwater heaters, 1 deaerator, and 3 low pressure closed feedwater heaters. The analysis shows that the original regenerative-reheat system configuration was designed by disregarding the high pressure turbine steam extraction. Moreover, the original reheat steam design pressure was setup according to the rule-of-thumb which is at 23.7% to that of main steam pressure. Using mass and energy balance equation, all cycle equipment have been analyzed individually. Energy efficiency have been calculated. Thermodynamic simulation software is used for performing analysis. This software has already been included in the simulation software in which steam cycle has been implemented and it can be applied in a comfortable and cost effective way. The result of the simulation indicates that the gross efficiency of actual cycle is 43.88% and the modified cycle gross efficiency is 44.39%. Therefore, the gross efficiency increases about 0.52% after the modification.

Keywords: Reheat and regenerative Rankine Cycle, feedwater heater, thermal efficiency improvement

Introduction

In many countries, steam power plant cycles have been removed due to low efficiency, environmental pollution, and especially insufficient fossil resources and have been put back by high efficiency and economic power plant system [1].

Recently fuel costs demand that the maximum amount of energy be moved from each pound of steam generated [2]. To help in this effort, when both process steam and shaft power are needed, many plant designers are turning to extraction turbines.

Regenerative Turbine incorporates a number of extraction branches, through which small proportions of the steam are continuously extracted for the purpose of heating the boiler feed water in a FWH to increase the thermal efficiency of the plant [3].

As the number of stages of FWH increase, Carnot efficiency is approached. Therefore, the number of pumps, the piping, the extraction points, and the heat exchangers are also increased. Actual large power stations may have 8 to 12 FWH (including a deaerator) [4].

The major power plant in Indonesia is coal-fired steam power plant, it is crucial to conduct research on optimization the cycle of these power plants [5]. The average efficiency of all coal power stations in the world recently stand at around 31% [6].

The investigations for bleed pressure and mass fraction of bleed steam are done by incorporating two and three FWHs [7]. It has been found that there will be significant improvement in efficiency by using three FWHs and further gain in efficiency is possible by making provision for more FWHs.

According to the above description, one of the appropriate solution is to improve the thermal efficiency of the plant by adding one more feedwater heater. It will benefit not only in solving GHGs emission problem but also reducing the coal consumption in power plant.

The objective of this work is to present a systematic method to improve the gross thermal efficiency of an existing 420 MW reheat and regenerative steam power plant by rearrangement and addition of the feedwater heating system.

The power plant employs 1 main steam generator, 1 reheat steam generator, 1 high pressure turbine, 1 intermediate pressure turbine, 1 set of low pressure turbine, 3 high pressure closed feedwater heater, 1 deaerator, and 3 low pressure closed feedwater heater. Through the First Law analysis, the gross thermal efficiency of the original power plant was 43.9%.

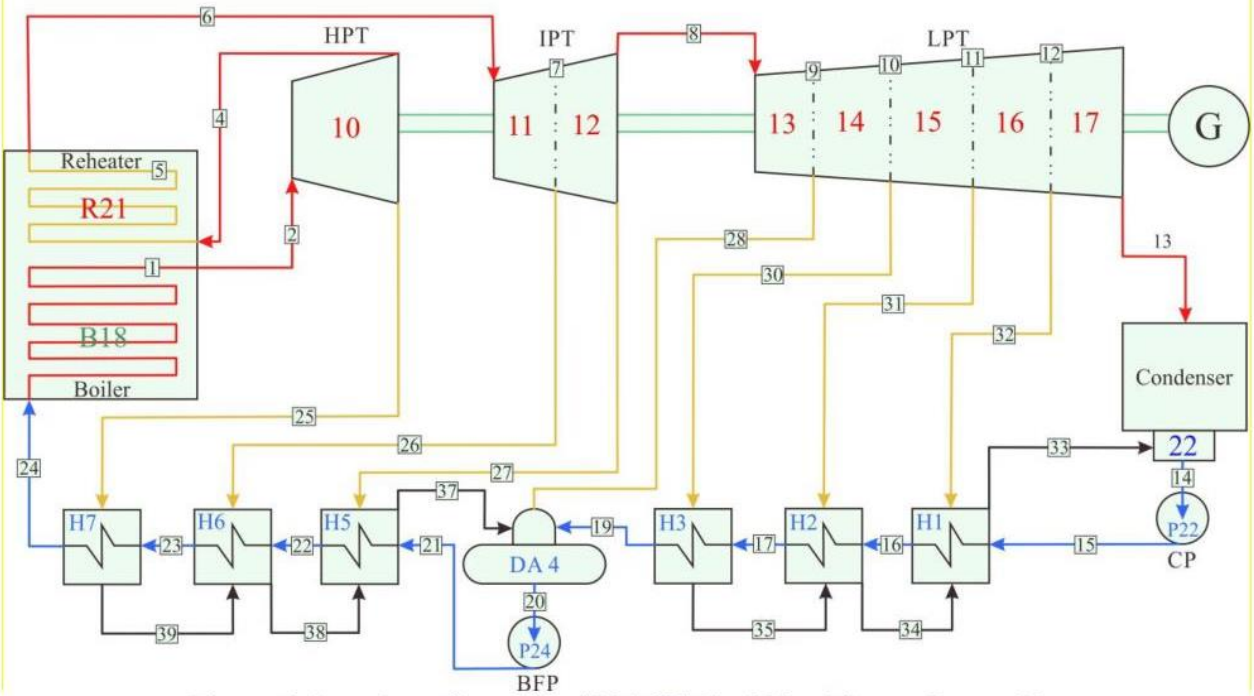

Figure 6 Actual configuration 420 MW Coal Fired Steam Power Plant

Research Methodology

Taking rearrangement of feedwater heating system in a reheat and regenerative Rankine cycle for the route of improving thermal efficiency requires sound insights.

The control volume equations for the components are set up as follows:

Turbine 10

$m_2 = m_4$

$m_2h_2 = m_4h_4 + W_{t10}$

Turbine 11

$m_6 = m_7 + m_{26}$

$m_6h_6 = m_7h_7 + m_{26}h_{26} + W_{t11}$

Turbine 12

$m_7 = m_8 + m_{27}$

$m_7h_7 = m_8h_8 + m_{27}h_{27} + W_{t12}$

Turbine 13

$m_8 = m_9 + m_{28}$

$m_8h_8 = m_9h_9 + m_{28}h_{28} + W_{t13}$

Turbine 14

$m_9 = m_{10} + m_{30}$

$m_9h_9 = m_{10}h_{10} + m_{30}h_{30} + W_{t14}$

Turbine 15

$m_{10} = m_{11} + m_{31}$

$m_{10}h_{10} = m_{11}h_{11} + m_{31}h_{31} + W_{t15}$

Turbine 16

$m_{11} = m_{12} + m_{32}$

$m_{11}h_{11} = m_{12}h_{12} + m_{32}h_{32} + W_{t16}$

Turbine 17

$m_{12} = m_{13}$

$m_{12}h_{12} = m_{13}h_{13} + W_{t17}$

Condenser

$m_{13} + m_{33} = m_{14}$

$m_{13}h_{13} + m_{33}h_{33} = m_{14}h_{14} + Q_{rej}$

Heater 1

$$m_{32}h_{32} + m_{34}h_{34} - m_{33}h_{33} = m_{16}h_{16} - m_{15}h_{15}$$

Heater 2

$$m_{31}h_{31} + m_{35}h_{35} - m_{34}h_{34} = m_{17}h_{17} - m_{16}h_{16}$$

Heater 3

$m_{30}h_{30} - m_{35}h_{35} = m_{19}h_{19} - m_{17}h_{17}$

Heater 4

$m_{19}h_{19} + m_{28}h_{28} + m_{37}h_{37} = m_{20}h_{20}$

Heater 5

$$m_{27}h_{27} + m_{38}h_{38} - m_{37}h_{37} = m_{22}h_{22} - m_{21}h_{21}$$

Heater 6

$$m_{26}h_{26} + m_{39}h_{39} - m_{38}h_{38} = m_{23}h_{23} - m_{22}h_{22}$$

Heater 7

$$m_{25}h_{25} - m_{39}h_{39} = m_{24}h_{24} - m_{23}h_{23}$$

Boiler

$$m_{24}h_{24} + Q_b = m_1h_1$$

Reheat

$$Q_{reh} + m_5h_5 = m_6h_6$$

Pump power

$$W_p = m_{15}(h_{15} - h_{14}) + m_{21}(h_{21} - h_{20})$$

Net work

$$W_{net} = W_{t10} + W_{t11} + W_{t12} + W_{t13} + W_{t14} + W_{t15} + W_{t16} + W_{t17} - W_p$$

Efficiency

$$\eta = \frac{W_{net}}{Q_b + Q_{reh}}$$

Result and Discussion

The analysis shows that the original regenerative system configuration was designed by disregarding the high pressure turbine steam extraction. Moreover, the original reheat design pressure was set according to theoretical.

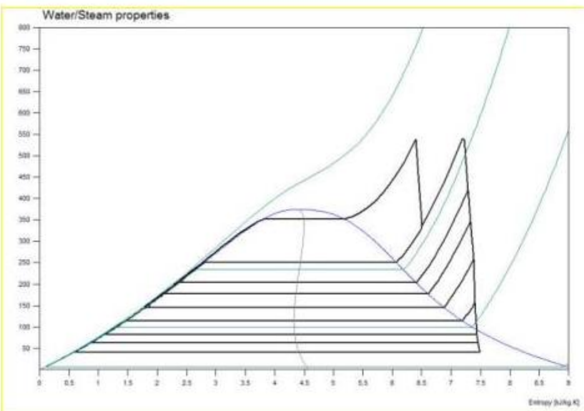

Figure 1 T-s diagram of actual design 420 MW steam power plant

Improving efficiency increases the amount of energy extracted from a single unit of coal. A one percentage point improvement in the efficiency of a conventional pulverized coal combustion plant results in a 2-3% reduction in CO_2 emissions [8].

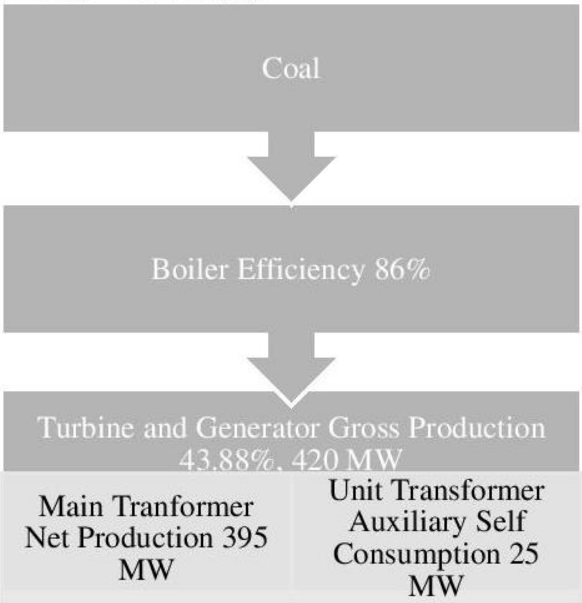

Figure 2 Energy conversion coefficient 420 MW steam power plant (performance test #5 unit 3 in 08 July 2014)

Based on Figure 2, the boiler efficiency is 86%. Moreover, the turbine and generator gross production efficiency and power are 43.88% and 420 MW, respectively. Then the gross thermal efficiency is 37.73%. Therefore, the net thermal efficiency is 35.49%.

Based on Figure 8, the design of 420 MW Coal Fired Steam Power Plant didnt explore the extraction steam from high pressure turbine. It means there is a opportunity to increase the overall efficiency cycle if we extract some steam from high pressure turbine.

We have the actual power plant configuration which is equipped by six CFWHs and one OFWH. The modification is to add one more FWH to the system. There are two main modifications of the actual steam line of the power plant system.

Firstly, for the actual system, the steam is extracted from the LPT13 to FWH4 and the steam of IPT12 is extracted to the FWH5. For the modified system, the steam is extracted from the IPT12 to FWH4 and the steam from LPT13 is extracted to the FWH8 which is the new additional FWH.

Secondly, for the actual system, the steam of HPT10 has only one extraction to FWH7 and reheats to IPT11. For the modified system, the steam of HPT has two extractions where the first extracted steam to FWH7 and the second extracted steam to FWH6. Finally,the third extraction is extracted to FWH5.

It is possible to suggest the new FWH exchanger network configurations and reducing steam consumption from turbine bleeds, achieving optimum power plant efficiency. Results show a feasible improvement of the overall plant efficiency of 0.7 points. An economic analysis confirms the feasibility of the proposals analyzed and demonstrates important additional yearly incomes [9].

Before making modification, the result of the simulation demonstrates that the gross efficiency of actual cycle is 43.88% achieved by using seven FWHs. The energy analysis has been carried out of the Power Plant having seven FWHs. The optimization has also been done by adding one FWH extracted from the HPT. After having modified, the gross efficiency is essential improvement in 44.39% by using eight FWHs. Thus the gross efficiency significantly increases about 0.52% after optimization.

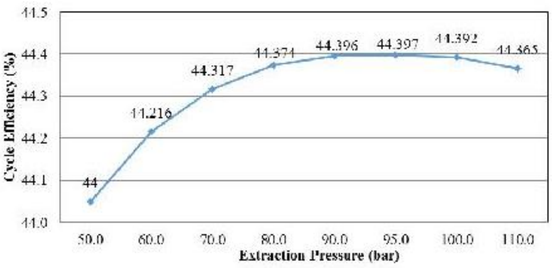

Figure 3 Extraction pressure of high pressure turbine Vs cycle efficiency

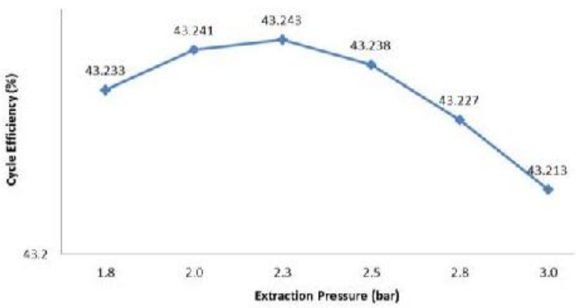

Figure 4 Extraction pressure of low pressure turbine Vs cycle efficiency

According to the curve as shown in Figure 3, the best efficiency is at pressure 95 bar where the steam is extracted. Based on Figure 4, the extraction from the low pressure turbine will cause the efficiency reduction. Therefore, the extraction from the HPT provides the better efficiency than the extraction from the LPT.

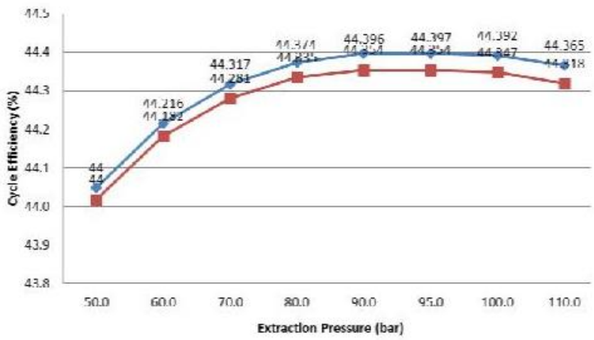

Figure 5 Before and after changing dearator pressure Vs cycle efficiency

The blue curve is the graph after having varied the pressure of OFWH and the red curve is the graph before changing the OFWH pressure as shown in Figure 5. We can conclude that the after the variation of OFWH pressure, there will be a significant improvement on the cycle efficiency.

Table 1 Actual table

Delivered	Apparatus	Energy	Totals
		[kW]	[kW]
Absorbed Power	Reheater	133528,84	
	Boiler	700528,38	
			834057,25
Delivered Gross Power		366000	
Aux. Power Consumption		7353,04	
		294,06	
Delivered net power			358330,91
Efficiencies	Gross	43,882	
	Net	42,963	

FWHs have two primary functions in power plants such as to provide the means for increasing the feedwater temperature, which improves the overall plant efficiency and to minimize the thermal effects in the boiler [10].

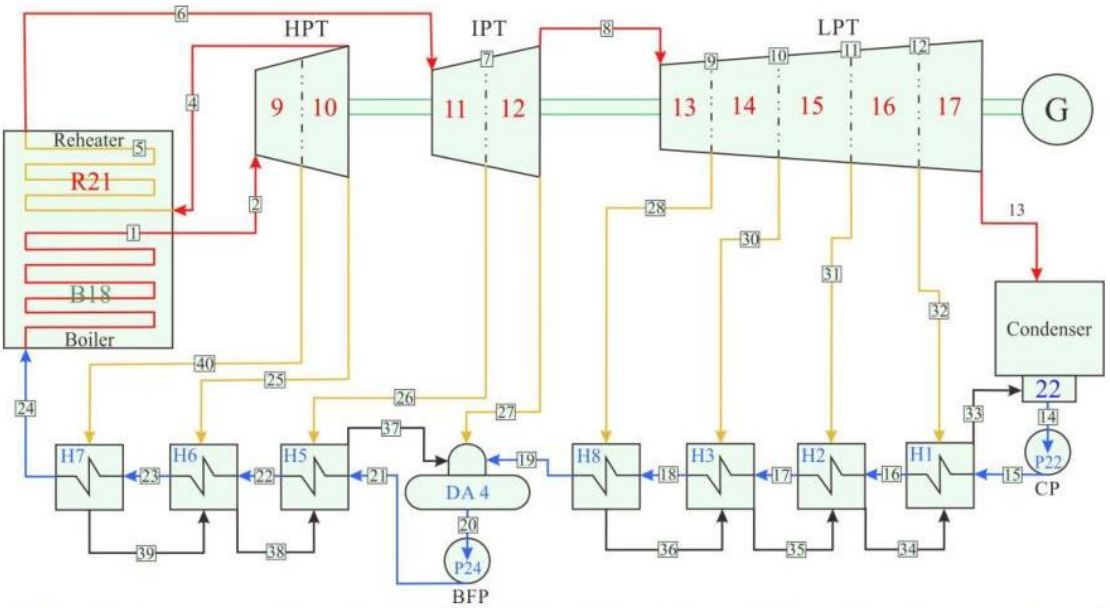

Figure 6 Modified cycle configuration 420 MW Coal Fired Steam Power Plant by one extra steam extraction from high pressure turbine

Table 2 Modified table

Delivered	Apparatus	Energy	Totals
		[kW]	[kW]
Absorbed Power	Reheater	130391,58	
	Boiler	693989,44	
			824381,7
Delivered Gross Power		366000	
Aux. Power Consumption		8496,02	
		665,1	
Delivered net power			356838,88
Efficiencies	Gross	44,397	
	Net	43,287	

Due to the modification, the boiler cannot support the cycle to produce amount of steam to get 420 MW. Before modification, it needs 347 kg/s steam to produce 420 MW. After modification, with the same amount of steam, it only produces 366 MW. Therefore, it reduces 54 MW because the additional extraction pressure decreases the number of steam inside the main steam line. So the power will be decreased. If we want to produce a high load plant as before modification, the additional feedwater heater may be closed so the cycle will be return to the before modification.

In Table 1 and Table 2, the saved boiler power consumption is 9675 kW because the efficiency of the cycle is increase. The auxiliary power consumption by modified cycle is increase 1492 kW. It because the amount of mass flow to produce turbine power by modified cycle is higher that the actual design.

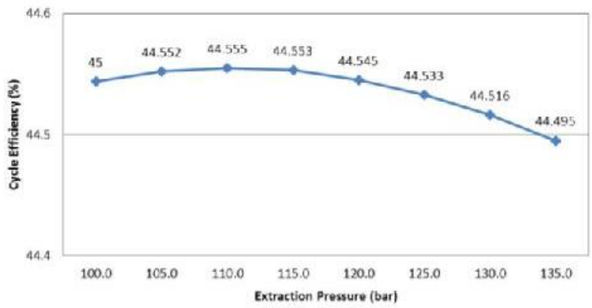

Figure 7 Cycle efficiency by adding more than one FWHs

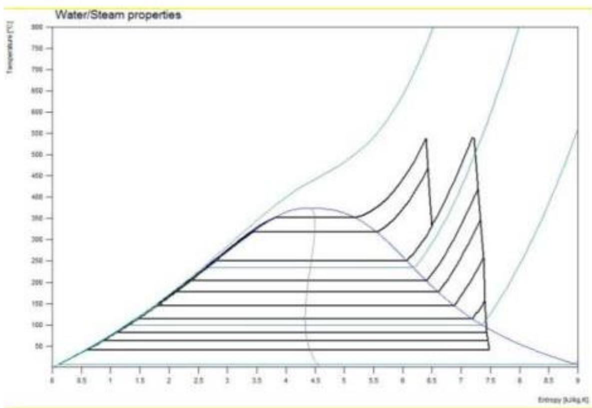

Figure 8 T-s diagram of modified design 420 MW steam power plant

As shown in Figure 7, we do not have to add more than one FWHs because when we add two or more FWH, the efficiency is 44.555% while the one FWH addition is 44.397%. So the benefit of the second extra FHW only increases the efficiency about 0.158% and it is not so worth.

Conclusion

In this paper, steam cycle efficiency of Power Plant in Indonesia by using energy analysis with individual unit capacity of 420 MW and all its equipment were analyzed in terms of energy. In order to contribute to further increase efficiency, FWH arrangement is studied and optimized by thermodynamic and economic approach. Furthermore, an optimized steam cycle design is achieved. A case application study has revealed that with a new FWH addition raise overall power plant efficiency up to 0.52% and cost analysis has proved that the utilization of these networks is also a profitmaking alternative. In this case, the simulation software program is used to analyze the performance of the cycle. The maximum efficiency equal to 43.88% can be achieved by using seven FWHs. It has been found that by using eight FWHs there is a significant improvement in maximum efficiency (44.39%).

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Appendix

Table 3 Operating conditions of the power plant

Operating conditions	Value	Unit
Heat rate	1960	kcal/kWH
Capacity	1168	ton/h
Vapor pressure outlet superheater	174	kg/cm^2
Vapor temperature outlet superheater	540	^{o}C
Vapor pressure inlet reheater	40	kg/cm^2
Vapor temperature inlet reheater	336	^{o}C
Vapor temperature oulet reheater	540	^{o}C
Vapor pressure outlet reheater	40	kg/cm^2
Reheater vapor mass flow	1023	ton/h
Burner	35	set
Fuel	Coal	
Initial ignition fuel	Diesel fuel	
Type radiant boiler	Natural Circulation, Single Drum	

Table 4 Nomenclature

m	Mass flow rate	T	Temperature
BFP	Boiler feed pump	v	Velocity
CP	Condensate pump	z	Elevation
HPT	High pressure turbine	*Greek symbol*	
IMT	Intermediate turbine	η	Efficiency
LPT	Low pressure turbine	*Subscripts and superscripts*	
CFWH	Closed feed water heater	b	boiler
OFWH	Open feed water heater	reh	reheat
h	Specific enthalpy	net	net
P	Pressure	o	Outlet
FWH	Feedwater heater	i	inlet
s	Entropy	rej	reject

Table 5 Thermodynamic properties of points in cycle

Node	T(°C)	P(bar)	m(kg/s)	h(kJ/kg)	s(kJ/kg.K)
1	538	170	346.708	3395.2	6.4036
2	538	170	346.708	3395.2	6.4036
4	332.65	40.4	346.708	3048.26	6.5068
5	332.65	40.4	315.113	3048.26	6.5068
6	538	38.2	315.113	3534.53	7.2248
7	420.27	16.6	298.074	3297.86	7.2859
8	346.47	9.27	285.396	3152.16	7.3276
9	257.4	4.2	269.598	2979.11	7.3858
10	156.75	1.64	254.363	2785.54	7.4098
11	81.32	0.5	245.67	2590.53	7.593
12	62.33	0.222	237.283	2473.95	0.86046
13	40.57	0.0761	237.283	2464.59	8.245
14	40.57	0.0761	269.598	169.9	8.245
15	40.65	8.6	269.598	171.01	0.58073
16	59.33	7.3	269.598	248.96	0.82249
17	78.32	5.7	269.598	328.3	1.0552
19	111.05	4.2	269.598	466	1.4302
20	145.38	4.2	346.708	612.33	6.8792
21	148.1	187.9	346.708	635.68	1.8029
22	173.62	182.9	346.708	744.62	2.0551
23	204.8	178	346.708	880.59	2.3505
24	247.95	170	346.708	1076.58	2.7452
25	332.65	40.4	315.113	3048.26	6.5068
26	420.27	16.6	17.039	3297.86	7.2859
27	346.47	9.27	12.677	3152.16	7.3276
28	257.41	4.2	15.798	2979.12	7.3858
30	156.75	1.64	15.236	2785.54	7.4098
31	81.32	0.5	8.693	2590.53	7.593
32	62.33	0.222	8.387	2473.95	0.86046
33	45.65	0.222	32.316	191.16	0.64714
34	62.33	0.222	23.929	269.3	0.86046
35	81.32	0.5	15.236	348.96	7.593
37	153.1	9.27	61.311	645.91	1.8728
38	181.3	16.6	48.634	769.25	2.151
39	209.8	40.4	31.594	897.56	2.419