A 1000MW ultra-supercritical secondary reheat unit Energy consumption analysis of thermodynamic system

Hu Zhang *, Jinxu Lao, Huitao Cheng, Kai Liang

State Grid Shandong Electric Power Research Institute, Jinan250003, China

Abstract: Taking the thermodynamic system of a 1000MW ultra-supercritical secondary reheating unit as the research object, the modeling energy consumption analysis was carried out, and the spatial distribution of energy consumption was determined, so as to provide a scientific basis for the operation optimization and energy-saving transformation of the unit. The analysis results show that: Boiler is one of the largest equipment factory irreversible loss, make up the loss by 85.1% of the total loss of the system, although the number of its external loss is not big but internal loss is very big, and the loss is high grade of energy, the number of the steam turbine cold source loss although large irreversible loss is not big but the grade is not high, its loss make up only 2.32% of the total loss system.

Key words: ultra-supercritical, thermodynamic system, secondary reheat unit, energy consumption analysis, Non reversible loss, Purpose (exergy) efficiency, Exergy loss coefficient.

1. Introduction

Under the guidance of national energy conservation and emission reduction policy, high-efficiency and low-pollution power generation technology has become the mainstream. Improving steam parameters and increasing reheating times are effective ways to improve unit efficiency, and ultra-supercritical secondary reheating technology is an important technical means to improve thermal economy of generating units[1].Compared with the supercritical unit, the thermal efficiency of the ultra-supercritical unit can be increased by 3%-4%, and the thermal efficiency of the whole plant is higher than 50% by adopting the secondary reheating technology[2-4].The waste heat recovery system is generally designed for the secondary reheating ulra-supercritical units, which further optimizes the thermal system, boiler efficiency, pipeline efficiency, turbine flow efficiency and plant power consumption rate[5].

The traditional method of heat balance analysis is based on the first law of thermodynamics. The inner efficiency of boiler and the absolute inner efficiency and cycle efficiency of steam turbine are used to describe the closeness of the actual steam cycle to the ideal cycle.However, the traditional thermal balance analysis method only focuses on the quantity balance of energy without considering the difference of energy in "quality", only calculates the external loss of the system but ignores the internal loss, and ignores the internal loss caused by the irreversibility of the process.Therefore, this method only shows the result of energy conversion, but cannot reveal the essential cause of energy loss, cannot accurately point out the location of energy saving potential, and sometimes even gives false appearance[6].For example, in the analysis of the condenser as a circulating cold source, the traditional heat balance analysis method thinks that most of the system loss occurs here, and it seems that the main energy saving space of the power plant is also here,But exergy analysis, based on the second law of thermodynamics, suggests that the loss here is not great, because the amount of heat emitted from the condenser is large but the energy of that heat is not high.In contrast, the conventional thermal balance analysis method calculates that the loss of the boiler is not large, and the efficiency of the boiler in the power plant can reach 90% or more, but the exergy analysis method considers the loss of the boiler to be large, because the amount of energy lost by the boiler is small but the loss of high grade energy[7-10].In this paper, a 1000MW ultra-supercritical secondary intermediate reheating unit is taken as the research object. Based on the first and second laws of thermodynamics, the loss of work capacity due to irreversibility in the cycle process is analyzed, and the location of energy loss is accurately located, so as to provide a reference for targeted energy saving and potential exploration.

* Corresponding author: 13075336627@163.com

2. Unit energy consumption analysis evaluation index

2.1 Purpose (exergy) efficiency of a device or system:

$$\eta_p = \frac{\Delta E_{out}}{\Delta E_{in}} \quad (1)$$

Where, ΔEout is the net income related to the purpose exergy and ΔEin is the net consumption to achieve the purpose exergy.The above equation is a general expression for exergy efficiency,The expression of specific exergy efficiency varies depending on the purpose for which the system or device is used.For example, ΔEout of the boiler plant is the feed water and reheated steam obtained in the boiler exergy, ΔEin is the fuel chemistry exergy.For the engine island, ΔEout is the output shaft work and ΔEin is the net input exergy.ΔEout of the heat exchanger device is the cold fluid obtained in the heat exchanger exergy, ΔEin is the hot fluid reduced in the heat exchanger exergy.

2.2 Exergy loss factor of a device or system:

The thermal system is divided into several subsystems, in which the ratio of the exergy loss of any subsystem to the total exergy consumption of the system is the exergy loss coefficient of the subsystem.For a power plant, the total exergy consumption of the system is the chemistry exergy of the fuel.

3. Unit energy consumption analysis example

3.1 Maching series Data

The boiler of a 1000MW ultra-supercritical secondary reheating unit in China adopts Single furnace tower arrangement, Tangential burning at four corners, swing and tail flue baffle temperature regulation, balanced ventilation, steel frame suspension structure, semi-open air arrangement, and AIR-cooled dry slag removal system.The steam turbine adopts a single-axis five-cylinder four-row steam mode, and a two-stage external steam cooler is used in the high-pressure heater side to make cross-stage utilization of the superheat energy.The main design parameters of boilers and steam turbines are as follows:

Table1 Boiler design parameters

Items	Unit	THA
Superheated steam flow rate	kg/s	710.349
Outlet pressure of superheated steam	MPa	31.62
Outlet temperature of superheated steam	℃	605
Primary reheat steam flow rate	kg/s	632.624
Primary reheat steam inlet pressure	MPa	10.4
Primary reheat steam inlet temperature	℃	424
Primary reheat steam outlet pressure	MPa	10.19
Primary reheat steam outlet temperature	℃	623
Secondary reheat steam flow rate	kg/s	544.852
Secondary reheat steam inlet pressure	MPa	3.3
Inlet temperature of secondary reheat steam	℃	445
Secondary reheat steam outlet pressure	MPa	3.06
Secondary reheat steam outlet temperature	℃	623
Feed water temperature	℃	324
Economizer inlet pressure	MPa	35.17
coal	t/h	376.3
Low calorific value of fuel	kJ/kg	19850
Total fuel moisture	%	16.1
ow thermal efficiency	%	95.03

Table 2 Steam turbine design parameters

Items	Unit	THA
power	MW	1000
main steam flow	kg/s	710.349
main steam pressure	MPa	30.138
main steam temperature	℃	600
High pressure cylinder inlet steam flow rate	kg/s	632.624
Exhaust steam pressure of ultra-high pressure cylinder	MPa	10.643
Exhaust steam temperature of ultra-high pressure cylinder	℃	425.5
Steam inlet pressure of high pressure cylinder	MPa	10.004
Inlet steam temperature of high pressure cylinder	℃	620
Steam inlet flow of medium pressure cylinder	kg/s	544.852
Exhaust steam pressure of high pressure cylinder	MPa	3.455
Exhaust steam temperature of high pressure cylinder	℃	447
Steam inlet pressure of medium pressure cylinder	MPa	3.041
Inlet steam temperature of medium pressure cylinder	℃	620
Back pressure	kPa	3.8
Feed water temperature	℃	325
Feed water pressure	MPa	36.095
Steam turbine heat consumption rate	kJ/kW.h	7038

Relevant (exergy) parameters are calculated according to the unit design parameters as shown in the following table:

Table 3 THA unit exergy analysis related parameters table

Items	number	flow rate F kg/s	enthalpy h kJ/kg	Entropy s kJ/kg.°C	exergy e kJ/kg
superheated steam	1	710.349	3447.59	6.21762	1627.795
One reheat steam outlet	2	632.624	3680.83	6.95838	1643.881
Secondary reheat steam outlet	3	544.852	3734.75	7.55987	1521.474
A reheat steam inlet	4	632.624	3161.63	6.29218	1319.977
Secondary reheat steam inlet	5	544.852	3329.24	7.02136	1273.828
Furnace side feed water	6	710.349	1450.48	3.37178	464.943
fuel	7	104.528			20242.518
The main steam turbine side	8	710.349	3445.6	6.23412	1620.968
Inlet steam of high pressure cylinder	9	632.624	3674.91	6.9599	1637.515
Exhaust steam of ultra-high pressure cylinder	10	632.624	3161.51	6.28276	1322.619
Inlet steam of medium pressure cylinder	11	544.852	3728.05	7.55521	1516.14
Exhaust steam of high pressure cylinder	12	544.852	3331.64	7.00425	1281.244
turbine side feed water	13	710.349	1455.04	3.37725	467.899
NO.1 extraction	14	72.473	3161.51	6.28276	1322.619
NO.2 extraction	15	51.394	3513.25	6.98505	1468.483
NO.3 extraction	16	38.486	3332.1	7.00489	1281.517
NO.4 extraction	17	19.209	3550.27	7.58889	1328.487
NO.5 extraction	18	11.546	3383.54	7.60378	1157.392
NO.6 extraction	19	19.299	3274.57	7.61681	1044.602
NO.7 extraction	20	29.240	3109.7	7.63388	874.728
NO.8 extraction	21	16.04	2877.75	7.72708	615.457
NO.9 extraction	22	18.74	2728.4	7.73638	463.38
NO.10 extraction	23	20.948	2581.63	7.78599	302.067
To Feed pump turbine steam extraction	24	35.787	3383.54	7.60378	1157.392
Steam turbine exhaust	25	376.453	2396.31	7.97461	61.453
Inlet steam of #2 High-pressure heater outside steam cooler	26	51.394	3513.16	6.99811	1464.564
Inlet steam of #4 High-pressure heater outside steam cooler	27	19.209	3550.33	7.60245	1327.572
Inlet steam of #1 High-pressure heater	28	72.473	3161.42	6.29446	1319.099
Inlet steam of #2 High-pressure heater	29	51.394	2970.51	6.21709	1150.87
Inlet steam of #3 High-pressure heater	30	38.486	3331.89	7.01767	1277.56
Inlet steam of #4 High-pressure heater	31	19.209	3088.13	6.94063	1056.384
Inlet steam of Deaerator	32	11.546	3383.55	7.626	1150.888
Inlet steam of #6 low-pressure heater	33	19.299	3274.5	7.63939	1037.913
Inlet steam of #7 low-pressure heater	34	29.240	3109.71	7.65584	868.3
Inlet steam of #8 low-pressure heater	35	16.04	2877.83	7.74926	609.034
Inlet steam of #9 low-pressure heater	36	18.74	2728.48	7.7589	456.858
Inlet steam of #10 low-pressure heater	37	20.948	2582.1	7.8095	295.645
outlet water of #1 High-pressure heater	38	710.349	1402.99	3.2894	441.602
drain of #1 High-pressure heater	39	72.473	1239.34	3.06349	344.178
Inlet water of #1 High-pressure heater	40	710.349	1206.85	2.94412	346.681
Inlet water of #2 High-pressure heater	41	710.349	1052.56	2.65369	277.531
drain of #2 High-pressure heater	42	123.867	1073.11	2.76451	265.594
Inlet water of #3 High-pressure heater	43	710.349	891.307	2.32875	211.534
drain of #3 High-pressure heater	44	162.354	902.314	2.43073	192.646
Inlet water of #4 High-pressure heater	45	710.349	810.628	2.15652	181.344
drain of #4 High-pressure heater	46	181.563	817.573	2.25616	159.08
outlet water of deaerator	47	710.349	764.404	2.14221	139.315
inlet water of deaerator	48	517.24	687.088	1.96829	112.984
Inlet water of #6 low-pressure heater	49	517.24	587.907	1.73446	82.35
drain of #6 low-pressure heater	50	19.299	611.739	1.7926	89.138
Inlet water of #7 low-pressure heater	51	517.24	432.009	1.33895	42.396
drain of #7 low-pressure heater	52	48.539	455.198	1.40188	47.137
Inlet water of #8 low-pressure heater	53	452.661	342.426	1.09372	24.702
Inlet water of #9 low-pressure heater	54	452.661	244.043	0.80678	10.435
drain of #9 low-pressure heater	55	18.74	353.425	1.12736	25.839
Inlet water of #10 low-pressure heater	56	452.661	136.27	0.46806	1.958
drain of #10 low-pressure heater	57	20.948	254.826	0.84222	10.829
The drain water after mixing	58	39.688	301.398	0.97933	17.206
outlet drain water of drain water cooler	59	39.688	144.999	0.49973	1.403
Inlet water of drain water cooler	60	452.661	122.485	0.42268	1.476
Inlet steam of feed pump turbine	61	35.787	3383.55	7.626	1150.888
exhaust steam of feed pump turbine	62	35.787	2468.52	8.15938	79.498
hot well water	63	451.928	117.833	0.4105	0.395
inlet water of Feed water pump	64	710.349	764.404	2.14221	139.315
outlet water of Feed water pump	65	710.349	810.628	2.15652	181.344
power P	1000000 kW				

Note: The ambient temperature is 20°C

3.2 Efficiency of a device or system:

The boiler, steam turbine and pipeline efficiencies are shown in the following table:

Table 4 THA operating device or system efficiency

Items	Unit	Exergy efficiency	Heat balance efficiency
boiler	%	55.1	95.03
pipe	%	99.6	99.89
Steam turbine generator	%	92.256	98.57
Turbine island	%	87.24	51.15
Plant efficiency (Positive balance)	%	47.26	48.2

The plant efficiency calculated by the exergy analysis method is slightly lower than the plant efficiency calculated by the thermal balance method. The difference between the two is due to the characteristics of the fuel itself, namely, the low calorific value of the fuel and its chemistry exergy.Although the total plant efficiency calculated by the two methods is approximately the same, the loss distribution calculated by the two methods is quite different.The boiler efficiency calculated by heat balance method is 95.03% and that calculated by exergy analysis method is 55.1%.The thermal efficiency of the turbine island calculated by the thermal balance method is 51.15%, while the thermal efficiency of the turbine island calculated by the exergy method is 87.24%.The reason is that the two efficiencies stand on different ground. Thermal balance calculation focuses on the quantity of each loss, while exergy analysis focuses on the quality of each loss, that is, the loss of the work capacity of the working medium.The working medium absorbs the heat transferred by the flue gas in the boiler. Due to the huge heat transfer temperature difference, the heat transfer process is inevitably accompanied by a huge irreversible loss.Such processes as combustion, heat transfer with finite temperature differences, logistic mixing of different parameters, and frictional resistance are not considered losses in traditional thermal equilibrium calculations because they obey the first law of thermodynamics, which theoretically conserved energy in quantity.But in exergy analysis these are all losses, because the capacity of energy to do work is reduced.A large amount of effective energy in the energy is converted into invalid energy in the boiler, which cannot be utilized in the later energy conversion process and can only be released to the environment through the condenser and cooling tower to form waste heat. Therefore, the heat balance analysis method believes that the main energy loss of the system occurs at the turbine side. The exergy analysis says that the main energy loss of the system has occurred on the boiler side but that the emission of this energy is on the turbine side.The energy consumption distribution of the whole plant thermal system is shown in the following table:

Tabie 5 Exergy loss coefficient of a plant or system in THA condition

Items	Exergy loss coefficient
boile	0.499
pipe	0.009261
Steam turbine generator	0.03967
steam cooler	0.001226
#1 High-pressure heater	0.001526
#2 High-pressure heater	0.0009793
#3 High-pressure heater	0.001847
#4 High-pressure heater	0.000586
deaerator	0.000779
#6 low-pressure heater	0.00117
#7 low-pressure heater	0.00196
#8 low-pressure heater	0.000619
#9 low-pressure heater	0.000765
#10 low-pressure heater	0.001006
mixed drain water	0.00001333
drain water cooler	0.0001933
Feed pump turbine system	0.004011
condenser	0.01222
NO.1 extraction pipe	0.00012056
NO.2 extraction pipe	0.00009518
NO.3 extraction pipe	0.0000719636
NO.4 extraction pipe	0.0000355429
NO.5 extraction pipe	0.0001454904
NO.6 extraction pipe	0.0000610128
NO.7 extraction pipe	0.0000888236
NO.8 extraction pipe	0.0000486837
NO.9 extraction pipe	0.0000577613
NO.10 extraction pipe	0.000063579
Overall plant exergy efficiency (counterbalance)	47.2385%

Through calculation and analysis, the irreversible loss of the system mainly occurs at the boiler side, and its loss accounts for 85.1% of the total loss of the system.The loss is mainly caused by the irreversibility of combustion and heat transfer.In the process of fuel combustion, chemical exergy is transformed into the physical fire of flue gas, which will be accompanied by a large amount of available energy loss. The furnace is the place with the highest working temperature of the boiler, and the heat transfer temperature difference can reach thousands of degrees. The huge heat transfer temperature difference leads to a great heat transfer loss.The incomplete combustion of fuel, heat transfer loss, heat dissipation loss, smoke exhaust loss and other factors combine to cause a great loss of available energy at the boiler side.

The irreversible loss of the turbo-generator body is the second largest loss source in the power plant, and its irreversible loss accounts for 7.52% of the total loss of the system.This loss includes nozzle, rotor blade, blade height, sector, impeller friction, partial steam intake, steam leakage, wet steam, residual speed loss and other losses.

The turbine cold source loss is the third largest loss source in power plant, and its irreversible loss accounts for 2.32% of the total system loss.Although the amount of steam turbine cold source loss is large, the steam exhaust temperature of the steam turbine is only 28.1℃, which is not big difference with the ambient temperature, so the grade of this part of heat is very low.

When the working medium flows through the main steam pipeline, water supply pipeline, primary reheating cold and hot section pipeline and secondary cold and hot section pipeline, the irreversible loss caused by the heat dissipation and pressure loss of the pipeline accounts for 1.755% of the total loss of the system, which is the fourth largest loss source in the power plant.

In the high pressure heater system, the design end difference of #1 high pressure heater and #3 high pressure heater is the same. The temperature rise of water supply in #1 high pressure heater and #3 high pressure heater is 39.8℃ and 36.5℃, respectively. According to the design data, the heat transfer temperature difference between #1 high pressure heater and #3 high pressure heater is 26.83℃ and 30℃, respectively.Although the heat exchange of #3 high pressure heater is less than that of #1 high pressure heater, the irreversible loss of #3 high pressure heater is greater than that of #1 high pressure heater due to the large heat exchange temperature difference. Since the use of an external steam cooler reduces the heat transfer temperature difference between the #2 and #4 high pressure heaters, the irreversible loss of the #2 and #4 high pressure heaters is lower than that of the #1 and #3 high pressure heaters.

The irreversible loss of the low pressure heater system is slightly higher than that of the high pressure heater system. In the low-pressure heater system, the design end difference of the #6 low-pressure heater and the #7 low-pressure heater is the same. The temperature rise of the condensate in the #6 low-pressure heater and the #7 low-pressure heater is 23℃ and 36.7℃, respectively. According to the design data, the heat transfer temperature difference between the #6 low-pressure heater and the #7 low-pressure heater is 31.26℃ and 29.34℃, respectively. Although the heat transfer temperature difference of the #7 low-pressure heater is less than that of the #6 low-pressure heater, the irreversible loss of the #7 low-pressure heater is greater than that of the #6 low-pressure heater due to the large heat transfer.

The water drain of the #8 low-pressure heater flows into the outlet of the #8 low-pressure heater through the water drain pump. This method reduces the heat transfer temperature difference of the heater and is conducive to reducing the irreversible loss of heat transfer.

4. Conclusion

Through modeling and analyzing the thermal system of the unit, the following conclusions are drawn:

The boiler is the equipment with the largest irreversible loss in the power plant. Although the amount of lung heat emitted by the condenser is very large, the heat temperature carried by the exhaust steam of the steam turbine is not different from the ambient temperature. The taste of the exhaust steam of the steam turbine is very low, and the loss of work capacity is not large.

The difference between the whole-plant exergy efficiency calculated by exergy analysis and the whole-plant thermal efficiency of the first law depends on the characteristics of the fuel consumed in the plant. It depends on the difference between the low calorific value of the fuel and the chemical exergy.

Based on the second law of thermodynamics of exergy analysis takes into account not only the traditional heat balance analysis method have noticed in the system caused by the external loss but also considers the internal process within the irreversible loss, help us to understand the nature of the energy loss reasons, focus on how to reduce all kinds of irreversible factors in the system of debasement of energy, In order to make better use of energy.

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