Energy-Saving Retrofit Technology Analysis for Fluorine Removal in Aluminium Electrolysis Flue Gas Treatment

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Abstract

The fluorine removal system is an essential component of the dry purification process for aluminium electrolysis flue gas treatment. Currently, many domestic aluminium smelters face issues such as high operational resistance and excessive power consumption in their fluorine removal systems, presenting significant potential for energy savings. This paper analyses the original fluorine removal system of aluminium electrolysis flue gas in response to the demand for energy-saving retrofitting and proposes an energy-saving retrofitting plan. By retrofitting the gas collection flue at the top of the electrolytic cell, balancing the flue gas flow between electrolytic cells, adding a flue gas duct cooling system, and modifying the main draft fan and its duct system, the operational resistance of the fluorine removal system is reduced, and the efficiency of the main draft fan is improved, leading to a reduction in power consumption. Analysis shows that the fluorine removal system can reduce power consumption by 65 kWh/t Al.

Keywords: Aluminium electrolysis, Electrolysis flue gas purification, Fluorine removal system, Power consumption, Energy-saving retrofit.

1. Introduction

The power consumption per tonne of aluminium for domestic dry fluorine removal systems is between 110–190 kWh/t Al (excluding desulfurization systems), accounting for 0.9–1.4 % of the total power consumption in aluminium electrolysis, with significant variation between different companies. This suggests considerable potential for energy savings. Therefore, retrofitting dry fluorine removal systems to improve energy efficiency can directly lower production costs for aluminium smelters, helping the industry transition to a low-carbon model.

2. Analysis of Operational Resistance Loss in Fluorine Removal System

2.1 Process Flow of Dry Fluorine Removal System

Under the negative pressure of the fan, electrolysis flue gas is collected through the flue gas branches and enters the main flue gas duct outside the plant. The distance between each electrolytic cell and the fan differs, so manual butterfly valves are installed on the flue gas branches to adjust the flue gas flow. This ensures that the negative pressure is the same at the exit of each electrolytic cell, maintaining uniform gas collection efficiency. The collected flue gas is distributed into the flues of each dust collector, where it undergoes an adsorption reaction with a controlled amount of fresh alumina and recycled alumina in the Vertical Radial Injector (VRI) reactor to remove HF. The mixed flue gas then enters the bag filter for solid-gas separation to remove particulate matter. The purified gas, under the negative pressure of the fan, is discharged into the atmosphere via the chimney, while the separated alumina enters the fluidized bed at the bottom of the dust collector. The fluorine-loaded alumina that is captured is partially recycled as an adsorbent, with the remaining part conveyed via an air-driven chute to a bucket elevator for storage in the fluorine-loaded warehouse for use in electrolysis [1].

2.2 Pressure Loss and Power Consumption

The core equipment of the dry fluorine removal system mainly includes the fluorine removal pulse bag filter, the upper gas collection system of the electrolytic cell, the main flue fan, and its associated flue gas duct system. Currently, the total pressure loss of the fluorine removal system typically ranges between 3500 and 5500 Pa, with the pulse bag filter and flue duct pressure losses accounting for over 75 %. These high-pressure losses directly lead to increased power consumption. The relationship between flue gas flow and duct pressure loss is primarily governed by fluid dynamics principles. As shown in the Darcy-Weisbach Equation (1), pressure loss is proportional to the square of the velocity (v^2). For instance, when the velocity increases from 10 to 20 m/s, the pressure loss will increase by a factor of four.

$$\Delta P = \frac{1}{2}\lambda\frac{L}{D}\varrho v^2 \tag{1}$$

where:

ΔP	Pressure loss, Pa
λ	Darcy friction factor, dimensionless
L	Length of the duct, m
D	Diameter of the duct, m
ρ	Flue gas density, kg/m^3
v	Flue gas velocity, m/s

As per Equation (2), when the flue gas flow increases and the duct cross-sectional area remains constant, the velocity increases proportionally.

$$v = {}^{Q}\!/_{A} \tag{2}$$

where:

v	Flue gas velocity, m/s
Q	Flue gas volume flowrate, m^3/s
A	Duct cross-sectional area, m^2.

When the flue gas flow increases or the duct cross-sectional area decreases, the velocity increases, leading to a significant rise in pressure loss.
The pressure loss impact on power consumption is given in Equation (3).

$$P = \frac{\Delta P \cdot Q}{\eta_1 \cdot \eta_2} \tag{3}$$

where:

P	Power, W
ΔP	Total system pressure loss, Pa
Q	Processing airflow, m^3/h
η_1	Fan efficiency, %
η_2	Motor efficiency, %

There is a nonlinear positive correlation between flue gas volume and duct pressure loss. Velocity serves as a key intermediary variable. The pressure loss of the flue gas purification system is positively correlated with power consumption. For every 100 Pa increase in pressure loss, power consumption rises by approximately 10–15 %. Duct parameter design, optimization of local structures, and matching of fan performance are necessary to achieve an efficient flue gas system.

2.3 Total Airflow and Pressure Loss Calculation

Calculation of the total exhaust airflow for a single fluorine removal system:

$$Q = [q_1(n_1 - n_2) + q_2 n_2 + q_3] \times \frac{273+T}{273} \times \frac{101325}{p} \times (1+k) \tag{4}$$

where:

Q	Total airflow per purification unit, m^3/h
q_1	Exhaust volume when the cell is not in operation, Nm^3/h
q_2	Exhaust volume when the cell is operating, Nm^3/h
q_3	Airflow introduced into the purification system, Nm^3/h
n_1	Number of cells per purification unit, set
n_2	Number of operating cells per purification unit, set
T	Flue gas temperature at the fan, °C
p	Atmospheric pressure, Pa
k	Leakage coefficient, %.

Calculation of total resistance for a single fluorine removal system (excluding desulfurization system):

$$H = h_1 + h_2 + h_3 + h_4 \tag{5}$$

where:

H	Total pressure loss, Pa
h_1	Exhaust pressure loss of the electrolytic cell, Pa
h_2	Pressure loss of the exhaust duct, Pa
h_3	Pressure loss of the fluorine removal reactor, Pa
h_4	Pressure loss of the dry fluorine removal bag filter, Pa.

2.4 Exhaust Fan Efficiency

The exhaust fan is a key piece of equipment in the fluorine removal system's power consumption, typically accounting for over 68 % of the total power consumption. The operational efficiency of the fan directly affects global power consumption. In Chinese fluorine removal systems, the motor efficiency of the exhaust fans can reach over 92 %, but the efficiency of the fans generally falls between 60 % and 70 %, indicating that the fans are operating inefficiently. For example, the efficiency of the exhaust fan in a certain company is given in Table 1.

Analysis of the results shows that:
1) The fan efficiencies for two fluorine removal systems are between 60 and 67 %, indicating a low operational efficiency.
2) These fans operate at high flow and low pressure, which affects their operational efficiency.

In summary, the technical approach to reduce power consumption in the fluorine removal system includes retrofits of the fluorine removal system to reduce system resistance losses and of the fans to improve their efficiency.

Table 1. Fan testing results for fluorine removal system.

No.	Item	Unit	1# Fluorine Removal System		
			2# Exhaust Fan	3# Exhaust Fan	4# Exhaust Fan
1	Input power	kW	946.03	960.64	1037.01
2	Shaft power	kW	849.15	862.26	930.81
3	Fan efficiency	const.	64.82 %	67.46 %	66.53 %
No.	Item	Unit	2# Fluorine Removal System		
			5# Exhaust Fan	7# Exhaust Fan	8# Exhaust Fan
4	Input power	kW	826.00	794.00	787.00
5	Shaft power	kW	741.41	712.69	706.40
6	Fan efficiency	const.	60.78 %	61.38 %	63.69 %

3. Energy-Saving Retrofit Technology for the Fluorine Removal System

From the analysis of the existing electrolytic flue gas fluorine removal systems, the most promising energy-saving retrofit technologies are reducing system pressure losses and upgrading to high-efficiency fans. By optimizing the flue gas draft and improving its distribution inside the electrolytic cell to make it more uniform, the potroom environment can be improved, reducing fugitive emissions and electrolytic heat losses. Specific measures are as follows.

3.1 Retrofit of the Upper Gas Collection Flue of the Cell

The upper horizontal flue of the electrolytic cell, from the tapping end to the flue end, has a uniform cross-section of 550 mm (height) × 250 mm (width), and the collection hood diameter is designed the same. While the flue near the flue end can meet the exhaust requirements, the tapping end cannot generate negative pressure as effectively, resulting in poor exhaust performance at the tapping end [2]. The uniform design of the collection hood diameter leads to uneven draft distribution. The design of the upper horizontal flue is flawed; the negative pressure at the flue end is high, and the gas velocity is high. At the tapping end, the gas velocity in the flue is only about 3 m/s, causing alumina to easily settle within the horizontal flue, increasing system resistance. To ensure effective gas collection at the far end of the electrolytic cell (tapping end), the overall draft must be increased, leading to a higher exhaust volume per cell than the design value, thereby increasing system pressure drop and fan power consumption.

The outcome of the optimization of the upper gas collection is presented in Figure 1. The uniform cross-section of the horizontal flue is concerted to a gradually changing section, reducing the flue cross-sectional area at the tapping end. The optimal cross-sectional shape is determined by CFD simulation, and local constriction accelerates airflow, keeping draft balanced between each collection hood. A venturi acceleration section was also added to the collection hoods with a gradually narrowing-expanding structure at key points to accelerate airflow and reduce turbulent energy losses. Guide plates and rectifier grids were also installed. Using curved guide plates with smooth inner surfaces at bends and changes in diameter to reduce vortex regions, improved flow uniformity with a velocity deviation of less than 10 %. Ensuring that the gas velocity in the flue after collecting gases from all collection hoods is not less than 12 m/s, prevents the settling of alumina in the flue. Simultaneously, the deviation of gas flow between the collection hoods at the flue end and those at the tapping end of the electrolytic cell is within ±5%, improving the gas collection efficiency of the electrolytic cell. Under the same collection efficiency, the exhaust flow rate per cell is reduced by 5–7 % and the operating pressure loss of the purification system is reduced by approximately 10 %.

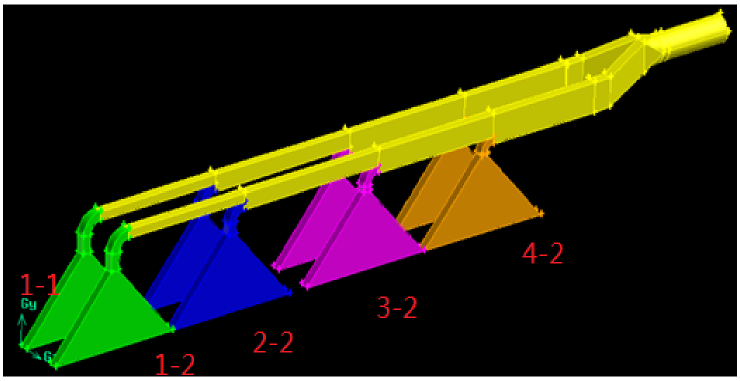

Figure 1. Model of the cell gas collection flue retrofit.

3.2 Balancing Flue Gas Flow Between Cells

Balancing gas flow between cells is generally achieved by adjusting the opening of the manual flapper valve on the external gas collection duct of the cells. During actual production, workers often adjust the valve opening away from the design standard, leading to significant deviations in gas flow between cells, unbalanced negative pressure distribution, and uneven exhaust volume, which reduces the overall system's gas collection efficiency [3]. Additionally, flapper valves increase system resistance in the duct. To improve the workshop environment, the only way is to increase the draft by increasing the fan speed, thereby increasing the total negative pressure of the fluorine removal system. However, this method cannot accurately distribute the increased negative pressure to the requiring cells, and increasing the fan operating frequency results in higher power consumption.

To address the issue of uneven gas flow distribution between cells, it is recommended to replace the duct before the valve on the outlet branch of the electrolytic cell with a reducing duct without changing the existing outlet branch (see Figure 2). Eliminate the original flapper valve design and use CFD simulation to model the gas flow balance between cells, accurately designing the diameter of the reducing duct. The reducing duct adjusts the gas flow between each electrolytic cell uniformly, avoiding manual interference and deviation from the design value, and keeping the gas flow deviation between each electrolytic cell within ±10 %.

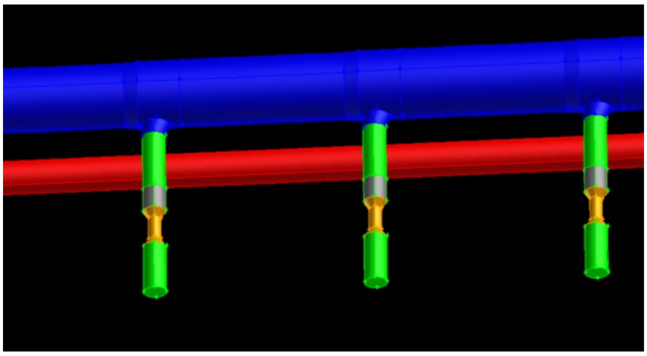

Figure 2. Model of reducing duct adjusting cell gas flow balance.

For some existing gas duct design, some electrolytic cell gases need to travel a long distance to reach the fluorine removal system. To address the problem of the long flue gas path from the end electrolytic cell in each plant, auxiliary flue gas ducts can be added to shorten the gas path (see Figure 2). The use of auxiliary flue gas ducts also increases the cross-sectional area of the flue gas ducts, reducing the flow rate and thus reducing the frictional pressure loss within the ducts, lowering the system pressure loss.

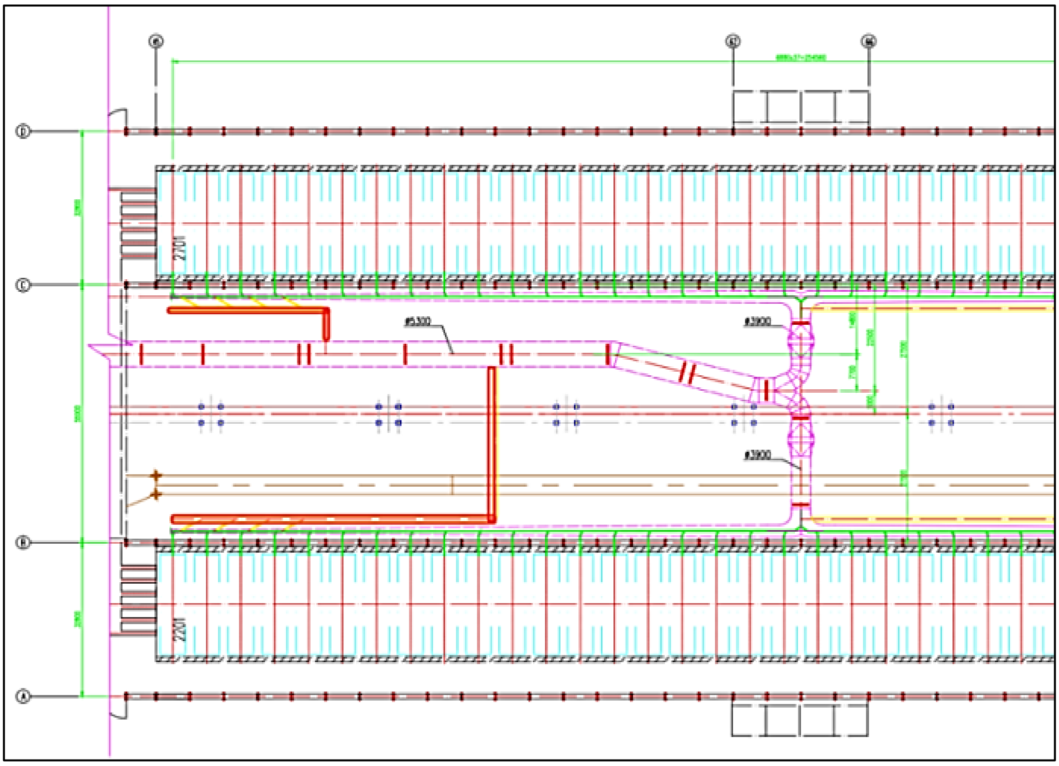

Figure 3. Schematic diagram of auxiliary flue gas duct route for end cells.

3.3 Addition of a Flue Gas Cooling System

The relationship between flue gas temperature and flow rate is of significant importance in industrial production and environmental protection. Changes in flue gas temperature affect its physical properties, which in turn indirectly influence its flow rate. When the flue gas temperature rises, gas molecules gain kinetic energy, increasing the frequency of collisions with the duct walls, causing volume expansion (at constant pressure) and an increase in gas flow rate. Conversely, when the flue gas temperature decreases, its density increases, resulting in reduced flow rate and slower velocity. In industrial production, high flue gas temperatures lead to higher flow rates under working conditions, which increases frictional resistance in the flue ducts and thus elevates system power consumption.

To reduce the temperature of electrolysis flue gas, a cooling system can be added to the duct. Figure 4 details its principles:
1) Installation of flue gas diversion ducts and finned heat exchange structures on the exhaust flue to increase the flue's cross-sectional area, reduce gas velocity, and enhance forced convection with the external environment, thereby lowering flue gas temperature, reducing operational flow rate, and ultimately decreasing frictional resistance losses inside the duct.

2) Addition of flue heat exchange units to the exhaust flue to enhance heat exchange efficiency, lower flue gas temperature within the system, reduce the flow rate under working conditions, and consequently reduce frictional resistance losses.

These flue heat exchange systems are positioned on the side of the main flue. However, attention must be paid to designing the diversion duct and finned heat exchanger with anti-dust accumulation features. Additionally, to minimize resistance from the cooling equipment itself, all heat exchange components must be installed on the outer wall surface of the flue to further reduce frictional resistance within the duct.

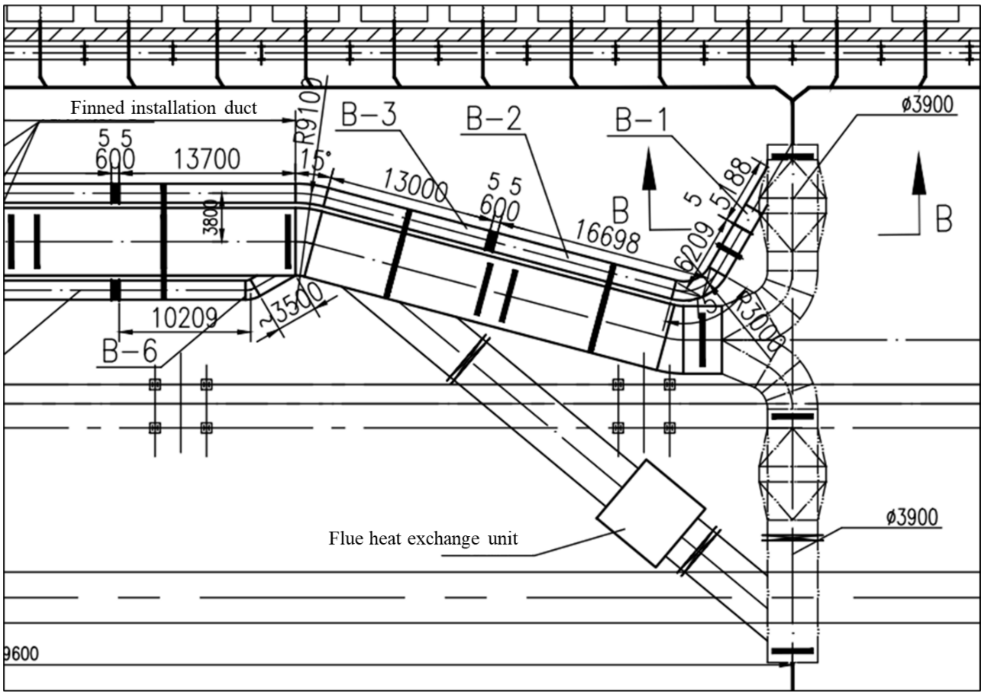

Figure 4. Schematic diagram of the flue gas cooling system retrofit.

3.4 Retrofit of Fans and Their Duct Systems

In a smelter, the operational airflow of the fans exceeds rated parameters, but the pressure is relatively low. The on-site fan operation deviates from optimal conditions, with measured operating efficiency only between 60–68 %. The output is below design specifications, and the actual motor current is nearly at its rated limit. The current fan system consumes high energy and fails to meet the energy reduction needs of the fluorine removal system. Moreover, the original fan inlet and outlet valves are flapper valves. These include shafts and valve plates inside the duct, increasing system pressure loss. The inlet branch duct of the fan connects to the main flue duct at a 90° angle, resulting in high duct pressure loss. Numerical simulations of the current system show that when four fans operate simultaneously, the flue pressure loss alone is about 140 Pa. It is essential to retrofit the existing low-efficiency fans, valves, and duct to improve fan performance and reduce system operating resistance.

The proposed retrofit plan for optimizing the low-efficiency fans and duct systems of the fluorine removal system contains:
1) The fan replacement with high-efficiency fans, using flow field simulations to design optimal structures and aerodynamic performance based on actual working conditions, ensuring smooth airflow within the impeller, reducing losses from vortices and backflow, and achieving optimal

matching among the casing, impeller, and air inlet. This upgrade can increase fan efficiency to over 85 %, while reusing the existing motor to reduce cost.

2) The replacement of the original outlet butterfly valve with a slide gate valve, which introduces no internal resistance when fully opened.

3) The modification of the fan inlet branch duct from a 90° angle to a curvature suited to working conditions, using smooth arc transitions at duct bends to lower resistance, increasing flue gas velocity and pressure.

4. Results from Energy-Saving Retrofit Technologies of the Fluorine Removal System

Taking a smelter with an annual production of 400 kt Al/y and two fluorine removal systems as an example, implementing the above measures can reduce the system pressure losses and improve fan efficiency to over 85 %, leading to lower the total energy consumption. As shown in Table 2, after completing the energy-saving retrofit of the electrolysis flue gas fluorine removal system, total energy consumption can be reduced by approximately 65 kWh/t Al. Consequently, the current system's total power consumption can drop from about 140 kWh/t Al to approximately 75 kWh/t Al. Assuming an annual production of 400 kt Al/y, the power savings would be around 26 GWh/y. Based on an electricity price of 430 RMB/MWh (60 USD/MWh approx.), the estimated annual cost savings would be approximately 11.18 million RMB (1.55 MUSD/y approx.).

Table 2. Energy savings achieved after fluorine removal system retrofit.

No.	Item	Result	Power consumption reduction (kWh/t Al)
1	Retrofit of the upper gas collection flue of the cell	System resistance loss reduced by about 10 %	-22
2	Balancing flue gas flow between the cells	System resistance loss reduced by about 12–14 %	-15
3	Addition of a flue gas cooling system	System resistance loss reduced by about 6–8 %	-8
4	Retrofit of fans and their duct systems	Fan efficiency improved to over 85 %	-20
5	Total		-65

After the energy-saving retrofit of the fluorine removal system, the reconstruction of the upper gas collection flue of the cells enables a more rational distribution of negative pressure, increasing the negative pressure at the aluminium tapping end. The deviation in flue gas flow rate among collection hoods at both the flue duct end and aluminium tapping end remains within ±5 %, improving the gas collection efficiency of the cells. Through balancing flue gas flow between cells without increasing the total system flue gas volume, the flow rate of previously underperforming cells increases. As a result, cells that previously emitted visible flue gas no longer do so after the flow rate is increased. The gas collection efficiency of the electrolysis flue gas system has increased from the previous 98.5 % to above 99 %, significantly improving the working environment in the potroom. Unorganized emissions of pollutants such as sulphur dioxide, dust, and fluorides have been substantially reduced, improving the surrounding plant environment and supporting the enterprise's sustainable development. Meanwhile, with the completion of the flue gas cooling system retrofit, the total exhaust volume of the fluorine removal system has decreased, thereby reducing the total gas emissions.

5. Conclusions

The energy-saving retrofit of the electrolysis flue gas fluorine removal system is of great importance for reducing electrolytic production costs and improving the potroom environment. In production operations, high system pressure loss, poor draft balance inside the cells and low efficiency of the main exhaust fan are the primary causes of excessive power consumption. Energy-saving retrofits for fluorine removal systems must focus on reducing system pressure losses, improving draft balance inside each cell and improving fan efficiency. This paper proposes four technical solutions as a reference for energy-saving and consumption-reduction efforts in fluorine removal, aiming to achieve low-consumption and high-efficiency operation. Traditional energy-intensive environmental protection facilities can indeed attain both economic and sustainable development goals.

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