High-Efficiency Catalytic Oxidation Technology for Tight-Gas Flash Gas Based on High-Activity Catalysts and an Integrated Reactor

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Abstract: The exhaust gas emitted from atmospheric flash tanks in tight gas fields contains large quantities of volatile organic compounds (VOCs) and methane, causing atmospheric pollution. Effective treatment is therefore urgently required to achieve compliant emissions. After a comparative analysis of various VOCs treatment technologies, catalytic oxidation was selected. Because flash gas is composed mainly of methane and low-chain alkanes, whereas conventional transition-metal catalysts or catalysts with low precious-metal contents show relatively low conversion efficiencies for such components, this study focused on the effects of Pt/Pd precious-metal loading and space velocity on conversion efficiency and reaction temperature rise, and optimized the catalytic furnace structure to achieve effective temperature-rise control. When the precious-metal content in the catalyst exceeded 3 kg/m^3, the methane conversion efficiency exceeded 98.5% at an ignition temperature of 390 °C. Meanwhile, owing to the high heat release during catalytic oxidation, dilution with 180 volumes of air, combined with in-furnace heat-recovery design, effectively controlled the maximum temperature of the catalytic furnace within 450 °C. Increasing the Pt/Pd precious-metal loading in the catalyst can effectively solve the difficulty of removing VOCs and methane from flash gas; controlling the amount of supplemental air can effectively suppress reaction temperature rise; and coupling these measures with a novel catalytic oxidation furnace structure featuring heat recovery enables the efficient, stable, and safe treatment of atmospheric flash-gas exhaust in tight gas fields.

1 Introduction

Tight gas fields, during the production process, deliver oil-gas mixtures from the high-pressure subsurface environment into atmospheric flash tanks at the surface. During depressurization and temperature increase, volatile organic compounds (VOCs) such as light hydrocarbons desorb from the oil phase and flash out. When the liquid level and gas pressure in the flash tank reach the preset values, the system releases this portion of waste gas. This waste gas is rich in VOCs and methane and is an important source of atmospheric pollutants[1-3].

As key precursors in photochemical smog reactions, VOCs participate in the formation of ozone (O_3) and secondary organic aerosols (SOA), thereby exerting significant effects on urban atmospheric oxidizing capacity and fine particulate matter ($PM_{2.5}$) pollution. In addition, methane is a potent greenhouse gas with a global warming potential (GWP) far higher than that of carbon dioxide[4-6]. Therefore, effective treatment of the exhaust gas emitted from atmospheric flash tanks in tight gas fields is of great practical significance and strategic value for safeguarding regional environmental security, controlling greenhouse gas emissions, and promoting the sustainable development of the oil and gas industry.

At present, VOCs treatment technologies mainly include thermal incineration, catalytic oxidation, absorption, adsorption, condensation, low-temperature plasma, and photocatalytic oxidation. Among them, thermal incineration (open-flame combustion) and catalytic oxidation (flameless combustion) can not only remove VOCs but also effectively oxidize methane[7-8]. However, thermal incineration imposes strict requirements on site safety and may generate black smoke because of incomplete combustion when treating exhaust gases containing long-chain hydrocarbons. Considering that the gas emission from atmospheric flash tanks in tight gas fields is relatively small, consists mainly of low-boiling hydrocarbons, and fluctuates considerably in flow rate, catalytic oxidation is more suitable. The catalysts currently used in catalytic oxidation are mostly designed for conventional VOCs and generally exhibit low oxidation efficiencies for methane and other low-chain alkanes, and they are mostly applicable to low-concentration exhaust gas[9]. Therefore, developing an efficient catalytic oxidation technology suitable for flash gas with high concentration and high methane content, while addressing key issues such as catalyst activity and reaction temperature-rise control, has become a major technical priority. In response to these challenges, this study systematically investigated catalyst selection,

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strategies for controlling reaction temperature rise, and the optimized design of the catalytic furnace structure, with the aim of providing technical support for the efficient treatment of atmospheric flash-gas exhaust in tight gas fields.

2 Technical Analysis

2.1 Characteristics of the Exhaust Gas

The waste gas emitted from atmospheric flash tanks in tight gas fields consists mainly of methane (CH_4), while the remaining components are mostly low-chain alkanes such as ethane and propane, together with a small amount of nitrogen. However, owing to differences in geological conditions among gas fields, the specific composition of flash-gas exhaust also varies. A typical composition analysis is shown in Table 1.

Table 1 Typical analysis report of flash-tank exhaust-gas composition

Component content			
Component	Mole percentage	Component	Mole percentage
Methane (C_1)	73.5296	Hexane (C_6)	0.3778
Ethane (C_2)	12.8960	Heptane (C_7)	0.0288
Propane (C_3)	6.0663	Octane (C_8)	0.0451
Isobutane (iC_4)	1.9397	Carbon dioxide (CO_2)	0.0000
n-Butane (nC_4)	2.3984	Nitrogen (N_2)	0.8622
Isopentane (iC_5)	1.0937	Hydrogen sulfide (H_2S)	0.0000
n-Pentane (nC_5)	0.7624	Total component content	100
Characteristic parameters			
Total heavy hydrocarbons (%)	0.4518	Relative density	0.7888
Compressibility factor	0.9917	Critical temperature (k)	232.1157
Higher heating value (MJ/m^3)	49.9372	Critical pressure (MPa)	4.5370
Lower heating value (MJ/m^3)	45.4052	Density (g/L)	0.9612

2.2 Analysis of Existing VOCs Treatment Processes

At present, VOCs treatment technologies mainly include thermal incineration, catalytic oxidation, absorption, adsorption, condensation, low-temperature plasma, and photocatalytic oxidation[7], as well as combined processes based on these technologies. The principles, advantages, and disadvantages of these technologies are compared in Table 2.

Table 2 Principles, advantages, and disadvantages of existing VOCs treatment technologies[10-12]

Technology	Principle	Advantages	Disadvantages
Pressurized recovery	VOCs partial pressure is increased by pressurization, followed by throttling and cooling to below the saturated vapor pressure to achieve liquefaction and recovery.	Resources can be recovered and utilized.	High energy consumption; high requirements for stable operating conditions; high failure rate under large fluctuations.
Thermal incineration	VOCs are directly oxidized into CO_2 and H_2O by open-flame combustion.	High removal efficiency; suitable for high-concentration exhaust gas.	High safety requirements; incomplete combustion may occur when treating exhaust gas containing long-chain hydrocarbons, generating black smoke; NOx may also be produced.
Catalytic oxidation	A catalyst is used to lower the activation energy of the oxidation reaction so that VOCs are oxidized to CO_2 and H_2O below the ignition temperature.	Flameless operation with high safety; high precision in outlet concentration control; relatively low energy consumption.	The oxidation process is exothermic, so temperature rise must be controlled for highly exothermic components such as alkanes; conventional catalysts show low methane oxidation efficiency.
Condensation	The gas is cooled below the dew point of VOCs to condense and liquefy them.	VOCs can be recovered.	For low-boiling, high-vapor-pressure components such as C1-C3, the required condensation temperature is extremely low, leading to very high energy consumption; poor outlet concentration control accuracy.
Adsorption	VOCs are adsorbed through van der Waals forces by porous	High removal efficiency; suitable for	Only transfers pollutants rather than destroying them completely; adsorbents require periodic

	adsorbents such as activated carbon.	low-concentration exhaust gas; outlet concentration can reach the ppm level.	regeneration or replacement, posing a risk of secondary pollution; unsuitable for high-concentration exhaust gas.
Low-temperature plasma / photocatalysis	High-energy electrons or photogenerated radicals are used to oxidize and decompose VOCs.	Can operate at ambient temperature and pressure.	Generally low removal efficiency; prone to secondary pollutants such as ozone; current specifications mostly restrict them to deodorization rather than VOCs-compliance treatment.

A comprehensive analysis indicates that the waste gas emitted from atmospheric flash tanks in tight gas fields is characterized by small gas volume, high component concentration, predominance of low-boiling hydrocarbons such as C_1-C_3, and large flow-rate fluctuations. Therefore, pressurized recovery is unsuitable because of its high energy consumption and stringent requirements for stable operating conditions. Thermal incineration (combustion/flare) offers high removal efficiency but imposes strict safety requirements and is prone to black-smoke generation because of incomplete combustion. Condensation requires extremely low temperatures for low-boiling, high-vapor-pressure components, resulting in high energy consumption and poor outlet concentration control. Adsorption shows high removal efficiency, but it merely transfers pollutants rather than destroying them completely and therefore cannot independently ensure compliance. Photocatalysis and low-temperature plasma technologies exhibit low removal efficiencies, and current standards have explicitly limited them to deodorization rather than VOCs treatment. In contrast, catalytic oxidation is more suitable for such exhaust gas because it is flameless and offers high precision in outlet concentration control. However, the high alkane content in flash gas leads to substantial heat release during catalytic oxidation, making a significant temperature rise likely and thereby affecting catalyst lifetime and equipment safety. At the same time, the stable molecular structures of low-chain alkanes make oxidative bond cleavage difficult, placing higher demands on catalyst activity[13]. Therefore, catalyst performance, effective control of reaction temperature rise, and catalytic-reactor structural design are the key challenges for the successful implementation of this technology.

3 Construction of Experimental Apparatus

3.1 Catalyst Selection

In this study, a cordierite honeycomb ceramic body was used as the primary carrier, while high-performance modified alumina and rare-earth composite oxides were used as the secondary carriers. A highly dispersed and uniformly coated preparation process was adopted, and transition metals such as Ti, V, and Co were loaded as the main active components to prepare a catalyst for organic waste-gas purification. Such transition-metal-loaded catalysts have already been widely applied in VOCs treatment projects in industries including food processing, machinery, automobile manufacturing, and petrochemicals, and they show high removal efficiencies for oxygen-containing organic compounds such as alcohols, ethers, and esters[14]. However, for tight-gas flash gas composed mainly of methane and low-chain alkanes, their catalytic oxidation activity is generally insufficient. Therefore, on the basis of the above catalyst, this study further loaded precious metals such as Pt and Pd, with the aim of preparing a catalyst capable of efficiently oxidizing and converting low-chain alkanes and methane[15-17].

3.1.1 Selection of Catalyst Composition

According to engineering practice, in order to achieve efficient removal of low-chain alkanes and methane from tight-gas flash gas, with a target removal efficiency of at least 90%, the catalyst must be loaded with precious metals such as Pt and Pd at relatively high loadings[18-19]. To this end, Pt/Pd precious metals with different loadings were loaded onto a cordierite honeycomb ceramic carrier, and their catalytic oxidation efficiencies for methane at different temperatures were investigated. The results are shown in Figure 1.

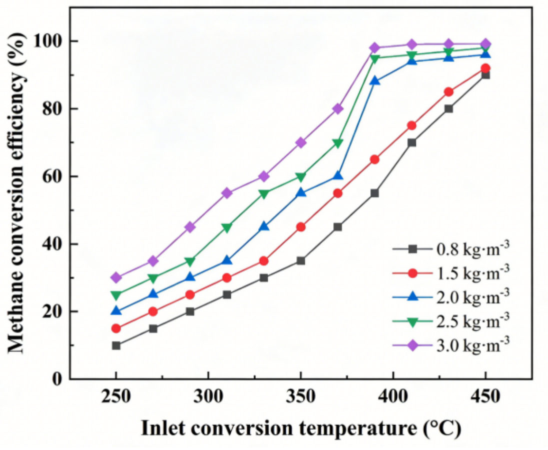


Figure 1 Effect of catalysts loaded with different amounts of Pt/Pd precious metals on methane oxidation conversion efficiency

The experimental results indicate that the Pt/Pd precious-metal loading is a key factor affecting methane catalytic oxidation efficiency. At the same temperature, methane conversion efficiency increases significantly as the precious-metal content in the catalyst increases[20], and this effect becomes particularly obvious above 375 °C. At a reaction temperature of 450 °C, when the precious-metal content is below 2 kg/m^3, the methane conversion efficiency remains below 90%. When the content reaches 2 kg/m^3, the conversion efficiency can reach 95.0%; however, the catalytic furnace temperature is then relatively high and the system energy consumption increases, which is unfavorable for long-term stable operation. Considering conversion efficiency, energy consumption, and operational economy comprehensively, the Pt/Pd precious-metal loading of the catalyst was ultimately determined to be not less than 3 kg/m^3. Under this condition, when the reaction temperature is controlled at approximately 390 °C, methane conversion efficiency can exceed 98.0%, thereby achieving the optimized goal of high conversion efficiency with low energy consumption.

3.1.2 Selection of Space Velocity

Space velocity is a key operating parameter affecting catalytic oxidation efficiency. The higher the space velocity, the shorter the residence time of the waste gas in the catalyst bed, which leads to a decrease in the catalytic oxidation efficiency of methane and low-chain alkanes[21-22]. Accordingly, this study prepared a catalyst with a Pt/Pd loading of 3 kg/m3 and tested its methane oxidation efficiency at various space velocities. The results are shown in Figure 2.

The experimental results indicate that, at the same temperature, methane conversion efficiency decreases with increasing space velocity. When the reaction temperature is 390 °C and the space velocity is no more than 20,000 m^3/h, the conversion efficiency exceeds 93%; when the space velocity is no more than 15,000 m^3/h, the conversion efficiency can reach 98%. However, space velocity is proportional to the required catalyst volume, and a lower space velocity means a larger catalyst filling volume is needed. Experimental data show that the catalyst packing volume at a space velocity of 10,000 m^3/h is approximately 1.5 times that required at 15,000 m^3/h, which would significantly increase equipment investment and catalyst replacement costs and would therefore be economically less favorable. Taking treatment efficiency, catalyst consumption, and long-term operational economy into account, the optimal space velocity was finally determined to be 15,000 m^3/h. Under this space velocity, with a precious-metal loading of 3 kg/m^3 and a reaction temperature of approximately 390 °C, methane conversion efficiency can be stably maintained at 98.0%, thereby balancing the dual objectives of high efficiency and high economic benefit.

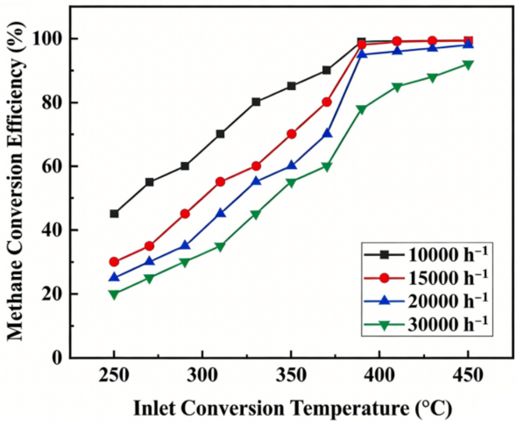
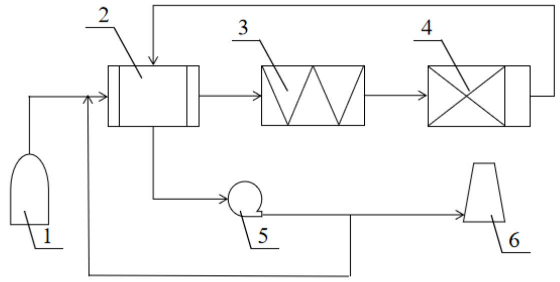


Figure 2 Effect of catalysts loaded with 3 kg/m^3 Pt/Pd precious metals on methane oxidation conversion efficiency under different space velocities

3.2 Process Flow

Based on the catalyst performance and the composition characteristics of tight gas, this study established a set of experimental apparatus for the catalytic oxidation of exhaust gas from tight gas fields, and its process flow is shown in Figure 3.



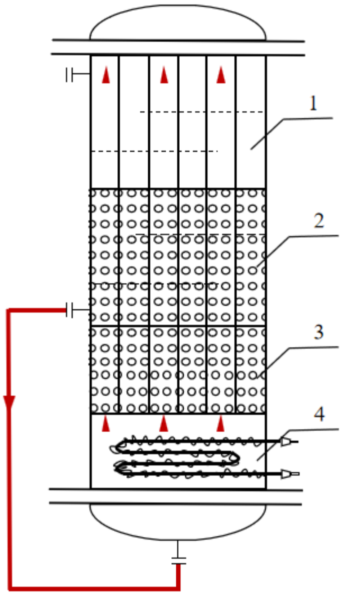
1 Tight gas mixture simulation cylinder
2 Mixer
3 Heat exchange zone
4 Heating zone
5 Catalytic reaction zone
6 Fan
7 Chimney

Figure 3 Simulation device for tight gas VOCs treatment

In this study, a tight gas mixture simulation cylinder was used to supply the multi-component simulated exhaust gas required for the experiment. The gas first entered the mixer to be blended with air and part of the high-temperature purified gas. After uniform mixing, it flowed into the heat exchange zone (3) for countercurrent heat exchange with the high-temperature purified gas from the subsequent catalytic reaction, thereby realizing heat recovery and preheating.Subsequently, the gas entered the heating zone (4) and was precisely heated to the target reaction temperature, before passing into the catalytic reaction zone (5), where efficient catalytic oxidation of methane and volatile organic compounds (VOCs) was completed under the action of the catalyst.The high-temperature purified gas after the reaction re-entered the heat exchange zone (2) to be cooled by heat exchange with the feed gas, and was then delivered by the fan (5) to the chimney (6) for discharge up to standard. According to operational conditions, a small portion of the cooled purified flue gas after heat exchange was recycled back to the mixer.Through thermal coupling circulation, this device effectively improved the system energy utilization efficiency, providing a reliable experimental platform for performance evaluation and mechanism research on the catalytic purification of exhaust gas from tight gas fields.

3.3 Catalytic Furnace Structure

The core of the tight gas VOCs treatment technology in this study resides in the reactor. Accordingly, an integrated tubular catalytic oxidation reactor was designed with a tube-shell configuration. Active control of the reaction temperature was realized via internal heat exchange, so as to mitigate the temperature rise caused by the high exothermic reaction [24–25].



1 Preheating zone 2 Catalytic / temperature control Zone
3 Deep oxidation zone 4 Heating zone

Figure 4 Schematic diagram of the catalytic oxidation reactor structure

As shown in Figure 4, the reactor is designed axially into four functional zones in sequence.The diameter of the reactor is 250mm and the height of the reactor is 1500mm，The preheating zone is 600 mm in height, the catalytic/temperature control zone is 400 mm, the deep oxidation zone is 300 mm, and the heating zone is 200 mm. The loading volume of the cylindrical catalyst is 35 L.The first zone is located at the top of the reactor and serves as the preheating/heat-exchange zone. No catalyst is packed in the tube side, which is used only as a preheating passage for the cold mixed gas. The high-temperature outlet gas flowing through the shell side transfers heat to the gas in the tube side by heat exchange, thereby realizing energy recovery, and the tube-side outlet temperature in this zone is approximately 320℃, the shell-side outlet temperature is about 235℃. The second zone is the catalytic/temperature-control zone. The tube side is packed with a catalyst for the main catalytic oxidation reaction, while the shell side continues to use the waste heat of the high-temperature outlet gas to heat the reaction zone and maintain temperature stability, thereby effectively suppressing reaction temperature rise,and the tube-side outlet temperature in this zone is approximately 450℃, the shell-side outlet temperature is about 360℃. The third zone is the deep oxidation zone. The tube side is likewise packed with catalyst, but no external heat exchange is applied. This zone operates at a relatively high temperature to ensure complete oxidation of residual VOCs and thus guarantee compliance with the final emissions,and the tube-side outlet temperature in this zone is approximately 450℃, the shell-side outlet temperature is about 390℃. The fourth zone is located at the bottom of the reactor and serves as the auxiliary heating zone. It is equipped with an internal electric heating device to provide supplementary heat during system start-up or under low-load operating conditions, thereby maintaining the minimum temperature required for the reaction[26].

In summary, by integrating heating, catalytic reaction, and heat-recovery functions into a single device, the catalytic oxidation reactor not only realizes efficient energy utilization and effective control of temperature rise during the reaction process, but also simplifies the system flow and reduces equipment investment and operating energy consumption. It therefore provides key equipment support for the stable, efficient, and energy-saving treatment of atmospheric flash-gas exhaust from tight gas fields.

4 Experimental Procedures and Methods

Experimental equipment and instruments: catalytic oxidation reactor (custom-fabricated), standard mixed gas（Prepared according to the main components of tight gas）, platinum resistance thermometer (Pt100), and gas chromatograph equipped with a flame ionization detector (GC-FID) for detecting methane and total non-methane hydrocarbons.

Experimental method: The experimental process flow is shown in Figure 5. First, the valve of the standard mixed-gas cylinder was closed, the air valve was opened, air was introduced, and the system was preheated using the built-in electric heating device of the reactor. When the outlet temperature of the catalytic bed reached 390 °C, the air supply was stopped and the air valve was closed. Subsequently, the valve of the standard mixed-gas cylinder was opened, and the simulated waste gas was introduced into the reaction system. The temperature of the reaction bed was maintained within the range of 390-500 °C through the temperature-control system. The tail gas after reaction was monitored online in real time using GC-FID to determine the concentration of non-methane hydrocarbons (NMHC) and evaluate the catalytic oxidation performance.

The exhaust gas flow rate of the system during operation is 0.6 m^3 /h.

4.1 Supplemental Air Addition

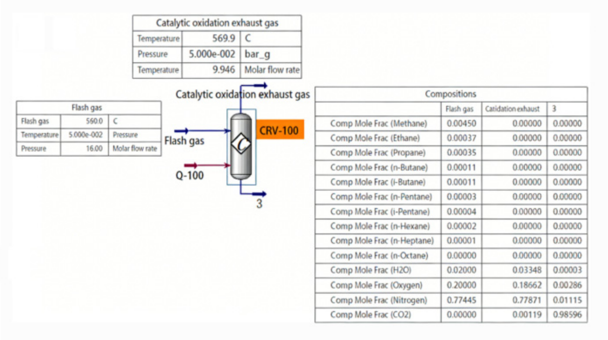
Because the waste gas emitted from the flash tank itself contains no oxygen, air must be added to the waste gas to provide the oxidant required for catalytic oxidation[23]. However, because flash gas consists mainly of alkanes, its catalytic oxidation is a strongly exothermic process that releases a large amount of heat, causing a sharp increase in the temperature of both the reaction gas and the catalytic furnace, that is, reaction temperature rise. Excessive temperature rise not only seriously affects catalyst activity and selectivity, but may also lead to catalyst sintering and deactivation. At the same time, excessively high furnace temperatures also threaten the material strength of the reactor and the safety of long-term operation. Therefore, effective control of reaction temperature rise is a key aspect of this technical scheme. In this study, the amount of supplemental air was controlled to dilute the flash gas and reduce the initial concentration of reactants, namely alkanes, thereby effectively controlling heat release and the final temperature rise during the reaction process. The relationship between dilution ratio and concentration is shown in Table 3.

Table 3 Component concentrations of the mixed gas under different air dilution ratios

Component	Flash gas concentration V%	Dilution 80 V%	Dilution 100 V%	Dilution 120 V%	Dilution 150 V%	Dilution 180 V%
Methane	80.91	1.011	0.809	0.81	0.6743	0.4495
Ethane	6.71	0.084	0.067	0.07	0.0559	0.0373
Propane	6.39	0.080	0.064	0.06	0.0532	0.0355
n-Butane	2.02	0.025	0.020	0.02	0.0168	0.0112
i-Butane	1.89	0.024	0.019	0.02	0.0158	0.0105
n-Pentane	0.51	0.006	0.005	0.01	0.0043	0.0029
i-Pentane	0.79	0.010	0.008	0.01	0.0066	0.0044
n-Hexane	0.44	0.005	0.004	0.00	0.0036	0.0024
n-Heptane	0.12	0.002	0.001	0.00	0.0010	0.0007
n-Octane	0.04	0.001	0.000	0.00	0.0003	0.0002
H_2O	0	2.00	2.00	2.00	2.00	2.00
Nitrogen	0.18	77.40	77.60	77.60	77.73	77.96
O_2	0	19.35	19.40	19.40	19.43	19.49

4.1.1 Simulation of Temperature Rise under Operating Conditions after Air Addition

To evaluate the effect of the amount of supplemental air on reaction temperature rise, simulation software was used to model the operating conditions. The mixed-gas compositions under different dilution ratios, shown in Table 3, were used as inputs, and complete oxidation of all components, that is, a conversion rate of 100%, was assumed in order to calculate the adiabatic temperature rise. Taking the case of adding 180 volumes of air as an example, the simulation results are shown in Figure 5.



Catalytic oxidation exhaust gas		
Temperature	569.9	C
Pressure	5.000e-002	bar_g
Temperature	9.946	Molar flow rate

Flash gas		
Flash gas	560.0	C
Temperature	5.000e-002	Pressure
Pressure	16.00	Molar flow rate

Compositions			
	Flash gas	Catidation exhaust	3
Comp Mole Frac (Methane)	0.00450	0.00000	0.00000
Comp Mole Frac (Ethane)	0.00037	0.00000	0.00000
Comp Mole Frac (Propane)	0.00035	0.00000	0.00000
Comp Mole Frac (n-Butane)	0.00011	0.00000	0.00000
Comp Mole Frac (i-Butane)	0.00011	0.00000	0.00000
Comp Mole Frac (n-Pentane)	0.00003	0.00000	0.00000
Comp Mole Frac (i-Pentane)	0.00004	0.00000	0.00000
Comp Mole Frac (n-Hexane)	0.00002	0.00000	0.00000
Comp Mole Frac (n-Heptane)	0.00001	0.00000	0.00000
Comp Mole Frac (n-Octane)	0.00000	0.00000	0.00000
Comp Mole Frac (H2O)	0.02000	0.03348	0.00003
Comp Mole Frac (Oxygen)	0.20000	0.18662	0.00286
Comp Mole Frac (Nitrogen)	0.77445	0.77871	0.01115
Comp Mole Frac (CO2)	0.00000	0.00119	0.98596

Figure 5 Simulated results of reaction temperature rise after air addition

The simulation results show that under the condition of adding 180 volumes of air, that is, dilution by a factor of 180, the methane concentration in the mixed gas decreases to 0.45%, and the adiabatic temperature rise during catalytic oxidation is 180 °C.

4.1.2 Simulated Operating Results and Conclusions

Table 4 Temperature rise in catalytic oxidation of flash gas under different dilution ratios

No.	Dilution ratio	Methane concentration V%	Temperature rise °C
1	80	1.01%	393.7
2	100	0.81%	318
3	120	0.67%	266
4	150	0.54%	215
5	180	0.45%	180

According to the simulation results in Table 4, when the dilution ratio is 80, the adiabatic reaction temperature rise reaches as high as 393.7 °C. If the ignition temperature is 390 °C, the outlet temperature of the catalytic bed will rise to approximately 783.7 °C, far exceeding the upper temperature limit for safe catalyst operation, which is usually no more than 650 °C, and making catalyst sintering and deactivation highly likely. As the dilution ratio increases, the reaction temperature rise decreases significantly. Taking reaction efficiency, equipment safety, and operating cost into comprehensive consideration, the optimal amount of supplemental air was ultimately determined to be 180 times the gas volume, that is, dilution by a factor of 180. Under this condition, the adiabatic temperature rise is 180.0 °C, which can effectively prevent thermal damage to both the catalyst and the reactor.

4.2 Laboratory Experiments

4.2.1 Simulated Gas Preparation

Methane, ethane, and propane typically account for more than 90% (volume fraction) of tight gas. Therefore, methane, ethane, and propane were used in this experiment to prepare two types of simulated gases with methane volume fractions of 46.37% and 90.05%, respectively, the detailed compositions are shown in Table 5.

Component 1 : Composed of 46.37 mol% methane, 18.43 mol% ethane, and 16.64 mol% propane. After 180-fold dilution, the inlet total hydrocarbon (THC) concentration was approximately 5039.4 mg/m³, and the inlet non-methane total hydrocarbon (NMHC) concentration was about 3194.6 mg/m³.

Component 2 : Dominated by 90.05 mol% methane, with 1.94 mol% ethane and 3.16 mol% propane. After 180-fold dilution, the inlet THC concentration was approximately 4072.3 mg/m³, and the inlet NMHC concentration was about 489.9 mg/m³.

Table 5 Experimental gas composition

Component	Species	Mole Fraction / %	Diluted Mole Fraction / %	Inlet Concentration / (mg·m^{-3})
Component 1	$CH_4(C_1)$	46.37	0.258	1844.8
	$C_2H_6(C_2)$	18.43	0.102	1347.2
	$C_3H_8(C_3)$	16.64	0.0925	1820.4
Component 2	$CH_4(C_1)$	90.05	0.500	3582.4
	$C_2H_6(C_2)$	1.94	0.0108	144.6
	$C_3H_8(C_3)$	3.16	0.0175	345.3

4.2.2 Experimental results

The experimental system investigated the effect of reaction temperature (220–400 °C) on the catalytic oxidation performance of two-component oil and gas storage tank waste gases. Component 1 (from a gas gathering station condensate oil storage tank) consisted of 46.37 % methane, 18.43 % ethane, and 16.64 % propane, while Component 2 (from the Jinqian 816 platform flash evaporation unit) contained 90.05 % methane, 1.94 % ethane, and 3.16 % propane. The results are presented in the figures. in Figure 6 and Figure 7.

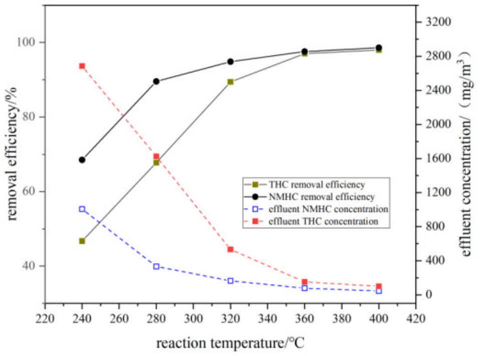


Figure 6 Removal efficiency of component 1 at different reaction temperatures in laboratory simulation

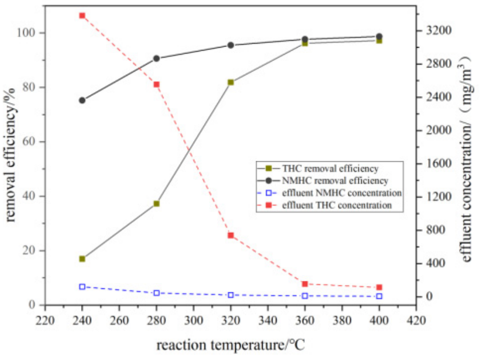


Figure 7 Removal efficiency of component 1 at different reaction temperatures in laboratory simulation

As shown in the figures, when the reaction temperature increases from 220 °C to 360 °C, the total hydrocarbon removal efficiency rises rapidly from approximately 65 % to over 95 %, and remains stable within the range of 360–400 °C. Among them, the variation trend of non-methane total hydrocarbons (NMHC) removal efficiency is highly synchronized with that of total hydrocarbons, further confirming the efficient catalytic activity of the catalyst toward C_2–C_3 alkane components.

Combined with the inlet concentration data (after 180-fold dilution, the inlet concentrations of Component 1 are 1844.8 mg/m³ for methane, 1374.2 mg/m³ for ethane, and 1820.4 mg/m³ for propane; for Component 2, the inlet concentration of methane is 3582.4 mg/m³ after 180-fold dilution), the slow growth of removal efficiency in the low-temperature stage (220–280 °C) is mainly attributed to the high reaction activation energy, insufficient activation of active sites on the catalyst surface, and limited rate of organic oxidation reactions. With the continuous increase in temperature, molecular thermal motion intensifies, the activity of adsorbed oxygen species on the catalyst surface is significantly enhanced, and the cleavage efficiency of C–C and C–H bonds is greatly improved, leading to an exponential rise in removal efficiency.

From the perspective of outlet concentration variation, the total hydrocarbon outlet concentration exhibits a trend of sharp decline followed by stabilization with increasing temperature: the peak total hydrocarbon outlet concentration is close to 2800 mg/m³ at 220 °C, dropping to below approximately 30 mg/m³ at 360 °C, with no obvious fluctuation at 400 °C. This change indicates that 360 °C has reached the critical temperature for complete oxidation of VOCs in this system. Further temperature rise cannot improve the removal efficiency, but may instead increase the system energy consumption.

A comparison of the removal differences between the two components reveals that propane shows the largest increase in removal efficiency, followed by ethane, while methane exhibits a relatively gentle trend. This is related to the C–H bond energies and adsorption properties of different alkanes — propane molecules have more branched chains in their structure, resulting in higher C–H bond activity and easier oxidation by reactive oxygen species on the catalyst surface. In contrast, methane, as an inert component, requires a higher temperature to drive the reaction to completion.

5 Conclusion

(1) By loading a high content of Pt/Pd precious metals, not less than 3 kg/m^3, and optimizing the reaction space velocity at 15000 m^3/h and the amount of supplemental air at 180 times the gas volume, the oxidation efficiency of methane and low-chain alkanes in tight-gas flash gas can be significantly improved. At an ignition temperature of 360 °C, methane conversion efficiency can exceed 95%.

(2) Because the catalytic oxidation process releases a large amount of heat, dilution with air at 180 times the gas volume, combined with internal heat exchange in the designed shell-and-tube integrated reactor, can control the

adiabatic reaction temperature rise within 180 ℃, thereby effectively avoiding catalyst deactivation caused by overheating and ensuring safe and stable system operation.

(3) The integrated catalytic oxidation reactor designed in this study organically combines preheating, catalytic reaction, deep oxidation, and auxiliary heating functions, while also realizing recovery and utilization of reaction heat. Thereby verifying the efficiency, stability, and feasibility of this technical scheme in engineering applications.

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