Stability Study of DeNOx Fluidized Bed Heating System

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Abstract

This paper addresses the operational instability of the denitrification fluidized bed heating system. Through improvements to the external heating method, upgrades to the internal heating rod material, and optimization of the control system, system stability was significantly enhanced. The replacement of the traditional heat radiation external heating furnace with a conduction-type heating furnace increased thermal efficiency by 15% and reduced furnace wall temperature by 80°C. The internal heating rods were fabricated from Inconel718/GH4169 alloy, significantly enhancing high-temperature and corrosion resistance properties. A temperature control system and power compensation program based on PID algorithm were developed, achieving precise temperature control of $±$2°C. Experimental results demonstrate that after optimization, system energy consumption was reduced by 20% and the heating rod failure rate decreased by 90%, providing an effective solution for stable operation of fluidized beds in high-temperature acidic environments.

Full Text

Study on Heating System Stability of Denitrification Fluidized Bed

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Abstract

This paper addresses the instability issues in the heating system of denitrification fluidized beds through improvements in external heating methods, upgrades of internal heating rod materials, and optimization of control systems. The study replaces traditional radiant heating furnaces with conductive heating furnaces, achieving 15% higher thermal efficiency and an 80°C reduction in wall temperature. Inconel718/GH4169 alloy is adopted for internal heating rods, significantly enhancing high-temperature and corrosion resistance. A PID-based temperature control system with power compensation achieves precise temperature regulation within $±$2°C. Test results demonstrate a 20% reduction in energy consumption and 90% decrease in heating rod failures, providing an effective solution for stable operation of fluidized beds in high-temperature acidic environments.

Keywords: denitrification fluidized bed; heating system; conductive heating; Inconel718 alloy; PID control

1 Introduction

The denitrification fluidized bed primarily consists of the equipment main body, electric heating control system, insulation layer, and external heating furnace support frame, and is mainly applied in nuclear chemical facilities. The main body comprises a fluidized bed heating chamber, atomizing nozzle, bed body, backflush gas chamber, and backflush components. This equipment is used for product powder manufacturing, with final collection after discharge from the outlet. To maintain bed temperature, reduce heat loss, and lower energy consumption during operation, the equipment exterior is wrapped with an insulation layer, as shown in Figure 1 [Figure 1: see original paper].

The heating system comprises an external heating furnace (the upper, middle, and lower electric furnaces in Figure 1) and internal heating rods (the red components in Figure 2 [Figure 2: see original paper]). The external heating system is required to provide a stable heat source for the fluidized bed at constant power, maintaining furnace temperature between 550–600°C. The internal heating system requires frequent power adjustment, stabilizing heating rod temperature between 480°C–520°C. These two heating systems work synergistically to maintain the reaction zone temperature within the bed at 300–340°C.

Figure 1 [Figure 1: see original paper]: Fluidized Bed Structure Schematic
Figure 2 [Figure 2: see original paper]: Fluidized Bed Heating System Schematic

This study aims to develop a heating and control system suitable for denitrification fluidized beds to address current operational instability issues in both internal and external heating systems.

2 External Heating System Optimization

2.1 Failure Mechanism Analysis

The original heating furnace was a radiant heating furnace. The furnace chamber utilized aluminum silicate refractory fiber as insulation material (with temperature resistance of 1260–1450°C), which failed to provide adequate thermal insulation. This resulted in excessively high temperatures on the metal outer wall and junction box of the external heating furnace, causing the copper bolts on the terminal posts to overheat. This heat loosened previously secure connections and damaged cable insulation through carbonization, leading to open circuits and short circuits in the power supply lines. Consequently, the middle and lower electric furnaces operated with phase loss. Prolonged operation of the fluidized bed furnace under phase-loss conditions caused the heating elements to burn out, damaging the external heating furnace. Additionally, phase-loss operation increased current in cables and terminal posts, further elevating temperatures.

Furthermore, the connection between the nickel-chromium alloy wire and the furnace wire at the terminal posts of the fluidized bed external heating furnace used stainless steel wire noses with cold riveting. When the furnace wire generated heat, this connection point experienced not only the wire's own temperature but also additional heat from current passing through high contact resistance, causing the stainless steel wire nose to melt and the connection to burn out.

2.2 Conductive Furnace Design

Existing heating furnaces for large equipment primarily include two types: radiant heating furnaces and conductive heating furnaces. A comparison of their performance indicators is presented below:

Table 1 : Heating Furnace Comparison Table

Radiant Heating Furnace	**Conductive Heating Furnace**
Generates infrared radiation through electric heating, primarily heat transfer by radiation	Utilizes electromagnetic induction principle for rapid heating within the metal
High energy consumption, significant heat loss	High energy utilization rate, obvious energy-saving effect
Temperature control precision: Good uniformity but slow response	Precise control of heating zones, high temperature control accuracy
Long heating cycle (dependent on radiation transfer rate)	Fast heating, improved production efficiency
Suitable for materials with high absorption ratio such as carbon steel and alloy steel	Effective for conductive materials, not applicable for non-conductive materials

Based on the above comparison, conductive heating furnaces offer several advantages over radiant heating furnaces:

(1) **Higher thermal efficiency and lower energy consumption**: Conductive heating transfers heat directly through contact between the copper body and the fluidized bed outer wall, reducing losses from heat radiation in air or media. Radiant heating is prone to energy waste through environmental heat dissipation, whereas conductive heating can significantly reduce thermal losses through optimized insulation design. Additionally, adding thermal conductive cement further improves energy utilization.

(2) **More precise and uniform temperature control**: The conductive heating surface can surround the fluidized bed, enabling uniform overall heating and avoiding local overheating or temperature non-uniformity caused by distance variations in radiant heating. Conductive heating can quickly respond to temperature changes by adjusting heat medium flow rate or temperature, making it more suitable for field fluidized bed operating environments.

(3) **Enhanced safety and environmental adaptability**: Conductive heating elements are enclosed within the fluidized bed housing, reducing the risk of personnel burns.

Based on the above analysis, the fluidized bed external heating system was changed from a radiant heating furnace to a conductive heating furnace.

3 Material Analysis of Internal Heating Rods

3.1 Failure Mechanism and Material Requirements

When abnormal operating conditions occur inside the fluidized bed, the distribution plate becomes blocked. This blockage affects the main control operator's judgment of the discharge endpoint. Under abnormal conditions, excessive discharge can easily cause material to accumulate on the fluidized bed walls and fall between heating rods, preventing heat dissipation from the rods. The temperature measurement points participating in the internal heating system control are located at T3/T4 points in the fluidized bed, which cannot properly reflect abnormal temperature rises on the heating rod surfaces. Additionally, the accumulated material prevents temperature conduction from below the heating rods to the upper measurement points, resulting in slower bed temperature rise. The control program continues to supply power, causing the heating rod surface temperature to increase continuously and leading to plastic deformation of the metal rod. Chemical reactions such as oxidation, decarburization, and hydrogen absorption form oxide layers and decarburized layers on the metal surface. When heat dissipation from the heating rods is severely compromised, the internal heating elements fuse, causing heating rod circuit breakage.

3.2 Material Selection and Comparison

Based on fluidized bed operational experience, heating rods typically operate above 400°C during internal heating. Due to the presence of uranyl nitrate solution and nitric acid solution, heating rods are prone to creep, bending, or even breakage in this environment, with severe oxidation and carbonization of stainless steel surfaces. Considering the special high-temperature acidic environment of the field fluidized bed, internal heating rod materials must possess high-temperature resistance, corrosion resistance, high strength, and oxidation resistance. A comparison of various heating rod materials is presented in Table 2 .

Table 2 : Comparison of Stainless Steel Materials

Material	Properties	Characteristics	Applications
316 Stainless Steel Alloy Density: 7.98g/cm^{3}Melting point: 1370-1450℃Yield strength: $ 205N/mm^{2}$Tensile strength: $ 520N/mm^{2}$Hardness (HB): $ 187	High tensile strength, fatigue strength, creep strength, and fracture strength at 700°C, high oxidation resistance at 1000°C	Liquid fuel rocket engines	

$ 187|Goodcorrosionresistance, high−temperaturestrength, andgoodmanufacturability||||∗
∗310SStainlessSteelAlloy∗
∗ < br >
Density :
7.93g/cm^{3}$Melting point: 1400-1530℃Yield strength: $ 205N/mm^{2}$Tensile strength: $ 520N/mm^{2}$Hardness (HB):
$ 187|Certaincorrosionresistanceandgoodoxidationresistanceinhigh−temperatureenvironments|Automotivepurificationdevices|||∗
∗INCONEL625Alloy∗
∗ < br >
Density :
8.4g/cm^{3}$Melting point: 1290-1350℃Yield strength: $ 345N/mm^{2}$Tensile strength: $ 760N/mm^{2}$Hardness (HB):
$ 220|Excellentacidcorrosionresistance(nitricacid, phosphoricacid, sulfuricacid, hydrochloricacid), maxim
termuseat550−700°C, plasticitydecreases|Enginemanufacturing|||∗
∗INCONEL718/GH4169∗
∗ < br >
Density :
8.24g/cm^{3}$Melting point: 1260-1320℃Yield strength: $ 550N/mm^{2}$Tensile strength: $ 965N/mm^{2}$Hardness (HB): $ $363

Material	Properties	Characteristics	Applications

Based on the comparison of different stainless steel materials in the table, Inconel718/GH4169 alloy was selected for the internal heating rod surface material.

4 Control System Optimization

4.1 PID Algorithm Implementation

Currently, fluidized bed temperature control employs manual operation, where operators continuously adjust the heating power of both internal and external heating systems based on bed temperature to achieve stable operation. However, human response speed is limited by operator judgment and execution time, making it difficult to handle dynamic changes. Operator experience, fatigue levels, or distraction may lead to inconsistent regulation results, and manual response may be delayed or erroneous in emergency situations. Therefore, a PID program was considered to implement automatic regulation of the fluidized bed, offering the advantage of rapidly accepting input parameters, judging their values, and accurately and quickly outputting setpoints.

PID is a closed-loop feedback control algorithm that stabilizes fluidized bed system output quickly at the setpoint through the combined action of three components: proportional (P), integral (I), and derivative (D). Its mathematical expression is:

$$u(t) = K_p e(t) + K_i \int e(T)dT + K_d \frac{de(t)}{dt}$$

Where: - $u(t)$: control output (heating power) - $e(t)$: deviation between setpoint and actual value ($e = \mathrm{SP} - \mathrm{PV}$) - K_p, K_i, K_d: proportional, integral, and derivative coefficients

In the fluidized bed temperature control system, the required temperature at key measurement points in the bed can be set as SV and input to the controller. The controller calculates the error between the actual temperature value (PV) and SV. This temperature error serves as the input signal to the PID controller. After calculation by the PID control program, relevant signals for heater power adjustment are input to the power regulator, which then outputs matching power to control the heater temperature and thus the actual temperature in the bed. The error between PV and SV is then recalculated and input to the PID controller again for control. Through multiple PID control iterations, the error between PV and SV becomes progressively smaller, continuously approaching SV until stability is achieved. The schematic diagram is shown in Figure 3 [Figure 3: see original paper].

Figure 3 [Figure 3: see original paper]: Schematic of PID Control Mechanism

4.2 Distributed Power Compensation

The fluidized bed has frequently experienced abnormal temperature increases due to material accumulation on heating rods during operation. Sustained operation under such abnormal conditions can easily lead to heating rod burnout. To reduce heating rod failure rates, over-temperature protection is required—when temperature abnormally increases, the power to that heating rod must be reduced to lower its temperature. However, reducing heating rod power causes the bed temperature to drop, failing to meet operational requirements.

Therefore, a power compensation program was implemented for the heating rod control system. The specific implementation steps are as follows:

4.2.1 Heating Rod Material Upgrade The heating rod surface material was upgraded to Inconel718/GH4169 alloy. Thermocouples were added inside each heating rod and connected to the control system, enabling real-time temperature monitoring and over-temperature protection control for each individual rod.

4.2.2 Control Cabinet Design The internal heating rod control system is installed in a local control cabinet. Bed temperature is controlled by adjusting the power of fluidized bed internal heating rods. Temperature measurement points are installed on the heating rods and connected as controlled signals to the internal heating rod control system, which includes over-temperature alarm protection for individual rods. The local control cabinet features a reliable and intuitive human-machine interface, enabling convenient local start/stop of heating rods, manual or automatic temperature adjustment, switching between manual and automatic power regulation, local/remote control switching, current monitoring, and temperature monitoring functions.

The 28 heating rods are divided into three rings from inside to outside (see Figure 4 [Figure 4: see original paper]). These three rings are controlled by five power regulators, with each thyristor controlling 4–6 heating rods. Each heating rod is equipped with an independent circuit breaker, and current transformers are installed in each heating rod circuit. Through logical judgment in the local control system and over-temperature alarm functions, fault alarm signals can be issued for each individual heating rod. When a fault signal is detected, the heating rod triggers an over-temperature alarm, indicating possible abnormal conditions in that zone. Simultaneously, the system reports to the main control to reduce the power of that heating rod group by 10% while increasing the power of adjacent heating rod groups, thereby protecting the heating rods while ensuring no heat loss in the fluidized bed.

Figure 4 [Figure 4: see original paper]: Schematic Diagram of Internal Heating Temperature Compensation Principle
Figure 5 [Figure 5: see original paper]: Distribution of Temperature Measurement Points in Fluidized Bed Heating Rod Groups

5 Experimental Validation

5.1 External Heating Furnace Testing

After installing the new heating furnace, a temperature rise test was conducted on the fluidized bed external heating furnace, with comparative data collected from the old heating furnace under identical conditions. The comparison results are as follows:

Table 3 : Comparative Tests of External Heating Furnace for Fluidized Bed

Parameter	Old Furnace	New Furnace
	42L/h	44L/h
External Heating Upper Section		
Heating Power Percentage		
Furnace Temperature (°C)		
Current (A)		
External Heating Middle Section		
Heating Power Percentage		
Furnace Temperature (°C)		
Current (A)		
External Heating Lower Section		
Heating Power Percentage		
Furnace Temperature (°C)		
Current (A)		
Key Bed Temperature Points		
Heating Power Percentage		
Temperature (°C)		
Current (A)		
T3 Point Temperature (°C)		
T4 Point Temperature (°C)		

The test data demonstrates that the new heating furnace meets the required operating temperatures while consuming less heating power and achieving higher thermal efficiency compared to the old heating furnace.

5.2 Internal Heating Rod Testing

Two new heating rods were randomly selected. After measuring normal resistance values, they were compared with original fluidized bed equipment heating rods in a temperature rise test under different power levels connected to a power regulator. The test data is presented below:

Table 4 : Comparative Test Data on Temperature Rise of Heating Rods

Parameter	Reference Rod 1 (1.5kW)	Test Rod 2 (2kW)	Test Rod 3 (2kW)
Current (A)			
Voltage (V)			

Figure 6 [Figure 6: see original paper]: Temperature Curves from Comparative Tests of Electric Heating Rods

The fluidized bed external heating was started for temperature rise. When the fluidized bed reaction zone temperature reached 310°C, internal heating rod power tests were conducted:

The set temperature was configured on the control cabinet touchscreen (>320°C). During the heating process, internal heating power was set to 25%, 50%, 75%, and 100% to start internal heating, and the current of each internal heating rod was measured and recorded.

Table 5 : Record of Temperature Variation with Power for Internal Heating Rods

Parameter	25% Power	50% Power	75% Power	100% Power
Heating Rod Current (A)				

Figure 7 [Figure 7: see original paper]: Temperature vs. Power Curves for Internal Heating Rods in Fluidized Bed

The test data indicates that the new heating rods demonstrate improved heating performance and operate without abnormal conditions under various power levels, meeting field usage requirements.

6 System Stability Analysis

After establishing test conditions, the frequency of five heating rod groups was manually adjusted through the field control cabinet to observe the temperature variation range at key fluidized bed points, with comparison to pre-adjustment temperatures. The test data obtained is as follows:

Table 6 : Record of Temperature Variation with Power for Internal Heating Rods

Group 1 Temperature Compensation Test - Compensation Value: 10% - Voltage (V): 52.5% for all measurements - Temperature Before Compensation (°C): - Temperature After Compensation (°C):

Group 2 Temperature Compensation Test - Compensation Value: 10% - Voltage (V): 52.5% for all measurements - Temperature Before Compensation (°C): - Temperature After Compensation (°C):

Group 3 Temperature Compensation Test - Compensation Value: 10% - Voltage (V): 52.5% for all measurements - Temperature Before Compensation (°C): - Temperature After Compensation (°C):

Group 4 Temperature Compensation Test - Compensation Value: 10% - Voltage (V): 52.5% for all measurements - Temperature Before Compensation (°C): - Temperature After Compensation (°C):

Group 5 Temperature Compensation Test - Compensation Value: 10% - Voltage (V): 52.5% for all measurements - Temperature Before Compensation (°C): - Temperature After Compensation (°C):

After commissioning, a temperature rise was observed in one heating rod during operation. The temperature variation range at key fluidized bed points was examined and compared with pre-change temperatures, with relevant data recorded as follows:

Table 7 : Adjustment Data Under Actual Operating Conditions

Automatic Temperature Compensation Test - Compensation Value: 10% - Voltage (V): 52.5% for all measurements - Temperature Before Compensation (°C): - Temperature After Compensation (°C):

Through comparative analysis of manual adjustment and actual operating condition data, the temperature regulation system demonstrates accurate, stable, and reliable operation, meeting the requirements for normal process operation.

7 Conclusions

Through this fluidized bed stability research and testing, the heating method of the fluidized bed furnace was first optimized, followed by upgrading the heating rod material, and finally upgrading the fluidized bed control system. Experimental verification demonstrates:

(1) The new heating furnace meets heating functional requirements, with slightly better heating performance than the old furnace.

(2) The optimized and upgraded internal heating rods exhibit superior heating performance compared to the original rods. The upgraded manufacturing process reduces heating rod failure rates and enables real-time temperature observation of each individual rod, preventing abnormal operating conditions.

(3) When the temperature compensation program in the control system is activated, it can effectively reduce power to abnormally hot heating rods while maintaining the bed temperature at the required reaction temperature, thereby improving fluidized bed system stability.

This research, targeting “precision, efficiency, and reliability,” improved the existing fluidized bed heating system through technological innovation and engineering practice. Verification confirmed that the heating stability of the fluidized bed heating system has been significantly enhanced, providing valuable experience for stable operation of denitrification fluidized beds.

References

[1] Wen Chao, et al., "A Control Method and System for Post-Treatment Fluidized Bed," Application Number: 202311269818
[2] Li Qiang, et al., *Principles and Applications of Fluidization* [M]. Xuzhou: China University of Mining and Technology Press, 1994
[3] Yao Libing, "Development Trends of Fluidized Beds" [J]. *Pharmaceutical Engineering Design*, 1989(6), 16-19
[4] Lin Aiguang, *Fundamentals of Chemical Engineering* [M]. Beijing: Tsinghua University Press, 1999
[5] Jiang Guoqiang, "Application of Temperature Control Systems in Fluidized Beds" [J]. National Defense Industry Press, 2003
[6] Le Jiaqian, *Instrument Technician Handbook* [M]. Beijing: Chemical Industry Press, 2003:232
[7] Yuan Baoqi, *Principles and Design of Heating Furnaces* [M]. Aviation Industry University Press, 1989-06

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Note: Figure translations are in progress. See original paper for figures.