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Indoor Air Purification Using Functional Wall Covering

Abstract

Development of a novel wall covering product is a goal of current research. The main aim is to develop a novel cost-effective and efficient product able to degrade indoor air pollutants. For this purpose a top-coating with an addition of modified titanium dioxide will be designed and applied on a contract wall covering. This novel product will be characterized, assessed in terms of durability and degradation of indoor air pollutants, both inorganic and organic. Kinetic reaction rate model will be built and later on used for the 3-D model by applying Computational Fluid Dynamic software.

Introduction

Air pollution, as many of us feel, poses a significant threat to health worldwide. More than two million premature deaths each year can be attributed to the effects of urban outdoor and indoor air pollution (1). Problems connected with air pollution in urban areas have been known for many years, but even that the attitude towards them is still ambiguous.

The majority of the people stay indoors approximately 80% of their time, exposing themselves to the indoor environment more than to the outdoors (2). Following the rising settlement inside buildings, there seems to be an increasing rate of diseases related to the poor indoor air quality (IAQ). The major sources of indoor air pollution include combustion of solid fuels, tobacco smoking, outdoor air pollutants, emissions from construction materials and furnishings, and improper maintenance of ventilation and air conditioning systems (1). The impact of indoor air pollutants on human being may consist of undesired health effects of different types, ranging from sensory annoyance or discomfort to severe health injuries.

The goal of this research is to contribute to the improvement of the IAQ. The main aim is to develop a novel cost-effective and efficient product with the function of degrading the indoor pollutants. This product will be a top-coated wall covering with a coating able to decompose indoor pollutants by photocatalytic technology. The basic idea is to use a modified titanium dioxide (TiO_2), semiconductor catalyst responsive to visible light irradiation, solution as a final coating to a wall covering.

This product will be characterized, assessed in terms of durability and appearance, and it will be tested on degradation of indoor pollutants, both inorganic and organic, by photocatalytic oxidation. Finally a kinetic model of toluene degradation will be built and later used for the 3-D modeling applying Computational Fluid Dynamic software.

Heterogeneous Photocatalysis (PCO)

Common methods of increasing IAQ include controlling pollution source, increasing ventilation rates or using air purifiers. Controlling pollution sources can often be very difficult and increasing ventilation rates can propagate pollution indoors while increasing energy demand (3; 4). The usage of air purifiers gains more acceptance nowadays due to less complications in its usage, but its principle lies on transforming contaminants to another phase rather than eliminating them, so additional disposal or handling steps are required.

An alternative methodology, which solves these issues, might be the use of photocatalytic oxidation (PCO). Operating at ambient conditions, PCO can degrade a broad range of contaminants into harmless products solely with the energy input of electromagnetic radiation (which could be artificial or natural light) depending on the catalyst characterization and synthesis.

Heterogeneous photocatalytic oxidation technology is one of the very promising methods for degrading indoor and outdoor pollutants and thus improving the air quality. This technology has been studied for several decades and shown as an effective method for water or air purification (5). Pure or doped metal oxide semiconductors (e.g. TiO_2, ZnO) are commonly used as the photocatalysts in PCO reaction. TiO_2's strong resistance to chemicals and photocorrosion, safety, low selectivity of pollutant degradation and low cost are the convenient reasons for its selection (6).

PCO mechanism

PCO can be divided into three main steps: (1) mass transport and adsorption of pollutants from the bulk air to the surface of catalyst; (2) photochemistry reaction on the catalyst; (3) desorption and mass transport of the reaction products from the surface of catalyst to air. Overall photocatalytic reactions may be summarized as follows:

$$(Ox_1)_{ads} + (Red_2)_{ads} \xrightarrow[hv>Eg]{} Red_1 + Ox_2 \qquad \text{(eq.1.1)}$$

The photocatalytic degradation of VOCs can be expressed by following equations: (7)

(Electron/hole pairs) $\mathrm{TiO_2} + \mathrm{hv} \rightarrow \mathrm{e^-} + \mathrm{h^+}$ (eq.1.2)

(Adsorption)

$TiO_2 + H_2O \rightarrow \mathrm{Ti}O_2\_H_2O$ (eq.1.3)

$TiO_2 + O_2 \rightarrow TiO_2\_O_2$ (eq.1.4)

$TiO_2 + pollutant \rightarrow TiO_2\_pollutant$ (eq.1.5)

(Recombination) $\mathrm{e^-} + \mathrm{h^+} \rightarrow \mathrm{heat}$ (eq.1.6)

(Formation of super-oxide radicals) $\mathrm{e^-} + \mathrm{O_2} \rightarrow \mathrm{O_2^{\bullet -}}$ (eq.1.7)

(Formation of hydroxyl radicals) $h^{+} + H_2O \rightarrow OH^{\bullet} + H^{+}$ (eq.1.8)

(Radical oxidation of VOCs) $OH^{\bullet} + pollutant + O_2 \rightarrow intermediates + xCO_2 + yH_2O$ (eq.1.9)

Materials

The goal of this research is to develop a top-coating on the wall covering (substrate) using a modified, visible light responsive TiO_2 photocatalyst as an additive. The optimal coating composition (binder, solvent, additives) and the preparation/application process will be developed. The morphology, durability and PCO efficiency of the developed coating will be assessed.

Titanium dioxide (TiO_2)

A carbon-doped TiO_2 (Kronos, Germany) will be initially used as photocatalyst in this research. The carbon-doped TiO_2 is produced by mixing a fine grained titanium compound with an organic carbon compound and subsequent thermal treatment at temperatures up to 350ºC (8). By doping the anatase phase with carbon, the cut-off wavelength is shifted from 388 nm (band gap of 3.20 eV) to 535 nm (band gap of 2.32 eV) which corresponds to bluish green light (9). The modification indicates that only 2.32 eV needs to be absorbed which means the visible light can be used to activate the powder as photocatalyst.

This material was selected based on the previous work (10). In this work the carbon-doped TiO_2 was used as a photocatalyst, which can be activated by visible light irradiation, due to the shortage of the UV light in indoor conditions. Newly developed gypsum plasterboard cover paper was used as a substrate. Nitric oxide was used in this study as a target pollutant. The results indicated that this technology is effective in decontamination of indoor air pollutants.

Coating

Commercially used waterbased top-coating, provided by BN International, will be initially used and various dosages of C-TiO_2 will be tested. Addition of different additives, such as nano-silica, and their effect on the properties of the top-coating, will be studied in detail. Characteristics such as durability will be tested according to the relevant wall covering standards. Morphology of the coating and possible influence of TiO_2 on organic compounds inside the coating, due to the strong oxidative characteristics, will be analyzed.

Model pollutant

Toluene was chosen as a model pollutant for this research. Toluene is a clear, colourless liquid with a sweet, pungent odour. Indoor sources of toluene include building materials (solvent- and water-based adhesives, floor coverings, paints, etc.), consumer and automotive products (cleaners, polishes, oils, etc.), and tobacco smoke. In attached garages, toluene generated by running engines or by product storage may also infiltrate into the indoor environment.

Table 1 Properties of toluene

Properties of toluene	
molecular formula	$C_6H_5CH_3$
Molecular weight	92.13 g/mol
Vapor pressure	28.7 mm Hg at 25 ºC
Boiling point	110.6 ºC
Conversion factor (in air 25ºC)	1 ppm = 3.76 mg/m^3 1 mg/m^3 = 0.266 ppm

Toluene levels in indoor environments are expected to be significantly higher than outdoor levels in those situations involving non-occupational use of paints and thinners, and also where tobacco smoke is present (11). The lowest observed adverse health effect level for effects on the central nervous system from occupational studies, is approximately 332 mg/m^3 (88 ppm). A guideline value of 0.26 mg/m^3, which is applied as a weekly average (12).

Studies were already conducted on the degradation of the toluene (13-16). However, in these studies the indoor air conditions were not entirely considered, for example by using UV light irradiation with different intensities, high concentration of model pollutant or enormous flow rate. The results from these studies confirmed, on the laboratory scale, that the application of the photocatalyst products has good efficiency in toluene degradation. However, efficiency in real indoor conditions – visible light irradiation, low pollutant concentration, low flow rate, multiple pollutants – will be with the same products considerably different and modifications will be probably required. This indicates the need for the current research.

Experimental methodology

The essential part of the current research is the analysis of the PCO efficiency of the developed wallcovering product. This will be done in several steps. Firstly a plug flow reactor, which is introduced in the following sub-section, will be used. This will be followed by investigation using a batch reactor, which will be designed and built, to simulate indoor air conditions. Finally a real scale demonstration, in a model office room, will be conducted.

Experimental set-up

The PCO efficiency of toluene degradation will be initially tested using the experimental set-up which is illustrated in Figure 1. Experimental set-up consists of pollutant source, which could be inorganic (e.g. nitrogen oxide) and organic (e.g. volatile organic compound), transport gas supply, humidifier, mass controller meters, parameter measurement apparatus like temperature and relative humidity, reactor cell, UV/visible light source and analyser for inorganic (e.g. NO_x analyzer HORIBA) and organic pollutants (e.g. GC/MS).

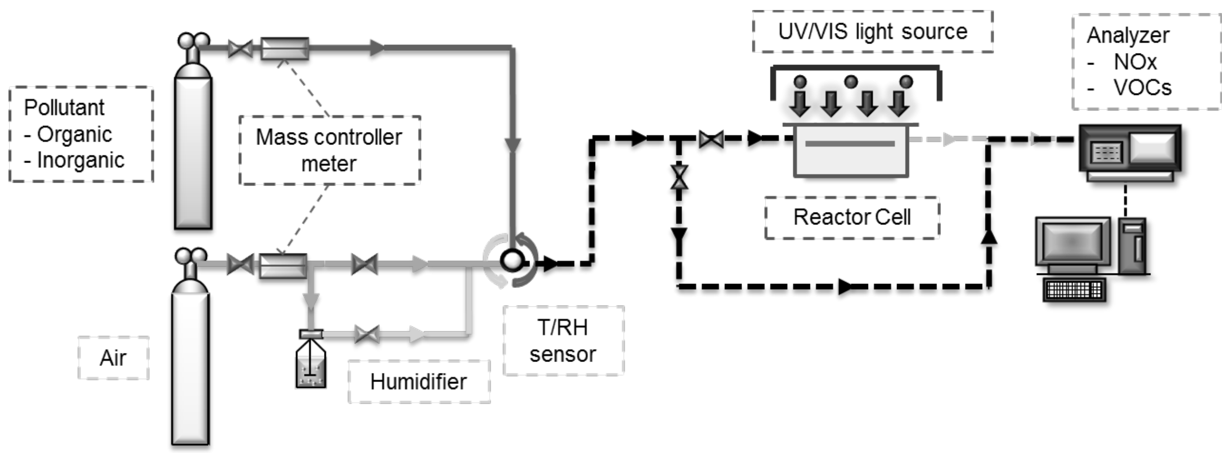

Figure 1 Experimental set up scheme

This set-up was built on the plug flow basis and it was used in the previous research to analyse the degradation of nitrogen oxide according to ISO Standard 22197-1 (10). Current research will use ISO Standard 22197-3, which is focused on the test method of air purification performance of semiconducting photocatalytic materials on removal of toluene, as a reference. The method described in this standard will be used with one difference and that is use of a visible light source instead of ultraviolet one. This will simulate indoor conditions accurately, because ultraviolet irradiation is in indoor conditions negligible.

This experimental set-up will be used for both the analysis of inorganic and organic indoor air pollutants. Firstly degradation of inorganic pollutant (NO_x) will be investigated. Later on, toluene will be used as a model organic pollutant and Thermal desorption/Gas chromatographer/Mass spectrometer (TDS/GC/MS) will be used for the analysis of its degradation and the intermediates produced by the PCO under visible light irradiation. Based on these results a reaction mechanism will be proposed.

The principal of the process is as follows: Pollutant is mixed with synthetic air to reach a desired target concentration and humidified by humidifier prior to introducing to the reactor cell, where the prepared sample is embedded. After the experimental conditions in the reactor are stabilized the light source is turned on to start the photocatalytic reaction and the results of pollutant degradation (inlet/outlet concentration) are recorded and analysed. The conversion of toluene will be calculated from the difference between the inlet and outlet toluene concentrations, as:

$$\%\, conversion = \frac{[Toluene]_{in} - [Toluene]_{out}}{[Toluene]_{in}} \cdot 100 \qquad \text{(eq. 1.10)}$$

The mineralization will be determined by comparing the concentration of carbon dioxide (CO_2) produced ($CO_{2\ meas.}$) to the theoretical one ($CO_{2\ theor.}$). If mineralization is complete: 1 mole of toluene should lead to the formation of 7 moles of CO_2 (13).

$$\% \, Mineralization = \frac{[CO_2]_{meas.}}{[CO_2]_{theor.}} \cdot 100 \qquad \text{(eq. 1.11)}$$

Where, $$[CO_2]_{theor.} = \frac{7 \cdot \% \, conversion \cdot [Toluene]_{in}}{100} \qquad \text{(eq. 1.12)}$$

Later on, a batch reactor will be designed and built to simulate the indoor conditions more precisely. Developed product will be applied on the walls of the reactor and the degradation of toluene will be analysed. To our knowledge no ISO standards cover the intended testing method. After verification of the efficiency of the developed product on the lab scale a real scale experiment will be performed. For this purpose a model office room available in Eindhoven University of Technology will be used.

Modelling

Kinetic modelling of the PCO of toluene on the developed product is part of the research. New kinetic reaction rate model of the toluene degradation will be proposed and later on this model will be used for 3-D model of the batch reactor and the degradation process within. For this part Computational Fluid Dynamic (CFD) software will be used, specifically FLUENT software, which was proved to be effective in the previous research (17).

Summary

"Indoor air purification using functional wall covering" project aims to develop a novel wall covering able to decompose indoor air pollutants by using photocatalytic technology. The idea is to use modified titanium dioxide, which is responsive to visible light irradiation, and apply it as an additive to a top-coat on the contract wall covering. This product will be tested for both the degradation of inorganic pollutant, such as nitrogen oxide (NO), and organic indoor air pollutants, specifically toluene, by PCO into harmless products.

C-doped TiO_2 will be initially used as a visible light responsive catalyst. The optimal composition (binder, solvent, additives, etc.) of the novel top coating will be experimentally designed and mix procedure will be developed. Furthermore the substrate preparation, application method and the drying procedure of the developed coating solution will be evaluated and optimized.

Kinetic modeling of the toluene degradation on the developed product will be built and used for the 3D modeling in the batch reactor under indoor air conditions using visible light irradiation.

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