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Enhancement of adsorptive chemical filters via titania photocatalysts to remove vapor-phase toluene and isopropanol

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ABSTRACT

Adsorption-type chemical filtration is essential in many indoor purification applications. However, these chemical filters are expensive and have a limited filter life after breakthrough of contaminants. With toluene and isopropanol (IPA) as model contaminants, this study investigates the breakthrough behaviors of adsorptive chemical filters and TiO_2-enhanced chemical filters with various configurations—a chemical filter containing TiO_2-preloaded activated carbon (Scenario A), a chemical filter preceded by a TiO_2-coated non-woven sheet (Scenario B), and a chemical filter pressed against a TiO_2-coated non-woven sheet (Scenario C). The photocatalytic performance of the TiO_2-coated non-woven sheet was evaluated using several key operating parameters such as air moisture (relative humidity), TiO_2 loading density, light intensity, and challenge concentrations of model contaminants. The generation and accumulation of oxidative intermediate products from photocatalysis of toluene and IPA were also examined. Additionally, the Yoon–Nelson breakthrough model was experimentally validated and applied to generate adsorption breakthrough curves of several hypothetical challenge concentrations. The breakthrough studies indicate that the life of the filter in Scenario C was markedly longer than those of filters in scenarios A and B, even when photocatalysts were de-activated as a result of benzaldehyde accumulation from toluene decomposition. By pressing the TiO_2-coated non-woven sheet against the front face of the chemical filter, TiO_2 particles in the non-woven sheet and activated carbon granules in the chemical filter comprised a quasi-homogeneous system, yielding synergistic effects that enhance the operating lifespan of a chemical filter via photocatalysis.

1. Introduction

Chemical filters are typically designed to purify indoor air, with applications for both general indoor uses and for controlled environments that have low contamination tolerance, exemplified by their use as critical components of ventilation systems in manufacturing "cleanrooms" for microelectronic devices, optoelectronic devices, and pharmaceutical products. The detrimental effects of trace contamination in the gaseous phase, often called airborne molecular contamination (AMC), on microelectronics product reliability have been identified [1]. Chemical filters in ventilation control systems in these environments must be integrated to identify possible contaminant sources, including outside air, recirculating air, and point-of-use sub-environments, which require purification of specific contaminants. External contaminant sources vary with plant location, its proximity to traffic, and building design. Generally, external pollutants are removed by the make-up air unit (MAU), whereas contaminants generated indoor are removed by recirculating air-handling units (AHUs). Chemical filtration equipment installed in systems with MAUs are typically designed to remove sulfur oxides (SO_x), nitric oxides (NO_x), O_3, and volatile organic compounds (VOCs); however, those for point-of-use applications must be designed to target specific airborne molecular contaminants.

Generally, chemical filters in cleanroom applications must be capable of dealing with high volumetric flow and low outgassing from filter materials. Chemical filters targeting inorganic contaminants, such as ammonia, sulfur dioxide, nitrogen dioxide, and hydrochloric and hydrofluoric acids, have been developed. For instance, activated carbon can be impregnated with either phosphoric (or citric) acid for absorption of basic gases, or potassium permanganate (or hydroxide) for absorption of acidic gases [2]. Ionic exchange beads have also been utilized to capture ionic gas components, and have better initial removal efficiency and breakthrough times for ammonia than chemical filters that use chemical absorption [3]. Both chemical absorption and ion exchange processes are highly selective for target contaminants and are tailored to specific applications.

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Controlling organic contaminants through van der Waals adsorption (i.e., physisorption) using activated carbon in granular or fibrous structures remains a common design due to its proven efficiency for a broad range of organic compounds. A number of designs, including impregnated activated carbon [4], blended adsorbent media [5], and adsorbent-loaded nonwoven filters [6], have been applied to increase the removal efficiency of organic airborne molecular contaminants and/or extend filter life. Models for predicting the effective lifespan of these adsorptive filters have been developed and tested [7,8]. Furthermore, modified chemical adsorption processes involving chemical impregnation onto the surface of a base media have also been used to overcome the lack of a "driving force" (i.e., concentration gradient) for pore diffusion that decreases physisorption effectiveness due to the presence of trace levels of organic contaminants. Shiratori et al. [9] developed a novel "layer-by-layer self-assembly film" by chemically depositing poly(allylamine hydrochloride) (PAH) and poly(acrylic acid) (PAA) in sequence onto a fibrous glass filter. Contaminants passing through this filter are adsorbed by the films due to the coulombic force and react with polymers.

The most significant problem with these chemical filter designs is that sorbent materials eventually become saturated so that filter replacement is necessary to maintain the required air cleanliness. One possible method to prolong the effective life of a chemical filter is to incorporate photocatalysts, most commonly titanium dioxide (TiO_2), in the filter structure combined with an appropriate light source. For instance, TiO_2-mediated photocatalysis has been used to remove gaseous organic contaminants using filter fabrics as a support [10,11]. Recent studies focused on immobilizing TiO_2 on activated carbon filters have demonstrated that this combination has higher removal efficiencies for toluene [12–14] and acetylene [15] than those with only activated carbon and/or TiO_2 photocatalysis. To further examine the feasibility of incorporating TiO_2 into carbon-based chemical filters, and investigate the effects of different design strategies on filter life, this study assesses the removal of toluene and isopropanol (IPA) from contaminated airstreams using an activated carbon-based chemical filter combined with TiO_2 photocatalysis in a homogeneous unit and in heterogeneous configurations—(a) a chemical filter containing activated carbon preloaded with TiO_2 powder (Scenario A), (b) a chemical filter preceded by a TiO_2-loaded non-woven filter (Scenario B), and (c) a chemical filter pressed against a TiO_2-coated non-woven filter (Scenario C). Fig. 1 shows the conceptual schemes of the three scenarios. In the homogeneous unit, the adsorbent is preloaded with photocatalysts, whereas in heterogeneous configurations, the photocatalytic unit is in a unit separate from the adsorbent bed. This study uses toluene and IPA as the challenge contaminants based on their common use in industrial applications and indoor environments, and also because they are two of the most important classes of organic contaminants, namely, aromatics and simple acyclic alcohols, respectively.

2. Materials and methods

2.1. Reactor description

Fig. 2a schematically depicts the test unit. Vaporizing contaminant solvent (toluene or IPA) from a syringed pump (KDS101; KD Scientific, USA) through a heated (80 °C) three-way glass branch supplied the contaminant vapor, whose concentration was controlled by adjusting the syringing rate and airflow rate. All experiments were conducted in an air-conditioned room with a constant temperature of 300 °K and 30% relative humidity (RH). To study the effect of RH on the photocatalytic process, two independent air pumps were used—one air pump passed air through a water vessel containing deionized water, and the other transported silica-gel-dried air before being mixed with the contaminant vapor and was then introduced into the test reactor. The RH and temperature were monitored using a thermohygrometer at the outlet end of the vapor mixing flask.

The test reactor comprised a cylindrical Pyrex column (i.d. 100 mm) with two removable segments, namely, a photocatalytic section (length, 150 mm) and a cone-shaped outlet section (total length, 55 mm) (lower part in Fig. 2a). Test pieces were fitted for attachment to the two sections and rendered airtight using an O-ring. A quartz tube (OD, 45 mm; length, 140 mm) in concentric with the column contained a 13-W or 18-W ultraviolet (UV) lamp (Sankyo, Japan) irradiating a primary wavelength centered at 279 nm, as measured with a fiber optic spectrometer (EPP2000; StellarNet, USA). Irradiance, measured near the test piece center (1 cm from the lamp tip) by a radiometer (UVP, USA), was 1.0 mW/

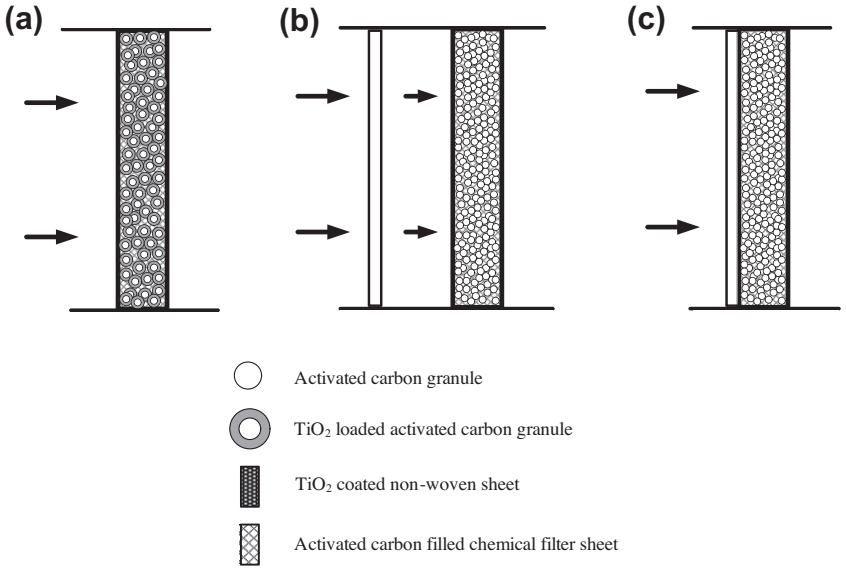

Fig. 1. Schematic diagram of different combination of activated carbon filled chemical filter enhanced with photocatalysts: (a) chemical filter containing activated carbon granules loaded with TiO_2 powders (Scenario A); (b) chemical filter preceded with a TiO_2-coated non-woven sheet (Scenario B); (c) chemical filter pressed with a TiO_2-coated non-woven sheet (Scenario C).