ECONOMICAL RESEARCH ON OPTIMIZING HEATING PARAMETERS OF STEAM HEATING CONDENSATE RECOVERY IN THERMAL POWER PLANTS

by

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The paper starts with calculating the share of heat of condensate in thermal power plants in the total heat of steam, expounds the purpose, significance, and principle requirements of condensate recovery. Introduces the composition and classification of condensate recovery system, proposes technical and economic indicators for condensate recovery, and derives them a simple algorithm for the benefit of condensate recovery is presented. Finally, two calculation examples are used to illustrate the considerable benefits of condensate recovery.

Key words: *thermal power plant, steam heating, condensate, recovery system, economy*

Introduction

The system that collects the condensed water in the heating equipment where the heating medium is steam and the condensed water in the steam pipe-line along the way and returns it to the heat source is called the condensate recovery system [1]. After the condensate in the steam heating system is recovered, it can directly enter the boiler or return to the boiler make-up tank to mix with the make-up water before entering the boiler, which can produce the following benefits:

– Reduce boiler fuel consumption and save boiler operating costs. Steam condensate has a much higher temperature and enthalpy value than boiler make-up water, so the required heat absorption per unit evaporation of the boiler is reduced, the fuel consumption of the boiler is reduced under the same output, the fuel cost required for boiler operation is reduced, and the boiler is saved operating costs. This is the main purpose of condensate recovery in steam heating systems.
– Save boiler make-up water and save water resources. The system steam condensate is sent to the boiler as boiler feed water, which reduces the boiler feed water. The more condensate is recovered, the more the boiler feed water is reduced. The condensed water is recycled and reused in the system, saving water resources. In theory, if the condensate can be recovered 100%, then the boiler make-up water will tend to zero.
– Reduce the amount of sewage discharged from the boiler and reduce the waste of heat and water resources taken away by the sewage. Qualified steam condensate enters the boiler part as boiler feed water, no blowdown is required, only the boiler feed water part needs to be blown off. The more the amount of condensate recovered, the less the boiler make-up water, and the less the corresponding sewage discharge. In theory, if the condensate can be recovered 100%, *zero pollutio*n can be achieved.

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– Increase boiler steam-to-coal ratio. In the industry, the performance of boilers is often roughly evaluated by the ratio of steam to coal, that is, the amount of steam produced per unit mass of coal. Condensate recovery reduces the coal consumption per unit of boiler evaporation. On the other hand, the amount of steam produced per unit mass of coal is increased, and the boiler steam-to-coal ratio increases. This point is essentially the same as the first point. It is just a different perspective to express the coal-saving benefits of condensate recovery.

According to GB/T12712-1991 *Condensate Water Recovery and Steam Trap Technical Management Regulations for Steam Heating Systems*, the condensate recovery should follow the following principles and requirements:

– The national energy policy and environmental protection policy must be implemented, and the overall plan must be combined with long-term and short-term plans to achieve advanced technology, reliable equipment, and reasonable economy.
– On the premise of meeting the process requirements, steam-using equipment should try to use steam indirect heating to increase the recovery of condensate.
– The condensed water generated by the steam-using equipment must be recovered on the premise of technically feasible and economically reasonable, and the condensate recovery rate shall not be less than 60%.
– For condensed water that may be contaminated or that is indeed contaminated, after technical and economic comparisons, it is confirmed that it has recovery value, water quality monitoring or purification devices should be installed to monitor recovery or purification and recovery, and those that cannot be recovered should also Try to recover its heat energy.
– The heat energy of steam and high temperature condensed water generated by the secondary evaporator should be utilized as much as possible.
– When the recovered condensate is used as boiler feed water, its water quality must meet the relevant regulations of GB/T1576 *Industrial Boiler Water Quality*. If it does not meet the standard requirements, it must be treated with water, and it can be used in the boiler only after it is qualified; Still unqualified, can be used for other purposes.
– The heat of steam and condensed water

Condensate recovery is the most effective method among the many energy-saving measures for steam heating systems. Of the total heat possessed by steam, for various steam-using equipment or devices, the main part that can be effectively used is the latent heat of vaporization of the steam. As for the sensible heat part, the heat of condensate, it is hardly used or only extremely used a small part [2]. The heat of condensed water accounts for about 20-30% of the total heat of steam, as shown in tab. 1 (the steam humidity is calculated as 3%).

Table 1. Summary of calculation results of the percentage of condensed water in the total heat of steam

Steam pressure, p [MPa]	0.4	0.7	1	1.25	1.6	2.5
Saturation temperature, t_b [°C]	151.85	170.42	184.06	193.35	204.3	226.03
Feed water temperature, t_{gs} [°C]	20	20	20	20	20	20
Enthalpy of saturated steam, h [kJkg^{-1}]	2748.52	768.42	780.42	787.3	2793.8	2801.2
Saturated water enthalpy, h [kJkg^{-1}]	640.1	720.9	781.1	822.5	871.8	971.7
Enthalpy of wet steam, h [kJkg^{-1}]	2685.2	2707	20720.4	20728.4	20736.1	20746.3
Enthalpy of water supply, h [kJkg^{-1}]	84.4	84.7	85	85.2	85.6	86.5
Saturated steam heat, Q [kJkg^{-1}]	2664.1	2683.7	2695.4	2702.1	2708.2	2714.7
Wet steam heat, Q [kJkg^{-1}]	2600.8	2622.3	2635.4	2643.2	2650.5	2659.8
Condensed water heat, Q [kJkg^{-1}]	555.7	636.2	696.1	737.3	786.2	885.2

The relevant calculation formula in the table:

$$h_{sq} = \frac{100-M}{100} h_{bq} + \frac{100-M}{100} h_{bs} \tag{1}$$

$$Q_{bq} = h_{bq} - h_{gs} \tag{2}$$

$$Q_{sq} = h_{sq} - h_{gs} \tag{3}$$

$$Q_{ns} = h_{bs} - h_{gs} \tag{4}$$

$$r_{ns}^{0} = \frac{Q_{ns}}{Q_{bq}} \times 100\% \tag{5}$$

$$r_{ns} = \frac{Q_{ns}}{Q_{sq}} \times 100\% \tag{6}$$

where h_{ba}, h_{bs}, and h_{sq} [kJkg^{-1}] are the saturated steam enthalpy, saturated water enthalpy, and wet steam enthalpy corresponding to the steam pressure p, t_b [°C] – the saturation temperature corresponding to the steam pressure p, t_{gs} [°C] – the feed water temperature, h_{gs} [kJkg^{-1}] – the feed water enthalpy, M [%] – the steam humidity, Q_{bq}, Q_{sq}, and Q_{ns} [kJkg^{-1}] – the heat of dry saturated steam, wet steam, and condensed water, r_{ns}^{0}, r_{ns} [%] – the heat of condensed water in the heat of dry saturated steam and wet steam the percentage.

Composition and classification of condensate recovery system

System composition

The condensate recovery system refers to the entire system in which the condensed water flows out of the steam equipment and returns to the heat source through the trap, pipe network, condensate tank, and condensate pump. Including: steam trap, user condensate tank, user condensate pump, total condensate tank, feed water pump, pipe-line, valve, water seal, *etc.*, as shown in fig. 1.

System classification

Divided into open system and closed system according to whether the system is in communication with the atmosphere

The open condensate recovery system represents a condensate recovery system in which the condensate tank is directly connected to the atmosphere, as shown in fig. 2. The open system is an atmospheric system with simple system structure and low cost, but low recovery efficiency. When the initial condensate temperature is greater than 100 °C, it is easy to produce secondary steam flashing and cause losses, and the condensate will drop below 100 °C, which is a low temperature condensate [3]. The closed condensate recovery system represents the condensate recovery system in which the different atmospheres of the condensate tank are directly connected, as shown in fig. 3. The closed system does not have the loss caused by the secondary steam flashing. The system is pressurized, the structure is complicated, and the cost is higher, but the condensate temperature is higher and the recovery benefit is higher.

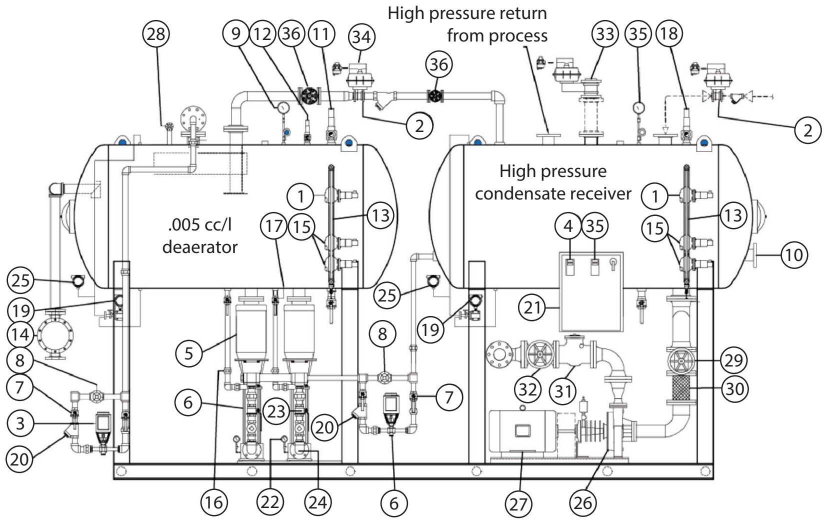

Figure 1. Schematic diagram of condensate recovery system; *1 – high water alarm switch, 2 – prssure control valve, 3 – make-up control valve, 4 – level controller, 5 – deaeratorpump motor, 6 – deaerator pump, 7 – make-up gate valve, 8 – make-up globe valve, 9 – pressure gauge (0-15#) w/cock, 10 – temperature gauge w/thermowel, 11 – safety relief valve (set at 50#), 12 – sentinal relief valve (set at 20#), 13 – sight glass assembly, 14 – overflow trap, 15 – low water alarm and cut off switch, 16 – re-circulation orifice union, 17 – re-circulation ball valve, 18 – safety reliet valve (steel, set at 120#), 19 – level transmitter, 20 – make-up Y-strainer, 21 – control panel, 22 – discharge pressure gauge (0-400#), 23 – discharge ball valve, 24 – discharge check valve, 25 – pressure transmitter, 26 – boiler feed pump, 27 – boiler feed pump motor, 28 – vent gate valve, 29 – suction gate valve, 30 – suction coupling, 31 – discharge check valve, 32 – discharge gate valve, 33 – back pressure relief valve, 34 – pressure controller, 35 – pressure gauge, and 36 – steam line shut off valve*

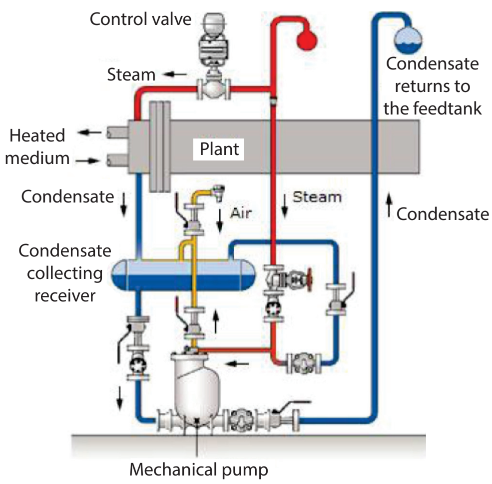

Figure 2. Schematic diagram of open system condensate tank

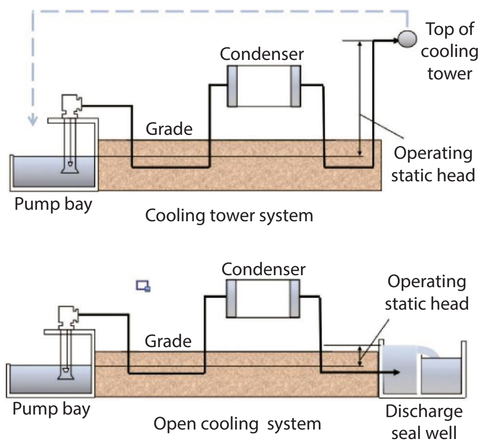

Figure 3. Schematic diagram of closed system condensate tank

According to the power of condensate flow, it is divided into back pressure, gravity, pressure and hybrid systems

The back pressure (surplus pressure) condensate recovery system represents a condensate recovery system that uses the back pressure of the steam trap as the power. The back pressure of the trap is the residual pressure of the condensed water at the outlet of the trap. The gravity condensate recovery system represents a condensate recovery system that uses the potential energy of the condensate as power. Potential energy is the potential energy formed by the height difference between the condensate discharge point and the condensate tank inlet. The pressure (pressurized) condensate recovery system represents a condensate recovery system powered by the kinetic energy of a water pump or other equipment [4]. The mixed condensate recovery system represents a condensate recovery system that comprehensively utilizes more than two methods such as back pressure, gravity or pressure.

Divided into single-phase flow system and two-phase flow system according to the flowing medium and its flow state in the condensate pipe network

The single-phase condensate recovery system represents a condensate recovery system in which single-phase condensate flows in the pipe network. The single-phase flow system is divided into slam flow and non-slam flow system according to the full state of water flow on the cross-section of the pipe-line. The flow state where the cross-section of the pipe is completely filled with water is called slam flow. The flow state where the cross-section of the pipe is not completely filled with water is called sub-slam flow [5]. The two-phase flow condensate recovery system represents a condensate recovery system in which steam and condensate coexist in the pipe-line network.

Divided into separated secondary steam system and non-separated secondary steam system according to the way of condensate return

The separated secondary steam condensate recovery system represents a condensate recovery system that uses a secondary evaporator to separate the secondary steam so that there is no steam in the condensate pipe. The non-separated secondary steam condensate recovery system represents the condensate recovery system that does not separate the secondary steam, and there is a condensate recovery system in which steam and water flow together in the condensate pipe [6]. Finally, it should be pointed out that the actual condensate recovery system in steam heating projects is often not a single type of system, but a composite recovery system composed of multiple types.

Technical indicators of condensate recovery system

The percentage of the annual amount of qualified condensate that is actually recovered to the annual indirect heating that can be recovered:

$$\eta_n = \frac{G_{ns}}{G_{ns}^0} \times 100\% \tag{7}$$

where η_n [%] is the condensate recovery rate, G_{ns} [t] – the actual amount of qualified condensate recovered annually, and G_{ns}^0 [t] – the amount of condensate that can be recovered from indirect heating in a year.

Qualified condensate representative refers to the condensate that meets the relevant requirements of boiler water quality standards and can be used as boiler feed water. Although the initial water quality does not meet the requirements, those that meet the requirements after water treatment are considered. Recyclable condensate produced by indirect heating refers to the condensed water produced by indirect heating equipment for production, heating, and domestic steam that must be recovered on the premise of technically feasible and economically reasonable [7]. For long distances, complex terrain, scattered steam points, low condensed water (below 100 kg/h) or condensate may be contaminated, technical and economic analysis should be carried out to determine whether to recycle, where the investment pay-back period is three years Measures should be taken to recycle within, where the value of recycle is not great, the heat can be recovered on the spot and discharged.

The lowest limit. According to GB/T12712-1991, the condensate recovery rate η_n should not be less than 60%. Energy-saving grading index value. According to JB/T50181-1999 *Energy-saving Classification of Heating System*, the energy saving of heating system is divided into three grades: first, second and third grade, corresponding to different grades of condensate recovery rate indicators. The values are listed in tab. 2, and those that do not reach the third class are out of class.

Table 2. Condensate recovery rate of heating system grading index value [%]

Energy saving level of heating system	First class	Second class	Third class
Condensate recovery rate, η_n	≥80	<80-70	<70-60

Subcooling. The actual condensed water temperature in the steam heating system is lower than the saturation temperature during condensation, that is, the condensed water is in a supercooled state, and the degree of supercooling depends on the working characteristics of the steam equipment. The so-called subcooling is the difference between the saturation temperature of the steam condensing and the actual temperature of the condensing water:

$$\Delta t_n = t_b - t_{ns} \tag{8}$$

where Δt_n [°C] is the supercooling degree of steam condensate, t_b [°C] – the saturation temperature under the corresponding pressure when the steam condenses, and t_{ns} [°C] – the actual condensate temperature. The subcooling of the condensate means that the sensible heat of the steam condensate is partially used, so in fact the percentage of the heat of the condensate to the total heat of the steam is less than 20-30%.

Condensed water temperature value. Condensed water is divided into high temperature condensed water and low temperature condensed water according to the temperature. The two are limited to 100 °C. The condensate whose water temperature is higher than or equal to 100 °C is called high temperature condensate. The condensate whose water temperature is lower than 100 °C is called low temperature condensate [8]. The condensate temperature firstly depends on the working characteristics of the steam-using equipment, and secondly is related to the type of condensate recovery system, and also related to the length of the condensate pipeline and thermal insulation performance.

The working characteristics of steam equipment are affected. The higher the working pressure of the steam-using equipment, the higher the saturation temperature. As shown in tab. 1, even if there is a degree of subcooling of 30-50 °C, the condensate temperature may not drop below 100 °C.

Influence of the type of condensate recovery system. For the closed recovery system, the condensate temperature mainly depends on the process parameters of the steam, and it is possible to be greater than 100 °C or lower than 100 °C. For the open recovery system, the condensate temperature must drop below 100 °C.

The length of the condensate recovery pipe-line and the thermal insulation performance. The long condensate pipe-line and poor thermal insulation will cause excessive heat dissipation loss. When the condensate returns to the condensate tank, the temperature may drop below 100 °C. Therefore, for the condensate pipe network with long pipe-lines, attention should be paid to thermal insulation reduce heat loss and obtain as high condensate temperature as possible.

Condensate recovery benefit calculation

In engineering calculations, condensate recovery can adopt simple algorithms, and the calculation results have sufficient accuracy to meet engineering design requirements. The benefit of condensate recovery depends on two aspects, one is the recovery rate of the condensate, and the other is the temperature of the condensate. The way that condensate recovery enters the boiler as boiler feed water depends on the condensate temperature. When the water temperature is lower than 100 °C, it is generally sent to the boiler make-up water tank first, mixed with the boiler make-up water, and then sent to the boiler via the feed water pump. When the water temperature is higher than 100 °C, there are two options, one is that the boiler uses heat also deaeration method can send the condensed water to the thermal deaerator; the other is that the boiler does not use the thermal deaeration method, and the condensed water recovery device can be directly introduced into the drum [9]. The benefit calculation is carried out based on 1 steamed ton as the basic accounting unit.

Coal saving calculation

The amount of coal saved by condensate recovery:

$$\Delta B_{ns} = \frac{s\left(h_{ns} - h_{gs}\right)}{\eta Q_{net,ar}} \times 10^3 \tag{9}$$

$$\varepsilon = \frac{G_{ns}}{D} \times 100\% \tag{10}$$

The fuel cost saved by condensate recycling:

$$\Delta\theta_r = \Delta B_{ns} g \theta_{ri} \times 10^{-3} \tag{11}$$

where ε [%] is the overall recovery rate of condensate, which is different from the aforementioned η_n which the percentage of condensate recovery and boiler evaporation, h_{ns} [kJkg^{-1}] – the enthalpy of condensate, $h_{ns} = 4.1868t_{ns}$, h_{gs} [kJkg^{-1}] – the enthalpy of feed water, $h_{gs} = 4.1868t_{ns}$, G_{ns} [th^{-1} or kgh^{-1}] – the amount of condensate recovered, D [th^{-1} or kJkg^{-1}] – the boiler evaporation, η [%] – the boiler thermal efficiency, $Q_{net,ar}$ [kJkg^{-1}] – the low calorific value, θ_{ri} (ton per hour) – the amount of coal-fired into the furnace, and ΔBns [RMB per ton] – the unit price of coal.

Water saving calculation

The boiler make-up water volume without condensate recovery:

$$G_b = \left(1 + \frac{P}{100}\right) \times 10^3 \text{ [kg/zt]} \tag{12}$$

The boiler make-up water volume with condensate recovery:

$$G_b' = \left[1 + \frac{P}{100}\left(1 + \frac{\varepsilon}{100}\right)\right] \times 10^3 \text{ [kg/zt]} \tag{13}$$

The reduction in boiler make-up water:

$$\Delta G_b = G_b - G'_b = \left(1+\frac{p}{100}\right)\frac{\varepsilon}{100}\times 10^3 \ \text{[kg/zt]} \tag{14}$$

The water cost saved by condensate recycling:

$$\Delta\theta_s = \Delta G_b g\theta_{si}\times 10^3 \ \text{[kg/zt]} \tag{15}$$

where p [%] is the boiler blowdown rate and θ_{si} [Yuan per ton] – the unit price of boiler make-up water. It is obvious from eq. (14) that the amount of water saved includes the amount of saved sewage.

Calculation example

Calculation Example 1

The boiler make-up water temperature is 20 °C, the blowdown rate is 5%, the boiler thermal efficiency is 88%, the coal fired low level calorific value is 24300 kJ/kg, the system condensate water recovery rate is 70%, and the condensate temperature is 90 °C. The condensate is sent to the make-up tank for mixing and then enter the boiler [10]. The unit price of coal is 1000 Yuan per ton, and the unit price of make-up water is 4 Yuan per ton. Try to find the coal and water-saving benefits of mixed water temperature and condensation recovery.

Solution:

$$t_{gs} = 20\ ^\circ\text{C},\ h_{gs} = 4.1868\times 20 = 83.7$$

$$t_{\text{ns}} = 90\ ^\circ\text{C},\ h_{ns} = 4.1868\times 90 = 376.8$$

– Calculation of mixed water temperature

$$G_{ns} = \frac{\varepsilon}{100}\times 10^3 = \frac{70}{100}\times 10^3 = 700$$

$$G'_b = \left(1+\frac{p}{100}\right)\left(1-\frac{\varepsilon}{100}\right)\times 10^3 = \left(1+\frac{5}{100}\right)\left(1-\frac{70}{100}\right)\times 10^3$$

$$t_{ns} = \frac{G_{ns}t_{ns}+G_b t_{gs}}{G_{ns}+G'_b} = \frac{700\times 90+315\times 20}{700+315} = 68.3$$

– Coal saving calculation

$$\Delta B_{ns} = \frac{\varepsilon\left(h_{ns}-h_{gs}\right)}{\eta Q_{net.ar}}\times 10^3 = \frac{70\left(376.8-83.7\right)}{88\times 24300}\times 10^3 = 9.59$$

$$\Delta Q_r = \Delta B_{ns} g\theta_{ri}\times 10^{-3} = 9.59\times 1000\times 10^{-3} = 737$$

– Water saving calculation

$$\Delta G_b = \left(1+\frac{p}{100}\right)\times\frac{\varepsilon}{100}\times 10^3 = \left(1+\frac{5}{100}\right)\times\frac{70}{100}\times 10^3 = 735$$

$$\Delta Q_s = \Delta G_b g\theta_{si}\times 10^{-3} = 735\times 4\times 10^{-3} = 2.94$$

– Total cost savings per steamed ton

$$\Delta Q_{zt} = \Delta\theta_r + \theta_s = 9.59 + 2.94 = 12.53$$

Calculation Example 2

A 10 ton per hour steam boiler heating system has an overall condensate recovery rate of 30%, a condensate temperature of 140 °C, a boiler blowdown rate of 5%, a feed water temperature of 20 °C, a boiler thermal efficiency of 80%, and a coal-fired low calorific value of 20930 kJ/kg, the unit price of coal is 900 Yuan per ton, the unit price of boiler feed water is 4 Yuan per ton, and the total annual steam output is 6 × 104 steam tons. Try to find the benefit of condensate recovery.

Solution:

$$t_{gs} = 20\ ^{\circ}\text{C},\ h_{gs} = 4.1868 \times 20 = 83.7$$

$$t_{ns} = 140\ ^{\circ}\text{C},\ h_{ns} = 4.1868 \times 140 = 586.2$$

– Coal saving calculation

$$\Delta B_{ns} = \frac{\varepsilon\left(h_{ns} - h_{gs}\right)}{\eta Q_{net,ar}} \times 10^3 = \frac{30 \times \left(586.2 - 83.7\right)}{80 \times 20903} \times 10^3 = 9.00$$

$$\Delta Q_r = \Delta B_{ns} g \theta_{ri} \times 10^{-3} = 9.00 \times 900 \times 10^{-3} = 8.10$$

– Water saving calculation

$$\Delta G_b = \left(1 + \frac{p}{100}\right) \times \frac{\varepsilon}{100} \times 10^3 = \left(1 + \frac{5}{100}\right) \times \frac{30}{100} \times 10^3 = 315$$

$$\Delta \theta_s = \Delta G_b g \theta_{si} \times 10^{-3} = 315 \times 4 \times 10^{-3} = 1.26$$

– Total annual benefit

$$\Delta \theta_{zt} = \Delta \theta_r + \Delta \theta_s = 8.10 + 1.26 = 9.36$$

$$\sum \Delta \theta_{ns} = \Delta \theta_{zt} g \sum D = 9.36 \times 6 \times 10^4 = 56.16$$

Conclusions

- The condensed water of the steam heating system has considerable heat and should be recovered. As the most effective method of system energy saving measures, it should be used as much as possible in the contract energy management project.
- The condensate recovery of steam heating system has obvious energy-saving and water-saving benefits. The recovery benefit depends on the two factors of condensate recovery rate and condensate temperature, and strive to obtain larger condensate recovery rate and higher condensate water temperature.
- It is not advisable to use an open recovery system for condensate recovery in steam heating systems, especially when the initial condensate temperature in the system is higher than 100 °C, the open system will cause secondary steam flash loss and low temperature condensate water, which will cause condensation. Water recycling efficiency is greatly reduced.
- The simple algorithm for condensate recovery benefit has sufficient accuracy. Pay special attention the two data of overall recovery rate and condensate temperature during on-site inspections, plus data on boiler thermal efficiency, blowdown rate and low fuel calorific value, which can be easily calculated.
- When the recovered condensate is used as boiler feed water, its water quality should meet the requirements of industrial boiler water quality standards. For this reason, water quali-

ty monitoring devices should be installed and water quality supervision and management should be strengthened.

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