Comparative Analysis of Final-Effect Secondary Steam Cooling Methods in Evaporation Stations of Alumina Plants

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https://doi.org/10.71659/icsoba2025-aa039

Abstract

This paper conducts an in-depth study on the cooling methods for the final effect secondary steam in evaporation units of alumina refineries, detailing the process principles and technical characteristics of traditional direct cooling and the new indirect cooling using evaporative condensers. Taking a single-train evaporation unit with a water evaporation capacity of 500 t/h in an alumina project as an example, a systematic comparative analysis is performed from multiple perspectives, including technical parameters, construction footprint, circulating water consumption, configuration methods, operational power consumption, investment, and economic benefits. The research shows that while the traditional direct cooling method offers advantages such as fast heat transfer, high vacuum, and lower investment, it suffers from large footprint requirements for the circulating water station and high operational power consumption. In contrast, the new evaporative condenser's indirect cooling method demonstrates significant advantages in saving fresh water, reducing footprint, lowering operational power consumption, and cutting production costs. However, it has drawbacks such as higher equipment investment, relatively lower vacuum, and difficulties in maintaining the heat exchange core. The findings of this study provide important reference for alumina refineries to rationally select the cooling method for the final effect secondary steam.

Keywords: Evaporation unit, Final-effect secondary steam, Direct cooling, Indirect cooling, Evaporative condenser.

1. Introduction

The integrated falling-film evaporators widely used in the alumina industry were initially introduced based on Kestner technology. After years of technological upgrades and improvements by domestic alumina refineries, the number of evaporation effects for sodium aluminate solution has now exceeded six (with most newly built alumina refineries adopting seven effects), and the steam-water ratio has dropped to below 0.2 t/t H_2O, achieving significant energy-saving effects. The 7-effect falling-film evaporator still utilizes new steam as the heat source, where new steam is introduced into the first effect, and the secondary steam from each effect heats the next effect's green liquor. The secondary steam from the final effect (7th effect) is cooled using circulating cooling water, and non-condensable gases are vented to the atmosphere via vacuum pumps.

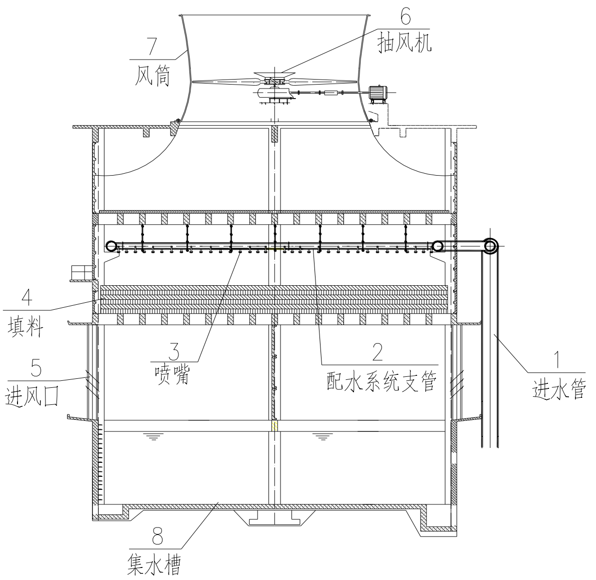
The traditional cooling method for the final-effect secondary steam is direct cooling, where the final-effect secondary steam directly exchanges heat with circulating water in a water cooler, and the condensed secondary steam water returns to the circulating water station along with the circulating water. A few alumina refineries (specialty alumina refineries) employ an improved indirect cooling method, where the final-effect secondary steam indirectly exchanges heat with circulating water in a novel evaporative condenser, and the condensed secondary steam water enters a condensate tank without mixing with the circulating water. Simultaneously, the cooling of the circulating water also occurs within the evaporative condenser, eliminating the need for a separate circulating water station. Given the current production and operation status in domestic alumina refineries, both of the aforementioned cooling systems for the final-effect secondary steam have practical engineering applications. The following section provides an introduction and analysis of these two cooling methods.

2. Traditional Direct Cooling Method

2.1 Process Principle

The final-effect secondary steam from the evaporation unit enters the water cooler from the bottom and directly exchanges heat with the cooling water entering from the top. The cooling water absorbs heat and rises in temperature, while the secondary steam cools down and turns into condensate, which, along with the heated cooling water, flows into a downstream water seal tank. Utilizing the height of the water seal tank, the water self-flows back to an open counterflow cooling tower for cooling, where it is cooled and then pressurized by a circulating water pump to re-enter the water cooler, to continue cooling the secondary steam from the final effect of the evaporator train, thus forming a circulating system. Non-condensable gases are vented to the atmosphere using vacuum pumps.

An open counterflow cooling tower, also known as a mechanical draft counterflow wet cooling tower, refers to a tower where circulating hot water flows into the tower through Inlet Pipe 1, is uniformly distributed onto lower drenching Fillers 4 via Distribution System's Branch Pipe 2 and Nozzle 3. The hot water flows downward in the form of droplets or a water film, while cold air enters the tower from the lower Air Inlet 5. The hot water and cold air exchange heat and mass in the drenching fillers to reduce the water temperature. The heated moist air is drawn out of the tower by top-mounted Exhaust Fan 6 through Wind Tunnel 7. The cooled water flows into lower Collection Tank 8. A schematic diagram of the open counterflow cooling tower's structure is shown as Figure 1.



1 Inlet Pipe
2 Distribution System's Branch Pipe
3 Nozzle
4 Fillers
5 Air Inlet
6 Exhaust Fan
7 Wind Tunnel
8 Collection Tank

Figure 1. Schematic diagram of open counterflow cooling tower structure.

2.2 Technical Characteristics

The technical characteristics of this cooling method include: (1) The latent heat released during the condensation of the final-effect secondary steam is transferred to the atmosphere through two devices in series: the water cooler and the cooling tower. The final-effect secondary steam first transfers its heat to the circulating water in the water cooler, and the heated circulating water returns to the open cooling tower, where it transfers its heat to the atmosphere. (2) The final-effect secondary steam directly exchanges heat with the circulating water in a convective heat transfer mode, resulting in good heat transfer efficiency and high final-effect vacuum. (3) A separate evaporation circulating water station needs to be configured near the evaporation unit.

3. Indirect Cooling Method of Novel Evaporative Condensers

3.1 Process Principle

An evaporative condenser is a special type of cooler that integrates the cooling system for the final-effect secondary steam and the circulating water-cooling system into a single device, enabling indirect cooling of the final-effect secondary steam from the evaporation unit. Using water and air as cooling media, water evaporates and air acts as a carrier to remove the heat released during the condensation of the steam in the heat exchange tubes.

The final-effect secondary steam from the evaporation unit enters Heat Exchange Tubes 2 of the evaporative condenser. The spray water from Circulating Spray Water Pump 9 is evenly sprayed onto the outer surface of Heat Exchange Tubes 2 through Spray Nozzle 10, forming a uniform water film. The steam inside the tubes undergoes indirect heat exchange with the water film and air, resulting in the formation of condensate. The condensate flows by gravity into Condensate Tank 4 for collection and is then pressurized by Condensate Pump 5 and sent to the process workshop for utilization. Axial-flow Fan 12 at the top forcibly draws air from outside the equipment through the air inlet at the bottom of the equipment. This air rapidly passes through the outer side of Heat Exchange Tubes 2 and the spray water. Under the forced air-inducing action of the axial-flow fan, a slight negative pressure state is formed on the outer surface of the heat exchange tubes. The water film on the outer side of the heat exchange tubes absorbs heat and vaporizes, and the water vapor is quickly discharged from the equipment along with the air, thereby carrying away the heat released during the condensation of the steam inside the heat exchange tubes. The unvaporized spray water is cooled by the fresh air during its descent and falls into the bottom Water Tank 8 for recycling. The non-condensable gases inside the heat exchange tubes enter Non-condensable Gas Collection Chamber 6 and are removed by Vacuum Pump 7 to maintain the vacuum inside the heat exchange tubes. The structural schematic diagram of the evaporative condenser is shown as Figure 2.

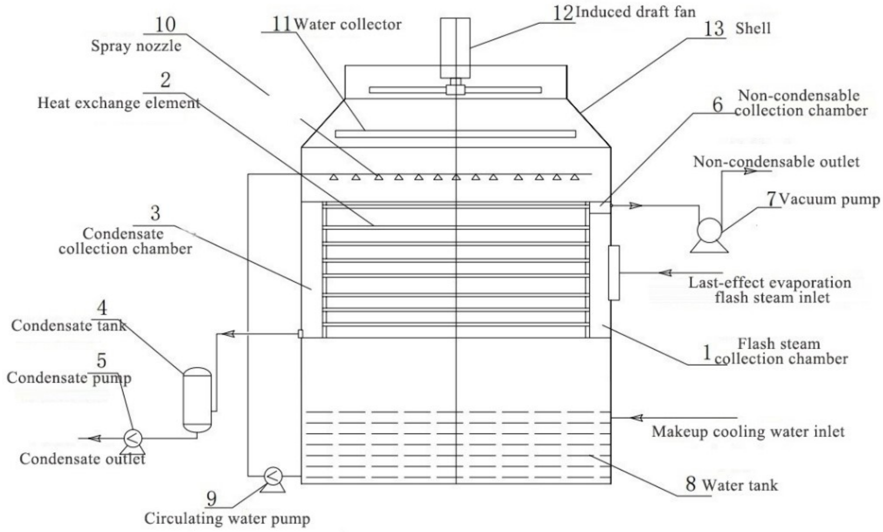


Figure 2. Schematic diagram of evaporative condenser structure.

Its working characteristic is that cooling water is sprayed downward onto the upper part of the heat exchange tubes, forming a thin water film on the outer surface. Air is drawn upward by a fan from below the tube bundle, rapidly passing over the tubes. The water film on the outer surface quickly evaporates, significantly enhancing heat transfer on the outer surface and achieving the cooling and condensation of the medium inside the tubes. During low temperatures, the axial fan draws in air through louvers, causing the air to pass upward through the tube bundle from below. The cold air can remove the heat from the medium inside the tubes, allowing some evaporative condensers to reduce water usage by stopping the spray water. Therefore, evaporative condensers are also water-saving.

3.2 Technical Characteristics

The technical characteristics of this cooling method include: (1) The latent heat released during the condensation of the final-effect secondary steam is transferred to the atmosphere within a single device, the novel evaporative condenser. The final-effect secondary steam enters the tube layer of the evaporative condenser, exchanges heat with the spray water film on the outer tube wall, and condenses into water, while the spray water heats up and exchanges heat with the air entering from the bottom of the tower in a counterflow manner. The moisture and heat emitted by the spray water are carried away by the air exiting the tower top. (2) The final-effect secondary steam indirectly exchanges heat with the circulating water in a heat conduction mode, featuring a large heat transfer area and generally moderate final-effect vacuum. (3) The traditional evaporation circulating water station is eliminated, and the cooling of the final-effect secondary steam and circulating water occurs simultaneously within the evaporative condenser, reducing both the circulating water volume and conveyance distance. (4) The novel evaporative condenser is configured on the framework of the evaporation unit, eliminating the need for additional land occupation. However, the equipment load on the evaporation unit increases, as does the structural steel usage.

4. Comparative Analysis of the Two Cooling Methods

Taking an alumina project's evaporation unit with a single-train water evaporation capacity of 500 t/h as an example, a systematic analysis and comparison of the two different cooling technologies are conducted.

4.1 Traditional Direct Cooling Solution

Two evaporation trains are set up, each with a water evaporation capacity of 500 t/h. The final-effect secondary steam volume evaporated by each train is 95 t/h, with a maximum of 114 t/h, at a temperature of 50 °C. The required circulating water volume is 5 000 m^3/h, with a maximum of 6 000 m^3/h. The total circulating water volume for the two trains is 10 000 m^3/h, with a maximum of 12 000 m^3/h. The circulating water supply temperature is 35 °C, and the return temperature is 48 °C, with a supply-return temperature difference of 13 °C.

The traditional direct cooling scheme consists of a water cooler, water seal tank, and circulating water station. The circulating water station mainly includes an evaporation cooling water pool, power distribution room, pressurization equipment, cooling equipment, and circulating water bypass filtration equipment. The circulating hot water utilizes the static pressure generated by the height of the water seal tank to directly enter the cooling tower for cooling. The cooled water enters a collection tank and then flows into the evaporation cooling water pool. After being pressurized by a cold water pump, it is sent to the water cooler for the final-effect secondary steam of the evaporation unit. The water cooler and water seal tank are located inside the evaporation unit, and the circulating water station occupies a land area of 72 × 60 m.

The main equipment configuration for the traditional direct cooling scheme is shown in Table 1.

Table 1. Main equipment configuration table for traditional direct cooling scheme.

Sequence No.	Equipment Name and Model	Equipment Parameters	Qty	Remarks
S-1	High-Efficiency Intelligent Self-Priming Pump	Q = 3000 m^3/h H = 45 m	5 sets	4 in use, 1 standby
Attachment	Electric Motor	N = 620 kW n = 980 rpm	5 sets	V=10 kV
S-2	High-Efficiency Intelligent Self-Priming Pump	Q = 650 m^3/h H = 35 m	2 sets	1 in use, 1 standby (bypass filtration)
Attachment	Electric Motor	N = 120 kW n = 1490 rpm	2 sets	1 in use, 1 standby
S-3	GQL_{2B}-3000 Fiber Ball Filter	Q = 210 m^3/h N = 18.5 kW	3 sets	Installed in parallel
S-4	LF-85III Fan Cooling Tower	Q = 3500 m^3/h △t = 15 °C	4 sets	
Attachment	Wave 160-45 Type Water Collector	Block length L=1475 mm δ = 0.45 mm	1360 m^2	
Attachment	Reflection Type III Spray Device	Nozzle diameter φ26 Material: ABS engineering plastic	1216 units	
Attachment	T25-60 ° Trapezoidal Wave Drenching Filler	L×B×H=1000×500×250 δ=8~10 mm Modified polyvinyl chloride	4 sets	
Attachment	Cooling Tower Glass Steel Guide Circle	Geometric shape: Round in, square out Material: Polyester glass steel φ × L = φ 9630 × 18000 mm δ = 0.5 mm H = 1650 mm	4 sets	
Attachment	LF-85III Cooling Tower Fan	Air volume: G = 2.73 Mm^3/h; Total pressure: P = 158.82 Pa; Blade speed: n = 136 rpm Blade number: 8; Total pressure efficiency: 85.6 %	4 sets	
Attachment	Electric Motor	N=160 kW V=380 v IP55	4 sets	Outdoor type
Attachment	Oil Temperature Alarm and Vibration Alarm System		4 sets	
Attachment	Oil Level Gauge and Platinum Thermal Resistor		4 sets	
Attachment	JF85A Energy-Saving Recovery Type Glass Steel Wind Tunnel		4 sets	
S-5	Water Cooler	Φ5.8 × 10 m	2 sets	Located in the evap. unit
S-6	Water Seal Tank	Φ4.5 × 3 m	2 sets	Located in the evap. unit

4.2 Indirect Cooling Solution by Novel Evaporative Condensers

The Phase II project of Guangxi Huasheng New Materials Co., Ltd.'s 2-Mtpa alumina project consists of two evaporation units, each evaporating 95 t/h of final-effect secondary steam, with a maximum of 114 t/h. The total final-effect secondary steam volume for the two units is 190 t/h, with a maximum of 228 t/h, at a temperature of 50 °C. The temperature of the condensed secondary steam water is also 50 °C.

The evaporative condenser mainly consists of a heat exchange system, external water circulation system, draft system, condensate collection system, and non-condensable gas discharge system. Each evaporation unit is equipped with an evaporative condenser located on the top floor of the unit, utilizing the space available. The top floor dimensions are 72.3 × 49.2 m, which meets the space requirements.

The main parameters of the evaporative condenser are shown in Table 2.

Table 2. Main parameter table for evaporative condenser.

Sequence No.	Equipment Name and Model	Single Evaporation	Dual Evaporation	Remarks
1	Spray Pump Installed Power	220 kW	440 kW	IP55
2	Total Spray Circulation	2200 m^3/h	4400 m^3/h	
3	Total Fan Air Volume	810 × 104 m^3/h	1620 × 104 m^3/h	
4	Total Fan Power	720 kW	1440 kW	IP55
5	Air Pressure	200 Pa	200 Pa (single set)	
6	Outer Diameter of Heat Exchange	32 mm	32 mm	Material: 304
7	Design Pressure of Coil	0.2 MPa	0.2 MPa	
8	Overall Equipment Resistance	< 600 Pa	< 600 Pa	
9	Allowable Noise Level (at Dm15)	< 85 dB(A)	< 85 dB(A)	
10	Tower Body Combination Type	Integrated	Single integrated	
11	Fan Cylinder Material	Glass steel	Glass steel	
12	Blade Material	Glass steel	Glass steel	
13	Condensate Tank	Φ2.8 × 3 m 1 set	Φ2.8 × 3 m 2 sets	
14	Condensate Pump	Q = 120 m^3/h H = 32 m 1 set	Q = 120 m^3/h H= 32 m 2 sets	

4.3 Technical and Economic Comparison

A comparative analysis of the traditional direct cooling method and the novel evaporative condenser in terms of technical parameters, construction land occupation, circulating water volume, configuration mode, operating power, investment, and economic benefits is conducted, as detailed in Table 3.

Table 3. Comparative table of traditional direct cooling method and novel evaporative condenser indirect cooling method (dual evaporation).

Sequence No.	Content Name	Traditional Direct Cooling	Novel Evaporative Condenser Indirect Cooling	Remarks
1	Final-effect Secondary Steam Volume to be Cooled	228 t/h	228 t/h	
2	Final-effect Secondary Steam Temperature	50 °C	50 °C	
3	Condensed Secondary Steam Water Temperature	48 °C	50 °C	
4	Circulating Water Volume	12 000 m^3/h	4 400 m^3/h (external spray)	
5	Circulating Water Operating Temperature	Supply water temperature 35 °C Return water temperature 48 °C	Spray water temperature 35 °C Intermediate temperature rise 3-5 °C, then drops to 35 °C	
6	System Makeup Water Volume	360 m^3/h	288 m^3/h	
7	Operating Vacuum	-0.089 MPa	-0.088 MPa	
8	Fan Air Volume	1092 × 104 m^3/h	1620 × 104 m^3/h	
9	Construction Land Occupation	Land size 72 × 60 m	Located on the top floor of the evaporation unit, no additional land occupation	
10	Total Operating Power	3 296 kW	1 880 kW	
11	Annual Operating Electricity Cost	Approximately 13.16 million RMB	Approximately 7.5 million RMB	Electricity price at 600 RMB/MWh
12	Total Investment	Approximately 23 million RMB (including the entire circulating water station)	Approximately 35 million RMB (including only the evaporative condenser)	Dual evaporation units
13	Evaporation Unit Construction	Approximately 50 million RMB	Approximately 52.6 million RMB	Steel structure differences

Sequence No.	Content Name	Traditional Direct Cooling	Novel Evaporative Condenser Indirect Cooling	Remarks
	Engineering Investment			
14	Configuration Mode	The evaporation unit and circulating water unit are configured far apart, with long conveyance pipelines and large circulating water volumes.	Located on the top floor of the evaporation unit, with short conveyance pipelines and small circulating water volumes.	
15	Advantages	1. Fast heat transfer, with instantaneous condensation of secondary steam. 2. High vacuum in the evaporation system. 3. Low investment. 4. Easy maintenance of the cooling tower.	1. No circulating water station, saving land occupation. 2. Lower equipment operating power consumption, energy-saving. 3. Comparatively water-saving.	
16	Disadvantages	1. Large land occupation for the circulating water station and long circulating pipelines. 2. High equipment operating power consumption and electricity costs.	1. High equipment investment for the evaporative condenser. 2. Relatively lower vacuum compared to direct cooling. 3. Difficult maintenance of the heat exchange core.	

Note: The formula for calculating annual operating electricity cost in the above table is: Operating power × 24 × 365 × 0.95 × 0.8 × 0.6, where 24 hours/day, 365 days/year, 0.95 system operation rate, 0.8 active power coefficient, and RMB/kWh.

Through comparison, it is evident that both the traditional secondary steam direct cooling technology and the novel secondary steam indirect cooling technology can meet the condensation requirements for the final-effect secondary steam in the evaporation system of alumina production.

In terms of freshwater consumption, the novel final-effect secondary steam indirect cooling technology has a lower external spray water makeup volume than the direct heat exchange circulating water makeup volume. Moreover, during low temperatures, the axial fan can draw in air through louvers, utilizing the cold air to remove the heat from the medium inside the tubes, allowing some evaporative condensers to reduce water usage by stopping the spray water. Therefore, the evaporative condenser is water-saving. In terms of construction land occupation, since the novel final-effect secondary steam indirect cooling technology eliminates the evaporation circulating water station, there is no need for a circulating water pool and open cooling tower. Additionally, the evaporative condenser can be located on the 21 m plane of the evaporation unit, increasing the equipment load and structural steel usage but saving construction land. In terms of construction investment, since the novel final-effect secondary steam indirect cooling technology involves indirect heat exchange between the secondary steam and circulating water, the heat transfer efficiency is far lower than that of direct cooling, requiring a larger heat transfer area. Due to the difficulty in large-scale production of single heat exchangers, the corresponding evaporative condenser equipment quantity is larger, and all are located on the 21 m plane of the evaporation unit, increasing the floor load. Therefore, the construction investment is higher than that of the traditional final-effect secondary steam direct cooling technology. In terms of operating power consumption, in the novel final-effect secondary steam indirect cooling technology, the process of releasing latent heat from the final-effect secondary steam condensation into the atmosphere is completed entirely within the evaporative condenser, eliminating the need for circulating water to circulate back and forth between the evaporation process and the circulating water station in the traditional direct cooling technology. The operating power consumption is saved.

5. Conclusion

In summary, compared to the traditional direct cooling technology, the final-effect secondary steam indirect cooling technology in the evaporation system offers advantages in conserving freshwater, footprint, operating power consumption, and production costs. However, in terms of equipment configuration, the evaporative condenser requires a larger quantity, resulting in higher construction investment. Additionally, the uniform distribution of the final-effect secondary steam needs to be considered. During operation, it is essential to ensure that the spray water in the evaporative condenser is a clean soft water to prevent scaling on the heat exchange tubes. The material and processing quality of the heat exchange core must be reliable to prevent leaks and damage to the tubes, ensuring stable and reliable operation of the evaporative condenser.

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