ISSN: 2586-6036
JWMAP website: http://accesson.kr/jwmap
doi: http://dx.doi.org/10.13106/jwmap.2026.vol9.no2.13

Pilot-Scale Evaluation of Continuous Treatment for High-Boiling Pollutants in UV Coating Exhaust

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Received: March 22, 2026. Revised: March 26, 2026. Accepted: April 07, 2026.

Abstract

Purpose: This study developed and pilot-scale evaluated a continuous treatment system for reducing high-boiling compounds and fine particles associated with adhesive and fouling-prone behavior in UV coating exhaust gas. **Research Design & Data:** The study combined material screening and pilot operation to assess adsorbent applicability, THC breakthrough behavior, fine-particle removal, differential-pressure development, and overall inlet–outlet particle reduction under continuous operating conditions. Activated-carbon media were compared using breakthrough behavior, and pilot-scale data were interpreted from an integrated engineering perspective emphasizing downstream protection and operational stability. **Research Results:** UV-LED pre-treatment delayed THC breakthrough and lowered the early loading imposed on the downstream adsorption-support section. Fine-particle removal remained higher and more stable with pre-treatment, indicating reduced transport of fouling-prone particulate matter to downstream components. Differential-pressure development showed earlier loading in the upstream pre-filter and a more limited increase in the downstream spherical activated-carbon filter, supporting the staged treatment concept. Inlet–outlet particle profiles in the field pilot system confirmed particle-load reduction under continuous operation. These findings support a field-oriented strategy for practical industrial application. **Conclusion:** The proposed continuous treatment system showed pilot-scale engineering applicability for simultaneously improving pollutant control and downstream operational stability in UV coating exhaust treatment, although long-term commercial-scale validation remains necessary.

Keywords : UV Coating Exhaust Gas; Pilot-Scale Evaluation; Activated Carbon; THC Breakthrough; Operational Stability

JEL Classification Code : Q52, Q53, Q55, Q57, O14

1. Introduction[1]

UV coating processes are widely applied in industrial manufacturing because they enable rapid curing, high

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surface quality, and improved production efficiency. However, these processes also generate exhaust gases containing complex pollutants, including organic compounds released during UV curing and coating operations. Previous studies have shown that UV-curing and coating-related processes can emit diverse VOC mixtures, and that the composition and release characteristics of these emissions vary with formulation and process conditions (Salthammer et al., 2002; Stachowiak-Wencek et al., 2014; Zheng et al., 2013; Qi et al., 2019).

High-boiling compounds in UV coating exhaust gas are particularly problematic because their physical behavior can change during transport and treatment. Depending on temperature and process conditions, such compounds may remain in the gas phase, partition between gas and particle phases, or condense onto pre-existing particles and internal surfaces (Pankow, 1994; Robinson et al., 2007; Li et al., 2011). In addition, sticky fine particles can aggravate fouling and clogging by promoting deposit formation within process lines and treatment devices, and particle loading by oily or adhesive materials can significantly affect pressure-drop development in filtration systems (Thomas et al., 2001; Hsiao and Chen, 2015).

Conventional treatment methods such as simple adsorption, filtration, and wet scrubbing are widely used for VOC control, but they often show limited performance when applied to exhaust streams containing condensable and adhesive substances (Khan and Ghoshal, 2000). In practice, the accumulation of such materials may reduce gas-flow stability, decrease the effective treatment area, increase pressure drop, and shorten the service life of downstream control devices, as reported in studies on filter clogging and loading behavior (Thomas et al., 2001; Hsiao and Chen, 2015). These limitations indicate the need for an integrated treatment approach capable of simultaneously managing gaseous pollutants and sticky particulate matter while maintaining operational reliability.

To address these challenges, a continuous treatment system can be designed by combining pre-treatment, particle separation, adsorption support, and flow stabilization. For gaseous organic pollutants, activated-carbon adsorption is one of the most established control options, and its practical applicability is strongly influenced by adsorption capacity, bed configuration, and breakthrough behavior (San et al., 1998; Carratalá-Abril et al., 2009; Balanay et al., 2015). Therefore, the technical significance of such a system lies not only in its pollutant removal capability, but also in its potential to suppress fouling, reduce pressure buildup, protect downstream treatment units, and improve the sustainability of industrial exhaust-gas management (Khan and Ghoshal, 2000; Thomas et al., 2001; Hsiao and Chen, 2015). In this context, evaluation of material performance, pollutant breakthrough behavior, particle removal characteristics, and pressure-drop development is essential for assessing the applicability of the treatment system under pilot-scale operating conditions.

Accordingly, this study aims to develop and evaluate a continuous treatment system for removing high-boiling compounds and sticky fine particles from UV coating exhaust gas. The study examines the adsorption characteristics of the selected activated-carbon media, the breakthrough behavior of total hydrocarbons (THC), the removal performance for fine particles, the differential-pressure characteristics of major treatment components, and the overall performance of the field pilot system. Through this approach, the study provides a structured technical basis for understanding the design rationale, operational behavior, and practical applicability of continuous treatment systems for UV coating exhaust gas.

2. Theoretical Background

2.1. Characteristics of UV Coating Exhaust Gas

UV coating processes are widely used in industrial manufacturing because of their rapid curing speed, high surface quality, and improved production efficiency. However, these processes also generate exhaust gas containing organic pollutants released during UV-curing and coating operations, and previous studies have shown that UV-cured coating systems can emit various volatile and semi-volatile compounds depending on coating formulation and process conditions (Salthammer et al., 2002; Stachowiak-Wencek et al., 2014).

High-boiling compounds are particularly problematic because their physical behavior differs from that of low-molecular-weight volatile compounds. Under variations in temperature, pressure, and flow conditions, these compounds may remain in the gas phase, partition between gas and particle phases, or partially condense onto internal surfaces, resulting in deposit formation within ducts, fans, filters, and adsorption units (Pankow, 1994). In addition, when fine particles are associated with oily or adhesive materials, fouling, agglomeration, and clogging can be intensified, leading to pressure-drop increase and deterioration of filtration performance (Hsiao and Chen, 2015).

Therefore, UV coating exhaust gas should be understood not simply as a gaseous emission stream, but as a mixed-phase pollutant system requiring integrated control of gaseous, condensable, and particulate components. Based on these characteristics, condensation, adhesion, and accumulation are closely related to downstream operational problems such as duct contamination, filter clogging, fan fouling, and adsorbent deterioration (Pankow, 1994; Hsiao and Chen, 2015).

Table 1: Key Characteristics of UV Coating Process Exhaust Gas and Their Operational Implications

Pollutant/property	Technical characteristic	Operational implication
High-boiling compounds	Condensable and adhesive behavior under variable temperature and flow conditions	Surface deposition in ducts, fans, and downstream treatment units
Sticky fine particles	Fine particulate phase with fouling and agglomeration tendency	Filter clogging, pressure drop increase, and reduced gas flow stability
Mixed-phase exhaust gas	Coexistence of gaseous, condensable, and particulate pollutants	Difficulty in treatment by single-stage control systems
Continuous industrial exhaust flow	Long-term and high-throughput process operation	Requirement for stable, durable, and continuously operable treatment systems

As shown in Table 1, the target exhaust stream should be regarded as a mixed-phase pollutant system rather than a simple gaseous emission stream. In this regard, the combined effects of organic emissions from UV-curing materials, gas-particle partitioning of condensable compounds, and adhesive particle loading provide the theoretical basis for interpreting the operational instability of downstream treatment systems (Salthammer et al., 2002; Stachowiak-Wencek et al., 2014; Pankow, 1994; Hsiao & Chen, 2015).

2.2. Operational Problems Caused by High-Boiling Compounds and Sticky Fine Particles

The presence of high-boiling compounds and sticky fine particles in exhaust gas creates several operational problems in industrial air pollution control systems. First, these contaminants may reduce the effectiveness of downstream treatment units by blocking gas-flow pathways and decreasing the available active surface area of filters or adsorbents. Studies on fibrous filter loading have shown that particle deposition leads to progressive clogging, structural changes in the deposited layer, and a continuous increase in pressure drop during operation (Thomas et al., 2001). In addition, studies on liquid-aerosol filtration have reported that sticky or droplet-like deposits can alter both pressure-drop behavior and penetration characteristics depending on operating conditions and deposit redistribution within the filter medium (Contal et al., 2004).

Second, these contaminants may accelerate equipment fouling, resulting in more frequent maintenance, shorter service life of treatment units, and increased operating costs. In particular, when condensable or adhesive materials accumulate within filters and packed treatment sections, the effective treatment zone may be reduced and the internal flow path may become unstable. For adsorption-based units, previous work has also shown that fixed-bed VOC adsorption can be accompanied by significant thermal effects and moving adsorption fronts, which may complicate long-term operation under high pollutant loading conditions (Delage et al., 2000).

Third, these characteristics indicate that removal efficiency alone is not sufficient as an evaluation criterion for UV coating exhaust treatment. Instead, treatment technology should also be assessed in terms of its ability to maintain continuous operation, protect downstream control facilities, and prevent the accumulation of adhesive contaminants within the overall treatment line. In industrial coating facilities, these requirements are especially important because exhaust-gas treatment systems must operate under long-term and high-throughput process conditions rather than short-term laboratory conditions. From this perspective, pressure-drop development, clogging tendency, and operational stability are key engineering indicators in addition to pollutant removal efficiency (Thomas et al., 2001; Contal et al., 2004; Delage et al., 2000).

A conceptual fouling sequence caused by condensation, adhesion, particle deposition, and progressive pressure buildup may be presented as a supplementary schematic if needed. However, in the present study, the engineering significance of fouling is discussed primarily in relation to pressure-drop development and pilot-scale operational stability in the later sections. This framing is consistent with prior studies that described staged pressure-drop evolution during filter clogging and operational effects associated with non-isothermal adsorption behavior in fixed beds.

2.3. Need for Continuous Treatment Technology

Conventional treatment approaches such as simple filtration, adsorption, or wet scrubbing often show limitations when applied independently to UV coating exhaust gas containing condensable and adhesive pollutants. In VOC control practice, single-process systems are often constrained by process-specific drawbacks, and direct condensation can become impractical when very low condensation temperatures are required. Likewise, adsorption-based treatment may suffer from reduced practical efficiency when the pollutant loading pattern is unstable or when the adsorbent is exposed directly to complex exhaust streams without sufficient upstream conditioning (Belaissaoui et al., 2016; Xia et al., 2022). Belaissaoui et al. analyzed a hybrid membrane/condensation process for VOC recovery and reported that hybridization can improve energy efficiency relative to standalone condensation for certain VOC classes, while Xia et al. proposed twin-bed tandem adsorption to improve actual adsorbent utilization in industrial fixed-bed VOC control.

For this reason, continuous treatment technology has attracted attention as a more suitable approach for managing UV coating exhaust gas. In the present study, continuous treatment refers not merely to uninterrupted operation, but to an integrated process configuration in which multiple treatment functions are sequentially combined to improve removal performance and maintain operational stability. Previous studies have shown that such sequential or hybrid concepts can include pre-concentration followed by condensation, tandem-bed adsorption for more efficient fixed-bed operation, and adsorption/catalytic-oxidation coupling strategies for VOC abatement (Belaissaoui et al., 2016; Xia et al., 2022; Yang et al., 2019). Yang et al. reviewed VOC abatement technologies and explicitly treated adsorption and catalytic oxidation as complementary approaches that can be coupled in integrated control systems.

The technical significance of this approach lies in its ability to reduce pollutant loading to downstream units, minimize fouling-related deterioration, and support long-term stable operation in industrial plants. In particular, hybrid membrane/condensation systems have been studied as a way to stabilize recovery performance under variable VOC conditions, tandem-bed adsorption has been proposed to improve adsorbent utilization and breakthrough management, and adsorption/catalytic oxidation coupling has been highlighted as a promising route for efficient VOC abatement (Belaissaoui et al., 2016; Xia et al., 2022; Yang et al., 2019).

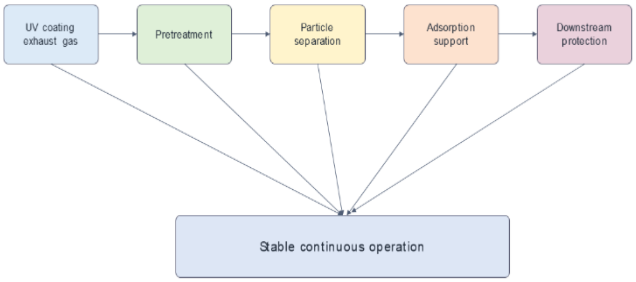

Figure 1: Conceptual Configuration of the Continuous Treatment System for UV Coating Exhaust Gas.

Figure 1 presents the conceptual configuration of the continuous treatment system for UV coating exhaust gas, including pre-treatment, particle separation, adsorption support, and downstream protection functions.

2.4. Functional Roles of Individual Treatment Components

The performance of a continuous treatment system depends on the coordinated function of its individual treatment units. Pre-treatment units are important for reducing the initial burden of condensable and adhesive contaminants before they reach sensitive downstream facilities. In integrated VOC treatment, upstream condensation or equivalent pre-removal steps have been used to reduce the concentration load applied to downstream adsorption units and to support repeated continuous operation of the overall process (Song et al., 2021).

Particle-separation units may remove sticky fine particles that would otherwise deposit on ductwork and filters. Studies on multilayer fibre filters for oil-mist removal have shown that layered structures and drainage-assisting configurations can improve droplet capture, lower steady-state pressure drop, and distribute the operational burden across different layers, which is directly relevant to the removal of adhesive fine particles in mixed-phase exhaust streams (Chen et al., 2023).

Adsorption-support or protective units may help prolong the service life of downstream adsorbents by lowering the load of high-boiling compounds and preventing premature surface deactivation. In a multilayer adsorption-catalytic bed system, Jarczewski et al. (2022) reported that an inert separator played an essential protective role by shielding the carbon adsorbent from undesirable degradation while improving the effectiveness and stability of the integrated system. This suggests that intermediate support or protection layers can serve not only as auxiliary components, but also as key design elements for preserving downstream treatment performance (Jarczewski et al., 2022).

In addition to pollutant removal, each treatment unit contributes to the operational stability of the overall system. Therefore, the design of a continuous treatment system should not be interpreted simply as a collection of separate devices, but rather as an integrated structure in which each component performs a distinct protective and removal-related role. This system-level view is especially important in UV coating exhaust treatment, where pollutant characteristics directly influence the reliability of plant operation.

As shown in Table 2, the proposed treatment configuration is intended not only to remove pollutants, but also to protect the continuity and durability of the entire treatment train. The engineering basis for this interpretation is consistent with previous studies that emphasized staged load reduction, layer-specific separation behavior, and the protective function of intermediate bed components in integrated gas-treatment systems (Song et al., 2021; Chen et al., 2023; Jarczewski et al., 2022).

Table 2: Functional Roles of Individual Treatment Components in a Continuous Treatment System

Treatment component	Main function	Expected technical benefit
Pretreatment unit	Reduce initial loading of condensable and adhesive pollutants	Lower burden on downstream treatment facilities
Particle separation unit	Remove sticky fine particles from the exhaust stream	Prevent filter clogging and fouling-related deterioration
Adsorption-support unit	Capture residual high-boiling compounds and improve gas polishing	Increase treatment stability and support pollutant removal efficiency
Protective/downstream stabilization unit	Maintain performance of subsequent treatment units	Extend equipment life and reduce maintenance frequency

2.5. Material and Process Basis for Pollutant Removal

Although The removal of high-boiling compounds and sticky fine particles is based on the control of both physical transport behavior and physicochemical interaction with treatment media. High-boiling compounds may be captured or stabilized through adsorption using porous carbon-based materials, whereas sticky fine particles may be reduced through pre-treatment, flow control, and particle-separation mechanisms before they reach sensitive downstream units. Previous studies have shown that the adsorption performance of activated carbon is strongly affected not only by pore and surface characteristics of the adsorbent, but also by the physicochemical properties of the target compounds. In particular, adsorption capacity has been reported to increase with increasing molecular weight, dynamic diameter, boiling point, and density of VOCs, while decreasing with increasing polarity index and vapor pressure, indicating that material selection should be considered in relation to the characteristics of high-boiling organic compounds expected in the exhaust stream (Li et al., 2012).

From this perspective, the performance of the selected adsorbent material is an important basis for system design. In particular, the breakthrough behavior of activated-carbon media provides useful preliminary information for evaluating their relative applicability to UV coating exhaust treatment. Fixed-bed studies using granular activated carbon have shown that breakthrough time and adsorption capacity vary significantly with bed length, inlet concentration, and gas flow rate, demonstrating that dynamic breakthrough behavior is a key criterion for practical adsorbent evaluation rather than equilibrium capacity alone (Mohan et al., 2009). In addition, dynamic adsorption studies using activated carbon fiber have shown that breakthrough characteristics are strongly influenced by temperature, gas concentration, flow rate, and adsorbent amount, and that breakthrough curves can be used to assess the suitability of different carbon-based adsorbents under process-relevant operating conditions (Das et al., 2004).

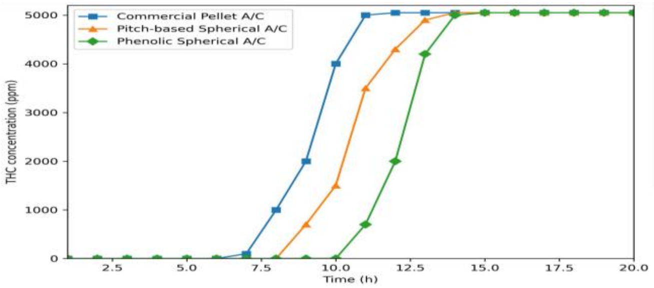

Figure 2: Breakthrough Behavior of Different Activated Carbons for Toluene Removal.

Figure 2 compares the breakthrough behavior of the activated-carbon media using toluene as a surrogate compound and provides a preliminary material-screening basis for selecting the adsorption-support component of the continuous treatment system.

Accordingly, the comparison shown in Figure 2 should be interpreted as a surrogate-based evaluation for relative adsorbent screening rather than as a direct representation of the full complexity of actual UV coating exhaust gas. As shown in Figure 2, adsorbent selection should therefore be understood not only in terms of nominal adsorption capacity, but also in relation to breakthrough delay and mass-transfer behavior under model-compound loading conditions relevant to preliminary screening. This material-level evaluation is consistent with previous studies emphasizing the importance of dynamic fixed-bed performance and adsorbate-dependent affinity when selecting carbon media for VOC control applications (Li et al., 2012; Mohan et al., 2009; Das et al., 2004).

2.6. Importance of System Stability and Downstream Protection

Recent A key technical issue in UV coating exhaust-gas treatment is the protection of downstream control facilities. If high-boiling compounds and sticky particles are not sufficiently managed in the early stages of treatment, they may reduce the performance of subsequent units, including adsorption systems, filters, and fans. Previous studies on aerosol-loaded filters have shown that particulate deposition and adhesive loading can accelerate pressure-drop development and performance deterioration in downstream units (Thomas et al., 2001; Hsiao and Chen, 2015). In addition, pilot- and full-scale VOC treatment studies have reported that unstable loading conditions, fouling-related operational problems, and inadequate upstream conditioning can significantly affect the long-term performance of treatment systems (Webster et al., 1999; Martínez-Soria et al., 2009).

From this perspective, treatment success should be evaluated in terms of both environmental and operational outcomes. Environmental performance involves the reduction of pollutant emissions, whereas operational performance includes reduced fouling, lower maintenance frequency, prolonged service life of control devices, and improved process continuity. This broader understanding is particularly relevant for industrial implementation, where technology adoption depends not only on removal efficiency but also on long-term operational reliability. Webster et al. described operational and performance problems encountered in pilot/full-scale VOC treatment under unsteady industrial conditions, while Martínez-Soria et al. reported that installation of a buffering activated-carbon prefilter considerably improved system performance and compliance in a furniture-manufacturing facility. Likewise, Zhang et al. demonstrated in a pilot-scale biotrickling filter study that pressure-drop control was essential for maintaining stable long-term operation.

Accordingly, the concept of continuous treatment should include not only pollutant removal itself, but also system stabilization and protection of the entire treatment train. In this study, the performance of the proposed system is therefore evaluated in terms of THC breakthrough behavior, fine-particle removal efficiency, differential-pressure development, and overall pilot-scale performance. Such an evaluation framework is consistent with previous literature emphasizing that treatment efficiency alone is insufficient when industrial systems are exposed to fouling, unstable loading, and pressure-drop buildup over extended operation (Thomas et al., 2001; Hsiao and Chen, 2015; Webster et al., 1999; Martínez-Soria et al., 2009; Zhang et al., 2019).

2.7. Basis for Field Application

The field applicability of continuous treatment technology for UV coating exhaust gas can be discussed from three technical perspectives: pollutant compatibility, operational compatibility, and system scalability. First, from the perspective of pollutant compatibility, the technology should be capable of handling mixed and variable VOC streams similar to those encountered in industrial coating facilities. Second, from the perspective of operational compatibility, the technology should function under real plant conditions involving continuous airflow, fluctuating pollutant loading, and long-term operation. Third, from the perspective of scalability, the treatment concept should be applicable not only to pilot-scale systems but also to full industrial implementation. These requirements are consistent with previous pilot-scale studies conducted in the plastic coating sector and furniture manufacturing facilities, where VOC treatment systems were evaluated under practical field conditions rather than simplified laboratory conditions (Álvarez-Hornos et al., 2011; Martínez-Soria et al., 2009).

These considerations indicate that field application requires more than simple proof of removal efficiency. It also requires an integrated understanding of system design, treatment mechanisms, maintenance implications, and downstream equipment protection. In particular, the reported pilot-scale applications in coating-related industries suggest that successful field implementation depends on stable performance under irregular emissions, variable operating conditions, and prolonged continuous use

(Álvarez-Hornos et al., 2011; Martínez-Soria et al., 2009). On this basis, the following sections present quantitative evaluation results for THC control, particle removal, pressure-drop behavior, and pilot-scale system performance.

3. Materials and Methods

3.1. Study Design and Scope

This study was conducted to develop and evaluate a continuous treatment system for removing high-boiling compounds and sticky fine particles from UV coating exhaust gas. The study was designed to examine the treatment system from both material and process perspectives, with emphasis on (1) adsorbent selection, (2) pollutant removal behavior, (3) pressure-drop development, and (4) pilot-scale applicability under continuous operating conditions. This scope is consistent with previous pilot-scale research in industrial coating-related VOC treatment, where system performance was evaluated under practical operating conditions rather than simplified laboratory settings (Álvarez-Hornos et al., 2011).

Unlike the earlier conceptual version of this work, the present study incorporates quantitative evaluation of major engineering performance indicators. These indicators include breakthrough behavior of total hydrocarbons (THC), fine-particle removal efficiency, differential-pressure development across major treatment components, and overall removal performance of the field pilot system. Accordingly, the study was structured to link material characteristics, process configuration, and pilot-scale operational behavior within a continuous treatment framework.

The scope of the study therefore extends beyond simple pollutant removal and includes operational stability and downstream protection. This systems-oriented design is particularly relevant for UV coating exhaust gas, because the target pollutants exhibit condensable, adhesive, and particulate behavior that may directly affect long-term operation of industrial air pollution control facilities. In this respect, pilot-scale studies in coating-sector VOC control suggest that field applicability should be interpreted not only in terms of emission reduction, but also in relation to operational continuity and engineering feasibility under continuous plant conditions (Álvarez-Hornos et al., 2011).

3.2. Continuous Treatment System and Adsorbent Materials

The continuous treatment system considered in this study was configured to sequentially reduce pollutant loading and improve downstream operational stability. The system concept included pre-treatment, particle separation, adsorption support, and downstream protection functions. The engineering basis of this configuration was to intercept condensable and adhesive pollutants before they could accumulate in filters, ducts, fans, and subsequent treatment units.

As the adsorption-support component is critical to the treatment of residual high-boiling compounds, activated-carbon media with different structural characteristics were considered in the material-selection stage. Their breakthrough behavior was compared as a basis for material-level assessment and for selecting an adsorbent suitable for integration into the continuous treatment system. This comparison approach is consistent with previous adsorption studies in which granular activated carbon and different activated carbon fibers were evaluated using breakthrough data, critical bed depth, and adsorption capacity as practical criteria for media selection. Balanay et al. (2011) reported that adsorbent structure and surface area significantly affected breakthrough-related performance, indicating that material selection should be based not only on nominal capacity but also on dynamic adsorption behavior under continuous flow conditions.

The adsorbent evaluation was intended not only to compare nominal material performance, but also to identify a medium suitable for integration into a continuous treatment train operating under pollutant-loading conditions relevant to UV coating exhaust gas. In this respect, the comparison of breakthrough behavior among candidate carbon media provides a practical material-level basis for selecting the adsorption-support component of the proposed system (Balanay et al., 2011).

3.3. Pilot System Configuration and Operating Conditions

A pilot-scale continuous treatment system was used to evaluate the engineering applicability of the proposed treatment concept under conditions representative of industrial UV coating exhaust-gas treatment. The pilot system was operated to examine the removal behavior of hydrocarbon pollutants and sticky fine particles, as well as the operational stability of the treatment train over time. This approach is consistent with previous pilot-scale research conducted in the plastic coating sector, in which treatment performance was evaluated under practical industrial operating conditions rather than simplified laboratory conditions (Álvarez-Hornos et al., 2011).

The pilot evaluation focused on major process responses associated with continuous operation. These responses included changes in THC concentration, fine-particle removal efficiency, and pressure-drop development across major treatment components during system operation. In addition, the overall inlet–outlet particle removal behavior of the pilot system was examined to assess its practical treatment performance under field-related conditions. In this respect, pilot-scale studies in coating-sector VOC treatment have shown that engineering evaluation should include not only pollutant removal itself but also operational behavior under continuous and variable plant conditions (Álvarez-Hornos et al., 2011).

The operating concept of the pilot system was therefore not limited to pollutant capture alone, but also addressed the engineering need to suppress fouling, delay performance deterioration, and protect downstream facilities during continuous treatment. This system-level interpretation is consistent with previous pilot-scale studies emphasizing the practical feasibility of coating-related exhaust-gas treatment technologies under realistic industrial conditions (Álvarez-Hornos et al., 2011).

3.4. Analytical Items and Performance Indicators

To evaluate the treatment system, four major analytical items were considered. First, the breakthrough behavior of THC was used to assess the removal performance of gaseous and condensable hydrocarbon components during pilot operation. Time-dependent changes in THC concentration were interpreted as indicators of pollutant breakthrough and adsorbent-loading behavior. This interpretation is consistent with previous fixed-bed activated-carbon studies in which breakthrough curves were used as the primary indicator of dynamic adsorption performance under continuous flow conditions (Mohan et al., 2009).

Second, the removal efficiency of sticky fine particles was evaluated to determine the ability of the treatment system to control particulate-phase contaminants associated with fouling and clogging. Fine-particle removal performance was considered important because such particles may accelerate deterioration of downstream filters and adsorbent units. Third, differential pressure across major treatment components was examined as an operational indicator of fouling progression and resistance buildup within the treatment train. Previous filtration studies have shown that particle loading is accompanied by simultaneous changes in filtration efficiency and pressure drop, making these variables important indicators of filter clogging and operational deterioration (Thomas et al., 2001).

Fourth, the overall performance of the field pilot system was assessed using inlet–outlet comparisons of particle-related indicators. This system-level assessment was used to examine the practical applicability of the treatment concept under pilot-scale continuous operating conditions. Accordingly, the main performance indicators of the present study were selected to reflect both environmental performance and operational reliability, combining dynamic breakthrough analysis for gaseous pollutants with efficiency and pressure-drop monitoring for particle-related fouling behavior (Mohan et al., 2009; Thomas et al., 2001).

3.5. Data Interpretation Strategy

The data obtained from material comparison and pilot operation were interpreted from an integrated engineering perspective. Rather than treating each variable independently, the study examined how material performance, pollutant breakthrough, fine-particle control, and pressure-drop behavior were interrelated within the continuous treatment system. This interpretation strategy is consistent with previous studies showing that breakthrough behavior in fixed-bed activated-carbon systems reflects dynamic adsorption performance under continuous flow, while pressure-drop development in particle-loaded filters reflects progressive fouling and operational deterioration.

This interpretation strategy was adopted because the target pollutants do not simply reduce outlet quality; they also influence the durability and continuity of the treatment line. For this reason, the present study evaluates the proposed system in terms of both pollutant removal and operational protection. Breakthrough delay was regarded as a positive indicator of improved adsorbent applicability and delayed exhaustion, whereas sustained particle-removal efficiency together with controlled pressure-drop increase was interpreted as evidence of reduced fouling tendency and improved process stability (Mohan et al., 2009; Thomas et al., 2001).

Based on this analytical approach, the quantitative results are presented in the following sections. THC breakthrough behavior, fine-particle removal performance, pressure-drop characteristics, and pilot-scale system performance are discussed in relation to downstream protection and long-term operational stability. In this sense, the analytical framework of the present study combines dynamic adsorption interpretation with clogging-related operational interpretation, rather than assessing each indicator as an isolated removal metric (Mohan et al., 2009; Thomas et al., 2001).

3.6. Limitations of the Study

This study has several limitations. First, although quantitative pilot-scale data were incorporated, the available dataset was not obtained from a fully controlled experimental design with repeated trials and formal statistical replication. Second, some of the engineering interpretation was based on technical reports and field-related materials associated with system development and pilot operation. Third, the study did not compare multiple treatment systems under identical operating conditions.

Nevertheless, the present study provides a meaningful engineering evaluation of a continuous treatment system for UV coating exhaust gas by integrating adsorbent selection, pilot-scale operational behavior, and system-level performance indicators. The findings may serve as a basis for future controlled validation, commercial-scale optimization, and long-term field implementation.

4. Results and Discussion

4.1. THC Breakthrough Behavior

The breakthrough behavior of total hydrocarbons (THC) was evaluated to examine the effectiveness of the proposed continuous treatment system for controlling gaseous and condensable hydrocarbon components in UV coating exhaust gas. As shown in Figure 3, the system operated with UV-LED pre-treatment maintained a lower outlet THC concentration for a longer period than the system operated without pre-treatment. This result suggests that the pre-treatment step reduced the loading of condensable hydrocarbon species reaching the downstream adsorption section and delayed the onset of breakthrough. Such an interpretation is consistent with fixed-bed adsorption studies in which breakthrough behavior was used as an indicator of dynamic adsorbent loading and exhaustion under continuous flow conditions (Mohan et al., 2009).

Although the material comparison shown in Figure 2 was conducted using toluene as a surrogate compound for preliminary adsorbent screening, the pilot-scale THC breakthrough result in Figure 3 provides process-level evidence under actual UV coating exhaust-gas conditions. In UV coating exhaust-gas treatment, breakthrough behavior is an important performance indicator because high-boiling compounds do not simply pass through the system as ordinary low-boiling gaseous pollutants. Instead, their retention behavior depends strongly on physicochemical properties such as molecular weight, boiling point, and vapor pressure, which influence how readily they are retained by carbon media and how the effective loading of the adsorption section develops over time (Li et al., 2012). Therefore, delayed breakthrough suggests not only improved pollutant control, but also improved preservation of the adsorption-support function under practical operating conditions.

The result also highlights the importance of process sequencing in the proposed system. By introducing pre-treatment before the main adsorption-support stage, the system reduced the early burden imposed on downstream treatment media. From an engineering perspective, this is significant because stable control of THC-related pollutants contributes to both pollutant removal and downstream equipment protection. A similar logic has been reported in tandem fixed-bed adsorption studies, in which staged loading control improved effective adsorbent utilization and reduced the burden on downstream sections of the treatment system (Xia et al., 2022).

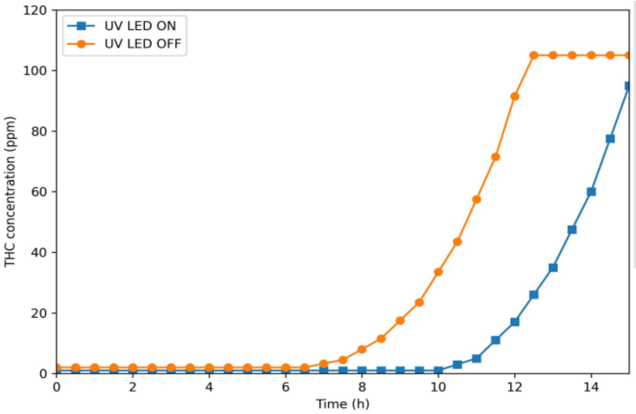

Figure 3: THC Breakthrough Curves during Pilot Operation with and without UV-LED Pre-treatment.

4.2. Fine-Particle Removal Performance

The removal performance of fine particles associated with adhesive and fouling-prone behavior was evaluated to determine whether the proposed treatment system could effectively control particulate-phase pollutants relevant to fouling and clogging in UV coating exhaust treatment. As presented in Figure 4, the system with UV-LED pre-treatment showed higher and more stable fine-particle removal efficiency over the operating period than the system without pre-treatment. This finding suggests that the treatment configuration reduced the transport of particulate matter with fouling potential to downstream components. Similar behavior has been reported in liquid-aerosol and oil-mist filtration studies, where filter structure and staged separation strongly influenced the stability of downstream particle concentration during continuous operation. In particular, Chen et al. showed that a combined oleophobic fibre filter with an increasing pore-size gradient improved submicron droplet separation efficiency and reduced the steady-state concentration of downstream droplets, indicating that staged particle-control structures can improve the stability of fine-particle removal.

This result is important because fine particles with adhesive characteristics are not only emission-related pollutants, but also major contributors to operational deterioration. Once deposited on filters, ducts, or adsorption media, these particles may promote agglomeration, surface blinding, and pressure-drop increase. Contal et al. monitored filtration efficiency and pressure drop simultaneously during clogging by submicron liquid particles and described a multistep clogging sequence, showing that deposited liquid particles affect both separation behavior and resistance buildup. Hsiao and Chen likewise reported that filters loaded with oil-coated particles exhibit transition pressure-drop behavior that depends on the degree of liquid coating, further supporting the interpretation that adhesive particulate loading is closely related to downstream fouling and operational instability.

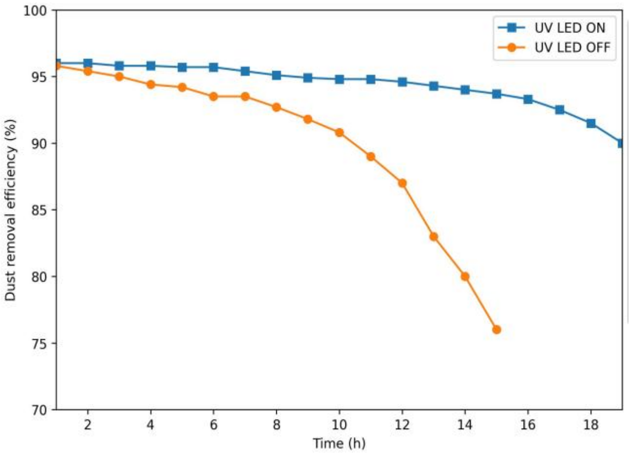

Figure 4: Fine-Particle Removal Efficiency during Pilot Operation with and without UV-LED Pre-treatment.

The trend shown in Figure 4 also supports the view that pre-treatment and staged particle control play a protective role in the continuous treatment system. By reducing the particulate burden in the upstream section, the system can maintain more stable gas flow and delay deterioration of downstream treatment units. This is particularly relevant in UV coating processes, where exhaust gas may contain adhesive and mixed-phase pollutants under continuous industrial operation. From this perspective, sustained fine-particle removal should be interpreted not only as evidence of pollutant capture, but also as an indicator of downstream protection and overall system reliability under continuous loading conditions.

4.3. Differential-Pressure Development and Operational Stability

Operational stability of the proposed treatment system was further examined through differential-pressure development across the major treatment components. As shown in Figure 5, the differential pressure across the pre-filter exhibited an earlier increase during operation, whereas the spherical activated-carbon filter showed a more limited increase over the same operating period. Although the two components are presented on different pressure scales in Figure 5, the overall pattern suggests that the upstream stage intercepted a substantial fraction of pollutant loading before it reached the downstream adsorption-support component. Such an interpretation is consistent with previous filtration studies showing that pressure-drop evolution reflects progressive loading and clogging inside the upstream medium during dynamic filtration, while the transition from depth filtration to more severe surface loading is associated with a marked increase in resistance development.

From an engineering standpoint, pressure-drop behavior is a critical indicator because excessive pressure buildup may reflect fouling progression, filter blockage, or surface blinding by adhesive pollutants. In systems exposed to liquid-containing or oil-coated particles, this issue becomes even more important because pressure-drop evolution does not necessarily follow the same pattern as solid-particle loading alone. Hsiao and Chen reported that filters loaded with oil-coated particles exhibit distinct transition pressure-drop behavior, and that the loading curve depends on the liquid fraction as well as the surface tension and viscosity of the coating liquid. This supports the interpretation that adhesive pollutants in UV coating exhaust may accelerate non-linear resistance buildup and operational instability, particularly in the upstream section of the treatment train.

These results support the intended design logic of the continuous treatment system. Rather than relying on a single unit to handle all pollutant phases simultaneously, the proposed configuration distributed treatment functions across multiple stages. This type of staged configuration is beneficial because it helps maintain stable flow conditions, protects sensitive downstream media, and reduces the risk of rapid system deterioration during continuous plant operation. Kampa et al. showed for oil-mist coalescence media that wet pressure drop is governed by distinct liquid-transport mechanisms and that sandwiched combinations of different media exhibit separate pressure-drop transitions for different layers, which supports the idea that multi-stage treatment can distribute loading and delay downstream burden.

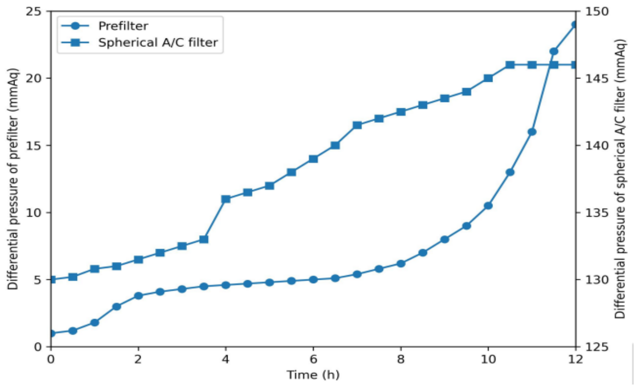

Figure 5: Differential Pressure Development Across the Prefilter and Spherical Activated-Carbon Filter during Pilot Operation.

4.4. Pilot-Scale Removal Performance

The practical applicability of the proposed treatment technology was evaluated through pilot-scale performance analysis under field-related operating conditions. Figure 6 presents the particle-removal performance of the field pilot system based on inlet–outlet comparison. The outlet profile was substantially lower than the inlet profile over the measured particle-size range, indicating that the pilot system reduced particle loading during continuous operation.

This result is meaningful because it indicates that the treatment concept is not limited to material-level or component-level feasibility, but can also function as an integrated treatment train under pilot-scale conditions. In UV coating exhaust-gas treatment, such pilot-scale validation is particularly important because pollutant behavior is influenced by continuous flow, mixed-phase loading, and operational duration. Previous pilot-scale studies in coating-related industrial facilities have likewise emphasized evaluation under practical field conditions rather than simplified laboratory conditions, including VOC-control applications in the plastic coating sector and furniture manufacturing facilities.

The pilot-scale result also has practical implications for downstream protection. Reduced inlet–outlet particle loading suggests that the proposed system can lower the burden imposed on subsequent control units, thereby contributing to improved durability, lower maintenance frequency, and enhanced process continuity. In this sense, the pilot result should be interpreted not only as a removal-performance outcome, but also as evidence of operational benefit at the system level. This interpretation is consistent with industrial pilot/full-scale treatment studies reporting that practical applicability depends not only on pollutant removal itself but also on stable operation and the avoidance of operational and performance problems over time.

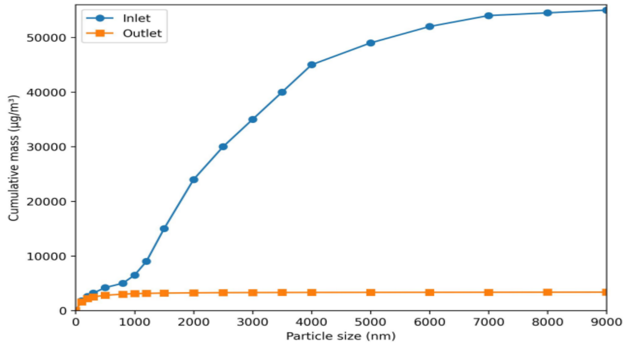

Figure 6: Mass-Based Particle Removal Performance of the Field Pilot System.

4.5. Integrated Discussion on Downstream Protection and Continuous Operation

Taken together, the results presented in Figures 3–6 indicate that the proposed continuous treatment system provides both environmental and operational advantages in the treatment of UV coating exhaust gas. Delayed THC breakthrough, sustained fine-particle removal, and staged pressure-drop development collectively suggest that the system reduced pollutant loading while helping preserve the stability of downstream treatment components.

These findings are particularly important in the context of UV coating exhaust gas, where high-boiling compounds and fine particles with adhesive and fouling-prone behavior can contribute to progressive deterioration of ducts, filters, fans, and adsorption units. The present results show that successful treatment should not be interpreted solely in terms of pollutant removal efficiency at the outlet. Instead, treatment performance should also be evaluated in relation to fouling suppression, protection of downstream facilities, and the maintenance of stable continuous operation.

The proposed system therefore has significance as an integrated engineering approach rather than as a single removal device. Its practical value lies in the coordinated interaction of pre-treatment, particle control, adsorption support, and downstream protection. From this perspective, the continuous treatment system can be understood as a pilot-scale, field-oriented strategy for simultaneously addressing pollutant control and operational reliability in industrial UV coating facilities.

4.6. Limitations of Result Interpretation

Although the present results provide meaningful pilot-scale engineering evidence, several limitations should be acknowledged. First, the available data were not obtained through a fully controlled experimental design with repeated statistical validation. Second, some aspects of the present interpretation remain pilot-scale and engineering-oriented rather than based on direct comparison with multiple alternative treatment systems under equivalent conditions. Third, long-term commercial-scale performance, maintenance cycle optimization, and full economic assessment were beyond the scope of the present study and therefore require further validation.

Nevertheless, the results provide a useful basis for understanding the applicability of continuous treatment technology to UV coating exhaust gas containing high-boiling compounds and fine particles associated with adhesive and fouling-prone behavior. Future studies should focus on replicated performance testing, long-term fouling behavior, adsorbent life evaluation, and economic analysis under defined industrial operating conditions.

5. Conclusions

This study investigated the development and pilot-scale evaluation of a continuous treatment system for reducing high-boiling compounds and fine particles associated with adhesive and fouling-prone behavior in UV coating exhaust gas. The study focused on the engineering challenge of simultaneously achieving pollutant control and maintaining stable continuous operation under conditions relevant to industrial UV coating processes.

The results showed that the proposed treatment system provided meaningful performance in both environmental and operational terms. The THC breakthrough behavior indicated that the application of pre-treatment delayed the increase in outlet hydrocarbon concentration and helped preserve the stability of downstream adsorption support. In addition, the fine-particle removal results showed that the system maintained relatively stable removal performance for particulate matter associated with fouling potential during operation. Taken together, these findings suggest that the proposed configuration contributed not only to pollutant reduction, but also to reducing the transport of problematic condensable and adhesive substances to downstream units.

The differential-pressure results further supported the engineering significance of the staged treatment configuration. The observed pressure-drop development suggested that pollutant loading was intercepted preferentially in the upstream section, thereby reducing the immediate burden on the downstream spherical activated-carbon filter. This behavior is important because it suggests improved resistance to fouling, better protection of sensitive treatment media, and enhanced operational stability during continuous exhaust-gas treatment.

The pilot-scale performance evaluation also supported the practical applicability of the proposed treatment concept under field-related operating conditions. The inlet-outlet particle removal behavior of the field pilot system showed that the integrated treatment train reduced particle loading during continuous operation. This result indicates that the proposed system has value not only as a conceptual treatment strategy, but also as a pilot-scale engineering approach with practical relevance for UV coating facilities.

Taken together, the findings of this study indicate that continuous treatment technology can help address the combined environmental and operational problems associated with UV coating exhaust gas containing high-boiling compounds and fine particles with adhesive and fouling-prone behavior. The significance of the proposed system lies in its integrated structure, in which pre-treatment, particle control, adsorption support, and downstream protection are functionally connected. Therefore, the performance of such a system should be understood not only in terms of pollutant removal efficiency, but also in relation to fouling suppression, protection of downstream facilities, and long-term process continuity.

Although the present study provides meaningful pilot-scale engineering evidence, several limitations remain. The available data were not obtained from a fully controlled experimental design with repeated statistical validation, and long-term commercial-scale performance was not directly verified. In addition, the target pollutants were evaluated mainly through engineering performance indicators rather than through comprehensive compound-specific characterization of all high-boiling and adhesive components in the exhaust stream. Therefore, future studies should focus on replicated performance testing, long-term fouling behavior, adsorbent service life, maintenance interval, and economic feasibility under defined industrial operating conditions. Such efforts will be important for establishing the scientific reliability and commercial applicability of continuous treatment technology for UV coating exhaust gas.

Acknowledgements

The research was conducted as a component of the Ministry of Climate, Energy and Environment(MCEE)-funded Graduate School Specialized in Climate Change

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